

Low-frequency Tidal and Seasonal Water Level Variations in Florida Bay

by

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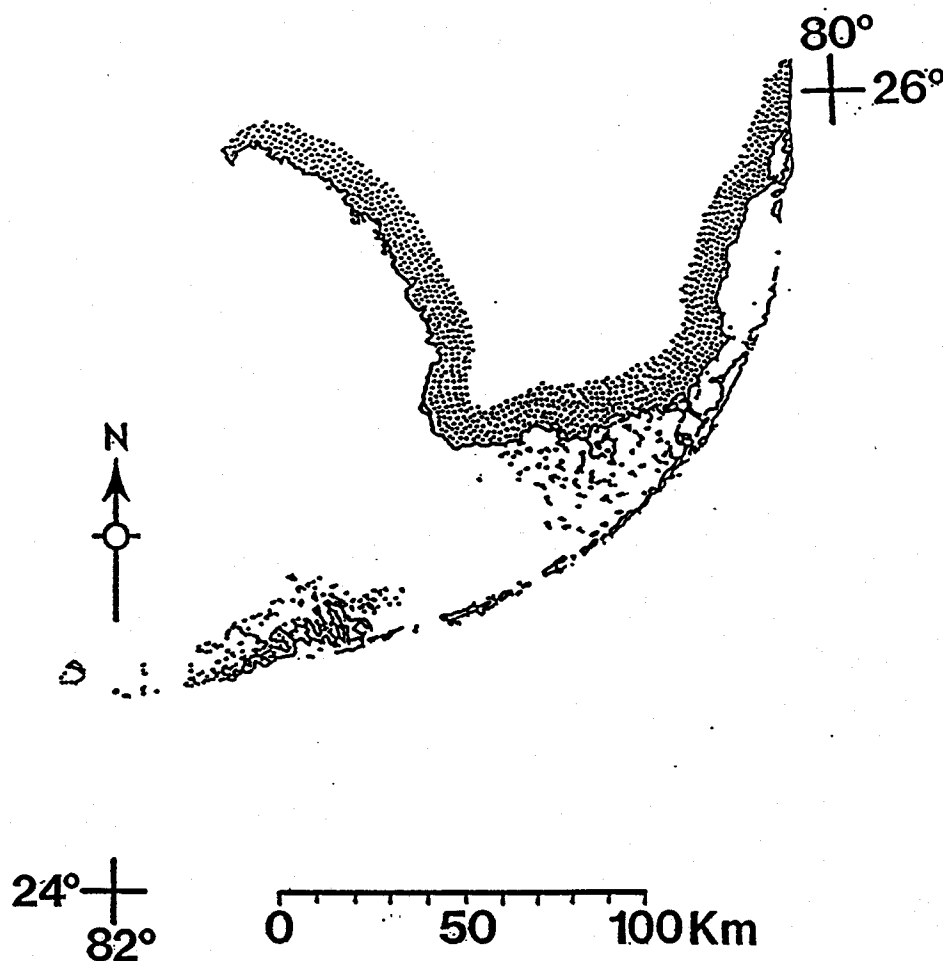
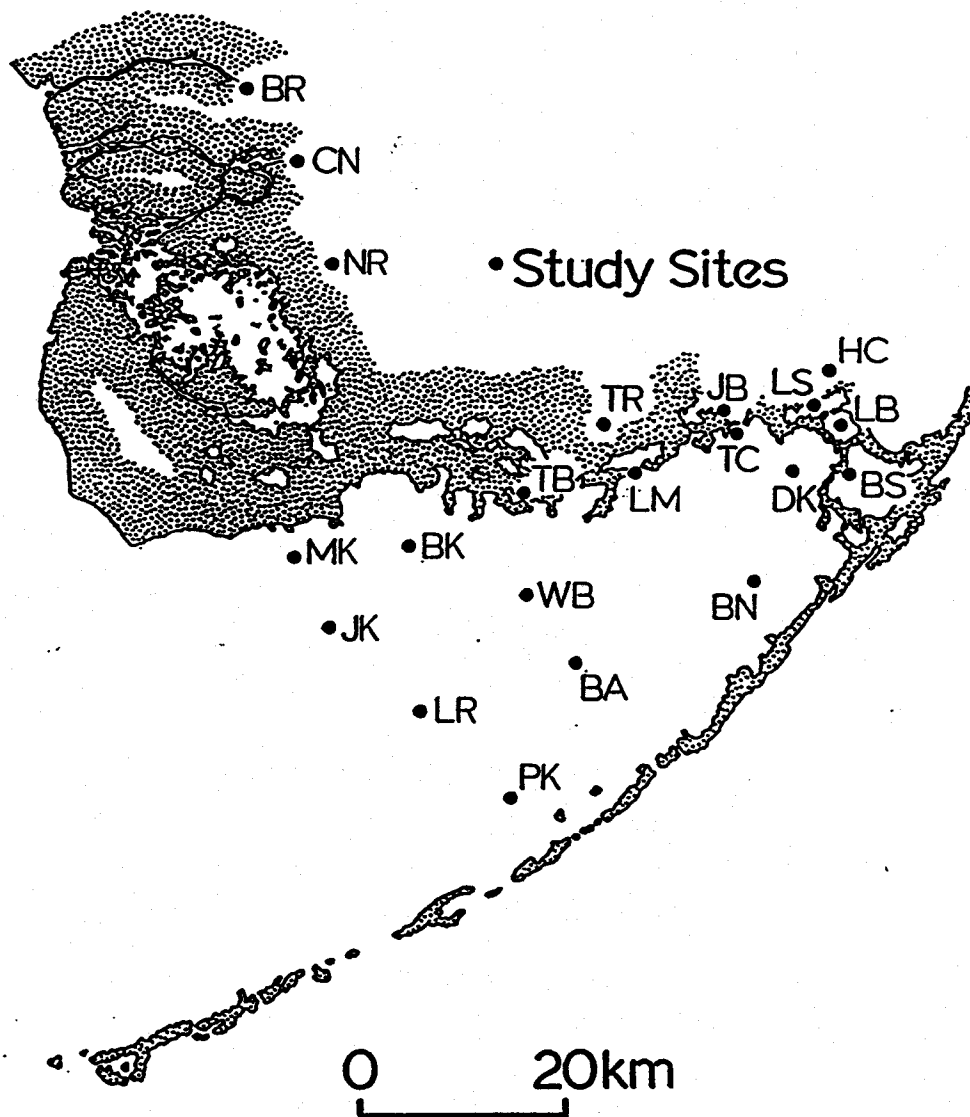


Figure 1. Map of Florida Bay, showing the Study area between the southern tip of the Florida Peninsula and the Florida Keys.

Figure 2. Map showing the locations of the 21 water level recording stations within and adjacent to Florida Bay.



long time series are retained, the number of stations contributing usable data decreases by 50%.

We loosely subdivide these stations into two broad categories, including (1) the study sites that lie outside Florida Bay proper,

above. The time scales over which sea level rises and falls in response to these mechanisms are on the order of 1-2 weeks when forced by meso-scale weather patterns, and one year when forced by the changing of the seasons.

The purpose of this report is to quantify and characterize water level variations in Florida Bay at the long-period end of the spectrum. Specifically, we include tables of harmonic constants (amplitudes and local phase angles) for the five tidal constituents noted above, and plots of low-pass filtered water level records that show the response to both tidal and meteorological forcing. We also use harmonic analysis to investigate the seasonal sea level cycle. Insofar as is possible with a limited ancillary data base, we attempt to determine the relative importance of the nontidal forcing mechanisms noted above.

DATA

This report focuses specifically on data collected at 21 stations within Everglades National Park (Figure 2). The first report, which dealt with much shorter time scales, was based upon a much broader data base. Time series must be on the order of one year long, however, to quantify long-period water level fluctuations. This eliminated a large fraction of the data base that was available for the characterization of diurnal and semidiurnal tidal constituents. For example, the NOS data base included diurnal and semidiurnal tidal constituents, but rarely fortnightly and longer constituents. Similarly, the Harbor Branch data base included time series that seldom exceeded two months in length. When only the

10-minute mean values represent a time of 5 minutes past the hour--the midpoint of the averaging period. For the long-period tidal constituents, the effect of a 5-minute time shift on the local phase angle is negligible, and the analysis assumed that water levels represent conditions at the top of the hour.

Water levels are recorded relative to a local datum, which is not related to NGVD, nor to local tidal conditions (mean low water, for example). The lack of a common datum has no effect on computations of tidal amplitudes. Similarly, plots of low-pass filtered time series need a stable datum when components are concatenated, but not a common datum between stations. A common datum plane will be required when the data base is used to investigate the surface topography of Florida Bay associated with wind forcing or fresh-water outflow.

Table 1 is a listing of National Park Service water level stations, and the segments of the water level records that were found to be suitable for plotting and analysis. The initial criteria for retaining any segment of a water level record involved both timing errors and depth errors. A record was dropped from further consideration if the timing error exceeded 5 minutes, or if the depth error exceeded 3 centimeters.

METHODS

Harmonic constants were quantified by the National Ocean Service least squares harmonic analysis computer program, known as "LSQHA" (Schureman 1958). The program was obtained directly from the NOS and verified by comparing results of their analysis of

and (2) the study sites that lie within Florida Bay itself. The distinction is important, because bodies of water isolated from each other respond to local forcing largely independently of each other. The study sites that are not located within Florida Bay proper include Broad River, Cane Patch, North River, Taylor River, Joe Bay, Highway Creek, Long Sound, Blackwater Sound, Little Blackwater Sound and Terrapin Bay. Study sites within Florida Bay include Murray Key, Johnson Key, Buoy Key, Whipray Basin, Little Rabbit Key, Peterson Key, Bob Allen Key, Little Madiera Bay, Trout Cove, Duck Key and Butternut Key.

The data base used in this report is restricted to water level records collected by National Park Service personnel from early 1990 through early 1994. The full data base begins as early as March, 1988, but some of the first records have been judged unreliable as a result of errors in timing or water level. Also, these records were not incorporated into this report, because in most cases additional data were not needed to characterize water level over sub-seasonal to annual time scales. More recent records were not used, because an arbitrary cut-off time was needed to stop adding data and start the analysis and interpretation.

All data reported here are from float-counterweight water level recorders. The rotation of the sprocket wheel is mechanically coupled to a potentiometer, which in turn sends a signal to a potentiometric recorder. The recorder takes a reading once each second, and values are averaged every ten minutes. Before analyzing a water level record, the five 10-minute averages from ten minutes to sixty minutes after the hour were discarded. The hourly

Plots of low-frequency water level variations were obtained by filtering the hourly data with a low-pass numerical filter (Lanczos 1956). The filter produces a 50% reduction of variance at a period of 37 hours, and a 90% reduction at a period of 48 hours. It is applied to 127-hour blocks of the input time series. Thus, the filtering process eliminates approximately two and a half days of data at both ends of the input time series. This is not a significant problem when the time series covers time intervals on the order of several thousand hours.

Harmonic analysis (Panofsky and Brier 1963) is used as a curve-fitting technique to reproduce the observed seasonal cycle. With four harmonics (12-, 6-, 4- and 3-month periodicities), 99.5% of the variance in the original curve can be reproduced (see Whitaker 1971, Marmer 1954).

RESULTS

a. Sea Level Rise

While the secular rise in sea level is not a required component of the second report, a review of sea level rise in the immediate vicinity of Florida Bay provides a useful perspective for the long-period variations in sea level that are the focal point of this report. Uninterrupted water level records have been made in Key West since 1913, and water level measurements--with gaps--extend back as far as 1846 (Maul and Martin 1993). Figure 3 is a plot of annual mean water levels calculated from the uninterrupted Key West time series through 1990. The linear slope calculated for this 79-year period is 1.9 mm yr^{-1} . This is in good agreement with

their data with results of our analysis of the same data. When our results matched theirs, we judged our version of the program to be in working order.

The computer program requires an input time series of at least 180 days of hourly data. However, our experience suggests that amplitudes and local phase angles computed for the annual tidal constituent are unreliable if the time series is less than one year long. Thus, we quantify the Sa and Ssa constituents only when we have a full year of data. Sixteen stations have produced uninterrupted one-year water level records to date. Five stations (Broad River, Murray Key, Duck Key, Little Blackwater Sound and Taylor River) have not provided one-year time series for analysis. All time series between 6 and 12 months long can be used to quantify the fortnightly and monthly tidal constituents, however.

While a one-year record provides a valid measure of the amplitude and local phase angle for the station and the time period in question, considerable scatter often appears when several one-year time series are available from the same station. To obtain a reliable measure of the amplitude or local phase angle, a time series must span a minimum of several tidal cycles. An unwritten rule in time series analysis suggests that seven full cycles must be included to damp the spurious effects of nontidal processes adequately. Because the Sa and Ssa constituents should vary little through Florida Bay, we have vector-averaged harmonic constants for many one-year analyses at a given location, and/or many stations from throughout the bay to obtain representative harmonic constants for these two tidal constituents.

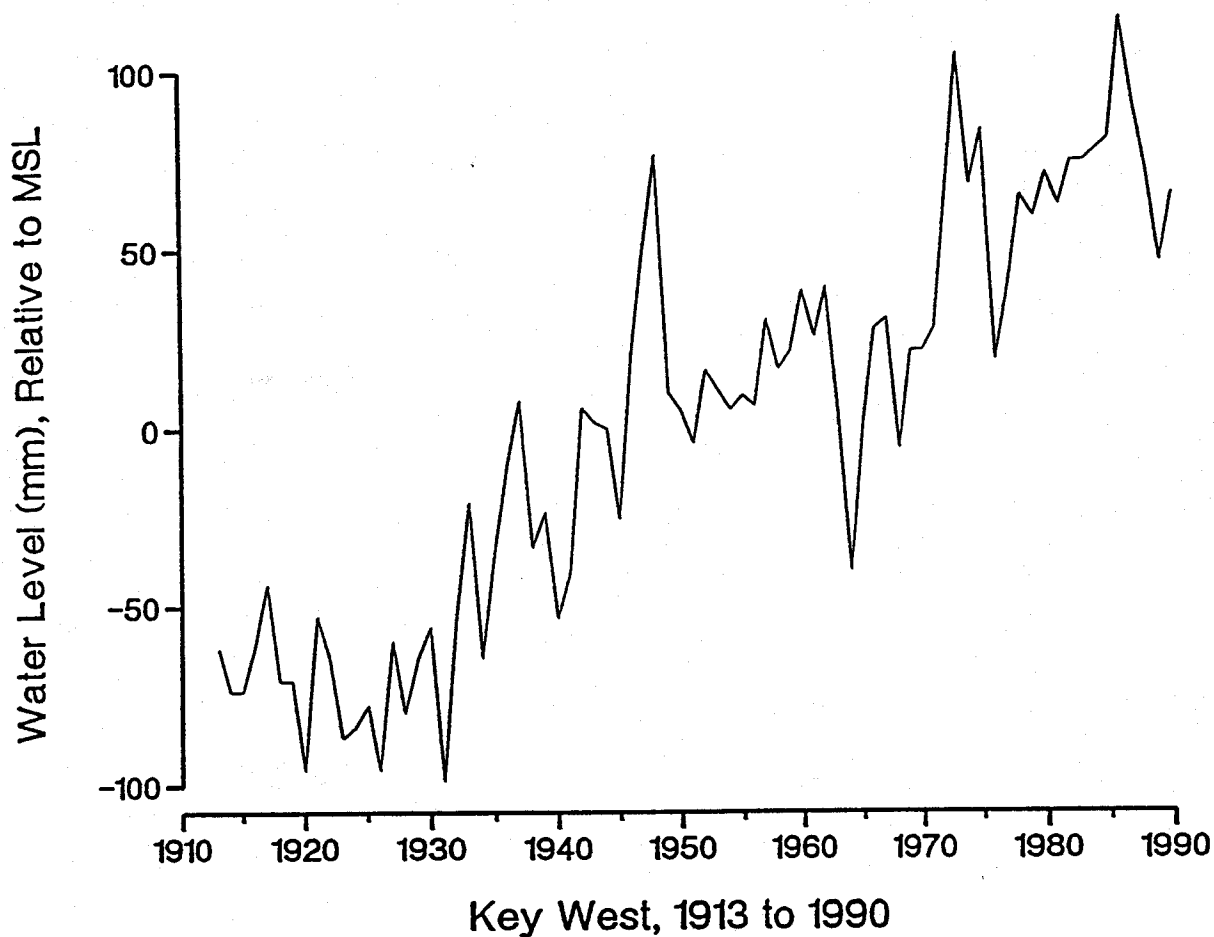
surrounding Key West. Subtracting the linear increase in sea level from the Key West data, the standard deviation of the detrended time series is approximately 2.5 cm. It is useful to keep this measure of interannual sea level variability in mind when assessing the importance of tidal and nontidal water level fluctuations over annual and shorter time scales.

b. The Seasonal Cycle

The seasonal cycle of sea level has been a subject of considerable interest for many decades. This is especially true in areas with low-amplitude astronomical tides, where the seasonal rise and fall in sea level governs the exposure and inundation of mud flats, for example, as much as the shorter period rise and fall of the tide. Mairner (1954) compiled multiannual monthly mean sea levels from stations around the fringe of the Gulf of Mexico. From this and other studies, regional differences appear, but the general pattern consists of a late-winter minimum, followed by a slow and irregular rise to an annual maximum sea level that usually occurs in October. The average annual range varies from just under 20 cm at Havana to just over 40 cm in Tampico. The range at Key West is 22 cm, which is 5 cm less than the average range for all stations around the Gulf of Mexico.

Figure 4 shows the sea level cycle at Key West, simulated from the 12-, 6-, 4- and 3-month harmonics that were calculated from multiannual mean monthly water levels. Following the annual low in February, the curve rises to a midsummer plateau, and then to the annual maximum in early October. The curve then decreases abruptly in late fall and early winter, as it approaches the annual minimum

Figure 3. Annual mean water levels from Key West, Florida, 1913 to 1990. Values, in mm, are departures from the 1913-1990 mean.



sea levels calculated throughout the world--where the local rise or fall of the coast itself does not mask the effect of sea level rise (Emery and Aubrey 1991). It is assumed that the increase in sea level recorded at Key West is a close approximation of sea level rise for Florida Bay, although long-term variations in freshwater runoff would certainly impact Florida Bay more than the waters

seasonal rise and fall of sea level in Florida Bay.

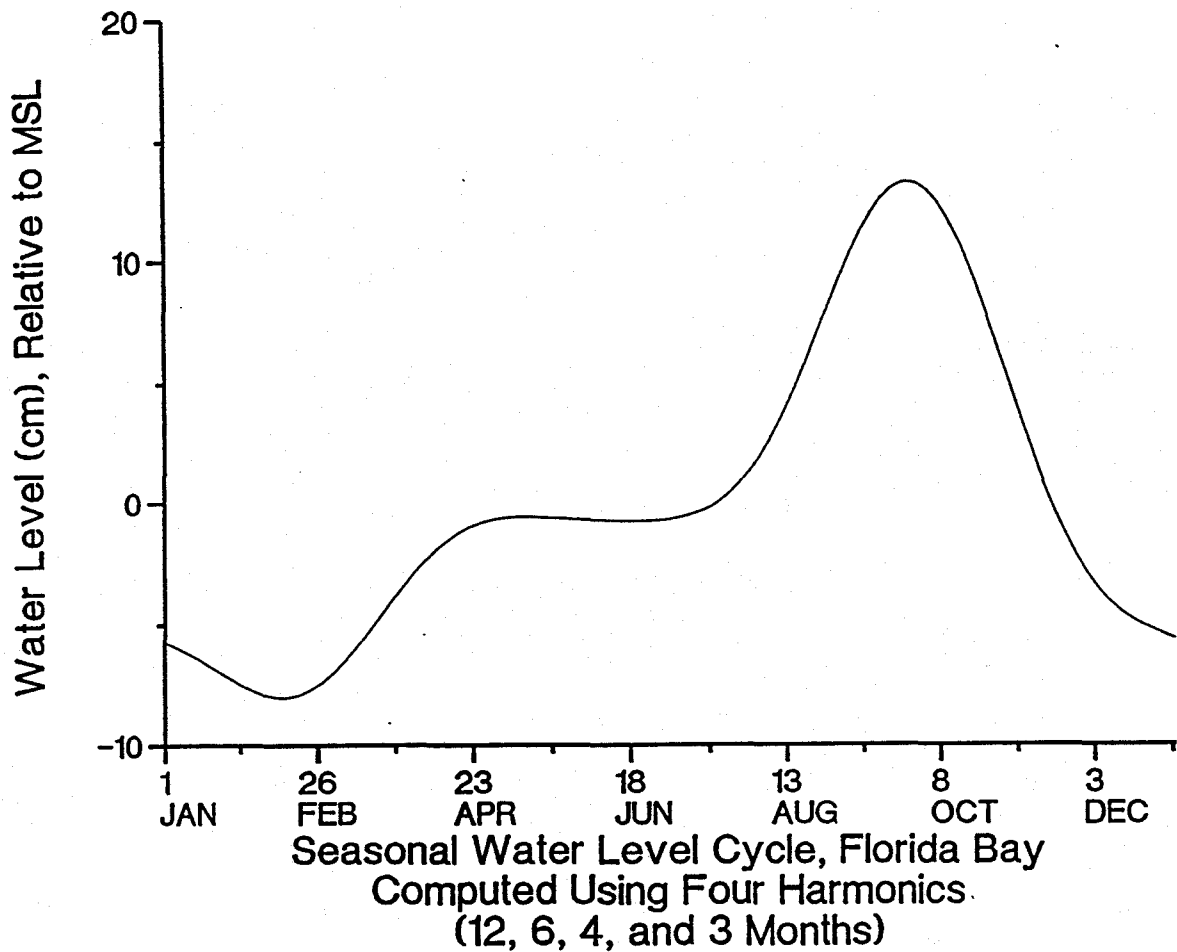
1. fortnightly and monthly tidal constituents

The fortnightly, Mf and Msf, constituents, and the monthly, Mm, constituent describe the long-period tidal rise and fall in sea level over sub-seasonal time scales. Results of the harmonic analyses to quantify the long-period tides are summarized in Table 2. Harmonic constants are included only when amplitudes exceed 0.5 cm. The Mf tidal constituent is of such small amplitude that it is of negligible practical importance. None of the analyses produced an amplitude greater than 1.7 cm, and amplitudes were greater than 1 cm at only four stations. Because this constituent has such small amplitudes, it was dropped from further consideration.

The Msf constituent, with a periodicity of 354.4 hours (or 14.77 days), arises from the interaction of the sun's and moon's tide-producing forces as the moon revolves around the earth every synodic month (29.53 days). The co-amplitude chart for the Msf constituent is shown in Figure 5. As discussed earlier, it is relatively featureless, because data from only ten study sites within Florida Bay proper are available, and because the frictional damping of long-period tidal constituents is negligible even in shallow water. Figure 5 indicates slightly higher amplitudes in the northwestern corner of the bay. The highest value was 3.5 cm at Johnson Key. In the north-central and northeastern parts of the bay, all amplitudes are within a few tenths of 2.0 cm.

The Mm tidal constituent arises from the elliptical orbit of the moon around the earth. The anomalistic month has a periodicity of 27.55 days, but this is nevertheless referred to as a monthly

Figure 4. The seasonal sea level cycle for Florida Bay, computed from monthly means of water levels recorded at Key West.

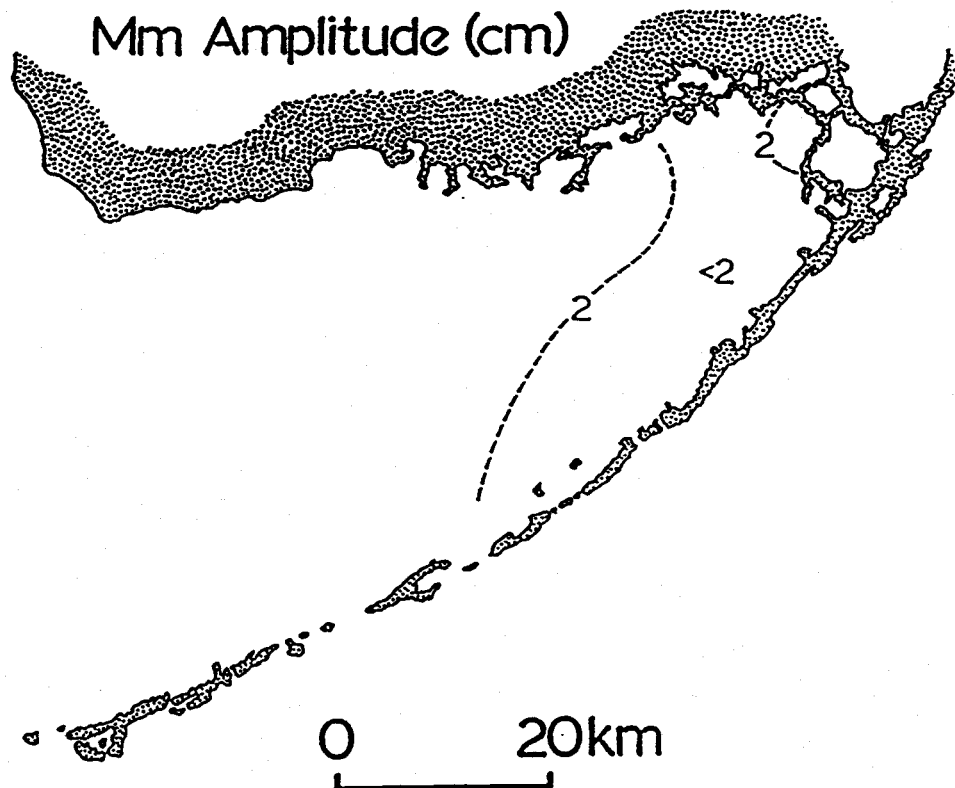


noted above. Freshwater outflow may be more important at stations in the interior of Florida Bay, but the general shape of the curve should be similar.

c. Long-period Tides

This sub-section includes both the fortnightly and monthly tidal constituents, and the longer semiannual and annual tidal constituents. The latter two constituents explain a large part of the

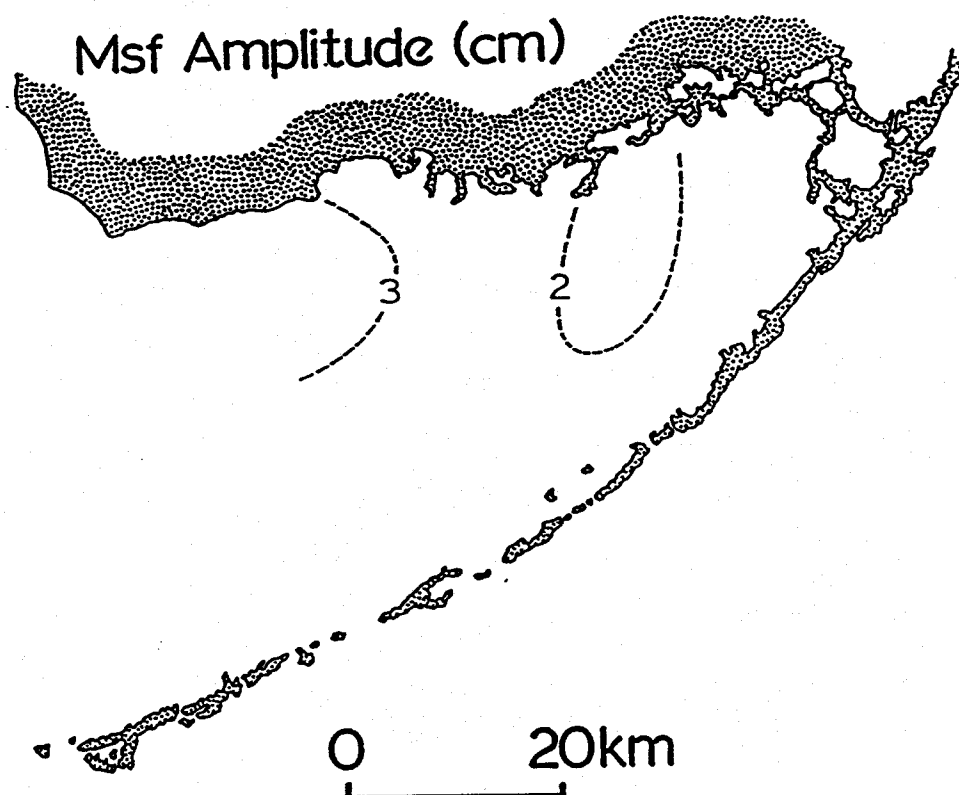
Figure 6. Co-amplitude chart for the monthly Mm tidal constituent in Florida Bay. Amplitudes (in cm) are computed using results from 14 stations.



2. semiannual and annual tidal constituents

Harmonic constants for the semiannual, Ssa, and annual, Sa, tidal constituents are summarized with a harmonic dial (Figure 7). Amplitude is represented by the radial distance from the center of the dial; the local phase angle is represented by the clockwise angle, with 0° at the top of the dial. Due to the amount of non-tidal contamination occurring over these same time scales--wind effects, steric effects, etc.--considerable scatter appears for

Figure 5. Co-amplitude chart for the fortnightly M_{sf} tidal constituent in Florida Bay. Amplitudes (in cm) are computed using results from 14 stations.



constituent. Results, shown in Figure 6, are similar to those found for the M_{sf} constituent. All amplitudes are between 1.9 and 2.5 cm, and differences from one station to the next may not reflect a persistent spatial pattern. Again, however, highest amplitudes appear in the northwest corner of the bay. With the exception of Duck Key, lowest amplitudes occur along the eastern fringe of the bay.

use the tide prediction techniques described by Schuremann (1958) to construct the curve shown in Figure 8. The pattern includes a low water level in early February, approximately 10 cm below the annual mean, followed by a gradual and irregular rise during spring and summer months to the autumnal high in early October. The cycle is completed with a relatively rapid drop of about 20 cm during late fall and winter months. The sea level curve simulated by these two tidal constituents does not reproduce the midsummer plateau, nor does it provide a sharp peak in October. The corre-

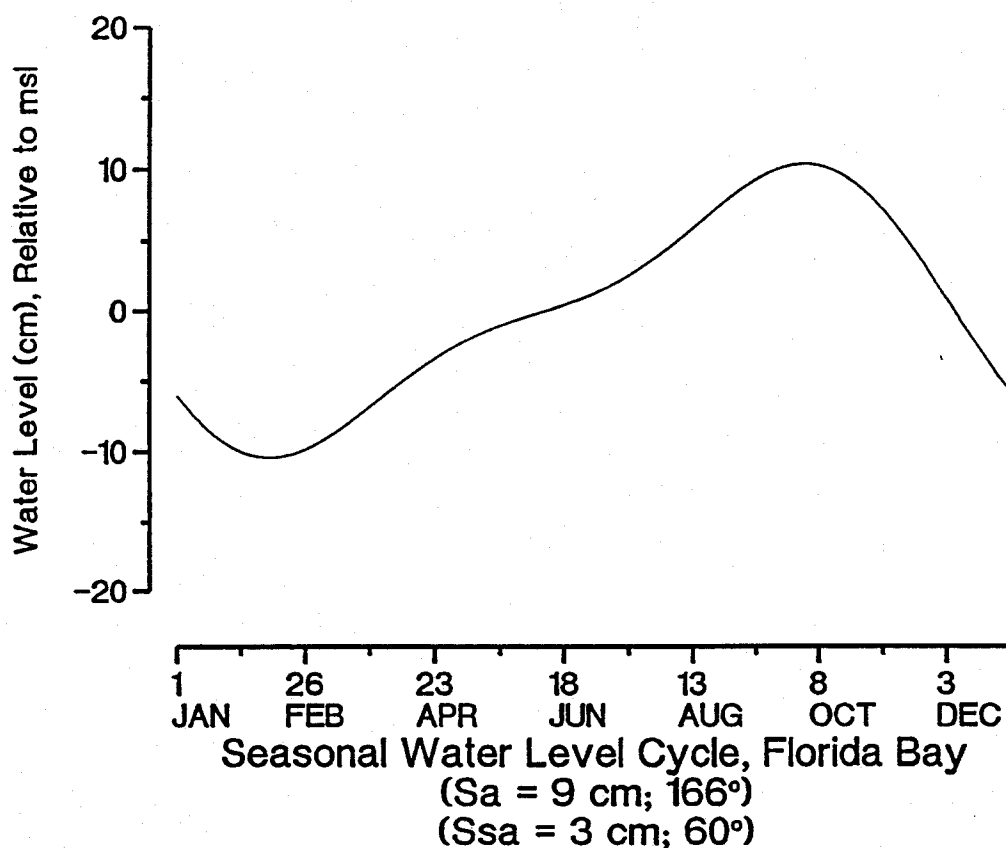
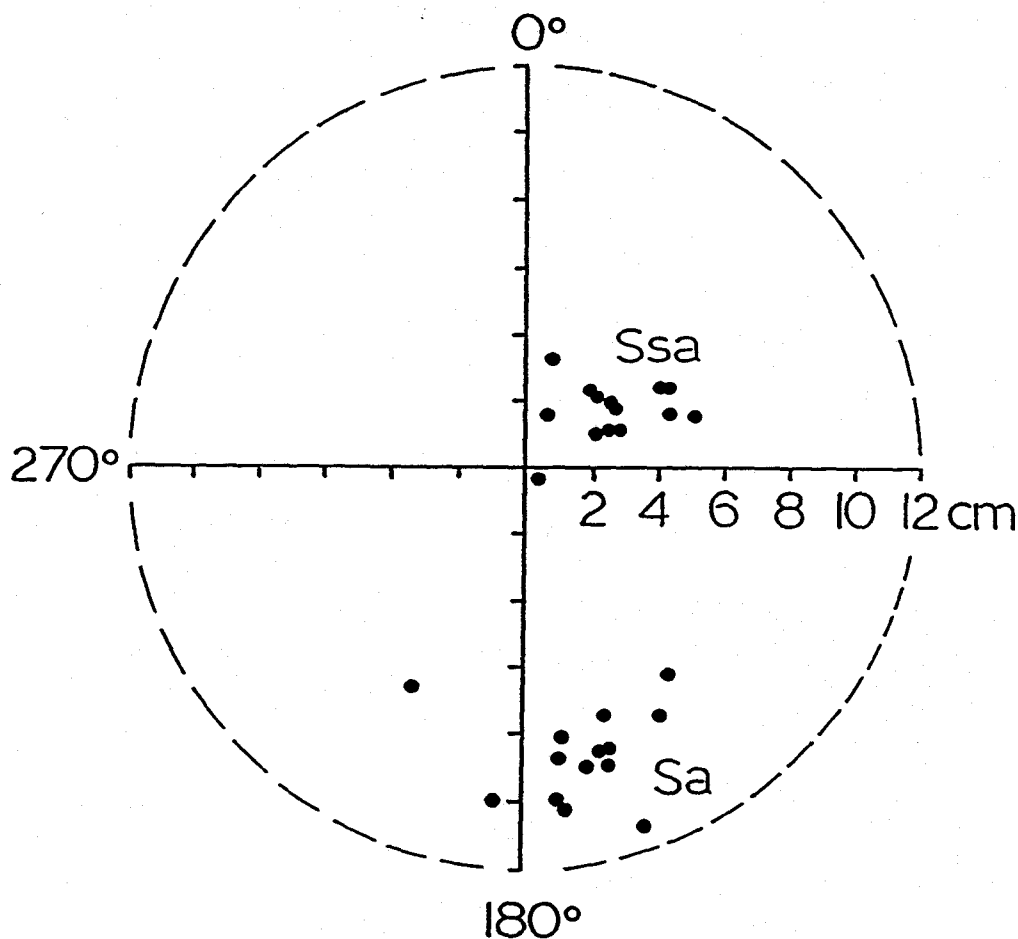


Figure 8. The seasonal sea level cycle for Florida Bay, computed from the S_a and S_{sa} tidal constituents.

Figure 7. Harmonic dial, combining amplitudes (in centimeters) and local phase angles (in degrees) of the annual (Sa) and semiannual (Ssa) tidal constituents for 14 stations in Florida Bay. Amplitudes are given by the radial distance from the center of the dial; local phase angles are given by the clockwise angle from the top of the dial. Calculations were made using uninterrupted one-year time series in the NOS least squares harmonic analysis computer program.



both constituents. Nevertheless, representative values emerge. The Sa constituent has an amplitude of approximately 9 cm and a local phase angle of about 166°; the Ssa constituent has an amplitude of about 3 cm and a local phase angle of about 60°.

With the assumption that the seasonal variation in sea level can be represented by the Sa and Ssa tidal constituents, one can

cy variability obscures the underlying seasonal cycle, while in other cases components of the seasonal cycle are simply missing. This year-to-year and station-to-station variability in the seasonal pattern is directly related to the considerable amount of scatter noted earlier in the harmonic constants of the S_a and S_{sa} tidal constituents (Figure 7). Data from Johnson Key recorded during 1990 (Figure NWLJK), for example, show great variability throughout the year. Similarly, water levels from Whipray Basin, (Figure NWLWB) remain relatively flat throughout 1992. In some cases, parts of the seasonal cycle appears, while other parts are poorly defined. In Figure NWLHC for Highway Creek (1992) or Figure NWLWB for Whipray Basin (1992), a midwinter minimum appears, but the autumn high is poorly developed or missing. In general, 1992 seems to have been a poor year for the October maximum in the level of the bay. On the other hand, the 1990 and 1991 data from Butter-nut Key (Figure NWLBK) show the seasonal cycle relatively clearly, even though the nontidal fluctuations raise and lower water level 5-10 cm relative to the seasonal norm.

Nontidal fluctuations within a given season vary distinctly over the course of the year. Generally speaking, over time scales ranging from days to weeks, nontidal variations in bay level are significantly greater in winter months than in summer months. This is an expected feature, because midsummer months tend to be relatively quiescent in terms of meteorological forcing. Figure NWLBK, for example, shows for Buoy Key a transition from relatively large nontidal water level variations early in the year to relatively small fluctuations from June through September. It is noteworthy,

lation coefficient calculated from the hourly data used in Figures 4 and 8 is +0.93, indicating that 87% of the variance of the seasonal cycle (constructed from monthly mean water levels) can be accounted for by the Sa and Ssa tidal constituents. The remaining 13% arises from the same nontidal processes that combine to produce the scatter in the harmonic constants of the annual and semiannual constituents.

d. Low-frequency Nontidal Water Level Variations

Low-frequency, nontidal water level variations include the rise and fall of the level of the bay primarily over two time scales. The first is the 1-2 week quasi-periodic time scale normally associated with the movement of weather systems through the study area. The second is the annual time scale that is associated with seasonal changes in wind speed and direction, seasonal variations in surface air pressure patterns and seasonal variations in rainfall. While the relative importance of the forcing mechanisms summarized by Montgomery (1937) can be determined only with a data base that is prohibitively expensive, the effects themselves are revealed by filtering the hourly water level records and plotting the results. Appendix A contains low-pass filtered water level records from 21 stations, collected between January 1990 and early 1994. We do not describe each figure individually, but we choose individual figures to make some general points regarding both the low-frequency (days to weeks), as well as seasonal variability in the water level of Florida Bay.

It is difficult to characterize the annual signal in the plots of low-frequency nontidal water level. In some cases, low-frequen-

was sufficient to raise the level of the exposed part of Florida Bay by about 40 cm. The absence of a similar signal in the data from Joe Bay (Figure NWLJB) and Long Sound (Figure NWLLS) and Taylor River (Fig. NWLTR), for example, reinforces the idea that study sites within and outside of Florida Bay proper do not respond to meteorological forcing in a similar way.

Nontidal sea level related to freshwater outflow sometimes takes on a distinctive appearance, consisting of a relatively sharp rise followed by a relatively gradual decrease. Data from Taylor River (Figure NWLTR) contains several of these features in the plot constructed from the 1992 water level records. In late June, for example, water level rises approximately 25 cm very quickly, then drops back to near its starting level over the following month.

DISCUSSION

While co-amplitude and co-phase charts formed the basis of the first report, summarizing calculations in this way is inappropriate when investigating annual and semiannual tidal constituents. Relatively few stations are available to provide the data needed to contour isopleths of amplitude and local phase angle (see Figure 2). Even with more stations from the western and southeastern margins of the bay, one would find relatively little damping of these long-period tidal constituents. Frictional resistance to the very slow filling and draining of the bay is small. As a result, there is little exterior-to-interior decrease in amplitude. Finally, the scatter that arises from year-to-year variability in the seasonal sea level cycle at a given location is of the same magnitude as the

however, that this feature is poorly defined in 1992. Similarly, the 1991 data from Johnson Key (Figure NWLJK) shows damped water level variations from June through September.

Not quantified in this report, yet apparent upon close examination of many of the plots, is the similarity of the low-frequency component fluctuations. Superimposing data obtained from Bob Allen Key (Figure NWLBA) and Whipray Basin (Figure NWLWB), for example, reveals a striking degree of similarity over time scales on the order of a few days. This result supports the conclusion that over these time scales the water level of Florida Bay more or less rises and falls together throughout the bay. Comparing data from stations within and outside the bay proper, however, one gets a different picture. Data from Buoy Key (Figure NWLBK) and Taylor River (Figure NWLTR), for example, show similar features only in the most general sense. The latter is much more responsive to freshwater runoff effects, while the former is more closely coupled to wind effects--the set-up or set-down of water levels--along the northern rim of the bay.

One feature that appears in most of the plots from stations in Florida Bay proper is the response to the "storm of the century" in mid March of 1993. Strong winds out of the westerly quadrant forced water into the bay and produced a "spike" in the plots of the data from Bob Allen Key (Figure NWLBA), Buoy Key (Figure NWLBK), Duck Key (Figure NWLDK), Peterson Key (Figure NWLPK) and Terrapin Bay (Figure NWLTB). Several time series are interrupted at that time, suggesting that the storm was strong enough to damage the platforms from which water level is recorded. This wind event

pheric pressure, and vice versa. The response of sea level to air pressure is approximately 1 cm mb^{-1} . This process does not involve the compression and expansion of the water column, thus the adjustment to air pressure will occur only when and where water can move horizontally from regions of increasing surface atmospheric pressure to regions of decreasing surface pressure. The inverse barometer is of negligible importance in small, enclosed basins, but over long time scales it can be important even in basins with severely restricted exchanges. Because water exchanges relatively freely between Florida Bay and both the Gulf of Mexico and the Atlantic Ocean, one might expect sea level to rise 4 cm from January to May, when monthly mean atmospheric pressure falls from 1018 to 1014 mb. Similarly, sea level should fall 2 cm during June and July, when air pressure rises 2 mb. The coincidence of high sea level with low air pressure in October is further evidence of an air-sea coupling by the inverse barometer effect. The correlation coefficient computed from mean monthly sea level and mean monthly surface air pressure is -0.75. While this is statistically significant and supports the suggestion that the inverse barometer effect plays an important role, it demonstrates that this is only one of the processes that influence the seasonal sea level cycle.

The effect of wind on the seasonal cycle of sea level in Florida Bay is not clear, but climatological data from Key West and Miami (U.S. Dept. of Comm. 1985) suggest that the set-up and set-down of bay water level is minor at best. Monthly resultant wind directions are southeast or east-southeast from February through September, then northeast or east-northeast from October through

station-to-station differences in a given year. With significant nontidal contamination, very long time series must be available to construct co-amplitude and co-phase charts.

The extent to which the observed seasonal rise and fall of the level of Florida Bay can be attributed to nontidal forcing is limited by the amount of ancillary data, especially local weather data during the 1990-1994 time period. Nevertheless, some inferences can be made using climatological data from Miami and Key West, and using hydrographic data from surrounding Atlantic and Gulf waters.

The steric component of the annual rise and fall in sea level has been quantified by Whitaker (1971), who calculated the seasonal expansion and contraction of the upper 150 meters of the water column using hydrographic data from throughout the Gulf of Mexico. Results (not shown) indicate that the water column expands about 8 cm from the late-winter low value recorded in March. This suggests that, on average, steric contraction explains about half (3.4 cm) of the midwinter minimum in sea level (7 cm below the annual mean), while steric expansion accounts for one-third (4.5 cm) of the autumn maximum sea level (13.5 cm above the annual mean).

Climatological data from Key West and Miami (U.S. Dept. of Comm. 1985) suggest that seasonal variations in surface air pressure contribute to the seasonal sea level cycle, especially to the midsummer plateau, through the inverse barometer effect. A plot of monthly mean surface pressure (not shown) shows highest values in midwinter months, and a secondary maximum in July. Lowest values occur in May and September-October. The inverse barometer effect states that sea level will be lower under regions of higher atmos-

Current penetrates well into the Gulf of Mexico, the southward flowing, downstream end can lower water level along the southwest Florida coast and in the Keys. The effect of the Florida Current alone is greater than the observed rise at Key West from June to October (about 15 cm), again suggesting that several processes interact to produce the observed sea level cycle.

It is likely that the annual variation in rainfall (and the resulting surface runoff) contributes to both the midsummer and the fall maximum sea levels. Rainfall data from Miami (NOAA 1986) indicate that highest monthly totals occur in June and September (23 and 20 cm, respectively). Because direct rainfall data are not available for the bay, and because evaporation data are not available to calculate the net effect, the response to freshwater gains and losses cannot be quantified. One can only conclude tentatively that precipitation (including the indirect effects of surface runoff) plays a significant role in the seasonal rise and fall in the level of the bay.

Clearly, one of the more important effects of low-frequency and seasonal variations in bay level is the alternate exposure and inundation of extensive shallow-water areas. This is especially true in the interior of the bay, where the semidiurnal and diurnal rise and fall of the tide are virtually absent. Low-frequency fluctuations are commonly between 10 and 20 cm, and the range of the semidiurnal and diurnal tide is less than 5 cm through much of the interior of the bay. The interplay of tidal and nontidal water level variations determines the observed rise and fall in the level of the bay, but it is clear that the long-period processes are pri-

January. Wind-driven transport in shallow water is very nearly in the direction of the wind (not 90° to the right, as theory predicts for deep water). Thus, the wind-driven transport of water from the Gulf into the bay should be slight when winds are out of the southeasterly quadrant. The lowering of bay levels from October through January, on the other hand, may be aided by winds out of the northeasterly quadrant, which would act to remove water from the bay. Monthly resultant wind directions do not suggest that winds consistently force water into the bay in any season of the year. The importance of wind forcing cannot be quantified with the available data base, but this qualitative comparison suggests that wind effects are of distinctly secondary importance over seasonal time scales.

The Loop Current and the Florida Current might also be playing a role in raising and lowering Florida Bay levels. Major ocean currents such as these have measurably lower water levels along their left boundaries, looking downstream. For example the mean sea level difference between Bimini and Miami is 62 cm (Maul 1986). Seasonal variations in volume transport are highly correlated with seasonal variations in the sea level difference across the current, with most of the variation occurring on the Florida side (Maul et al. 1985). A 1 Sv ($1 \text{ Sverdrup} = 10^6 \text{ m}^3\text{s}^{-1}$) change in Florida Current volume transport produces an approximately 3 cm change in the Bimini-Miami sea level difference. Between late summer and late fall, the mean volume transport of the Florida Current decreases by approximately 8 Sv, suggesting a sea level increase of about 25 cm along the southeast coast of Florida. Similarly, when the Loop

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marily responsible for prolonged periods of exposure or inundation in the interior of the bay. Even where the semidiurnal and diurnal rise and fall of the tide covers a range of several centimeters, long-period processes are dominant. Low tide levels in October, when seasonal sea level is highest, can actually be higher in the interior of the bay than high tide levels in January, when seasonal water levels are lowest. The rise and fall of the intertidal zone makes it impossible to define a stable intertidal zone, containing plant and animal communities that require or tolerate alternate exposure and inundation over time scales on the order of hours. The important point here is that while the annual and semiannual tidal constituents may be unimportant in terms of flushing because of their very long periodicities, they may play a valuable role in the ecology of the bay by providing persistent inundation or exposure to air and sunlight.

Joe Bay	DJB9091	1405 Jan. 04, 1990	1405 Mar. 19, 1991	10,537
	DJB91A	1005 Oct. 21, 1991	1405 Dec. 16, 1991	1,349
	DJB92A	1305 Jan. 23, 1992	1505 July 16, 1992	4,203
	DJB9293	1005 July 20, 1992	0805 May 24, 1993	7,391
	DJB9394	1105 June 14, 1993	1205 Jan. 12, 1994	5,090
Johnson Key	DJK8990	1805 Nov. 28, 1989	1305 Feb. 09, 1990	1,748
	DJK90A	1405 Mar. 26, 1990	2105 Aug. 04, 1990	3,152
	DJK9091	1705 Sep. 08, 1990	1305 Sep. 17, 1991	8,973
	DJK9192	1505 Oct. 23, 1991	1205 May 13, 1992	4,870
	DJK93A	1205 Feb. 10, 1993	0505 Mar. 13, 1993	738
	DJK93B	1305 Mar. 24, 1993	1005 May 26, 1993	1,510
	DJK93C	1405 Sep. 09, 1993	2005 Oct. 25, 1993	1,111
Little Blackwater Sound	DLB9192	1505 Sep. 11, 1991	1005 Mar. 30, 1992	4,820
	DLB9293	1305 Apr. 14, 1992	1305 Mar. 10, 1993	7,921
	DLB9394	1105 June 13, 1993	1105 Jan. 24, 1994	5,401
Little Madeira Bay	DLM9092	1605 Jan. 04, 1990	1105 Dec. 31, 1992	26,204
	DLM93A	1505 Feb. 16, 1993	0805 May, 19, 1993	2,202
	DLM9394	1505 Sep. 07, 1993	1505 Jan. 13, 1994	3,073
Little Rabbit Key	DLR9093	1405 Jan. 03, 1990	1305 Mar. 12, 1993	27,936
	DLR93A	1105 Mar. 24, 1993	1505 May 26, 1993	1,517
	DLR93B	1105 June 25, 1993	1105 Nov. 12, 1993	3,361
	DLR9394	1505 Dec. 27, 1993	1405 Jan. 25, 1994	696
Long Sound	DLS9092	1205 Jan. 04, 1990	1305 Apr. 14, 1992	19,946
	DLS9293	1205 Nov. 20, 1992	1005 May 18, 1993	4,295
	DLS9394	1205 June 14, 1993	1205 Jan. 24, 1994	5,377
Murray Key	DMK93A	1305 Feb. 10, 1993	0405 Mar. 13, 1993	736
	DMK93B	1105 Apr. 26, 1993	1005 May 26, 1993	720
	DMK93C	0905 June 25, 1993	0105 Oct. 31, 1993	3,065
	DMK9394	0905 Nov. 12, 1993	1505 Jan. 20, 1994	1,663
North River	DNR90A	1705 Feb. 03, 1990	0805 June 19, 1990	3,256
	DNR9091	0605 July 03, 1990	1505 Feb. 14, 1991	5,434
	DNR9192	1105 Mar. 20, 1991	1105 July 22, 1992	11,761
	DNR93A	1405 Jan. 12, 1993	0605 Mar. 13, 1993	1,433
	DNR93B	1205 Mar. 16, 1993	1505 Apr. 27, 1993	1,012
	DNR93C	1305 June 20, 1993	1705 Aug. 04, 1993	1,085
	DNR9394	1405 Sep. 15, 1993	1605 Jan. 11, 1994	2,835
Peterson Key	DPK9091	1505 Jan. 05, 1990	0505 Nov. 14, 1991	16,263
	DPK9192	1105 Nov. 18, 1991	0205 July 17, 1992	5,700
	DPK92A	1205 Aug. 14, 1992	0905 Nov. 25, 1992	2,470
	DPK9293	0505 Nov. 27, 1992	1605 May 26, 1993	4,332
	DPK9394	1105 June 25, 1993	1505 Jan. 25, 1994	5,141
Taylor River	DTR9091	1005 June 12, 1990	1105 Apr. 25, 1991	7,610
	DTR91A	1105 June 17, 1991	1105 Dec. 12, 1991	4,273
	DTR9192	0705 Dec. 14, 1991	1305 Mar. 06, 1992	1,999
	DTR92A	1505 Mar. 20, 1992	1205 May 15, 1992	1,342
	DTR9293	0905 May 17, 1992	1205 Apr. 22, 1993	8,164
	DTR93A	1005 July 27, 1993	1305 Dec. 22, 1993	3,556

Table 1. Summary of the National Park Service water level records used to quantify tidal harmonic constants and construct analog plots. Times are in Eastern Standard Time. The column labelled 'Obs'ns' contains the number of hourly data points in each record.

Study Site	Filename	Start Time & Date	End Time & Date	Obs'ns
Blackwater Sound	DBS9193	1305 Oct. 22, 1991	0905 Feb. 11, 1993	11,469
	DBS93A	1705 Oct. 06, 1993	1505 Nov. 15, 1993	959
	DBS94	1105 Jan. 04, 1994	1005 Jan. 24, 1994	480
Bob Allen Key	DBA9092	1105 Jan. 03, 1990	1005 Mar. 19, 1992	19,344
	DBA9293	1005 Apr. 17, 1992	1705 May 26, 1993	9,704
	DBA9394	1205 June 25, 1993	1605 Jan. 25, 1994	5,141
Broad River	DBR90A	1305 Jan. 18, 1990	1105 Oct. 12, 1990	6,407
	DBR9091	1305 Nov. 13, 1990	1005 Feb. 14, 1991	2,230
	DBR91A	1405 Mar. 20, 1991	1005 May 15, 1991	1,341
	DBR91B	1405 June 19, 1991	1205 Sep. 19, 1991	2,207
	DBR9192	1605 Dec. 18, 1991	1305 July 22, 1992	5,206
	DBR93A	1405 Mar. 09, 1993	1105 Apr. 30, 1993	1,246
	DBR9394	0705 June 20, 1993	1305 Jan. 11, 1994	4,927
Buoy Key	DBK9091	1705 Jan. 03, 1990	1505 Mar. 15, 1991	10,463
	DBK9192	1405 Apr. 08, 1991	1605 Mar. 19, 1992	8,307
	DBK92A	1305 Apr. 01, 1992	0005 Oct. 08, 1992	4,548
	DBK9293	1205 Oct. 13, 1992	1105 May 21, 1993	5,280
	DBK9394	0805 June 25, 1993	1405 Jan. 20, 1994	5,023
Butternut Key	DBN9091	1004 Jan. 03, 1990	1505 Oct. 17, 1991	15,654
	DBN9192	1605 Nov. 21, 1991	0905 Mar. 30, 1992	3,114
	DBN9293	1505 Apr. 13, 1992	1405 Mar. 11, 1993	7,920
	DBN93A	0905 Mar. 12, 1993	1505 May 27, 1993	1,831
	DBN93B	0505 June 15, 1993	1605 Nov. 11, 1993	3,684
	DBN9394	0705 Nov. 20, 1993	1305 Jan. 24, 1994	1,567
Cane Patch	DCN90A	1705 Jan. 19, 1990	1005 July 24, 1990	4,458
	DCN9091	1505 Sep. 01, 1990	1505 June 19, 1991	6,985
	DCN9192	1405 July 19, 1991	1405 July 22, 1992	8,857
	DCN93A	1405 Jan. 08, 1993	1405 Apr. 30, 1993	2,689
	DCN9394	1105 June 20, 1993	1505 Jan. 11, 1994	4,925
Duck Key	DDK90A	1104 Jan. 05, 1990	1404 Apr. 30, 1990	2,764
	DDK9192	1505 Nov. 19, 1991	1405 Aug. 17, 1992	6,528
	DDK9293	1505 Sep. 15, 1992	1305 May 18, 1993	5,879
	DDK9394	1005 Aug. 06, 1993	1105 Jan. 12, 1994	3,818
Highway Creek	DHC9091	1105 Jan. 04, 1990	1705 Mar. 21, 1991	10,591
	DHC9192	1805 Mar. 22, 1991	1205 Sep. 15, 1992	13,027
	DHC9293	1305 Oct. 19, 1992	1405 Mar. 10, 1993	3,410
	DHC93A	1205 Mar. 17, 1993	1105 May 18, 1993	1,488
	DHC9394	1405 June 14, 1993	1405 Jan. 21, 1994	5,305

Table 2. Harmonic constants of the fortnightly, monthly, semi-annual and annual tidal constituents for National Park Service water level data from study sites in Florida Bay. Amplitudes (η) are in cm s^{-1} and phase angles (κ) are in degrees. Single asterisks (*) indicate unreliable amplitude and phase angles due to inadequate time series lengths. Double asterisks (**) indicate amplitudes less than 0.5 cm s^{-1} and, therefore, unreliable phase angles.

Study Site		Sa	Ssa	Mm	Msf	Mf
Blackwater Sound	η κ	9.4 185	5.2 091	1.1 351	1.4 089	1.0 352
Bob Allen Key	η κ	7.5 172	2.9 056	2.4 045	1.9 059	0.5 319
Broad River	η κ	* *	* *	1.9 047	1.7 075	** **
Buoy Key	η κ	7.8 147	3.7 061	3.3 064	2.7 083	1.1 216
Butternut Key	η κ	9.0 161	2.5 037	2.4 076	2.3 114	1.2 295
Cane Patch	η κ	17.0 171	1.4 302	1.1 005	1.9 081	0.7 020
Duck Key	η κ	* *	* *	1.5 123	0.7 161	0.7 107
Highway Creek	η κ	10.3 173	4.6 070	1.7 047	1.6 105	0.9 018
Joe Bay	η κ	9.5 157	4.0 056	3.7 100	2.2 151	0.6 263
Johnson Key	η κ	7.6 145	0.5 139	.21 015	3.5 037	1.7 280
Little Blackwater Sound	η κ	* *	* *	1.7 032	1.4 063	1.3 057
Little Madeira Bay	η κ	8.8 163	2.7 066	2.1 058	1.8 090	** **
Little Rabbit Key	η κ	8.2 172	3.0 068	2.1 037	2.5 048	** **
Long Sound	η κ	9.2 172	5.4 057	2.5 064	1.7 083	1.0 009
North River	η κ	10.3 161	1.3 021	1.1 062	2.5 088	1.3 313
Peterson Key	η κ	8.8 173	4.7 059	2.0 050	2.3 058	0.9 291

Terrapin Bay	DTB91A	1305 Sep. 12, 1991	1405 Dec. 12, 1991	2,186
	DTB9193	0905 Dec. 14, 1991	1205 Mar. 19, 1993	11,068
	DTB93A	0705 Mar. 22, 1993	1105 May 06, 1993	1,085
	DTB9394	0605 June 25, 1993	1705 Jan. 27, 1994	5,196
Trout Cove	DTC90A	1305 Jan. 04, 1990	0805 Oct. 09, 1990	6,668
	DTC9092	1505 Nov. 08, 1990	1405 July 16, 1992	14,784
	DTC92A	1405 Sep. 03, 1992	2305 Oct. 02, 1992	706
	DTC92B	1140 Nov. 23, 1992	1140 Dec. 30, 1992	889
	DTC93A	1105 Feb. 12, 1993	1105 Mar. 11, 1993	649
	DTC93B	1105 Apr. 23, 1993	1305 May 17, 1993	579
	DTC93C	0905 June 14, 1993	0705 Oct. 21, 1993	3,095
	DTC9394	1205 Nov. 10, 1993	1405 Jan. 12, 1994	1,515
Whipray Basin	DWB9093	1305 Jan. 05, 1990	1505 Mar. 12, 1993	27,891
	DWB93A	1105 Mar. 19, 1993	1205 May 19, 1993	1,466
	DWB9394	0705 June 25, 1993	1005 Jan. 25, 1994	5,140

APPENDIX

This appendix contains plots of low-pass filtered, nontidal water levels from the 21 study sites shown in Figure 2. Gaps appear where the water level recorders did not function properly, or where the water level records contained unacceptable errors in timing or water level. The numerical filter used to remove semi-diurnal and diurnal tidal fluctuations (along with seabreeze effects, etc.) suppresses virtually all of the rise and fall in water level over time scales of one day or less; for periodicities of two days and longer, over 90% of the variability in the input time series is removed.

Taylor River	η η	* *	* *	0.9 061	** **	** **
Terrapin Bay	η K	8.8 164	1.1 095	1.3 030	2.9 061	0.6 056
Trout Cove	η K	11.3 161	1.7 022	0.9 005	2.2 097	1.2 345
Whipray Basin	η K	8.8 165	2.3 064	2.2 051	2.4 062	0.5 289

Figure NWLBA. Nontidal (low-pass filtered) water levels recorded at Bob Allen Key (25°01'33"N, 80°40'55"W), January 1990 to January 1994.

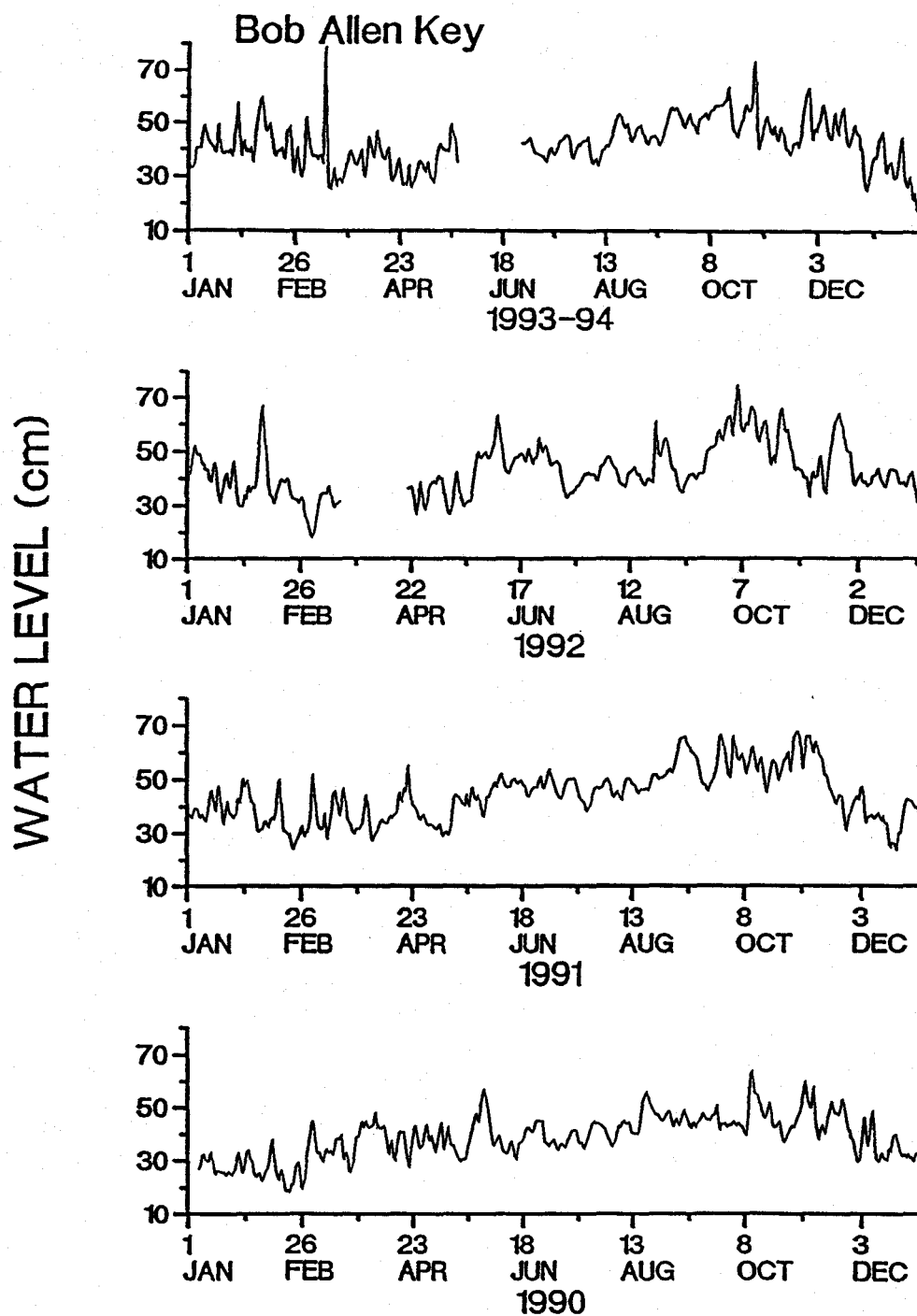


Figure NWLBS. Nontidal (low-pass filtered) water levels recorded in Blackwater Sound (25°10'42"N, 80°26'18"W), October 1991 to January 1994.

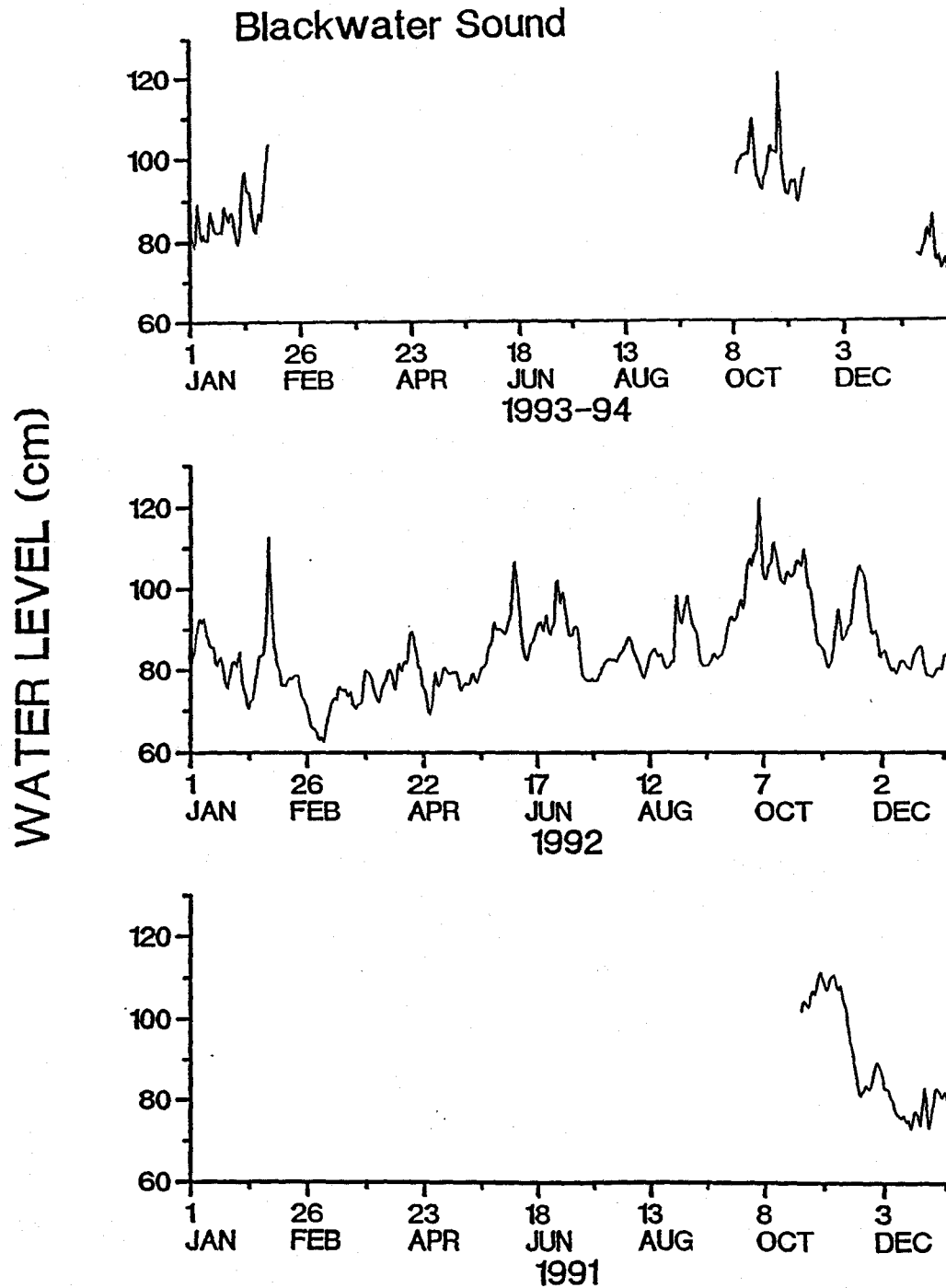


Figure NWLBK. Nontidal (low-pass filtered) water levels recorded at Buoy Key (25°07'15"N, 80°50'02"W), January 1990 to January 1994.

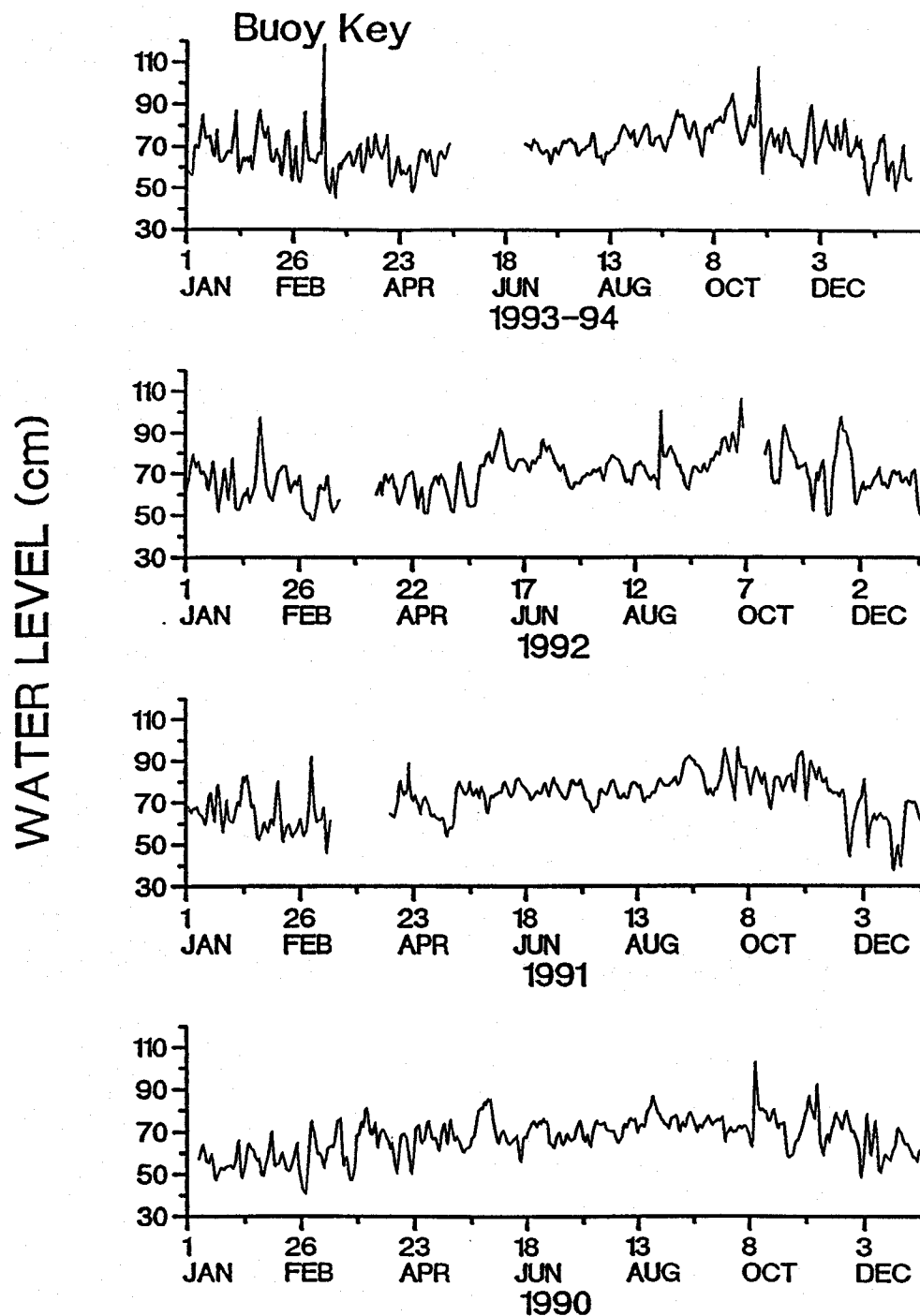


Figure NWLBR. Nontidal (low-pass filtered) water levels recorded at Broad River (25°28'40"N, 80°59'23"W), January 1990 to January 1994.

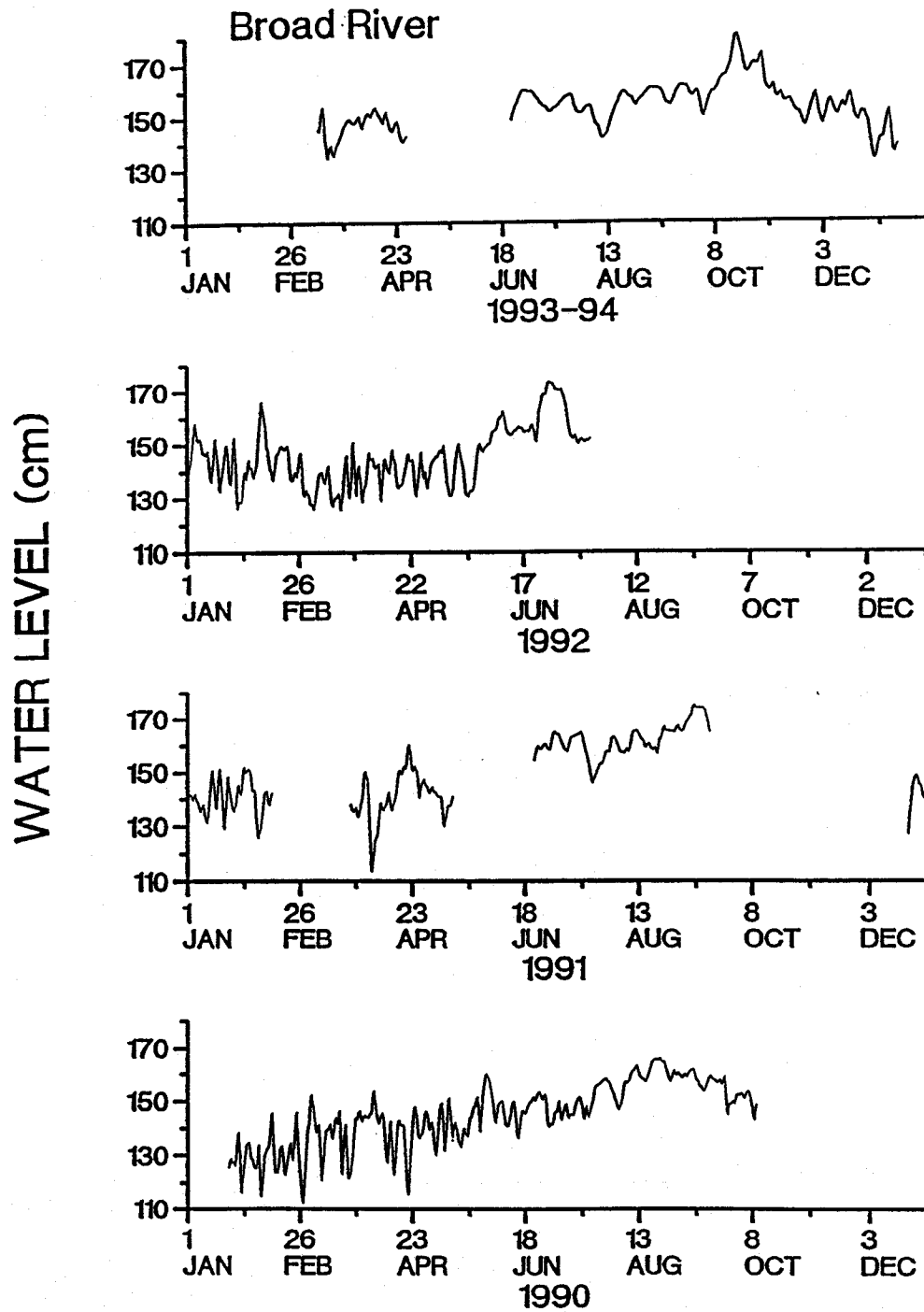


Figure NWLCN. Nontidal (low-pass filtered) water levels recorded at Cane Patch (25°25'18"N, 80°56'33"W), January 1990 to January 1994.

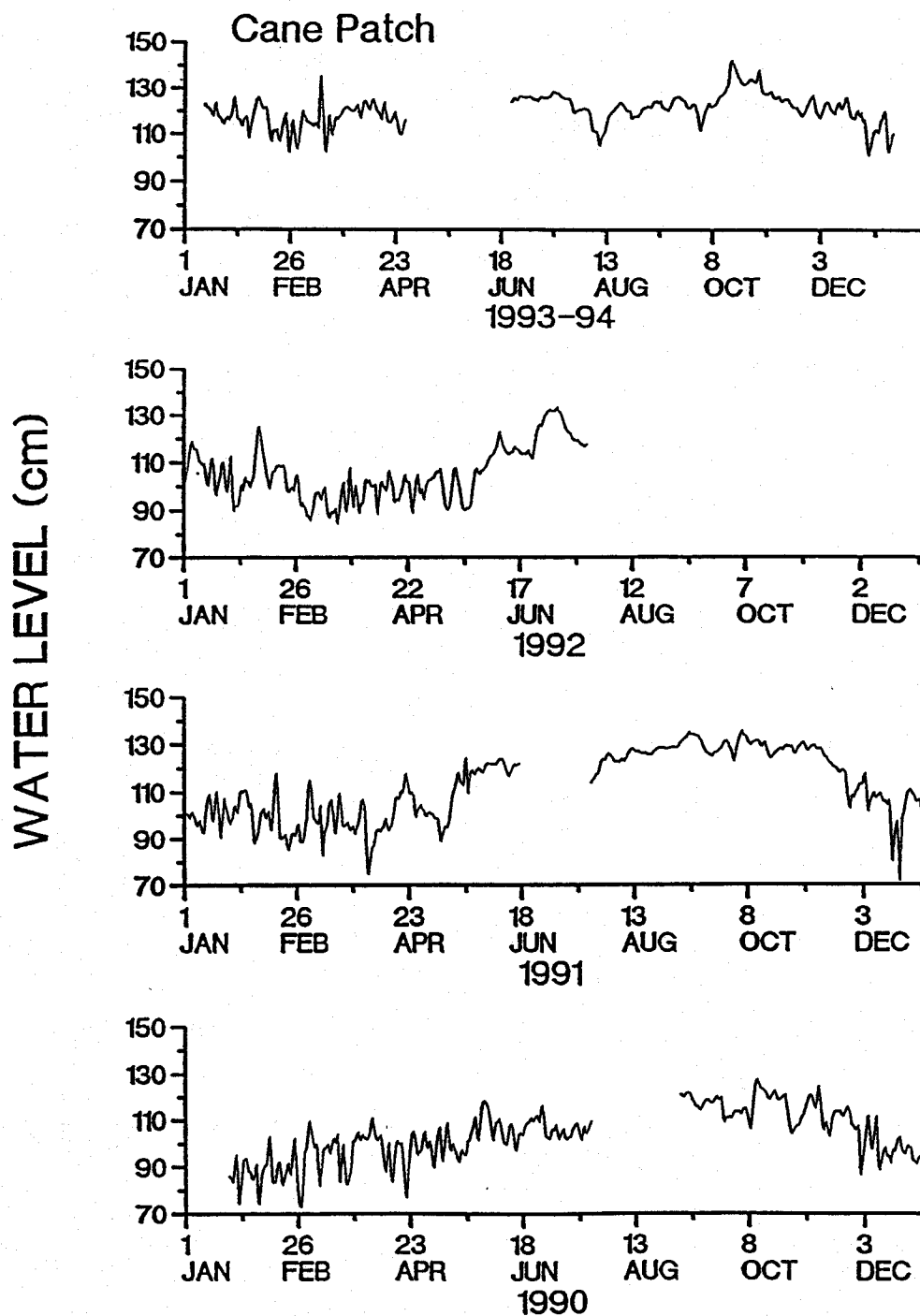


Figure NWLBN. Nontidal (low-pass filtered) water levels recorded at Butternut Key (25°05'08"N, 80°31'06"W), January 1990 to January 1994.

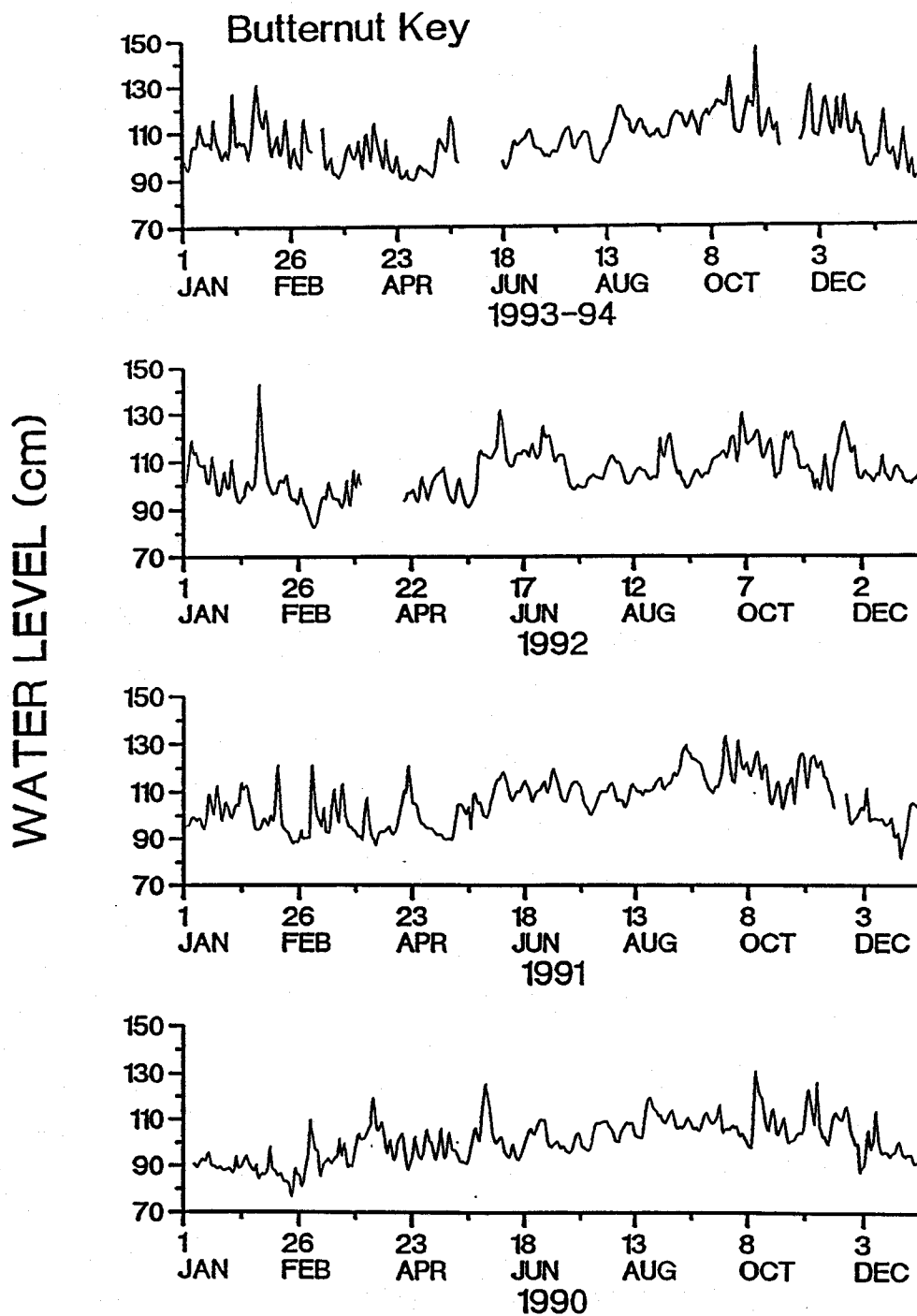


Figure NWLHC. Nontidal (low-pass filtered) water levels recorded at Highway Creek (25°15'14"N, 80°26'41"W), January 1990 to January 1994.

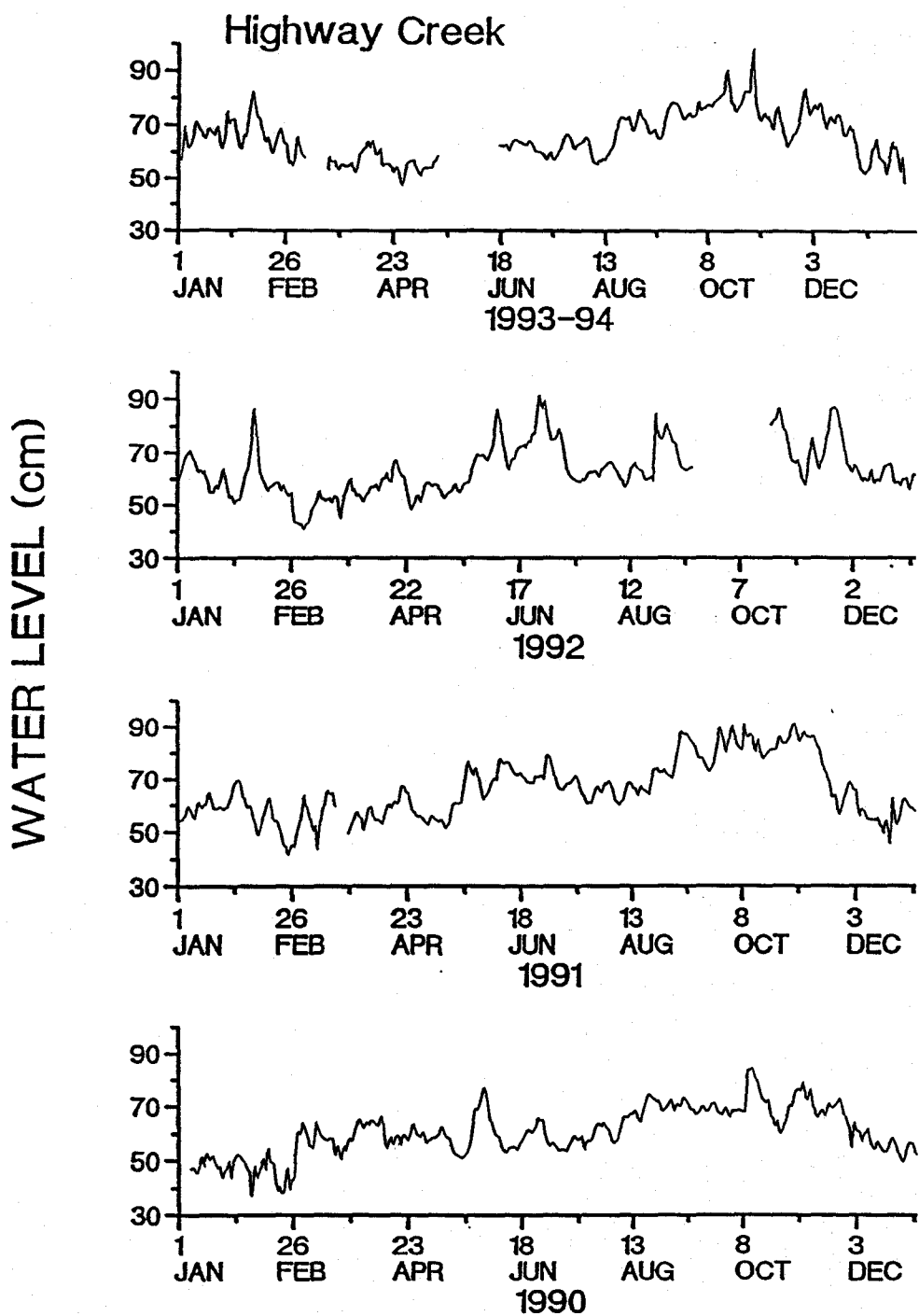


Figure NWLDK. Nontidal (low-pass filtered) water levels recorded at Duck Key (25°01'45"N, 80°29'23"W), January 1990 to January 1994.

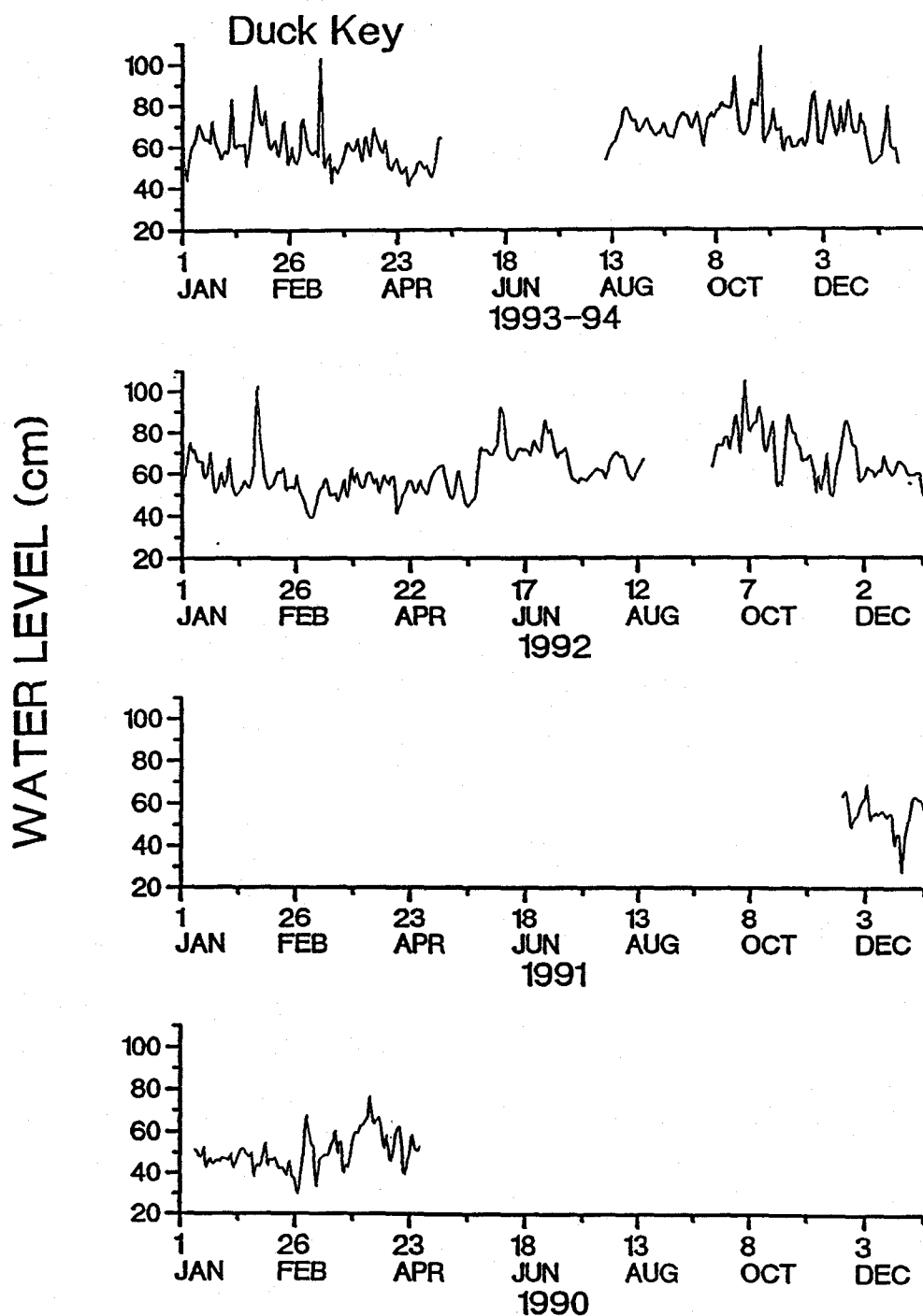


Figure NWLLM. Nontidal (low-pass filtered) water levels recorded at Little Madeira Bay ($25^{\circ}10'31''\text{N}$, $80^{\circ}37'56''\text{W}$), January 1990 to January 1994.

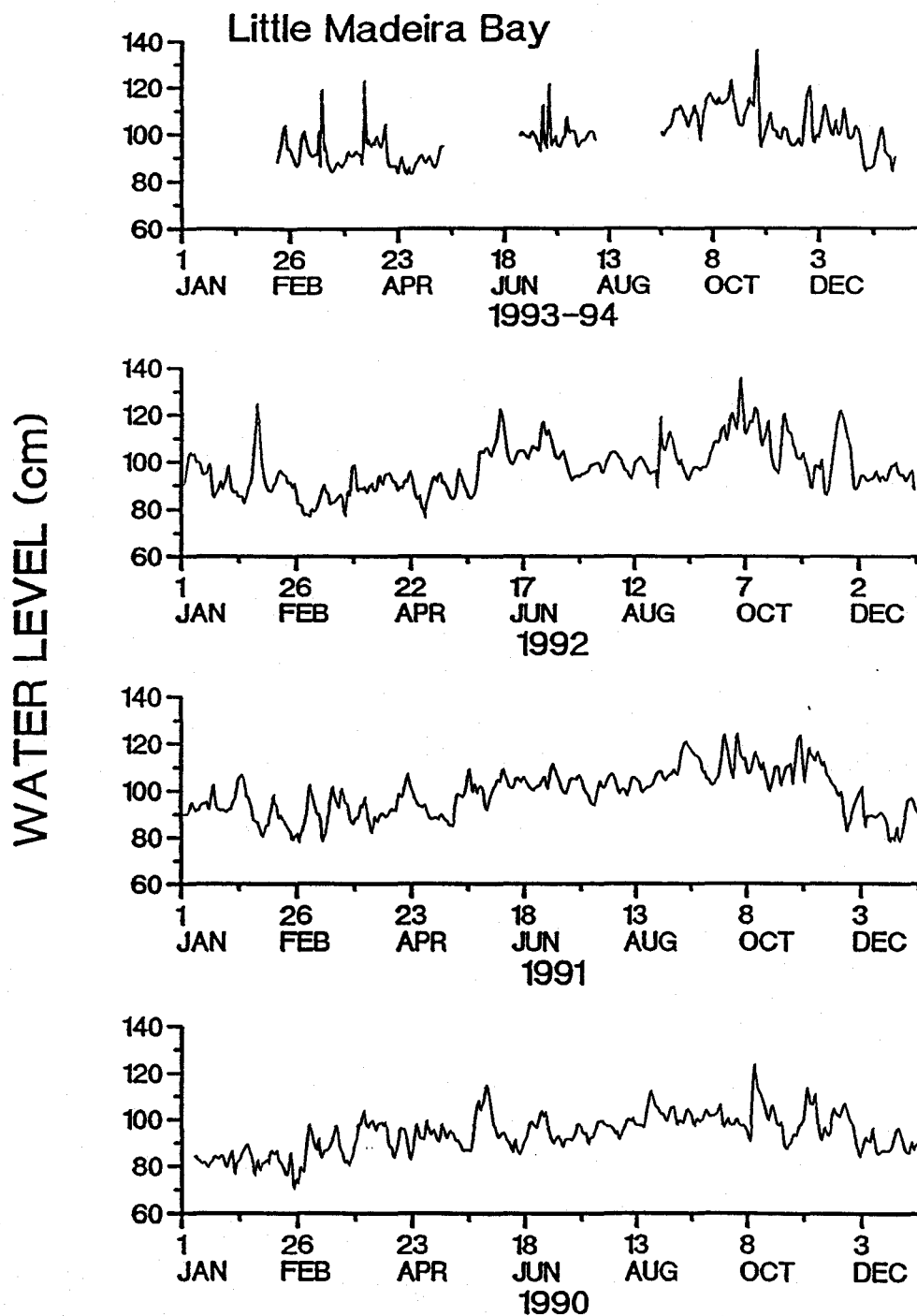


Figure NWLJB. Nontidal (low-pass filtered) water levels recorded at Joe Bay ($25^{\circ}13'26''\text{N}$, $80^{\circ}32'29''\text{W}$), January 1990 to January 1994.

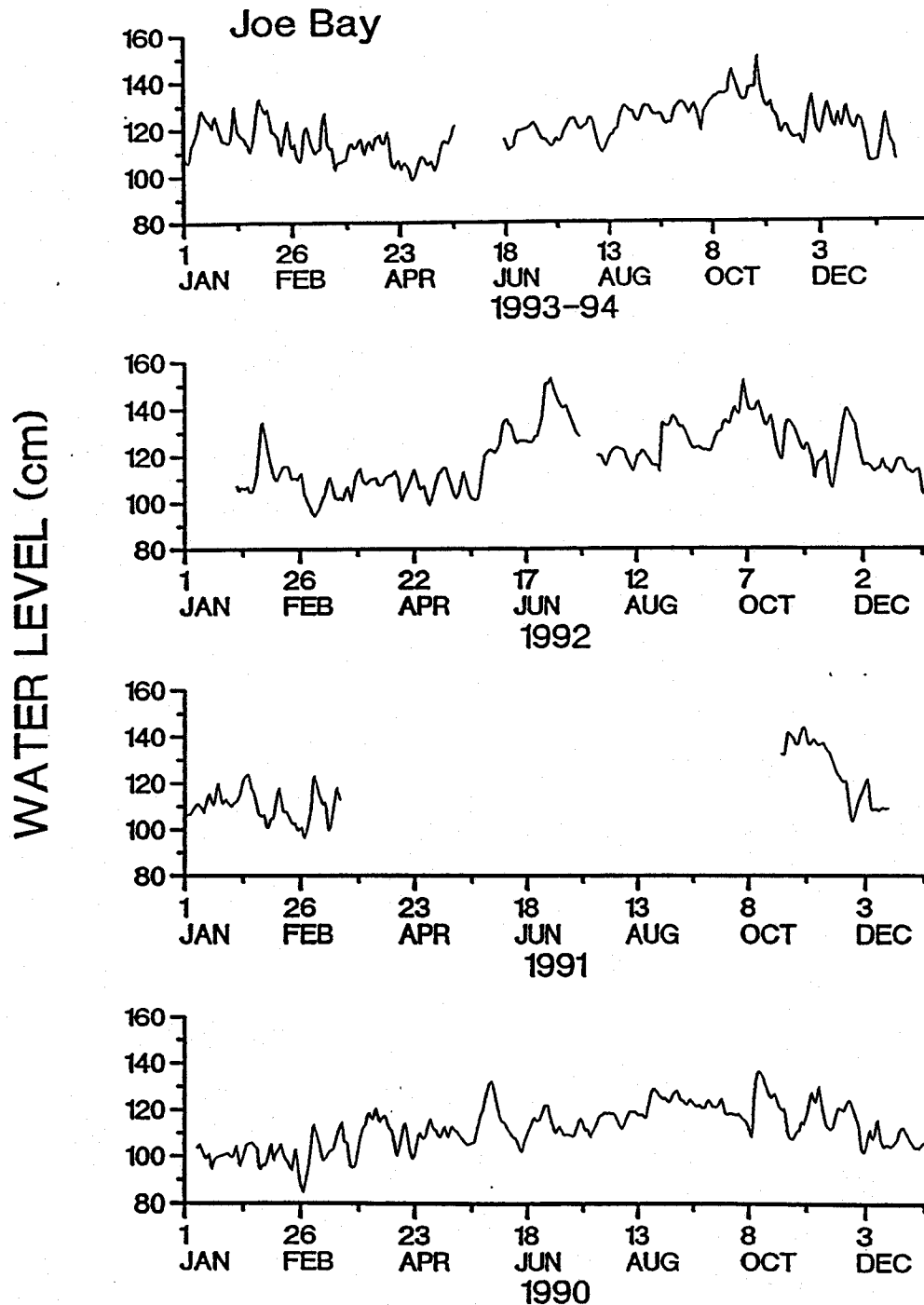


Figure NWLJK. Nontidal (low-pass filtered) water levels recorded at Johnson Key (25°03'07"N, 80°54'13"W), January 1990 to October 1993.

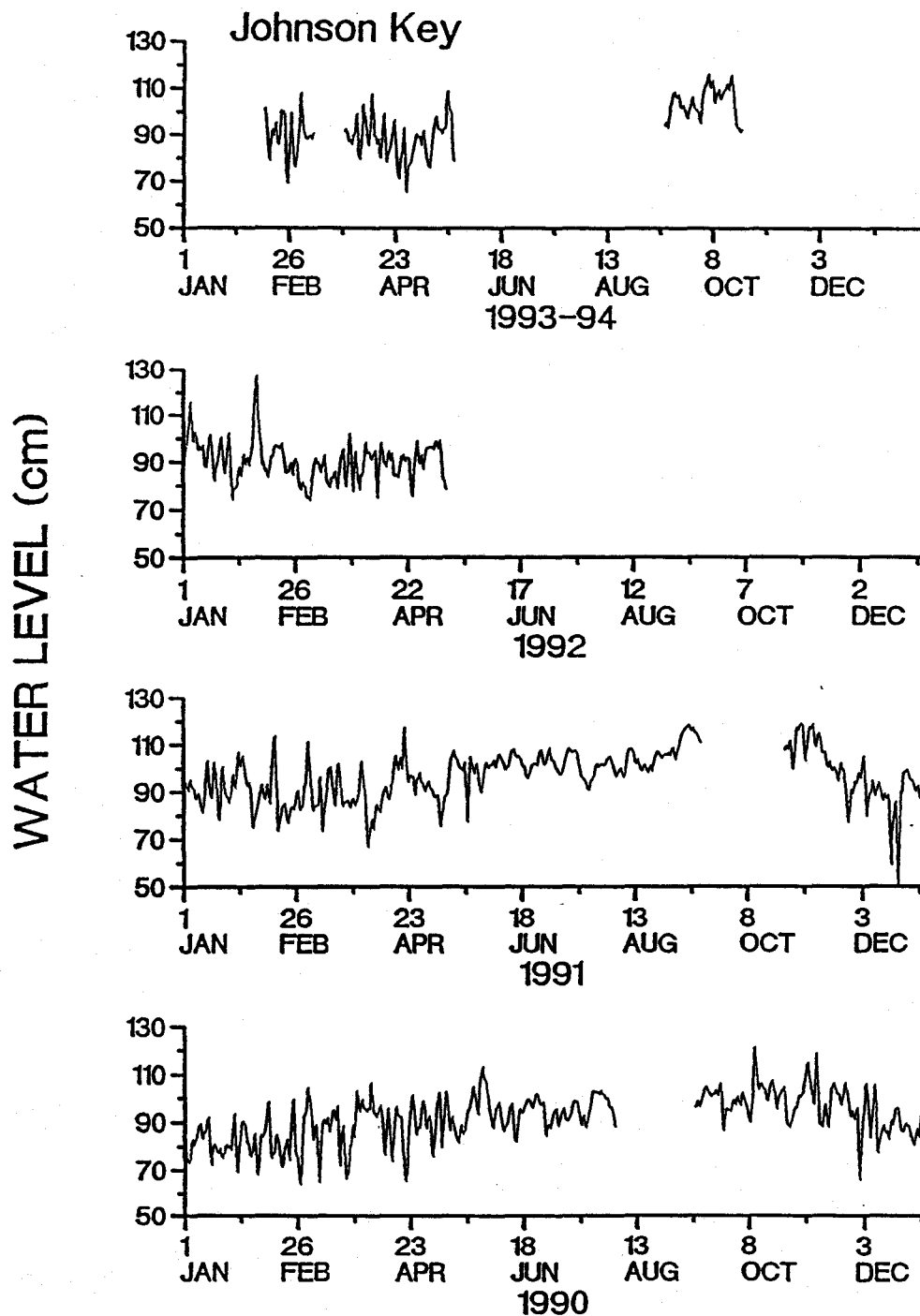


Figure NWLLR. Nontidal (low-pass filtered) water levels recorded at Little Rabbit Key ($24^{\circ}58'52''\text{N}$, $80^{\circ}49'33''\text{W}$), January 1990 to January 1994.

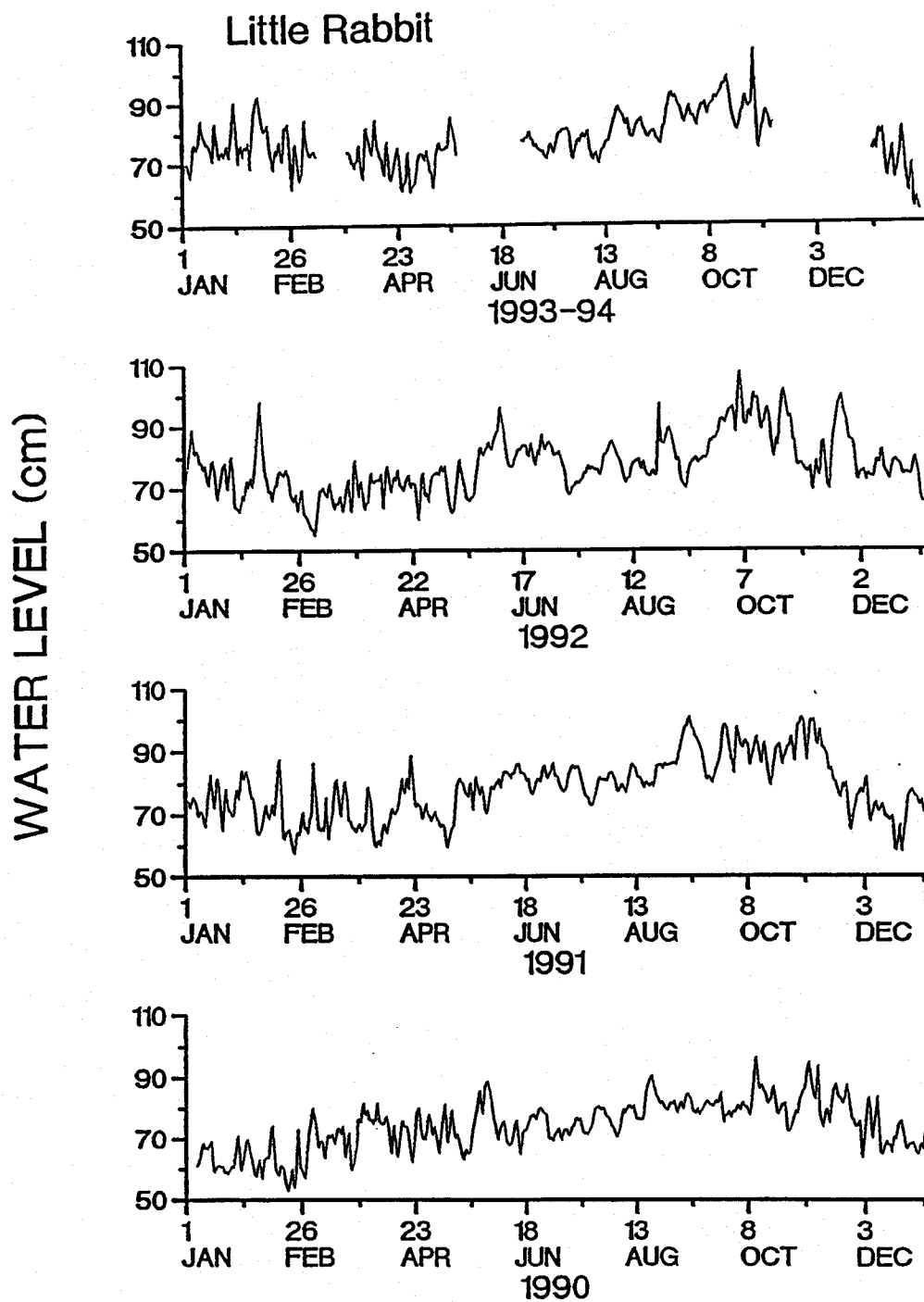


Figure NWLLS. Nontidal (low-pass filtered) water levels recorded at Long Sound (25°14'05"N, 80°27'27"W), January 1990 to January 1994.

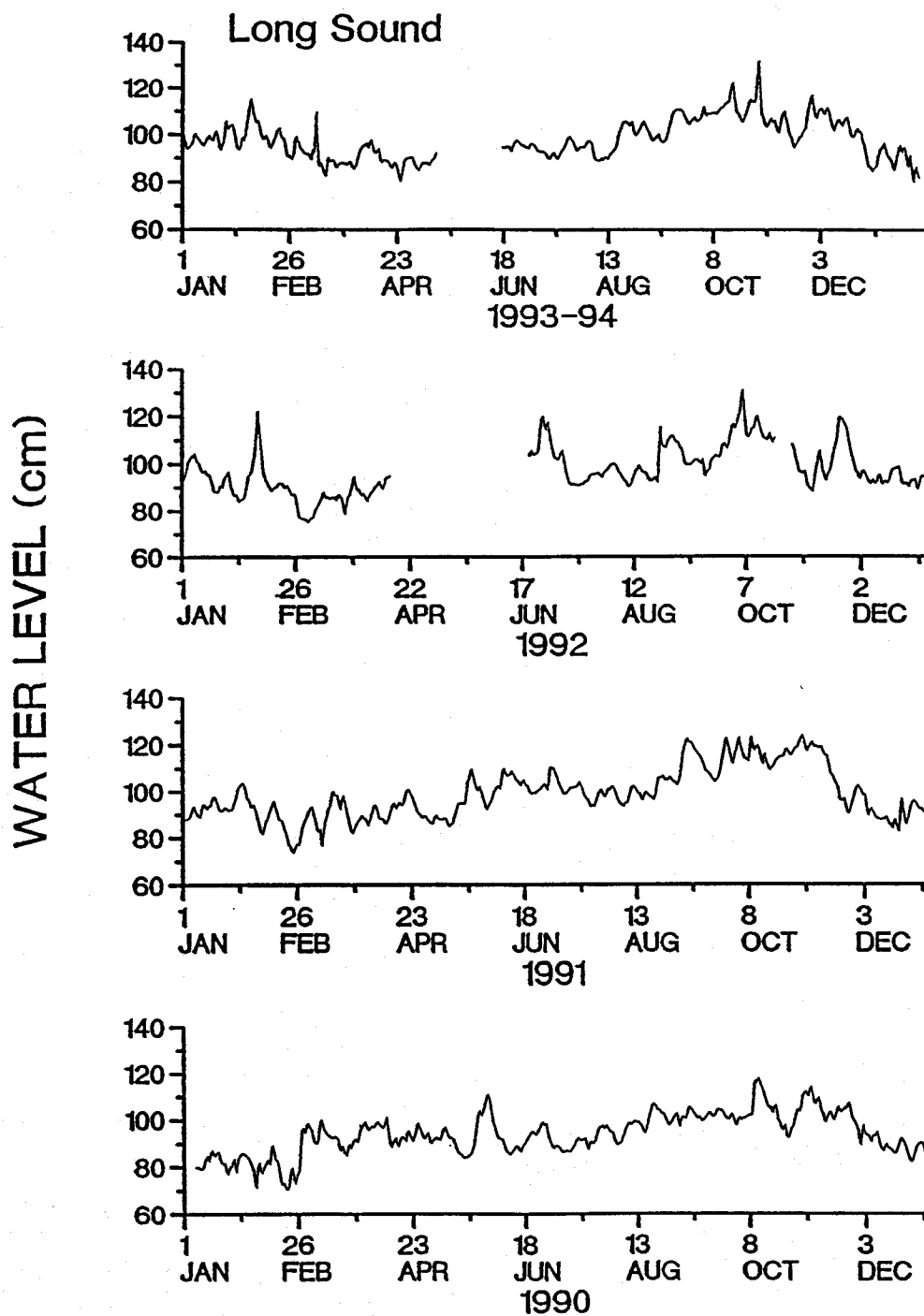


Figure NWLMK. Nontidal (low-pass filtered) water levels recorded at Murray Key ($25^{\circ}06'20''\text{N}$, $80^{\circ}56'32''\text{W}$), February 1993 to January 1994.

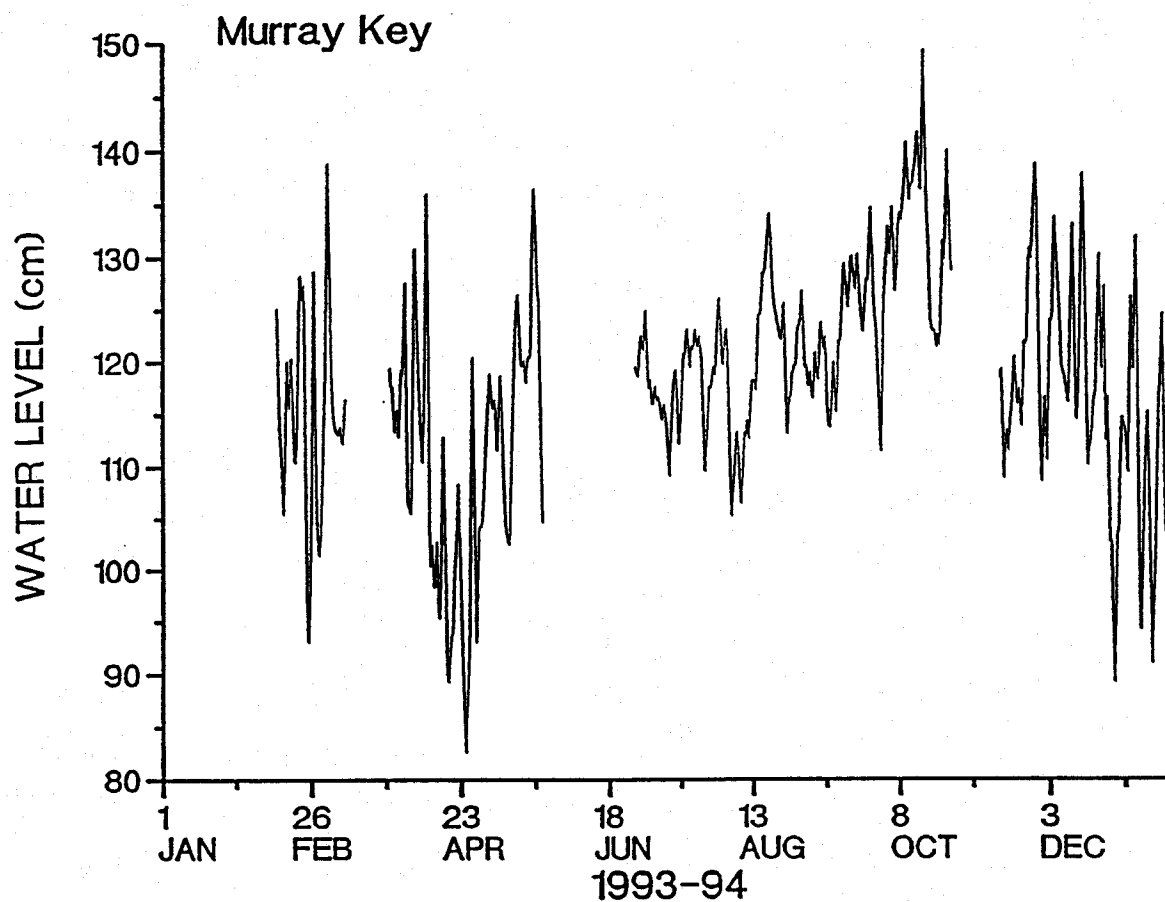


Figure NWLNR. Nontidal (low-pass filtered) water levels recorded at North River (25°20'23"N, 80°54'41"W), February 1990 to January 1994.

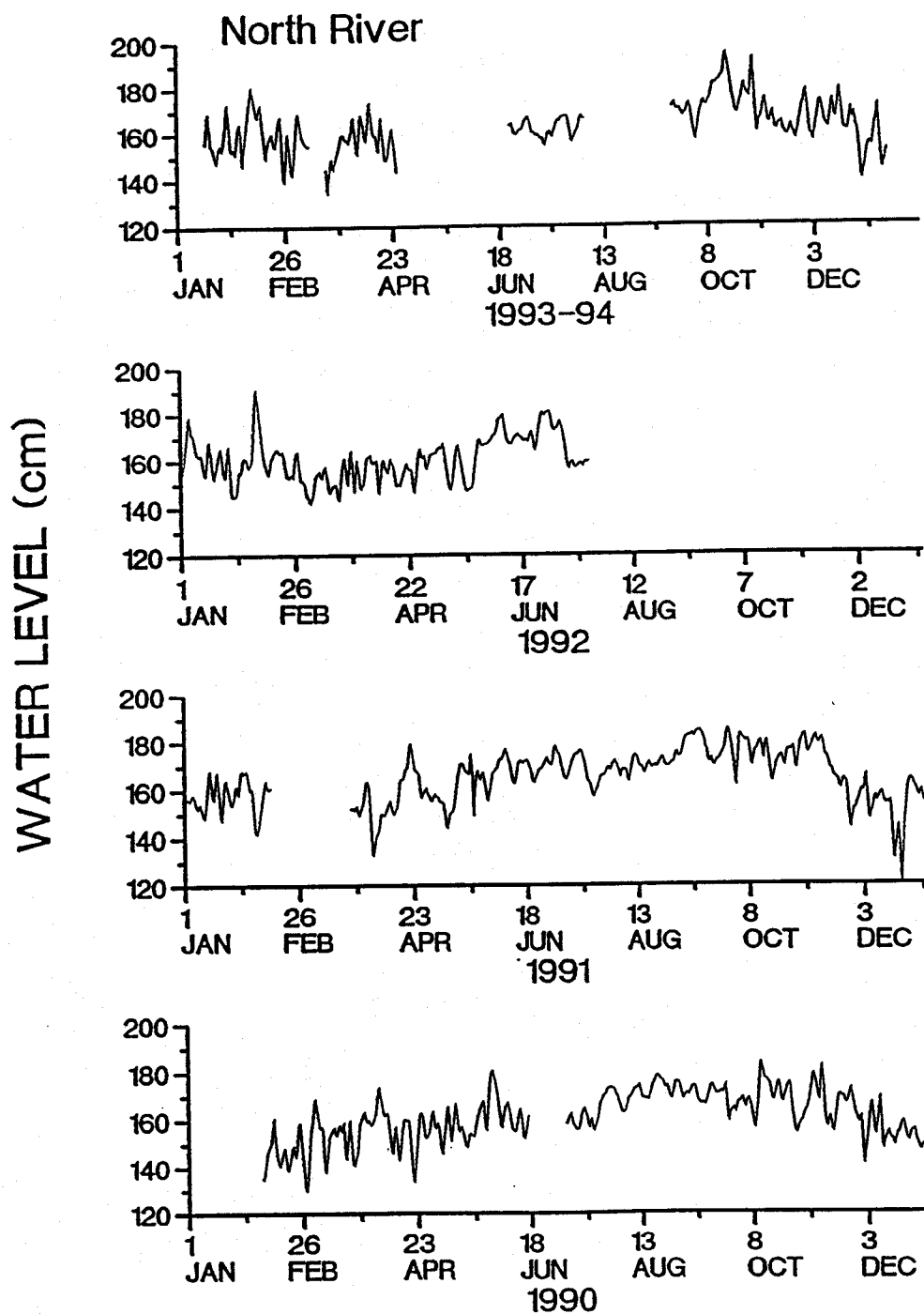


Figure NWLPK. Nontidal (low-pass filtered) water levels recorded at Peterson Key ($24^{\circ}55'05''\text{N}$, $80^{\circ}44'46''\text{W}$), January 1990 to January 1994.

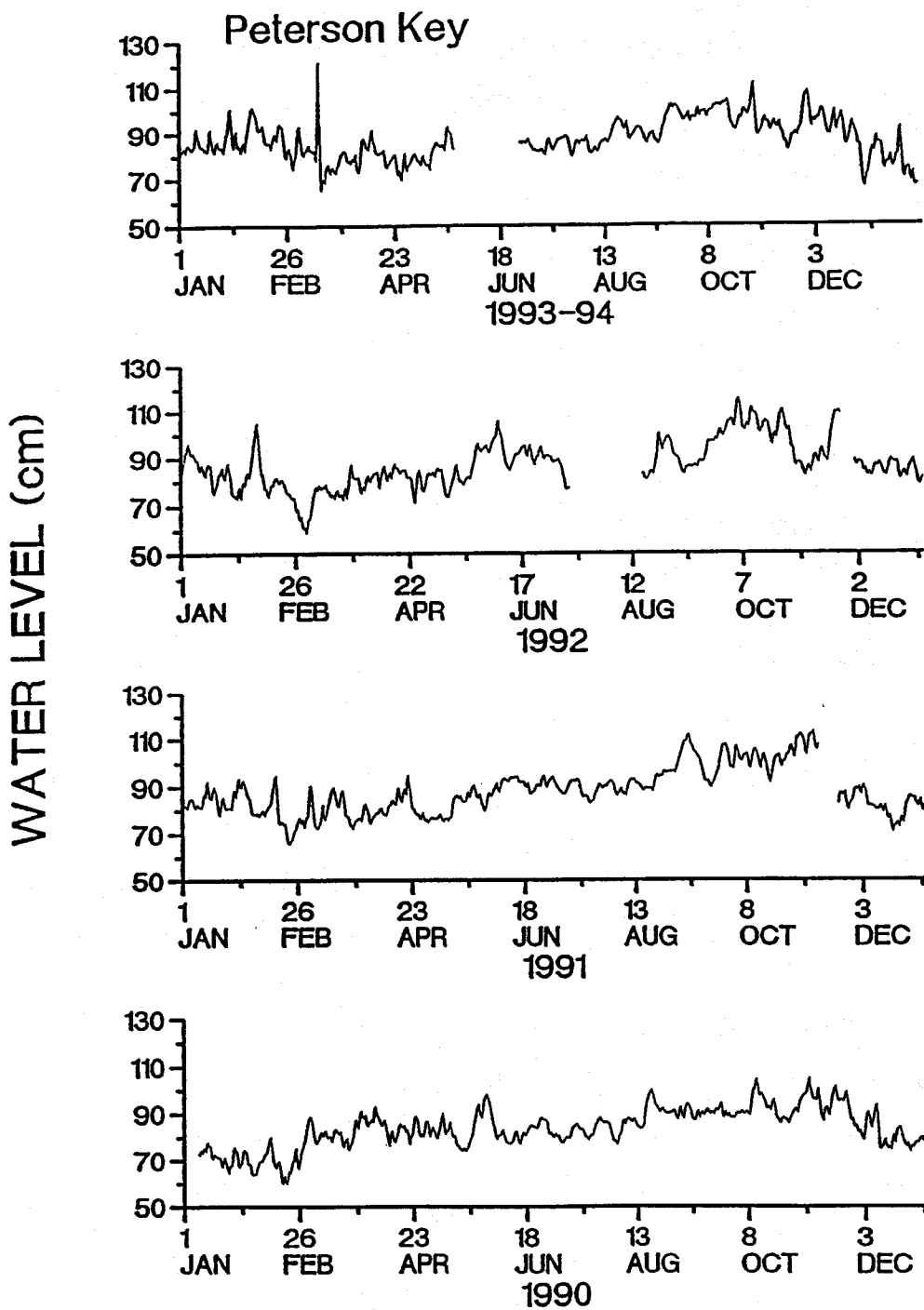


Figure NWLTR. Nontidal (low-pass filtered) water levels recorded at Taylor River (25°13'28"N, 80°39'11"W), June 1990 to December 1993.

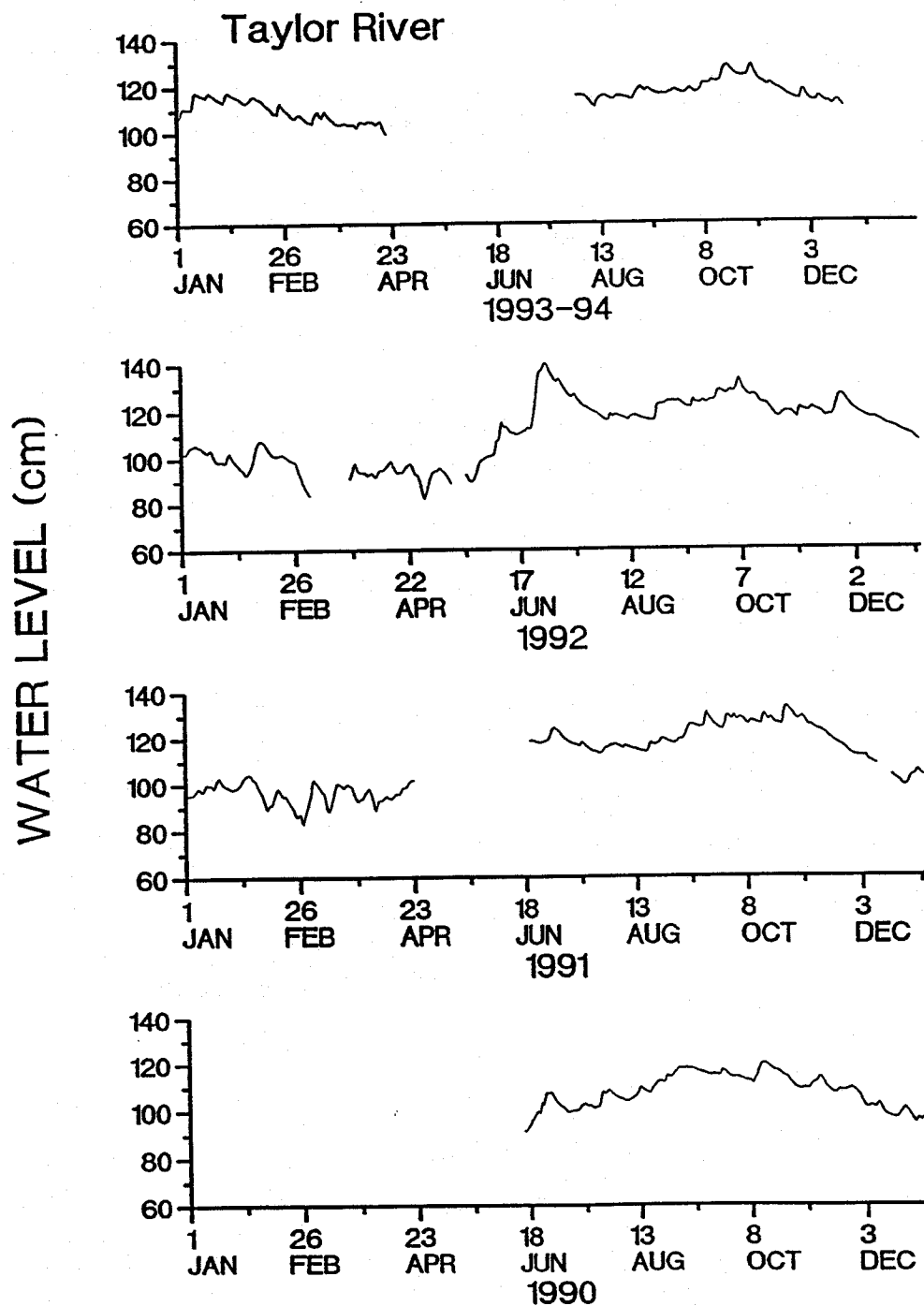


Figure NWLTB. Nontidal (low-pass filtered) water levels recorded at Terrapin Bay ($25^{\circ}09'24''\text{N}$, $80^{\circ}43'30''\text{W}$), September 1991 to January 1994.

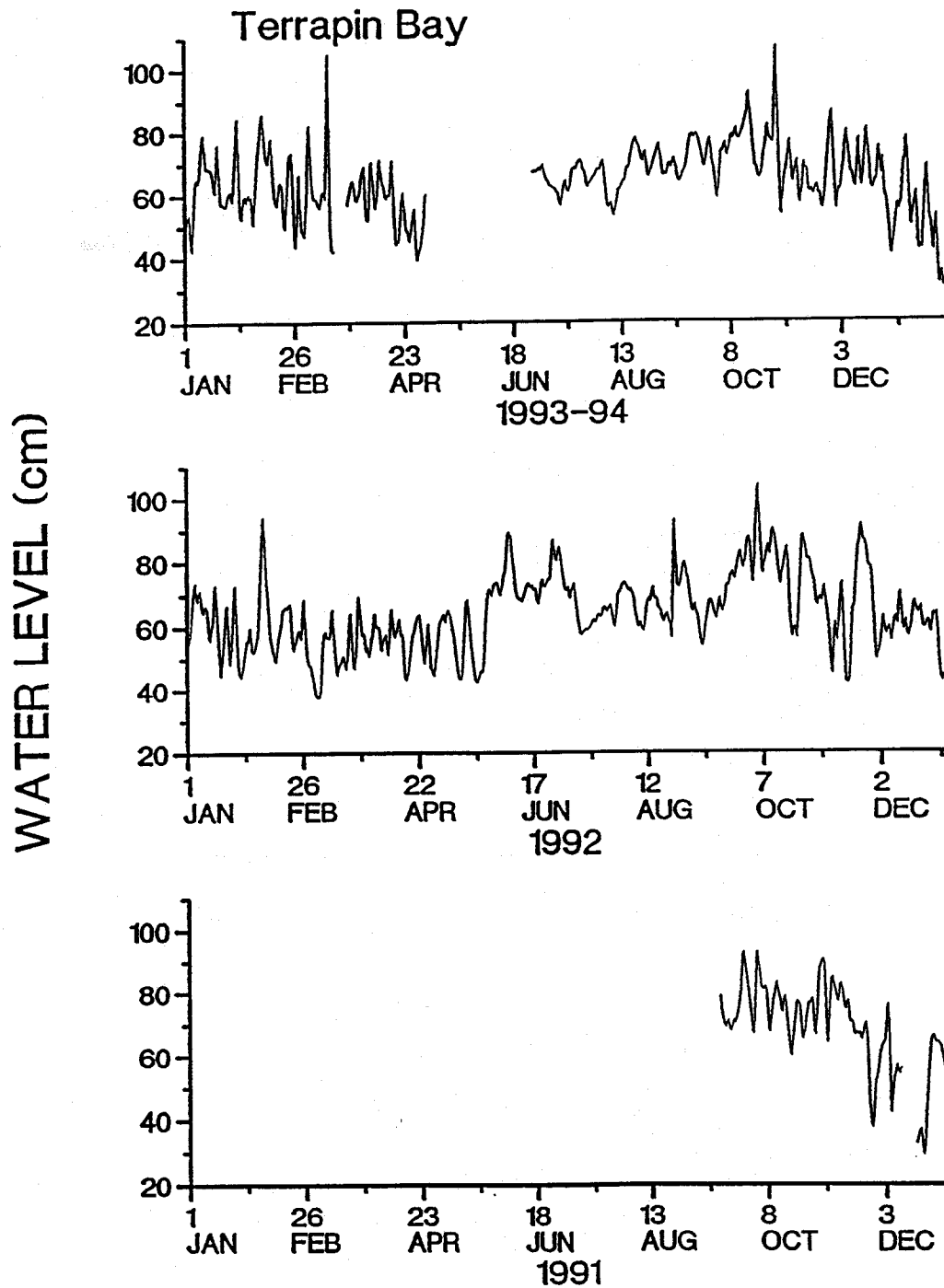


Figure NWLTC. Nontidal (low-pass filtered) water levels recorded at Trout Cove ($25^{\circ}12'44''\text{N}$, $80^{\circ}32'01''\text{W}$), January 1990 to January 1994.

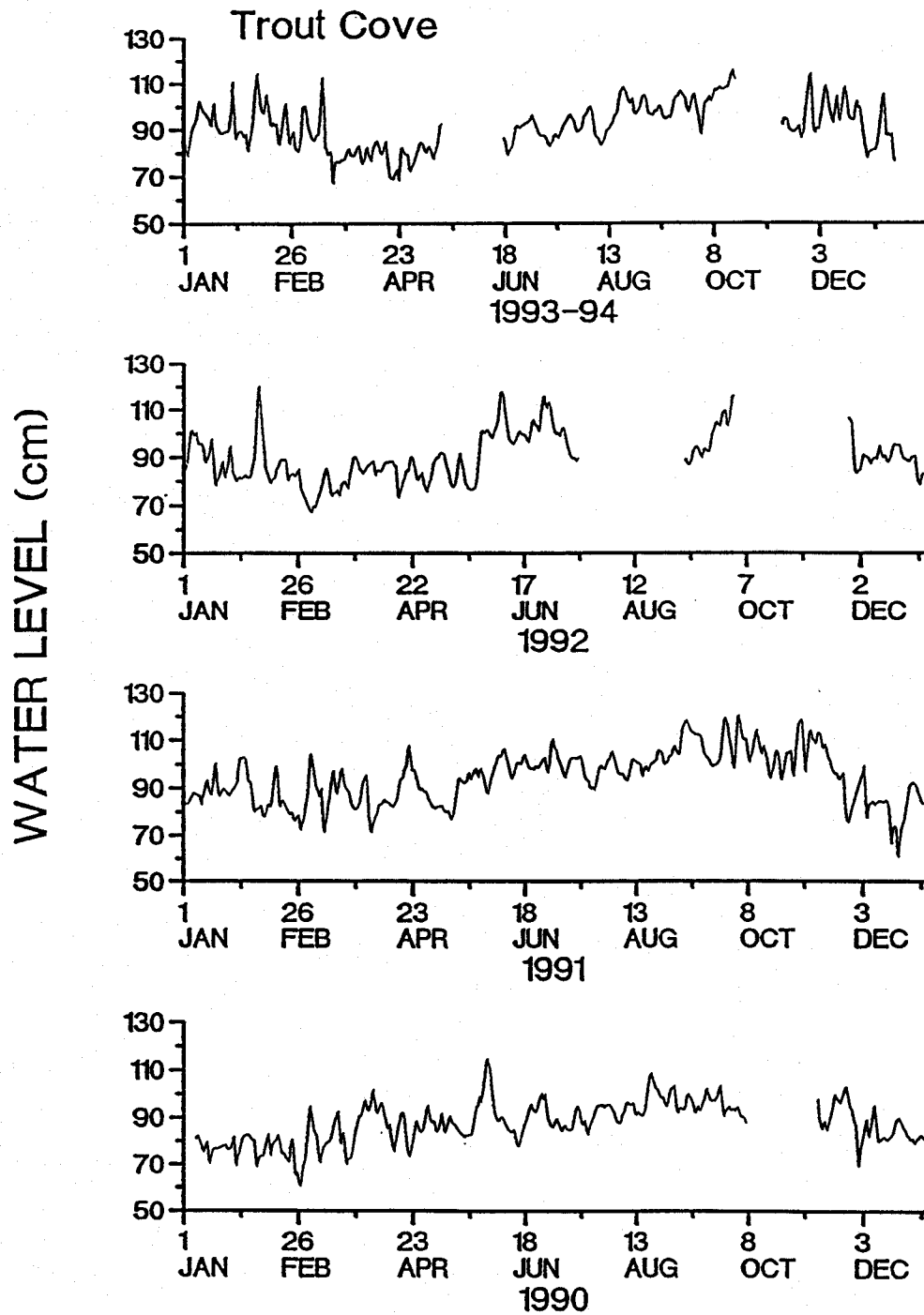


Figure NWLWB. Nontidal (low-pass filtered) water levels recorded at Whipray Basin ($25^{\circ}04'41''\text{N}$, $80^{\circ}43'39''\text{W}$), January 1990 to January 1994.

