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Collection and Analysis of Monthly Mean Sea Level Data in the Mediterranean and the Black Sea

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ABSTRACT

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The database of the Permanent Service for Mean Sea Level is available to any interested researcher and provides a major collection of sea level data worldwide. In this report, the sea level data available from the database of PSMSL for the Mediterranean and the Black Sea are discussed and analyzed. The spatial and temporal distribution of the tide-gauges in comparison with published literature indicate that additional data that can significantly extend the data set may exist and that the installation of new tide-gauges data in a large part of the Mediterranean is needed. The database operation in the area is reviewed and a short analysis of the data is presented. Trends in the eight stations that span for more than 30 years are less than 2.2 mm/yr. The annual and semi-annual cycle and the longer term variability are briefly analyzed and shown to be consistent over the area.

ADDITIONAL INDEX WORDS: *Sea level trends, annual cycle, semi-annual cycle, decadal variability, Permanent Service for Mean Sea Level.*

INTRODUCTION

The sea level in the Mediterranean and the Black Sea has been measured for more than a century. The instrumentation, the frequency of the measurements and the procedures used to process the sea level data determine the accuracy of the measurements.

The measurements were initially made from readings of tide poles, while later on self recording instruments became available. The frequency of measurements was variable from one reading per day to continuous records on paper charts. When averaged over a monthly period, these measurements provide the mean sea level value for the gauge site relative to the level of the nearby land. To ensure continuity and intercomparison of the measurements at a location for a long period, a vertical land reference level (Tide Gauge Benchmark) is usually defined. When sea level is recorded for very long periods in a location, modifications of the port or catastrophic events can force relocation or reinstallment of the tide-gauge. In such cases, continuity of sea level observations is ensured by measurement by means of conventional levelling between the old and the new benchmarks. Therefore, the measurement of sea level is always relative to the land and includes information from land movements that cannot be distinguished from sea-level movements, without additional measurements of land movements from new geodetic techniques or model assumptions (Carter *et al.,* 1989).

The application purpose of the derived sea level recording is the key factor to determine the processing of the data, the care taken during the analysis and consequently the resulting accuracy of the mean (daily, monthly etc.) sea level values. For example, in areas sensitive to flooding, like Venice, knowledge of all the parameters of sea level variation (*e.g.,* tides, surges and long term sea level trends) has long been demanded. In areas with low tides and not endangered from flooding (*e.g.,* Aegean Sea), sea level was observed mainly for use on hydrographic charts. In such cases, errors of a few centimetres in the estimation of sea-level were irrelevant to the purpose of the measurement. Unfortunately, this practice results in unreliable sea level records for long term mean sea-level studies.

To obtain land movements at tide gauges, a network of GPS stations can be used. Such a network is being developed in the Mediterranean and the Black Sea in the framework of a European Union funded research project, Sea Level Fluctuations, Geophysical Interpretations and Environmental Impacts (SELF). Our involvement in this project provided us with the opportunity to reexamine the data available to PSMSL and to reestimate sea level trends and seasonal cycles in this region, but more importantly, to identify unreasonable gaps in the data availability and possible sources of further data.

METHODS

Operational Procedures and Statistics of the PSMSL Database

In 1933, the PSMSL was established and started the collection of data from around the globe. The provision of data to this Service is on a voluntary basis and the collected data

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are available freely to anyone interested (SPENCER and WOODWORTH, 1993).

The information is obtained by the PSMSL from correspondence with contributing authorities. In Table 1, the latest year of mean sea-level information available in the PSMSL database is shown for each Mediterranean station. In addition, for data received since 1988, the date this information was added to the database is shown. The total number of stations with data in this region is 132, and for 39 of these, the latest year of data is 1990 or later.

Data receipts vary considerably in quantity, method of transmission and delay between recording and receipt. For a few, data are received within one month of a year end. Receipts within 12–18 months are more general for most data. Table 2 lists the authorities which have supplied data to the PSMSL. Without wishing to make excessive demands on those authorities, the Service requests certain additional information about the data and the station benchmarks in order to maintain an authoritative databank. The form in Table 3 shows the details required, although data can be handled equally well in any format and via any medium (*e.g.,* floppy disk or paper listings).

The data as received is added to the "Metric" file for that station. Routine checks are made on the data (IOC, 1985, 1994; WOODWORTH *et al.,* 1990). With the datum and station information available, the PSMSL then adjusts the monthly and annual means and reduces the data to a common datum for each station individually. In the Mediterranean and Black Sea areas, 70 stations have data in this "Revised Local Reference" (RLR) format. At each station, the RLR datum is defined with respect to the TGBM. Often in the process of updating data files, queries are noted such as anomalous values or apparent shifts in datum. These are followed up with the supplier whose advice and cooperation is gratefully acknowledged.

The pattern of data distribution has changed noticeably in recent years and the most used method of accessing PSMSL data now is by anonymous FTP across Internet. Full details on how the data on the public access disk can be acquired are given in Appendix 5 of the PSMSL 'Data Holdings' publication (SPENCER and WOODWORTH, 1993). Occasionally data is requested for a small number of stations as either computer printout and or floppy disk. PSMSL no longer supplies data on magnetic tape. Comments from users of the database are welcomed and any queries are investigated.

In addition to supplying data, the Permanent Service is pleased to assist with advice on methods of data processing and tide gauge instrumentation. Two volumes of the "Manual on Sea Level Measurement and Interpretation" (IOC, 1985, 1994) are available which were prepared by the PSMSL on behalf of the Intergovernmental Oceanographic Commission.

Temporal and Spatial Coverage

The spatial distribution of the available tide-gauges is shown in Figure 1. Most of the tide-gauges are located on the north coasts of the Mediterranean. Gaps exist at the northern Mediterranean coasts of Spain and the Albanian coast. With the exception of the Egyptian coast and the Strait of Gibraltar, there are no data available from the northern coasts of Africa. In the Black Sea, the distribution of tide-gauges is less dense and no data from the northern coasts of the Black Sea are included in the database.

The temporal distribution of the tide-gauges is shown in Figure 2. In general, most stations cover the second part of the present century. Nevertheless, there is a group of Italian stations that, although operational at the end of the last century, stopped at around 1920. Of course, additional data exist that are not included in the PSMSL database. For example, PALUMBO and MAZZARELLA (1985) used sea level data from Naples (1958–1983) and Palermo (1958–1965) that never became available to PSMSL. From personal communications (AUBREY, D.; MAMAYEV, V.; WILSON, P.), we also know that data exist from more than 30 stations on the ex-Soviet Union coasts of the Black Sea with data going back to 1875. Also from knowledge of tidal constant information, one can infer that additional tide gauges exist or have existed for short periods in several other parts of the Mediterranean, including the north coasts of Africa. Although some of the data may have been lost or destroyed, it would be of interest to retrieve, study and conserve the data that have survived, and a part of the PSMSL activity aims to identify such situations and persuade the relevant authorities that such research is worthwhile. Therefore, there is the potential for future expansion of the database, not only regarding newer tide-gauges but also in completing and expanding the information from the past.

The cumulative distribution of data available is shown in Figure 3. As pointed out earlier, there is a minimum of available data between 1920 and 1950. The sudden increase of the data after 1970 is due to the inclusion of the tide-gauges in Greece. Checking through the documentation of one of the Greek stations (Piraeus), we were surprised to learn that the first tide-gauge installed in this port dated back to 1890. Unfortunately we were not able to find any relevant data. The sudden drop of data after 1985 is due to the delay in supply of the data to PSMSL and not necessarily to a real reduction in the operational tide gauges; the relative importance of Greek stations in particular to this drop can be inferred from Table 2.

Preparation of the Data

The data in the database are routinely scrutinised for errors by means of a set of tests (WOODWORTH *et al.,* 1990). These result in a number of stations or station-years is being flagged as "suspect". However, these tests are not definitive and are not as comprehensive as would be possible if original data (*e.g.,* hourly values) were available in addition to the monthly values. The definition of RLR is connected with the available information on the benchmark and datum position and does not in itself guarantee a good quality time series.

In Figure 4, the stations of Tarifa (Spain) and Patra (Greece) are shown as examples of suspicious RLR data that have been flagged in the database. Although in both cases the relevant authorities have provided benchmark history, it is evident that in Tarifa a datum shift has taken place while in Patra a trend seems to start around 1975. The situation

Table 1. *Tide-gauges included in the PSMSL database for the Mediterranean and the Black Seas.*

Station	Lat	Lon	CC	SC	AC	LY	Updated
Gibraltar	36 07 N	5 21 W	215	001	10	1990	07-02-94
Cadiz I	36 30 N	6 12 W	220	001	20	1965	
Cadiz II	36 32 N	6 19 W	220	002	20	1990	17-11-93
Algeciras	36 07 N	5 26 W	220	011	68	1987	05-09-89
Tarifa	36 00 N	5 36 W	220	021	68	1987	05-09-89
Malaga	36 43 N	4 25 W	220	031	68	1987	06-03-89
Almeria	36 50 N	2 29 W	220	041	20	1991	30-03-94
Cartagena	37 36 N	0 58 W	220	046	20	1987	07-04-89
Alicante I	38 20 N	0 29 W	220	051	20	1991	17-11-93
Alicante II	38 20 N	0 29 W	220	052	20	1991	17-11-93
L'Estartit	42 03 N	3 12 E	220	081	H9	1994	20-01-94
Palma	39 35 N	2 38 E	225	001	68	1966	
Banyuls	42 29 N	3 07 E	230	001	18	1974	
Port Vendres	42 31 N	3 06 E	230	006	19	1983	
Sete	43 24 N	3 42 E	230	021	19	1979	
Port de Bouc	43 24 N	4 59 E	230	031	19	1983	
Martigues	43 24 N	5 03 E	230	041	19	1983	
Marseille	43 18 N	5 21 E	230	051	19	1992	01-07-93
Toulon	43 07 N	5 55 E	230	061	18	1973	
Nice	43 42 N	7 16 E	230	081	19	1992	01-07-93
Monaco (Condamine)	43 44 N	7 25 E	233	011	19	1980	
Monaco	43 44 N	7 25 E	233	021	19	1921	
La Maddalena	41 14 N	9 22 E	240	001	22	1913	
Cagliari	39 12 N	9 10 E	240	011	22	1934	
Porto Maurizio	43 52 N	8 01 E	250	001	22	1922	
Genova	44 24 N	8 54 E	250	011	22	1992	22-04-94
Livorno	43 32 N	10 18 E	250	021	22	1911	
Civita Vecchia	42 03 N	11 49 E	250	031	22	1922	
Miseno	40 47 N	14 05 E	250	035	G7	1993	12-04-94
Pozzuoli Stabilimento Sofer	40 50 N	14 07 E	250	036	G7	1991	12-04-94
Pozzuoli Molo Caligoliano	40 49 N	14 07 E	250	037	G7	1993	11-04-94
Nisida	40 48 N	14 10 E	250	038	G7	1993	11-04-94
Napoli (Arsenale)	40 52 N	14 16 E	250	041	22	1922	
Napoli (Mandraccio)	40 52 N	14 16 E	250	051	22	1922	
Naples	40 50 N	14 15 E	250	052	C5	1989	07-02-90
Napoli Molo Carmine	40 50 N	14 16 E	250	053	G7	1993	01-02-94
Torre Del Greco	40 47 N	14 22 E	250	054	G7	1993	22-04-94
Castellammare di Stabia	40 41 N	14 28 E	250	055	G7	1993	12-04-94
Reggio Calabria	38 06 N	15 39 E	250	061	23	1967	
Messina	38 12 N	15 34 E	260	001	22	1923	
Palermo	38 08 N	13 20 E	260	011	22	1922	
Mazaro del Vallo	37 40 N	12 34 E	260	021	24	1916	
Capo Passero	36 40 N	15 18 E	260	028	23	1969	
Catania	37 30 N	15 08 E	260	031	23	1971	
Valletta	35 54 N	14 31 E	265	001	E3	1991	30-04-92
Taranto	40 26 N	17 16 E	270	006	22	1966	
Otranto	40 08 N	18 30 E	270	011	23	1970	
Brindisi	40 38 N	17 56 E	270	014	22	1991	22-04-94
Manfredonia	41 37 N	15 55 E	270	019	23	1971	
Ortona	42 21 N	14 24 E	270	026	23	1972	
Ancona	43 35 N	13 29 E	270	030	23	1972	
Venezia (Diga Sud di Lido)	45 21 N	12 23 E	270	031	B6	1987	24-08-88
Porto Corsini	44 30 N	12 17 E	270	035	23	1972	
Venezia (Arsenale)	45 25 N	12 21 E	270	041	22	1913	
Venezia (S. Stefano)	45 25 N	12 20 E	270	051	22	1920	
Venezia (Punta Della Salute)	45 26 N	12 20 E	270	054	23	1967	
Trieste	45 39 N	13 45 E	270	061	23	1994	27-01-95
Pola	44 52 N	13 51 E	270	071	22	1913	
Koper	45 33 N	13 44 E	279	002	E1	1991	03-02-93
Rovinj	45 05 N	13 38 E	280	006	E1	1991	03-02-93
Bakar	45 18 N	14 32 E	280	011	27	1991	03-02-93
Gazenica	45 05 N	15 16 E	280	014	26	1988	31-05-90
Zlarin	43 42 N	15 40 E	280	017	26	1988	31-05-90
Zirje	43 40 N	15 40 E	280	018	E1	1991	03-02-93
Split Rt Marjana	43 30 N	16 23 E	280	021	E1	1991	05-02-93
Split Harbour	43 30 N	16 26 E	280	031	E1	1991	03-02-93
Vis-Ceska Vila	43 04 N	16 12 E	280	040	E1	1991	03-02-93

Table 1. *Continued.*

Station	Lat	Lon	CC	SC	AC	LY	Updated
Vis	43 04 N	16 12 E	280	041	26	1957	
Sucuraj	43 08 N	17 12 E	280	046	E1	1991	
Usce Neretve	43 01 N	17 27 E	280	051	26	1957	
Ubli	42 45 N	16 50 E	280	056	E1	1991	03-02-93
Mali Ston	42 50 N	17 42 E	280	061	26	1959	
Broce	42 49 N	17 43 E	280	071	26	1959	03-02-93
Dubrovnik	42 40 N	18 04 E	280	081	E1	1991	03-02-93
Hercegnovi	42 27 N	18 32 E	281	001	26	1958	
Bar	42 05 N	19 05 E	281	011	E1	1991	03-02-93
Ulcinj	41 55 N	19 12 E	281	021	26	1955	
Preveza	38 57 N	20 46 E	290	001	65	1989	06-12-94
Levkas	38 50 N	20 42 E	290	004	65	1989	28-11-94
Posidhonia	37 57 N	22 57 E	290	011	65	1989	06-12-94
Patrai	38 14 N	21 44 E	290	014	65	1989	28-11-94
Katakolon	37 38 N	21 19 E	290	017	65	1989	24-11-94
Kalamai	37 01 N	22 08 E	290	021	65	1985	06-12-94
North Salaminos	37 57 N	23 30 E	290	030	65	1989	28-11-94
Piraievs	37 56 N	23 37 E	290	031	65	1989	28-11-94
Rafina	38 02 N	24 00 E	290	032	65	1989	28-11-94
Khalkis South	38 28 N	23 36 E	290	033	65	1988	29-11-94
Khalkis North	38 28 N	23 36 E	290	034	65	1988	24-11-94
Volos	39 23 N	22 56 E	290	041	65	1940	
Thessaloniki	40 37 N	23 02 E	290	051	65	1989	28-11-94
Kavalla	40 55 N	24 25 E	290	061	65	1986	29-11-94
Alexandroupolis	40 51 N	25 53 E	290	065	65	1988	06-12-94
Khios	38 23 N	26 09 E	290	071	65	1989	25-11-94
Siros	37 26 N	24 55 E	290	081	65	1989	25-11-94
Leros	37 05 N	26 53 E	290	091	65	1989	28-11-94
Soudhas	35 30 N	24 03 E	290	097	65	1985	06-12-94
Iraklion	35 20 N	25 08 E	290	101	65	1988	29-11-94
Rodhos	36 26 N	28 14 E	290	110	65	1987	06-12-94
Nesebar	42 38 N	27 46 E	295	031	B9	1992	16-09-93
Constanta	44 09 N	28 40 E	297	021	C2	1969	12-05-89
Tuapse	44 06 N	39 04 E	300	001	02	1993	12-07-94
Poti	42 10 N	41 41 E	305	021	G2	1990	06-09-93
Trabzon	41 00 N	39 43 E	310	011	87	1973	14-10-88
Samsun	41 17 N	36 20 E	310	021	87	1983	26-03-92
Ereglisi	41 17 N	31 25 E	310	031	87	1962	
Arnavutkoy	41 04 N	29 03 E	310	036	88	1943	
Erdek	40 24 N	27 52 E	310	038	87	1992	30-03-94
Karsiyaka	38 24 N	27 10 E	310	040	87	1977	02-06-92
Karsiyaka/Izmir	38 24 N	27 10 E	310	041	87	1970	02-06-92
Mentes/Izmir	38 26 N	26 43 E	310	042	87	1992	30-03-94
Bodrum	37 02 N	27 25 E	310	045	87	1973	14-10-88
Bodrum II	37 02 N	27 25 E	310	046	87	1992	30-03-94
Antalya	36 53 N	30 42 E	310	051	87	1977	13-05-92
Antalya II	36 53 N	30 42 E	310	052	87	1992	30-03-94
Iskenderun	36 37 N	36 07 E	310	061	87	1973	14-10-88
Famagusta	35 07 N	33 57 E	315	001	C4	1940	09-10-89
Haifa	32 49 N	35 00 E	320	011	89	1976	
Hadera	32 28 N	34 53 E	320	016	H1	1993	11-07-94
Jaffa	32 03 N	34 45 E	320	021	89	1970	
Ashdod	31 50 N	34 39 E	320	031	89	1980	
Port Said	31 15 N	32 18 E	330	001	90	1946	
Deversoir	30 25 N	32 21 E	330	011	90	1941	
Kabret	30 16 N	32 30 E	330	021	90	1941	
Geneffe	30 10 N	32 34 E	330	031	90	1941	
Suez (Port Taufig)	29 56 N	32 34 E	330	041	C6	1986	05-02-90
Alexandria	31 13 N	29 55 E	330	071	91	1989	23-10-92
Ceuta	35 54 N	5 19 W	340	001	68	1964	
Villa Sanjurjo	35 15 N	3 55 W	340	004	68	1949	
Ceuta-A	35 54 N	5 19 W	340	005	68	1974	25-11-93
Ceuta-B	35 54 N	5 19 W	340	006	68	1977	25-11-93
Ceuta-C	35 54 N	5 19 W	340	007	68	1980	25-11-93
Ceuta-D	35 54 N	5 19 W	340	008	68	1991	25-11-93

CC: country code, SC: station and AC: Authority code in the database. Latest year (LY) available and latest update (for data received after 1988) is also shown.

Table 2. *Authorities contributing sea level data in the Mediterranean and Black Sea part of the PSMSL database, NN number of authority in the database.*

NN	Address	Country
02	World Data Centre B1, 6 Korolev Str., Obnisk, Kaluga, Reg. 249020	Russia
10	Tidal Branch Hydrographic Department M.O.D., Taunton, Somerset, TA1 2DN	UK
18	Service Hydrographique et Oceanographique de la Marine, Etablissement Principal, B.P.426, 29275, Brest	France
19	Institut Geographique National, 2 Avenue Pasteur, 94160 Saint-Mande (Seine)	France
20	Instituto Geografico Nacional, Seccion de Nivelaciones (Mareografos), General Ibanez de Ibero 3, 28003, Madrid	Spain
22	Instituto Idrografico della Marina, 16100, Genova	Italy
23	Instituto Thalassografico di Trieste, Viale R. Gessi 2, I-34123, Trieste	Italy
24	Instituto Geografico Militaire, Reparto Geodetico, 50100, Firenze	Italy
26	Hidrografski Institut JRM, Split	Croatia
27	Andrija Mohorovicic Geophysical Institute, Faculty of Science, University of Zagreb, Horvatovac BB, YU-4100, Zagreb	Croatia
65	Hydrographer of the Navy, Hellenic Navy Command, TGN 1040, Athens	Greece
68	Instituto Espanol de datos Oceanograficos, Instituto Espanol de Oceanografia, Av.Brasil, 31, 28020, Madrid	Spain
87	Harita Genel Komutanligi, 06100m, Ankara	Turkey
88	Kandilli Observatory, Cengelkoy, Instanbul	Turkey
89	Coastal Study Division, Israel Ports Authority, P.O.B. 5 Ashdod	Israel
90	Egyptian National Oceanographic data Centre, Institute of Oceanography and Fisheries, Kayet Bay, Alexandria	Egypt
91	Coastal Research Institute, 15 El Pharaana Str., El Shallalat, 21514, Alexandria	Egypt
B6	Consiglio Nazionale delle Ricerche, Palazzo Papadopoli, 1364 San Polo, 30125, Venezia	Italy
B9	National Hydrometeorological Service, Institute of Hydrology and Meteorology, BLVD Lenin 66, 1184 Sofia	Bulgaria
C2	Institute of Hydrotechnical Research, Bucuresti 17, Splaiul Independentei 294	Romania
C4	Dept. of Lands and Surveys, Nicosia	Cyprus
C5	Univerita degli Studi di Napoli, Dipartimento di Geofisica e Vulcanologia, Largo S. Marcellino 10, 80138 Naples	Italy
C6	Suez Canal Research Center, Suez Canal Authority, Ismailia	Egypt
E1	Hidrografski Institut of Republic of Croatia, Zrinjsko-Frankopanska BB, 5800 Split	Croatia
E3	Malta Council for Science and Technology, 112 West Street, Valletta	Malta
G2	Dept. of Oceanology and Meteorology, Tbilisi State University, Chavchavadze Prospect 1	Georgia
G7	Osservatorio Vesuviano, Via A. Manzoni, 249, Napoli 80123	Italy
H1	Israel Oceanographic and Limnological Research Ltd., Tel Shikmona, POB 8030, Haifa 31080	Israel
H9	Dr. Josep Pascual Massaguer, STA. ANNA, 49, E 17258 L'Estartit (Girona)	Spain

Table 3. *The information acquired with the sea level data.*

FORMAT FOR SUBMISSION OF MONTHLY AND ANNUAL SEA LEVEL DATA TO THE PERMANENT SERVICE FOR MEAN SEA LEVEL (PSMSL)

Country Station
Latitude Longitude
Year

Month	Values	Number of days for which no data is available	XX if interpolation used
January			
February			
March			
April			
May			
June			
July			
August			
September			
October			
November			
December			
Annual mean			

Unit used:
Datum of observations:
Reference Bench Mark (by name or number):
Description of Reference Bench Mark:
Vertical distance between Datum of observations and Reference Bench Mark:
Details of any changes in this distance which have occurred during the year:
No. of observations per day used to calculate mean:
Type of gauge:
Name:
Date: Authority and address:

in Patra is not clear and datum shifts are also suspected (VEIS, G., Technical University of Athens, *personal communication*). Another indicative test is plotting the detrended differences between time series from near-by tide gauges. Even for the longer time series of Marseille and Genova (considered as mostly reliable), differences exhibit some of the

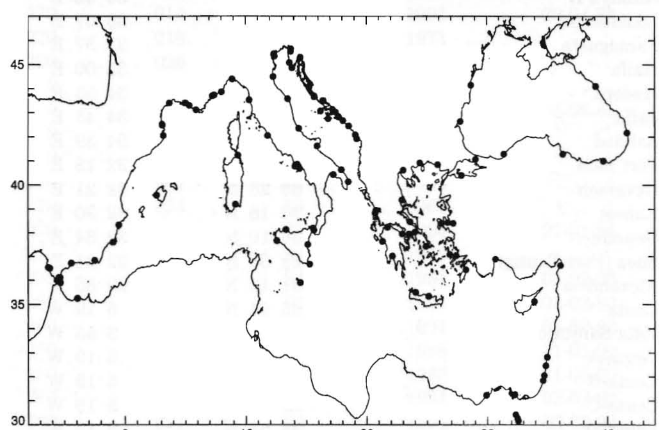

Figure 1. The location of tide-gauges for which data exist in the PSMSL database.

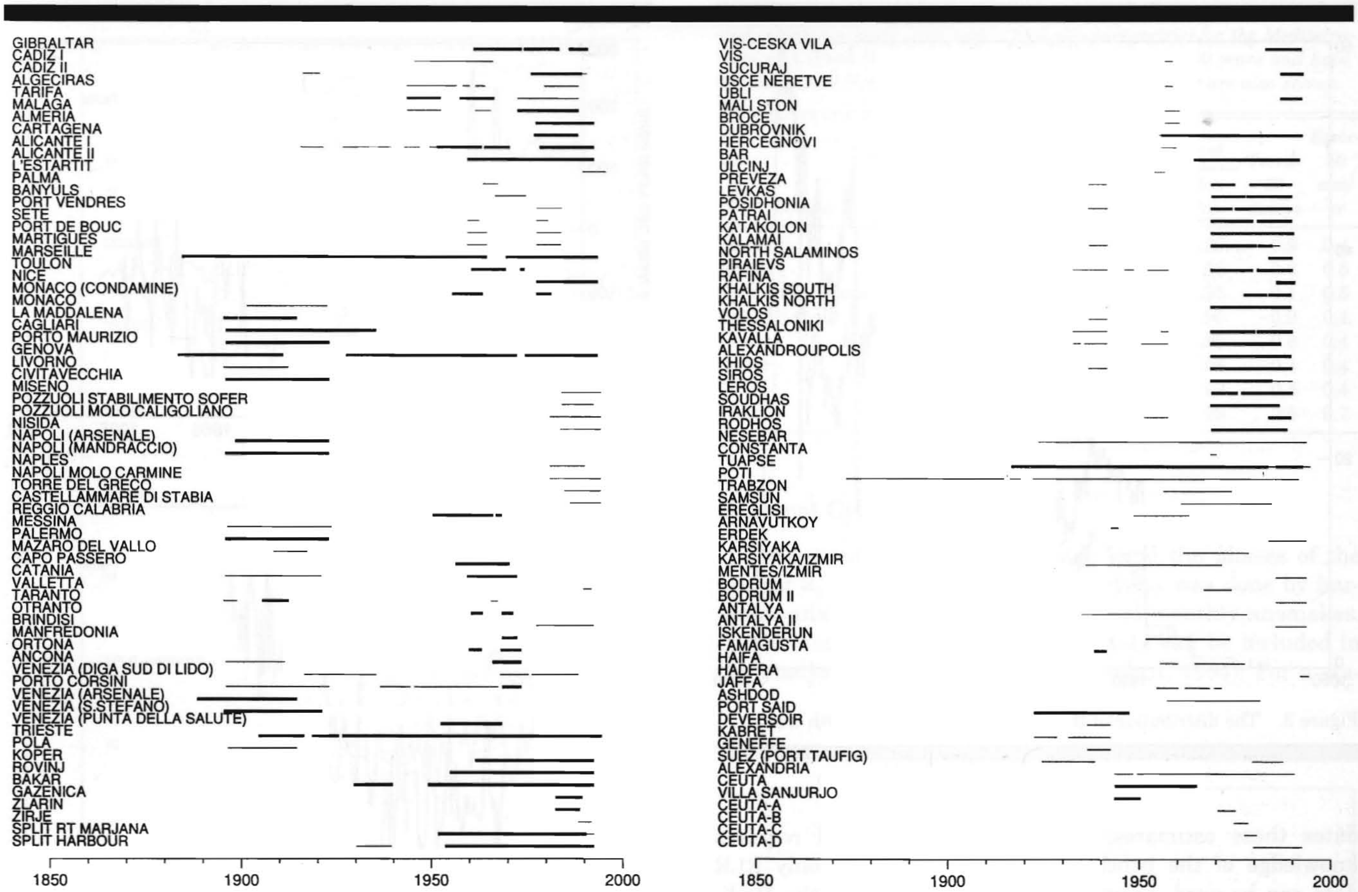

Figure 2. The temporal distribution of tide-gauge records. RLR records (thick line), METRIC records (thin line).

problems found in sea level records (Figure 5). The peak in 1951–1952 has been confirmed as erroneous by the authorities in Marseille. After this peak, a gradual change of sea level between the two stations is evident until 1956, when their difference returns to values around zero (these values are flagged in the PSMSL database). Other large differences can be detected at 1906 and 1988 (see also DOUGLAS, 1992). Of course, with two stations is it almost always impossible to tell which one is correct. Therefore, group comparisons are needed when there are more than one nearby stations.

The overall quality of data in the Mediterranean area is not good. The exceptions are a few long stations where for most years continuous and reliable sea level data and benchmark information is provided. These stations are Trieste, Marseille, Genova, Port Tuapse and the network of ex-Yugoslavian stations which was partly destroyed during the recent war.

MOSETTI and PURGA (1991) described the condition of mean sea level data in the Mediterranean as "catastrophic". The lack of a central authority was considered responsible for the numerous gaps and inconsistencies in most of the Italian data (MOSETTI and PURGA, 1991). Nevertheless, a few local services such as these responsible for Trieste and Genova have maintained their consistency over the years. In Greece where there is a central service, the records are almost unusable for the calculation of trends with unjustified large datum shifts and large inconsistencies between stations less than 200 km apart. The root of the problem seems to be a lack of understanding of the significance of accurate benchmark information and poor techniques employed in the monitoring of the performance of the tide-gauges and of the processing of the data. France and Spain can claim only one useful station each in the Mediterranean, Marseille and Alicante respectively. The Turkish stations are relatively short and are included only in the Metric dataset and therefore are not useful as yet for trend estimation.

ANALYSIS AND RESULTS

Relative Sea Level Trends

Information that can easily be extorted from PSMSL data includes estimates of local sea level trends and the main seasonal cycles, the annual and the semi-annual. Because of the interannual and interdecadal variability, the accurate estimation of these parameters requires long time-series. Several authors have given trend estimates for the area (*e.g.,* PIRAZZOLI, 1987; FLEMMING and WOODWORTH, 1988; EMERY *et al.,* 1988; MOSETTI and PURGA, 1991) and the present study up-

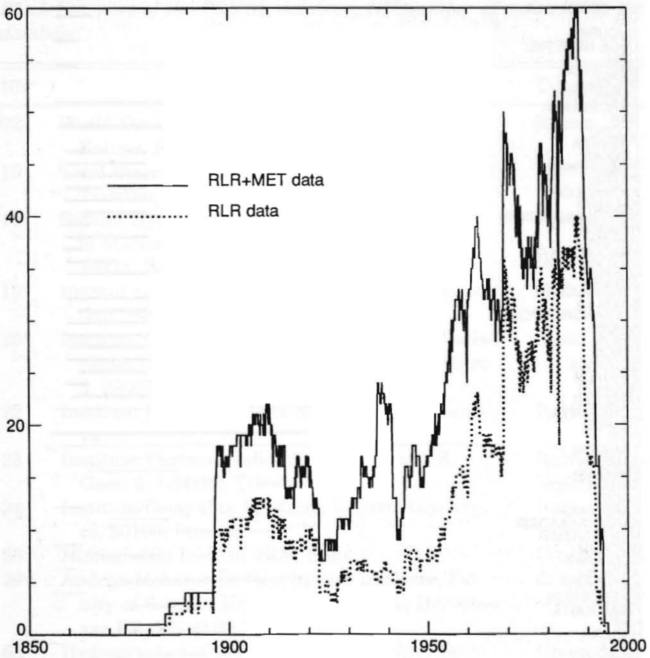

Figure 3. The distribution of the total and RLR records with time.

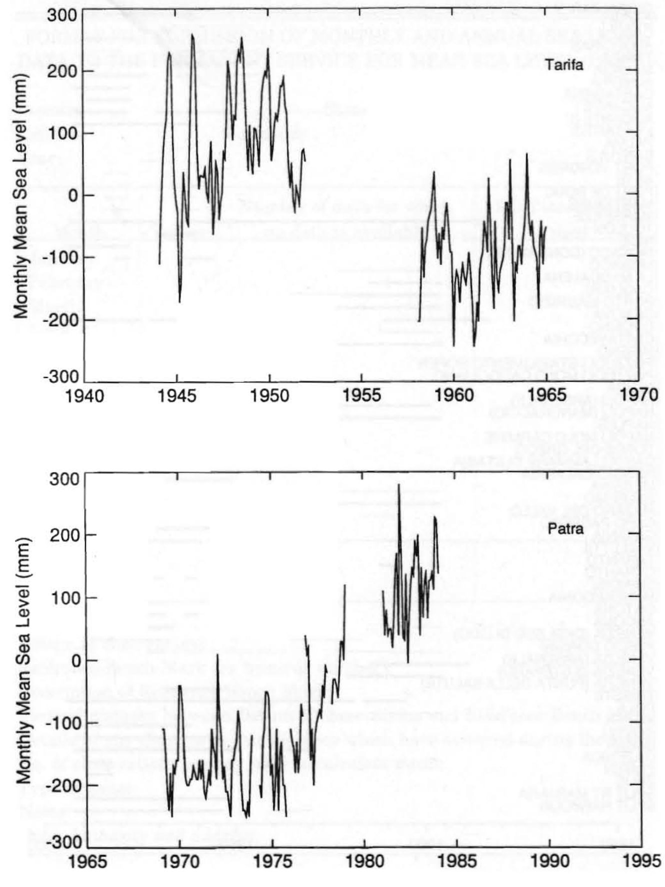

Figure 4. The monthly time series for two RLR problematic stations. Top: Tarifa (Spain), bottom: Patra (Greece).

dates these estimates. The estimation of trend requires knowledge of the benchmark information; thus only RLR data can be used. From the available stations in the Mediterranean and the Black Sea, eight have time series that span more than 30 years: Marseille and Genova in the western Mediterranean; Trieste, Bakar, Rovinj, Split Harbour and Split Marjana in the Adriatic; and Tuapse in the Black Sea. These time series are shown in Figure 6. For these longer time series, the trends were estimated by a linear regression of their RLR annual values. The results are shown in Table 4. The trend values are in the range of −0.7 to 2.2 mm/yr. The standard errors of the regression coefficient and the parametric level of significance is also shown.

To estimate whether these trends are statistically significant, the bootstrap method can also be used (EFRON, 1981). The advantage of this non-parametric method is the fact that no correction for serial correlation is necessary. If M_i are the annual sea level values, then N (N = 1,000) random combinations of these values are produced. The trend for these N combinations are calculated and then compared with the trend value estimated from the real time-series. If M of these combinations give trend values larger than the observed, then (1 − M/N) is the level of significance for the trend. The resulting level of significance is shown at the sixth column of Table 4 and agrees with the parametric estimations for most of the stations. Notably, the trend values for the 4 stations on the east coast of the Adriatic are smaller than the values of the other stations. These stations cover periods mainly after 1950. Therefore, the trends for all (long) stations were recalculated for 1950 forward. The resulting values (Table 4, last two columns) are indeed slightly lower than the longer

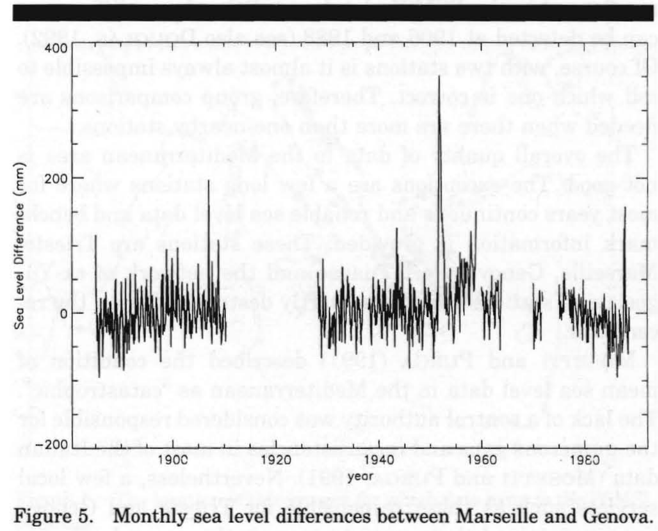

Figure 5. Monthly sea level differences between Marseille and Genova.

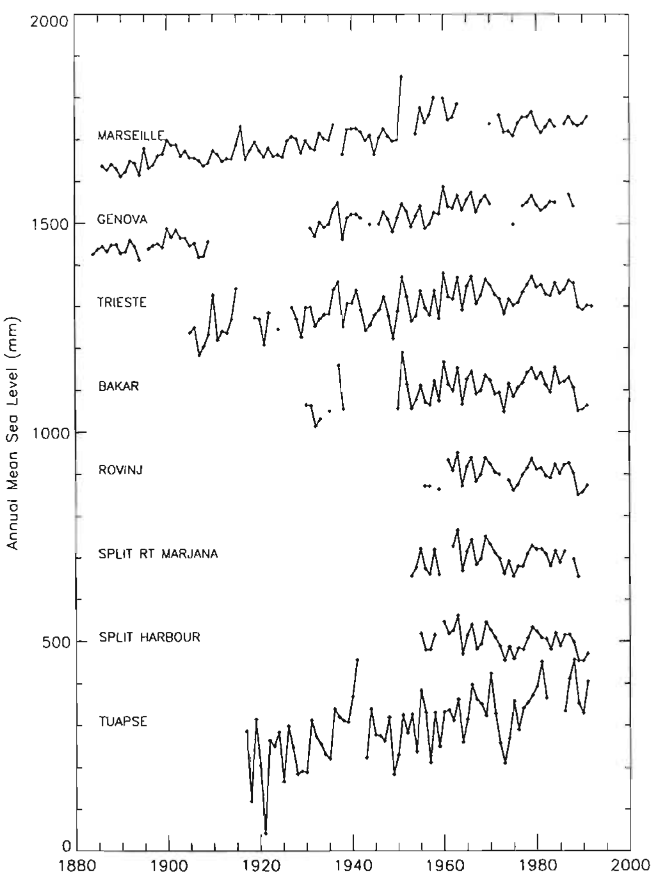

Figure 6. Annual mean sea level for the longest available records. The time series have been artificially offset for demonstration.

term values in the Mediterranean, but in view of the associated standard errors, they cannot be considered significantly different in most cases.

Another empirical way of estimating the error in the trends is by dividing the time series into overlapping segments of variable span DT and estimating the average trend and its standard deviation for each DT. In Figure 7a, the difference of the average trend from the final value is plotted for the stations in Table 4. Notably the average trend is less than 0.5 mm/yr from the long term value after 40 years. Similarly, the standard deviation of the segment values is less than 0.5 mm/yr for spans longer than 40 years (Figure 7b). This empirical calculation of the errors in trends yields higher values than those estimated through regression. The slightly larger values for Tuapse indicate either larger interdecadal variability or lower quality data, but in the absence of any other available RLR station in the area, this matter cannot be resolved. It should be noted that as the span approaches the maximum available years, the number of combinations is reduced and therefore the STD decreases to zero. Therefore, Figure 7 should only be considered as an approximately indicative test only.

Table 4. *Relative sea level trends and their associated standard errors and confidence levels (parametric and non-parametric) for the Mediterranean and Black Sea stations that span for more than 30 years and have Revised Local Reference (RLR) data. Trends after 1950 are also shown.*

Station	Span yr	Complete yr	Trend mm/yr	Error mm/yr	Conf. Level Par.	Conf. Level Non Par.	Trend-50 mm/yr	Error-50 mm/yr
Marseille	105	83	1.1	0.1	0.99	0.99	0.9	0.4
Rovinj	36	35	−0.3	0.4	0.54	0.56	−0.2	0.5
Split Rt Marjana	37	35	0.1	0.5	0.16	0.25	0.1	0.5
Split Harbour	37	37	−0.7	0.4	0.91	0.90	−0.9	0.4
Genova	105	74	1.3	0.1	0.99	0.99	0.8	0.4
Bakar	62	49	0.7	0.3	0.98	0.98	0.4	0.4
Trieste	88	82	1.2	0.2	0.99	0.99	0.4	0.4
Tuapse	75	71	2.2	0.3	0.99	0.99	2.5	0.7

Seasonal Cycles

The estimation of the amplitudes and the phases of the annual S_a and the semi-annual S_{sa} cycles was done by harmonic analysis of the average sea level monthly anomalies. In this case, both Metric and RLR data can be included in the analysis (TSIMPLIS and WOODWORTH, 1994). For a sta-

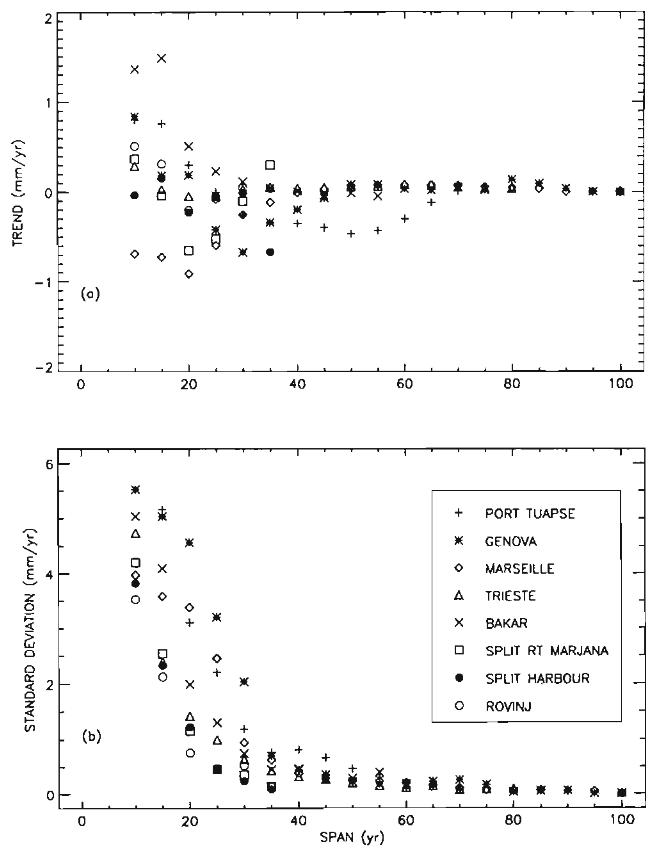

Figure 7. Empirical estimation of trends. Average trend difference from the overall value derived from overlapping constant span records (a). The associated standard deviations (b).

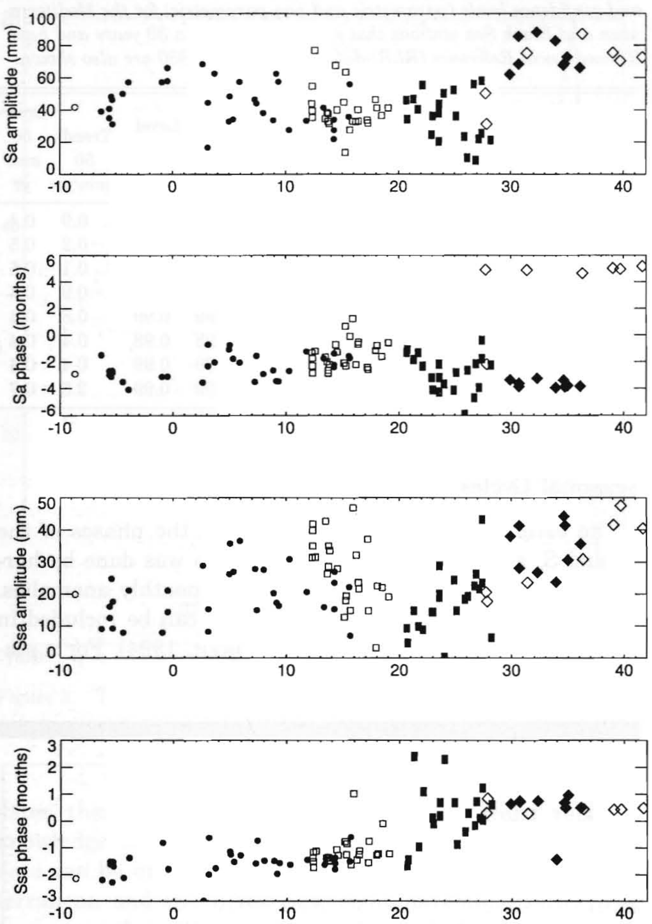

Figure 8. Longitudinal variation of the seasonal parameters. From top: amplitude of the annual cycle, phase of the annual cycle, amplitude of the semi-annual cycle, phase of the semi-annual cycle. Phases are expressed in months centred at the 1st of January. West Mediterranean (filled circles), Adriatic (squares), Aegean and Ionian (filled squares), Black Sea (diamonds), East Mediterranean (filled diamonds), Lagos (circles).

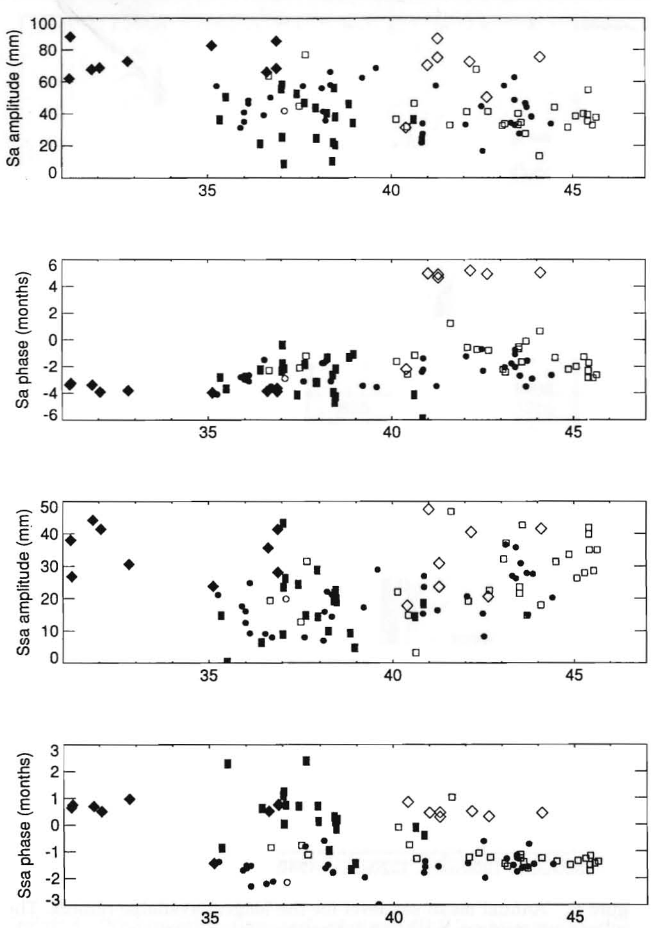

Figure 9. Latitudinal variation of the seasonal parameters. From top: amplitude of the annual cycle, phase of the annual cycle, amplitude of the semi-annual cycle, phase of the semi-annual cycle. Phases are expressed in months centred at the 1st of January. West Mediterranean (filled circles), Adriatic (squares), Aegean and Ionian (filled squares), Black Sea (diamonds), East Mediterranean (filled diamonds), Lagos (circles).

tion with N years of data, mean annual values M_j were calculated from mean monthly sea level values X_{ij} (month i, year j):

$$M_j = \frac{1}{12} \sum X_{ij} \qquad i = 1, 12 \tag{1}$$

Monthly anomalies Y_{ij} were then calculated by removing the average annual values M_j *e.g.*: $Y_{ij} = X_{ij} - M_j$. Then the average of monthly anomalies MA_i were calculated by:

$$MA_i = \frac{1}{N} \sum Y_{ik} \qquad k = 1, N \tag{2}$$

A least square fit was then made in order to determine the amplitudes A_{Sa}, A_{Ssa} and the phases P_{Sa}, P_{Ssa} of the annual and semi-annual cycles:

$$MA_i = A_{Sa}\cos\left(\frac{2\pi}{12}(t - P_{Sa})\right) + A_{Ssa}\cos\left(\frac{2\pi}{6}(t - P_{Ssa})\right) \qquad i = 1, 12 \tag{13}$$

where $t = i - 0.5$ to account for MA_i being the average of the ith month. The phases P_{Sa} and P_{Ssa} correspond to the maxima of the two annual and the semi-annual cycles in the range $[-6, 6]$ and $[-3, 3]$, respectively from the beginning of the year. Only stations with more than 5 full years were included in the analysis.

The longitudinal and latitudinal distribution of the four parameters A_{Sa}, A_{Ssa}, P_{Sa} and P_{Ssa} are shown in Figures 8 and 9, respectively. In these plots, Lagos is also included as an indicator of the seasonal cycle outside the Strait of Gibraltar. The amplitude of the annual cycle is less than 10 cm in the whole Mediterranean. The larger values are found in the area east of Crete and in the Black Sea. The phases show a slight

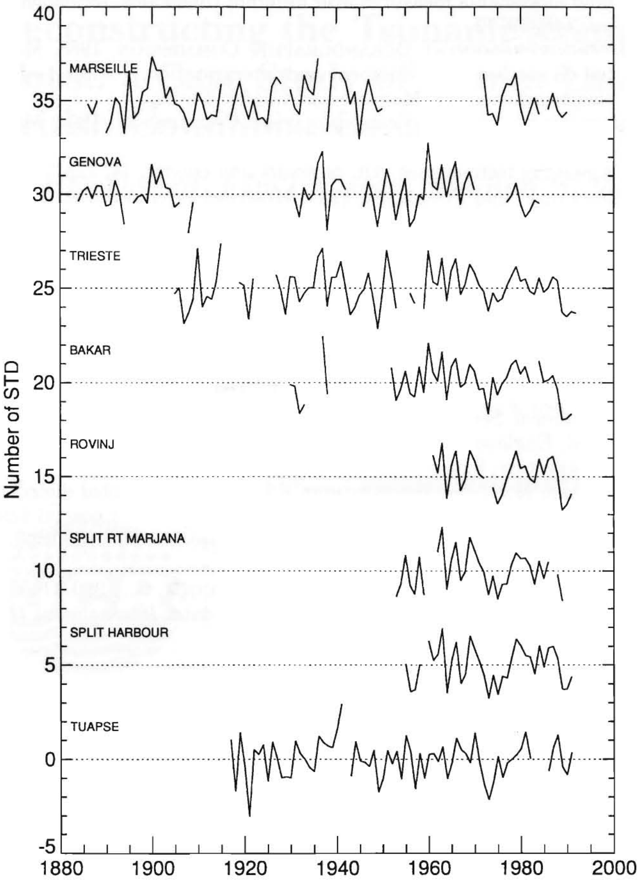

Figure 10. Long term variability of sea level. Annual values detrended and non-dimensionalised with respect to the standard deviation of each time series. The time series have been artificially offset for presentation.

latitudinal increase with the Black Sea having significantly different phases. The semi-annual cycle has amplitudes less than 5 cm. The amplitudes' values are more scattered than those of the annual cycle. This could be due to the fact that the semi-annual cycle may arise from the shifting of the annual cycle from year to year and does not necessarily represent a directly forced signal and to the fact that the years analyzed are not the same for all the stations. Nevertheless, some similarity in the longitudinal distribution of the amplitudes of the annual and the semi-annual cycles is evident with larger amplitudes of the semi-annual cycle corresponding to larger values of the annual amplitude. The longitudinal phase distribution is more consistent with the west Mediterranean and the Adriatic having a couple of months difference from the rest of the Mediterranean and the Black Sea.

The statistical significance of the cycles was investigated by again using the bootstrap method. In order to use all the Metric data, monthly anomalies for each year were calculated, randomly remixed and the annual and semi-annual cycles re-estimated. The values of the amplitudes of the cycles were then compared to the distribution of the amplitude estimations of the random samples. The annual cycle at stations that had more than 10 years of data had amplitudes that were significantly different to zero at levels higher than 90%. In the semi-annual cycle, the same level of significance was found for stations with more than 15 years of data. Notably the stations of suspect quality give the lowest significance level.

Low Frequency Variability

To examine the spatial coherence of interdecadal and decadal variability, cross-spectral analysis, singular spectrum analysis and low pass filters can be used. Because all the time series include gaps, these techniques cannot be employed readily unless assumptions for the missing data can be made which in turn will affect the estimation. The technique is a simple method in which each time series is detrended and its variance re-normalised with respect to its standard deviation. Even this simple approach has problems since the removal of the trend and the mean for different periods means that some of the interdecadal variability is lost. The results are plotted in Figure 10. A two to five year oscillation is evident and in phase in all the records. During the period 1955–1965, sea level seems to have been slightly higher than the previous and following decade (this probably accounts for the reduced trends after 1950). The low values in the early 1970's are evident both in the Mediterranean and the Black Sea Stations. Because Tuapse shows agreement for this 2–5 year variability and the minimum in the 70's and the flow between the two basins is very small, it is implied that the source should be sought at atmospheric and climatic variables.

DISCUSSION AND CONCLUSIONS

The PSMSL dataset for the Mediterranean and the Black Seas has been reviewed. Despite the large number of stations included in the database, there are virtually no stations along the north African coast and only a few stations in the Black Sea. More stations are known to exist, but it has not been possible to acquire their data in spite of repeated attempts to contact the relevant authorities.

Only a few of the available stations are long enough to be useful for trend estimation. For them, the relative sea level trends are less than 2.2 mm/yr. The coasts of the Adriatic give a rather coherent picture of trends very close to zero after 1950. The longer stations that extend to the end of the previous century give higher values. The estimation of the annual and semi-annual cycle is more coherent since the entire dataset can be employed, not only the RLR subset with benchmark stability. The annual cycle is found to be stronger in the Black Sea with a quite distinct phase difference to the Mediterranean.

As altimetric data become increasingly available and more reliable, the need for accurate coastal measurements of sea level for calibration and comparison also increases. A new proposal "Eurogloss" (BAKER, T.F. *et al.*, 1994), if accepted by the nations of the region, will hopefully help in creating a reliable database for the future.

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