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Global sea level rise?
New techniques for the absolute sea level measurement

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A brief review is given of recent papers on the relative mean sea level, global sea level rise effect, and the predictions to the year 2100. The influence of vertical crustal movements on the relative sea level is visible in the longest sea level records. Both modern space geodetic techniques and absolute gravity measurements have now achieved the accuracy within a centimetre that is comparable to the quality of mean sea level records. As the extraction of land movements from the tide gauge records is possible after about a decade of measurements, a number of international projects have been (*e.g.* SELF) and will be (*e.g.* MedGLOSS) launched with the aim of determining the absolute sea level.

Keywords: Sea level, global sea level rise, GPS

Introduction

Due to increasing public attention and the evidences of changes of the Earth system, the aspect of sea level rise has recently come into focus. A global rise of sea level is considered as one of the more severe consequences of the predicted global warming (Warrick and Oerlemans, 1990), especially if an acceleration of the sea level rise can be detected (Woodworth, 1990; Douglas, 1992). Changes in global sea level due to volumetric changes of the ocean water are thought to constitute the climate signal in the sea level, which is composed of two major parts: (1) warming of the ocean that increases the volume of the water, and (2) melting of land-based ice adds water to the ocean.

Mean sea level is measured using tide-gauges, which provide values of the sea level relative to the level of land at the tidegauge. It is then not clear whether the change in the sea level indicated by tide-gauge records is due to the actual rise of the sea level, to the local ground movement, or to the unknown combination of these two processes. In order to monitor the absolute changes in the sea level, it is therefore necessary to monitor the land uplift or subsidence which occurs at tide-gauge sites.

In 1988, the Commission on Mean Sea Level and Tides of the International Association for Physical Sciences of the Ocean (IAPSO) reviewed the geodetic fixing of tide gauge bench marks (TGBM) at workshop held at the Woods Hole Oceanographic Institute in the USA (Carter at al., 1989). The IAPSO Committee recommended that TGBMs should be linked to the International Terrestrial Reference Frame (ITRF) and monitored through episodic Global Positioning System (GPS) campaigns, with simultaneous measurements made at tide gauge GPS stations and fundamental (fiducial) ITRF stations (Ashkenazi et al., 1993).

Besides GPS, other satellite techniques have also been developed – *e.g.* DORIS (Lefebvre et al., 1996). Vertical land movements can be measured by means of absolute gravity too (Marson et al., l995). The land and sea level components of relative sea level measured by tide-gauge can be decoupled at sites where tide-gauge and geodetic measurements are made together, or nearby (Baker et al., 1997). The complementarity of the long-term tide-gauge (relative sea level) and geodetic (land level) monitoring has been recognized by international working groups linked to the Global Sea Level Observing System (GLOSS) (Carter et al., 1989; Carter, 1994), European regional groups such as SELF (Zerbini et al., 1996), EUROGAUGE (Ashkenazi et al., 1994), the Baltic sea level project (Kakkuri, 1995) and MedGLOSS (Rosen, 1997).

A review of recent efforts made on observing and modelling the global sea level rise will be presented here. Furthermore, the principles of GPS and absolute gravity techniques of measuring the vertical crustal movements will be given, as well as a brief review of the MedGLOSS project.

Sea level rise? Observations and modelling

Secular trends in the eustatic global sea level corresponding to a change in ocean volume, have been studied over the past century by a large number of authors (*e.g.* Emery and Aubrey, 1991; Woodworth, 1993; Douglas, 1995) using the Permanent Service for Mean Sea Level (PSMSL) dataset (Spencer and Woodworth, 1993). A central problem in identifying trends in eustatic sea level from tide gauge records is how to account for the processes which affect such measurements. The determination of long-term trends in sea level changes at coastal stations is masked by seasonal and other climatic fluctuations such as steric effect, wind induced set-up, wave induced superelevation, atmospheric pressure, general circulation, post-glacial rebound (PGR), etc. On the scale of tens and hundreds of years the most important global process is PGR that produces vertical land movements. This can be easily seen in the plot of the longest tide gauge records in Europe (Fig. 1). It is clear that the mean sea levels at Cascais (Portugal), Brest (France),

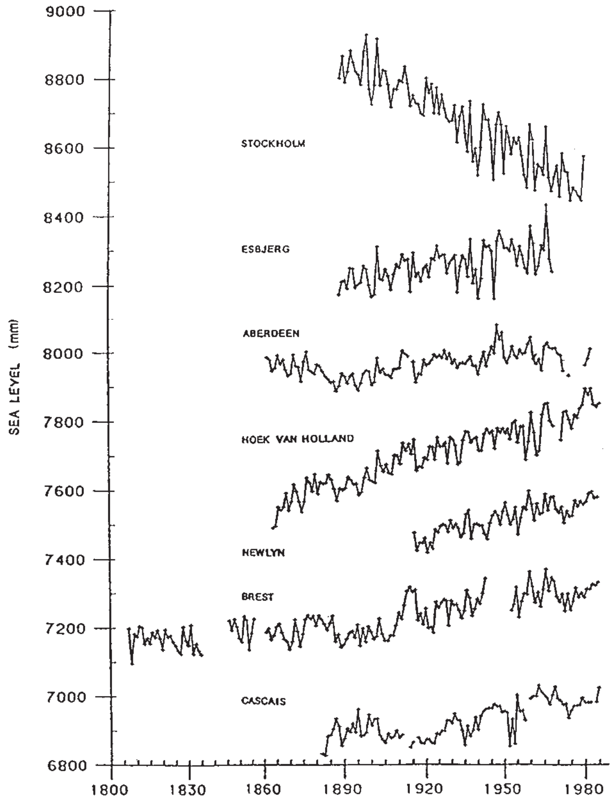

Figure 1. Some examples of long time series of European annual mean sea levels. Each record has been offset vertically for presentation purposes (after Baker, 1993).

Newlyn (UK) and Hoek Van Holland (Netherlands) are rising by 1.5–2.0 mm/year, as found in the other parts of the world (Fig. 2). However, it is also clear from Fig. 1 that the mean sea level in Northern Europe behaves in a markedly different way. In Stockholm (Sweden) the mean sea level is falling by about 4 mm/year, and in Aberdeen (Scotland) the mean sea level trend is very small. The process responsible for that is the post-glacial rebounding (PGR) since the end of the last ice age. It has the largest influence in the Scandinavian region, which was then fully covered by ice. This process is the only globally coherent geological contribution to the sea level changes which is investigated and understood properly.

Models of PGR (*e.g.* Tushingam and Peltier, 1991) were developed in order to remove this signal from the data. Douglas (1991) calculated the global sea level rise of 1.8 ± 0.1 mm/year, using 21 tide gauge records with an average length of 76 years during the period 1880–1980. Peltier and Tushingam (1989, 1991) and Trupin and Wahr (1990) obtained similar results. Uncertainties in the PGR models are of the order of 0.5 mm/year, depending on the

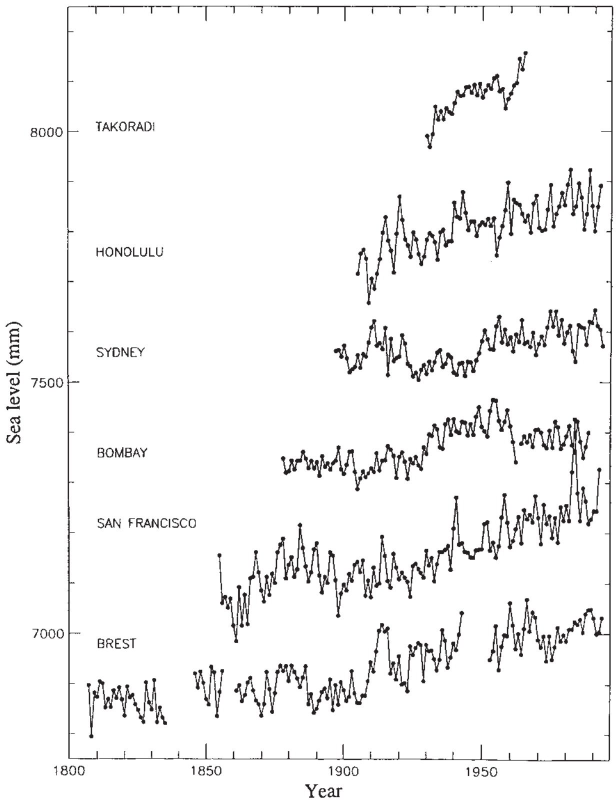

Figure 2. Six long sea level records from major world regions: Takoradi (Africa), Honolulu (Pacific), Sydney (Australia), Bombay (Asia), San Francisco (N. America) and Brest (Europe). Each record has been offset vertically for presentation purposes (after IPCC, 1992).

Earth structure parameterization employed in the model (Mitrovica and Davis, 1995). Some authors have used geological data for sites adjacent to tide gauges, a procedure which, in principle, should accommodate other geological processes in addition to PGR (Gornitz and Lebedeff, 1987). This sort of analysis has been conducted for the North Sea region of Europe, which has an extensive tide gauge and geological sea level data set (Shennan and Woodworth, 1992). Most of these studies yield results of 1–2 mm/year, with some bias towards the lower end of the range (Gornitz, 1995).

In the Mediterranean Sea, and in the Adriatic as well, surprisingly the sea level rise seems to be recently decelerated (Douglas, 1992; Orlić and Pasarić, 1994). This behaviour may be related to the building of the Assuan Dam which reduced the Nile discharge, and consequently increased the salinity of the Mediterranean. The increase of salinity in the Adriatic really appeared during the sixties and the seventies (Zore-Armanda et al., l991). So, in relatively isolated seas such as the Mediterranean, the processes such as steric effects may play important roles in the sea level changes.

Predictions of the global sea level rise can be attempted, but only roughly because of unknown and unexplored processes which influence the sea, *e.g.* the processes in the Antarctica (IPGC, 1992). The best estimation of sea level rise (mean estimation) is 49 cm to the year 2100 (Fig. 3), with the lowest value of 20, and the highest of 86 cm in that year. The estimates are based on a climate temperature increase of 2.5 °C. The largest part contributing to the sea rising will be thermal expansion contributing 28 cm (Fig. 4). The melting of glaciers/ice caps (16 cm), the Greenland ice melting (6 cm) and Antarctica processes (–l cm) will also play a significant role.

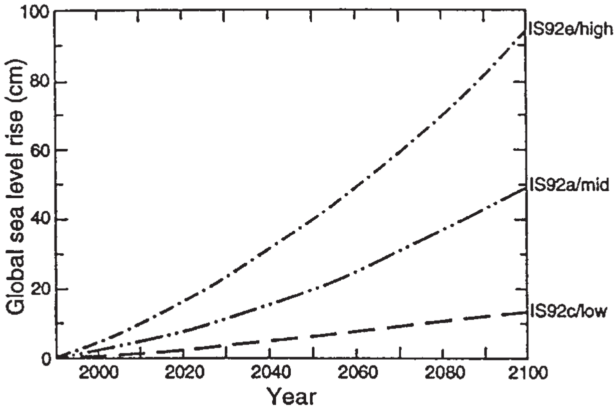

Figure 3. Projected global mean sea level rise from 1990 to 2100. The highest sea level rise curve assumes a climate sensitivity of 4.5 °C and high ice melt parameters, the lowest 1.5 °C and low ice melt parameters and the best (mid) 2.5 °C and mid ice melt parameters (after IPCC, 1992).

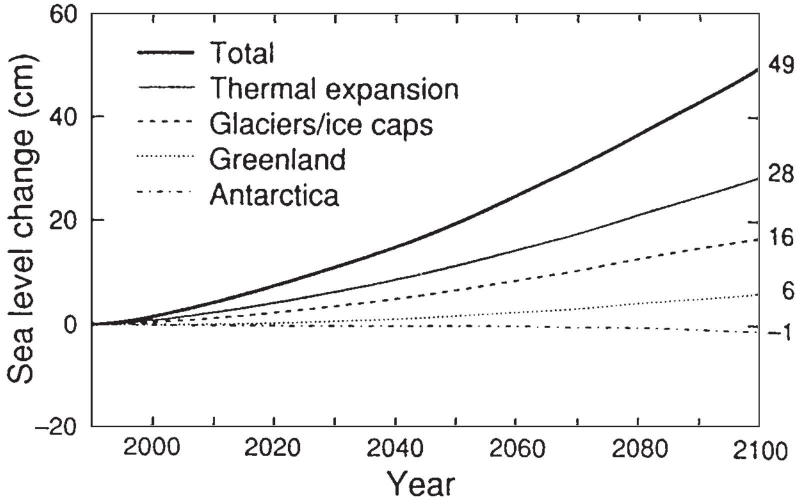

Figure 4. Projected individual contributions to global sea level change to the year 2100 (after IPCC, 1992).

Measurement of vertical land movements

GPS technique

Over the last ten years the U. S. Department of Defense has been launching satellites as part of a satellite based Global Positioning System (GPS). During 1997 their number reached 24 at an average altitude of 20000 km (12 h orbital period), in 6 orbital planes, arranged so that at any time at least 4 satellites are visible from any point on the Earth's surface. The satellites transmit coded modulations on two carrier frequencies with wavelengths of 19 and 24 cm. By knowing positions in space and time of at least 4 satellites and after measuring the reception time of waves traveling from the satellite to the GPS antenna, one can obtain the position of the GPS receiver in the space (x, y, z coordinates) and the clock error. With access to the codes, a user with a GPS receiver can determine his real position to an accuracy of an order of a few tens of metres. The key development that is now giving the accuracy required for measuring the crustal movements is to use the phases of the two carrier waves rather than the codes (Fig. 5). This method is called the carrier phase interferometry, and needs a pair of dual frequency GPS re-

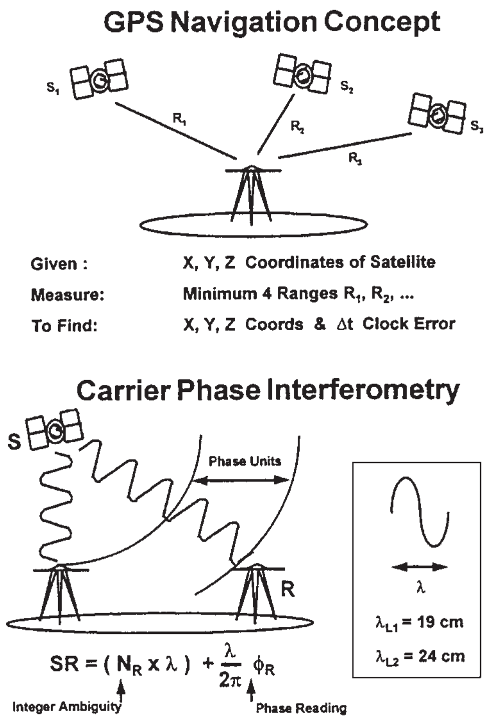

Figure 5. (a) Global Positioning System navigation concept: using at least 4 satellites it is possible to determine the spatial and temporal coordinates; (b) Carrier phase interferometry, a way to obtain precise coordinates with a centimetre accuracy.

ceivers. Knowing the precise position of one receiver (the so-called fiducial GPS receiver) within the geodetic reference frame it is possible to make a relative vector positioning to the other receiver using simple formulas (Fig. 5). For details on positioning the fiducial receiver using other methods see *e.g.* Dixon (1991) and Bilham (1991). Nowadays, the achieved accuracy in the vertical coordinate is of the order of centimetres for baselines of up to 1000 km in length (Baker, 1993).

Following the workshop report of Carter (1994), several research groups have investigated the various error sources in GPS measurements of vertical crustal movements. In Europe, the results of Ashkenazi et al. (1993, 1994), Kakkuri (1995) and Zerbini et al. (1996) show that short GPS campaigns can be used to fix a tide gauge bench mark in a geocentric reference frame with an accuracy better than 20 mm. Due to the interannual and decadal variability of the sea level, the typical standard deviation of the annual mean sea level at a tide gauge is about 30 mm. 30 to 40 years of mean sea level data are therefore required in order to determine the trend in mean sea level with a standard error of the order of 0.5 mm/year. This means that GPS campaigns are already capable of determining the vertical crustal movements at a tide gauge with an uncertainty of less than 1 mm/year in a shorter time span than is required for determining the relative mean sea level of similar accuracy from a tide gauge record. Permanent GPS measurements at tide gauges offer the possibility of determining the vertical crustal movement to an accuracy of 1 mm/year with a significantly shorter span of data (Johansson et al., 1996).

Absolute gravimetry

The principles of absolute gravimetry are straightforward and were demonstrated by Galileo in his experiment which measured the Earth's gravity acceleration in Pisa, Italy, hundreds of years ago. The contemporary free-fall absolute gravimeters employ the same physical principles and precise techniques of spatial and temporal measurements for measuring the free-fall acceleration of an object in the vacuum. The FG5 absolute gravimeter (Fig. 6) consists of three major parts: (l) the upper part has a drag-free chamber with lens reflecting the laser wave; the corner cube is free-falling in the chamber, (2) laser device with system of plates necessary to measure the position of the corner cube, and (3) supersprings that compensate ambient oscillations. Least squares parabola fit through the experimental gravity data gives the value of absolute gravity g. To obtain g with an accuracy approaching 10^{-9} ms^{-2}, spatial and temporal coordinates must be known to the accuracy better than 10^{-10} m (s). For this purpose the vertical fall path is measured using an iodine stabilized HeNe laser, and the time is measured by a rubidium atomic clock, both achieving accuracy better than 10^{-10} m (s). The vertical crustal

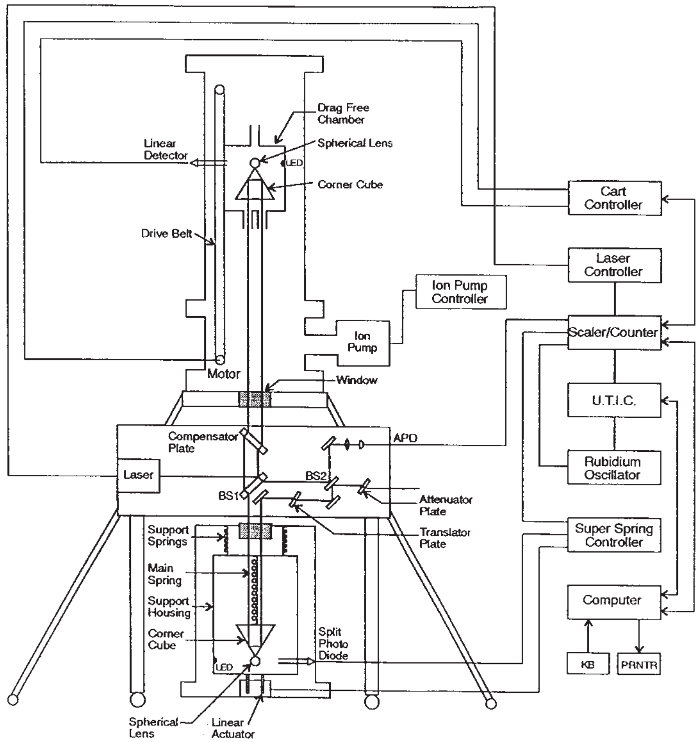

Figure 6. Schematic diagram of the FG5 Absolute Gravimeter. It consist of three basic units: falling unit (falling corner cube), measuring unit (laser device) and superspring unit (removes the microseismic noise).

movement of 1 cm is, according to the Newton's law, equivalent to the gravity change of approximately 3×10^{-8} ms^{-2} or 3 microgals (μgal).

Absolute gravimeters (Marson et al., 1995) can achieve an accuracy of 3 to 4 μgal, which is equivalent to 15 to 30 mm of vertical movement of the instrument (caused by vertical land movements). Thus, the absolute gravimetry and space geodetic techniques are both approaching the equivalent accuracy of 1 cm that is required for measuring vertical land movements.

MedGLOSS project

Although the Mediterranean/Black Sea basin is of relatively small size when compared to oceans, and with weak tides and small sea level changes, some areas can be seriously affected by increase of the sea level (for example Northern Adriatic, the Nile delta, etc.). It therefore seems important to launch the project dealing with long-term sea level and crustal movements

(Rosen, 1997) in that area. The MedGLOSS, a monitoring network system for systematic measurement of the sea level in the Mediterranean and the Black Sea, will be developed applying basic GLOSS requirements and methodology (UNESCO, 1985, 1994).

The major task of MedGLOSS will be to detect regional long-term relative and absolute sea-level changes, trends and acceleration rates, as well as to determine plate tectonic movements by creation of a densified regional long-term sea level monitoring network in the region. The determination of longterm trends in the sea level changes at coastal stations is, as mentioned above, masked by seasonal and other climatic fluctuations, so the long-term monitoring of the fluctuations of the atmospheric pressure, sea-water temperature, wave height and direction, winds, currents, etc. will be encouraged. The schematic proposal for measuring the absolute sea level is shown in Fig. 7. Tide gauge bench mark is related to the mean sea level or some other constant (such as the tide gauge constant), and also to the at least two other bench marks. Tide gauge benchmarks will be linked to the GPS receiver and to the absolute gravimeter by levelling in order to determine the vertical crustal movements.

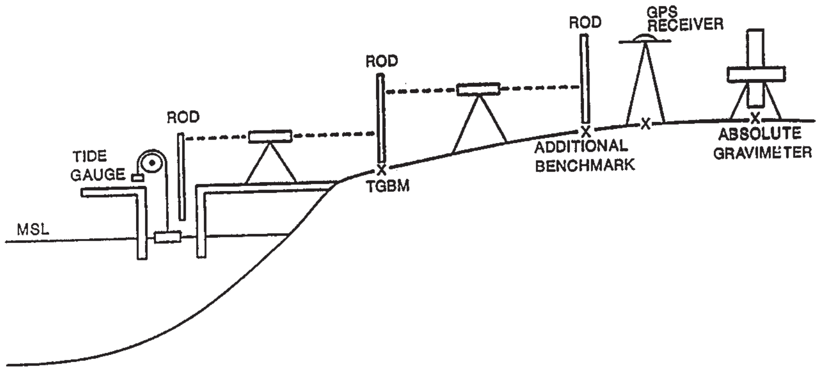

Figure 7. Schematic diagram of a tide gauge to measure absolute sea level using GPS and absolute gravity techniques.

Table 1 contains the proposed list of pilot network stations of MedGLOSS. The pilot network will consists of 27 stations, including the stations operating within GLOSS, stations with digital output and stations with long recording. Most of the proposed stations are float-operated tide-gauges, with only chart recording. The minimum requirements of the Project will be met by installing the monitoring equipment with digital PC compatible output (with the minimum accuracy and the minimum resolution of sea level measurements of 1 cm), the atmospheric barometer with digital output, and a

Table 1. List of selected stations for the MedGLOSS pilot network (after Rosen, 1997).

No.	Staion name	State	Data since	GPS plans
1	Gibraltar	U.K.	1961	visit
2	Alicante	Spain	1916	fix
3	Palma	Spain	1964	visit
4	Marseille	France	1885	visit
5	Genoa	Italy	1884	fix
6	Naples	Italy	1899	visit
7	Catania	Italy	1960	fix
8	Brindisi	Italy		visit
9	Trieste	Italy	1905	visit
10	Split	Croatia	1954	visit
11	Dubrovnik	Croatia	1956	fix
12	Preveza	Greece	1975	visit
13	Kalamata	Greece	1936	visit
14	Piraieuss	Greece	1933	visit
15	Soudhass	Greece	1973	fix
16	Rodhos	Greece	1981	visit
17	Burgas	Bulgaria		visit
18	Katsivily	Ukraine		visit
19	Tuapse	Russia	1917	f ix
20	Erdek	Turkey	1985	visit
21	Mentes	Turkey	1986	visit
22	Bodrum	Turkey	1986	visit
23	Antalya	Turkey	1986	visit
24	Hadera	Israel	1958	fix
25	Alexandria	Egypt	1958	visit
26	Mallieha Bay	Malta	1990	visit
27	Ceuta	Spain	1944	visit

phone link to the centre. Permanent GPS stations will continuously transmit data, while other stations will be visited twice a year. The data will be submitted daily (on-line stations) or every two months (off-line) to the five regional centres where the data will be processed and qualitatively examined.

The expected outcome of the MedGLOSS are the rates of tectonic movements, seasonal maps of the relative sea levels and relative sea level changes based on ground-true and satellite altimetry, and wave and circulation maps based on gathered data and regional numerical models.

Conclusions

Recent developments of new techniques for absolute positioning and of absolute gravity measurement will be applied in order to examine the most disturbing process in the oceans – the increase of volumes of oceans that produces the global sea level rise. Global sea level rise in this century is estimated to be 1.5–2.0 mm/year, and for the next 100 years it is estimated to be 20–86 cm (the best estimate is 49 cm). The monitoring of vertical crustal movements may be done with a precision within a centimetre both using the GPS methods and absolute gravity measurements, which is good enough to monitor land movements. Using these techniques it is possible to extract influence of crustal movements from the sea level records.

The existing projects, such as SELF, GLOSS, etc., and subsequent ones, such as MedGLOSS, are expected to give answers related to the sea level rise, both on the global scale and on the regional scales.

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SAŽETAK

Globalni porast razine mora? Nove tehnike određivanja apsolutne razine mora

Ivica Vilibić

U radu je dan kratak pregled novijih radova koji analiziraju relativnu razinu mora, efekt globalnog porasta razine mora te predviđanja porasta do godine 2100. Utjecaj vertikalnih geotektonskih gibanja sadržanih u mjerenoj relativnoj razini mora se jasno vidi na podacima najdužih mareografskih nizova. Geodetska tehnika preciznog pozicioniranja i apsolutna gravimetrija danas postižu centimetarsku preciznost mjerenja vertikalnih pomaka, usporedivu s geološkim pomacima tla uključenim u registraciju relativne razine mora. Iz istih je moguće, kontinuirano mjereći poziciju i razinu mora oko desetak godina, izdvojiti pomake tla. Stoga je pokrenuto (npr. SELF) ili će se pokrenuti (npr. MedGLOSS) više međunarodnih projekata s ciljem određivanja apsolutne razine mora.

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