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THE GEOID AND MEAN SEA LEVEL

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The surface of the sea would be a physical reproduction of the geoid, the equipotential surface of the field of gravity, if the ocean was at rest and if its density and the atmospheric pressure prevailing at its surface were spatially uniform. In fact, that is not the case. The ocean is constantly in motion which results in spatial and temporal variability of its topography, which is, moreover, extremely complex, and the differences of which, compared with the geoid, forms an index rich in information on the characteristics of such motion.

Since the last century, measuring the level of the sea's surface has been carried out continuously at a certain number of ports. These observations have been acquired primarily for the needs of hydrography, but the study of these long-term series has also made possible — among other scientific results — a better appreciation of the problems involved in exploiting sea level observations in terms of mean sea level: its actual definition, its relationship to the geoid, its spatial and temporal variations, their extent, and the importance of the relationships between various tide-gauge and geodetic benchmark datums.

With the growth in industrial activities and advances in technology, tide gauge observation stations (thus called because they are generally intended, in the first place, to study and predict the tide) have increased in number all over the world and now provide global world-wide coverage. A register of about 800 permanent tide gauges was recently drawn up following an investigation in 1983 by the IOC (Intergovernmental Oceanographic Commission) for UNESCO. An international office archives the mean monthly and yearly sea level values recorded by those tide gauges. Its name is the PSMSL (Permanent Service for Mean Sea Level). The number of observation stations is certainly large, but their distribution around the globe is very irregular, characterized by high density in developed economic areas (North America, Europe, Japan) and scarcity in the southern hemisphere (except for Australia). In addition, the data collected vary greatly in quality. That is why the IOC is now endeavouring to set up, on the basis of this existing set of stations, a limited network of approximately 200 observation points, evenly spread along the coasts and on islands in the oceans, in order to acquire high-quality measurements to enable a long-term study

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to be made of variations in mean sea level on a climatic scale; this project is known as the GLOSS (Global Sea-Level Observing System) programme.

It is relevant to note that, for the last twenty years or so, observation of sea surface variations has been extended to the open sea with the aid of pressure sensors placed on the sea bed, principally on the continental shelves but also in mid-ocean. About a hundred observations at great depths were recorded by Cartwright, Zetler and Hamon in 1979; a new count in 1984 increased that number to over 200, and other new series will certainly have been acquired since that date. Scientists are beginning, therefore, to have an extensive set of sea level observations at their disposal.

Determining the 'mean level' of seas, based on these observations, is not simple. This notion has significance only if a time scale is associated with it (monthly, yearly, etc...) and if the calculated means correctly eliminate all the variabilities with periods less than the scale chosen. The spectrum of such variabilities is extremely wide: from a few seconds (surges) or a few hours (seiches, tides) to several months (seasonal and inter-annual effects), or even secular scales (climatic effects and movements of the earth's crust).

Conventional tide gauges are designed to filter waves hydraulically, but these techniques can never eliminate the spatial variations of mean sea level induced locally by the non-linear processes which accompany wave propagation in shallow-water areas. These modifications of the mean sea level between the coast and the open sea can attain several tens of centimetres, for instance in areas of breaking waves. The existence of this contribution of waves to the variability of differences in mean sea level compared with the geoid must therefore not be overlooked, although they never appear in the recordings taken by conventional tide gauges.

It is the tides which generally leave the most vigorous mark but they are relatively easy to eliminate; very efficient filters have been conceived for the purpose (Demerliac, 1973). It is important to stress in this respect that the 'mean level' is often very different from the mean of high and low waters and that, in coastal areas, the mean levels on a daily, monthly or longer time-scale basis may show systematic differences compared with the geoid, due to the non-linear nature of tidal dynamics on continental shelves. In the English Channel, for instance, the mean sea surface thus shows a depression of about 5 cm in its central part (between the meridians 1°W and 2°W), which deepens to some tens of centimetres round the headlands: St. Catherine in the Isle of Wight, England, Barfleur, and particularly La Hague, France (Chabert d'Hières and Le Provost, 1970).

Another important contribution in this range of periods — from one to several days — is that of the meteorological impact resulting from the action of the wind on the sea surface, and variations in atmospheric pressure. It is linked with atmospheric depression systems, the typical time scale of which is effectively of the order of one to ten days. The impact of variations in atmospheric pressure is often termed the 'inverted barometer effect', mistakenly referring to the purely static correction (1.01 cm per millibar) which is sometimes associated with it. Such a correction is, in fact, valid in the open sea, in mid-ocean. Studies carried out, for instance, by Brown et al., (1975) in the Atlantic Ocean proved this. But along coasts and on continental shelves the response is far from static; the adjustment is effected through gravity waves which propagate very rapidly along the coastline in the form of shore waves, correlating over long distances variations in sea level thus resulting from non-local forcing.

Identification of such processes is made even more difficult by reason of the simultaneous action of the winds associated with these atmospheric depressions. The response of mean sea level to the constraints due to winds is not simple. Locally, and in a short time scale, it is obvious that the component of normal wind at the coast entails an elevation (or a depression) of the sea level. But in the longer term, it is the component of the wind parallel to the coast which plays an essential part, by reason of the combined effect of the Coriolis force due to the Earth's rotation, which deviates the water masses to the right of their motion in the northern hemisphere. According to Ekman's theory (1905), the global result is a shift which, vertically integrated in the water layer is directed 90° to the right (in the northern hemisphere) of the wind direction. Along a coast, these divergences or convergences of the surface water lead to rising surges of cold water or accumulations of warm water which are accompanied by a depression or a rise in the sea surface in the neighbourhood of the shores: these processes are referred to as 'downwelling' and 'upwelling'. These effects, due to local winds, entail variations in the vertical stratification of the medium and, generally, the associated variations in the level of the free surface are not easy to quantify directly in relation to wind intensity. Moreover, as with the impact of variations in atmospheric pressure, the dynamics of this are not purely local. The disturbances are propagated from areas of forcing and along the coasts the topography plays an essential part in guiding the waves, as has already been shown earlier (Crepon and Richez, 1982). All these variations in sea level, which can attain amplitudes in the order of a metre, have complex spectral characteristics and are generally of a transitory nature. Filtering them is therefore always difficult and the simple means must be considered as no more than a first approximation for the correct determination of true mean levels.

From monthly to yearly scales, the variability of mean sea level is less; it extends from two or three centimetres in low latitudes to tens of centimetres in high latitudes, with a strong seasonal marking of annual and sometimes semi-annual periods. These variations are to be associated with the seasonal modulations of the meteorological effects referred to earlier, but also with the variations in the thermal structure of the superficial ocean resulting from its warming up or cooling down with the seasonal changes in sunshine. According to an estimate by Gill and Niiler (1973) covering the Atlantic and the Pacific between 15° and 50°N, the modification of the water temperature over the first two hundred metres in summer and winter induces a variation in sea level which can, in certain places, exceed ten centimetres or so. At these time scales, a considerable proportion of the variation in mean sea level is also linked to the variability of the great ocean currents which, by geostrophy, affect the topography of the ocean surface. From spatial scales of some tens of kilometres and time scales exceeding the local period of inertia (about 17 hours in our latitudes), the dynamics of marine currents are governed by the balance between the pressure gradients and the Coriolis force: that is the geostrophic equilibrium. If the horizontal gradients of density are disregarded, the gradient of the open surface, perpendicularly to the direction of the current, is directly proportional to the intensity of the latter. The associated gradients are certainly very slight: a current of 1 m/s at 30° latitude corresponds to a difference in surface level of 37 cm in 100 km. But, especially on the western edges of oceans where geostrophic currents are the most intense (Gulf Stream, Kuro Shivo, Brazilian current, ...), there result differences between the mean levels and the geoid of the order of one metre, and the fluctuations of these, principally seasonal, can be observed on tide gauge recordings.

Beyond the annual periods, signs can be noted, particularly in equatorial areas, of the presence of inter-annual variability. The most typical is 'El Nino', which provokes, on the scale of the equatorial Pacific Ocean, variations in the open surface of some twenty centimetres, in the form of trapped waves which cross the entire Pacific and are reflected on the American coasts.

Finally, on the secular scale, several studies of long-term series of observations of level referred to above agree in concluding that a continuous and global rise in sea level has been taking place since the beginning of this century, of the order of 15 cm per century (Barnett, 1984). Among the possible causes of this increase, we may note the variations in oceanic circulation, the melting of the polar ice-caps and mountain glaciers, and the rise in the mean temperature of the ocean. The latter two causes are considered to be essential ones at the present time, with particular regard to a possible acceleration of the general rise in sea level resulting from the warming up of the planet due to the 'greenhouse effect' linked to the increase of carbon dioxide in the atmosphere.

Observation of sea level and the determination of the differences in the sea's mean level compared with the geoid is therefore, potentially, a very rich source of information. But, in view of what we have just seen concerning the extent of such differences and their spatial and temporal scales, it is obvious that the conventional observation of sea level with the help of tide gauges is insufficient to comprehend in a satisfactory way the phenomena involved. This explains the value of certain techniques or scientific programmes now being developed. We have already noted the existence of the GLOSS programme. To conclude, let us mention two other projects which are going to revolutionize observation of sea level.

First of all, the linking of tide gauges to a world geodetic system should permit their position to be located in an accurate way (to within a few centimetres) in a single geometric benchmark datum compared with the centre of the earth. If it is maintained in a continuous fashion over a certain number of judiciously chosen observation stations, this operation will finally provide the means of eliminating from sea level measurements any effects of subsidence of bases on earth on which tide gauges are installed. Such links are now feasible with an accuracy of less than ten centimetres by spatial techniques: the positioning of tide gauge observation stations is established by means of local geodetic surveys or differential radio-electric techniques to satellites (GPS, PRARE or DORIS) from a basic network determined by VLBI (Very Long Baseline Interferometry) based on the observation of radio sources, or by laser telemetry to appropriate satellites (LAGEOS, STARLETTE) or to the moon.

In addition, the synoptic observation of sea level is becoming a reality with the current development of satellite altimetry techniques which are going to make it possible to draw up charts of the topography of all the oceans to an accuracy of within a few centimetres. A first mission of the SEASAT satellite in 1978, prematurely cut short following a technical failure, reaped a considerable harvest of scientific information on the topography of the geoid, tides, and the mean surface of the ocean and its variability (see special issue of the 'Journal of Geophysical Research', 1983). A mission is under way at the moment: GEOSAT. Also, two projects are in preparation for 1990 and 1991: the European programme ERS1, which includes an altimeter among the payload sensors, and — above all — the Franco-American programme TOPEX-POSEIDON, which should make it possible even to better the accuracy extremes attained with this type of technology.

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