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A European network for sea level and coastal land level monitoring

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Abstract

Recommendations have recently been made by an international working group that a global absolute sea level monitoring system should be set up over the next few years by installing permanently operating GPS receivers at 100, or thereabouts, key tide gauges around the world. After giving a brief overview of these recommendations and of the current state of global and regional tide gauge and GPS networks, we propose the formation of a strategic European network for sea level and coastal land level monitoring. This will complement the sparser 'global' monitoring system and provide a European network infrastructure with common standards. It will provide a more regional basis for sea and land level monitoring, and can be further densified in local areas which have flood defence problems. The proposed system will provide data for determining regional changes in absolute mean sea levels due to climate change, identifying areas of coastal subsidence, monitoring flow through straits, and for helping to define a unified European vertical datum. We hope to stimulate discussions between European geodesists, oceanographers and tide gauge operators, with the aim of achieving extensive support for such a network. © 1997 Elsevier Science B.V.

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1. Introduction

In 1985, the Intergovernmental Oceanographic Commission (IOC) initiated the Global Sea Level Observing System (GLOSS), which is a programme for the establishment of approximately 300 scientific-quality tide gauges for global climate change and oceanographic sea level monitoring (IOC, 1990). GLOSS is now over two-thirds complete with the remaining third consisting primarily of sites from polar areas (Woodworth, 1991). The network puts on a more reliable and regular basis the supply of sea level data for scientific research, and serves as a global 'backbone' sea level network to which higher spatial density regional and national networks might be linked. Tide gauge data from GLOSS continue to serve as the primary source of information on global sea level change, although recent developments in the technique of satellite radar altimetry promise the

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eventual provision of truly-global sea level data sets (Fu et al., 1994).

Also commencing in the mid-1980's was a new generation of advanced geodetic techniques for the measurement of land levels, relative to the centre of the Earth, and of vertical land movements (Carter et al., 1989; Carter, 1994). Such geodetic measurements are based primarily upon the use of the Global Positioning System (GPS), although other satellite-based techniques have also been developed (e.g. DORIS, Lefebvre et al., 1996). Much of the discussion below with regard to GPS can also apply to DORIS, although that technique is less widely used. Vertical land movements can also be measured by means of absolute gravity (Marson et al., 1995). At sites where tide gauge and geodetic measurements are made together, or nearby, then the land and sea level components of relative sea level, as measured by a gauge alone, can be decoupled. One might argue that it is only the relative sea level (tide gauge) measurement which has practical importance, as it is that quantity which determines the degree of coastal impact. However, it is clear that, if one does not have as full a knowledge of processes at work, then the predictive utility of tide gauge sea level data is much reduced. A recognition of the complementarity of long term tide gauge (relative sea level) and geodetic (land level) monitoring has been obtained by international working groups linked to GLOSS (Carter et al., 1989; Carter, 1994; see Section 2 below), European regional groups such as SELF (Zerbini et al., 1996), EUROGAUGE (Ashkenazi et al., 1994) and the Baltic sea level project (Kakkuri, 1995) and national ones (e.g. Ashkenazi et al., 1993).

A second advantage of a network of combined tide gauge and GPS stations comes from the requirements of modern geodesy in combining old (sea level) datums, by means of which most national levelling systems are defined, to new (GPS based) ones.

When the GLOSS Implementation Plan was accepted by the nations of the IOC, it was recognised that the emphasis in the network on stations at ocean islands and along continental coastlines bordering the deep ocean, might not serve some regions adequately. In particular, these might include the coasts of marginal seas with large coastal infrastructure. However, where a good scientific and logistic plan for regional densification could be constructed, then GLOSS would encourage the effective expansion of the network. For example, such expansion has already taken place in the following regions:

(1) The tropical ocean, as part of the Tropical Ocean Global Atmosphere (TOGA) programme. In particular, the University of Hawaii and collaborating institutions have installed a number of gauges, additional to those required by GLOSS, in the tropical Pacific and Indian Oceans.

(2) The Caribbean area, where sea level monitoring across the straits between islands is particularly important in measuring flows which eventually force the Gulf Stream. This development is coordinated through an IOC regional project called IOCARIBE.

(3) The Southern Ocean, where the requirements of the World Ocean Circulation Experiment (WOCE) have resulted in additional gauges being installed, particularly at the 'choke points' of the Antarctic Circumpolar Current.

For each of these regions, there are working groups and data exchange organised under the auspices of either GLOSS, IOC, TOGA or WOCE, with considerable complementarity between the activities of each programme.

2. Summary of recent reports of working groups on geodetic measurements at tide gauges

In 1988, the International Association for the Physical Sciences of the Ocean (IAPSO) Commission on Mean Sea Level and Tides set up an ad hoc committee on the geodetic fixing of tide gauge benchmarks. There have been two workshops (Woods Hole, USA in November 1988 and Wormley, Surrey, UK in December 1993) and two corresponding workshop reports (Carter et al., 1989; Carter, 1994). The workshops identified the scientific requirements for the geodetic fixing of tide gauge benchmarks, evaluated the advances in the associated geodetic technologies and recommended strategies for future work.

The first workshop recommended that the global absolute sea level monitoring system should be based on the primary Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) stations of the International Earth Rotation Service (IERS)

Terrestrial Reference Frame (ITRF). Tide gauges should be connected to the IERS stations using GPS measurements and absolute gravity measurements should be made near tide gauges, at the IERS stations and in regions of post-glacial rebound.

During the past five years there have been significant advances in all these geodetic technologies. However, the advances in GPS have been the most dramatic due to cheaper and more reliable GPS receivers, the completion of the GPS satellite constellation and the ability to automatically process the large quantities of data over computer networks (Argus and Heflin, 1995). The International GPS Service for Geodynamics (IGS) of the International Union of Geodesy and Geophysics (IUGG) currently operates a global network of approximately 50 permanent GPS stations, which provide both GPS satellite orbits and station coordinates. It is expected that station velocities will be accurate to about 1 mm/year after about 5 years of observations. The second workshop therefore recommended that permanently operating GPS receivers should be installed at 100 or so tide gauges around the world and that these stations should be included directly in the IGS network. This would form the core network of a global absolute sea level monitoring system. Regional or local densification of this global network could be carried out either with permanently operating GPS receivers or with periodic GPS surveys at tide gauges. The exact mix of permanent and intermittent GPS measurements will depend upon future developments and the densification required in any particular area.

VLBI and SLR will continue to play important roles, since many sites are collocated with IGS stations and provide essential checks on the accuracy of the IGS coordinates. The 1994 report also recommends that absolute gravity measurements should be made in conjunction with the space geodetic measurements since the new generation of instruments are now achieving a precision of 2 μgal (equivalent to 1 centimetre of vertical crustal movement). Therefore, they can be used for a completely independent determination of vertical crustal movement and for testing post-glacial rebound and tectonic models.

Following the workshop reports of Carter et al. (1989) and Carter (1994), several research groups have investigated the various error sources in GPS and absolute gravity 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 a day to day and campaign to campaign repeatability of better than 20 mm. Similarly, work on comparing absolute gravimeters (Marson et al., 1995) shows that an accuracy of 3 to 4 μgal can be achieved (equivalent to 15 to 20 mm of vertical crustal movement). Due to the interannual and decadal variabilities of sea levels, the typical standard deviation of the annual mean sea level at a tide gauge is about 30 mm and 30 to 40 years of mean sea level data are required in order to determine the trend in mean sea level with a standard error of order 0.5 mm/year. GPS campaigns and absolute gravity are therefore already capable of determining the vertical crustal movement 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 trend from a tide gauge to similar accuracy. 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). It is therefore clearly an advantage to concentrate initially on installing permanent GPS at those tide gauges which already have very long and well controlled sea level data sets.

In Europe, the International Association of Geodesy (IAG) Working group of European Geoscientists for the Establishment of Networks for Earth science Research (WEGENER) have recently extended their activities (which were previously concentrated on plate movements in the Mediterranean) to include the measurement over the whole European region of horizontal and vertical crustal movements and the relationship of the latter with secular changes in mean sea levels. As part of WEGENER, Blewitt and Ambrosius have proposed that a permanent GPS network should be set up in Europe to determine crustal movements. The network is called WEGNET and it will be a regional densification of the global IGS network. Some of these WEGNET permanent GPS stations will be at tide gauges with long mean sea level records and therefore these will contribute to the present proposal.

3. Proposal

This proposal is concerned with defining an effective densification of GLOSS in the European region, where by 'Europe' we imply the entire Arctic, Baltic, Atlantic, Mediterranean and Black Sea coastline, including North Africa and Atlantic islands. While the Atlantic coastline and Atlantic islands are well represented in GLOSS (Fig. 1), much of the continent's coast borders the marginal seas of the North-West European continental shelf (North, Irish and Celtic Seas) and the Baltic, Black and Mediterranean Seas. The contribution of these latter areas to the network is small, with only 2, 2, 1 and 4 gauges in the North, Baltic, Black and Mediterranean Seas, respectively, as a result of the (quite logical) deep ocean bias in GLOSS itself.

The following points can be made on the proposed densification of GLOSS around Europe:

(1) Europe contains a long coastline with many areas of low-lying land and with many centres of dense coastal infrastructure and population.

(2) While GLOSS products may give a global average view of long term sea level change, it is recognised that there could be significant variations even in the deep ocean as a result of modification of the ocean circulation, let alone between the deep ocean and the marginal seas as a result of modification of local circulation patterns. For example, the General Circulation Model (GCM) work of Mikolajewicz et al. (1990) suggests that sea level rise in the North Atlantic in the next century may be significantly greater than elsewhere owing to modification of the rate of bottom water formation.

(3) Elements (1) and (2) make the case for some kind of 'permanent' European tide gauge and GPS network with a tide gauge spatial density greater than GLOSS and a GPS spatial density greater than that of Carter (1994). However, there is also a separate requirement also from geodesists in combining old and new methods of national datum definition.

(4) In several countries the elements of such a network exist already. In others, monitoring is less adequate. Increasingly, coastal researchers need information from neighbouring states in order to pur-

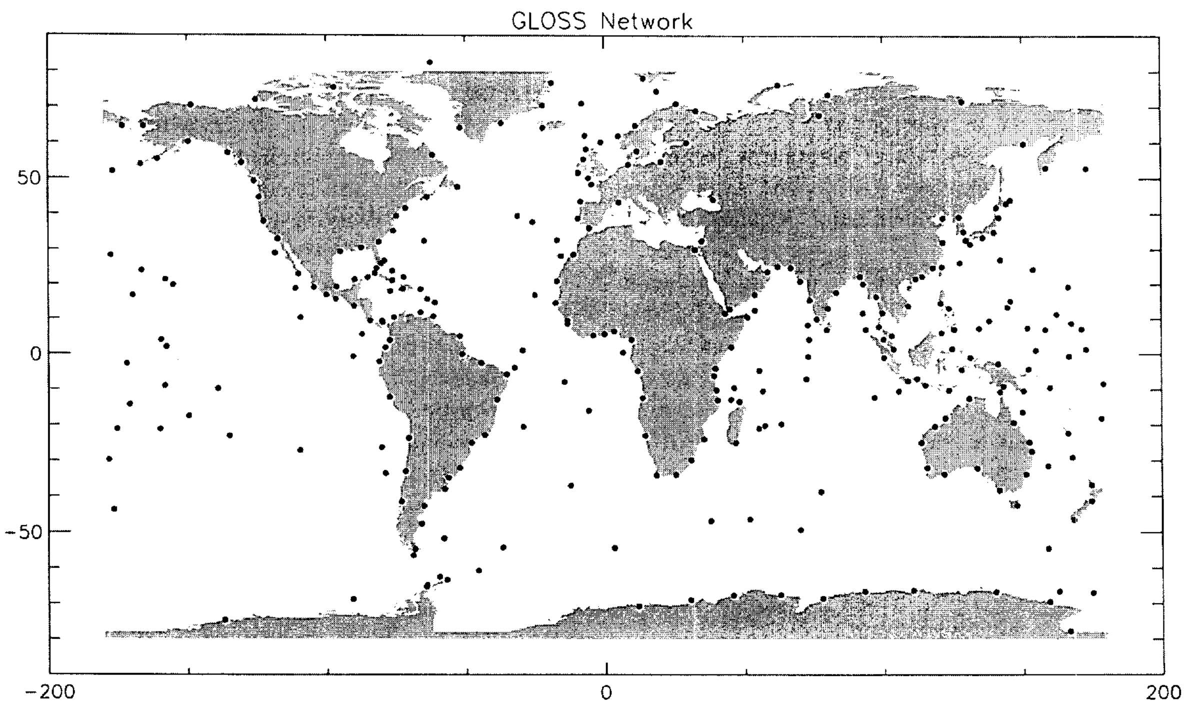

Fig. 1. Map of the GLOSS tide gauge network.

sue research adequately. The responsibilities and standards implied by participation in a continent-wide network will, therefore, eventually result in general in an increase in the quality and quantity of sea level information throughout Europe. The network should also encourage collaboration between neighbouring states.

(5) Even in countries well equipped with tide gauges (such as the UK, Netherlands, Italy, Sweden etc.), the definition of such a 'primary' European tide gauge and GPS network may complement existing activities. For example, there are over 40 tide gauges in each of the UK and Italian sea level networks. It would be impractical, and scientifically unnecessary, to perform regular GPS measurements of land movements at every one (i.e. to provide rates of absolute sea level change). However, it will certainly be necessary to perform such measurements at, say, at least six such sites in each country, in order to contribute to an adequate measurement of absolute sea level change on a regional basis. The international definition, and national recognition, of a densified European network should serve to ensure that such measurements are maintained by funding agencies.

4. Definition of the densified network

Our general criteria for the densified network are based partly on scientific requirements and partly on practical considerations.

In northern Europe, most parts of the coastline are equipped with tide gauges and, in many cases, there are large datasets of historical sea levels (Spencer and Woodworth, 1993). In addition, there is considerable experience with the GPS technique. GPS measurements of land movements are justified for comparison to geodynamic models of the Post Glacial Rebound (PGR), which is the main geological process, with the possibility of the models, or GPS data alone, being applied retrospectively to the historical sea level information should land movements indeed prove to be linear with time. The models may also then be applied with confidence to tide gauge records for which there have been no corresponding GPS measurements, and where local and regional geodetic controls show that there is no local subsidence at the gauge.

In southern Europe, and especially the eastern Mediterranean, the spatial scale of land movements is much shorter than in Scandinavia, for example, owing to local tectonic processes dominating the PGR signal. The flexibility of using models, and the possibility of applying land movement information retrospectively, are therefore much reduced. Also by contrast, there are relatively few tide gauges and small historical datasets.

Scientifically, there are two main requirements for a European densification of GLOSS. The first is the requirement to obtain an accurate regional measure of the rate of change of absolute sea level in each of the basins around the continent, for comparison to the global average values from the GLOSS network. 'Basins' might be taken to be the Arctic coast, Baltic, North Sea etc. and one might require perhaps six measurements from each basin in order to provide adequate quality control and data redundancy. If one further considers the Atlantic coastline and the Mediterranean to be large enough to be considered as two basins each, then it is clear that a network of approximately 50–60 stations is implied.

These 'Group A' combined tide gauge/GPS stations can be considered as comprising a continental 'primary' sea level and coastal geodetic network, with other, national gauges in between continuing to provide valuable records of relative sea level change.

The second requirement may be for the recognition that particular gauge sites, with or without parallel GPS measurements (but preferably with), are of particular interest within a densified European network. Examples might include gauges in the northern Adriatic and southern North Sea, where relative sea level is clearly the main measurement quantity of interest, and gauges which are of potential importance for monitoring the circulation around our coasts for regional oceanography, water quality modelling etc. The latter may comprise pairs of gauges at straits e.g. at Gibraltar for Mediterranean inflow studies, between the central Mediterranean islands, at either end of the Turkish Straits, across the Straits of Dover, across the Skagerrak etc. The case for such nominations would have to be on the basis of oceanographic study. These we call 'Group B'.

For this report, we have constructed a 'schematic' list, which to some extent satisfies both Groups A and B, by means of the following criteria:

1. A station is selected if it is already in GLOSS.
2. Between GLOSS sites, other stations have been selected on the basis of:
   2.1. the amount of historical sea level data available from the Permanent Service for Mean Sea Level (PSMSL),
   2.2. participation in past tide gauge/GPS campaigns,
   2.3. a good, relatively open ocean site (e.g. not in a river)
   2.4. proximity to geodetic 'fundamental points' (SLR, VLBI, permanent GPS stations) with advice from IGS experts,
   2.5. along coasts from where no historical tide gauge exists and where there are no geodetic fundamental points (e.g. North Africa), we have selected a small number of nominal stations on the basis of interest in future sea level recording expressed to IOC and PSMSL.

The dots in Fig. 2 show the locations of stations in a first version of our 'schematic list'. We stress that this is only a first version.

5. Responsibilities of participation in the network

The requirements for a gauge to be considered in the network would be:

(1) A commitment has been obtained by the responsible agency to install and maintain a gauge to GLOSS standards (IOC, 1985: IOC, 1994).

(2) Local geodetic controls (levelling between gauge and a set of local benchmarks) should be performed to standards described in Carter et al. (1989).

(3) Permanent or regular measurements of land movements at a benchmark near to the gauge by means of GPS equipment should be performed as described in Carter et al. (1989) and Carter (1994). Although it is not likely that all permanent GPS sites will be designated official IGS sites, the tide gauge

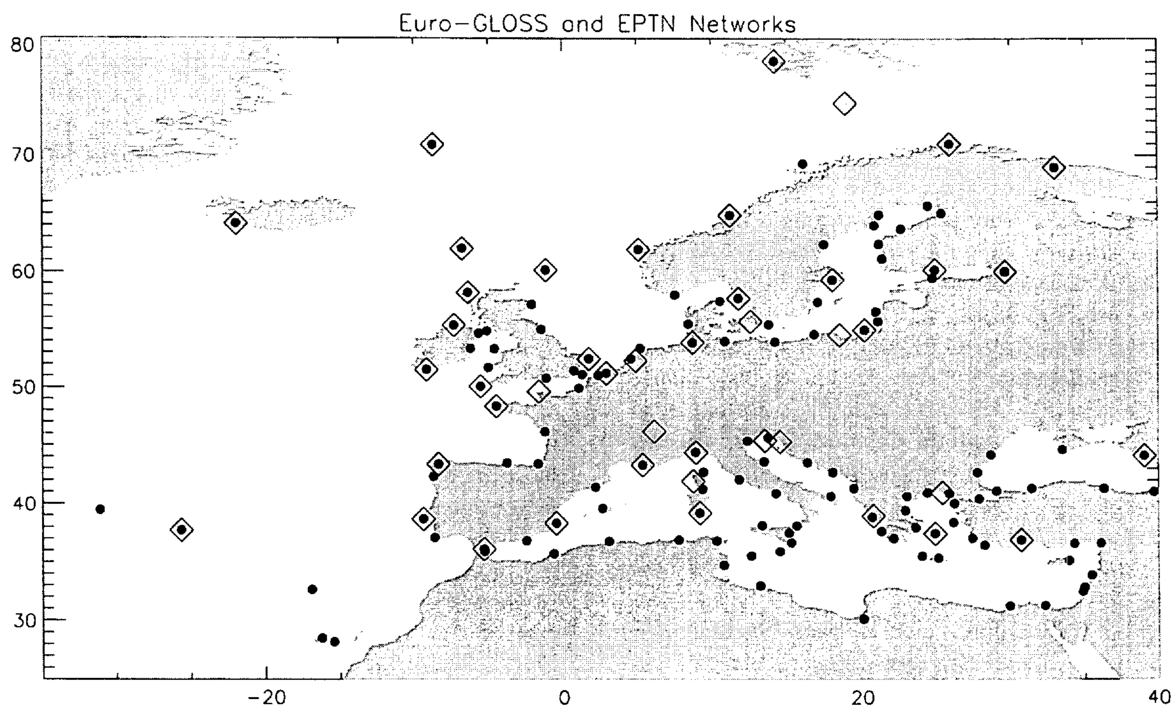

Fig. 2. Map of the proposed Euro-GLOSS (dots) and EPTN (diamonds) networks from Baker et al. (1994) and Boucher and Wöppelmann (1994), respectively. Note that some EPTN locations are at height system reference points as well as at tide gauges.

GPS sites should nevertheless meet IGS standards regarding operations, monumentation, and GPS equipment (in particular, receivers should produce dual-frequency phase and pseudorange observables). Whenever possible, land movements should be verified by regular absolute gravimeter measurements.

(4) Tide gauge data should be shared with all other agencies in the network. This includes:

(a) Monthly and annual means of sea level measured with respect to the tide gauge benchmark, and ancillary information described in Spencer and Woodworth (1993), should be submitted freely on a regular basis to the PSMSL at Bidston Observatory, UK. The PSMSL operates under the auspices of the International Council of Scientific Unions (ICSU) and is the global databank for long term sea level changes. It works closely with IOC with regard to the operation of GLOSS. In turn, the PSMSL undertakes to make contributed data available to any interested scientist or sea level agency.

Almost all European countries already contribute monthly and annual means to the PSMSL, and this commitment would not represent a change in that practice.

(b) The original tide gauge data (e.g. 15 minute or hourly heights) should be preserved by the operating agency in a form in which they can be provided freely (or at nominal handling charge) to any bona fide scientist or other sea level agency. (We recognise that provision of original data to commercial organisations is frequently made at present at higher charge). However, if possible, we would also request that copies of original data are sent to the PSMSL. The availability of original data to the PSMSL will provide an important long term archive function, and will enable monthly means to be recomputed if necessary.

(c) All local levelling information (i.e. sea level data in terms of local benchmarks) should be supplied to the PSMSL, as should a local map showing the positions of tide gauge and benchmarks.

(d) The operating agency should arrange for all original GPS data from permanent or routine occupation at tide gauge benchmarks to be made freely available via the Internet to IGS Associate Analysis Centers and other bona fide scientists within two weeks of acquisition. The operating agency should also provide timely information on hardware/software configuration, antenna phase centre eccentricities, etc., to those who use the GPS data, following IGS guidelines. In return for access to the data, analysis groups who use the GPS data should agree to submit geodetic estimates and standard errors to the PSMSL, who will then make the data generally available. The precise form of the geodetic estimates is yet to be decided, but will include vertical velocity estimates in a frame consistent with ITRF. Again, IGS guidelines should be followed as they evolve, particularly with regard to the densification of the global network and to the information content of geodetic solutions (Blewitt et al., 1993).

6. Anticipated products

The anticipated products from the densified network include:

(1) A continent-wide primary network for long term relative and absolute sea level monitoring, the high quality dataset from which will form the basis of scientific analysis of European sea level secular trends and accelerations into the next century. In turn, the scientific research from this dataset will provide a regional, as opposed to 'global', measure of change for input to coastal studies.

(2) A continent-wide dataset of high quality, original tide gauge data (hourly heights or similar), in addition to the monthly and annual means implied by (1), for input to studies of extreme levels, sea level variability over various timescales, and long term tidal changes. This dataset will also serve an important archive and reference function for the monthly and annual mean data.

(3) The provision by means of the same network of a coastal geodetic framework including sea level (the traditional effective datum of most national levelling systems) and modern (primarily GPS) measurements.

7. Suggested formal arrangements for acceptance, organisation and funding of the network

Our views on how best to arrive at formal international acceptance of the proposed regional densified network stem from our experiences with the development of GLOSS. In brief, these are:

(1) If monitoring of sea and land levels is to be performed on a long term basis, then it must be approved (and probably funded) by governmental agencies, although the participation of other organisations (e.g. universities) is also extremely valuable, particularly with regard to scientific input to network design, and to scientific data analysis.

(2) In our opinion, the most appropriate international agency for sponsoring the individual government funded sea level activities of this proposal is the Intergovernmental Oceanographic Commission (IOC). Firstly, while not all European countries are members of the European Union (EU), most are members of IOC. Secondly, GLOSS operates under the auspices of IOC. Thirdly, there is a European coastal component of the IOC-coordinated Global Ocean Observing System (GOOS), of which GLOSS is a part, to which one would expect a defined European sea level observing network to contribute. The coastal European component of GOOS is called 'Euro-GOOS'. Therefore, some of us have tentatively called the proposed network 'Euro-GLOSS'.

During the autumn of 1994, our initial proposals for a 'Euro-GLOSS' (Baker et al., 1994) were circulated to a large number of European tide gauge operators, with many favourable responses. In February 1995, our proposals were discussed at a meeting in Bordeaux of the IOC GLOSS Group of Experts (GE). The meeting responded enthusiastically to the proposal as an important regional activity of GLOSS, and requested its authors to proceed in collaboration with other scientists of the region to obtain as full support as possible. In December 1994, others of us circulated independently a proposal for a European Primary Tide Gauge Network (EPTN) (Boucher and Wöppelmann, 1994). This proposal was submitted to and endorsed by the EUropean REference Frame (EUREF) Technical Working Group at its meeting at Frankfurt during 15–16 December. Each of us now regards Euro-GLOSS and EPTN as essentially the same proposal (compare dots and diamonds in Fig. 2), although the EPTN proposal was written primarily from a geodetic viewpoint, whereas that of Euro-GLOSS was written primarily from an oceanographic one.

As regards funding, then if the example of GLOSS itself is followed, then all funding for activities within Euro-GLOSS/EPTN would take the form of contributions from individual states. However, other organisations, such as the EU will be very important in providing for expansion of the network to countries without tide gauge and/or GPS expertise so far, and for co-funding of central services. Without such additional funding, we do not believe that Euro-GLOSS/EPTN will function effectively. Scientific organisation of the project might best be made by means of a sub-committee of the GLOSS GE, with full representation from regional IGS activities, and from WEGENER and related programmes.

Since the Euro-GLOSS/EPTN proposals were written, important parallel developments have arisen from other working groups. A 'MedGLOSS' proposal for Mediterranean sea level monitoring has been accepted as a joint activity of IOC and the *Commission Internationale pour l'Exploration Scientifique de la Mer Méditerranée* (CIESM). We consider this to be an important regional contribution to our Euro-GLOSS/EPTN ideas. An EU programme entitled EOSS (European Sea-Level Observing System) for a series of discussion and coordination groups on sea level matters has also been proposed by Dutch colleagues.

8. Conclusions

This report has attempted to make the case for the formation of a strategic European network for sea level and coastal land level monitoring. Our two main reasons for writing it were our beliefs:

(1) that the geographical entity of Europe requires a strategic sea and coastal land level network to complement the sparser 'global' monitoring systems provided by GLOSS and IGS core networks. The underlying scientific bases for the regional network are with regard to long term changes in sea level due to climate change and land movements, and to the requirements of regional oceanographic studies of water movements (e.g. for water quality modelling).

and (2) that the adoption of common standards of data acquisition and transmission, training etc. implied by such a continental network will in turn improve the quality of national monitoring (which in some countries is non-existent or of poor quality) and of Europe's contribution to GLOSS and IGS themselves.

We observed that Europe is approximately the size of the USA which has one main organisation (NOS/NOAA) responsible for sea level recording, and for much of the monitoring of land levels at tide gauge sites by means of GPS. This will lead to better standards of quality control and to better data. By contrast, Europe presents a fragmented picture, with excellent systems in some countries, mediocre ones in others, and no systems at all in some areas. In short, the present European situation is unsatisfactory and needs significant national and international improvement.

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