I.O.S.

REVIEW OF THE POTENTIAL OF SATELLITE REMOTE SENSING FOR MARINE FLOOD PROTECTION

EDITED
BY
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INSTITUTE OF OCEANOGRAPHIC SCIENCES

BIDSTON

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Contents

ABSTRACT

For various aspects of flood protection studies, relevant satellite remote sensing techniques are discussed.

Operational use is limited by widely spaced orbits with repeat periods of several days for any one polar-orbiting satellite, or by cloud cover for visible and infra-red imagery spanning the orbit separation. Geostationary satellites have limited resolution at 50°-60°N.

Research and design applications are numerous, with potential for monitoring climate and mean sea level change, overviews of coastal development, sediment movement and wave behaviour, and establishing global wind and wave climatology.

There is scope for influencing the operation of ERS-1 (due for launch in 1990) and the plans for sensors in the Columbus programme (late 1990's).

This work has been commissioned by the Ministry of Agriculture, Fisheries and Food as part of its flood protection programme. The results will be used in the formulation of Government policy, but at this stage they do not necessarily represent Government policy.

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1. INTRODUCTION

Marine flooding is one of the main natural hazards in the UK, and for coastal areas world-wide. Protection against high sea levels and waves is the concern of UK research expenditure of some millions of £ annually, forecasting systems operated by the UK Meteorological Office and Water Authorities, and large-scale construction of sea walls and other coastal defences, most notably the Thames Barrier (which with related flood defences cost in excess of £500 million).

Although the disastrous 1953 surge in the North Sea initiated much of the UK research and present-day forecasting systems, more recent events illustrate continuing questions. For example, (i) Bristol Channel flooding in December 1981 suggested sensitivity to poorly observed weather systems over the south-west approaches to Britain. (ii) Severe but unexpected overtopping around Portland in 1979 suggested waves sensitive to the particular Mid-Atlantic storm track and speed. (iii) The continuing steady rise in high waters was one of the prime reasons for Professor Bondi recommending the construction of the Thames Barrier. The effects were allowed for in its design life of 60 years, but any sudden changes in mean sea level arising from the climatic changes referred to in subsequent sections would affect London in the same way as any other large conurbation protected from tidal flooding.

Remote sensing and other satellite measurements in recent years have provided meteorologists, oceanographers and geodesists with new techniques for observations. In relation to (i) to (iii) above, obvious examples are: (i) scatterometer winds and visible cloud marking weather systems; (ii) wave height estimates from altimeter returns and patterns shown by imaging radar; (iii) satellite altimetry for sea level variations, and satellite ranging for the measurement of vector distances between land sites, with the potential for estimating land movements affecting records of relative sea level.

The special feature of satellite remote sensing is spatial coverage, which (in one satellite pass) is near-instantaneous as regards most factors in flooding risk. Typically, returns are from a 'swath' parallel to the satellite track and of breadth several tens to thousands of kilometres according to the sensor. Conventional altimeters (and some other instruments) record returns essentially from just one line directly beneath the satellite, although the reflections take place from a few kilometres on either side of nadir. Only geostationary satellites over the equator can individually provide the continuous coverage usually associated with operational systems, but their height (36000 km) obviously affects spatial resolution. Satellites in near-polar orbits typically have repeat periods of 3 to 18 days after which the same swath will again be covered; wider swaths may overlap to give repeated coverage rather irregularly within the repeat period. Such coverage may be valuable for research and design purposes but not for operational systems; in particular, techniques sensing visible or infra-red radiation are rendered ineffective by cloud.

The short flight of Seasat in 1978 demonstrated many of the possibilities for altimetric measurements of varying sea level and wave and wind statistics, imaging radar for indicators of wave spectral distribution, and scatterometer measurements for wind direction. Similar observations are planned from the ESA Remote Sensing Satellite (ERS-1), now scheduled for launch in 1990, and from the US/France TOPEX/POSEIDON (emphasising altimetry). Discussions are now taking place on the operation of ERS-1, and on the possible sensors to be carried on satellites envisaged for the late 1990's. Sea level and geodesy measurements now include unclassified data from Geosat and the prospect of the Global Positioning System (GPS: 7 of 18 satellites are already in position enabling vector distance measurements a few times each day).

The new perspectives, forthcoming opportunities and the uncertainties of satellite remote sensing all suggest the appropriateness of a review of its potential for the important field of marine flood protection.

Aspects of flood protection studies are treated in turn in the following sections; the table gives a summary related to remote sensing method.

2. FLOODING EXTENT

The ideal would be to have high-resolution images of the entire flooded area at frequent time intervals, in real time, including an image at maximum flood. For satellites, a geostationary orbit or frequent passes with a number of satellites in low orbit would be required for time resolution to be high compared with tidal periods. All-weather capability is essential since cloud-free conditions around the British Isles are rare in any season, and especially at the time of storms which lead to flooding. Most sensors easily distinguish normally between land and sea, and hence indicate the instantaneous boundary. A spatial resolution of 1 km may be adequate for a general picture of the area, given landmarks or a suitable method of relating images to a map. For individual fields, roads and buildings, sensors with a resolution of tens of metres may be desirable.

The characteristics of various satellite instruments, with comments on the application to flooding extent, are as follows.

a) MSS. This is the Multi-Spectral Scanner, fitted to the Landsat series. It has four radiometers measuring radiance in the visible and near infrared range, and is therefore not of use in cloudy conditions. The spatial resolution is high (80m) and the swath width moderate at 185 km, but time resolution is poor, with a Landsat repeat period for any point of 18 days. The radiometers were not designed for oceanic applications, but are certainly adequate to show flooding extent. The latest Landsat series instrument, the Thematic Mapper (TM), has seven bands in the visible and near infrared and one in the thermal infrared range and a resolution of 30m (visible) and 120m (infrared).

On the other hand, infra-red imagery can map an area that has been flooded, for five days or more (possibly weeks) after the event. Vegetation which has been physiologically stressed by flooding reflects less infra-red. Soils remaining wet absorb infra-red radiation in contrast with reflective dry soils. Such imagery is potentially valuable for identifying areas at risk from flooding, perhaps especially in third world countries or where tide-gauge and ground-survey data are limited.

b) CZCS. This is the Coastal Zone Colour Scanner, fitted to the Nimbus 7 satellite. It has five visible and one infrared band, and was specifically designed to be an experimental ocean colour instrument. Spatial resolution is 825m and swath width 1636 km. The wide swath means time resolution is at least once per day. Otherwise comments on the MSS hold for the CZCS.

c) Lidar. This is analogous to radar, but with light generated by a laser. It is as yet untried from satellites, nor to present knowledge is a satellite lidar planned. Experiments have taken place from aircraft. In principle, since light penetrates water, it can be used for measurements of bathymetry in depths up to tens of metres, depending on the clarity of the water. It cannot penetrate clouds and gives only a result at nadir, not an image.

d) AVHRR. This is the Advanced Very High Resolution Radiometer, fitted to the NOAA series of polar-orbiting, sun-synchronous meteorological satellites. It measures in two visible and two infrared bands. Spatial resolution is 1 km and temperature resolution 0.12 K. Swath width is 2580 km. This is ideal for imaging ocean surface thermal features, with a repeat of at least once and often twice a day. (More than one NOAA satellite has been operating in the past.) The images, both visible and infrared, would indicate the extent of flooding, but the main disadvantage is the prevalence of cloud cover, making the system of no use for operational, reliable flood mapping.

e) ATSR. This is the Along Track Scanning Radiometer, being prepared for the ERS-1 satellite. It is designed to improve atmospheric corrections, and hence give an absolute temperature accuracy of better than 0.5 K (on average over 50 km squares) with a temperature resolution of 0.1 K. The swath width, however, is only 500 km, so repeat periods will be long. This makes cloud cover even more of a problem than for the AVHRR.

f) SMMR. This is the Scanning Multichannel Microwave Radiometer fitted to Seasat and Nimbus-7. It measures radiation emitted by the sea surface at microwave frequencies, which passes through clouds with little absorption. Therefore these microwave systems have the great advantage of all-weather capability. However, the spatial resolution is limited by the practical antenna size. This resolution is much worse than for visible and infrared systems, being 28 km for the highest of the five frequencies used and 136 km for the lowest which is most important for SST. The swath width was 600 km on Seasat and 800 km on Nimbus 7. The sea surface temperature resolution is about 1.5 K and the absolute temperature accuracy 2 K. Therefore both temperature and spatial resolution are inadequate for the mapping of flooding extent.

g) HRV. This is the High Resolution Visible sensor on the SPOT satellite. This has a resolution of only 10-20m (and provides stereoscopic pictures), but a swath width of only 60 km. The cloud cover problem and low time resolution make it unsuitable for flood studies.

h) Meteosat sensors. The geostationary satellite, Meteosat, over the Greenwich meridian, provides in principle continuous coverage within its field of view. In fact an image is provided every 30 minutes. The resolution at nadir is 5 km, and this is degraded further at mid- and high-latitudes because of the oblique angle of view. The limit for imaging coverage shown on ESA's map is only about 55°N, although the field of view does extend to over 70°N. Meteosat carries sensors for three bands, visible, infrared water vapour and infrared earth viewing.

i) SAR. This is the Synthetic Aperture Radar, which was carried by Seasat and is planned for ERS-1. It is an active microwave instrument, so is unaffected by cloud cover. It provides images with a resolution of only 25-30 m which clearly show the land-sea boundary as well as many detailed topographic features on the land. Sea waves, internal waves and submerged banks can also be seen in certain conditions. These characteristics are ideal for flood mapping. However the swath width is only 80 km (ERS-1) or 100 km (Seasat) and the power requirement and high data rates meant that the Seasat SAR was switched on only when reception at a ground station was arranged in real time. Similar constraints will apply to ERS-1 and SAR operating only 10% of the time, but this may include Britain with reception at West Freugh (Scotland).

j) Altimeter. As a nadir-pointing sensor, the altimeter spans only a footprint (about 10 km on Seasat) beneath the satellite track. Hence it lacks both a wide field of view and the resolution required for measurements near the coast. However, moist and flooded grounds give intense returns: highly specular reflection from sheltered water may reduce the effective footprint to 180m diameter (Seasat); a pond as small as 75m diameter has been detected (RAPLEY et al. 1987) together with its surface level to within 1m.

This survey of the relevant satellite sensors shows that none offers the ideal all-weather, high-resolution continuous coverage required for mapping of flooding extent. The SAR provides the necessary conditions of all-weather high resolution, but only with wider swaths and a number of satellites flying simultaneously, together with a system for dealing with the enormous quantity of data, can continuous coverage be approached. (But note (ROBINSON 1985, equation 12.2) there is a strong constraint implying a compromise between resolution and swath width).

3. CLIMATE (INCLUDING SEA SURFACE TEMPERATURE AND ICE COVER)

Changes in mean sea level and in the incidence of storm surges are two possible effects of climate change which are relevant to marine flood protection. The use of satellite altimetry to measure sea level is described elsewhere in this report. A long term scientific goal is to predict climate change, and satellite measurement may assist both by aiding our understanding of the present climate and by indicating changes.

Apart from the direct monitoring of sea level and ice cover, the greatest contribution of satellite remote sensing to climate studies is the establishment of global sea surface temperature (SST) data sets. Before satellites, these were limited to the tracks of ships on the main trade routes. One use of regular global SST data is to test estimates of global warming due to increases in atmospheric carbon dioxide (the "greenhouse effect"). The accuracy must be enough to detect an estimated mean global rise in SST of the order of 2 K per century. Another use of SST data sets is to detect SST anomalies (differences between observed values and long-term means), which are associated with changes in atmospheric circulation and hence the weather. One of the best known phenomena of this kind is the El Nino - Southern Oscillation, which is detectable in SST changes in the equatorial Pacific, but influences the atmosphere globally through teleconnections by means of planetary waves. There are also indications of an atmospheric response to anomalous large-scale SST patterns in mid-latitudes (NAMIAS et al. 1981), but useful interannual climate predictions are not yet available. The simple picture of fluctuations in the position of the Gulf Stream resulting in changes in the European winter is a "great folk myth" (WOODS 1984) - the actual mechanism of air-sea interaction in the north Atlantic is much more complex than that.

Variations in the climate on the interannual and longer time scales are therefore unpredictable at present, and remain a research topic. On the shorter time scale of a week or two approached by weather forecasts, monitoring to within 0.5 K resolves SST anomalies; these are significant forcing (through air-sea interaction) in long-range forecasting (HOUGHTON et al. 1984) and therefore can help with storm surge predictions. SST measurements also provide a means of estimating dynamic heights and local circulation patterns (e.g. EMERY et al. 1986). Other satellite measurements which can improve storm surge models directly, such as scatterometer observations for surface stress, are mentioned elsewhere in this report.

Although difficult to predict, climate change may have indicators detectable by satellite remote sensing. The most sensitive are probably SST and the extent of sea ice, together with mean sea level (see section 4). These would provide a signal of any rapid anthropogenic change such as "greenhouse effect" warming. Sea level rise of as much as a metre within a century has been suggested (ROBIN 1986), and this is serious enough to warrant a monitoring system which would give as early a warning as possible.

Instruments for measuring SST were described in the section on measuring flooding extent. The monitoring of global SST for climate change or use in weather prediction requires an absolute accuracy of better than 0.5 K, attainable to date only in the specification of the ATSR, as yet untested in space. Data sets from the AVHRR corrected for atmospheric effects have an uncertainty of at least 0.6 K. This is much better than for the SMMR. The AVHRR is, however, affected by cloud cover. For long period SST measurements the cloud cover problem can be reduced by automatic removal of data at pixels with clouds and time averaging over cloud-free pixels. All infrared systems measure only the skin temperature of the sea, from a thickness of less than 0.1 mm. This may be a few tenths of a degree less than the temperature a few cm below the surface. It can be up to a few degrees more than the average temperature of the top few metres on calm sunny days, but this difference disappears at night.

Ice cover can be monitored by visible band sensors (limited by cloud and darkness, very restrictive in the polar winter), by infrared sensors (limited by cloud and low ice-sea temperature differences), by the SMMR (but low resolution) and SAR. The altimeter can give accurate ice edge measurements; at high latitudes, the closer tracks compensate for the narrow swath.

Clearly, our ability to predict climate change is not adequate to make a contribution to operational flood protection, but the consequences of climate change for coastal flooding are so important as to justify research and monitoring programmes, which will be considerably aided by satellite remote sensing.

4. SEA LEVEL: TRENDS

As already emphasised, flood protection schemes have to consider the long-term, time-averaged level of the sea surface (i.e. 'mean sea level' or 'MSL'). Around the U.K. MSL varies throughout the year with a typical amplitude of about 10cm (WOODWORTH 1984) approximately half of which is meteorological in origin, and which would be reproduced by storm surge models discussed below, and approximately half due to steric (density) variations. Interannual variability on timescales from several years to decades is of similar magnitude, while the very long term 'secular trend' of MSL varies from approximately +2mm/year at Newlyn to 0mm/year in the north of Scotland (WOODWORTH 1987) with the largest trend to be found in the data from Portsmouth, approximately +5mm/year.

The higher-frequency MSL variability and secular trends recorded in the U.K. are of great scientific interest but are mostly too small to be of any great practical importance with regard to flood protection. In the next century, however, it is anticipated that global sea levels may rise at an accelerated rate (perhaps by the order of a metre by the middle or end of the next century (ROBIN 1986) and by several metres once the polar ice caps start to melt significantly) due to the general warming of the planet associated with the increase in 'greenhouse-gas' concentrations. A rise of sea level of a metre or more is of enormous economic importance to coastal homes and industry and to the natural ecosystems of estuaries and wetlands. Working groups to assess the possible consequences of a large rise in sea level have already been established (e.g. DELFT 1987).

At present, measurements of the rate of change of global sea levels are unsatisfactory in that they are based on data from an uneven geographical distribution of tide gauges, most of which are in the northern hemisphere. However, in the long term the problem of measuring truly global sea level changes may be solved by precise satellite altimetry with global sea levels monitored during the 3-5 year life of each satellite (BORN et al 1986) and with overlapping satellite missions. This technique will also remove a possible existing bias in the estimate of global sea levels arising through the chance of significant gyral spin-up and through conventional tide gauges being situated primarily on continental coastlines. In addition, altimetry over the polar ice caps and mountain glaciers (BROOKS et al. 1984) will provide measurements relevant to sea level rise through monitoring of the world's store of ice. Other forms of remote sensing will also play a crucial role in supplying an 'early warning system' for sea level rise through monitoring of other climatic parameters (e.g. surface temperatures and sea-ice cover) (THOMAS 1986), as further discussed above.

Altimetry will also play an important role in measuring the long-term changes in tidal patterns. For example, at many ports around the North Sea very different secular trends have been observed in mean high waters, low waters and mean sea level over the past century (e.g. see the Vlissingen data in VAN MALDE 1986) indicating a long-term increase in the tidal range as well as sea level. To some extent these tidal changes are in conflict with expectations from numerical elevation models assuming an increase in mean depth of approximately 20cm over the past century (RIJKWATERSTAAT 1986). Long-term altimetric measurements, coupled to precise land geodetic benchmarks, will provide such data over the whole coastal area rather than at individual ports.

5. HIGH PRECISION SPACE GEODESY AND MEAN SEA LEVEL

(a) INTRODUCTION

In 1971 the Royal Society held a discussion meeting entitled 'A Discussion on Problems Associated with the Subsidence of Southeastern England' (Philosophical Transactions of the Royal Society, London, 1972, A272, 79-274). This meeting considered the geological, archaeological, geodetic and tide gauge evidence for the subsidence of S.E. England in general, but with particular emphasis on the design of the Thames Barrier. Although there seemed to be agreement that the S.E. of England was subsiding by the order of 10cm per century, it was clear that the observational data relating to the current rate of movement was rather sparse. This was due to the sparsity of high quality and long duration (>20 years) tide gauge data and systematic errors in geodetic levelling. In particular, it was difficult to separate real crustal movement from regional or global changes in mean sea level and also to ascertain whether the Thames Estuary was subsiding at an increased rate due to man's activities.

In the next two sections the present results from geodetic levelling and from mean sea level observations are briefly reviewed. Finally, a short review is given of the recent developments in space geodesy and it will be seen that modern high precision space geodetic measurements can resolve many of the above problems.

(i) Geodetic Levelling. KELSEY (1972) compared the altitude of the fundamental benchmarks of Great Britain as determined by the 3rd geodetic levelling (1951-9) with the altitudes determined by the 2nd geodetic levelling (England and Wales 1912-21, Scotland 1936-52). By using the differences in the altitudes he hoped to determine the rate of vertical crustal movement in Britain at each of the fundamental benchmarks (approximately 50km spacing). Unfortunately, it was not possible to determine the subsidence of S.E. England since the 2nd geodetic levelling concentrated on areas that were considered to be geologically stable and therefore avoided the coasts of S.E. England (the 1st geodetic levelling of Great Britain, 1840-1860, was of too low a standard to be used for crustal movement measurements). He found that there had been an apparent small uplift of central and southern England relative to Newlyn of the order of 1 to 2mm per year. However, for northern England and southern Scotland there had been an apparent uplift of the land of 17.5cm in 32 years i.e. 5mm per year. This is in complete disagreement with mean sea level measurements at Scottish tide gauges which show that mean sea level is rising relative to the land by the order of 0.5 to 1mm per year (next section). In addition, the geodetic levellings of the British Isles also gave an apparent slope of mean sea level from the south to the north of the British Isles (up to the north) of the order of 35cm. This slope cannot be explained oceanographically (THOMPSON 1980, AMIN 1987).

Geodetic levelling is now regarded as a useful technique for crustal movement measurements over distances of up to 50 or 100km (JACHENS et al. 1983). However, over greater distances systematic errors accumulate which soon become too large for crustal movement studies. Levelling is a time consuming and expensive exercise and it has not therefore been possible to carry out a 4th geodetic levelling of the British Isles. The new space techniques provide more rapid and more accurate methods of determining crustal movements.

(ii) Mean Sea Level. By analysing a long series of tide gauge observations, the changes of mean sea level relative to the land can be determined. Many tide gauges around the world show a secular increase of mean sea level of the order of 1 to 2mm per year (BARNETT 1984). This is believed to be due to an increase in the volume of the oceans caused by an increase in global temperature and melting of the polar ice caps and glaciers. The global temperature rise is thought to be due to the greenhouse effect caused by the increase of CO_2 and other greenhouse gases in the atmosphere. Various estimates have been made of the sea level rise during the next century resulting from an accelerating greenhouse effect. Rises of 1 metre or more have been predicted and these would have serious consequences for marine flood protection. Detailed analyses of sea level data, including an assessment of local or regional crustal movement, are required in order to detect an acceleration in the rise of mean sea level.

The main present day crustal movements of the British Isles are thought to be associated with the isostatic adjustment of the Earth following the last ice age. In more local areas subsidence due to mining or other activities is important. ROSSITER (1967,1972) used mean sea level observations to determine vertical crustal movement. Assuming that there is a uniform rise of sea level due to the increasing volume of the oceans of 1mm/year, he concluded that Scotland is rising by the order of 0.5mm/year and southern England, the French and Dutch coasts are subsiding by 1mm/year. More locally, the Thames estuary appeared to be subsiding by over 2mm/year and North Shields subsiding by about 2mm/year (the latter probably due to mining subsidence).

WOODWORTH (1987) has analysed the longer data sets that are now available for secular trends in mean sea level. This work shows the importance of using the same epochs when comparing secular variations at different stations. This is due to real variations of sea level over time scales of the order of a decade. In particular, a fall in mean sea level of the order of 5-10cm from the mid-1960's to the mid-1970's was observed over a wide geographical area and this could possibly be caused by changes of wind stress and resulting North Atlantic gyral circulation over this period. In order to eliminate, to first order, real oceanographic variations of mean sea level, Woodworth looked at sea level differences between different gauges. The north-south tilting of the British Isles obtained by previous authors was verified with Aberdeen rising by 1 to 1.5mm per year with respect to Newlyn. Similarly, the south-east of England was found to be subsiding with respect to Newlyn by the order of 0.6mm/year. Interestingly, the mean sea level at Newlyn was found to be rising by 0.7mm/year faster than at Brest, just across the English Channel. A large secular rise in mean sea level was found for Portsmouth (5.0 ± 0.5mm/year) which is consistent with that found for Dieppe, just across the Channel (EMERY et al. 1985).

It is clear that the spatial variation of vertical crustal movement in the British Isles is more complicated than it was previously thought to be. The space methods described in the next section will provide a method of determining this spatial variation and resolving the present ambiguity between crustal movements and real sea level changes.

(b) SPACE GEODESY TECHNIQUES

(i) SLR and VLBI. Over the last 10 years or so two complementary space techniques have started to give important results which are being used for defining a global geodetic reference system and for measuring crustal movements. These are Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) using radio telescopes (FLINN 1981).

In SLR the return time of flight of a laser pulse is measured from a ground based laser to a satellite equipped with corner cube reflectors. The main satellite that is used in this work is the Lageos satellite (height 5900km). The best laser ranging stations now have an accuracy for the range measurement of 1 to 3cm. Tracking from several stations worldwide allows an accurate determination of the orbit, the tracking station coordinates and the length of the baselines between stations. The precision that is now being achieved is better than 5cm for the coordinates of the stations with respect to Earth's centre of mass and 3cm for intercontinental baselines (SMITH et al. 1985).

In VLBI pairs of radio telescopes are used to observe the radio signals from distant radio sources such as quasars. The difference in the arrival times of a wavefront from a quasar at two radio telescopes depends upon the vector baseline between the telescopes and the direction of the quasar. By observing a number of quasars repeatedly throughout a day with several radio telescopes, the vector baselines between all the radio telescopes can be determined. A global system of VLBI baselines can be used to define a global geodetic reference system which can then be referred to the Earth's centre of mass by collocating a few SLR and VLBI stations. Current VLBI baseline precisions are of the order of 3cm (CARTER et al. 1985) and 1cm is expected by the end of the decade.

(ii) GPS. The main problems with both SLR and VLBI are the costs and the relative sparsity of the stations. They are clearly valuable for defining a global geodetic reference system, measuring the movements of tectonic plates and the variations of the Earth's rotation and polar motion. Mobile SLR and VLBI systems are being used in certain areas of the world to look at regional tectonic deformations. However, in order to measure crustal movements on a more local scale, a cheaper technique with easily transportable equipment is required. GPS measurements have already shown that they can meet these requirements.

The Global Positioning System (GPS) is a satellite navigation system being developed by the U.S. Department of Defense. The system is planned to be fully operational by the end of the 1980's, when there will be 18 satellites in 6 orbital planes (altitude 20,200km, orbital period 12 hours). This configuration allows simultaneous visibility of at least 4 satellites at any time of day, almost anywhere in the world. The satellites continuously broadcast encoded signals in two L band channels (L_1=1575.42MHz and L_2=1227.6MHz). The encoded signals include the precise time of transmission from the satellite. By observing 4 satellites simultaneously, the encoded signals allow the determination of the three-dimensional position of the ground receiver instantaneously to an accuracy of about 10 metres. This is sufficient to meet the navigational objectives for which the satellites were designed. However, it was soon realised that by using the phases of the GPS signals as detected simultaneously by pairs of receivers, it was possible to obtain centimetre accuracy for the vector baseline between 2 receivers, at least over short baselines. This is similar to the method described above for VLBI, except that the satellite signals are far stronger than the quasar signals so that smaller, cheaper and easily portable receivers can be used.

Several manufacturers have developed GPS receivers and various methods have been developed for processing the signals (KING et al. 1985). At the present time there are 7 GPS satellites in orbit and, for a given area of the world, these provide a suitable geometrical configuration for a few hours per day. Several tests have already been carried out to assess the baseline accuracy that can be achieved. For short baselines many of the errors due to the ionospheric refraction and uncertainties in the satellite orbits cancel. The tests show that for single frequency GPS receivers an accuracy of 1cm in a 10km baseline can be achieved (KING et al. 1985). For crustal movement investigations, a 1cm accuracy in the vector baseline is required for baselines up to 100 or 200km in length. For these longer baselines dual frequency GPS receivers are required for removing the ionospheric effect and water vapour radiometers are required for determining the wet component of the tropospheric delay. In addition, the GPS satellite orbits have to be more accurately determined by tracking the satellites with dual frequency receivers at 3 or 4 tracking stations spanning the area of interest. BOCK et al. (1986) have compared dual frequency GPS measurements of a baseline of 245km in length with measurements of the same baseline using SLR and VLBI. These results show that accuracies of 1 part in 10^7 (1cm in 100km) can be achieved with dual frequency GPS measurements.

The U.S. National Oceanic and Atmospheric Administration (NOAA) have started a programme to monitor the vertical movement of tide gauges along the east coast of the United States (CARTER et al. 1986). Three VLBI stations are already in operation (Florida, Maryland and Massachusetts) and these will be regularly interconnected by GPS measurements at stations with about 100km spacing and with connections to the east coast tide gauges. The profile is also planned to extend across Canada in order to determine the crustal uplift, centred on Hudson's Bay, following the melting of the Laurentide ice sheet. It is hoped to achieve 1cm accuracy for both the VLBI and GPS baselines and with repeated measurements over several years to separate vertical crustal movement from real sea level rise and to identify those gauges where local movement is important.

Under the NERC/SERC Special Initiative in Geodesy the University of Nottingham, in collaboration with the University of Edinburgh and IOS, are about to start a project to make GPS measurements at some U.K. tide gauges and to assess their accuracy.

Several agencies around the world are now planning to replace geodetic levelling (and triangulation - trilateration) with GPS measurements since these are more cost effective. It should be noted, however, that for many applications heights must be determined with respect to an equipotential surface e.g. the geoid. Thus, for these so called orthometric heights, the relative geoid height between two stations is also required. Although the absolute geoid height at any point (with respect to the centre of the Earth or a standard ellipsoid) has an uncertainty of the order of 1 or 2 metres, geoid height differences have been obtained to an uncertainty of 3cm over 13km using gravimetric measurements (ENGELIS et al. 1985). GPS will clearly be a valuable surveying tool with applications, for example, in large scale civil engineering schemes associated with coastal defences.

High precision gravimetry is another geodetic technique that has advanced rapidly in recent years and that is now being used for crustal movement measurements. Relative gravity measurements with LaCoste and Romberg G and D spring gravimeters can now be made to a precision of 2 to 6 microgals even over distances up to 100km (JACHENS et al. 1983, LAGIOS et al. 1986). Absolute gravimeters, in which a falling corner cube forms one arm of a Michelson laser interferometer, are now commercially available. Portable absolute gravimeters currently have an accuracy of 8 to 10 microgals (ZUMBERGE et al. 1983) and laboratory instruments have been built with an accuracy of 1 microgal. The relationship between height change and gravity is not unique but is generally -2 microgals per centimetre uplift. HIPKIN (1978) has set up a microgravimetric network for measuring the vertical crustal movements of Scotland and is planning to extend this network down to the south coast of England.

(c) CONCLUSIONS

The available information on current relative changes of mean sea level around the British Isles is fairly sparse (only 11 gauges with >20 years data since 1916). However, it is clear that there are vertical crustal movements over a variety of spatial scales. Although the movements involved are usually fairly small (1 to 2mm/year) the cumulative effects over a century are important for coastal defences. In some places in the British Isles secular increases of mean sea level may be as large as 5mm/year.

Modern space geodetic techniques can now be used to measure these crustal movements. These would identify areas of local or regional movement, allow a separation of crustal movement from the real sea level changes and thus help to quantify any accelerating trends in mean sea level due to climatic changes.

Unfortunately, although the U.K. has radio telescopes, it does not, at present, have any geodetic VLBI capability. However, the coordinates of the SLR station at Herstmonceux are now known to $\pm$5cm with respect to the global network of SLR and VLBI stations and to $\pm$2 or 3cm with respect to the European stations. Using Herstmonceux as a base point, dual frequency differential GPS measurements could be used to find the vertical movement of U.K. tide gauges. For a 1cm accuracy in the relative vertical positions, GPS stations would be required at approximately 100km intervals. Since a time interval of the order of 10 years would be required to detect significant vertical displacements, it is important to begin these measurements as soon as possible.

A high precision gravity network would provide valuable confirmation of the measured changes. It would therefore be useful to have common sites for many of the gravity and GPS measurements. However, elevated coastal sites suffer direct attraction by the marine tide, including possibly significant time-mean non-linear contributions. Therefore, gravity stations should, wherever possible, be at least a few kilometres inland in order to accurately correct for the tidal effects.

6. SEA LEVEL: TIDES AND SURGES

Sea surface elevation models which have been developed for many of the world's coastal areas (e.g. FLATHER (1984) for the NW European continental shelf) provide estimates of the instantaneous sea surface topography using the depth-averaged hydrodynamic equations of motion in which the 'surge' (the sea surface distribution due to meteorological forcing) and the tide are not considered as independent quantities but interfere in a non-linear fashion to give significant 'tide-surge interaction'. The input of the best possible meteorological information (in the form of wind-stress and surface air pressure values) is essential as is good knowledge of the ocean tide across a wide area. Both should be more efficiently provided in future by remote sensing methods enabling a more reliable spatial parameterisation of still water levels. In addition, in order to assess the overall likelihood of storm damage or flooding, the coupling of elevation models to models of the wave climate, and the assimilation of remotely-sensed elevation and wave measurements into those models, presents a further major task.

(a) ALTIMETRY FOR TIDES

Tidal models of the N.W. European continental shelf, which form a subset of tide-surge elevation models, are thought to be accurate at present to approximately 10% in the amplitude of each constituent and 10° in phase, which corresponds in some areas to an uncertainty in instantaneous tidal height of a few decimetres. Better tidal models in coastal areas could be developed by the mid-1990's; the tides comprise a stationary sea level signal allowing the combined analysis of data from several altimeter projects with different sampling patterns. In due course, models of the geocentric tide (i.e. the tide measured by an altimeter) could be produced with centimetric accuracy using data from several of the present generation of nadir-pointing altimeters. To convert these geocentric models into ocean tide models (i.e. the tide measured by a tide gauge on land) requires the removal of the earth body tide, which is precisely known, and of the ocean loading tide, which has to be computed in an iterative procedure from an assumed ocean tide (e.g. see BAKER 1980). The loading tide will in turn be computed more reliably from better knowledge of the tides of the neighbouring deep ocean which will also be obtained from altimetry (e.g. MAZZEGA 1985; WOODWORTH et al. 1986).

(b) ALTIMETRY FOR SURGES

For storm surge model updating and forecasting, the fast delivery of altimetric information from the next generation of satellites (ERS-1, TOPEX/POSEIDON, etc.) is expected to result in sea surface height measurements of an adequate - decimetric - accuracy. In addition, by that time suitable facilities will exist in the U.K. (e.g. at the ERS-1 Data Centre) for rapid processing of remotely-sensed data for input to the models.

Studies such as CARTWRIGHT et al. (1981) and LE PROVOST (1983) using Seasat data have shown that sea level around the U.K. can be effectively measured by altimetry. However, the major drawback of a small number of nadir-pointing altimeters stems from the infrequent overflight of coastal areas, such as the North Sea, by satellites positioned at approximately 1000km altitude. Consequently, either a large number of altimetric satellites are required (together with the tracking and data-processing effort that implies) or the sea level dataset has to be effectively augmented by other techniques (such as coastal HF-radar current measurements). The development of cheap solid-state altimeters which can be deployed on 'satellites of opportunity', and thereby increase the number of altimetric satellites, is one of the goals of the TOPEX/POSEIDON programme.

A major possible development in the late-1990's concerns the replacement of the TOPEX generation of satellites for oceanographic monitoring (which will have typical operational lifetimes of 3 years) by long-duration, multi-purpose orbiters in near-equatorial and near-polar orbit. The near-equatorial orbiter (to be built by the USA) is intended to be a manned space station while the near-polar orbiters, of which there will be at least two, will be unmanned platforms capable of servicing by manned space vehicles. The European component of the polar-platform development is now called 'Columbus'. All orbiters will be at approximately 800km altitude and may carry radar altimeters. Such a facility, while of great interest to deep-sea oceanography, would not necessarily provide an improvement in the sampling of coastal areas given the continued employment of nadir-pointing altimeters. However, the use of advanced devices, such as multi-beam altimeters (GRIFFITHS et al. 1985), would enable the measurement of sea level and sea-level-slope both along-track and across a 50-100km swath beneath the satellite track. In the deep ocean this would remove the spatial-temporal compromise which always exists with nadir-pointing altimeters and would provide detailed coverage of the mesoscale, while coastal areas would be sampled much more frequently. The development and deployment of such a multi-beam altimeter is a major recommendation of the Columbus programme (ALLAN 1986).

7. SEA LEVEL: ASSIMILATION OF ALTIMETER DATA IN MODELS

The most direct application of water level measurements to marine flood protection would be to incorporate them in surge forecasts produced by numerical models. This would be achieved by introducing these data, together with observations from conventional tide gauges, during a "hindcast" calculation carried out using the model. There would result an improved definition of the initial fields from which the subsequent forecast would begin.

We consider some aspects of the available data and suitable methods of data assimilation.

(a) NATURE OF THE AVAILABLE DATA

Some key questions arise immediately concerning i) the sampling rate in both space and time and ii) the elapsed time between the measurement and availability of the data.

i) The rate at which sea surface elevation is sampled in space and time is determined by the orbit of the satellite. Generally, for oceanographic applications near global coverage is required such that a given track is repeated at intervals of a few days. The final choice must be such as to prevent aliasing of the tidal signal at low frequencies. Typical ground tracks over the N. Atlantic for 3- and 10-day repeat orbits, as used for Seasat and proposed for the TOPEX/POSEIDON mission, are shown in Figure 1. Altimetric data from such tracks can and have been used primarily to examine steady, slowly varying (compared with the repeat period) and periodic variations; principally the geoid, ocean surface topography from which the ocean circulation can be estimated, and the ocean tides. The data are not so useful for transient intermittent variations such as occur in storm surges, which typically last for about one day.

Considering the 3-day repeat orbit, shown in Figure 1, there are 6 tracks crossing some part of the NW European continental shelf, of which possibly half would contain information of significant value (the remainder are either mainly over land or are located in deep water, where the inherent measurement errors are substantial relative to likely surge magnitudes). So, on average, one track per day might contain useful information. For the TOPEX/POSEIDON mission, altimeter measurements would be made every 20km along each track (STEWART 1985). (This spacing is comparable with that in surge models and satisfactorily resolves most surge structure: track separation is the issue). Hence assuming a typical track length over the sea areas of the UK shelf of 500km gives, on average, about 25 data values per track. Since the orbital period is of order 1-2 hours, the data from one track over the UK shelf would be nearly synoptic. The quantity of data is, therefore, comparable with that provided by one tide gauge, sampling at hourly intervals. Although the 10-day repeat orbit gives increased spatial sampling, the increased repeat period means that the actual rate at which useful data would be produced is about the same. However, some of the additional tracks relate more closely to areas where significant surges occur, so that these data may be of greater value.

The above discussion relates to average rates, but in practice tracks need not cross the region of interest at regular intervals during the repeat period. Thus on some days there could be 2, 3 or even more passes and an others none at all. The value of the data will also depend on whether it coincides in space and time with some significant surge development.

(ii) The second (and related) aspect concerns the time at which the data becomes available in a usable form. Thus, after measuring the return time of the radar pulse, some considerable processing is required to derive from it the sea surface elevation, correcting for the many factors affecting the radar transmission and reflection from the sea surface (see, for example, ROBINSON 1985). At some appropriate stage during all this, the data must be transmitted to a receiving station. In order to be of use, the height data would need to be sent on to the Meteorological Office; the necessary tidal prediction carried out to remove the tidal contributions from the measured heights; and the resulting surge information incorporated into a suitable assimilation procedure; all within, say, 6 hours of the measurement. ERS-1 altimeter height data are to be included within the ESA Fast Delivery Product (i.e. within 3 hours). Fast Delivery heights would not have high absolute accuracy, but changes relative to the open ocean, an ice sheet or transponders could be useful. Plans for the TOPEX/POSEIDON mission anticipate the release of data to users within 6 <u>months</u>, the delay being necessary for verification and accurate calculation of elements of the orbit of the satellite. The most rapid release (within 4 hours) is planned for altimeter observations of wave height to the US Navy's Fleet Numerical Oceanographic Facility. Clearly a high priority would need to be established in order to obtain data within a short enough time.

To summarise, the data sampling rate from a satellite altimeter would be roughly equivalent to a single conventional tide gauge. This might improve by increasing the number of satellites carrying altimeters or by the development of altimeters with some kind of scanning capability to provide measurements along a broad swath rather than along a narrow track.

One other aspect is the potential of these measurements for statistical analysis in order to estimate extreme sea levels for design purposes. However, if the data required for this purpose from a conventional tide gauge is at least one year of values, then estimates along the 3-day repeat tracks in Figure 1 would require roughly $3/t_c$ years of data, and for the 10-day repeat tracks, $10/t_c$ years (where t_c is the autocorrelation time of the surge in days, typically $< \frac{1}{2}$). The design life of the TOPEX/POSEIDON satellite is 3 years.

(b) DATA ASSIMILATION METHODS

In view of the above discussion, it seems certain that satellite altimeter data would need to be used together with measurements from conventional tide gauges. A flexible assimilation method, capable of introducing both time series measurements at fixed points and near-synoptic data along a track would be required. To date, little work has been done on assimilation of data into surge models. An early contribution (FLATHER, 1976) examined the possible influence of real-time data from offshore tide gauges, and FLATHER et al. (1983) discussed a method making use of data from a single coastal tide gauge. In general, the high rate of frictional dissipation in shallow seas limits the period during which the influence of initial data predominates over the effect of forcing and, therefore, reduces the value of any initialisation procedure. Much effort has, however, gone into this aspect of weather forecast models, for which initialisation is all important, and some of the resulting techniques might be adopted.

It would be necessary to adjust both water levels and currents to obtain balanced fields and avoid the introduction of spurious oscillations. This might be best achieved by a dynamical initialisation approach in which all available data from the 12-hour period preceding a forecast would be introduced during a hindcast calculation carried out with the surge model. Being based on integration of the governing dynamical equations, balanced velocity fields matching the adjusted surface elevation distributions would be derived. This approach has yet to be developed and tried.

8. WATER DEPTH

(a) OBSERVING TECHNOLOGIES AND CHARACTERISTICS

Scanners of visible and near infra red radiation can indicate depth by two means. The instantaneous shoreline is clearly depicted in Band 7 (0.8 to 1.1 μm) of the Landsat series Multi-Spectral Scanner (MSS) and usually in other bands also, as used by the Thematic Mapper (TM) on Landsat 4 and subsequently. Images for various sea levels (especially, from high to low tide) then indicate an intertidal depth profile for the whole coastline, provided that the shoreline excurses much more than the 30m typical resolution of the scanner. Secondly, the differing transmission of different bands through clear water, before and after reflection from the bottom, can in principle be used to estimate depths up to 20m. The need for clear water is an obvious difficulty, compounded by the uncertain effects of any suspended matter in the water even if insufficient to obviously obscure the bottom.

Lidar estimates depth by the extra time of transmission of a laser beam from the sea surface to the bottom and back. Hence it too depends on sufficient clarity for the return transmission through the water depth, but less sensitively in that relative transmissivity is not involved. Maximum depths of 50m can be sounded in clear water, but suspended matter may reduce this to a few metres or less. Hitherto, the only planned or actual measurements are from aircraft.

Photography can also be used to estimate depths, using images from different angles above for triangulation. Again, this method has only been used from aircraft and depends on visible features on the sea floor.

All the above methods also depend on the absence of obscuring cloud.

Imaging radar, such as the Synthetic Aperture Radar (SAR) on Seasat (1978) and planned for ERS-1 (1990), operates through cloud but indicates (rather than measures) depth rather indirectly and uncertainly. It actually records an integrated intensity of scattering from sea-surface ripples of wavelength of about 30 cm (Seasat) or 8 cm (ERS-1). The recorded intensity may be modulated in various ways by swell (see section 11) which is refracted by depth variations, or by convergence and divergence in (say) tidal flow over varying depth.

Because SAR images also show other phenomena, notably internal waves, they need interpretation and ancillary information. For example, waves are refracted by spatial variations of current as well as depth. Convergence or divergence is likely to reverse with the tidal current (and be absent in slack water). However, when there is tidal flow, the alignment of linear sand-banks (say) is very clearly and accurately depicted (and their obliquity to the tidal flow is confirmed).

(b) USEFULNESS

Water depth is not usually required operationally, given the relatively slow movement of the sea bed level and other means of determining surface levels. Uncertainties indeed render the above methods unsuitable for operational use.

However, a few shoreline positions corresponding to different sea levels may substitute for a great deal of surveying, and directly yield map or chart contours. Average beach profiles follow. Of the other measurements, lidar would appear to be potentially the most effective. However, the resolution required for charts of shallow seas, their local nature and the need to avoid clouds, all suggest its use from aircraft.

The SAR images, while not measuring depth, can indicate areas of variation significant for wave propagation and tidal or surge currents. Areas requiring more precise survey may be indicated. (In principle, the refraction of various wavelengths can be inverted to yield depth as a function of horizontal position. However, such a procedure has not been carried out. The results would be sensitive to any currents present and to errors in refracted wavelength, which is uncertainly biased by SAR - section 11. The requirement

30m SAR resolution << refracted wavelength << topographic scale

restricts any conclusions to broad scales of hundreds of metres).

(c) POTENTIAL APPLICATIONS

Average beach profiles indicate the amount of wave run up and set up to be expected. The 30m resolution of the Thematic Mapper is useful in poorly surveyed areas or where erosion or deposition are changing beaches rapidly.

The <u>means</u> of SAR depth indication, although indirect, relate well to applications. Features significant for wave convergence, and hence increased waveheights or set up at coasts, can be seen. Thus the choice of sites for wave studies may be guided.

(d) PRESENT EXPERTISE

Landsat TM data is received at Farnborough over the European remote sensing network Earthnet, and images are formed there and at the NERC unit for Thematic Information Systems at the University of Reading. Bathymetry from such data and Lidar has been studied by Professor A.P. Cracknell (Dundee University). Topographic features depicted by SAR have been studied in IOS.

9. SEDIMENT TRANSPORT

The presence of suspended particles in the water affects the colour of the water as seen in the visible wavelengths of light - clear water is blue and muddy water is brown. However, these particles can be both organic and inorganic. Ocean colour is sensed by most satellites by use of a number (generally 4 to 6) of narrow band radiometers, each of which senses part of the visible and near-visible radiation spectrum. There is, of course, a degree of overlap between the bands. The different satellites have different resolutions ranging in terms of pixel size from a few tens of metres to several hundred metres. The frequency of transit is also very variable, but is normally of the order of once every 10 days. Since this is considerably longer than the tidal timescale, which is the dominant one affecting sediment transport, it restricts the use of the remote sensing to descriptive rather than quantitative studies.

The geometrically corrected remotely sensed radiances have to be corrected for atmospheric effects and for angle of view and sun's illumination, and use of the data is restricted to cloud-free situations. This is a major restriction in Britain since cloud-free satellite overpasses may occur very infrequently. Airborne remote sensing does not suffer to quite the same extent.

In order to enhance the sensitivity of the images to the sediment signal, subtraction of the radiances between different wavebands, or consideration of the ratios of radiances, particularly between the 0.5 - 0.6, and the 0.6 - 0.7 μm wavebands are used. Nevertheless the signals can only be transformed into concentrations by calibration with simultaneous ground truth observations. Many different calibration algorithms have been proposed for different areas, and it is obvious that there is no universal calibration. The calibration depends on such factors as particle type, grain size and size distribution, and these are likely to vary with time as well as from one region to another.

A cloud-free satellite image will show features that are obviously related to sediment sources and transport paths. Higher concentrations are visible in the turbidity maximum areas at the heads of estuaries, and near tidal flats; streaking or banding of concentration is observed in deeper channels with high tidal streams, and various eddy and vortex structures are often apparent. The satellite image can provide an excellent synoptic overview of the surface suspended sediment distribution, one that cannot be obtained by any other means. However, the results have to be interpreted carefully, with knowledge of the field conditions at the time, especially the tidal state, and wave and wind conditions. Otherwise the extra return from whitecapping (say) might be misinterpreted as additional suspended sediment radiance.

To quantify the results in terms of sediment transport rates requires obtaining a closely spaced sequence of images so that the differences between them can be considered. The movement of the concentration contours is then a measure of the transport rate. This density of information can be obtained from remote sensing from airplanes, but not from satellites. In areas such as the Severn Estuary, where the tidal and spring-neap variation of concentration is large, it is possible to build up a reasonable picture of the sediment dynamics from images taken occasionally over a considerable period. Even then there is the problem of the limited depth of penetration of the signals. In coastal and estuarine waters around Britain the depth of penetration is normally less than a metre. Because the driving force for the sediment movement is the shear stress at the bed, and the sediment concentration decreases from the bed to the surface in a still poorly understood way, the surface transport may bear little relation to the overall depth-integrated transport. Consequently interpretation of remote sensing is subjective. However, analysis of the images provides an excellent guide to the design of field observation programmes, and when considered in the light of those observations, remote sensing provides a useful mean of extending the results to gain a regional perspective. There is available a large archive of satellite remote sensed data that can be accessed relatively cheaply for results relating to particular areas. Airborne measurements, however, have to be set up specifically for each task.

10. WAVE PARAMETERS

(a) ALTIMETER

In addition to measuring the distance from the satellite to the sea surface, altimeters can also be used to measure the surface roughness and hence derive significant wave height. Pioneering work at IOS has shown that it is also possible to derive non-linear wave parameters from the altimeter echo and even a measure of wave period (GUYMER et al. 1985; CHALLENOR et al. 1985; SROKOSZ 1986). These extra wave parameters require more complex data processing than has been undertaken for current or past altimeters. The UK ERS-1 Data Centre is proposing to extract all these parameters. At present a single altimeter, on the US Navy satellite Geosat, is collecting data (there have been two previous missions: GEOS-3 and Seasat). In 1990 the European Space Agency plan to launch ERS-1 which includes an altimeter among its sensors. Some time after this the joint US-French satellite TOPEX/POSEIDON is due to be launched which will also carry an altimeter. Broad-swath altimeter designs are now being produced.

These instruments are expected to fly on the next generation of satellites associated with the Space Station, such as Columbus. Here discussion is limited to the present generation of instruments.

(b) USEFULNESS

The radar altimeter is a narrow swath instrument, the swath being only one footprint of approximately 7km wide. This means that data are only collected directly under the satellite. The satellite orbit is such that the minimum repeat period (the time between the altimeter sampling the same point on the ground) is three days. A short repeat period such as this means that adjacent satellite tracks are a long way apart. For ERS-1 with an inclination of 98.5° the tracks are 450km apart at 60°N with a three day repeat. A longer repeat period means that adjacent tracks are closer together. These problems with sampling mean that a satellite-borne altimeter is not a good instrument for the operational monitoring of wave conditions. (Ground-based HF radar would probably be much better suited to this role.) The great advantage of a satellite system is that wave statistics can be built up on a global basis regardless of weather conditions. Although the wave climate in UK waters is reasonably well understood conventional wave buoys cannot measure the non-linear parameters, such as the sea surface skewness, that can be obtained from the altimeter. A knowledge of these non-linearities in the wave field may well prove useful in the design of flood protection schemes as well as for research.

(c) POTENTIAL APPLICATIONS

One obvious application of the altimeter is the collection of wave statistics. Unfortunately of the commonly used wave parameters only significant wave height is measured. A measure of wave period can be obtained but its relation to the wave periods from buoys is at present obscure. The non-linear parameters may well prove to be the most useful aspect of the measurement of waves by altimeter. By measuring the change in sea surface skewness as the waves enter shallow water it should be possible to deduce the amount of steepening the waves have undergone and also the probability of overtopping. It should be stressed that altimeters are unlikely to be of any use operationally even with a number of satellites.

(d) PRESENT EXPERTISE

The UK has a large community of scientists interested in the radar altimeter. However, interest in waves is mainly concentrated in IOS and the Applications Development Unit of the BNSC (a group at the Mullard Space Science Laboratory is interested in altimetry over land-sea boundaries so may be interested in the problems of coastal protection, in particular the use of transponders, developed at the Rutherford Appleton Laboratory, to measure water elevation directly). At present there is no work being done directly connected with flood protection.

11. WAVE SPECTRUM

(a) OBSERVING TECHNOLOGY

Synthetic Aperture Radar (SAR) is hitherto the most appropriate satellite sensor for measuring wave length and direction (other than for ripples of cm wavelengths). It operated on Seasat (100 days in 1978, but limited by the absence of receiving stations in the southern hemisphere where it was winter) and for a few days on the shuttle (SIR-A and SIR-B).

SAR's synthesis of the image is controversial; prior to Seasat's demonstration, even an inability to image waves was argued. Doubts remain as uncertain biases or distortions are introduced into the image spectrum vis a vis the wave spectrum. There is no calibration for wave energy.

The spaceborne SAR's that have operated to date have been L-band (1.27 GHz/23.5 cm). ERS-1 will carry a combined scatterometer/SAR in the C-band (5.3 GHz/5.7 cm) and multi-frequency SAR's are probable for the 1990's. If returns are by Bragg scattering, then this is from sea surface ripples of approximate length 30 cm/8 cm for Seasat/ERS-1 (see e.g. ROBINSON, 1985).

The radar scans a swath about 100/75 km wide (Seasat/ERS-1) parallel and to one side of the satellite track. (Lateral) 'range' is determined by using a radar frequency which decreases during the course of each transmission pulse, and correlating the frequency/time-dependent returns. The along-track co-ordinate 'azimuth' is determined by timing the return's Doppler shift. Thus the strength of the return is recorded as a function of apparent range and azimuth with approximately 25/30 m resolution (Seasat/ERS-1); any one target stays in view for 2s while the satellite moves at typically 8 km/s to synthesise a 16 km antenna.

Waves of length exceeding about 100 m are imaged by the varying strength of return from different portions of the wave. (i) The wave orbital velocity converges forward of the wave crest, giving more intense ripples and returns from the crest. The effect is less for ripple propagation (i.e. radar beam) at right angles to the wave's propagation. Hence there is a bias favouring waves propagating in the range direction, and dependence on the wind component in this same sense for the ripples. Short wavelength radar is less effective as ripples of length << 10 cm decay in the convergence time in the wave. High sea states are not properly sensed because the ripple distribution is more chaotic. (ii) There is a stronger return from the slope of the wave facing the radar. Again, a component of ripple propagation (hence wind) is required in the range direction, and there is a bias favouring waves propagating in this direction. (iii) The moving sea surface Doppler-shifts the radar returns, thereby affecting the source location apparent to the frequency-dependent synthesis. Vertical motion is most effective, and gives apparent alternate concentration and dilution 'velocity bunching' of returns in a waves' length. The apparent source shift can easily reach $\frac{1}{2}$ wavelength or more for shorter or larger amplitude waves, resulting in self-cancellations. (For example, the orbital velocity of waves with 3 m height and 150 m wavelength is about 1 m/s, displacing the apparent source location by 100 m. Opposite displacements corresponding to opposite velocities at wave crests and troughs imply 200 m relative displacement from their half-wavelength separation 75 m. It was such an argument for confused imaging which led to doubt, prior to Seasat, that spaceborne SAR could image surface waves).

Hence the effect (iii) is biased towards waves propagating along the azimuth and towards long waves. This appears to be borne out in the few examples of quasi-azimuthal wave fields imaged by spaceborne SAR's where the shorter wave components are absent. The evidence is not yet conclusive, however, since no reliable 'in situ' observations were available. For large-amplitude waves, (iii) fails and spoils the results of (i) and (ii). (The effect also displaces SAR images of ships from their wake image).

Overall, it appears possible under favourable conditions (moderate winds) to estimate wavelengths exceeding 100m with 10% error and a tendency to overestimation, and directions with 10° error and a bias towards range propagation.

SAR requires considerable power to operate, and yields a high data rate: 1 number/$(10\text{m})^2$ over a swath of 100/75km for Seasat/ERS-1, requiring special data transmission and reception. On ERS-1 it will alternate with wind scatterometry and with a 'wave scatterometer' mode in which the distribution of wave lengths is transmitted. The latter do not function over land, whereas SAR is useful for agriculture, forestry, snow and ice studies, which may compromise the radar parameters for wave imaging. Moreover, forecasting centres would prefer wind fields to SAR imagery over the sea. All these factors mitigate against the operation of SAR every time it passes over UK waters.

However, the SAR on ERS-1 has a 'wave' mode which consists of taking 'snapshots' of small (5 x 5 km) scenes spaced 200-300 km apart. Its operation will not be affected by the duty cycle of the scatterometer but again its sampling may be inadequate for coastal monitoring especially since the vignettes cannot be guaranteed to repeat over the same small areas.

(b) USEFULNESS

The SAR observations give good spatial coverage of wave observations over the area imaged. However, the narrow swath width 100 km implies about 14 days for complete coverage of the earth's surface from one satellite, or about 8 days for coverage of UK latitudes (with an appropriate orbit). Hence any input to an operational wave model would be very sparse in space and/or time.

In any case, there remains some doubt on the usefulness of satellite SAR in imaging the azimuth-travelling component of surface wave field. Uncertain biases in wavelength and direction persist as 20% estimated errors for the ERS-1 wave scatterometer mode. Because some causes of bias are known as above, there is scope for error reduction through the accumulation of experience when ancillary data is available (particularly, wind speed and orientation independently for an estimate of the ripples, and of course in situ wave data for calibration). Thus SAR on ERS-1 will be useful for research purposes in improving understanding of the imaging, extending the validation data and assessing the operational potential of multi-satellite systems.

An alternative means of obtaining wave spectral information in particular regions is high-frequency radar operated from transmitting/receiving stations on land. Bragg-scattered returns Doppler-shifted to a range of frequencies centred on the transmission frequency have peaks corresponding to approaching and receding waves of half the radar wavelength, and other contributions from non-linear interactions with the remaining wave spectrum, about which inferences can be made. The method can observe for 100 km or more offshore from two well-separated stations (preferably, for better directional information). The range is greater for larger radar wavelengths, and may potentially be extended, by 'skywave' radar reflection from the ionosphere, to many hundreds of kilometres. Development work on inferring the wave spectrum continues, and the method does not provide the spatial detail with individual waves afforded by SAR. However, the land-based system appears better suited to operations.

(c) POTENTIAL APPLICATIONS

SAR imagery has a role in wave refraction and focusing studies, as remarked in section 8 'water depth'. By collecting images showing waves incident on the coast from a range of directions, locations vulnerable to focusing under particular conditions may be identified. As previously remarked, sites for in situ measurements may be chosen for their representativeness or otherwise. More widely, wave climate statistics could be built up in time (years).

(d) EXPERTISE

UK experience with SAR images and extraction of wavelength and direction resides in IOS and particularly BNSC. The Meteorological Office is investigating the assimilation of wave data into models as part of the Wave Modelling project (WAM).

12. WINDS

(a) OBSERVING TECHNOLOGIES

A number of methods exist for the determination of winds from remote sensing satellites and these are reviewed below. The first two make use of meteorological satellite data from visible and infra-red sensors, which have been available for some 25 years; the rest depend on microwave sensors which have been flown on oceanographic satellites in the last decade. Both types are planned for the foreseeable future.

(i) Cloud-track winds. Winds may be deduced from the displacement of clouds or cloud elements over intervals of time. It is assumed that the clouds are moving with the wind at their level. The main problem is in extrapolating winds at cloud level to the level of interest - in our case, to a standard height near the surface, say 10m. Polar orbiting satellites cannot be used because the time between observations is 100 minutes which is too long for clouds to remain identifiable. Geostationary satellites provide images every 15 minutes but distortions at high latitudes limit the effective use of the technique to less than 50° latitude. Also, high cloud may obscure low-level cloud. However, a large number of wind vectors are obtained globally by this technique, especially in tropical areas, and it is the only one of the methods discussed here which is capable of giving winds over land. An example of the coverage obtainable over the ocean is shown in Figure 2.

Visible or infra-red images of cyclonic cloud patterns have similar observing characteristics. They approximately locate some weather systems, with a rough indication of wind direction but not speed. The information provides a qualitative check rather than quantitative input to a weather forecast.

(ii) Sun glitter. Under cloud-free conditions, and for particular viewing geometries, specular reflections of the sun by the sea surface may affect remotely-sensed data. On visible wavelength imagery over the ocean, sun-glint is observed as an area of increased but diffuse brightness. The intensity and horizontal extent of this region depends on the variance of the surface slopes, which is dominated by small-scale roughness. This, in turn, is related to the near-surface wind; in calm conditions the surface acts like a mirror and a small, bright area is seen. As the wind roughens the surface the illuminated area becomes smeared. COX et al. (1954) conducted an aerial photography experiment near in-situ wind measurements and quantified the relationship between surface slopes and wind. Several workers (e.g. WALD et al. 1983; DESCHAMPS et al. 1984) have used the technique to extract sea-surface winds from polar-orbiting satellite imagery. The method is obviously limited by meteorological and geographical conditions, and areas such as the Mediterranean in summer are particularly favoured. Difficulties encountered include the possible effects of foam, and waves not driven by the local wind, i.e. swell. Some satellite sensors are deliberately configured such that sun-glint does not occur, thus precluding the use of this method.

(iii) Scatterometer. This instrument is an active microwave instrument (radar) which irradiates the surface at different angles and measures the backscatter intensity. The amount of energy returned has been found to depend on radar parameters such as incidence angle and radar frequency, and on sea-state. In particular, for incidence angles > 15° the return increases with wind speed as increased short gravity-wave activity occurs. Moreover, the return is anisotropic so that by viewing the same patch on the sea-surface from more than one azimuth some directional information is also obtained. This can be achieved by having more than one antenna. Systems flown up to now have used 2 orthogonally-mounted beams and this gives rise to between 2 and 4 directional ambiguities (directions which are indistinguishable in terms of their backscatter along the two beams). These ambiguities can be resolved by reference to external data or internal dynamical consistency checks but the process is very time-consuming. Future scatterometers will carry additional antennae which, theoretically, should reduce the number of ambiguities.

The scatterometer has a much narrower swath than visible and infra-red sensors on the meteorological satellites (500km compared with 2000km), though it is possible to view from both sides of the satellite. This limitation is compensated for by its ability to view the sea-surface in all weathers and actually provides an estimate of wind at the surface without the need for extrapolation. The technique is applicable to all of the world's oceans, except those which are ice-covered.

(iv) Altimeter. This is also a radar but it operates only at nadir. Although its primary purpose is for very high precision measurements of range to a target (as discussed in sections 6 and 7) the return signal strength is inversely proportional to wind speed. The mechanism involved is similar to that for (ii) in that the variance of the surface slopes increases with surface wind speed and this results in less specular reflection (at vertical incidence) of microwaves back to the altimeter antenna. Several satellite altimeters have been flown but problems have been encountered with the accuracy of wind retrievals at speeds > 12 m/s, partly through inadequate data on which to base the algorithm. (A recent extension to 21 m/s depends on comparison with scatterometer values 200 km off nadir; CHELTON et al. 1986). Only wind speed is obtainable (since there is no anisotropy at vertical incidence) and together with the very narrow swath (10 km) this means that the data are much less useful than those obtained from a scatterometer.

(v) Synthetic aperture radar (SAR). The third of the radar sensors is the SAR which has been flown on one satellite and two shuttle missions. Like the scatterometer it measures the radar backscatter over a range of incidence angles and uses the rapid horizontal motion of the antenna (7 km/s) to synthesise an antenna of length 13 km, resulting in spatial resolution cells of 25m across. In this way a very high resolution image, comparable with that of Landsat data, can be produced, allowing all-weather surveillance of 100 km - wide swaths of the surface. For the ocean most emphasis has been placed on the modulation of the backscatter by features such as swell waves, internal waves, subsurface topography and surface contaminants. A less well documented application is the derivation of wind velocity from areally-averaged backscatter using algorithms similar to those of the scatterometer (VESECKY et al. 1982). The spatial resolution of a few km and the ability to obtain uncontaminated data very close to land makes this potentially useful for coastal marine applications. Because of the very high data rates, SAR data can normally be obtained only for areas in which the satellite is within telemetry range of a special receiving station, though Satellite Relay Systems offer ways round this problem. A further hindrance is that the high power consumption of imaging radars means that they cannot be operated continuously (typically, a 10% duty cycle can be envisaged).

(vi) Passive microwave radiometers. The last satellite wind sensor which we shall consider operates in a passive mode receiving the very small microwave signals emitted by the earth-atmosphere system. The sea surface emits microwaves by virtue of its temperature but is not a black body, its emissivity depending on surface roughness, especially the amount of foam present. Atmospheric water, both in vapour and liquid form, also has a microwave signature as it absorbs and re-emits incident radiation. Thus the signal received by the sensor is due to a variety of effects. The ability to separate out the geophysical parameters of interest (in this case wind speed) depends on the fact that the sensitivity of the signal to a particular parameter varies with microwave frequency and polarization (see Figure 3). For wind speed retrieval 10 GHz is optimal. The most useful forms of the instrument, therefore, are those in which several frequencies are sampled, some of which give the primary estimate with the others providing corrections for the secondary dependence on other parameters. The Scanning Multichannel Microwave Radiometer on Seasat and Nimbus-7 operated in such a way and was conically scanned to give coverage over a 600 km swath. Unfortunately no directional information can be obtained. One of the problems of this sensor is that the footprint size for winds is rather large (100 km) for antenna diameters presently achievable. Effects of land and radio-frequency interference can also be severe near coasts, but the larger antennas made possible by the polar platforms or Space Station would largely overcome this.

(b) USEFULNESS IN OPERATIONAL FLOOD PROTECTION, DESIGN AND RESEARCH

Having outlined the types of remote sensing data and some of their characteristics, we now discuss their usefulness in three different areas and attempt to rate their potential contribution.

(i) Operational. Of the six techniques, only one (cloud-tracked winds) is used in an operational mode. Four satellites (GOES-E and GOES-W, GMS and Meteosat) are located in geostationary orbit, i.e. 40,000 km above the equator, and winds are routinely disseminated to national meteorological offices. In the latter part of its lifetime GEOS-3 provided real-time wind and wave data from its altimeter. Winds from the ERS-1 scatterometer and altimeter will be processed and disseminated to forecasting centres within 3 hours of acquisition by the satellite but, in general, data from the oceanographic satellites are processed in an off-line mode for use in research activities.

Even if the data discussed in (a) could be processed and made available in near real-time it is questionable as to how useful they would be in predicting or assisting decision-making in a flooding situation. Satellites provide very good spatial sampling (with the exception of the sun-glint method) but at the expense of good temporal sampling. The relatively narrow swath microwave sensors give winds at any location only twice per day at best and for some satellites, where exactly repeating orbits are required, certain locations may not be sampled at all. Eventually, there may be several wind-measuring satellites in orbit at the same time and adequate coverage for inputs to numerical models may be obtained. For the foreseeable future, however, remote sensing winds will supplement other sources of data. An example of the improved forecasts which can result from the assimilation of scatterometer data is shown in Figure 4. Thus, wind fields in coastal areas may be predicted more accurately, leading in turn to better sea-level predictions. Another use may be in the validation of the evolution of model predictions, rather than in direct assimilation, and hence in providing corroborating evidence on which to act to prevent flooding or to initiate warnings.

(ii) Design. Data from the sensors in (a) would probably be more useful in designing flood protection schemes than in operational planning. Two areas are envisaged:-

Climatological statistics. Provided several years of continuous wind estimates from satellites were available, they could be used to assess the wind conditions likely to be experienced at almost any oceanic location on the globe. These would be especially valuable in data sparse areas where the climatologies are rather doubtful. The climatological estimates could then be used, in combination with wave and sea-level data and models, to assess regions of vulnerability and to derive realistic design specifications for proposed protection schemes.

Construction of realistic flooding scenarios. The worst flooding results from a combination of factors. Wind fields from potential flooding occasions could be abstracted from remote sensing archives and used, via models and extremes of tides, runoff and sea-state, to produce worst-case but realistic flood scenarios. Analysis of such occasions may further assist the design of schemes to prevent flooding, especially taking regional differences into account.

Both of the above areas will involve the research community. Some of the possible topics of interest are: sub-synoptic scale variations of the wind field and its effects; assimilation of scatterometer and other data into shelf sea models; the combined use of scatterometer and altimeter data to investigate inverse barometer effects (the former giving an estimate of surface pressure gradients).

(c) POTENTIAL APPLICATIONS

Satellite wind data can be used to compile global atlases of wind climatology. Although their temporal sampling is limited it is probably sufficient to produce reliable monthly means. For coastal applications the finest spatial resolution is desirable and for this scatterometer and SAR data are likely to prove best. Ship-borne measurements are likely to result in unreliable mean values because they tend to avoid stormy areas and suffer problems with the exposure of sensors; remote sensing should overcome this although wind retrievals at the upper part of the dynamic range (which are of most interest for flooding) have not been well-validated.

Scatterometer wind vectors may be analysed to investigate along-shore wind-driven currents and their relation to sediment transport, possibly in conjunction with SAR and the Coastal Zone Colour Scanner. There is also evidence that orographic effects on wind flow can be detected from scatterometer data, both upwind and downwind from large islands; this may be important in understanding local sea-level variations.

(d) PRESENT EXPERTISE

IOS is participating in studies for the UK ERS-1 Data Centre as members of its scientific advisory group, the so-called Product Support Team. Its particular responsibilities include altimeter wind retrieval; as well as trying to produce an improved algorithm, specifications have been drawn up to ensure that the finest spatial sampling is obtained when the altimeter is operating near land. A study of the potential application of low data-rate sensors (i.e. excluding SAR) to semi-enclosed seas is being conducted for ESA by 4 European institutes, including IOS. The group has reanalysed, and in some cases reprocessed, Seasat data (scatterometer, altimeter and SMMR) and is now addressing the question of how ERS-1 data sets can be combined to investigate coastal problems. Some success has been achieved in simulating surges at Venice by assimilating Seasat scatterometer data into a model of the Adriatic.

13. RAIN

(a) OBSERVING TECHNOLOGIES

The requirement here is for rainfall measurements over catchment areas which will affect river and lake levels in coastal regions through runoff, rather than for estimates at sea which is a notoriously difficult task by conventional methods (because of poor exposure of rain gauges on ships, distortion of the airflow by the superstructure, etc.). However, for the purposes of forecasting rainfall over land, knowledge of rain distribution over the sea is also likely to be required and so both situations are addressed.

(i) Visible and infra-red data. A combination of VIS and IR data can be used to identify amounts of cloud and to estimate their depth, e.g. thunderstorms appear bright in both bands because they have very cold tops (low IR radiance, shown conventionally as white) and are optically dense (because they are composed of low cloud of high water content as well as thin ice crystals). Jet stream cirrus, by contrast, has a very different signature in the visible because it is often partially transparent to light and has a fibrous structure. These qualitative effects of multispectral behaviour and texture can be used to develop quantitative rainfall estimation schemes. Most success seems to be achieved in the case of severe thunderstorms. SCOFIELD et al. (1977) describe a scheme which relies on calculating the change of cloud parameters between successive geostationary images and knowing the water vapour profile from nearby upper air stations. Such techniques cannot be used with mid-latitude frontal rainfall, but are applicable to both land and ocean.

(ii) Passive microwave data. The SMMR data described in the section on winds can also be used to estimate precipitation. Higher microwave frequencies are involved and so a smaller footprint is obtained (about 40 km). The method is applicable only over the ocean since the emission from land would mask any atmospheric signal. For general rain areas of light to moderate intensity, SMMR estimates appear reasonable (KATSAROS et al. 1981) but convective precipitation occupying only part of the 40 km diameter footprint may go undetected. An instrument of this type was launched on MOS-1 by Japan in February 1987.

(iii) Radar altimeter. Altimeters which have been flown on satellites so far have clustered their range gates around the expected level of the sea, land or ice surface, since the concern has been to accurately measure the topography and roughness statistics of such targets. The inclusion of, say, eight pre-sea level gates, each 0.5 km wide, would make it possible to detect and measure rainfall in the beam (FOSTER et al. 1980). This sort of measurement would best be made at 1-3 GHz; if the more usual radar frequency of 13 GHz were to be used, extensive ground-based radar data at this frequency would need to be analysed. It is worth noting that SMMR estimates could be improved if the depth of rain cells could be obtained independently from altimeter rain-gate measurements.

(b) USEFULNESS

The Scofield/Oliver technique has been used in the U.S.A. on a quasi-operational basis for the past three years to support weather forecast offices and river forecast centres, and has been successful in analysing several flash flood events in real-time. However, additional research is needed before the technique can be successfully applied to all types of storms. Its uses either as an operational or research tool for the U.K. would appear to be limited. Probably, a combination of VIS/IR, passive microwave and altimeter with ground-based radars offers the best prospects for an operational rain-monitoring system. The satellite data can provide a large-scale context for the surface radars enabling short-time predictions to be extended to longer periods. The proper synthesis of such data streams and their assimilation into atmospheric models is a topic for research.

(c) POTENTIAL APPLICATIONS

As experience is gained with the use of data such as those previously described, it may be possible to identify with increased confidence the sort of meteorological situations in which active and intense mesoscale rain systems are likely to develop. The use of satellite atmospheric water data in the initialisation and verification of model development could lead to improved prediction of large runoff several days ahead. Analysis of rainfall climatologies derived from satellites may also assist in specifying design criteria for flood protection schemes.

(d) PRESENT EXPERTISE

The University of Reading, the Meteorological Office and NERC Institute of Hydrology are involved in relevant programmes, including the hourly estimation of clouds for rainfall over West Africa from the visible and infra-red data recorded by the geostationary Meteosat. The SERC Rutherford Appleton Laboratory has expertise in passive microwave sensors and altimetry.

14. DISCUSSION

(a) OPERATIONAL POTENTIAL

Most of the remote sensing methods discussed above appear best suited to research and development rather than operations. Hence it is appropriate to identify those which may be helpful for operations, where this might be appropriate (flooding extent, surges - assimilation in models, waves, wind and rain).

For flooding extent, the several useful sensors of visible and infra-red radiation all suffer (for operational use) from being obscured by cloud, which makes the gathering of information uncertain (even unlikely at the time of flooding). SAR provides hitherto the best images, penetrating cloud. On ERS-1, it will be operated for only 10 minutes per orbit (then excluding the only wind-scatterometer in prospect) but this can include the seas around the UK as the rapid data will be received at West Freugh (Scotland).

For surge monitoring and assimilation into forecast models, one altimetric satellite yields a similar quantity of data to one conventional tide gauge, on average. The satellite data is less regular, however (there could even be no useful data on the particular day of a surge) and expected errors exceed the 2 cm typical of coastal gauges. Improvement entails more altimeters with the 2 cm design accuracy of TOPEX/POSEIDON (1992?) and/or the adoption of multi-beam altimeters to cover a swath rather than a line beneath the satellite track, a possibility for the envisaged Columbus programme (after 1995?). Operational use requires the development of assimilation techniques (a numerical modelling study) and priority and effort devoted to rapid transmission of altimeter data and allowance for tides, for use in the surge model.

Wave height (and other parameters) from one altimeter has a similar operational status to surge level, the comparison now being with one (one-dimensional) wave buoy. Assimilation into a simple wave model (not taking separate account of wave direction) may be more straight-forward, but requires investigation, now taking place at the UK Meteorological Office. Again, priority and effort would be required for rapid altimeter data transmission and processing. Buoys and HF radar may prove better suited for operations.

Wave spectra are indicated by SAR. Although covering an 80 km swath, this provides in effect little more than a 'line' sequence of information in open seas where the spectra vary significantly only on this or larger scales, or for models with this resolution scale. There are also uncertainties in the inference of wavelength and direction. SAR from ERS-1 will be possible from seas around the UK. Land-based HF radar again seems to be a promising alternative for operations, although itself requiring development in deriving wave spectra. Assimilation of either, as relatively sparse data, into a sophisticated wave model for directional spectra, would require considerable further study.

For meteorological variables (wind and rain) the appropriate operational use of remotely sensed data would appear to be in weather forecasts driving surge and wave models, rather than directly (the data being only partial). It is is therefore appropriate for meteorological forecasting agencies to assess the value of visible cloud (for cyclone location, and for wind speed by cloud-tracking) and some combination of visible, infra red, microwave and altimeter sensing (for rainfall in conjunction with ground-based radar). Actual (rather than climatological) sea surface temperature would assist better medium range forecasting, but unfortunately is usually obscured by cloud from sufficiently accurate satellite remote sensing (by infra red). Assimilation in all these cases is a research topic. Because surge and wave models are influenced by meteorological data for a day or more beforehand, 'forecast' here refers also to the hindcast calculation by which assimilation is carried out.

(b) RESEARCH AND DESIGN

There are many fields where the spatial coverage of satellite remote sensing builds up a bank of information not previously available, opening new approaches for flood-protection studies.

Long-term changes of climate are important in flood protection through changing statistics (e.g. storm frequency and strength) and mean sea level trends. Sea surface temperature and ice extent are expected (from global climate models) to be sensitive indicators of climate change. They are sensed in the absence of clouds by infra-red and visible radiation with useful accuracy (½K absolute by the ATSR on ERS-1 from 1990; 1 km spatial resolution). The AVHRR already on NOAA 9 (and earlier) has slightly less absolute accuracy for temperature but a 2500 km swath giving global coverage daily (except for clouds). Ice extent may be somewhat obscured for visible imaging during the polar winter, but the largest problem for both surface temperature and ice extent is surely in data reduction to agreed representative parameters. Altimetry over polar ice caps and extensive glaciation can monitor the world's store of ice. To detect a future trend in any of these, an early starting date is required to establish initial values.

Mean sea level rise is the climatic effect most directly significant for flooding. A separate trend for each port (estimated from observations there) is presently allowed for in estimating its sea level statistics and extremes. However, such an approach fails to separate crustal movements from changes in ocean dynamics and volume, providing no basis for prediction when the latter may be subject to more rapid change. Crustal movements vary spatially to give mean sea level rise rates of up to 5mm/year (at Portsmouth). Accurate geodesy as described in section 5 gives the prospect, starting now, of identifying local and regional crustal movement (cumulating to a measurable quantity from about 10 years onwards). This movement separated from trends in mean sea level would allow the latter's variations to be better related to climate variables. In turn, accurate altimetry for global sea level coverage would remove the obvious Northern-hemisphere bias of present coastal sea level observation sites (there may also be a bias in their locations around the perimeters of main ocean gyres). Mean sea level trends (in particular any early warning of an accelerating rise) would be more reliable if based on global coverage. This is in prospect if the accuracy of TOPEX/POSEIDON is at least maintained by the Columbus programme and in subsequent decades.

Global climatology for winds is in prospect from the ERS-1 scatterometer if operated regularly world-wide. (The competing SAR may provide an alternative with better and near-coastal resolution around Britain). Seasat has already demonstrated the feasibility. Advantages compared with ships are fuller and unbiased coverage of remote and stormy seas, although large values need further validation.

As winds drive waves and surges which induce flooding, their climatology is obviously important. In the absence of (say) fifty or more years' observed wave and surge statistics at most coastal locations, modelling to extend the statistical basis with simulated data assumes importance (e.g. FLATHER, 1987). Because waves and surges develop over 1000 km or more, global wind climatology has a role here, including the possibility of enhancing the statistics through the many samples in space as a substitute for long-term data. Joint wind/wave or wind/surge statistics are difficult to obtain from one satellite, but have value in particular coastal locations for identifying flooding risks. Where freshwater runoff is a significant contributor to water levels, so also is rainfall climatology.

Global wave climatology (and to a lesser extent sea level variability) from altimetry provides a comparison with - or input for - model calculations. Risk assessment using models can be improved thereby.

More local wave behaviour inshore is imaged by SAR, with the potential for indicating areas of focusing and other refraction effects, under a wide range of conditions as a 'library' of images is built up. Thus scenarios of particular risk, and suitable locations for *in situ* observation may be identified.

Shoreline evolution and the extent of sandbanks on larger scales 0(100 m) can be monitored by the multi-spectral scanner or thematic mappers which continue on the Landsat series. Profiles follow from observations at different sea levels; then net deposition or erosion may be estimated. For submerged depths of up to 50m (in clear seas), aircraft lidar appears to be preferable although there is little experience hitherto. (NB above that SAR images some of the practical effects of shoaling depths).

Near-surface suspended sediment appears on visible imagery, notably from the Coastal Zone Colour Scanner, flown on Nimbus 7 but for particular localities perhaps more practically operated from aircraft. Flights over many states of the tide, and of winds driving longshore currents, may build up a regional perspective, and assist the design of fieldwork, essential to extrapolate from sea-surface sensing to total sediment transports.

15. CONCLUSIONS

Flooding may be imaged over that part of the UK sensed by ERS-1 in SAR mode at the time.

Useful surge and wave data assimilation for forecasts awaits the Columbus programme and requires its altimeters to have 0(2 cm) accuracy and to cover a swath 0(100 km) or more, as well as rapid data transmission and forecast model development.

Directional wave data assimilation would require further model development. For continuous data in specific areas, coastal HF radar may be more practical.

Several meteorological variables can be sensed for operational use via meteorological forecast models to wave and surge models.

For long term design, mean sea level trends (relative to land) are important. Their prediction will be improved by separating crustal movements from ocean circulation and climate effects.

Geodetic techniques now have the accuracy to distinguish vertical crustal movements in a period of decades from whenever initial measurements are made. This should be as soon as possible.

Accurate altimetry commencing with TOPEX/POSEIDON has the potential to establish a more reliable estimate of mean sea level through more even global sampling. A programme of coastal tide gauge installations (GLOSS) for the same purpose requires associated geodetic measurements. Monitoring trends requires successor satellites/geodesy decades ahead.

Several climate indicators (sea surface temperature, ice cover and storage) can be monitored to improve our understanding and prediction of sea level trends.

Global wind and wave climatology in prospect from ERS-1 should be used via models to improve surge and wave risk assessment. An ongoing ESA study involving IOS is relevant in this respect.

Local wave focusing and other information should be accumulated from ERS-1 SAR.

Extensive coastal morphology may be monitored by the continuing Landsat series. However, aircraft flights with Lidar and CZCS may be more practical for a sequence of images over a short period (hours-days) at specific localities.

In situ observations are necessary for quantitative sediment transports.

The time is now appropriate for influencing the operation of ERS-1 (1990) and the sensors of the Columbus programme (after 1995?).

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Table — Physical quantities of interest and relevant satellite-borne sensors. SLR, VLBI, GPS and gravimetry are special to geodesy (section 5) and not included.

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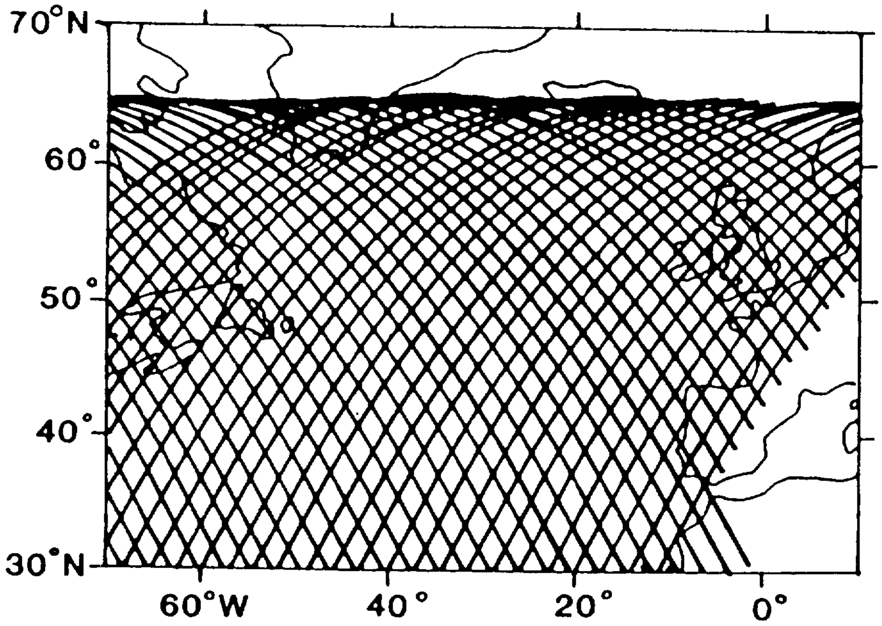
ACRONYMS/TERMS

ATSR	Along-track scanning radiometer
AVHRR	Advanced very high resolution radiometer
BNSC	British National Space Centre (Farnborough)
Columbus	European component of projected near-polar orbiters, late 1990's
CZCS	Coastal zone colour scanner
ERS-1	ESA Remote Sensing satellite due for launch 1990
ESA	European Space Agency
Geosat	Geodesy Satellite (US Navy, geodetic information declassified Nov. 1986)
GPS	Global Positioning System
HRV	High resolution visible sensor
IOS	Institute of Oceanographic Sciences (Deacon Laboratory of IOS and Proudman Oceanographic Laboratory from 1 April 1987)
Landsat	Originally Earth Resources Technology Satellite, series (NASA, 1972-)
Lageos	Laser geodynamics satellite (NASA, 1976-)
Lidar	Radar analogue using laser light
Meteosat	Geostationary meteorological satellite (ESA)
MOS-1	Marine Observation Satellite (Japan, launched 19 Feb 1987)
MSL	Mean sea level
MSS	Multi-spectral scanner
NASA	National Aeronautics and Space Administration (USA)
NERC	Natural Environment Research Council
NOAA	National Oceanographic and Atmospheric Administration (USA)
SAR	Synthetic aperture radar
SASS	Seasat-A satellite scatterometer
Seasat	Oceanographic satellite operated 28 June 1978 to 10 Oct 1978

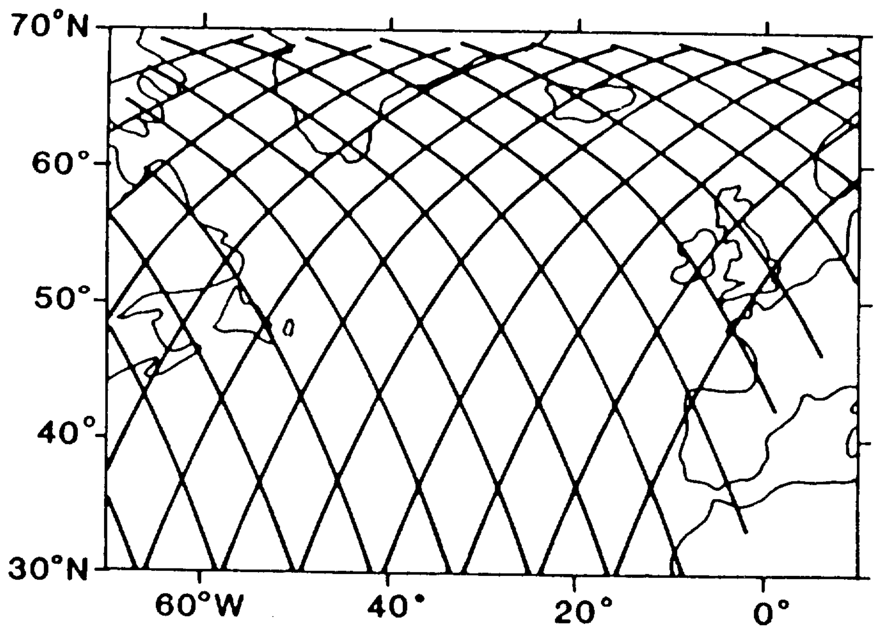
SERC	Science and Engineering Research Council
SLR	Satellite laser ranging
SMMR	Scanning multichannel microwave radiometer
SST	Sea surface temperature
TM	Thematic mapper
TOPEX/POSEIDON	(Ocean) Topography Experiment (USA/France), satellite launch 1992?
VLBI	Very long baseline interferometry

Table Physical quantities of interest and relevant satellite-borne sensors. SLR, VLBI, GPS and gravimetry are special to geodesy (section 5) and not included.

Sensor / availability characteristics / Physical Quantity	Visible	AVHRR	ATSR	Lidar	SMMR	scatterometer	SAR	altimeter
	CZCS Nimbus7; MSS/TM Landsat-5 MOS-1; 825m resolution 80/30m; 1636km swath 185km	continuing Meteosat (>5km resolution) MOS-1, NOAA 1km resolution 2580km swath	ERS-1 (1990) 1km resolution 500km swath	not planned from satellite aircraft hitherto	Seasat Nimbus-7 MOS-1 600/800km swath interference near land	Seasat (SASS) ERS-1 (1990) 500km swath no ice	Seasat ERS-1 (1990) special telemetry, not operable continuously 30m resolution 75km swath	GEOS-3 Seasat Geosat ERS-1 (1990) TOPEX/POSEIDON (1992?) Columbus (after 1995? 50-100km swath?)
	only without cloud							
flooding extent	HRV (Spot) narrow swath Meteosat poor resolution not for operations				inadequate resolution		best images poor coverage	
sea surface (skin) temperature		0.12K relative 0.6K absolute	0.1K relative 0.5K absolute		1.5K relative 2.0K absolute			
ice cover	fewer images in polar winter	poor when ice and sea temperatures close			poor resolution		good images coverage needs planning	ice store
sea level trends								long-term
tides and surges								At nadir. Eventually tides to O(1cm). Several to monitor surges.
water depth	3-D photogrammetry from aircraft. MSS/TM for shoreline			At nadir. To 50m for clearest sea			Indirect-waves refract, intensify	
sediment transport	synoptic view of sediment within 1m of surface: qualitative						coastline; sand bank alignment	
wave parameters								at nadir; waveheight, non-linearity, period
wave spectrum							only sensor applicable. Limitations.	
wind	Clouds give cyclone location (no wind speed) Cloud tracks for velocity at cloud height, 50°S-50°N sun glint (without cloud)				Speed only Resolution 2m/s, 100km	ambiguous direction Best overall	Good resolution	speed only
rain	In storms from geostationary				resolution 40km			Local radar returns from air column Not planned



Spatial distribution of the ground track over the N. Atlantic for a 10-day orbit repeat pattern.



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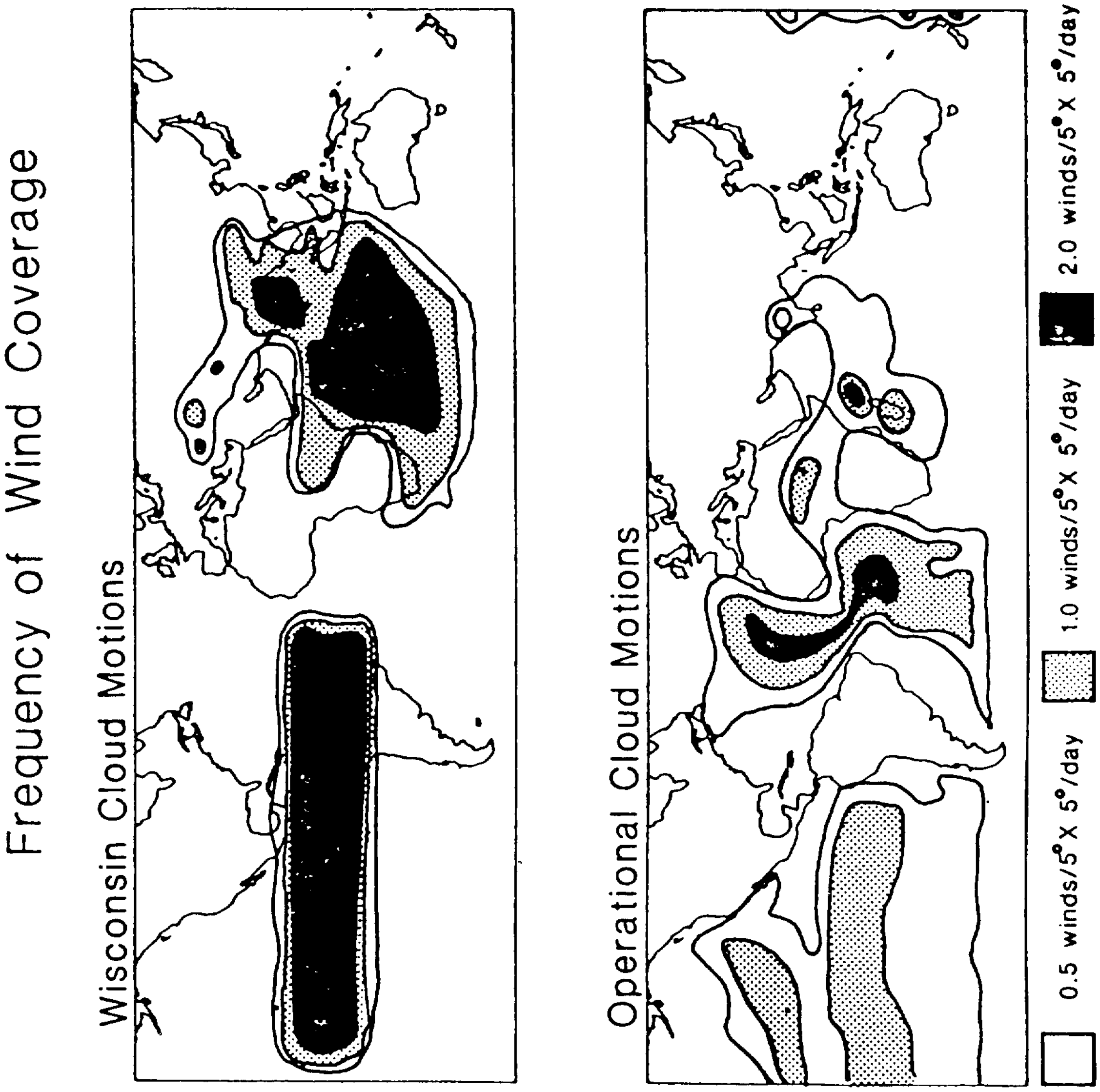

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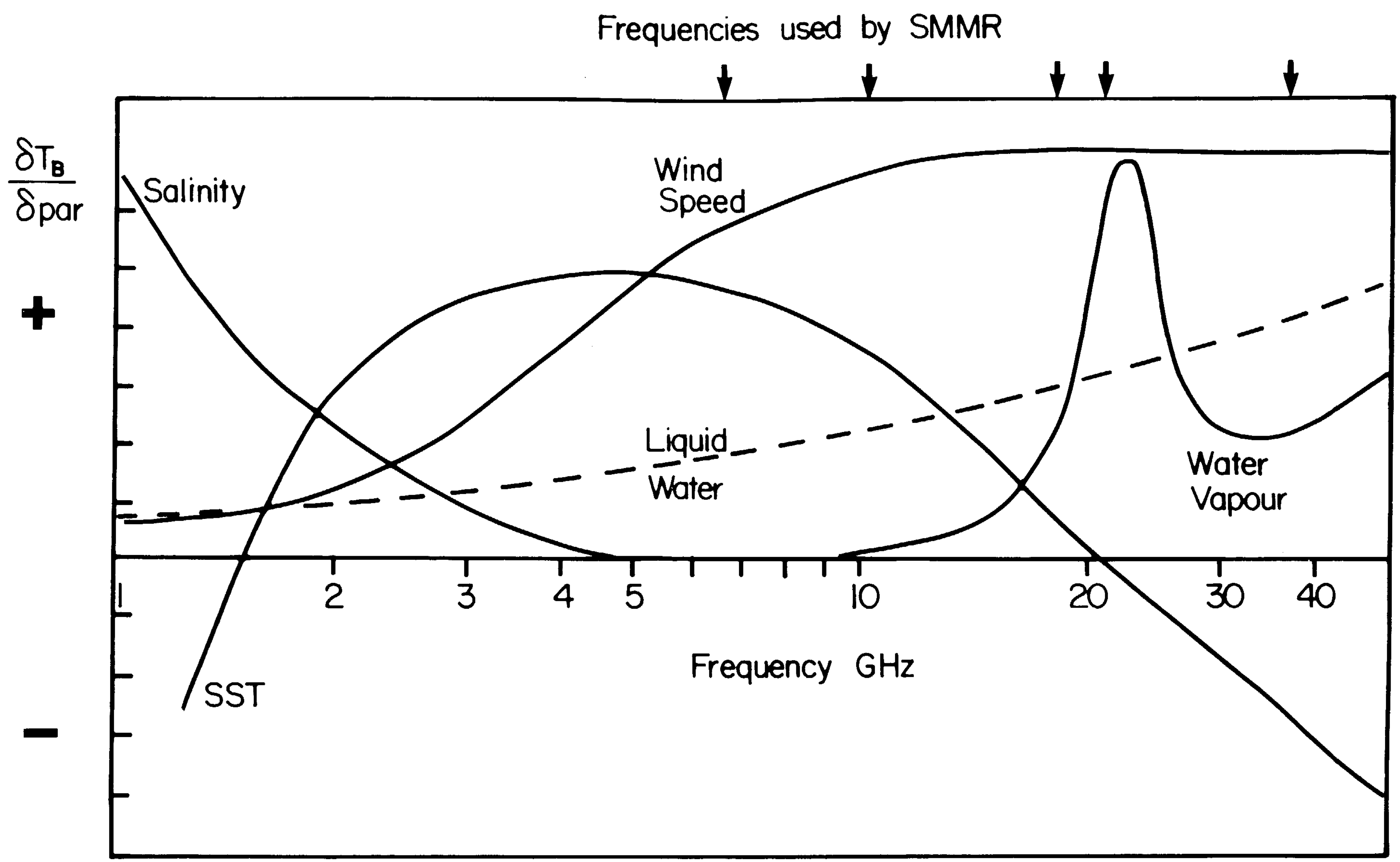

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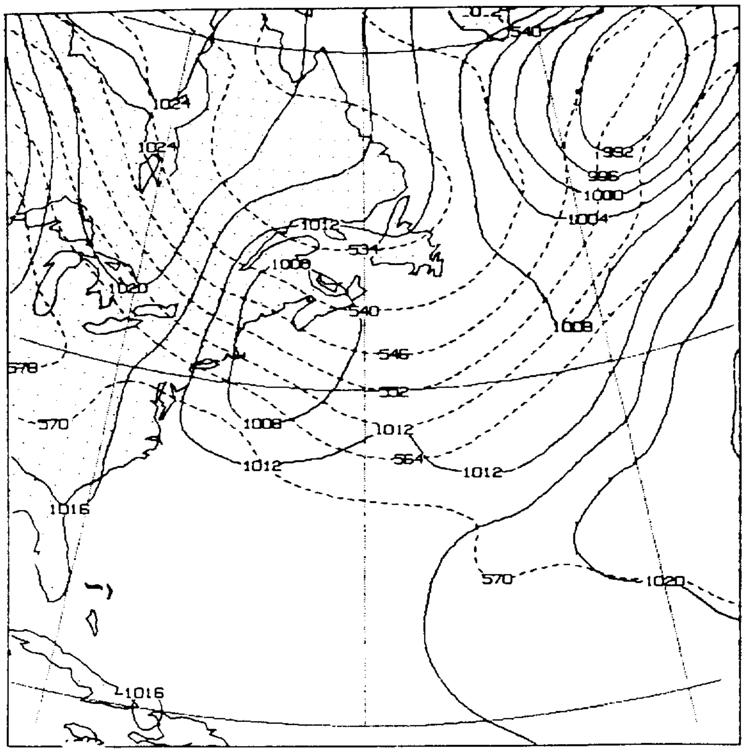
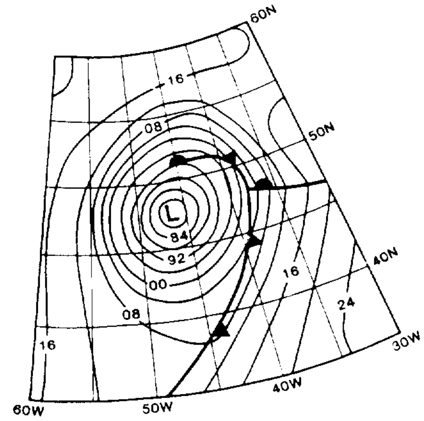
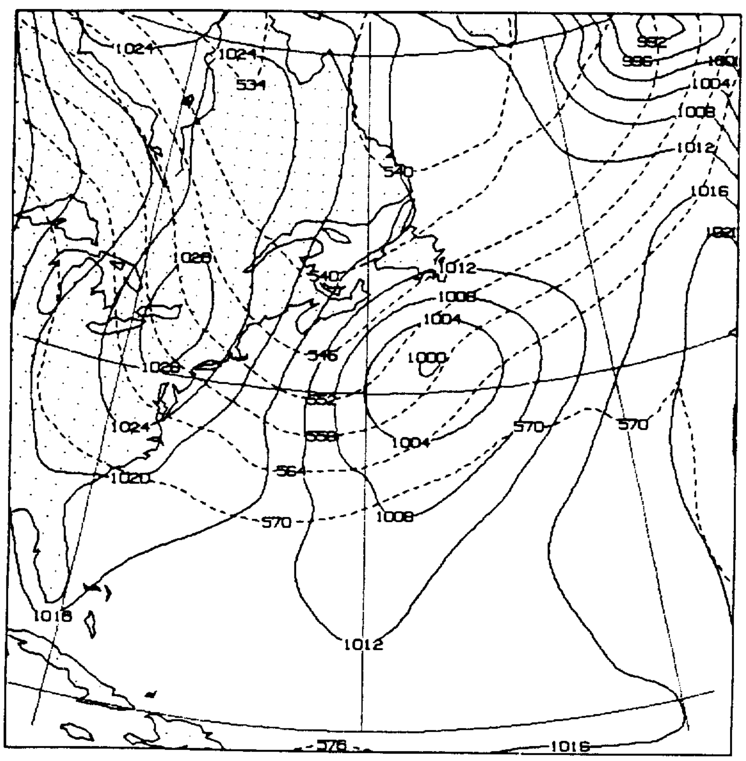


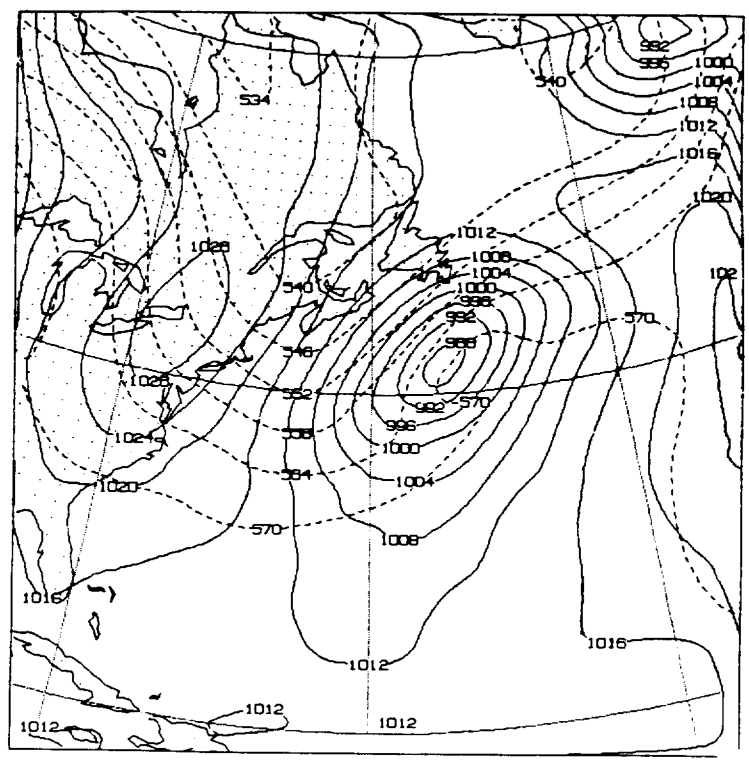
Initial sea level pressure (—) for 1200 UT,
9 September 1978



NMC hand analysis of observed sea level pressure at 0000 UT, 11 September 1978



36h control forecast sea level pressure (—) for 0000 UT
11 September 1978



36h forecast sea level pressure incorporating SASS (—)
for 0000 UT, 11 September 1978

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