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Final: April 2008

# Storm surge computations for the west coast of Britain using a finite element model (TELEMAC)

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ABSTRACT

An unstructured mesh finite element model of the sea region off the west coast of Britain is used to examine the storm surge event of November 1977. This period is chosen because accurate meteorological data to drive the model, and coastal observations for validation purposes are available. In addition previous published results from a coarse grid (resolution 7 km) finite difference model of the region and high resolution (1 km) limited area (namely eastern Irish Sea) model are available for comparison purposes. To enable a "like with like" comparison to be made, the finite element model covers the same domain and has the same meteorological forcing as these earlier finite difference models. In addition the mesh is based on an identical set of water depths.

Calculations show that the finite element model can reproduce both the "external" and "internal" components of the surge in the region. This shows that the "far field" (external) component of the surge can accurately propagate through the irregular mesh, and the model responds accurately, without over- or under-damping, to local wind forcing. Calculations show significant temporal and spatial variability in the surge in close agreement with that found in earlier finite difference calculations. In addition root mean square errors between computed and observed surge are comparable to those found in previous finite different calculations. The ability to vary the mesh in nearshore regions, reveals appreciable small scale variability that was not found in the previous finite difference solutions. However the requirement to perform a "like with like" comparison using the same water depths means that the full potential of the unstructured grid model to improve resolution in the nearshore region is inhibited. This is clearly evident in the Mersey estuary region where a higher resolution unstructured mesh model, forced with uniform winds, had shown high topographic variability due to small scale variations in topography that are not resolved here. Despite the lack of high resolution in the nearshore region the model showed results that were consistent with the

previous storm surge models of the region. Calculations suggest that to improve on these earlier results a finer nearshore mesh is required based upon accurate nearshore topography.

## 1. INTRODUCTION

Following on from the major flooding caused by the 1953 U.K east coast storm surge event, the main focus in storm surge modelling has been the prediction of storm surge elevations on the European shelf. Of particular importance has been their accurate prediction in shallow coastal regions where flooding can occur during major storms. In regions such as the Irish Sea and North Sea, early research showed that limited area finite difference models failed to reproduce the observed surge due to their neglect of shelf wide wind events (the external surge). Consequently early storm surge computations were performed with shelf wide finite difference models (e.g. Davies and Flather 1977), that necessarily used coarse grids due to computational limitations, hence their resolution was poor in coastal regions. Since the main objective of these models was the computation of surge elevations, the two dimensional hydrodynamic equations were used.

With enhancements in computing power, finite difference grids in shelf wide models were refined to the order of 12 km (Davies et al. 1998, 2000) and local (e.g. west coast of Britain) models of grid resolution 7 km (Davies and Jones 1992a, hereafter DJ92) or less (Jones and Davies 1996, Jones and Davies, 1998, hereafter JD98) were developed. However, such local models required open boundary input from a coarser shelf wide model, or a model which could account for changes produced by shelf wide winds. For example DJ92 used a 7 km resolution west coast of Britain model to simulate the November 1977 major surge event. For this simulation far field effects were taken into account using observations along the open boundaries. However, results showed that the 7 km grid of this model was not sufficiently fine to accurately resolve the local increase in storm surge elevation in the eastern Irish Sea. Consequently in subsequent work, this model was used to provide boundary conditions for a limited area eastern Irish Sea model of 1 km resolution, resulting in improved surge accuracy in the region (JD98). A similar approach of using a high resolution (of order 1 km) limited area model of the North Channel of the Irish Sea, forced by a coarse grid large area model, was used by Davies et al (2001) for a detailed study of tidal and wind forced currents in that area. Although this approach of nesting a high resolution limited area finite difference model within a coarser grid model enables a local improvement in resolution, if the nesting is two way then there may be problems at the interface between the two grids. In addition as shown by Davies and Hall (2002) in regions of rapidly changing current magnitude and direction produced by local changes in topography, a nesting approach could give rise to significant errors in the currents. An alternative approach, the method examined here, is to use a finite element technique in which the grid resolution varies gradually in space. By this means a coarse mesh can be used in offshore regions where the water is deep and surge elevations and currents show little spatial variability. As the water shallows and surge intensity and spatial variability increase in the nearshore regions then the grid is refined in these regions. In addition surge propagation into estuaries can be readily accomplished without nesting.

The finite element model with its ability to refine the mesh in nearshore regions has been very successful in a number of problems (e.g. Werner 1995, Ip et al 1998, Jones 2002, Fernandes et al 2002, 2004, Walters 2005, Levasseur et al 2007, Nicolle and Karpytchev 2007). Although in theory the grading of the mesh is arbitrary, in practice the computation of an optimal mesh is complex (e.g. Greenberg et al 2007, Legrand et al 2006, 2007 and Hagen et al 2001, 2002) and in the calculations presented here in order to make rigorous comparisons with earlier finite difference and finite element models, no attempt was made to produce an optimal mesh.

Previous calculations using a finite element (TELEMAC) model of the west coast of Britain showed that it could reproduce the dominant ($M_2$ component) tide in the region (Jones and Davies 2005), to an accuracy comparable to an existing finite difference model (Davies and Jones 1992b). Also recent calculations showed (Jones and Davies 2007a) that the model was comparable in accuracy to both west coast (Davies and Jones 1992b) and high resolution eastern Irish Sea models (Jones and Davies 1996) at reproducing the $M_2$, $S_2$, $N_2$, $K_1$ and $0_1$ components of the tide. In addition by refining the element size in the eastern Irish Sea region the higher harmonics of the tide could be accurately reproduced (Jones and Davies 2007b). Also tidal residual currents in the region could be accurately simulated (Jones and Davies 2007c) and the artificial flow in the nearshore region due to the "stair case" representation of the coast in finite difference models (Davies and Jones 1996) was not present. Recent calculations (Jones and Davies 2006) using this finite element model of the west coast of Britain, showed that its response to steady orthogonal wind forcing was consistent to that found with well established and proven finite difference models (Jones and Davies 2003a,b). In addition the finer Eastern Irish Sea resolution in the finite element model showed small scale wind induced circulation features that were not present in the finite difference model (Jones and Davies 2003a,b). These calculations suggest that the finite element model developed previously should be able to reproduce storm surges in the eastern Irish Sea to an accuracy comparable to the nested high resolution (1 km) eastern Irish Sea and coarser (7 km) finite difference west coast models used previously.

Besides investigating the response of the west coast of Britain to wind forcing, the objective of these earlier calculations namely Jones and Davies (2003a), Jones and Davies (2006, 2008) was to examine the processes influencing surges in the region and the role of tide-surge interaction. However, the objective of this paper is to use the previous west coast finite element model, that has been validated against a range of tidal constituents, to examine the mechanisms (namely external and internal surge generation) producing the storm surge of November 1977. In addition because this surge event has been computed with a range of finite difference models, the relative accuracy of the finite element model can be examined by comparing with observations and finite difference solutions. To ensure that this is a meaningful comparison, the same regional extent, open boundary forcing and meteorological forcing to that used previously (DJ92 and JD98) was applied. In addition the topography used in the model was identical over the Irish and Celtic Seas to that used in DJ92, and in the eastern Irish Sea to that in JD98. By this means a rigorous comparison with these earlier finite difference models could be performed. The surge of November 1977 was chosen because an accurate meteorological data set was available with which to force the model.

The finite element model is discussed in the next section, with following sections describing the meteorological forcing and detailed model/data comparisons. A final section summarises the main results.

## 2. THE FINITE ELEMENT MODEL AND FORCING

Since the focus of the paper is the application of a finite element model to the prediction of surge elevations in the Irish Sea for the major storm events in November 1977 it is sufficient to solve the two dimensional vertically integrated hydrodynamic equations. However since the region (Fig. 1) spans a range of latitudes, spherical coordinates were used as in earlier finite difference models. As the form of the non-linear hydrodynamic equations using these coordinates is given elsewhere (DJ92, JD98) they will not be repeated here. As details of the numerical methods used in TELEMAC to solve the hydrodynamic equations have been reviewed in Jones and Davies (2006, 2007a,b,c) and references therein, they will not be repeated here. In order to compare results with previous finite difference solutions, the region covered by the model was identical to that used in DJ92. In addition the water depth distribution was based on DJ92, with the addition of more accurate water depths and coastal resolution in the eastern Irish Sea taken from JD98.

The water depth distribution in the region is characterized by depths of the order of 100 m in the Celtic Sea, deepening to 150 m at the south west of this region (Fig. 1). Within the Irish Sea on its western side there is a deep channel, with water depths up to 100 m, although on its eastern side the water is much shallower (less than 50 m) with extensive nearshore regions where the water depth is below 25 m (Fig. 2). In these nearshore regions, "wetting and drying" occurs over the tidal cycle. Water depths in the North Channel can exceed 150 m (Fig. 1) with average depths to the north of this of order 100 m.

As tidal friction and tide-surge interaction are important in the region, the five dominant tidal constituents, namely $M_2$, $S_2$, $N_2$, $K_1$ and $O_1$ were included within all the calculations as input along the open boundary. This is consistent with the finite difference solution given in DJ92. It is important to note that this tidal forcing was used in all calculations, namely those including the computation of the external, internal and total surge (see later). Previous tidal calculations (Jones and Davies 2007a) showed that the finite element grid used in the present calculations (Fig. 3) could accurately reproduce these constituents and the associated higher harmonics produced by non-linear interaction in the region. Although in the eastern Irish Sea storm surge calculations of JD98, using a limited area high resolution (1 km) model of the region, the input storm surge on the open boundary was taken without adjustment from the coarser (7 km) west coast model, the tidal input along the boundary was adjusted to give an accurate representation of the tide in the region. In the present finite element calculation no tidal or storm surge adjustments were made to try and improve model accuracy, nor was the topography modified from that used in JD98.

To be consistent with DJ92 and JD98, identical meteorological forcing for the period 7-17 November 1977 was used, and the surge was computed by subtracting a tide only solution from one involving tidal and meteorological forcing. As a detailed discussion of the meteorological forcing is presented in DJ92, it will not be given here. However, as shown in

DJ92 the surge within the region covered by the west coast model (Fig. 3) is influenced by both local winds and “far field” effects produced by wind forcing outside the model and the resulting flow into the region. Consequently as in DJ92 it is necessary to take account of this external effect along the open boundary of the model. To be consistent with DJ92 this was accomplished by linearly interpolating observed surge elevations from Castletownsend and Newlyn along the southern boundary of the model. In addition observations from Malin were imposed along the northern boundary of the model.

To understand the influence of the external surge, and local wind forced surge, upon the total surge, three calculations were performed with the finite element model using the grid given in Fig. 3. Initially (Calc 1) the model was run with only boundary forcing to determine far field effects (external surge). Subsequently (Calc 2) only local meteorological forcing was applied (internal surge) and finally (Calc 3) the full surge was determined.

## 3. STORM SURGE CALCULATIONS

### 3.1 External surge

In an initial calculation (Calc 1) the model was forced using only the external surge taken from observations (see DJ92 for details), applied along the open boundary, although as stated previously tidal forcing through the open boundary was included. Consequently no wind or atmospheric pressure gradient forcing was applied over the model domain. In this calculation to be consistent with the coarse grid (7 km resolution) finite difference model of the whole domain (Fig. 1), observations from Castletownsend and Newlyn were interpolated along the southern boundary of the model. Observations from Malin were imposed along the northern boundary. This forcing was identical to that used in the coarse grid model of DJ92.

Time series (Fig. 4a) of the storm surge elevation at a number of ports in the eastern Irish Sea (for locations see Fig. 2) showed that although some of the main features of the surge at Douglas could be reproduced through open boundary forcing (the external surge), the model significantly underestimates surge peaks, which occurred at times of maximum wind forcing. However, at other times surge elevations were reproduced, suggesting that these arose from "far field forcing" that propagated into the region through the open boundaries. In addition the underestimation of the surge increased rapidly at shallow water locations such as Liverpool, Workington and Hilbre, suggesting that local wind forcing in the regions was a major contributor to the surge.

## 3.2 Internal surge

In a subsequent calculation (Calc 2), no external surge was applied along the open boundary, although as previously tidal forcing was included, however now meteorological forcing was provided by wind stresses and pressure gradients. Time series at all the eastern Irish Sea ports (Fig. 4b) show that the model could reproduce the major features of the observed surge. In particular the rapid increase in surge elevations to give peak values at 00 hr 12/Nov and during 14/Nov at times of strong wind forcing were reproduced. However at other times of weak wind forcing the model failed to reproduce the small negative external surge. As discussed above this was due to external forcing. Although the observed time variation of the surge is reproduced by the computed internal surge its magnitude is below the observed. However, the magnitude of the computed surge increases as the water shallows, suggesting that the contribution of the internal surge to the total surge elevation will be more important in shallow than deep water regions.

## 3.3 Total surge

In a final calculation (Calc 3) the model was forced with both the open boundary surge elevation as in Calc 1 and with the meteorological forcing as in Calc 2. As previously (Calcs 1 and 2) tidal forcing was included in the model. Time series at Douglas (Fig. 4c), located in deeper water on the western side of the eastern Irish Sea shows that the finite element model can reproduce the observed features of the surge at this location. In particular the surge peaks that occur at 00 hr 12/Nov and during the 14/Nov. In addition the time series is in close agreement with that computed by JD98. It is interesting that both the time series computed with the present finite element model and the finite difference model (FREISM) of JD98 are in such good agreement considering that JD98, used a large area coarse grid model (7 km) of the region shown in Fig. 1, to provide boundary conditions for a 1 km model of the eastern Irish Sea. In this 1 km model the $N_2$ and $S_2$ tides together with the higher harmonics of the tide along the open boundary had been adjusted to give the best possible solution in the interior. In the present finite element model, no such adjustment was made, and tide and surge have been propagated through the whole domain and into the eastern Irish Sea. This suggests that both the tide (a freely propagating wave) and the storm surge (a meteorologically forced event) can accurately propagate through the unstructured finite element mesh (Fig. 3). At shallow water locations e.g. Liverpool, both the present and previous (JD98) solutions exhibit similar features, with both models failing to reproduce the full magnitude of the surges that occurred at 00 hr 12/Nov and during the 14/Nov. This could be due to a lack of detailed local meteorological forcing in the region, which Calc 2, has shown to be important in shallow water, or a lack of local resolution. In the case of the local eastern Irish Sea finite difference model this was limited to 1 km. Although the finite element model uses finer elements in this region, in order to perform a “like with like” comparison identical topography based on a 1 km grid was used. This suggests that in order to take full advantage of the finite element model’s ability to refine the grid in nearshore regions, with a possible improvement in accuracy, higher nearshore bathymetry is required. Although differences in the two solutions are evident at Liverpool, the two solutions are in closer agreement at Heysham and Workington. Interestingly at Heysham the finite element model shows some higher frequency “spikes” between 18 hr 11/Nov and 00 hr 12/Nov that were not present in the finite difference solution. The reason for this will be discussed later, when the dynamics of the surge in the Morecambe Bay area and its distribution over the whole west coast are examined.

In order to quantify the accuracy of the storm surge computed with the finite element model, and compare with earlier finite different solutions (Jones and Davies (2001)) root mean square (rms) errors based on differences between observed and computed surge were determined at Douglas and Liverpool. These ports were chosen to represent deep and shallow locations, and because a continuous observed time series was available. Besides computing errors for the whole period (Table 1), sub-periods as in Jones and Davies (2001) were used. The first period is from 00h 9/Nov to 11h 12/Nov covering the first peak. The second is an extended version of the first, namely from 00h 9/Nov till 23h 13/Nov, in essence the period up to the start of the second peak. The third period again starts at 00h 9/Nov, until 23h 14/Nov and hence covers both surge peaks.

From rms errors in Table 1 it is evident that at Liverpool for all the periods, and the total, the rms error from the finite difference calculation is slightly less than that from the finite element model. There was however no significant difference in rms errors at Douglas which is located in deeper water. The fact that both models use the same topography, and no attempt was made to improve the accuracy of the finite element model by enhancing local topography, suggest that the difference in rms errors at Liverpool is not due to resolution. As discussed previously in the 1 km model of the eastern Irish Sea used by Jones and Davies (2001), the tidal input had been adjusted along the open boundary to given an optimal solution in the interior. Since in the present finite element model no such adjustment was made, and tide-surge interaction in the eastern Irish Sea has an important influence on the surge at Liverpool but not Douglas, it suggests this may account for the very small difference in rms errors between the models at Liverpool.

Although calculations (Jones and Davies 2008) have shown that tide-surge interaction is important in this region and hence a realistic storm surge could not be produced without including the tide, calculations showed that when the external and internal storm surges were added together (in essence time series in Figs. 4a and 4b) then the total surge was not significantly different (differences of less than 5 cm in the time series) from that found in the full surge calculation. This arises mainly from the fact that a large domain model was used, and hence the external surge was small and only significant at times when the internal surge was negligible.

## 4. STORM SURGE DYNAMICS

In order to understand the time variation of the surge within the eastern Irish Sea, and compare its offshore distribution in detail with that from the 7 km west coast model (DJ92) and 1 km eastern Irish Sea model (JD98) it is essential to consider the time varying response of the whole region to storm forcing.

Consideri initially the first major wind period (namely 12 hr 11/Nov to 06 hr 12/Nov, see DJ92 for detailed meteorological charts). During this period there were winds from the south-west over the region that forced water from the Celtic Sea, into the Irish Sea giving rise to an increase in sea level in the eastern Irish Sea, particularly in the Solway estuary and Morecambe Bay regions. It is evident from Fig. 5a, that although sea level rises at the entrance to the Solway estuary, Morecambe Bay and the Mersey estuary, the storm surge has not yet fully propagated into these shallow water regions. In addition there is significant spatial variability in the storm surge elevation in these regions, reflecting local changes in bottom topography. In the Heysham region situated at the southern end of Morecambe Bay there is significant small scale variability in the surge produced by local topography. As the surge enters the region, “wetting and drying” can occur giving rise to short period oscillations in the surge elevation as shown at this time in Fig. 4c. The magnitude and spatial variability of the storm surge elevation in the eastern Irish Sea is consistent with that found in the high resolution 1 km local area model of JD98 (compare Fig. 5a, with Fig. 14a of JD98).

Current vectors over the whole region (Fig. 6a(i)) show water flowing from the Celtic Sea into the eastern Irish Sea in the region to the south of the isle of Man. In addition some of the water that flows into the Irish Sea continues north along the east coast of Ireland, leaving the region through the North Channel. To the north of the Isle of Man, water leaves the eastern Irish Sea, and flows out through the North Channel. The ability of the finite element model to refine the mesh in regions such as the North Channel, where previous work (Davies et al 2001) required the nesting of a local high resolution model, is a significant advantage over earlier work using regular finite difference grids. In addition refining the mesh within the eastern Irish Sea allows more detail of the flow fields to be observed in the nearshore region (Fig. 6a(ii)). It is evident from Fig. 6a(ii), that there is a significant increase in current intensity in the nearshore region, with currents flowing parallel to the coastal boundary. As shown previously for the case of tidal residuals (Jones and Davies 2007c) coastal irregularities produced by finite difference "stair case" effects can introduce spurious eddies in near coastal regions. Complex spatial variations are evident in the currents close to the entrances to shallow water estuaries as can be seen in expanded plots of the Morecambe Bay (Fig. 6a(iii)) and Liverpool Bay (Fig. 6a(iv)) regions. At the entrance to Morecambe Bay (Fig. 6a(iii)), namely at about 54.05N, -3.1W (close to Heysham) currents change from 2.5 cm $s^{-1}$ to over 12.5 cm $s^{-1}$ over one element. This suggests that to resolve exchange between these estuaries and the outside region, and within the estuaries fine mesh resolutions of the order of 50 m or less are required. A similar complex distribution of currents is evident in the Liverpool Bay area at the entrance to the Mersey estuary. This clearly shows that although storm surge elevations may vary smoothly in space, the currents exhibit significant small scale variability that must be taken into account in any measurement programme.

Although the present model cannot take account of detailed topographic variations in the Mersey estuary, since to be consistent with earlier finite difference work (JD98) the topography in this region is taken from the 1 km grid of JD98, it is evident (Fig. 6a(v)) that there is some spatial variability in the currents within the Mersey. This suggests that to reproduce storm surge events at Liverpool a more accurate description of the Mersey such as that used by Jones and Davies (2006) is required.

In essence the surface elevation and current distributions shown in Figs. 5a and 6a, were produced by south westerly winds. However by 00hr 12/Nov the wind direction changed to one from the northwest. This gave rise to a rapid increase in elevations in the eastern Irish Sea (Fig. 5(b)), although elevations decreased in the Celtic Sea. The alignment and distribution of elevation contours in the deep water regions (Fig. 5b) corresponds very closely with those found in the coarse grid (7 km) model of DJ92 (compare Fig. 5b with Fig. 6b in DJ92). In the eastern Irish Sea, where the mesh is much finer, elevation contours are in good agreement with the high resolution (1 km) model results of JD98 (compare Fig. 5b with Fig. 14b in JD98).

Current vectors at 00 hr 12/Nov, reveal (Fig. 6b(i)) that unlike previously (Fig. 6a(i)) at this time there is an inflow of water into the Irish Sea through the North Channel, driven by the winds from the northwest. Some of this water flows due south in the deep region to the west of the Isle of Man, whilst some water flows into the eastern Irish Sea in the region to the south of the Isle of Man. An outflow from the eastern Irish Sea is evident to the north of the Isle of Man. Associated with this inflow and outflow a current gyre develops in the eastern Irish Sea to the northwest of the Isle of Man (Fig. 6b(ii)). As previously in coastal regions the flows are parallel to the coast, with intensity increasing very rapidly as the water shallows.

In the Morecambe Bay region (Fig. 6b(iii)) there is less spatial variability in the currents than previously (Fig. 6a(iii)) with a flow to the north in the shallow regions, and an elevation gradient forced flow out of the bay in the deeper central channel. Similarly in Liverpool Bay (Fig. 6b(iv)) there is a more spatially coherent directly wind forced flow (Fig. 6b(iv)), although at the entrance to the Mersey and within it the current (Fig. 6b(v)) has similar spatial variability to that found previously (Fig. 6a(v)).

As illustrated at 18hr 11/Nov, although surge elevation contours show a uniform distribution there is significant variability in the currents. This current variability tends to decrease at times of strong wind forcing due to the large scale wind which is spatially coherent, setting the space scale, rather than local elevation gradients in nearshore regions which have a small space scale due to variation in topography. However, as will be shown later, in terms of flow away from coastal effects, where elevation gradients are more uniform, the large scale pressure gradient forced flow is often spatially uniform.

By 06hr 12/Nov the wind's magnitude has decreased, although surge elevations in the eastern Irish Sea remain significant (of order 30 cm) (Fig. 5c). The presence of an appreciable west-east elevation gradient across the Irish Sea, comparable to that found in JD98 (compare Fig. 5c and Fig. 14c in JD98), and between the Irish Sea and the region beyond (compare Fig. 5c with Fig. 6c in DJ92), drives water out of the eastern Irish Sea, both to the north and south of the Isle of Man (Fig. 6c(i)). In addition in the north there is a net outflow from the Irish Sea, both through the North Channel and along the west coast of Scotland. A similar net outflow is evident in the south where water flows from the Irish Sea to the Celtic Sea. At this time the wind field over the region is negligible, and hence the storm surge elevation gradient that has developed over the region cannot be supported and forces flow out of the eastern Irish Sea. It is evident from Figs. 6c(i) and 6c(ii) that away from coastal boundary regions the spatial variability of this elevation pressure driven flow is appreciably less than that found at times of wind forcing. However in some regions, notably off the northeast corner of the Isle of Man there is a bifurcation in the flow with some flow going to the north and another flow to the south, which leads to local small scale variability. Similarly in shallow coastal regions such as Morecambe Bay (expanded plot not shown) and the entrance to the Mersey in Liverpool Bay (expanded plot not shown) there is some local small scale variability. In particular in both these regions current vectors show a strong offshore and out of estuary flow in the deeper water. Within the Mersey (expanded plot not shown) there is a near uniform outflow as sea surface elevations within the estuary decrease.

Calculations showed that as the depression that produced the surge of 00hr 12/Nov, moved out of the region, surge elevations decreased to near zero. However at 12hr 13/Nov, winds from the northwest moved over the region, and their intensity increased and their direction changed to winds from the north over the following 18 hrs.

By 12hr 14/Nov these winds had produced a decrease in elevation to the south of Ireland (Fig. 5d) with an increase in elevation to the north of Ireland and along the west coast of Scotland (Fig. 5d). The magnitude and spatial distribution of elevation contours associated with this wind event, computed with the finite element model over the west coast region (Fig. 5d) correspond very closely with those computed with the coarser mesh 7 km finite difference grid of DJ92 (compare Fig. 5d with Fig. 6d of DJ92). Similarly in the near coastal region of the eastern Irish Sea the computed surge elevation is in good agreement with that computed by JD98 using a limited area high resolution (1 km) model (compare Fig. 5d with Fig. 14d of JD98).

As surface wind stresses over the region decreased and changed to a wind stress from the north, the elevation gradient to the north of the North Channel could not be maintained and water flowed from the west coast of Scotland region, through the North Channel and into the Irish Sea (Fig. 6d(i)). A significant proportion of this water flows south in the deep channel to the west of the Isle of Man, with some water entering the eastern Irish Sea (Fig. 6d(i)). Within the eastern Irish Sea, as previously, away from the coastal boundary layer the flow field is fairly spatially uniform, although it changes rapidly in the region of estuaries (Fig. 6d(ii)). Within estuaries, see for example Morecambe Bay there is appreciable small scale variability in the currents (expanded plot not shown), associated with changes in topography. Similarly at the entrance to the Mersey (expanded plot not shown) and within the Mersey (expanded plot not shown) there is some spatial variability. However, since the wind field at 12hr 14/Nov has declined from its previous maximum value of 1 Pa (see JD98, for details of wind stress), and the flow is mainly surface elevation gradient forced into the Mersey from Liverpool Bay the distribution of current vectors in the Mersey is substantially smoother than that found previously.

The change in wind direction and increase in magnitude between 12h and 18h 14/Nov gives rise to a positive surge in the eastern Irish Sea at 18hr 14/Nov (Fig. 5e). However the winds from the north, namely offshore winds in the region to the south of Ireland produce a negative surge of about 50 cm to the south of Ireland (Fig. 5e). The location and magnitude of this negative surge and the distribution of elevation contours in the Celtic and Irish Sea (Fig. 5e) is in close agreement with that computed in DJ92 with the 7 km finite difference grid (compare Fig. 5e, with Fig. 6e in DJ92). Similarly in the eastern Irish Sea the rapid increase in surge elevation as the coast is approached and the subsequent decrease within the estuaries corresponds to that computed by JD98 using the fine grid model of the region (compare Fig. 5e, with Fig. 14e in JD98).

The influence of the strong wind from the north at this time (18h 14/Nov) is to force water from the west of Scotland, through the North Channel and into the Irish Sea (Fig.

6e(i)). Within the Irish Sea, there is a flow to the south in the deep channel (Fig. 1) to the west of the Isle of Man, that enters the Celtic Sea (Fig. 6e(i)). Some of the water flowing through the Irish Sea, enters the eastern Irish Sea along the northern and southern coastal regions of the Isle of Man (Fig. 6e(i)). Within the eastern Irish Sea there is significant spatial variability in the currents (Fig. 6e(ii)), produced by a combination of local sea level rise along the coast, which in Liverpool Bay produces an offshore flow, and wind forced flow from the Irish Sea entering the region. In addition directly wind forced currents within the eastern Irish Sea contributed to this spatial variability. The net effect of this combined forcing is to produce a large current gyre to the east of the Isle of Man, and a number of near shore gyres (Fig. 6e(ii)). Within Morecambe Bay (expanded plot not shown) there is significant spatial variability in both current magnitude and direction due to variations in topography and the interplay between local elevation gradient forced flow and that due to direct wind forcing.

Similarly in Liverpool Bay (expanded plot not shown) away from the nearshore region there is a uniform offshore flow, however in the nearshore region a detailed examination shows that the currents exhibit significant spatial variability. Nevertheless within the Mersey estuary a more uniform distribution of currents is evident. The uniform flow in the Mersey found in the present calculations primarily arises from a lack of resolution in this region. This is due to the fact that in order to compare surge solutions derived with the finite element model with those computed by JD98, identical topography was used within the Mersey. As shown by Jones and Davies (2006) for the case of the response of the Mersey to uniform wind forcing, when more detailed and accurate topography together with element sizes of order 50 m are used in the Mersey then a more complex spatial pattern arises. However the whole region surge plots clearly show that there was significant spatial and temporal variability in both the surge elevations and currents during the November 1977 storm surge event. This variability arises from time and space variations in the meteorology and the significant changes in water depth over the region. The existence of an accurate meteorological data set for model forcing and coastal gauges for comparison makes it an ideal period for testing models, and inter-comparing their performance.

Comparison with a previous coarse grid large area model (DJ92) and a high resolution limited area Eastern Irish Sea model (JD98), showed that the finite element model with its graded mesh could reproduce the large scale variability of the surge over the region. In addition its finer mesh in the eastern Irish Sea could resolve the small scale variability of the surge in this region.

## CONCLUDING REMARKS

An unstructured mesh finite element model of the sea region off the west coast of Britain has been used to model the storm surge event of November 1977. This period was chosen because an accurate meteorological data set was available to drive the model and coastal gauge data could be used to validate the model. In addition the solution from a large area coarse grid (7 km) finite difference model covering an identical region, and a limited area (eastern Irish Sea) high (1 km) model was available for comparison. By covering the same area as the coarse grid model and using identical water depth distributions to those used in the coarse and high resolution limited area model, a valid comparison with earlier finite difference solutions could be made, since all models used the same forcing.

Calculations showed that the external component of the surge was significant at all locations, although in the eastern Irish Sea, wind forcing, namely the internal surge was a major contributor. Consequently in any storm surge simulation, the model had to accurately propagate the surge into the eastern Irish Sea and account for wind forcing in the region, and local changes in topography. The finite element model with its ability to vary the mesh could accurately resolve narrow channels such as the North Channel (Figs. 1 and 3) where previously nested high resolution models had been used (Davies et al 2001) and the nearshore region of the eastern Irish Sea. This area had previously been modelled with a limited area high resolution (1 km) model (JD98).

Time series of the storm surge elevations at ports in the eastern Irish Sea, showed that the finite element model with its fine mesh in this region could reproduce surge elevations with comparable accuracy to the 1 km model of JD98. Similarly surface elevation contours both within the eastern Irish Sea and the region beyond where the mesh was much coarser could be reproduced by the model and were in close agreement with those computed in DJ92 and JD98. By using the same region, open boundary and meteorological forcing together with identical water depths showed that the solution was independent of the numerical method used to derive it (namely finite difference or finite element). In addition the close agreement in the solutions showed that the finite element model with its irregular mesh, could accurately reproduce the storm surge propagation through the region and account for local changes due to wind forcing and nearshore fine scale topography.

Although the use of identical topography enabled a valid model inter-comparison to be made, the use of a coarse representation of the nearshore region of Liverpool Bay and the Mersey as in JD98, meant that the storm surge was not accurately resolved in this region. The importance of high resolution in the Mersey in resolving details of the wind induced flow in this area has recently been reported by Jones and Davies (2006) for the case of uniform steady wind forcing. This suggests that in any future calculations of storm forced flow in the Liverpool Bay and Mersey estuary, an enhanced mesh refinement in this region as in Jones and Davies (2006) is required. This effect of such a mesh enhancement on storm surges is currently being investigated.

Certainly the ability of the finite element model to refine the mesh in regions of rapidly changing topography where high resolution and accuracy is required (e.g. the nearshore region or within an estuary) is a major advantage over the nested finite difference approach used previously (JD98, Davies et al 2001). As shown here, at the entrance to many estuaries, there is significant spatial variability in the flow, suggesting that nesting a fine mesh finite difference model of an estuary within a larger model would be very difficult. As shown by Davies and Hall (2002), nesting a local area model within a coarser model in regions of rapidly varying flow can significantly influence and sometimes reverse the flow in the limited area model.

These calculations suggest that the use of an unstructured mesh model with a progressively finer grid in the nearshore region should improve storm surge prediction, provided detailed and accurate bottom topography is available in these areas. However, as the mesh is refined, other processes such as wave-current interaction (Davies and Lawrence 1995, Jones and Davies 2001) and the three dimensional nature of the flow become important (JD98) and may need to be considered, in order to significantly improve storm surge prediction in an irregular mesh model.

ACKNOWLEDGEMENTS

The origin of the TELEMAC system is EDF-LNHE and is therefore ©EDF-LNHE. The authors are indebted to R.A. Smith for help in preparing diagrams and L. Parry for typing the paper.

REFERENCES


Davies, A.M. and Flather, R.A. (1977) Computation of the storm surge of 1-6 April 1973 using numerical models of the northwest European continental shelf and North Sea. Deutsche Hydrographische Zeitschrift, 30, 139-162

Davies, A.M. and Lawrence, J. (1995) Modelling the effect of wave-current interaction on the three-dimensional wind driven circulation of the eastern Irish Sea. Journal of Physical Oceanography, 25, 29-45.

Davies, A.M. and Jones, J.E. (1992a) A three-dimensional wind driven circulation model of the Celtic and Irish Seas. Continental Shelf Research, 12, 159-188.

Davies, A.M. and Jones, J.E. (1992b) A three dimensional model of the $M_2$, $S_2$, $N_2$, $K_1$ and $O_1$ tides in the Celtic and Irish Sea. Progress in Oceanography, 29, 197-234.

Davies, A.M. and Jones, J.E. (1996) Sensitivity of tidal bed stress distributions, near bed currents, overtides and tidal residuals to frictional effects in the eastern Irish Sea. Journal of Physical oceanography, 26, 2553-2575.

Davies, A.M., Kwong, S.C.M. and Flather, R.A. (1998) A three-dimensional model of wind-driven circulation on the shelf: Application to the storm of January 1993. Continental Shelf Research, 18, 289-340.

Davies, A.M., Kwong, S.C.M. and Flather, R.A. (2000) On determining the role of wind wave turbulence and grid resolution upon computed storm driven currents. Continental Shelf Research, 20, 1825-1888.

Davies, A.M., Hall, P., Howarth, M.J., Knight, P. and Player, R. (2001) A detailed comparison of measured and modeled wind driven currents in the North Channel of the Irish Sea. J. Geophys. Res., 106, 19,683-19,713.

Davies, A.M. and Hall,P. (2002) Numerical problems associated with coupling models in shelf edge regions. Applied Mathematical Modelling, 26, 807-831.

Fernandes, E.H.L., Dyer, K.R., Moller, O.O. and Niencheski, L.F.H. (2002) The Patos lagoon hydrodynamics during an El Nino event (1998). Continental Shelf Research, 22, 1699-1713.

Fernandes, E.H.L., Marino-Tapia, I. Dyer, K.R. and Moller, O.O. (2004) The attenuation of tidal and subtidal oscillations in the Patos Lagoon estuary. Ocean Dynamics, 54, 348-359.

Greenberg, D.A., Dupont, F., Lyard, F.H., Lynch, D.R. and Werner, F.E. (2007) Resolution issues in numerical models of oceanic and coastal circulation. Continental Shelf Research, 27, 1317-1343.

Hagen, S., Westerink, J., Kolar, R., Horstmann, O. (2001) Two dimensional unstructured mesh generation for tidal models. International Journal for Numerical Methods in Fluids, 35, 669-686.

Hagen, S.C., Horstmann, O., Bennett, R.J. (2002) An unstructured mesh generation algorithm for shallow water modeling. International Journal of Computational Fluid Dynamics, 16(2), 83-91.

Ip, J.T.C., Lynch, D.R. and Friedrichs, C.T. (1998) Simulation of estuarine flooding and dewatering with application to Great Bay, New Hampshire. Estuarine Coastal and Shelf Science, 47, 119-141.

Jones, J.E. (2002) Coastal and shelf-sea modelling in the European context. Oceanography and Marine Biology: an Annual Review, 40, 37-141.

Jones, J E and Davies, A M (1996) A high resolution three dimensional model of the $M_2$, $M_4$, $M_6$, $S_2$, $N_2$, $K_1$, and $O_1$ tides in the eastern Irish Sea. Estuarine Coastal and Shelf Science 42, 311-346.

Jones, J.E. and Davies, A.M. (1998) Storm surge computations for the Irish Sea using a three-dimensional numerical model including wave-current interaction. Continental Shelf Research, 18, 201-251.

Jones, J.E. and Davies, A.M. (2001) Influence of wave-current interaction and high frequency forcing upon storm induced currents and elevations. Estuarine Coastal and Shelf Science, 53, 397-414.

Jones, J.E. and Davies, A.M. (2003a) Processes influencing storm-induced currents in the Irish Sea. Journal of Physical Oceanography, 33, 88-104.

Jones, J.E. and Davies, A.M. (2003b) On combining current observations and models to investigate the wind induced circulation of the eastern Irish Sea. Continental Shelf Research, 23, 415-434.

Jones, J.E. and Davies, A.M. (2005) An intercomparison between finite difference and finite element (TELEMAC) approaches to modelling west coast of Britain tides. Ocean Dynamics, 55, 178-198.

Jones, J.E. and Davies, A.M. (2006) Application of a finite element model (TELEMAC) to computing the wind induced response of the Irish Sea. Continental Shelf Research, 26, 1519-1541.

Jones, J.E. and Davies, A.M. (2007a). A high resolution finite element model of the $M_2$, $M_4$, $M_6$, $S_2$, $N_2$, $K_1$ and $O_1$ tides off the west coast of Britain. Ocean Modelling, 19, 70-100.

Jones, J.E. and Davies, A.M. (2007b) On the sensitivity of computed higher tidal harmonics to mesh size in a finite element model. Continental Shelf Research, 27, 1908-1927.

Jones, J.E. and Davies, A.M. (2007c) On the sensitivity of tidal residuals off the west coast of Britain to mesh resolution. Continental Shelf Research, 27, 64-81.

Jones, J.E. and Davies, A.M. (2008) On the modification of tides in shallow water regions by wind effects. Journal of Geophysical Research (in press)

Legrand, S. Deleersnijder, E., Hanert, E., Legat, V. and Wolanski, E. (2006) High-resolution, unstructured meshes for hydrodynamic models of the Great Barrier Reef, Australia. Estuarine, Coastal and Shelf Science, 68, 36-46.

Legrand, S. Deleersnijder, E., Delhez, E. and Legat, V. (2007) Unstructured, anisotropic mesh generation for the Northwestern European continental shelf, the continental slope and the neighbouring ocean. Continental Shelf Research, 27, 1344-1356.

Levasseur, A., Shi, L., Wells, N.C., Purdie, D.A. and Kelly-Gerreyn, B.A. (2007) A three-dimensional hydrodynamic model of estuarine circulation with an application to Southampton Water, U.K. Estuarine Coastal and Shelf Science, 73, 753-767.

Nicolle, A. and Karputchev, M. (2007) Evidence for spatially variable friction from tidal amplification and asymmetry in a shallow semi-diurnal embayment: the Pertuis Breton Bay of Biscay, France. Continental Shelf Research, 27, 2346-2356.

Walters, R.A. (2005) Coastal ocean models: two useful finite element methods. Continental Shelf Research, 25, 775-793.

Werner, F.E. (1995) A field test case for tidally forced flows: a review of the tidal flow forum pg. 269-284 in Quantitative Skill Assessment for Coastal Ocean Models, ed. D.R. Lynch and A.M. Davies, published American Geophysical Union.

FIGURE CAPTIONS

Fig. 1: Water depths in the region covered by the model and places named in the text.

Fig. 2: Detailed topography of the eastern Irish Sea and location of tide gauges.

Fig. 3: Finite element grid used in the calculations.

Fig. 4: Time series of computed surge at a number of eastern Irish Sea locations computed with (a) "external" surge introduced through the open boundary, (b) "internal" surge due to local meteorological forcing and (c) the "total" surge.

Fig. 5: Elevation contours over the whole region at (a) 18hr 11/Nov, (b) 00hr 12/Nov, (c) 06hrs 12/Nov, (d) 12hrs 14/Nov and (e) 18hr 14/Nov.

Fig. 6a: Current vectors at 18hrs 11/Nov over (i) whole region, (ii) expanded plot in eastern Irish Sea, (iii) expanded plot in Morecambe Bay, (iv) expanded plot in Liverpool Bay, (v) expanded plot in Mersey estuary.

Fig. 6b: As Fig. 6a, but at 00hr 12/Nov.

Fig. 6c: As Fig. 6a, but omitting expanded plots (iii), (iv) and (v) at 06hr 12/Nov.

Fig. 6d: As Fig. 6a, but omitting expanded plots (iii), (iv) and (v) at 12hr 14/Nov.

Fig. 6e: As Fig. 6a, but omitting expanded plots (iii), (iv) and (v) at 18hr 14/Nov.

Table 1: Root mean square errors (cm) from the finite difference model (FD calc) (Jones and Davies (2001)) and finite element model (FE calc) at Liverpool and Douglas

| | | Period | | | |
|---|---|---|---|---|---|
| Calc | Port | 1 | 2 | 3 | Total |
| FD | Liverpool | 17.0 | 19.1 | 22.7 | 22.9 |
| | Douglas | 10.6 | 11.3 | 10.6 | 10.3 |
| FE | Liverpool | 21.5 | 23.2 | 28.9 | 27.7 |
| | Douglas | 10.0 | 11.8 | 11.2 | 11.0 |

FIG 1:

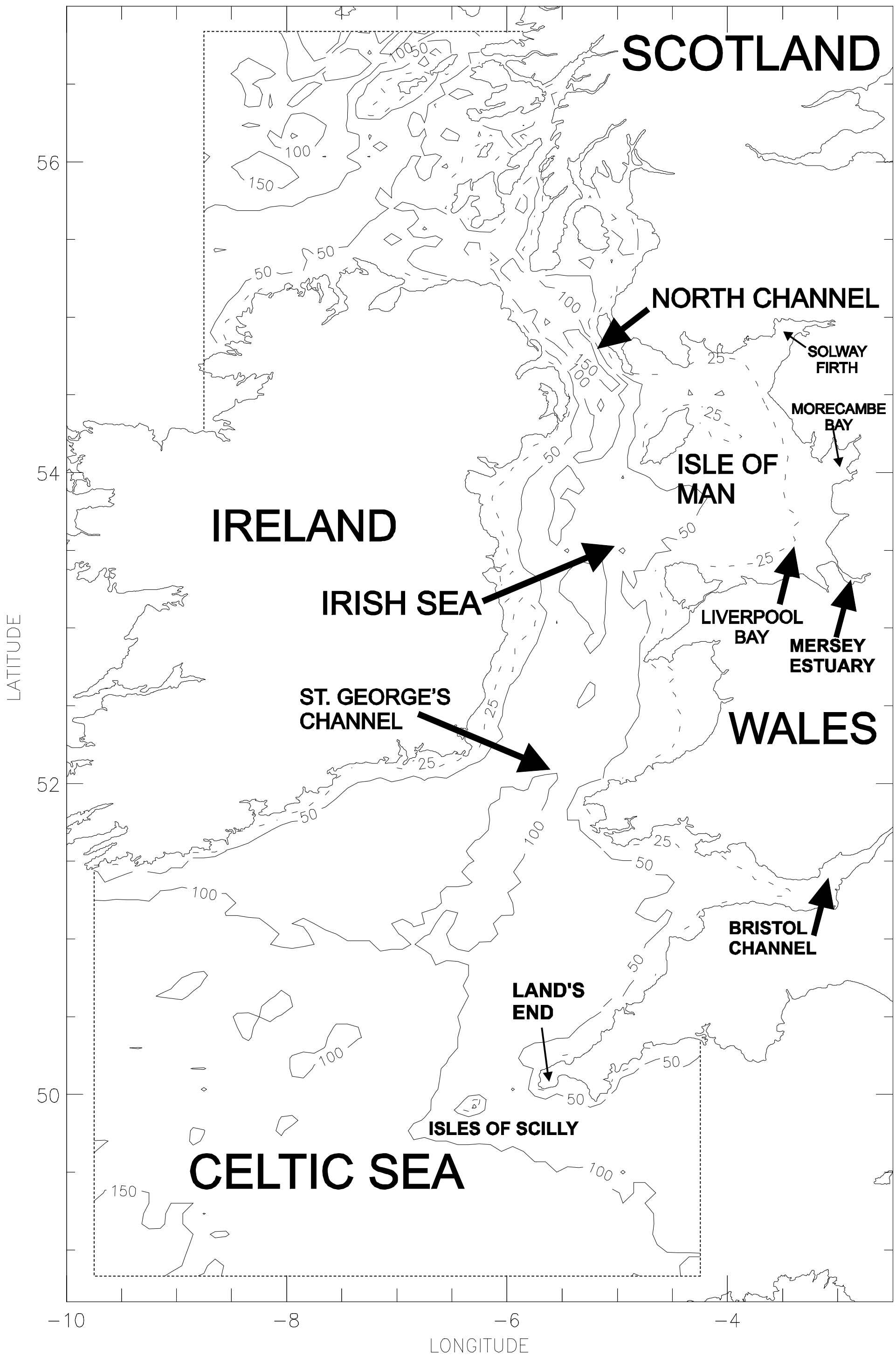

SCOTLAND
NORTH CHANNEL
SOLWAY FIRTH
MORECAMBE BAY
ISLE OF MAN
IRELAND
IRISH SEA
LIVERPOOL BAY
MERSEY ESTUARY
ST. GEORGE'S CHANNEL
WALES
BRISTOL CHANNEL
LAND'S END
ISLES OF SCILLY
CELTIC SEA
LATITUDE
LONGITUDE
56
54
52
50
−10
−8
−6
−4

FIG 2:

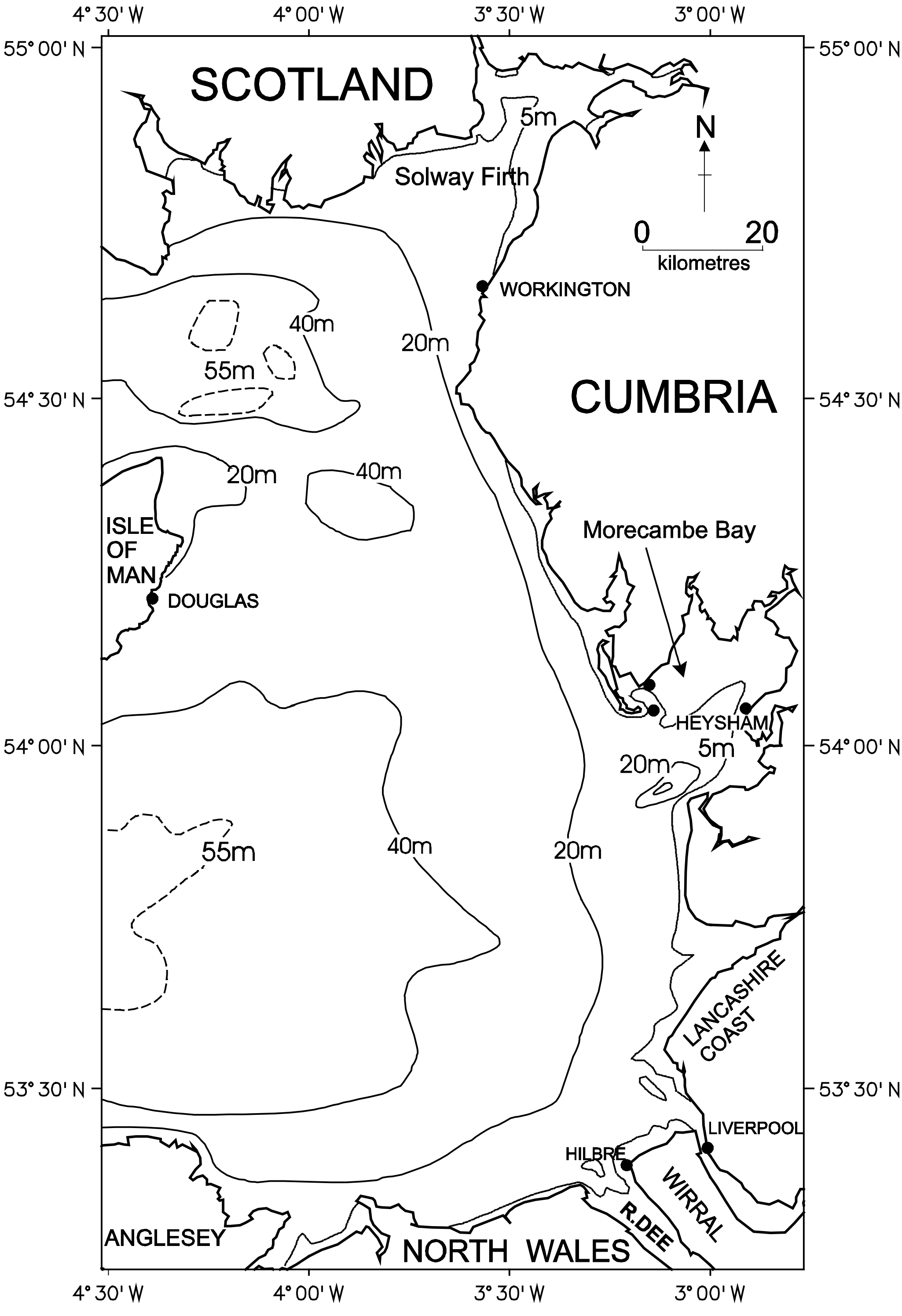

4° 30' W
4° 00' W
3° 30' W
3° 00' W
55° 00' N
54° 30' N
54° 00' N
53° 30' N
SCOTLAND
Solway Firth
5m
N
0
20
kilometres
WORKINGTON
40m
20m
55m
CUMBRIA
20m
40m
ISLE
OF
MAN
DOUGLAS
Morecambe Bay
HEYSHAM
5m
20m
55m
40m
20m
LANCASHIRE
COAST
LIVERPOOL
HILBRE
WIRRAL
R.DEE
ANGLESEY
NORTH WALES

FIG 3:

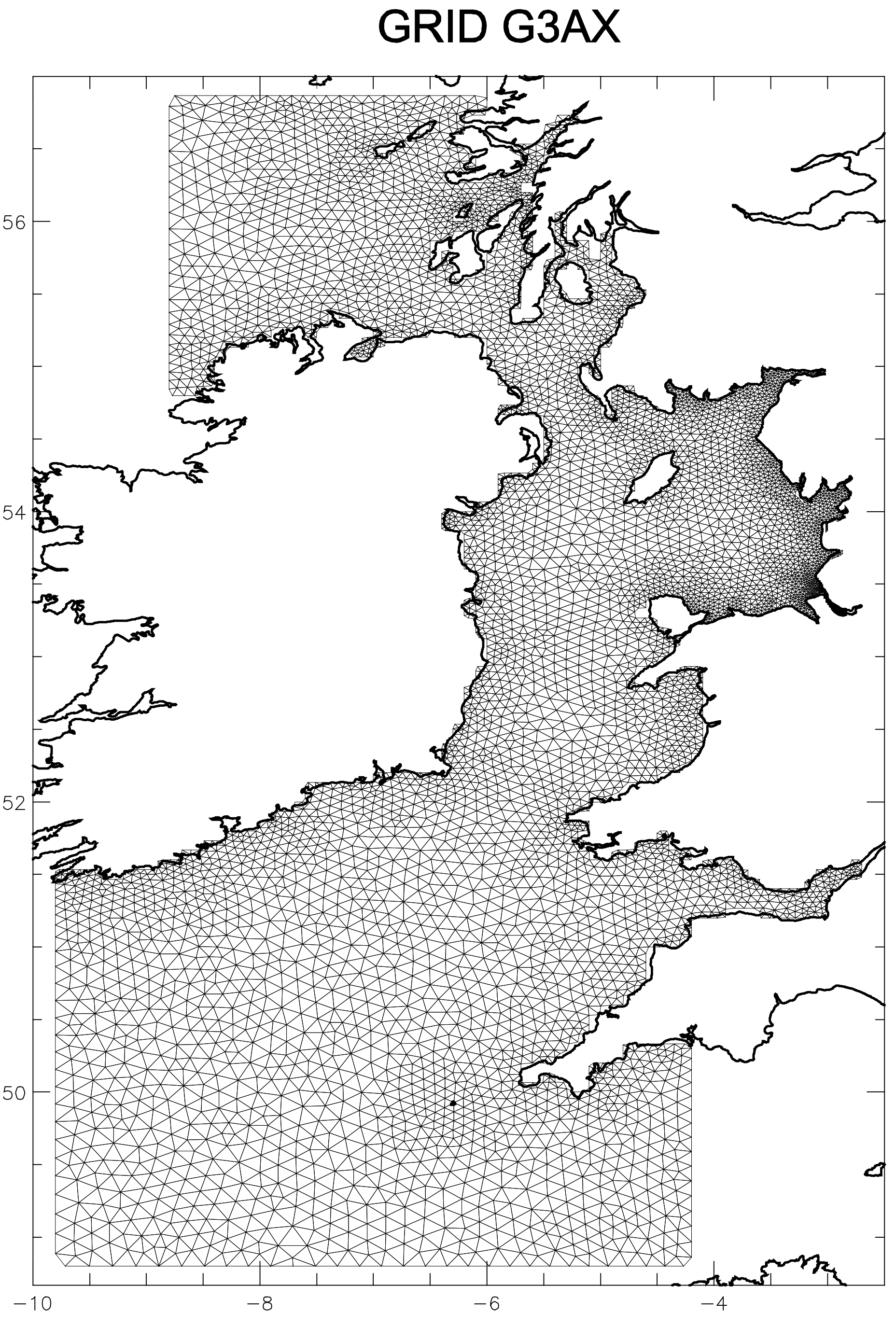


FIG 4a:

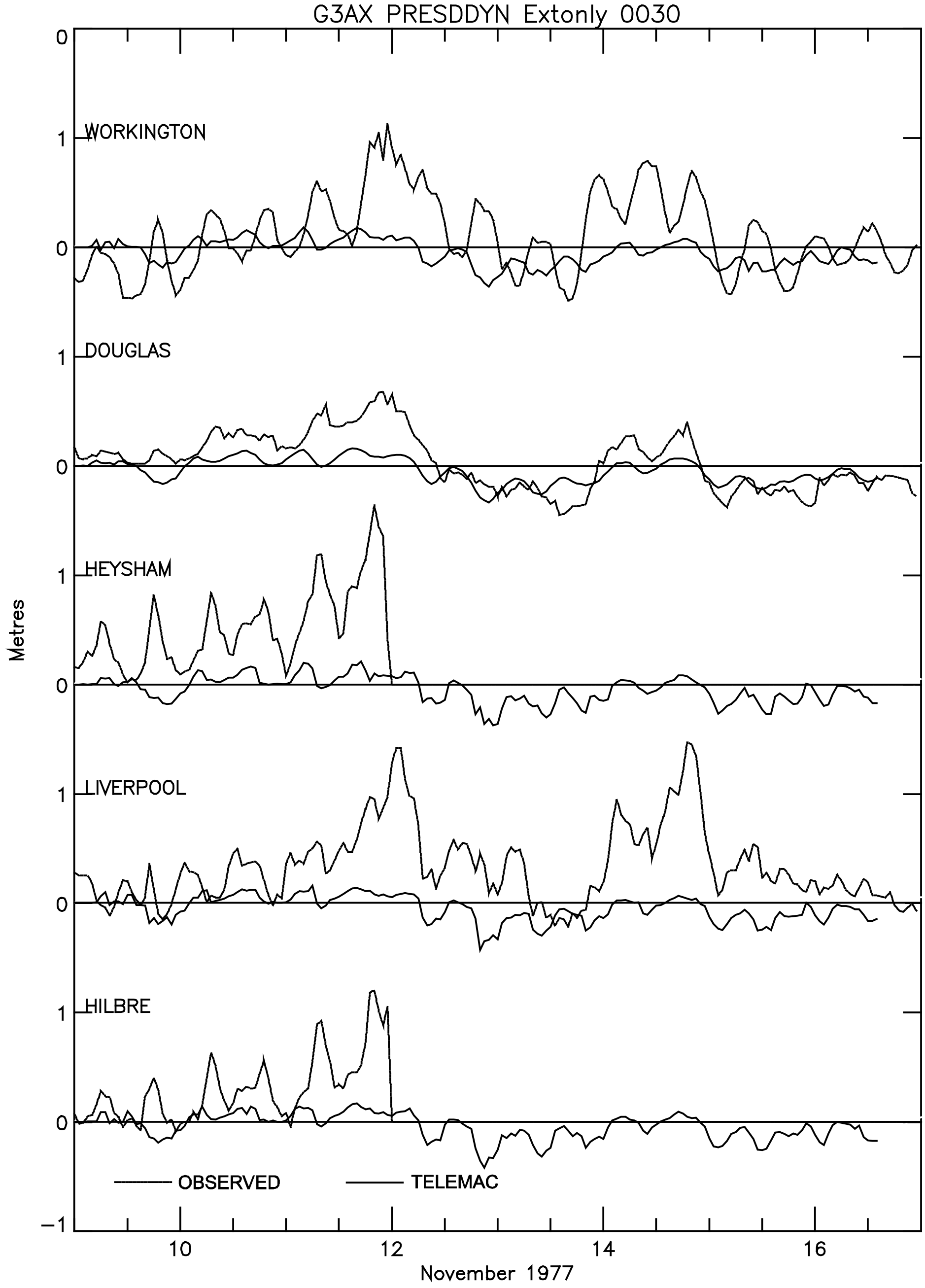
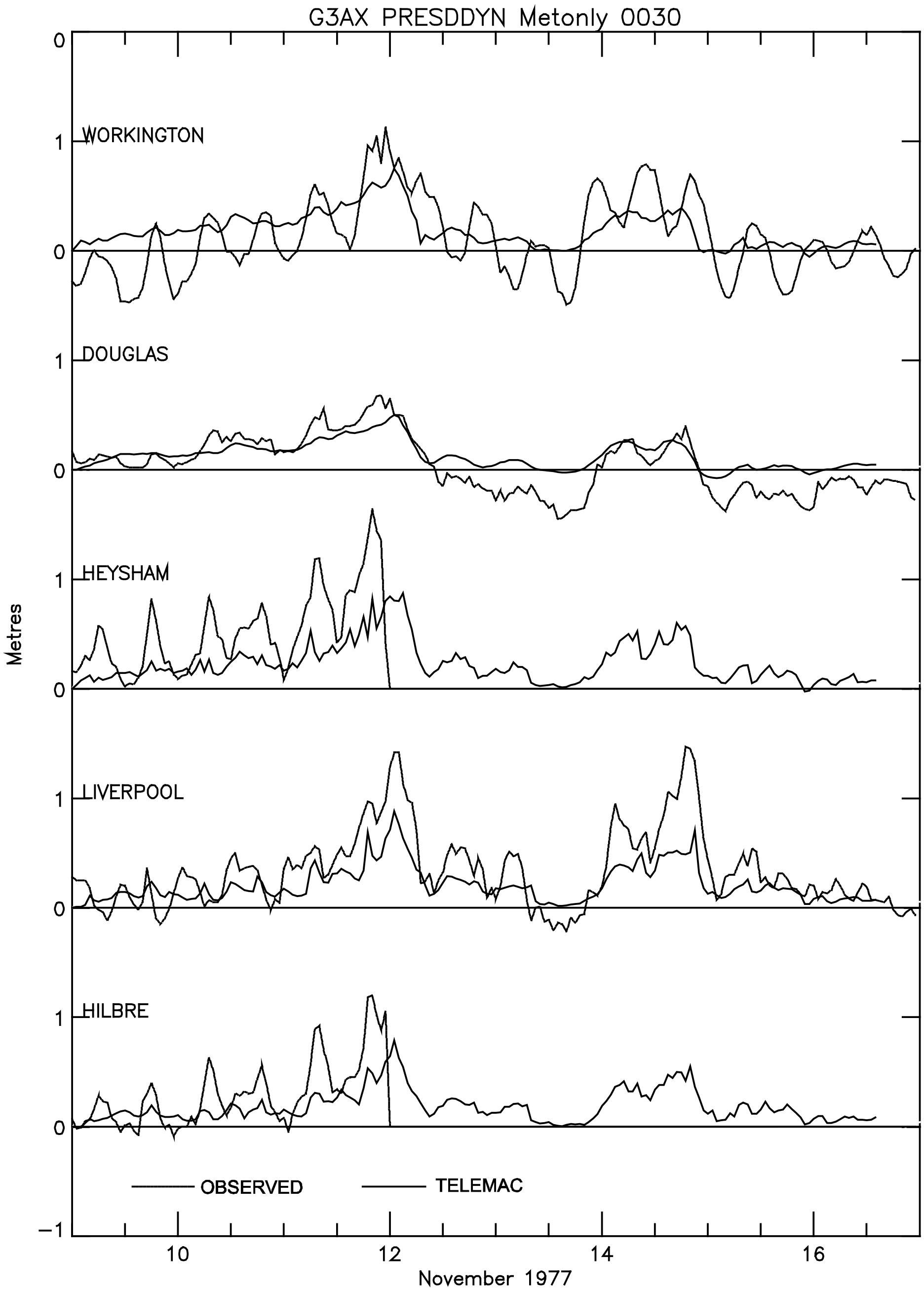
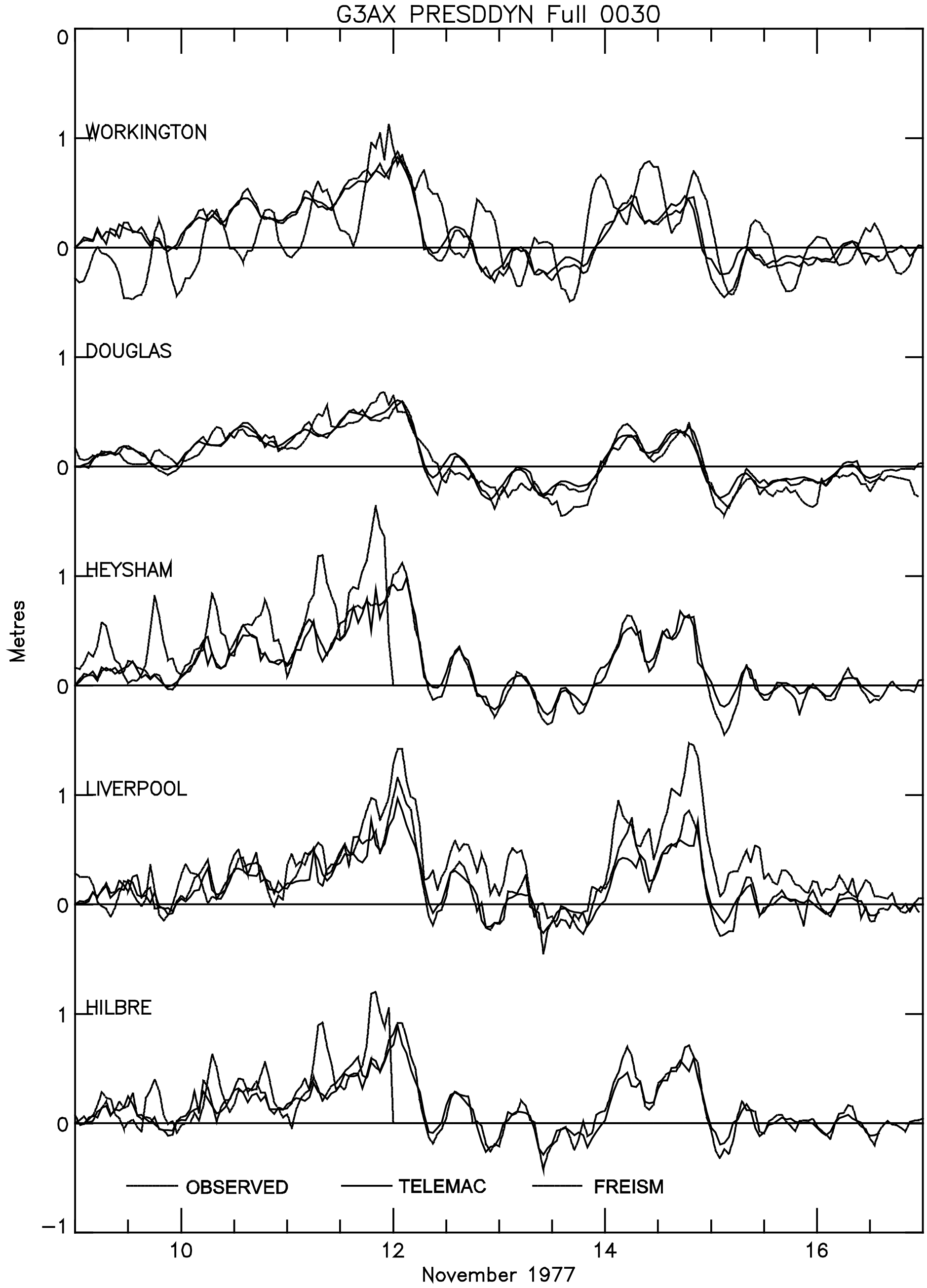

G3AX PRESDDYN Extonly 0030
WORKINGTON
DOUGLAS
HEYSHAM
LIVERPOOL
HILBRE
Metres
OBSERVED
TELEMAC
0
1
0
1
0
1
0
1
0
1
0
−1
10
12
14
16
November 1977

FIG 4b:



G3AX PRESDDYN Metonly 0030
WORKINGTON
DOUGLAS
HEYSHAM
LIVERPOOL
HILBRE
OBSERVED
TELEMAC
Metres
0
1
−1
10
12
14
16
November 1977

FIG 4c:



G3AX PRESDDYN Full 0030
WORKINGTON
DOUGLAS
HEYSHAM
LIVERPOOL
HILBRE
Metres
0
1
−1
OBSERVED
TELEMAC
FREISM
10
12
14
16
November 1977

FIG 5a:

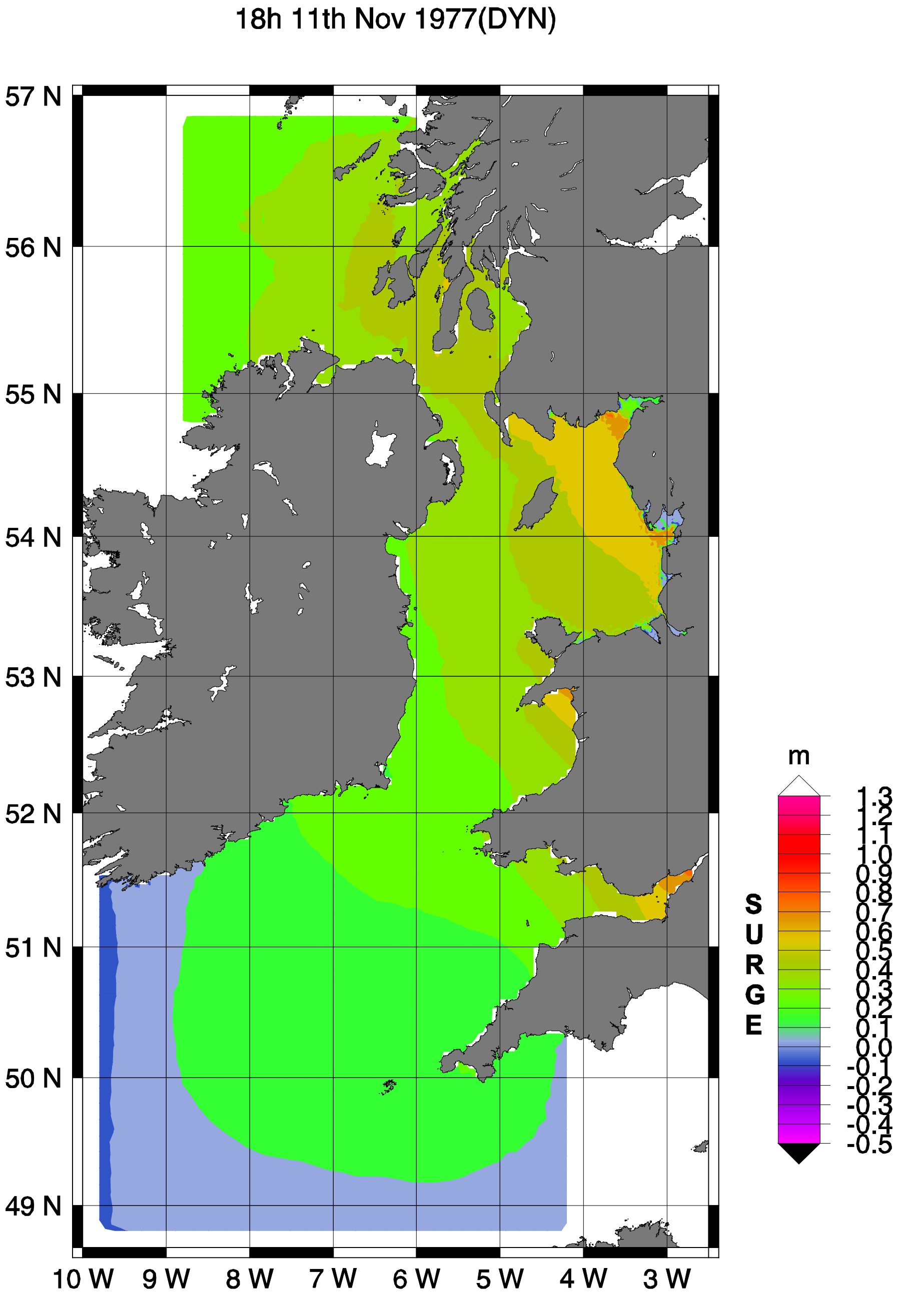

18h 11th Nov 1977(DYN)
57 N
56 N
55 N
54 N
53 N
52 N
51 N
50 N
49 N
10 W
9 W
8 W
7 W
6 W
5 W
4 W
3 W
m
SURGE
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5

FIG 5b:

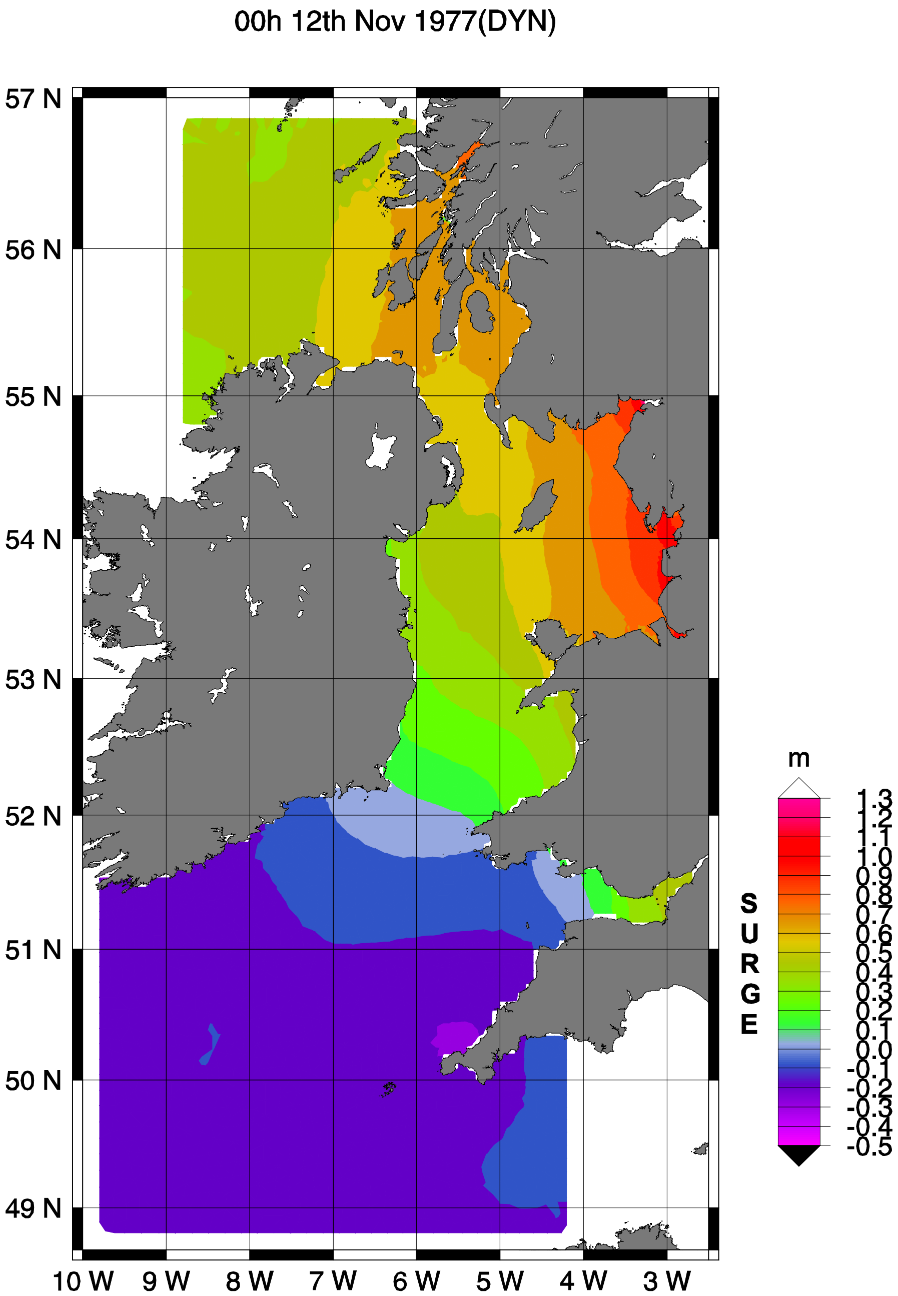

00h 12th Nov 1977(DYN)
57 N
56 N
55 N
54 N
53 N
52 N
51 N
50 N
49 N
10 W
9 W
8 W
7 W
6 W
5 W
4 W
3 W
m
SURGE
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5

FIG 5c:

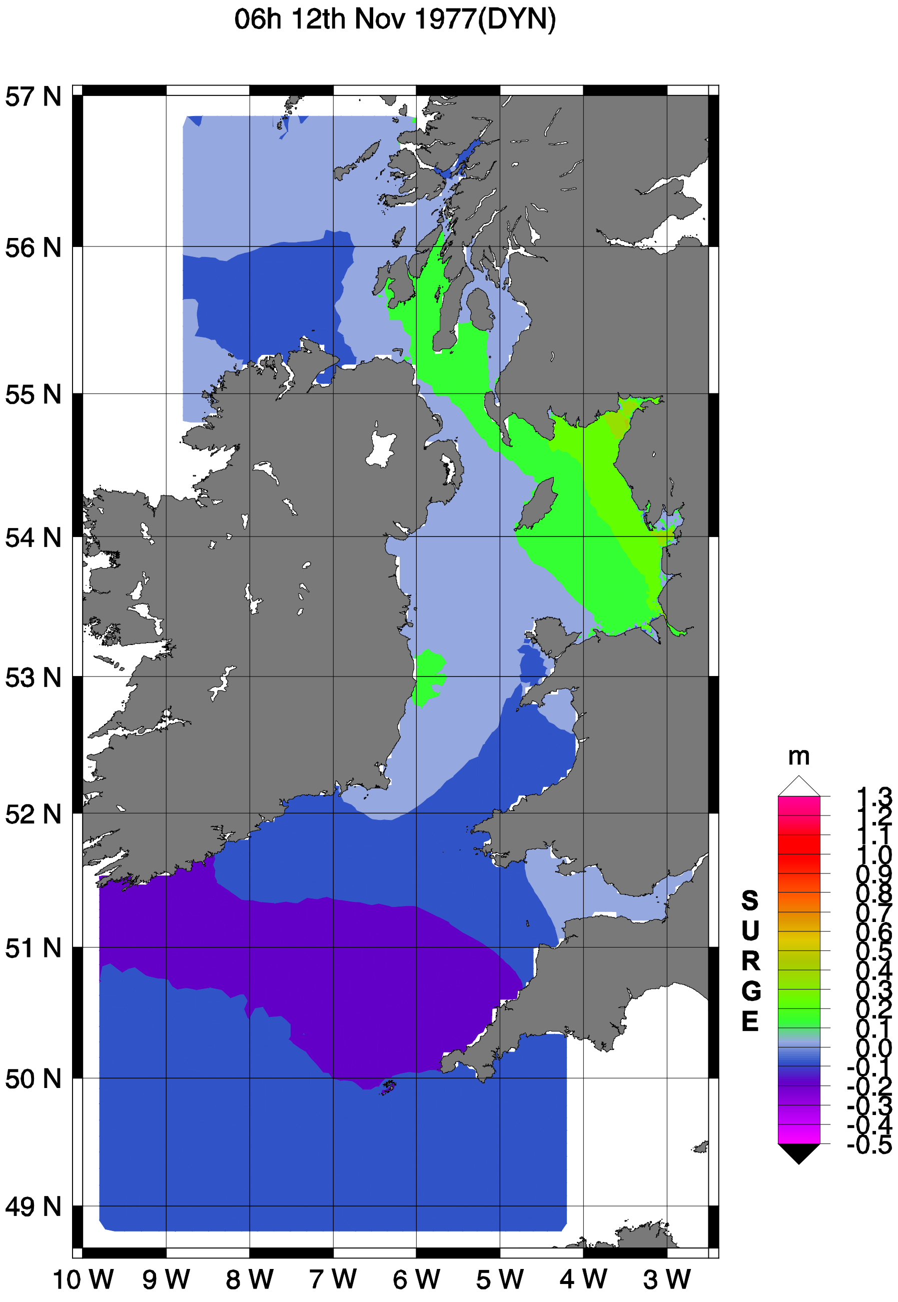

06h 12th Nov 1977(DYN)
57 N
56 N
55 N
54 N
53 N
52 N
51 N
50 N
49 N
10 W
9 W
8 W
7 W
6 W
5 W
4 W
3 W
m
SURGE
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5

FIG 5d:

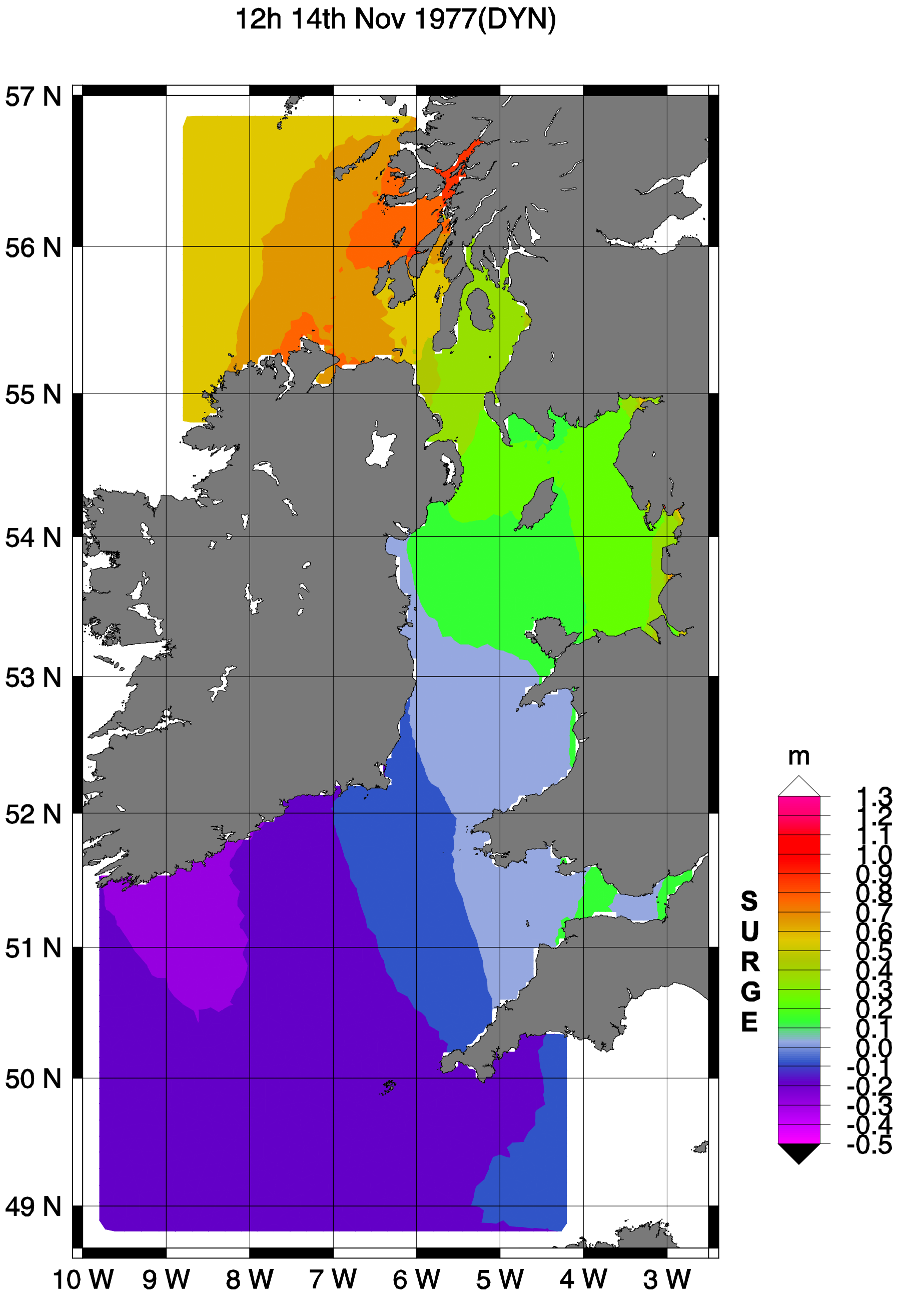
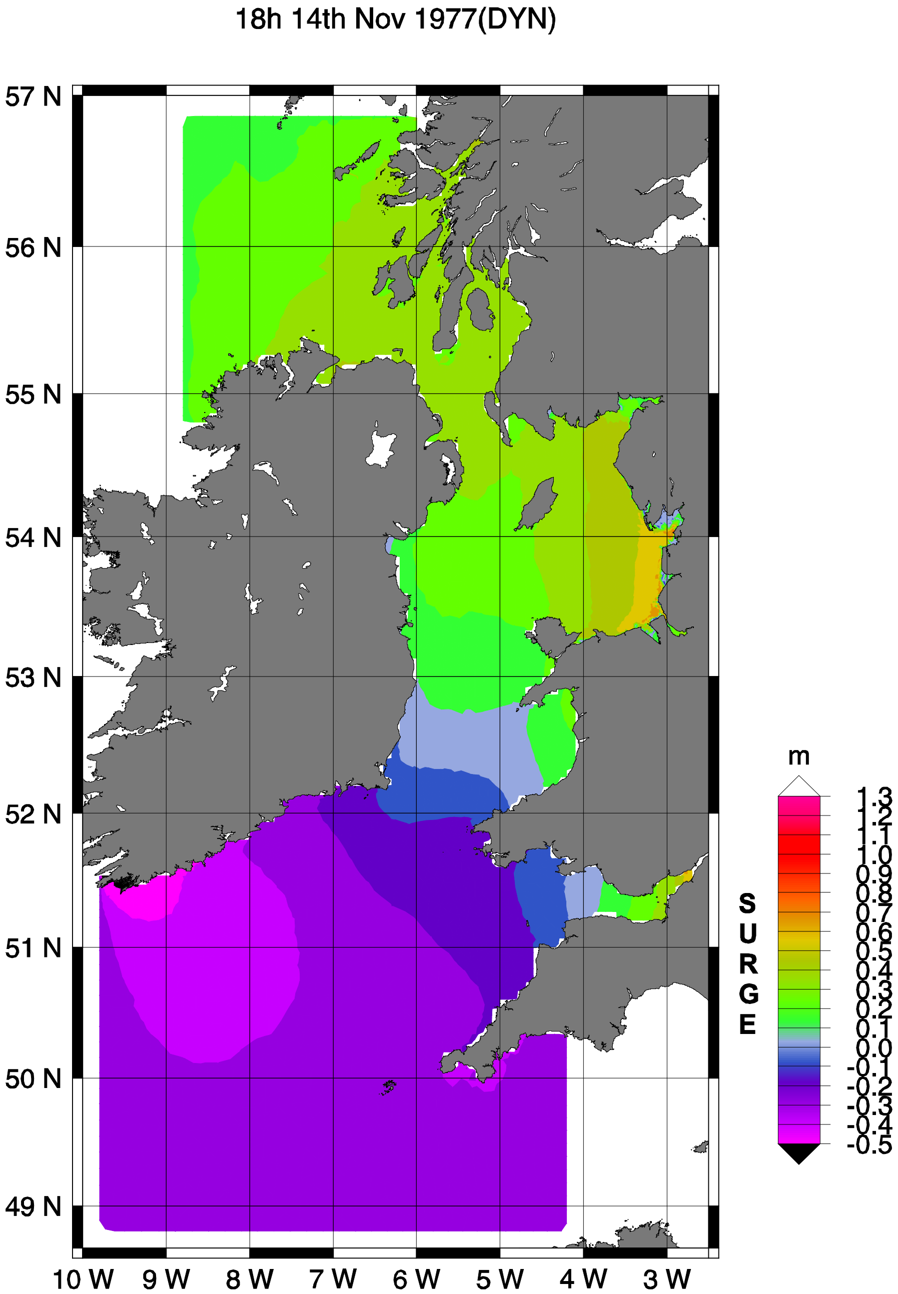
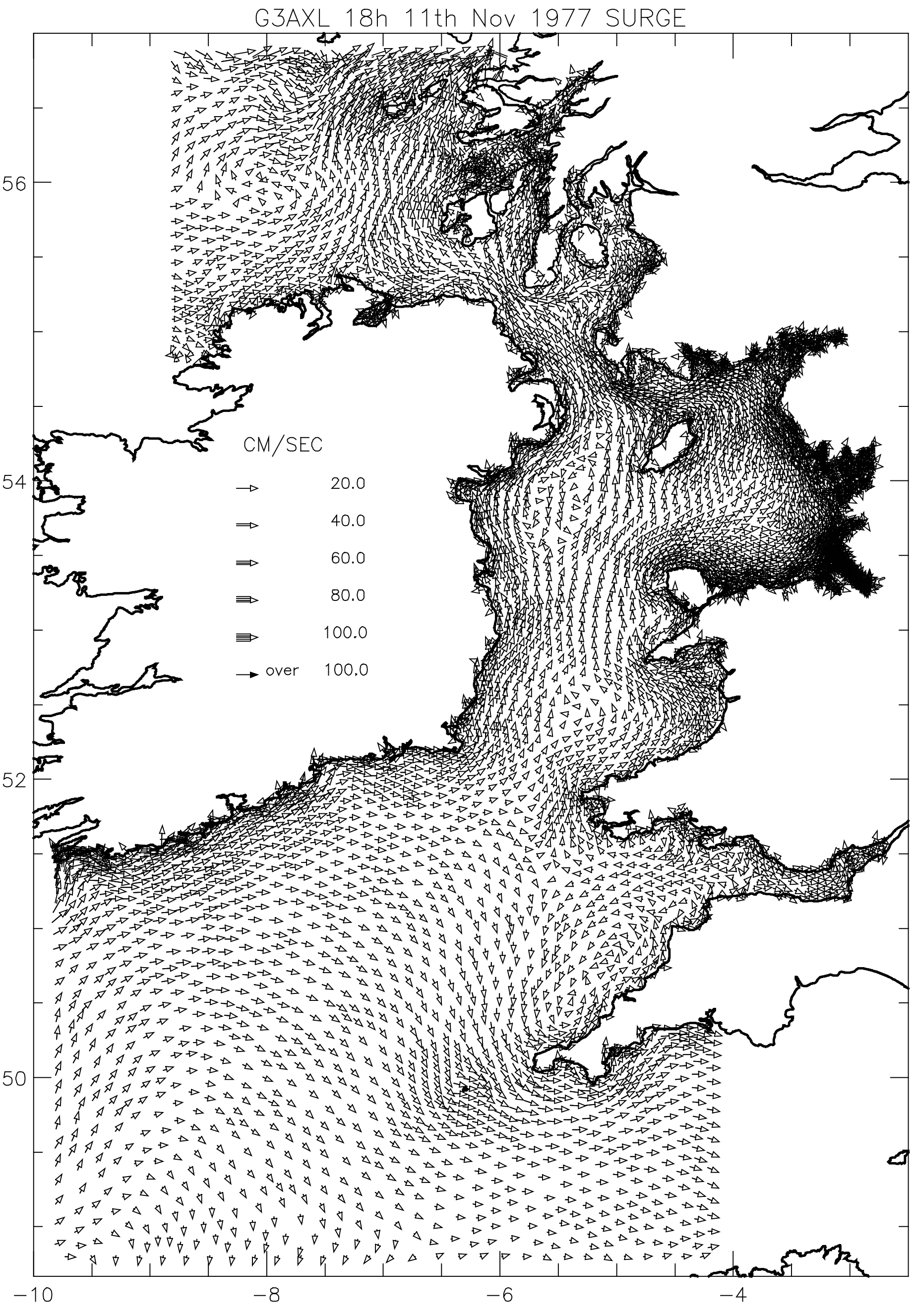

12h 14th Nov 1977(DYN)
57 N
56 N
55 N
54 N
53 N
52 N
51 N
50 N
49 N
10 W
9 W
8 W
7 W
6 W
5 W
4 W
3 W
m
SURGE
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5

FIG 5e:



18h 14th Nov 1977(DYN)
57 N
56 N
55 N
54 N
53 N
52 N
51 N
50 N
49 N
10 W
9 W
8 W
7 W
6 W
5 W
4 W
3 W
m
SURGE
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5

FIG 6a(i):



G3AXL 18h 11th Nov 1977 SURGE
CM/SEC
20.0
40.0
60.0
80.0
100.0
over 100.0
56
54
52
50
−10
−8
−6
−4

FIG 6a(ii):

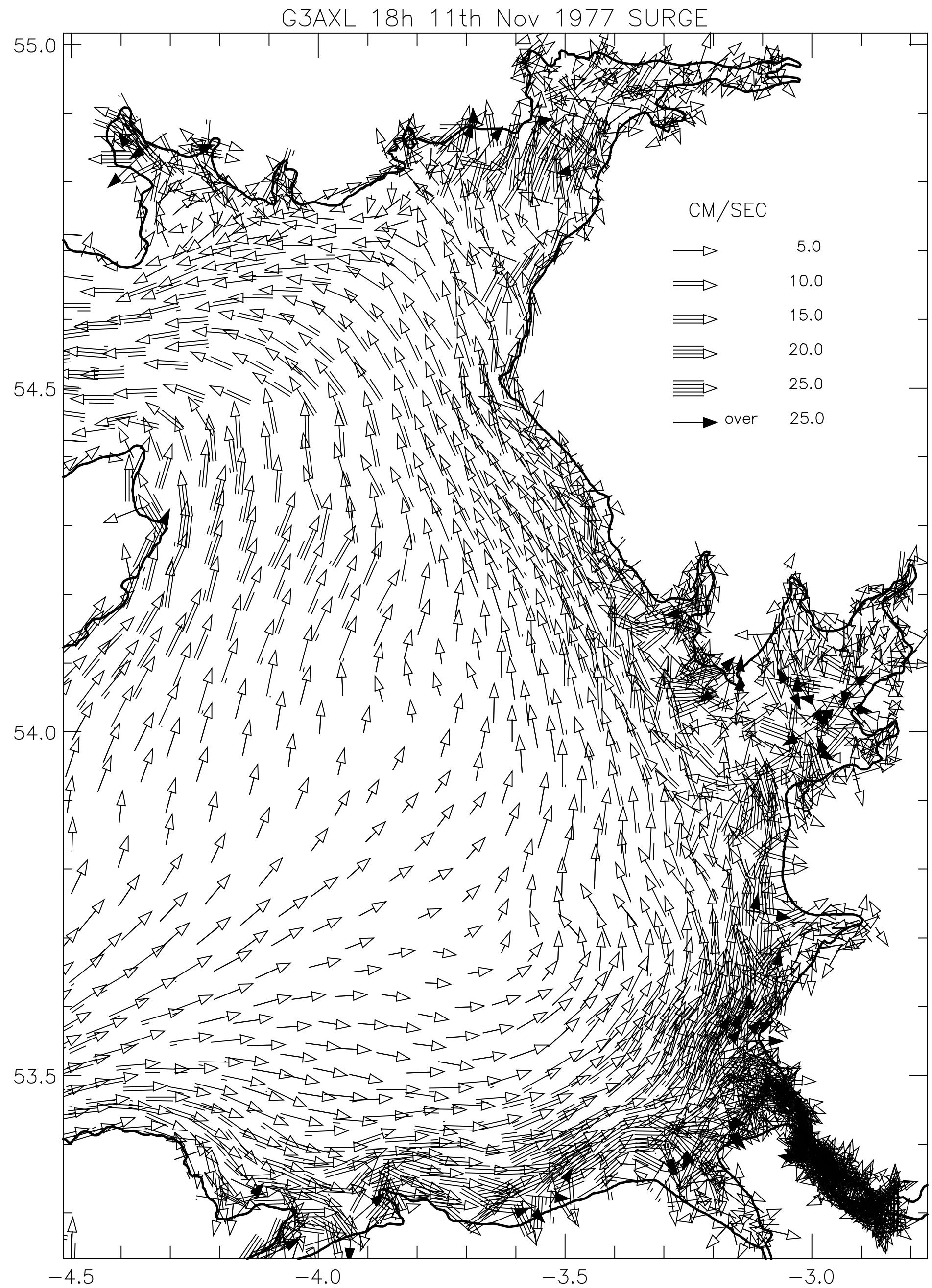

G3AXL 18h 11th Nov 1977 SURGE
CM/SEC
5.0
10.0
15.0
20.0
25.0
over 25.0
55.0
54.5
54.0
53.5
−4.5
−4.0
−3.5
−3.0

FIG 6a(iii):

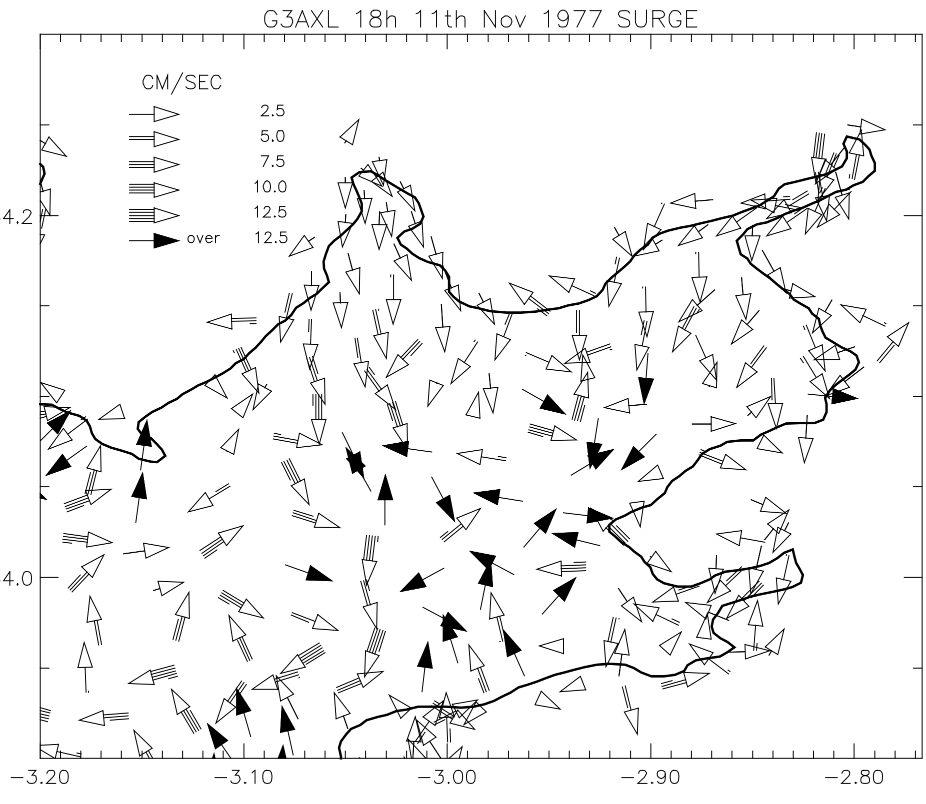

G3AXL 18h 11th Nov 1977 SURGE
CM/SEC
2.5
5.0
7.5
10.0
12.5
over
12.5
54.2
54.0
−3.20
−3.10
−3.00
−2.90
−2.80

FIG 6a(iv):

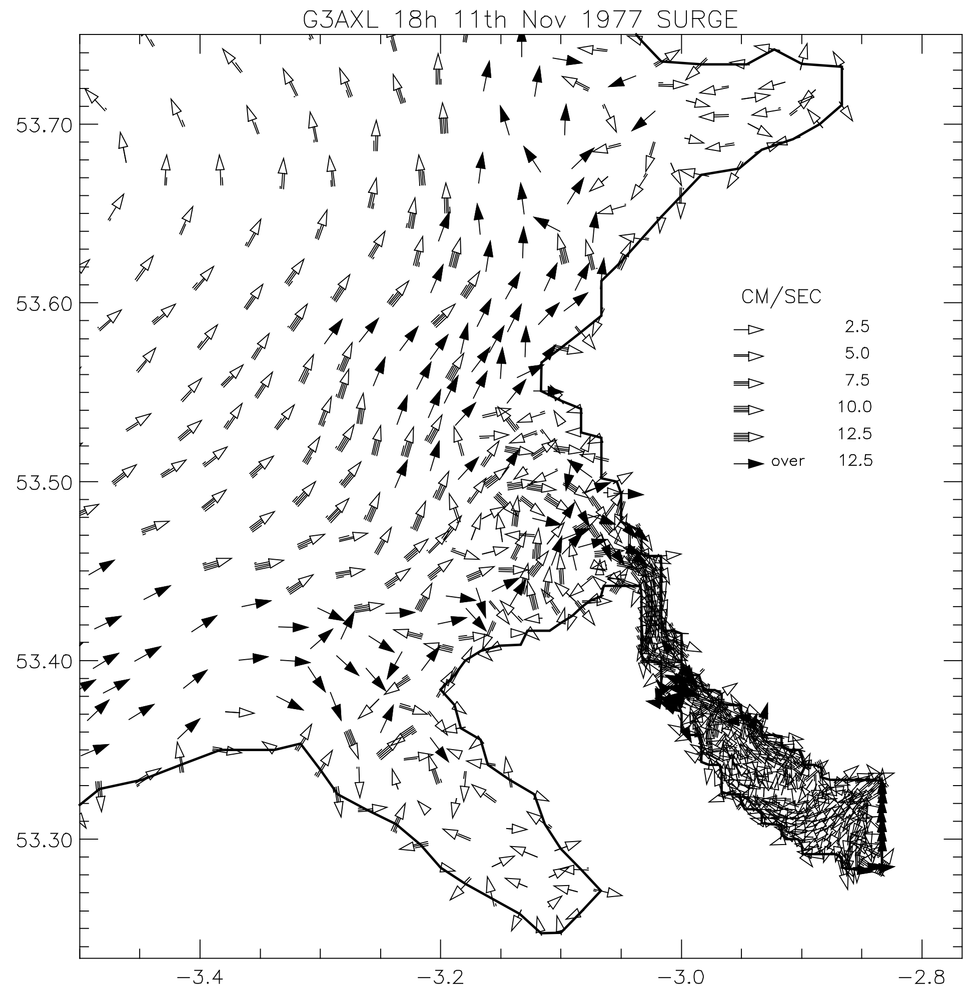

G3AXL 18h 11th Nov 1977 SURGE
53.70
53.60
53.50
53.40
53.30
−3.4
−3.2
−3.0
−2.8
CM/SEC
2.5
5.0
7.5
10.0
12.5
over 12.5

FIG 6a(v):

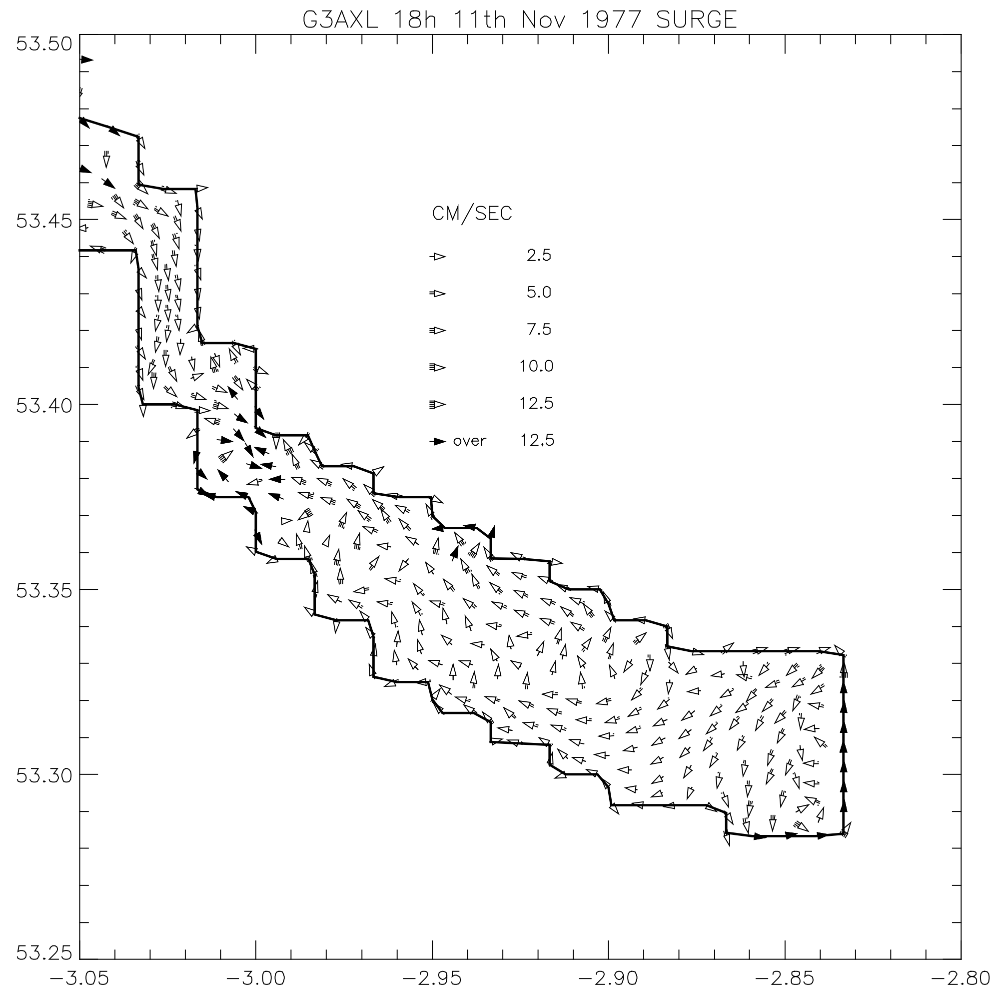

G3AXL 18h 11th Nov 1977 SURGE
CM/SEC
2.5
5.0
7.5
10.0
12.5
over 12.5
53.50
53.45
53.40
53.35
53.30
53.25
−3.05
−3.00
−2.95
−2.90
−2.85
−2.80

FIG 6b(i):

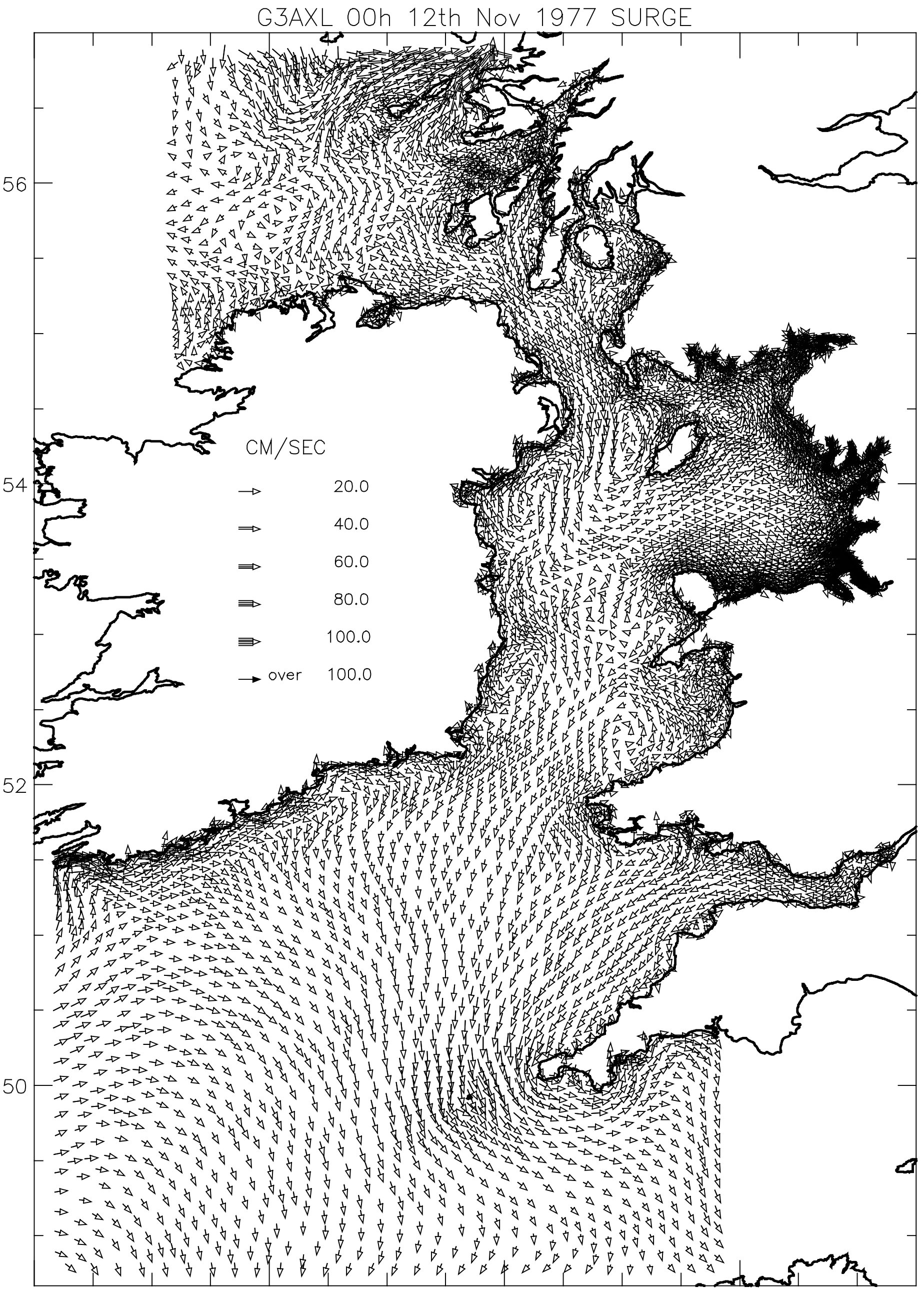

G3AXL 00h 12th Nov 1977 SURGE
CM/SEC
20.0
40.0
60.0
80.0
100.0
over 100.0
56
54
52
50
−10
−8
−6
−4

FIG 6b(ii):

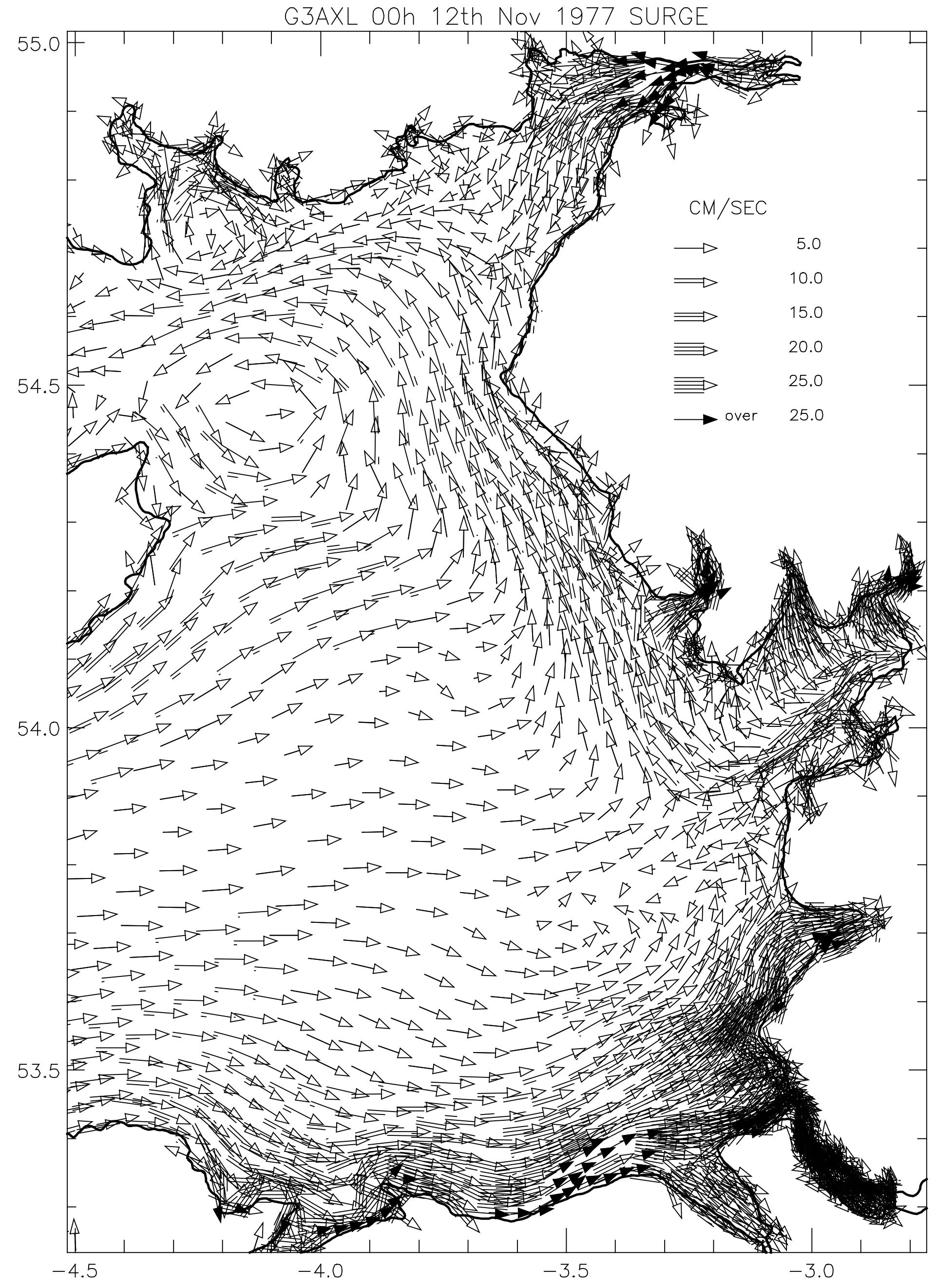

G3AXL 00h 12th Nov 1977 SURGE
CM/SEC
5.0
10.0
15.0
20.0
25.0
over 25.0
55.0
54.5
54.0
53.5
−4.5
−4.0
−3.5
−3.0

FIG 6b(iii):

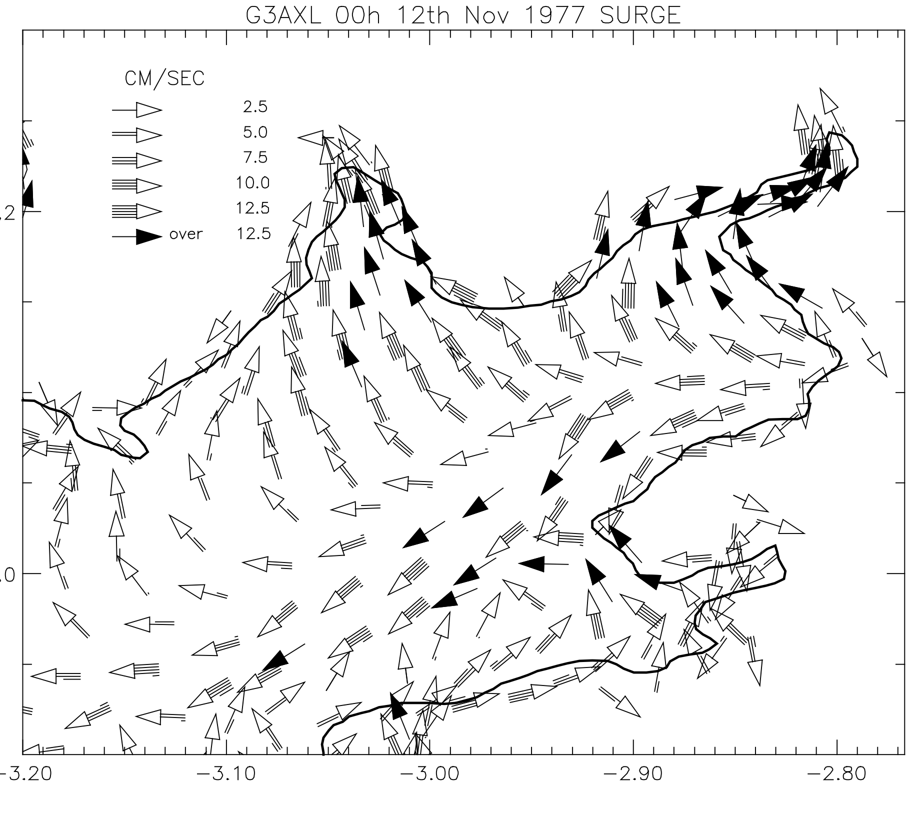

G3AXL 00h 12th Nov 1977 SURGE
CM/SEC
2.5
5.0
7.5
10.0
12.5
over
12.5
54.2
54.0
−3.20
−3.10
−3.00
−2.90
−2.80

FIG 6b(iv):

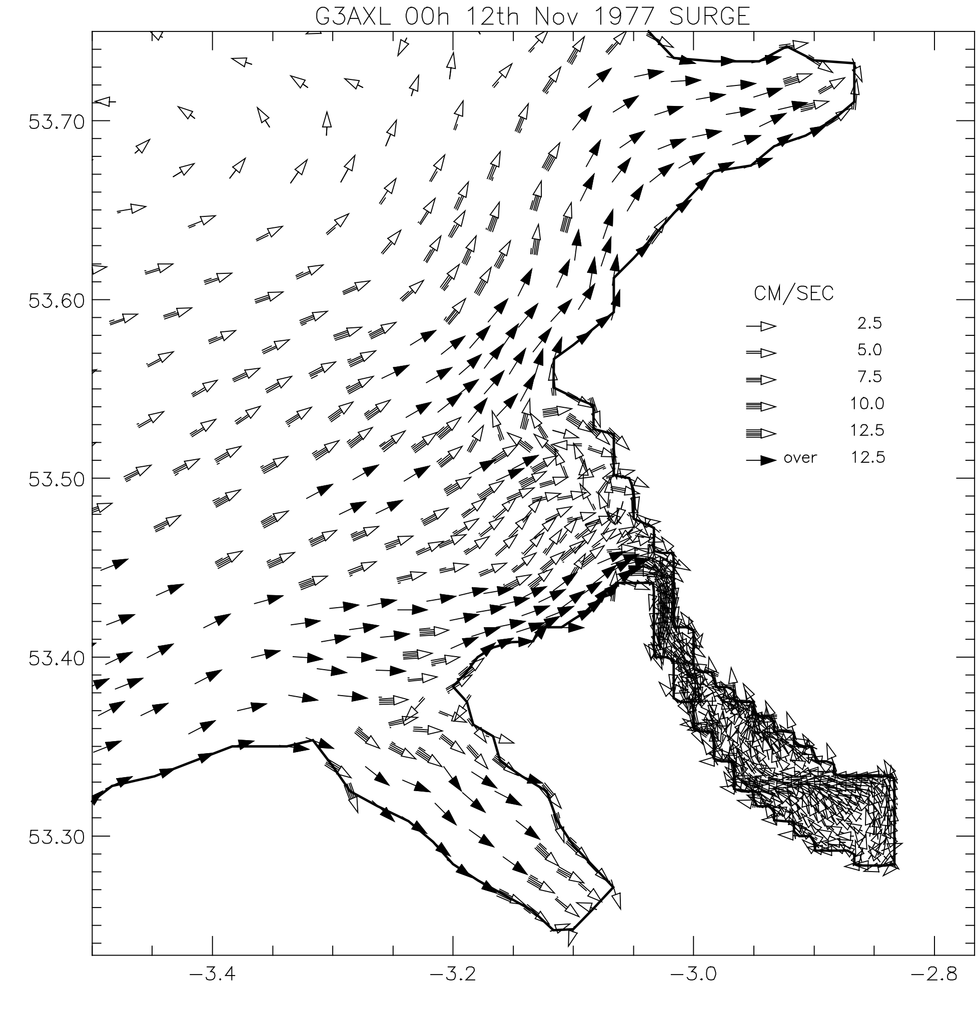

G3AXL 00h 12th Nov 1977 SURGE
CM/SEC
2.5
5.0
7.5
10.0
12.5
over 12.5
53.70
53.60
53.50
53.40
53.30
−3.4
−3.2
−3.0
−2.8

FIG 6b(v):

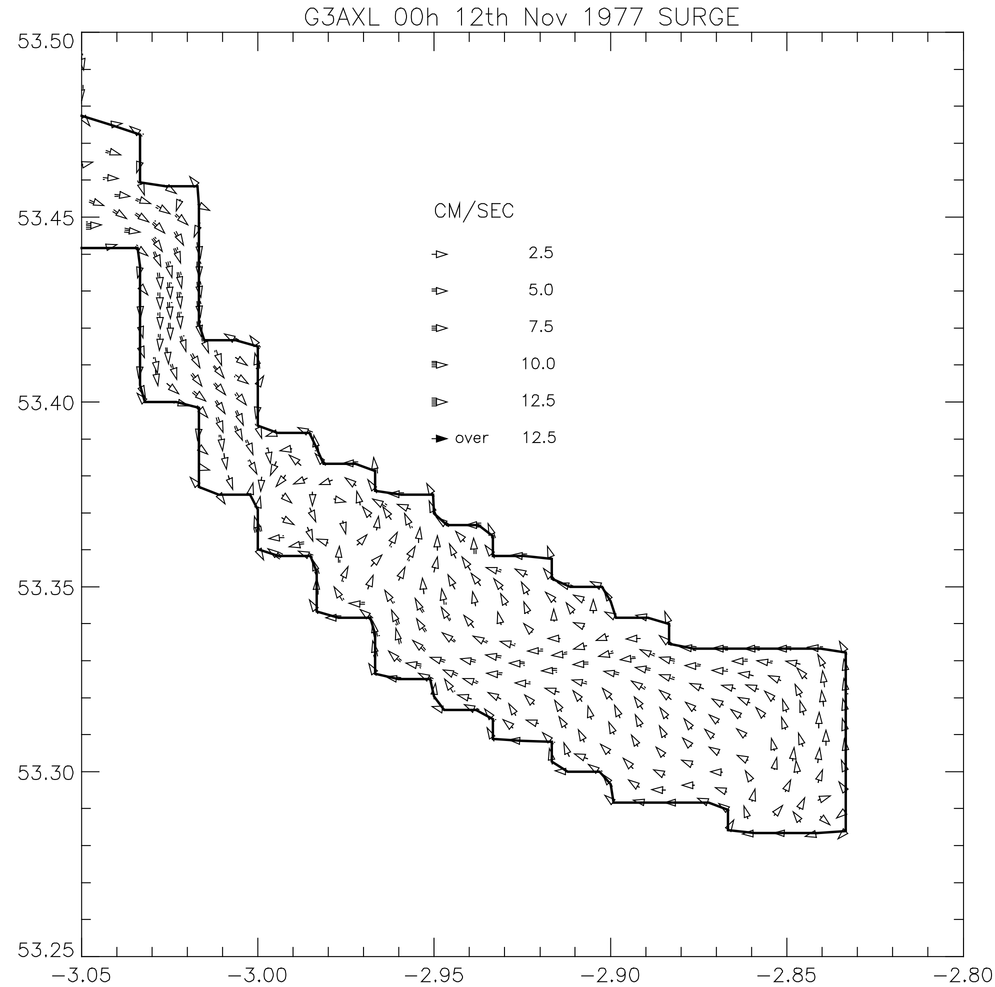
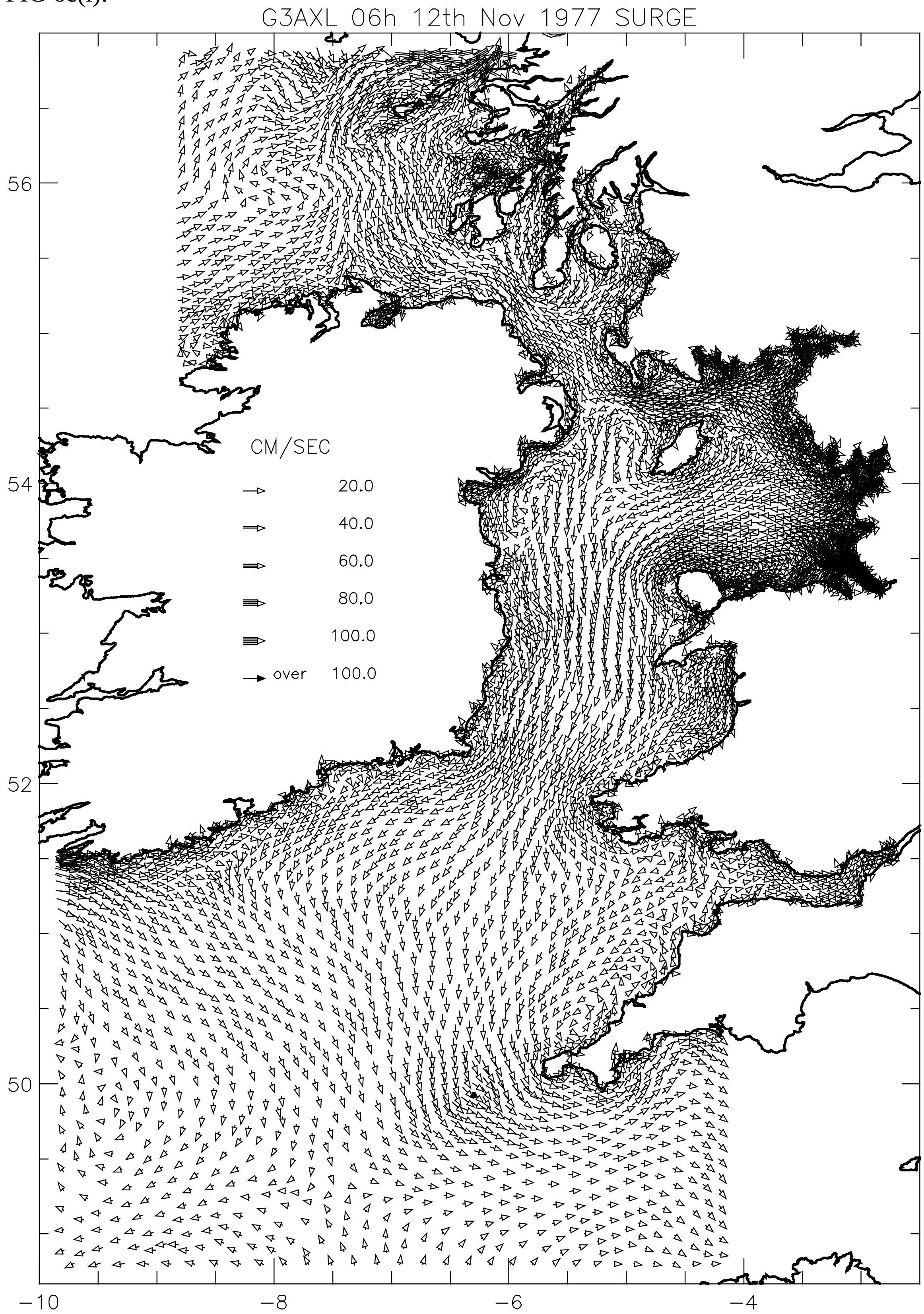

G3AXL 00h 12th Nov 1977 SURGE
CM/SEC
2.5
5.0
7.5
10.0
12.5
over 12.5
53.50
53.45
53.40
53.35
53.30
53.25
−3.05
−3.00
−2.95
−2.90
−2.85
−2.80

FIG 6c(i):



G3AXL 06h 12th Nov 1977 SURGE
CM/SEC
20.0
40.0
60.0
80.0
100.0
over 100.0
56
54
52
50
−10
−8
−6
−4

FIG 6c(ii):

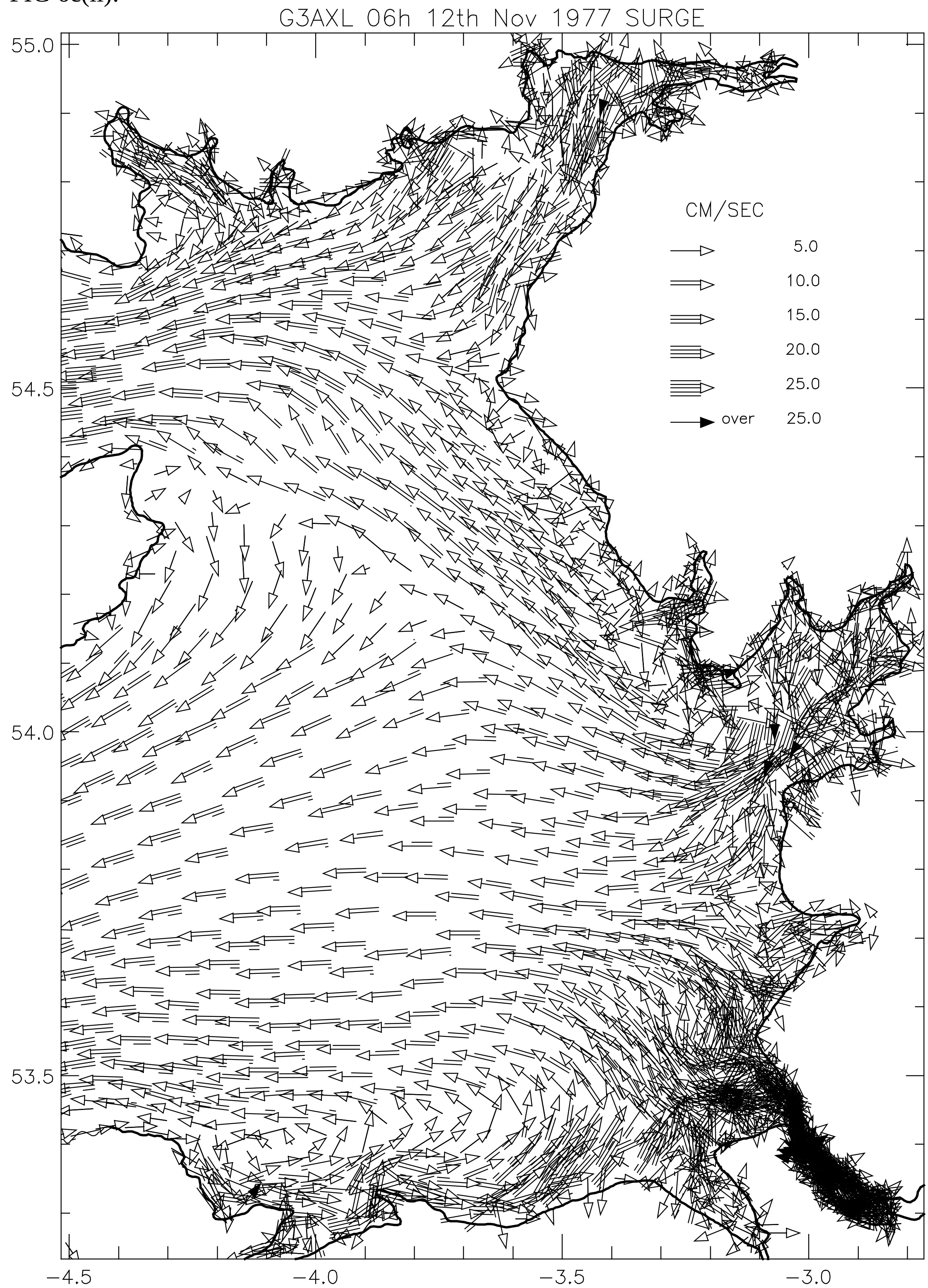

G3AXL 06h 12th Nov 1977 SURGE
CM/SEC
5.0
10.0
15.0
20.0
25.0
over 25.0
55.0
54.5
54.0
53.5
-4.5
-4.0
-3.5
-3.0

FIG 6d(i):

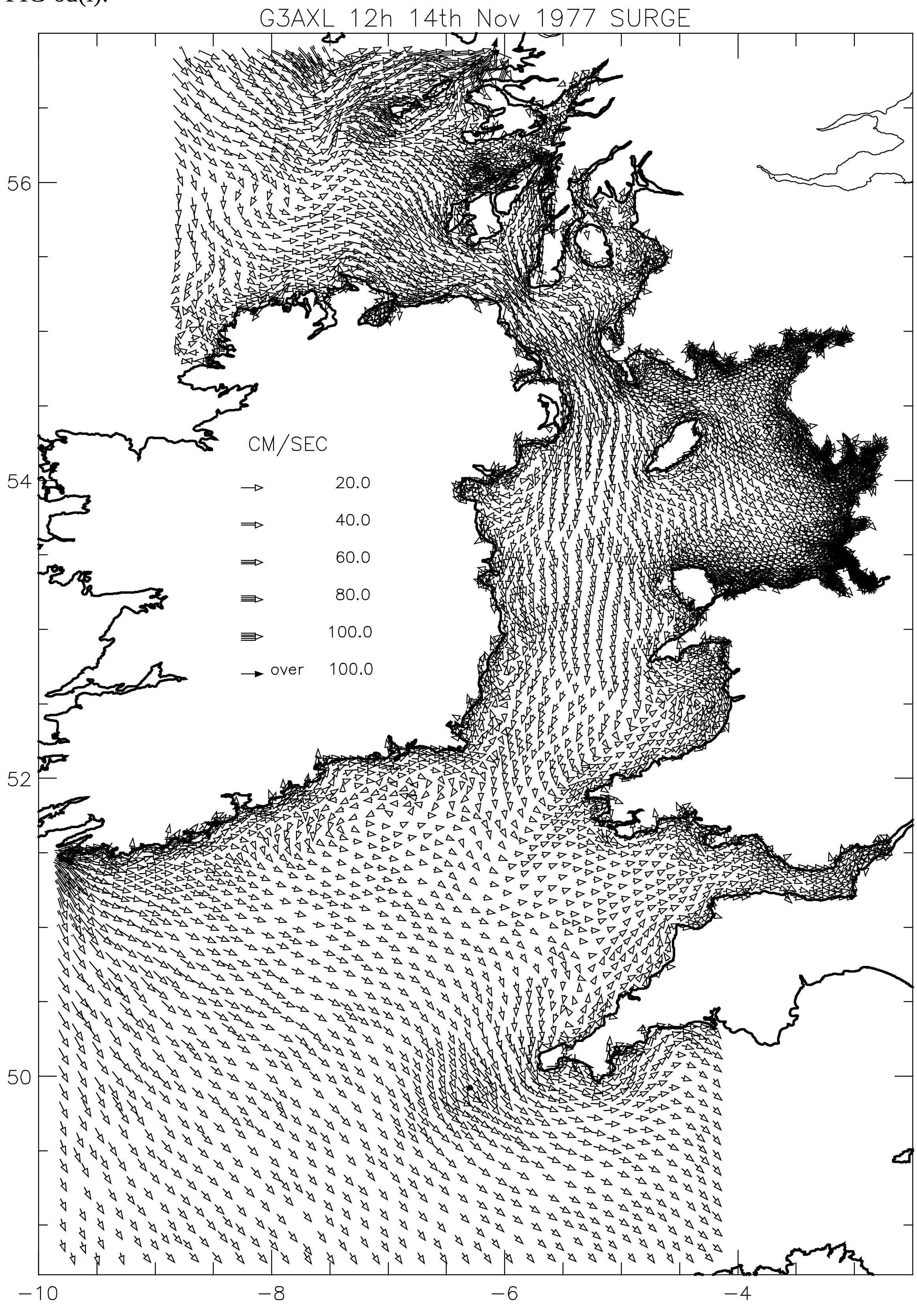

G3AXL 12h 14th Nov 1977 SURGE
CM/SEC
20.0
40.0
60.0
80.0
100.0
over 100.0
56
54
52
50
−10
−8
−6
−4

FIG 6d(ii):

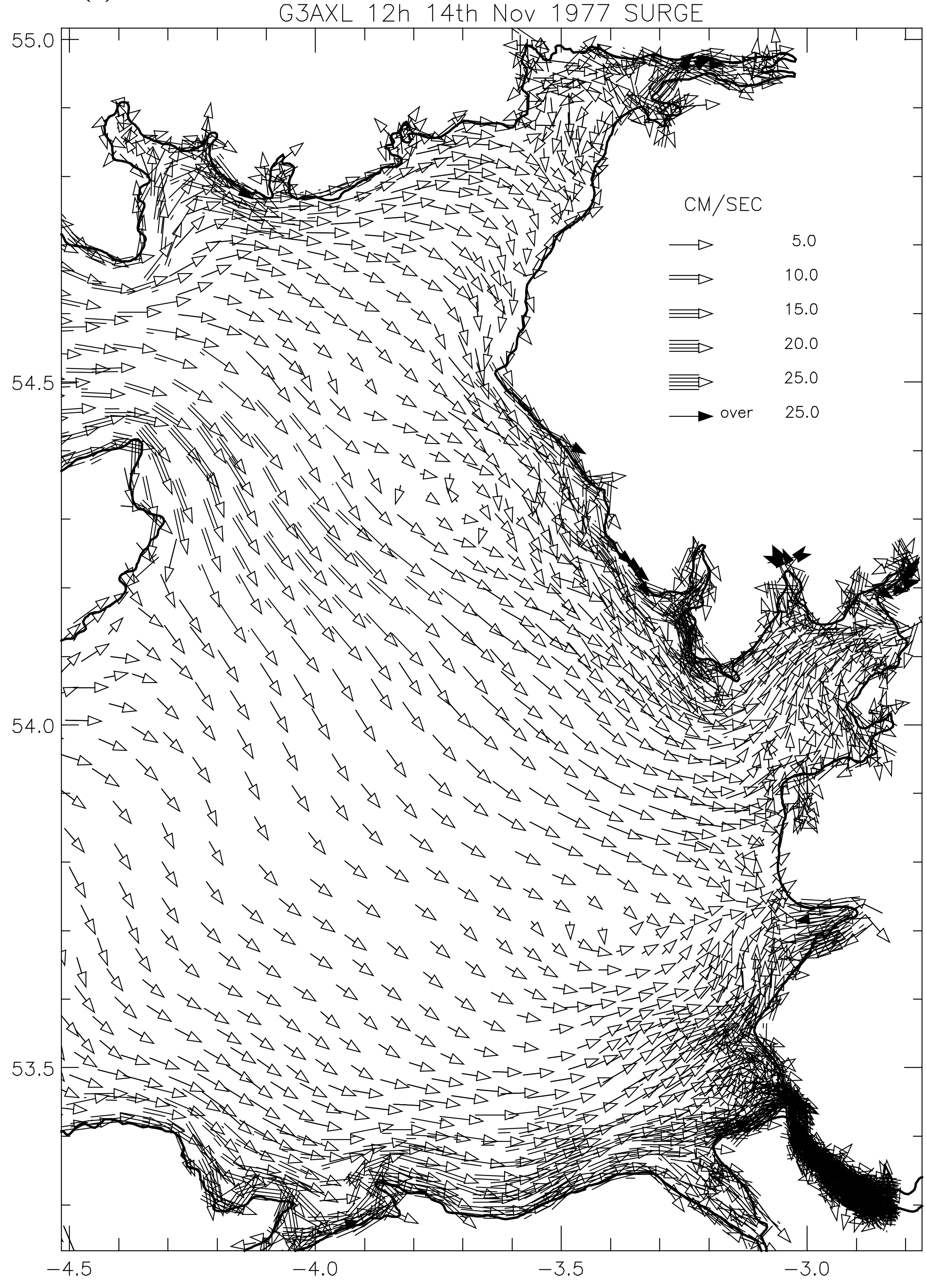

G3AXL 12h 14th Nov 1977 SURGE
CM/SEC
5.0
10.0
15.0
20.0
25.0
over 25.0
55.0
54.5
54.0
53.5
−4.5
−4.0
−3.5
−3.0

FIG 6e(i):

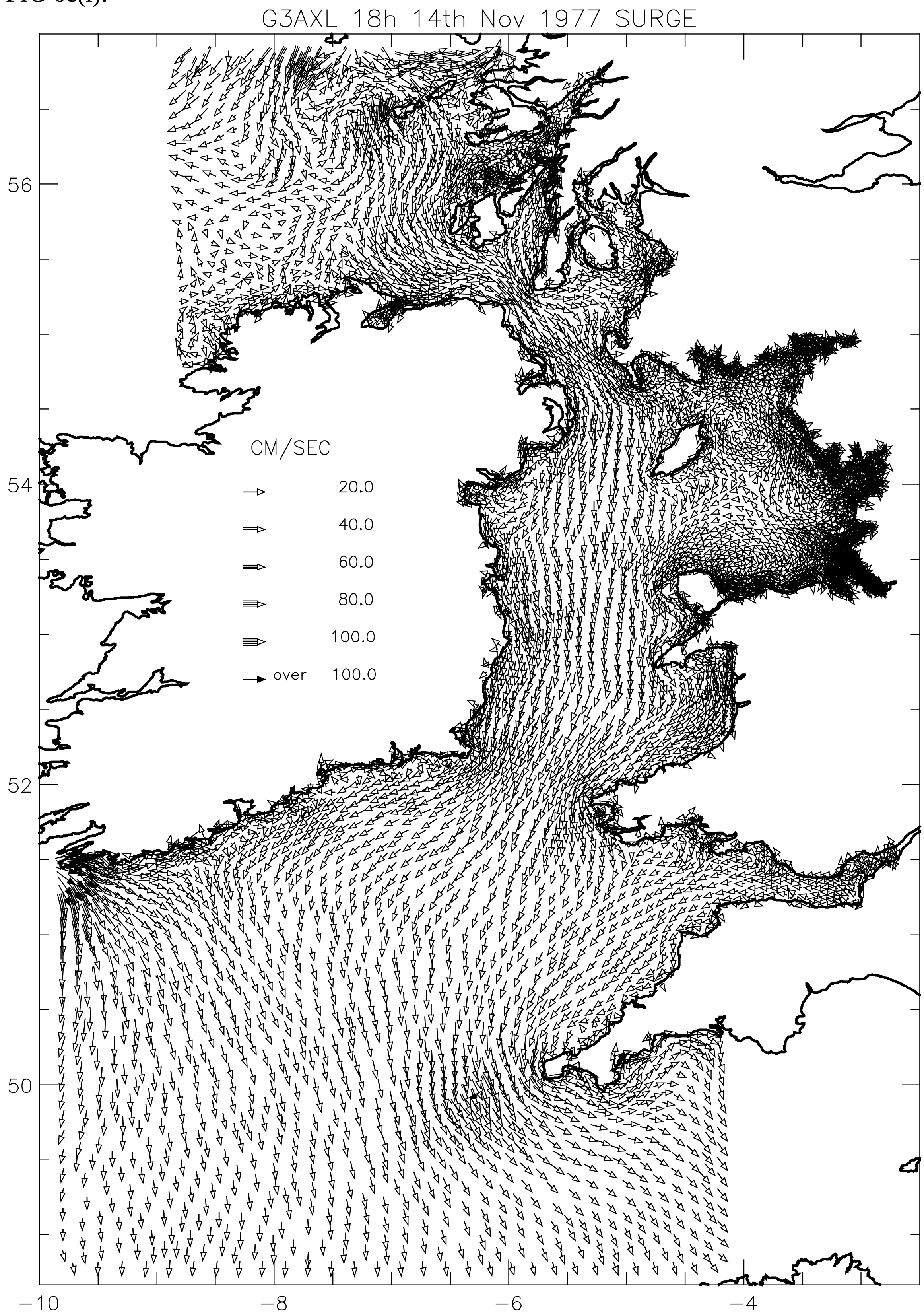
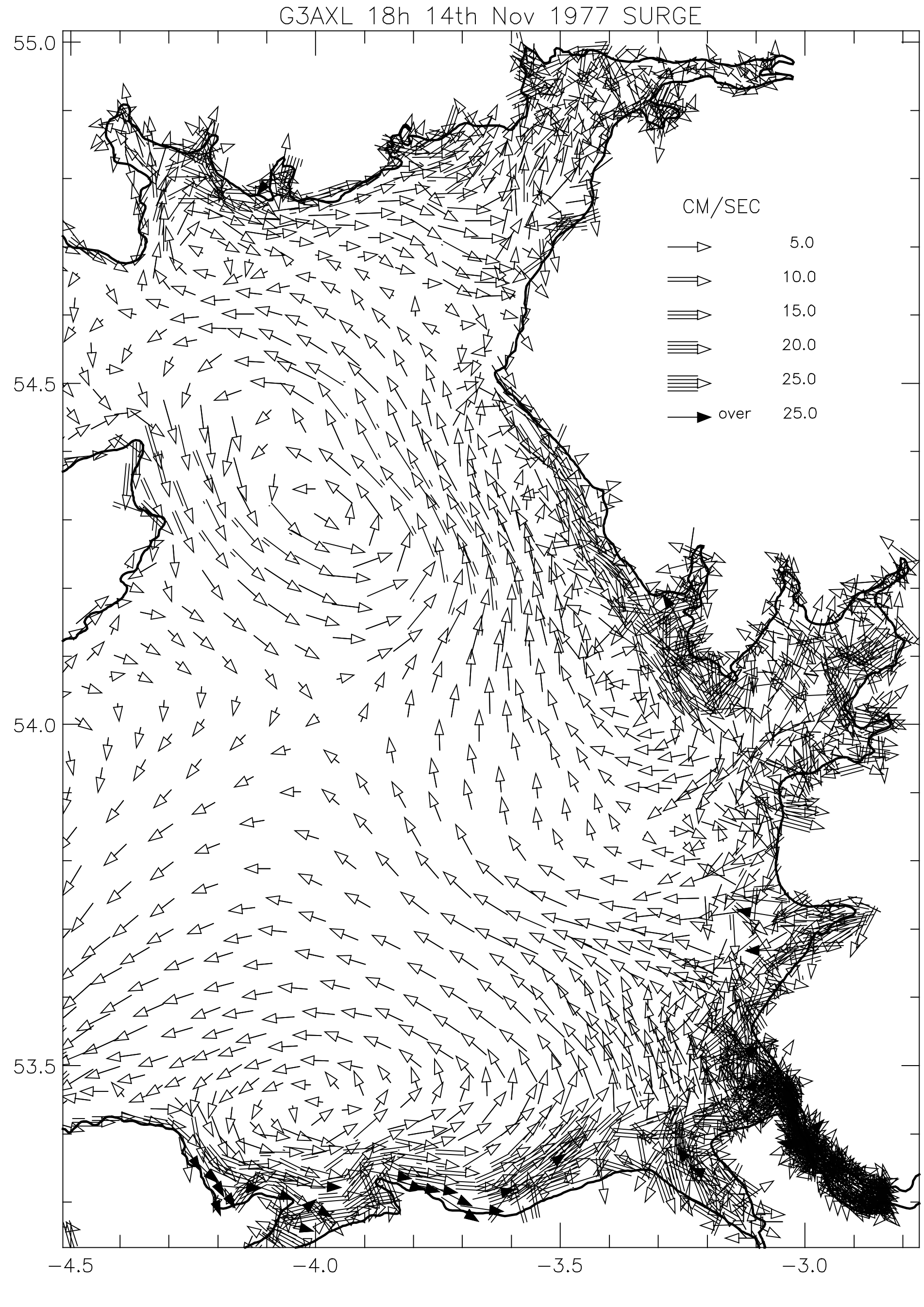

G3AXL 18h 14th Nov 1977 SURGE
CM/SEC
20.0
40.0
60.0
80.0
100.0
over 100.0
56
54
52
50
−10
−8
−6
−4

FIG 6e(ii):


G3AXL 18h 14th Nov 1977 SURGE
CM/SEC
5.0
10.0
15.0
20.0
25.0
over 25.0
55.0
54.5
54.0
53.5
−4.5
−4.0
−3.5
−3.0