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Vertical structure of extreme currents in the Faroe-Bank Channel

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Abstract. Extreme currents are studied with the aim of understanding their vertical and spatial structures in the Faroe-Bank Channel. Acoustic Doppler Current Profiler time series recorded in 3 deployments in this channel were investigated. To understand the main features of extreme events, the measurements were separated into their components through filtering and tidal analysis before applying the extreme value theory to the surge component. The Generalized Extreme Value (GEV) distribution and the Generalized Pareto Distribution (GPD) were used to study the variation of surge extremes from near-surface to deep waters. It was found that this component alone is not able to explain the extremes measured in total currents, particularly below 500 m. Here the mean residual flow enhanced by tidal rectification was found to be the component feature dominating extremes. Therefore, it must be taken into consideration when applying the extreme value theory, not to underestimate the return level for total currents. Return value speeds up to 250 cm s^{-1} for 50/250 years return period were found for deep waters, where the flow is constrained by the topography at bearings near 300/330° It is also found that the UK Meteorological Office FOAM model is unable to reproduce either the magnitude or the form for the extremes, perhaps due to its coarse vertical and horizontal resolution, and is thus not suitable to model extremes on a regional scale.

Keywords. Oceanography: Physical (Currents; General circulation; General or miscellaneous)

1 Introduction

There is a limited number of studies available on extreme currents occurring in the deep ocean. However, nowadays several fields of modern science and engineering have to deal with extreme current events. As Carter et al. (1987) pointed out, as exploration for offshore oil and gas resources move into deeper waters, so the need for estimates of extreme currents also extends into deeper waters. Moreover due to the present climate changes, there is the need to understand extremes, their variability and possible trends to relate them to the climatic phenomena by which they are produced or influenced.

While there is a considerable amount of literature available on statistical modelling methods for extreme sea levels (Blackman and Graff, 1978; Pugh and Vassie, 1980; Graff, 1981; Pugh, 1987; Tawn, 1988; Tawn and Vassie, 1989, 1991; Tawn, 1992; Flather and Smith, 1998; Flather et al., 1998; Dixon and Tawn, 1999), the same cannot be said of ocean currents (Pugh, 1982; Carter et al., 1987; Davies and Flather, 1987; Griffiths, 1996; Robinson and Tawn, 1997; Robinson et al., 2000).

Extreme sea currents are far more difficult to estimate than extreme sea levels first of all because of the lack of high quality long-term observational time-series. The problem is further complicated by the strong seasonal variations which occur in both tidal and surge activity, and while it is possible to allow for some seasonal tidal changes in the analysis and prediction processes, if less than a year has been sampled, the seasonal surge activity is more difficult to resolve and accommodate (Pugh, 1982). Also, current tides and surges are generally not linearly correlated so simply adding extreme tidal currents to extreme surge currents will not give realistic total current events (Pugh, 1987).

Extreme currents can be generated directly by extreme weather conditions both in shallow and deep waters, but there are also other mechanisms associated with large scale water circulation and the behavior of eddies as well as topography effects that contribute to the creation of extreme flows. Here extremes are associated with a number of these latter effects and are studied in order to understand their interactions to provide an improved basis for estimating extreme events. To do this, there is a need for high quality current measurements over a region and a systematic analysis approach in order to correctly describe and interpret the spatial and temporal scales of extremes caused, for instance, by the passage of storms.

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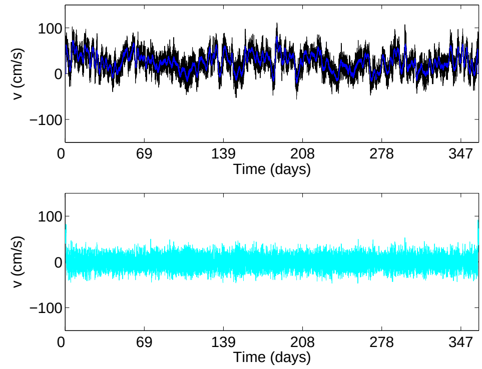

Fig. 1. Linearly interpolated raw data (black), low-passed data (blue) and high frequency data (cyan) are shown for v component at location FB, 524 m depth.

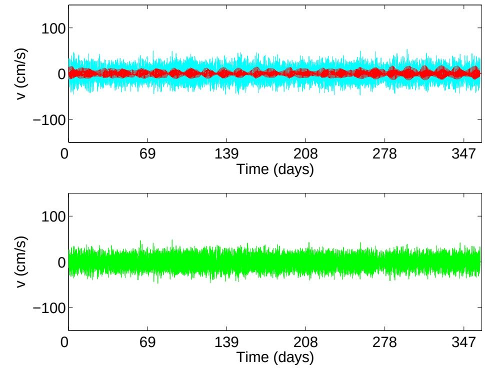

Fig. 2. High frequency data (cyan), tidal data (red) and surge data (green) are shown for v component at location FB, 524 m depth.

Such detailed analyses were performed here to understand the vertical structure of current and likely composition of extreme events, in the Faroe-Bank Channel (FBC) (see Carollo et al. (2005), Sect. 2). This paper follows on from a companion paper by the same authors (Carollo et al., 2005) dealing with the vertical structure of currents in three sections in the vicinity of the Iceland-Scotland Ridge. An application of this study is to determine to what extent ocean models can be used to reproduce and forecast extreme events in ocean currents, on a regional scale. A brief description of the physical dynamics characterising the FBC is given in the companion paper (their Sect. 2 and Fig. 1) along with the description of the data available for the application of the extreme value theory. The physical interpretation of the processes occurring in the FBC is important for the final interpretation of the results obtained from the extreme value analysis. This is to understand the forcing mechanisms producing extreme values in ocean currents.

Details of the methodology followed for the univariate and bivariate analyses of extreme events are given in Sect. 2. A discussion of the nature of extremes through depth is outlined in Sect. 3. Results and discussions are shown in Sects. 4 and 5 respectively. Conclusions are given in Sect. 7.

2 Methodology

Before applying the selected statistical methods for the analyses of extremes, the tidal, mean-residual and surge component were separated. As explained in the companion paper (see for details Carollo et al. (2005)) the methodology proposed by Graff (1986) was followed. The raw data, divided into u and v velocity components, were pre-filtered to separate out low (with frequency less than 1 cycle per day) and high frequency data (Fig. 1); the latter were passed to the harmonic tidal analysis to separate out the tidal and surge components (Fig. 2).

At the end of this process u and v were used to compute speed and direction and, therefore, to identify extreme events at different levels in the water column.

Interpolated values (see for details Carollo et al. (2005)) were removed to not create false data.

2.1 Univariate techniques

Several models have been proposed for the study of extreme sea-levels and adapted to extreme ocean currents (Pugh, 1982; Tawn, 1988; Davison and Smith, 1990; Griffiths, 1996).

Extreme currents can be studied following direct or indirect methods; the first being the ones to analyse total current and the second to analyse its components. Their performance is tested by Davison and Smith (1990) for sea-level data along the UK coasts. With direct methods, the mean level or flow is separated out to remove any trend before applying the extreme value theory. Large errors are found when applying the direct method due to its weakness in not considering seasonality. Indirect methods, e.g. the Joint Probability Method (JPM), include tidal non-stationarity in the analysis of extremes. Great differences are, therefore, found in evaluating the return level with these two methods. In fact, extreme events in total sea-level and current can be due to a different combination of processes. If total currents are considered it is not possible to evaluate which components produce extremes. A combination of the mean residual flow and surge can create extreme currents much larger than, for instance, an extreme surge event considered separately.

Most of the literature studies concentrate on the JPM proposed by Pugh and Vassie (1980), modified by Tawn and Vassie (1989), Tawn and Vassie (1991) and further developed by Robinson and Tawn (1997). Using this method the estimate of the distribution of extremes in total currents and levels is achieved through the estimate of the tail distribution of the surge component averaged over the predicted tidal currents. In this way both the tidal and surge information are taken into account.

Here a different approach was preferred and followed to initially study only the surge extremes.

The first method used is the analysis of the maximum order statistic. The distribution of observed maxima (each from a large number of observations of a random variable) is approximated to the Generalized Extreme Value distribution (GEV), G(μ,σ,ξ):

$$G(x) = exp\Big(- \Big[1 + \xi \Big(\frac{x - \mu}{\sigma}\Big)\Big]^{-\frac{1}{\xi}}\Big), \quad (1)$$

where ξ is the shape parameter, μ is the location parameter, and σ is the scale parameter. The shape parameter plays a critical role in determining whether the tail of the distribution is finite or infinite (Coles, 2001). If $\xi<0$ it means that the quantiles are bounded and the extrapolation has a finite limit (i.e. short tail, Weibull distribution); if $\xi\geq 0$ the distribution is unbounded and the extrapolation has an infinite upper limit (if $\xi=0$, the GEV becomes the Gumbel distribution with medium tail; if $\xi>0$, the GEV becomes the Frechet distribution with long or heavy tail) (Coles, 2001).

The second method used to analyse extreme currents is the threshold method. It requires the definition of a threshold l; all the observations exceeding l are modelled according to some distribution (Coles, 2001). The major problem related to this technique is how to define the value of the threshold. If it is too small, a bias is due to the invalidity of the asymptotic argument. If it is too high, there are too few exceedances (Ledford and Tawn, 1996). The Generalized Pareto distribution, defined as

$$G(x) = 1 - \Big(1 + \xi \frac{x}{\sigma}\Big)^{-\frac{1}{\xi}} \quad (2)$$

was used to model the distribution and the 0.90, 0.95 and 0.99 quantiles used as thresholds to analyse the top 10%, 5% and 1% of current speed, respectively.

The return level x_p corresponding to the $1/p$ return period is a very important parameter in the study of extremes. Plotting x_p against $(-log(1-p))$ a return level plot is obtained. This shows how the fitted model extrapolates from the sample information (Coles, 2001). From this plot it is possible to assess if the fitted model has a finite or infinite upper tail. If the estimated value of the shape parameter is negative, this is reflected by a concave extrapolation in the return level plot. When the shape parameter assumes a value close to zero the fit gives a near-linear extrapolation on the return level scale. Attention must be paid in evaluating the return level for long return periods particularly when short time series are analysed (Coles, 2001), as in the present study.

The analysis of extreme events has been performed using the S-plus software by Coles (2001).

2.2 Bivariate techniques

To better understand the vertical structure of extreme events, contingency tables (Table 1) for pairs of variables were built following Stephenson (2000). One variable (Y) is considered the predictor of a second one (X) later observed and measured. This technique is used with the aim to investigate if extreme values recorded at one depth can be used to describe the extreme values at other depths in the water column. Two parameters were evaluated: (1) ε, the base-rate (Eq. (3)) being the probability that an extreme event will occur,

Table 1. Example of contingency table for variables X and Y, k and j being the threshold for X and Y respectively.

	$X>k$	$X\leq k$
$Y>j$	a	b
$Y\leq j$	c	d

$$\varepsilon = \frac{a + c}{n} \quad (3)$$

where n=a+b+c+d, and (2) θ, the odds ratio, or the forecast skill, (Eq. (4)) being the ratio of the probability that the event is correctly forecasted or rejected to the probability that the event is not forecasted when it occurs or is forecasted when it does not occur

$$\theta = \frac{ad}{bc}. \quad (4)$$

3 Extremes through depth

From the analysis of the vertical current profiles shown in the companion paper (Carollo et al., 2005) it was found that extreme events in total currents are due to different components at different levels of the water column.

At the 3 analysed locations in the FBC extremes in total currents have values around 50/70 cm s^{-1} in near-surface waters and 90/160 cm s^{-1} in deep waters. Tides are generally very small and, therefore, they do not give a great contribution in determining extreme currents. The mean residual flow and surge show similar value in the surface-most measurements, at locations FA and FC. However, at location FB extremes in total currents above 400 m are entirely dominated by the surge component (with amplitude of 40/50 cm s^{-1}). In deep waters the dominant component is the mean residual flow (Carollo et al., 2005, Fig. 10). At depth there is also a strong topographic steering that drives the flow at 300/330°. The profile of high speed current is almost constant near the surface and near the bottom. In the intermediate layer the speed increases rapidly. This layer is thicker (200 m) on the Faroese side (FA) and gets thinner moving across the channel; at site FC it is about 100 m thick. This is probably due to an intermediate water mass (North Icelandic Winter Water/Arctic Intermediate Water (NI/AI)) contributing to the overflow, that is found on the Faroese side of the channel, particularly between May and September (Borenas et al., 2001).

In the literature the mean flow is generally considered as creating non-stationarity in the time-series; it is generally very small in coastal areas and normally removed. However, in the offshore locations considered here the mean residual component, that is made up of the low frequency data and mean flow, is at depth the dominant part of currents.

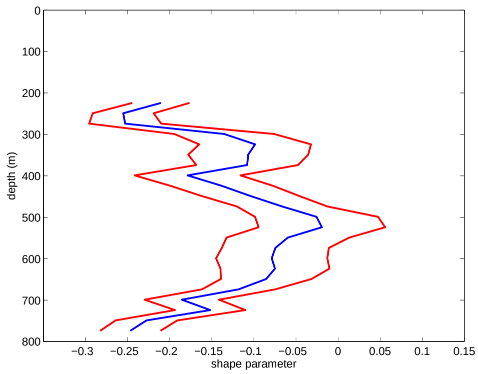

Fig. 3. Variation of the shape parameter (blue) and 95% confidence interval (red) with depth. The values of the shape parameter were obtained by fitting the GEV distribution to daily maxima at each available depth, at location FB.

4 Results

4.1 Surge extremes

The surge is considered a stationary process, therefore, the extreme value theory does hold and can be applied to the stochastic time-series.

The surge daily maxima were considered for the analysis of extremes using the GEV distribution and the top 1, 5 and 10% surge currents were, instead, used for the GPD.

A good fitting to the data sampled at different levels was generally obtained by using both the GEV and GPD. However, some departures from model accuracy can be seen in the upper tails at some depths.

The amplitude of surge extremes is in the range of 15/35, 20/50 and 20/60 cm s^{-1} in surface, mid and deep waters respectively, with no large differences between the three analysed locations. A strong directionality is found at locations FA and FB in near-surface waters (between 60/240° and 90/270°). In near-bottom waters extremes were found along the 30/210° at FA and FB and 120/300° at FC. As found in Carollo et al. (2005) the surge can be up to 90° out of phase in respect to the mean residual flow.

The shape parameter (Fig. 3) is generally negative but gets closer to zero between 400 and 600 m depth. This means that the processes are characterised by short or medium tails.

The extrapolated return level for 50/250 year return period is up to about 60/80 cm s^{-1} in near-surface waters, and 50/100 cm s^{-1} in deep waters with values up to 300/400 cm s^{-1} between 500 and 600 m depth (Fig. 4).

These results show an underestimation of the return level in deep waters due to the fact that only the surge was considered. This component alone does not fully explain the extreme events recorded in total currents, particularly below 500 m depth, where the mean residual flow is dominant. Therefore, the sum of the surge and mean residual flow has to be considered.

4.2 Extremes of the mean residual and surge component

4.2.1 GEV

The GEV distribution was applied to daily maxima of the sum of the surge and mean residual flow (Fig. 5). The extreme values are in the range 20/80, 20/100 and 80/100 cm s^{-1} in surface, mid and deep waters respectively. This shows that extreme currents considered for this analysis are larger than the surge extremes, particularly in deep waters, and in agreement with the values found for total currents.

The shape parameter is close to 0 in the surface-most measurements, where the confidence interval is very wide, as shown in Fig. 6. In deep waters the shape parameter is, instead, negative and the return level plot is bounded (Fig. 7).

The values for the return level are larger than in the previous case when only the surge was considered (for comparison see Figs. 4 and 7), and a more accurate estimate of extremes in total currents is now made. However, this method does not take into account the directionality of extremes.

4.2.2 Directional analysis

To account for the directionality of extreme currents, Pugh (1982) suggests dividing the total observed currents by sector. Thus, before applying the GPD, the sum of the surge and mean residual speed was divided into twelve 30° directional sectors. In each sector the direction of flow was considered constant.

In surface-most measurements currents do not show any preferred directionality (Fig. 8) but going down into deep waters extremes tend to occur along the 300/330° direction constrained by the bottom topography.

Using the GPD the threshold was defined as the 0.95 quantile for each depth and sector (Fig. 9).

In near-surface and mid-waters the largest return levels of 120/160 cm s^{-1} for 50/250 years return period were found for current flowing northward (Fig 10). In deep waters due to the strong topographic steering, all the data available for the extreme value analysis were in sectors 270/300°, 300/330° and 330/360° (Fig. 8). Figure 11 shows that the largest return levels (200/220 cm s^{-1}) are to be expected in deep waters, below 600 m.

4.3 Bivariate analysis

The value of the correlation coefficient is found to be around 0.6–0.8 for two close layers in the same location, but it decreases rapidly to 0 for distant layers.

To evaluate extreme dependence at different levels, base rate and odds ratio have been plotted on a log-log scale graph (Fig. 12). It was found that for two close layers the logarithm of the base rate decreases (that means an increase in the threshold) as the logarithm of the odds ratio increases. This result indicates dependence at extreme levels. However, when considering two layers that are far apart in the water

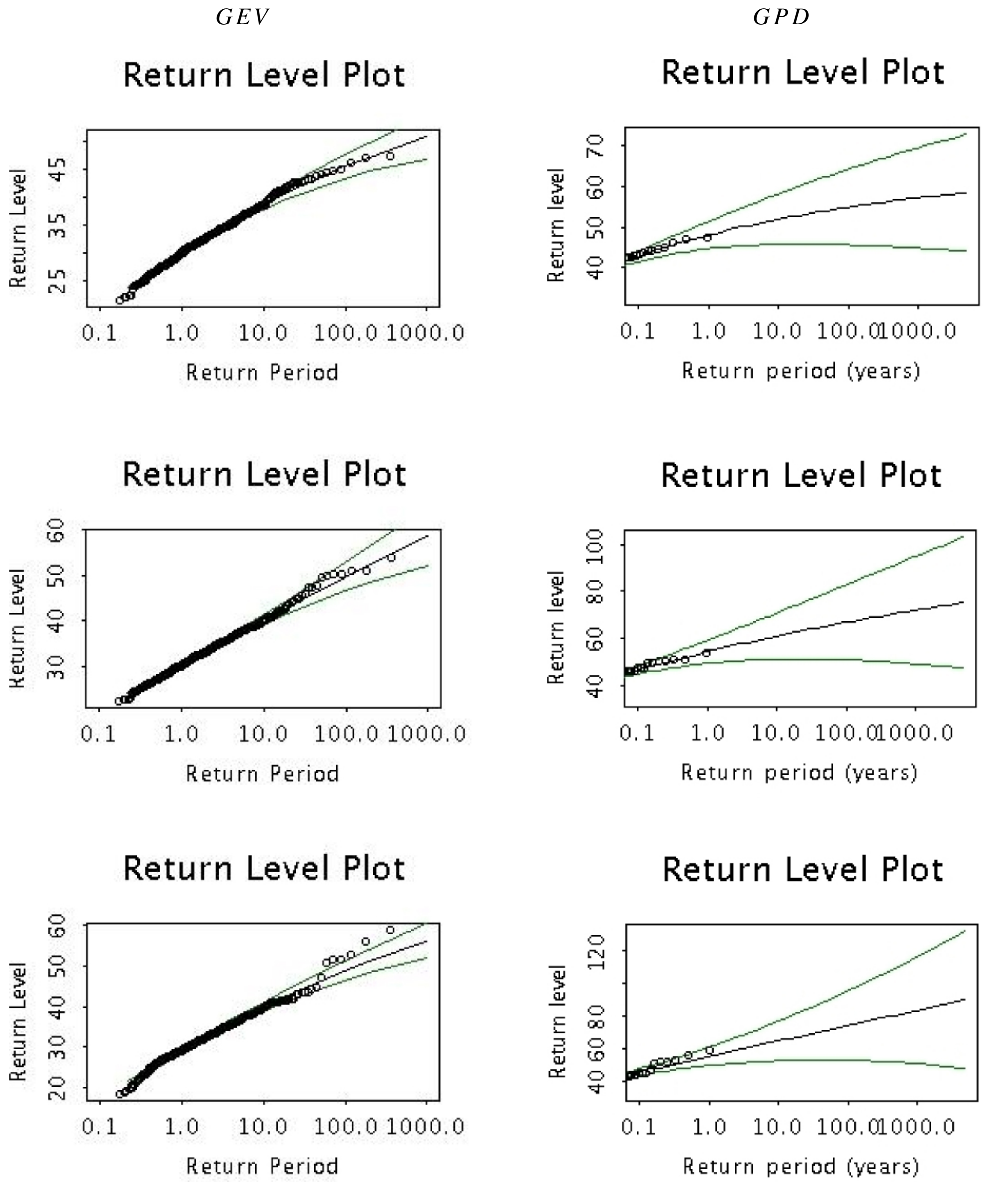

Fig. 4. Return level plot ($cm\,s^{-1}$) for the surge component at location FB, depths 349, 499 and 649 m from top to bottom. 95% confidence interval is also shown. The return period is in years when considering the results from the GPD (right column) but it is in days for the results from the GEV distribution.

column, this trend is not found. The larger the interval between two layers the smaller the association found. This indicates a poor forecast skill for extreme currents.

It can be concluded that there is dependence between extremes only for close vertical layers. Therefore, it is not possible to successfully forecast extreme events at one depth knowing extremes at another depth. This is probably due to the vertical stratification of the water column that does not allow extremes to propagate up nor down in the presence of different water masses.

5 Discussion

The above results show that the application of the extreme value theory to the surge component leads to biased return levels for extreme total currents. The bias is reduced when the mean residual flow is added. Moreover, for an accurate forecast of the return level, directional information needs to be included. In fact, extreme currents at a given depth and direction might not be extreme elsewhere. In the top 400 m extremes are either due to the surge or mean residual component, and therefore can be produced by different processes

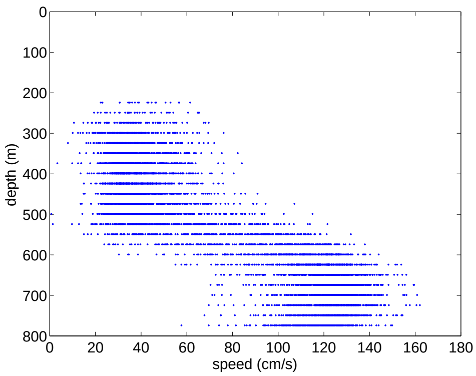

Fig. 5. Vertical distribution of the daily maxima taken into account for applying the GEV distribution, at location FB. Values of speed ($\mathrm{cm\,s^{-1}}$) are obtained by summing surge and mean residual flow.

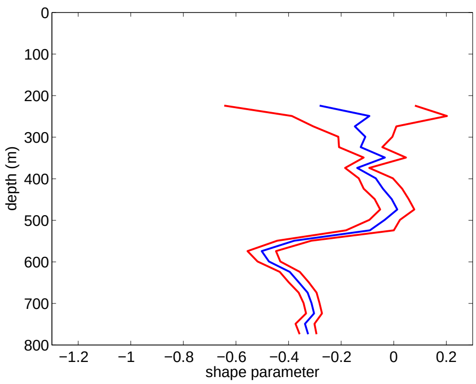

Fig. 6. Variation of the shape parameter (blue) and 95% confidence interval (red) with depth. The values of the shape parameter were obtained by fitting the GEV distribution to daily maxima of the sum of surge and mean residual flow at each available depth, at location FB.

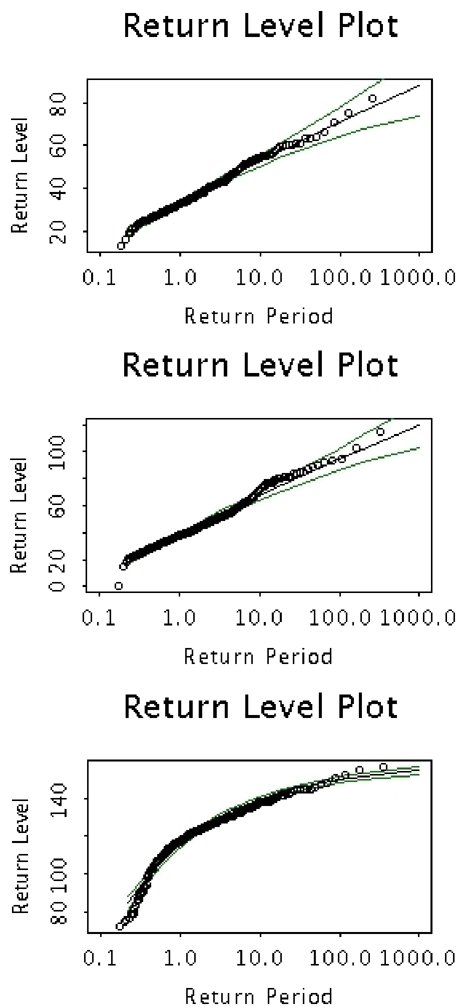

Fig. 7. Return level plot ($\mathrm{cm\,s^{-1}}$) for the sum of surge and mean residual flow at location FB, depths 349, 499 and 649 m, from top to bottom. The return period is in days.

like storms affecting the sea-surface. The largest return levels where either found in the outflow waters or in the interface between surface and deep waters. The bottom currents in this section are characterised by very high speed; the mean speed in the FBC, in excess of $100\,\mathrm{cm\,s^{-1}}$, is extreme for any bottom currents (Borenas et al., 2001). Here a strong directionality (300/330°) was found, probably due to the influence of the bottom topography giving rise to tidal rectification phenomena (Carollo et al., 2005). It is therefore evident that, with the current knowledge, if the flow does not change abruptly, large return values are expected to occur below 500 m depth constrained by the bottom topography to flow northwestward. However it could also be possible to have large return levels at the interface of the 2 different water masses. Here, in fact, the rapid change in the dynamics characterising surface inflow and bottom outflow could give rise to very large currents.

Exceedances over threshold were here considered temporally independent though they show a clear tendency to occur in clusters. Because of this temporal dependence a correction is therefore needed to the standard error of the shape parameter estimates. Values can be adjusted following the approach proposed by Smith (1990). A different approach is proposed by Tawn (1988), who uses covariates to estimate the trend in the data while simultaneously modelling extremes through the extreme value theory. A third possibility is the use of a declustering procedure as done in Davison and Smith (1990). Following this method the fitting is applied only to peak excesses in each cluster, leaving many data unused. However, as information about extremes are scarce it is highly desirable to use all the available data. Dependence in the data set must be accounted for correctly evaluating standard errors and produce estimates that are more likely to be closer to the true values. Here this was disregarded to focus on the main aim of characterising extreme events in total currents through depth, and identifying the dominant current components and physical phenomena producing them.

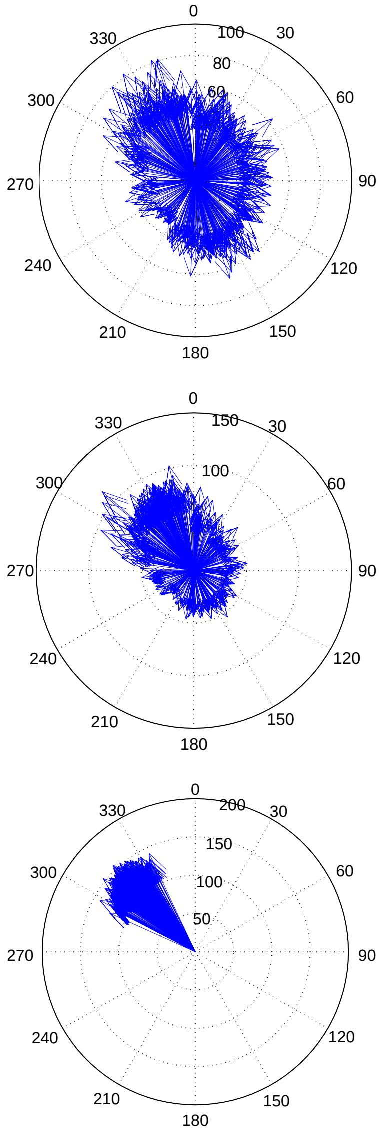

Fig. 8. Division of speed (given by the sum of surge and mean residual flow in cm s^{-1}) into twelve 30° directional sectors, at depths 349, 499 and 649 m from top to bottom.

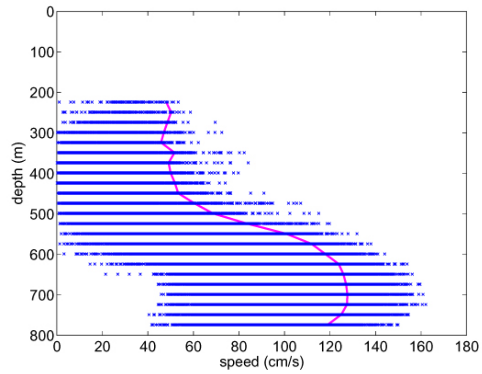

Fig. 9. Vertical variation of the threshold (0.95 quantile) in sector 300/330° at location FB. In blue all the available data and in magenta the threshold.

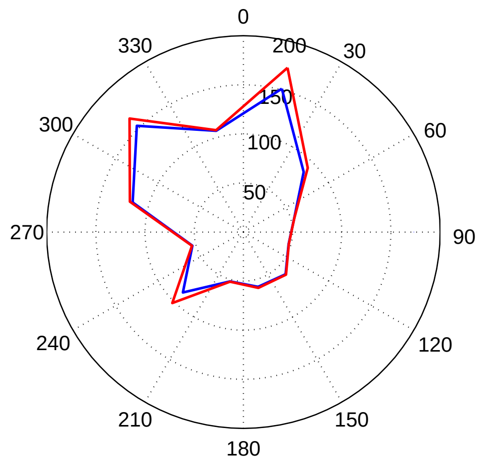

Fig. 10. Return level (cm s^{-1}) for 50 (red) and 250 (blue) years return period at location FB, 499 m depth.

As in Griffiths (1996) a big issue is the validity of 50 year return period extrapolation from only or less than one year data. Although Griffiths (1996) follows a systematic methodology, (1) no clear picture arises from the 50 year extrapolations; (2) the available data are insufficient to examine the vertical structure of the extreme surges as only five of the sites analysed have current meters at three or more depths; (3) the knowledge of currents in the near surface remains poor. In the present study, despite the lack of surface data, a clearer picture of the extreme current profile in total current and its components has been reached, due to the fact that current data were available for several vertical levels.

The short length of the time-series available for the extreme value analysis is a crucial factor in the interpretation of the results, particularly when considering the return level for very long return periods. Further analysis and longer time series are needed (as pointed out by Carter et al. (1987) and Griffiths (1996)) to obtain a reduction of standard errors.

The above mentioned literature studies take into considerations one or a few locations at only one or a few depths. A simple approach has been preferred here disregarding important factors (e.g. temporal dependence) to investigate, instead, the vertical profile of extreme currents considering the variations of the shape parameter and return levels with depth.

The dependence of extremes found between consecutive depths is probably due to a vertical propagation of flow, which is allowed only in layers characterised by the presence of the same water mass. The 2/3 layer structure found in the FBC prevents propagation up or down the water column and between levels filled in with different water masses.

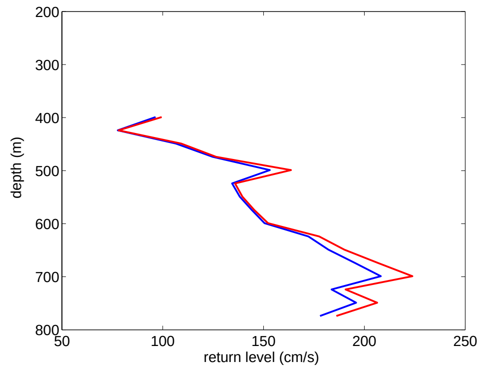

Fig. 11. 50 (red) and 250 (blue) years return level (cm s^{-1} obtained by fitting the GPD at different levels in sector 300/330°, at location FB.

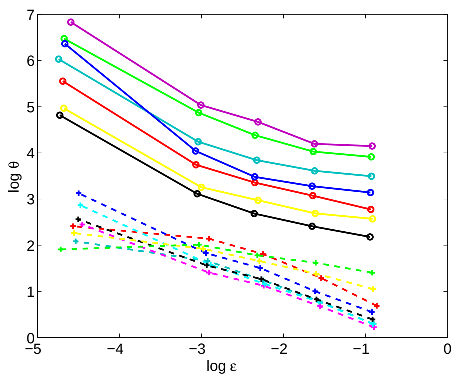

Fig. 12. Representation of the relationship between base rate and odds ratio on a log-log scale at site FB 699 m depth. The lines showing an upward trend refer to levels close to 699 m (from 599 to 774 m depth), while the ones showing a downward trend when the threshold increases refer to levels more distant from the reference depth.

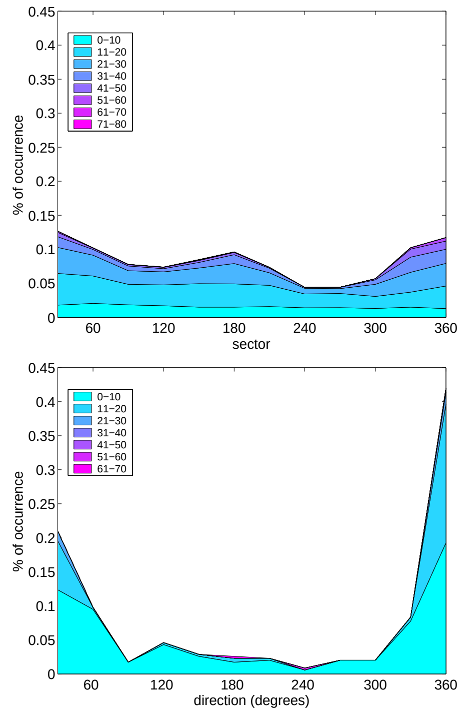

Fig. 13. Direction against percentage of occurrence for the current speed at location corresponding to VEINS FA/FB. Model (top) and observational (bottom) ata are shown at about 300 m depth.

6 Model currents

The main goal of the comparison between model and observational currents is to investigate whether incomplete General Circulation Models (GCM) like the Met Office's Forecasting Ocean Assimilation Model (FOAM) (see Foreman et al. (1996) and Heathershaw and Foreman (1996) for details on the model) could reproduce the characteristics of extreme events in ocean currents, particularly on a local scale. It should be noted that the model output contains no tidal information.

For this study only the 1/9° model time-series daily from 12 May 2002 were available. This was insufficient to allow application of the GEV and GPD extreme value distributions. However, great differences were found between the observational and model currents. Also, the FOAM data for the FBC are available only from 5 to 301 m depth. The horizontal resolution of the model is such that it cannot resolve FA and FB into separate grid boxes. That said, a strong northward directionality characterises the FOAM time-series in the near-surface layers in the FBC (Fig. 13). This was not found in the observational data from sites FB and FC (Fig. 13), but was at FA which is on the Faroese side of the channel.

The 0.95 quantile values were computed from observational measurements and were used as threshold for the analyses of the VEINS extreme currents. Fig. 14 shows that model currents throughout the water column in the FBC are generally smaller than the observed ones. Even after the tidal flow was removed from the VEINS time series the FOAM amplitudes were not as large as the sum of the VEINS low frequency and surge components (Fig. 14). Although, on average, the large currents were found to be smaller for the FOAM than VEINS data, the actual maximum value, in each layer, is generally similar for the model and measured currents.

In the model the value of the correlation coefficient between current speeds at two separate levels is very high (up to 0.98) for two close separation but decreases rapidly with increasing separation. This contrasts with the results found for the observational data presented above.

From what is shown in this study it can be said that FOAM is not able to fully reproduce the physical dynamics governing the flow pattern in the study area. One objection to this conclusion could be that the observational and model currents do not refer to the same year: the VEINS data used were collected from 1997 to 1999, while the FOAM time-series are more recent (2002–2003). However the observational currents as found in Carollo et al. (2005) are typical of the study area and follow the pattern described in the literature (Hansen and Østerhus, 2000). Hence, the model currents from this one year of data are, at the very least, atypical of the circulation pattern found from in-situ measurements.

It is thus found that both the FOAM vertical and horizontal resolutions are too coarse to represent the overflow through the FBC. The 1/9° resolution FOAM model reproduces eddies and fronts, however due to its relatively coarse resolution is not able to capture the mesoscale activity in sufficient detail to give a good description of these phenomena at the higher latitudes studied. This results in phenomena in this region being poorly represented. Higher resolution models (e.g. 1/12°) with also better vertical resolution in deep waters are suggested by this study to be needed to reproduce the observed circulation and to capture topographic and bathymetric changes and other physical phenomena influencing the flow.

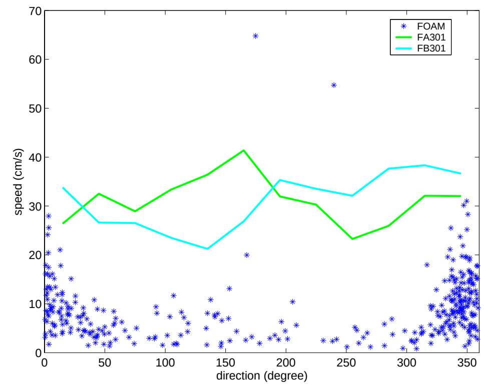

Fig. 14. Direction against model current speed at location corresponding to VEINS FA/FB, 301 m depth. The 0.95 quantiles used as thresholds were computed from the observational data at site FA 301 m depth (green) and at site FB 301 m depth (cyan).

7 Conclusion

In order to understand the main features of the extreme measures in the FBC, currents were separated into their components, namely tide, mean residual flow and surge. The stochastic current component (surge) was then analysed by fitting (1) the GEV distribution and (2) the GPD. The extreme value analysis was applied to several levels in the water column to detect extreme event characteristics through depth. The results showed an underestimation of extremes in total currents when analysing the surge component. A study of current profiles was performed and it was found that below 500 m the mean residual flow is the dominant component. It is therefore necessary to take this component into consideration when applying the extreme value analysis. GEV and GPD were then applied to the sum of surge and mean residual flow and new results obtained.

The shape parameter was found to be generally negative and return levels plots bounded. The return level for extremes in total currents can be easily determined by adding tides to the values found for defined return periods.

From the above results, it is possible to identify a three layer structure that divides the water column in surface, mid and deep waters. These are associated with the level of three different water masses (Borenas et al., 2001; Østerhus et al., 1999). This structure prevents vertical propagation. At these levels different components contribute in determining extremes in total currents and different processes occur, as outlined in the companion paper (Carollo et al., 2005). They show how, for instance, tidal ellipses reduce and change direction abruptly around 500 m depth, where the mean residual flow is enhanced by tidal rectification, and becomes the dominant component to determine extreme events in total currents.

This and the companion paper show the need to analyse the vertical current profiles prior to the application of the extreme value theory (1) to understand the different physical processes producing extremes in surface, mid, and deep waters; (2) to decide which components must be taken into consideration for the analysis of extreme currents; (3) to avoid underestimation of extremes in total currents.

The vertical structure of currents was considered to evaluate the current profile for given return periods. However no observational information were available for sea-surface currents. These currents would have been useful to create a link between atmospheric forcing and extremes occurring on the atmosphere-ocean interface.

The study of model data was made to obtain information about the ability of GCMs to reproduce extremes by comparing similarity in amplitude and direction with observational extremes. For the numerical ocean models that are global, there are two difficulties with the representation of the overflows. The first is concerned with the horizontal resolution of the channels through which the overflows move, and the second with the vertical resolution with which overflows are described (Saunders, 2001). For fine-resolution models (less than 1/4° and as fine as 1/10°) the former difficulty is less severe, although ideally several grid-points should span the channel (Saunders, 2001). But even where there is a good vertical resolution at shallow depths, like in FOAM (10 m intervals in the top 40 m), as the overflow descends the model vertical resolution coarsens, to something like 600 m intervals in excess of 2000 m in current models, which results in only one or two grid levels describing the vertical extent of the overflow (Saunders, 2001). These limitations have been witnessed here for the Met Office's FOAM in the FBC. Higher resolution model may prevent filtering out of extreme events and would also be a more useful tool for making predictions. Because of the inability of GCMs to resolve narrow passages, which serve as conduits for deep water flows, only a qualitative rather than quantitative comparison can be made between the modelled and observed currents. This is because the models do not yet contain all the physical processes that lead to current extremes: for instance, the dynamics related to the slope current along the European shelf and in presence of varying bottom topography. Hence, improving and understanding the physics of such flow mechanisms is fundamental to improve the inflow/outflow patterns in current numerical models.

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