Large Events in Ocean Currents

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***Abstract*-The variability of current speed is studied with the aim of predicting the return period and amplitude of large magnitude events in a given location. Time series of ccurrent profiles above three passages of the Iceland-Scotland Ridge are investigated. Their long-term variability has been subject of numerous studies, but no previous work has concentrated on instantaneous values, i.e. investigating large surge events, with the aim of understanding the vertical structure of extreme ocean currents. Spatial and temporal associations of large current events are also investigated. To understand the main features of large current events, tidal and non-tidal components are separated using a harmonic analysis approach and a filter is applied to remove the long-term trend. This allows the directionality of extremes to be studied. It is found that in these offshore locations the amplitude and directionality of extreme currents are mainly due to the non-tidal component. It is also observed, as to the vertical structure, that the amplitude of large currents decreases from the surface down to the sea floor.**

I. INTRODUCTION

This study attempts to analyze and understand spatial and temporal structures and associations of large or rare events in ocean currents with the aim to perform comparisons between observational and model derived data sets. This is to determine whether or not GCMs (General Circulation Models) can be used to predict large current events. To verify the simulation of large values in modeled ocean currents, it has to be assessed if observed and modeled extremes obey the same statistical description, showing similar amplitudes.

In this, analyses are made of variations in the current amplitude and direction in depth, space and time to investigate their possible dependence upon storms and bathymetry, and their possible seasonal clustering.

As this project focuses on large values of ocean currents, it necessarily restricts the available data sets. In fact, it involves the analysis of only the tail of the distribution of data. The second major aspect to take into consideration when analyzing extreme value distributions is the lack of long-term data with appropriate time resolution.

In order to understand the main features of measured large current events, tidal, non-tidal trend and stochastic components are first separated. The stochastic current speeds are then analyzed by (1) fitting the Generalized Extreme Value (GEV) distribution, and (2) using a threshold method, involving two different fitting distributions (Point Process Method and the Generalized Pareto Distribution), applied to detect large event features in the surge component.

Attempts are to be made to relate large currents to variables in the atmospheric storm record.

II. OBSERVATIONAL DATA SETS

Current profiles above three passages of the Iceland-Scotland Ridge (Fig. 1) are investigated. The passages are the Iceland-Faroes Gap (North East of the Faroe Islands), the Faroe-Bank Channel (West of the Faroe Islands), and the Faroe-Shetland Channel (South of the Faroe Islands).

The channels connect the North Atlantic Ocean to the Nordic Seas. Their importance lies in the exchange of water between the two basins: surface inflows of warm, saline water from the North Atlantic to the Nordic Seas and deep outflows of cold, dense water from the Nordic Seas to the North Atlantic [1]. These flows influence the regional climate and the global thermohaline circulation.

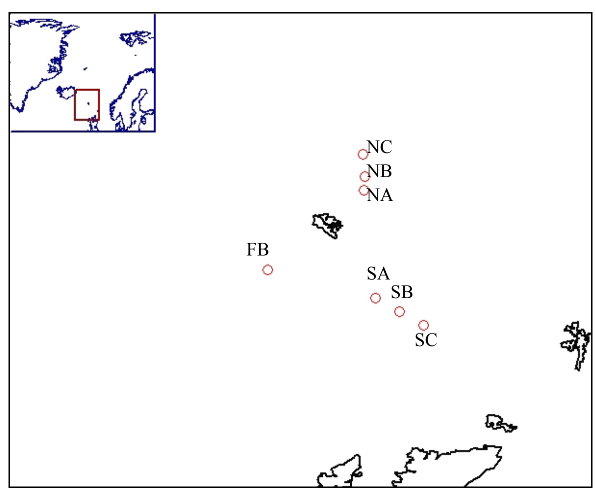

Fig. 1. VEINS moored ADCP in the Iceland-Scotland Ridge (from http://www.ices.dk/ocean/project/veins/).

It is extremely important to understand the variability of inflow and overflow currents; if they changed dramatically, in the worst case, they could cause the circulation to stop [9]. This would modify the climate over Northern European countries. For this reason, the long-term variability of these flows has been the subject of numerous studies; but no previous work has concentrated on instantaneous values, i.e. investigating large surge events, with the aim to understand the vertical structure in extreme ocean currents. These dynamic changes from the surface to the bottom are studied in this project.

The data used are upward-looking Acoustic Doppler Current Profiler (ADCP) records from the Variability of Exchanges in the Northern Seas (VEINS) project [3]. The measurements (in cm·s^{-1}) were taken from June 1997 to July 1999 in the three described passages from around 70 m depth down to between 300-900 m, according to the sea-floor depth at each location. They generally consist of a repeated one year-long record of 20-minute current speed versus depth profiles.

In the Iceland-Faroes Gap, where the Iceland-Faroes Front generally confines the Atlantic Water into a region north of the Faroe Islands, three main quasi-permanent mooring sites (NC, NB, NA) (Table I), plus a shorter deployment at a site ND (between NB and NC, but not considering in this study), were located on a north-south standard section, which crossed the flow (Fig. 1 and Fig. 2) [2]. From North to South (location NC to NA) there is a steep decrease in the bottom depth (from 1700 m to 300 m). At locations NB and NC measurements were taken every 25 m from around 70 m to around 600 m and at locations NA (shallow deployments) measurements were taken every 10 m from around 50 to around 280 m, such that velocities are available for 23/25 depths at each location.

So far, analyses have been performed only on data sets recorded in this channel.

From the observations, the Atlantic Water appears as a wedge-shaped current with relatively high temperature and salinity over the inner slope (Fig. 2). The current flows eastward as a jet with its core over the slope [1]. The jet shows no strong seasonal variability.

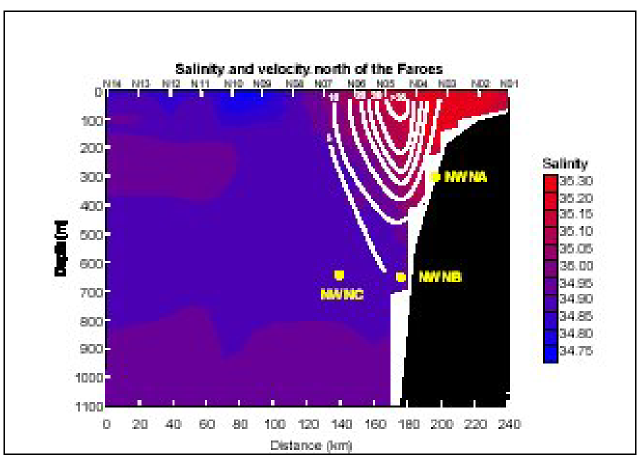

Fig. 2. VEINS moored ADCP North of the Faroes [1].

TABLE I
Deployment locations

	Year	Latitude	Longitude
NA	1996/1997	62° 7052N	06° 0862 W
NA	1997/1998	62° 7028N	06° 0840W
NB	1996/1997	62° 9135N	06° 0825W
NB	1997/1998	62° 9197N	06° 0817W
NC	1996/1997	63° 2737N	06° 1100W
NC	1997/1998	63° 2657N	06° 1048W

In the Faroe-Bank Channel the sill depth is around 840 m. This channel, the deepest of the Ridge, is the main outlet of cold waters: it carries a large amount of the overflows from the Nordic Seas, generally below 550 m [4]. At the central site, these cold waters flow northwestward in a current with average velocities exceeding 1 m/s in the core, centered about 120 m above the bottom. This core is located on the south west side of the channel along the slope of the Faroe-Bank [7]. Current measurements indicated that the overflow is formed in winter by ventilation processes, giving maximum overflow in August. More recent studies have shown that the seasonal variation is small relative to the magnitude of fluxes [8].

In the Faroe-Shetland Channel, from north to south (location SA to SC), the depth increases, from 300 m to 1100m. This is a deep and narrow channel and the overflow through it is one of the most important of the region. A seasonal cycle of the inflow with a peak in winter revealed by early measurements was found to be due to recirculation in the channel [8].

Surface currents in the Nordic Seas are generally cyclonic and consist of jets and re-circulation cells that are closely related to the bottom topography. The wind is the strongest force that leads to a variation in the strength of gyres and their interconnecting jets. This is the reason why current speed is higher in winter and in phases of high North Atlantic Oscillation Index (NAO) [9]. Despite the seasonal and interannual variability of the wind blowing over this region, the flows between the Nordic Seas and the North Atlantic seem to be very stable. So it could be that the response of the ocean circulation to the variation of this major force is confined, in this area, to the solely internal gyre re-circulations. In fact, a remarkable feature of the fluxes across the Iceland-Scotland Ridge is their steadiness [8]. This implies that the circulation over the ridges is characterized by strong re-circulations, guided by the local topography.

As the currents (surface inflows and deep overflows) flowing through the passages of the Iceland-Scotland Ridge are well known, it is expected to find a defined distribution pattern of large events characterized by statistical parameters with similar values at close locations, as described in literature for large gyres. Also, it is expected to see that large amplitude events have a well-defined temporal evolution and an evident seasonal feature (as the wind and the freshening of ocean water depend upon cyclical meteorological events).

These measured data sets from the VEINS project are not homogeneous (equally recorded) in time, space and depth. This fact is mostly due to how the experiment was defined and to the bathymetry of the area. Despite this lack of homogeneity, these data sets seem to be appropriate for answering the scientific questions of this study: considering the variability of ocean currents and, particularly, large events.

III. METHODOLOGY

Before applying the selected statistical methods for the analyses of observed large values, tidal, non-tidal trend and stochastic components are separated using a harmonic analysis approach and then filtered. This is made to statistically analyze only the stochastic components due to meteorological effects, after removing tides and trend.

The tidal component is removed from the raw u and v components ($cm \cdot s^{-1}$), using the POL/PSMSL (Proudman Oceanographic Laboratory/Permanent Service for Mean Sea Level) Tidal Analysis Software Kit 2000 (TASK2000). To allow this software to run a linear interpolation is required at some depths to fill in the gaps, due to missing data. These positions are then flagged and ignored by the software. A list of the constituents for one-year data made up of 58 harmonics is used for the analyses. This list includes a seasonal dependence for M2, but not long period tides [5].

For the filter, the Doodson X0 filter is chosen to remove the long-term trend (low frequency oscillations). This filter is designed to damp out the main tidal frequencies; it takes 19 values on either side of a central one and calculates a weighted average. It considers hourly values, so 57 values at the beginning and 57 values at the end of each time series are lost as measurements were taken every 20 minutes. In order to apply this filter another linear interpolation is performed to obtain continuous time series at every single depth. Subtracting this trend from the residuals with missing values leaves the surge. These are the stochastic time series necessary to detect large values in ocean currents.

With this methodology missing values are preserved and no new values are generated that could create errors in the analyses of the tails of the distributions.

At the end of this process the u and v components are used to evaluate speed and direction to identify large events at each depth.

The first approach used in studying the behavior of rare current events 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), $G(\mu,\sigma,\xi)$:

$$G(x) = exp\{-[1+\xi(x-\mu/\sigma)]^{(-1/\xi)}\}, \quad (3.1)$$

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. If $\xi<0$ it means that the quantiles are bounded and the extrapolation has a finite limit (i.e. short tail, Weibull distribution); if $\xi\geq0$ the distribution is unbounded and the extrapolation has an infinite upper limit (if $\xi\rightarrow0$, Gumbel distribution with medium tail; if $\xi>0$, Frechet distribution with long or "heavy" tail) [6].

To assess the fit, comparisons between empirical and model-based distributions (GEV) are also performed using the quantile-quantile and probability plots (Fig. 4). These are both graphical techniques for determining if two data sets come from populations with a common distribution. The first is a plot of the quantiles of the first data set against the quantiles of the second data set; the latter is the graph of recorded data against the theoretical distribution values. A 45-degree line is also plotted. If the sets come from a population with the same distribution, the points approximately fall along the reference line. The greater the departure from this reference line, the greater the evidence for the conclusion that the two data sets come from populations with different distributions.

The second method used to analyze large currents is the "threshold method". It requires the definition of a threshold (u); all the observations exceeding u are modeled according to some distribution. 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. The Generalized Pareto distribution, defined as

$$\Pr\{X_{n,i} > u + x \mid X_{n,i} > u\} = [1 + \xi (x/\sigma)]^{(-1/\xi)} \quad (3.2)$$

is used as the modeled distribution and the 0.90, 0.95 and 0.99 quantiles as thresholds to analyze the top 10%, 5% and 1% of currents, respectively. Two graphical techniques have been used to confirm the choice of the best value for the threshold: the mean residual plot and a second plot of maximum likelihood estimators against different values of the threshold (Fig. 6).

IV. RESULTS

The analyses of speed direction at each depth for the three locations show that large events do not generally appear in a preferred direction. However at most depths currents show larger values in differing sectors. This is evident from the results of the analyses of the top 1% of stochastic currents of the second year NA deployment (Fig. 3), in particular for the most surface measurements rather than for the deep ones. Also the first year NA and both NB deployments show some preferred sectors. For NC deployments, in particular for the first year, it seems currents are equally distributed in all the sectors and are characterized by very homogeneous values. This could be due to the distance of these deployments from the landmass. In fact the presence of the Faroe Islands could be one of the major causes of large currents in both NA and NB deployments that are closer to the Faroes than NC.

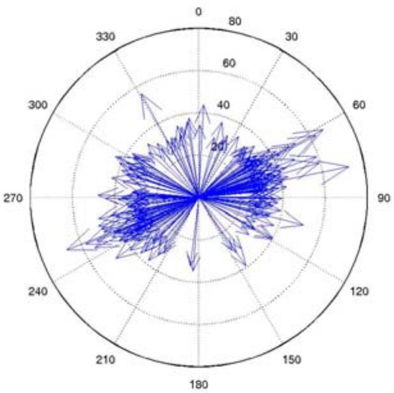

Fig. 3. Direction of the top 1% speed for the second year NA deployment.

Daily maxima are considered for the analyses of large currents using the GEV distribution. Generally medium tails characterize these processes; there are few long (mostly in the top measurements) and short-tailed processes. When the shape parameter estimate is very close to zero, the quality of the fitted model is doubtful especially in the upper tail, as can be seen from quantile plots. In fact the value of the standard error is quite big.

The results obtained from fitting the GEV distribution show that both probability and quantile plots assess the good quality of the fit in most of the analyzed cases, despite some departures from model accuracy in the upper tail in the quantile plot, which is much more sensitive than the probability plot.

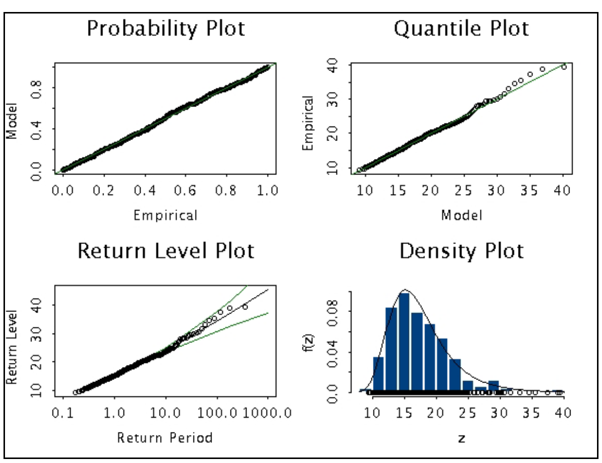

Fig. 4. Results obtained fitting the GEV distribution to the daily maxima for the first year NB deployment at 273 m. The return level is in cm·s^{-1}; the return period is expressed in days.

The return level plot, which includes 95% confidence intervals, shows how the fitted model extrapolates from the sample information [6]. When the shape parameter assumes a value close to zero the fit gives a near-linear extrapolation on the return level scale. When the estimated value of the shape parameter is negative, the fit gives a concave extrapolation in the return level plot. Once again it is possible to say that the fitted model has a generally medium upper tail, except in the top measurements.

The study of finite upper tails is assessed more carefully by examining the profile likelihood for the shape parameter (Fig. 5). From Fig. 5 it is clear that the 95% confidence interval is inside the negative domain, giving strong evidence that the shape parameter is negative. From this plot a general slight asymmetry can be detected, but a better method is the profile likelihood plot (Fig. 5) for different return periods that well point out strong asymmetries. Considering the $q_{1/m}$ quantile of the daily maxima the *m*-day return period is plotted.

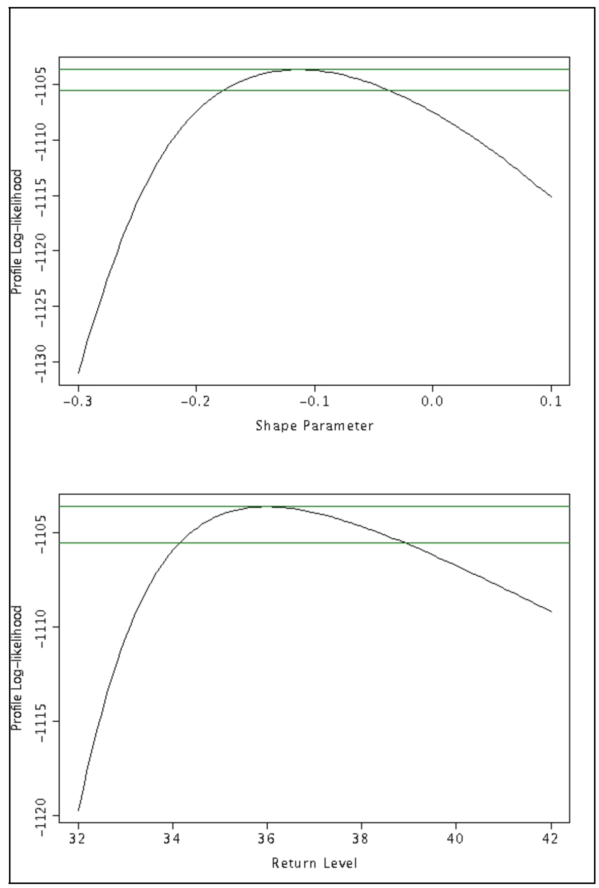

Fig. 5. Shape parameter profile log-likelihood (top) and return level plot for the second year NA deployment at 220 m. The return level is in cm·s^{-1}.

Results obtained from fitting the GEV distribution to the two different NA deployments show a trend in the shape parameter with depth: decreasing from the top measurements (around 50 m) down to about 200 m, then increasing. Long tails in the first 140 m, medium and few short tails characterize processes in these two locations.

As one of the aims of this project is to analyze association with storm events, the most important component to take into consideration is the effect of the wind on the surface measurements to explain this presence of large events in the first 200 m.

The two NB deployments show different results: for the first year the shape parameter shows a decreasing trend from the top measurements down to about 300 m, then the values oscillate around 0; this means that most of these processes are characterized by medium tails. For the second year the shape parameter shows a decreasing trend to around 400 m and then increasing to the bottom; once more medium tails characterize these processes. Results from NC deployments show that the shape parameter is generally smaller than in the previous cases at equal depths. The evidence is that the trend is decreasing from the surface (long tailed processes) down to the bottom (medium and short tailed processes).

Using the GPD mean residual life plot to find the best value for the threshold, the points show an upward trend, then the process is characterized by a heavy tail; data from a short tailed distribution would show a downward trend, as found for most of the considered depths in the two time series and shown in Fig.6.

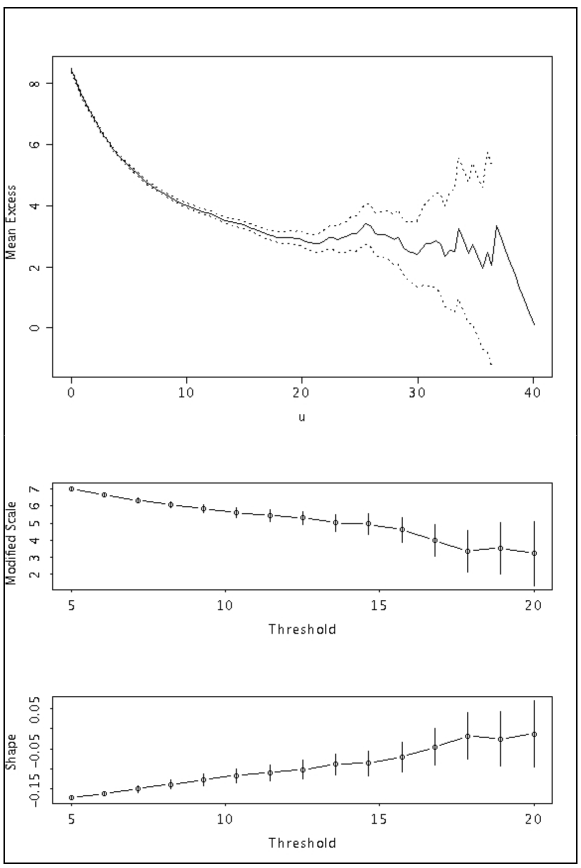

Fig. 6. Mean residual plot and maximum likelihood estimators against different values of the threshold for the second year NC deployment at 269 m. The value of the threshold u is in cm·s^{-1}.

If the empirical plot seems to follow a reasonably straight line with positive gradient above a certain value of u, then this is an indication that the data follow a GPD with $\xi>0$ in the tail area above u. If the choice of the threshold is correct, it should be that in the plot of the maximum likelihood estimators against different values of u (Fig. 6) the parameter estimates are more or less stable at a threshold where the asymptotics are valid. The value of the threshold found with these techniques is generally very close to the 0.95 quantile at each depth in all the time series.

As written above for the GEV distribution, probability and quantile plots provide a good fit (Fig. 7), despite the presence of some outliers in the top tail in quantile plots. Generally from these plots and from the shape parameter and its standard error, it seems that the best fit is the one obtained with the 0.95 quantile as threshold. This can also be seen from return level plots: increasing the value of the threshold from the 0.90 to 0.99 quantile the 95% confidence interval gets larger and less meaningful as the standard error also increases and the precision of a long term return period forecast decreases.

The value of the shape parameter for the two NA deployments is decreasing from the top measurements down to around 200 m and then increasing. This means that generally long tailed processes are in the top measurements for the first year deployment; for the second year the first few measurements are instead characterized by medium tails. For the first year NB deployment, the plot of the shape parameter against depth (Fig.8) suggests a decreasing trend from the surface (where measurements are not available) to about 120 m (long tailed processes), increasing from around 200 m and then again decreasing from 400 m (short tailed processes); below this depth the value of the shape parameter oscillates around zero.

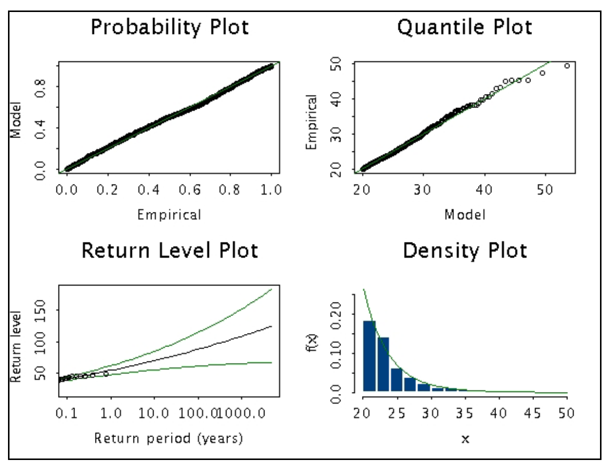

Fig. 7. Results obtained fitting the GPD with 0.95 quantile as threshold to the first year NC deployment at 223 m. The return level is in cm·s^{-1}; the return period is expressed in days.

For the second year NB deployment medium tailed processes are found down to around 320 m, followed by a region of short tailed processes, but the shape parameter shows an increasing trend from about 400 m to the bottom measurements: this is probably due to random effects. The results obtained analyzing the first year NC deployment show the same trend as the first year NB deployment, but with ξ slightly smaller. For the second year NC deployment the results generally show that processes are characterized by short tails (with few medium tails) all down the water column, with lowest values between 300-400 m.

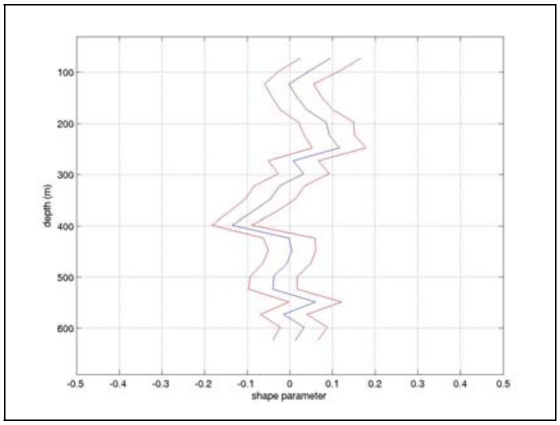

Fig. 8. Shape parameter and 95% confidence interval against depth for the first year NB deployment.

The Point Process distribution gives the same results for the shape parameter as the GPD fit; the GPD is preferred because it has the advantage of having only two parameters.

V. DISCUSSION

The indication that emerges from the analyses of large values in ocean currents is that for the deployments in NA and NB processes with long tails, i.e. $\xi>0$, are localized in the top 120-150 m; deep down medium and short tail processes dominate. These results are another proof to confirm the earlier observation that the processes creating large currents in locations NA and NB do not affect NC, as these locations are probably too far away from the source of the phenomenon. In fact, NC deployments are about 139 km in latitude and about 36 km in longitude away from Tórshavn (capital city of the Faroe Islands) and about 110 km in latitude and 12 km in longitude from Svínoy (30 km North and 22 km West of Tórshavn). If processes related to the presence of landmasses are the causes of large currents, this distance from the islands could be an explanation for what is found in the analyses.

These results are a confirmation of the speed pattern described in literature: the core of the highest speed is found to be over the slope, with decreasing large values from locations NA to NC.

It is however necessary to analyze storm tracks to verify if they were the cause of large values in the first two deployments that are about 63 and 39 km in latitude away from the third location and 76/100 km respectively in latitude and about 36 km in longitude from the capital city of the Faroe Islands.

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