FINNISH INSTITUTE OF MARINE RESEARCH – CONTRIBUTIONS

No. 9

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Finnish Institute of Marine Research, Finland
Helsinki 2004

Cover: Wave spectrum in slanting fetch conditions from the Gulf of Finland.

ISSN 1457-6805
ISBN 951-53-2589-7 (Paperback)
ISBN 952-10-1767-8 (PDF)

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Academic dissertation in Geophysics, to be presented, with the permission of the Faculty of Science of the University of Helsinki, for public criticism in the Auditorium XII of the main building, Unioninkatu 34, Helsinki, on May 8th, 2004, at 10 o'clock a.m.

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## CONTENTS

## LIST OF ORIGINAL ARTICLES

This thesis is based on the following articles, which are referred to in the text by their Roman numerals:

**I** Kahma, K.K. & Pettersson, H. 1994: Wave growth in a narrow fetch geometry. *The Global Atmosphere and Ocean System*, vol. 2, 253-263.

**II** Pettersson, H. & Kahma, K.K.: Directional measurements of wave growth in a short and narrow fetch geometry. Accepted with minor revisions to *Journal of Atmospheric and Ocean Science*.

**III** Pettersson, H., Graber, H.C., Hauser, D., Quentin, C., Kahma, K.K., Drennan, W.M. & Donelan, M.A. 2003: Directional wave measurements from three wave sensors during the FETCH experiment. *Journal of Geophysical Research*, vol. 108 (C3), 8061, doi:10.1029/2001JC001164.

**IV** Pettersson, H., Kahma, K.K. & Tuomi, L.: Predicting Wave Directions in a Narrow Bay. Submitted to *Journal of Physical Oceanography*.



## THE AUTHOR'S CONTRIBUTION

The author is fully responsible for the summary. In Paper **I** the author did the data analysis and contributed to a smaller extent to the writing. In Paper **II** the author took part of the field measurements, did large part of the analysis and most of the writing. In Paper **III** the author participated in the FETCH experiment and was responsible for the data from one of the sensors. The analysis and conclusions were made in close cooperation with the coauthors and the author did about half of the writing. In Paper **IV** the author is responsible for most of the work.

# Wave growth in a narrow bay

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Pettersson, H. 2004: Wave growth in a narrow bay. Finnish Institute of Marine Research – Contributions No. 9, 2004.

## ABSTRACT

Based on directional wave measurements from two narrow bays, the Gulf of Finland and Vanhankaupunginlahti in the Baltic Sea, and from Golfe du Lion in the Mediterranean Sea, the influence of the fetch geometry on the growth and spectrum of wind-generated waves has been studied. Reliable directional wave measurements are difficult to carry out, and different wave sensors can disagree significantly on the directional properties of the spectrum. A comparison of two of the wave sensors used in this thesis showed that the compatibility of these sensors was good. The measurements were divided into three categories, broad, narrow and slanting fetch geometries. When compared to wave growth from a straight shoreline, the growth was reduced when the waves grew along the bay. The change in the peak frequency was smaller than in the energy, indicating that the shape of the spectrum was not independent of the fetch geometry. In slanting fetch conditions the energy was reduced less and the peak frequency was comparable to that of the spectrum in the broad fetch geometry. The peakedness of the frequency spectrum decreased rapidly with increasing wave age in the narrow and slanting fetch geometries, but the decrease was much slower in the broad fetch geometry. The directional spreading parameter was not dependent on the wave age in any of the fetch geometries. The spreading in the narrow and slanting fetch geometries was of the same order and smaller than in the broad fetch geometry. The differences in the directional properties were visible already when the waves were young, but the differences in wave growth and in the shape of the frequency spectrum were smaller for young waves. Similarities with the spectral properties in the narrow fetch geometry were found in the spectra from Golfe du Lion during Mistrals that form a narrow belt of high, steady winds in the gulf. In a narrow bay like the Gulf of Finland, slanting fetch conditions are frequently encountered and they are the reason for the strong steering of wave directions to directions aligned with the axis of the gulf. The slanting fetch case was studied with three models with different assumptions of the directional coupling between the wave components. The comparison of the model results suggested that in slanting fetch conditions the nonlinear transfer is maintaining the peak of the spectrum in the direction of a longer fetch component by transferring energy from the higher frequencies in the wind direction towards the wave components at lower frequencies aligned with the longer fetch component.

Key words: wind waves, wave growth, fetch geometry, narrow bay, directional spectrum, wave sensor, wave modelling, Baltic Sea, Mediterranean Sea, Gulf of Finland, Golfe du Lion

# 1. INTRODUCTION

The wind-generated wave field resembles a chaotic ensemble of waves that are of different height, length, speed and direction. This fundamentally irregular phenomenon can be described by its statistical properties of which the wave spectrum is the most important. The directional wave spectrum, the distribution of wave energy in the frequency-direction space, has the information needed of waves in e.g. air-sea interaction studies and in many practical applications like the construction of off-shore structures, the operational safety of ships and the coastal management. The directional spectrum is the basis of the most developed wave models today. The evolution of the spectrum in deep water can be described by the transport equation:

$$\frac{\partial S(\omega,\theta)}{\partial t} + c_g \cdot \nabla S(\omega,\theta) = G_{in} + G_{nl} + G_{ds}$$

where S($\omega,\theta$) is the two-dimensional wave spectrum, $\omega$ the angular frequency, $\theta$ the direction of the wave component, and $c_g$ the group velocity. The three source terms on the right hand side are the wind input $G_{in}$, the weakly nonlinear interactions between the wave components $G_{nl}$ and the dissipation $G_{ds}$. The relative effectiveness of these terms define the evolution and the shape of the spectrum.

As measurements of directional spectrum have been, and still are, a difficult task (COST714 WG3 2004), most of the studies on factors that influence the growth of waves have been based on the measurements of the one-dimensional spectrum. Wave growth from a straight shoreline in steady winds is a rather well controlled situation, and according to the similarity theory presented by Kitaigorodskii (1962), the growth under these circumstances is controlled by the wind speed and the fetch length. The results from the experiments made in these conditions form the basis of our understanding of the wave growth. The JONSWAP experiment (Hasselmann & al. 1973) is one of the fundamental studies of the evolution of the one-dimensional spectrum in fetch-limited conditions and their form for the one-dimensional spectrum, the JONSWAP spectrum, is still widely applied. Their measurements showed that the peak of the spectrum shifted to lower frequencies when the fetch increased, but the shape of the spectrum remained nearly unchanged. Hasselmann & al. (1973) explained these features as the result of the nonlinear transfer between the wave components. The role of the nonlinear interactions $G_{nl}$ is to distribute the energy flux from the wind $G_{in}$ to the wave components, and if they are efficient enough they control the shape of the spectrum, also directionally. This assumption lead to parametric wave models, e.g. the model presented by Hasselmann & al. (1976) or the hybrid parametric wave model HYPA (Günther & al. 1979).

The assumption that the two-dimensional spectrum stabilizes to a universal form means that when the waves are growing along a narrow bay, or in situations when the wind is not straight from the shore, but from an angle to the shoreline (slanting fetch), the wave spectrum would still have the same shape and evolve like that from a straight shoreline. Saville (1954) was one of the first to discuss the possibility that the wave growth along a narrow bay is reduced. His method, that used a simple boxcar spreading function, produced an effective fetch to account for the fetch geometry effects, but still relying on the universal shape of the spectrum. Seymour (1977) argued that in the case of irregular coastline, it is not possible to define an effective fetch. He suggested that the waves grow directionally decoupled, and proposed a model for the spectrum, where each of the segments in the directional spectrum grow over a unique fetch, but having still the shape characteristics of a spectrum that grows from a straight shoreline.

The above studies were based mainly on one-dimensional spectra. When the directional wave measurements became more feasible, evidence was found that the nonlinear transfer is not efficient enough to shape the directional spectrum into a universal form in every situation. Hasselmann & al. (1985) and Janssen & al. (1994) found that this was the case in complex seas generated by a strongly variable wind. The experimental study of Donelan & al. (1985) is one of the most comprehensive studies on the directional spectrum. Their directional wave measurements from Lake Ontario showed that in slanting fetch conditions, i.e. when the distribution of the lengths of fetch components is not symmetric with respect to the wind direction, the direction at the peak of the spectrum had a tendency to align with a longer fetch component, while the shorter waves at higher frequencies were aligned with the wind direction. Based on these measurements, Donelan (1980) suggested that the direction of the dominant waves can be defined by the pair of the wind and fetch components that yields the largest period. This wave period will also have most of the total energy and consequently the shape of the spectrum is universal.

Holthuijsen (1983) reported similar results from the southern parts of the North Sea. He used stereophotography to measure the two-dimensional spectrum of waves in cases where shoreline was slanting or irregular. He applied the directionally decoupled model of Seymour (1977) to these cases and came to the conclusion that the waves grow directionally decoupled.

The third generation wave models, that represent the state of art in wave modelling today, solve in principle the transport equation without any assumptions on the spectral shape. Of the three source terms in the transport equation, only the nonlinear interactions $G_{nl}$ can be calculated exactly (Hasselmann & Hasselmann 1985), but the calculations have so far been too time-consuming for operational purposes. Hasselmann & al. (1985) developed an approximation to calculate the interactions, the discrete interaction approximation DIA, which produces the main features of the nonlinear interactions, like the downshifting of the spectral peak. As an approximation, the DIA has some shortcomings that require tuning of the source terms to produce the desired wave growth (van Vledder & al. 2000). The most well-known of the third generation wave models, WAM (WAMDI 1988, Komen & al. 1994), uses the DIA. The two other source terms, the wind input $G_{in}$ and the dissipation $G_{ds}$, are not as well known as $G_{nl}$ and consequently the balance of the source terms is known only approximately. This balance, on the other hand, is important for producing the fetch geometry effects.

Due to the difficulties in measuring the directional properties of the waves and the inaccuracies in the third generation wave models, the spectral response to the fetch geometry is still an open question. In this thesis directional wave measurements and models with different assumptions on the coupling between the wave components are used to study the influence of the fetch geometry on the growth and spectral properties of the wind-generated waves.

## 2. THE EXPERIMENTAL DATA

The experimental data in this study consist of three different data sets, of which the wave measurements in the Gulf of Finland in the Baltic Sea have a central role. This narrow gulf gives a good opportunity to study the influence of the fetch geometry on the growth of wind waves. The gulf is about 300 km long and between 70 to 120 km wide with reasonably straight shorelines. Papers **I** and **IV** give a more detailed description of the experimental area.

The Finnish Institute of Marine Research has made wave measurements periodically in the Gulf of Finland at three locations since the 1980's. Two of these sites, station Helsinki and station Porkkala, are situated in the narrowest part of the gulf, and the third, station Hanko, in the mouth of the Gulf of Finland (Fig. 1). In 1982-1985 waves were measured at station Helsinki with a wave buoy that does not measure the directional properties of the waves. In 1990-92, 1994 and since 2001 a directional wave buoy has been used at this station. Directional wave data were also obtained from the two other stations, station Porkkala in 1993 and station Hanko in 2001. The non-directional measurements in the 1980's were made with Waveriders and the directional measurements since the 1990's with Directional Waveriders. A short description of the Directional Waverider is given in Paper **III**.

The wind data was obtained from weather stations operated by the Finnish Meteorological Institute. The most important weather stations for this study are the automatic weather station Kalbådagrund for stations Helsinki and Porkkala, and Tulliniemi for station Hanko (Fig. 1). Of these two stations Kalbådagrund, a caisson lighthouse in the middle of the gulf, represent purely marine conditions, while Tulliniemi is situated on the southernmost tip of the peninsula of Hanko. The wind is measured at a height of 31.6 metres at Kalbådagrund and at a height of 44.7 metres at Tulliniemi.

The wind measurements from these two weather stations form the basis of the selection of the steady wind cases. The limits for the wind speed variation and trend were ± 30% and 1.6% per hour, and for the wind direction ± 30° and 2.5° per hour. The steadiness of the wind was further confirmed by wind measurements from weather stations at the northern coast of the Gulf of Finland and in the Baltic Proper, as well as by meteorological maps. The cases with swell were excluded from the data, except in Paper **IV**, where the data set includes cases with swell that were small and the peak frequency of which was clearly separated from the peak frequency of the wind sea.

At the measuring sites the water depth is 60 (Porkkala and Helsinki) and 75 metres (Hanko). The Gulf of Finland has a u-shaped topography and the waves long enough to feel the bottom tend to turn towards the shores. According to the refraction calculations (not shown) the refraction is insignificant for peak frequencies above 0.125 Hz, which was selected as a lower limit for accepted cases. These accepted cases were first divided into four data sets on the basis of the wave direction at the peak of the spectrum and the fetch geometry at each station. The north and south directions represent the broad fetch geometry. The directions along the bay in the east and southwest sectors were further divided into two subsections, narrow fetch and slanting fetch geometry data sets. The criteria for the narrow fetch data was that the spectrally weighted mean direction at frequencies higher than 1.5 times the peak frequency differed less than ± 10° from the mean direction at the peak of the spectrum. The strict limit for the direction at the high frequency part of the spectrum was chosen to ensure the quality of the narrow fetch geometry data set and consequently the slanting fetch data set includes weakly and strongly slanting fetch cases. The sectors for each station in the Gulf of Finland and the number of observations are given in Table 1.

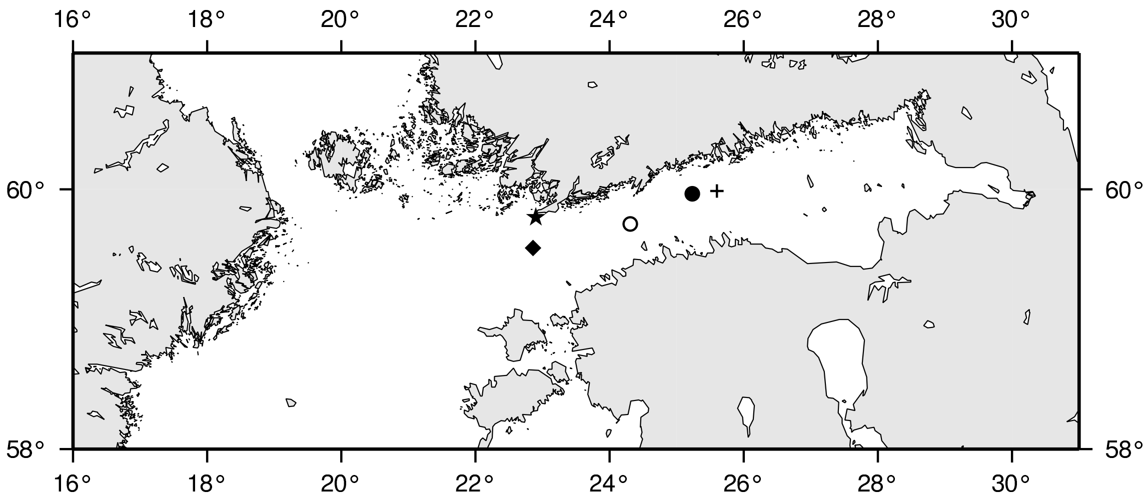



Fig. 1. Wave measuring sites in the Gulf of Finland, Hanko (diamond), Porkkala (open circle) and Helsinki (bullet). The automatic weather stations Tulliniemi and Kalbådagrund are denoted by a star and +, respectively.

Table 1. The geographical sectors for each station in the Gulf of Finland.

| Station | North | South | East | Southwest |
|---|---|---|---|---|
| Helsinki | 265° – 54° | 125° – 224° | 55° – 124° | 225° – 264° |
| Porkkala | 275° – 54° | 100° – 229° | 55° – 99° | 230° – 274° |
| Hanko | – | 90° – 210° | 50° – 89° | – |
| Number of obs. | broad: 29 | | narrow: 84 ; slanting: 146 | |

The two other data sets are from a small bay called Vanhankaupunginlahti and from the Mediterranean Sea. The data set from Vanhankaupunginlahti consists of short fetch directional wave measurements, made in a bay situated in the estuary of River Vantaa on the eastern side of the cape of Helsinki (Figure 1 in Paper **II**). The experimental arrangements and the wave data, measured with an array of six wave staffs, is described in detail in Paper **II**. The third data set is from Golfe du Lion in the western Mediterranean Sea where an experiment called FETCH (Flux, Etat de la mer et Télédétection en Conditions de Fetch variable) took place in March-April 1998 (Hauser & al. 2003, Paper **III**). The purpose of the experiment was to study the air-sea interaction processes, directional wave spectrum in fetch-limited conditions during high winds and the ocean circulation. This data set consists of directional wave measurement made with a Directional Waverider and an Air-Sea Interaction Spar, ASIS (Graber & al. 2000, Paper **III**). The criteria in selecting the steady wind cases in Golfe du Lion were the same than for the data set of the Gulf of Finland.

## 3. ONE-DIMENSIONAL PROPERTIES OF FETCH-LIMITED WAVES IN A NARROW BASIN

### 3.1. Dimensionless growth curves

The similarity law of Kitaigorodskii (1962) is an efficient and widely used tool in studying the properties of the fetch-limited wind waves in steady winds. According to the scaling law, the growth of waves in these conditions is controlled mainly by two factors, the fetch X and the wind speed U (and the gravity g). For the dimensionless parameters the following notation is used: the dimensionless fetch is $\tilde{X} = gX/U^2$, the dimensionless energy $\tilde{\varepsilon} = \varepsilon g^2/U^4$, where $\varepsilon = \int_0^\infty S(\omega)d\omega$ is the variance of the spectrum $S(\omega)$ and $\omega$ the frequency. The dimensionless peak frequency is $\tilde{\omega}_p = \omega_p U/g$ where $\omega_p$ is the peak frequency. In the cases studied here, the water can be considered deep, and the dimensionless peak frequency equals the inverse wave age $U/c_p$, where $c_p$ is the phase speed at the spectral peak. The wind speed represent the wind at a height that is not affected by the processes between the waves and atmosphere and usually the height of ten metres is chosen. The parameters can also be scaled with the friction velocity $u_*$ instead of $U_{10}$, but it is not clear which of the two parameters is the best choice (Kahma & Calkoen 1992, Komen & al. 1994). When direct measurements of $u_*$ are not available, it has to be calculated from the wind speed $U$, and the values are dependent on the calculation method itself (Kahma & Calkoen 1994). In principle the use of $u_*$ should account for the observed difference in wave growth in stable and unstable atmospheric stratification, but this has not yet been verified with direct measurements of $u_*$ (Kahma & Calkoen 1992).

The wave growth in terms of Kitaigorodskii's scaling law from orthogonal fetch and along a narrow gulf differ clearly from each other as shown in Paper **I**. The reduction in the dimensionless energy is pronounced, but the dimensionless peak frequency changes less, indicating that the fetch geometry modifies the spectral shape. Similar results from the narrow Lake Washington were also reported by Ataktürk (1991) and Ataktürk & Katsaros (1999). The different response of the energy and peak frequency to the restricted width of the fetch geometry also means that no simple effective fetch can be found for the wave growth in a narrow bay.

The analysis in Paper **I** was based on non-directional measurements from station Helsinki (1982-1985), and the division of the data into broad and narrow fetch geometries was made according to the wind directions. There were 10° - 20° spaces between each sector to ensure that the cases were orthogonal or along the gulf. The corresponding analysis, but including all the directions, made from the directional data divided into three categories, broad, narrow and slanting fetch geometries according to the criteria described in section 2, is shown in Figure 2. Evidently the broad fetch geometry data set in Paper **I** includes slanting fetch cases and contributes strongly to the large scatter in this data set. If the division of the present directional data into broad and narrow fetch geometries is done using the wind direction and the sectors in Paper **I**, the mean direction at the spectral peak in about 80% of the broad fetch geometry cases is aligned with the gulf. This indicates a strong steering of the wave directions in the Gulf of Finland (section 4.2 and Paper **IV**). Nevertheless, like in Paper **I**, the broad fetch geometry data agree well with the composite growth curves of Kahma & Calkoen (1992, hereafter KC92, see also Papers **I** and **II**), and the narrow fetch geometry data show a slower growth (Fig. 2). The slanting fetch cases have slightly higher energies than the narrow fetch geometry cases, but the evolution of the peak frequency is practically the same as in the broad fetch geometry. When the dimensionless energy is plotted against the dimensionless peak frequency (Fig. 2c), there is not much difference between the slanting and narrow fetch cases. It is evident that the $U_{10}/c_p$ scaling cannot be regarded as independent of fetch geometry when the waves are mature.

In the case of the younger waves, the Vanhankaupunginlahti short fetch data, the differences between the fetch geometries are not as clear (Fig. 2). The dimensionless energy for the narrow fetch data fall below the values predicted by the KC92 growth curve, but so do the broad fetch geometry data points. The reason for these lower energy levels in the broad fetch data set is not solved (Paper **II**). When data points from the WAM database (Kahma & Calkoen 1992) is added to the plot, the Vanhankaupunginlahti broad fetch data fall inside the scatter, and a slower growth in the narrow fetch geometry will become evident (Figure 4 in Paper **II**).

The Vanhankaupunginlahti broad fetch geometry data were measured during westerly winds. After a while the wind direction turned to the northwest, and the shoreline became weakly slanting with respect to the wind direction (Fig. 1 in Paper **II**), and the directional properties of the spectrum showed slanting fetch features (sections 4 and 5). These measurements are added to Fig. 2. The cases have more energy than the Vanhankaupunginlahti narrow and broad fetch geometry data, but they still fall below the KC92 growth curve. The dimensionless peak frequency is very close to the KC92 curve and the $\tilde{\omega}_p - \tilde{\varepsilon}$ plot in Fig. 2c does not show much differences between the three fetch geometries for the young waves, only the narrow fetch geometry data show a marginal deviation.

Some evidence of the sensitivity of the wave growth on the basin width can be seen in both narrow and slanting fetch geometry cases from the Gulf of Finland: the dimensionless energy was higher for waves from the broader eastern sector than for waves from the narrow southeastern sector (Fig. 1). On the other hand, the evolution of the peak frequency was nearly similar in both directions (not shown). The overall fetch geometry in the slanting fetch geometry cases are different in the Gulf of Finland and in Vanhankaupunginlahti. In the Gulf of Finland the narrowness of the gulf forms an additional restriction to the wave growth in slanting fetch conditions (Fig. 1), while in Vanhankaupunginlahti the bay is broader (point **b** in Fig. 1 of Paper **II**). In order to find out how strong influence the width of the basin has on the energy levels when the waves are more mature, a slanting fetch case from Golfe du Lion is added to Fig. 2. This Mediterranean case from 12 April 1998 is also from a rather weak slanting fetch situation. The Tramontane wind, a local wind that blows along the valley of Garonne, was from northwest, and the mean direction at the

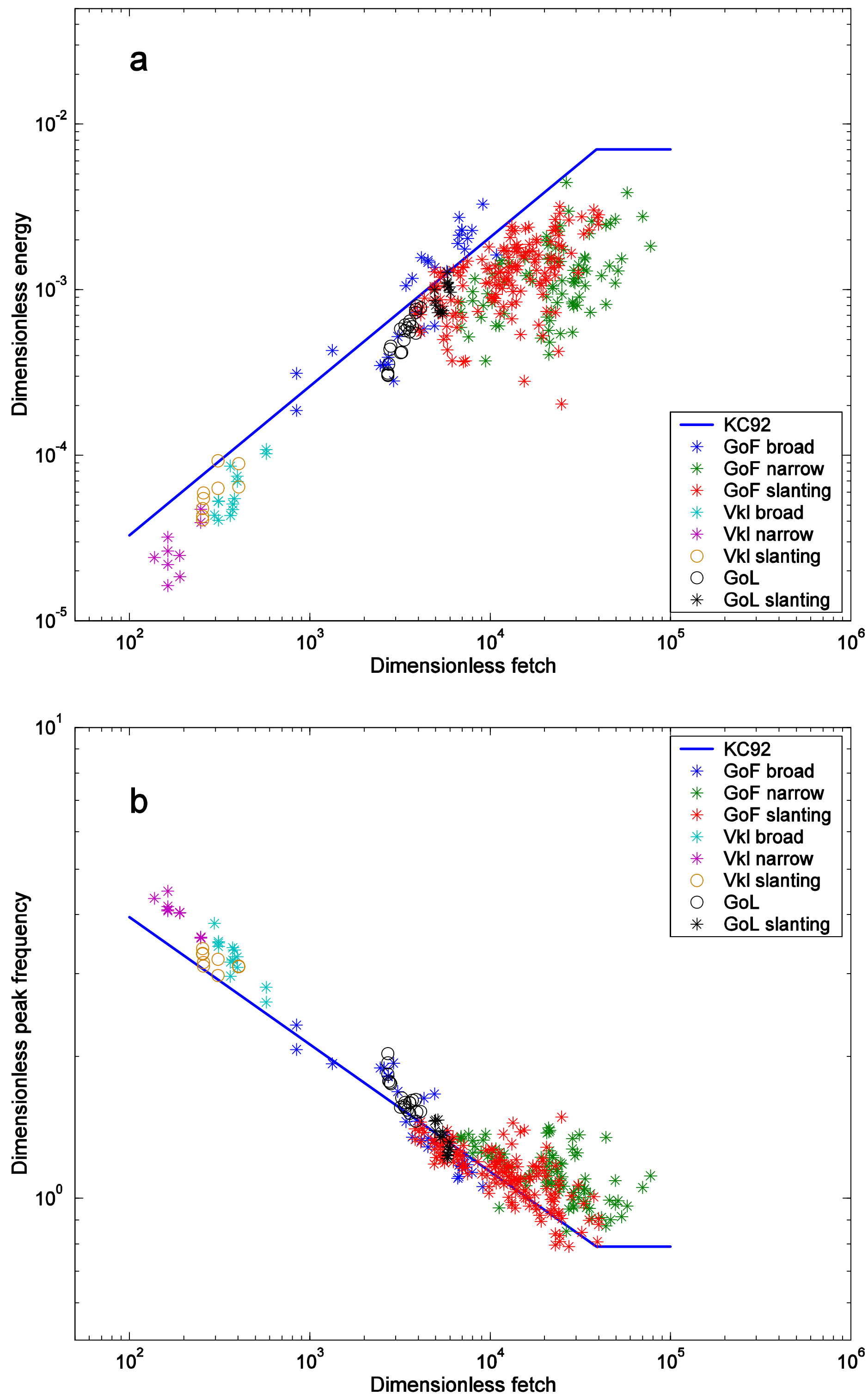



Fig. 2a-c. Dimensionless growth curves. Panel a shows the dimensionless energy versus dimensionless fetch, panel b the dimensionless peak frequency versus dimensionless fetch and panel c the dimensionless energy versus the dimensionless peak frequency. The solid line denotes the growth curves for composite data set from Kahma & Calkoen (1992), see also Paper **I**. GoF means the Gulf of Finland data, Vkl the short fetch measurements from Vanhankaupunginlahti and GoL the Golfe du Lion data.

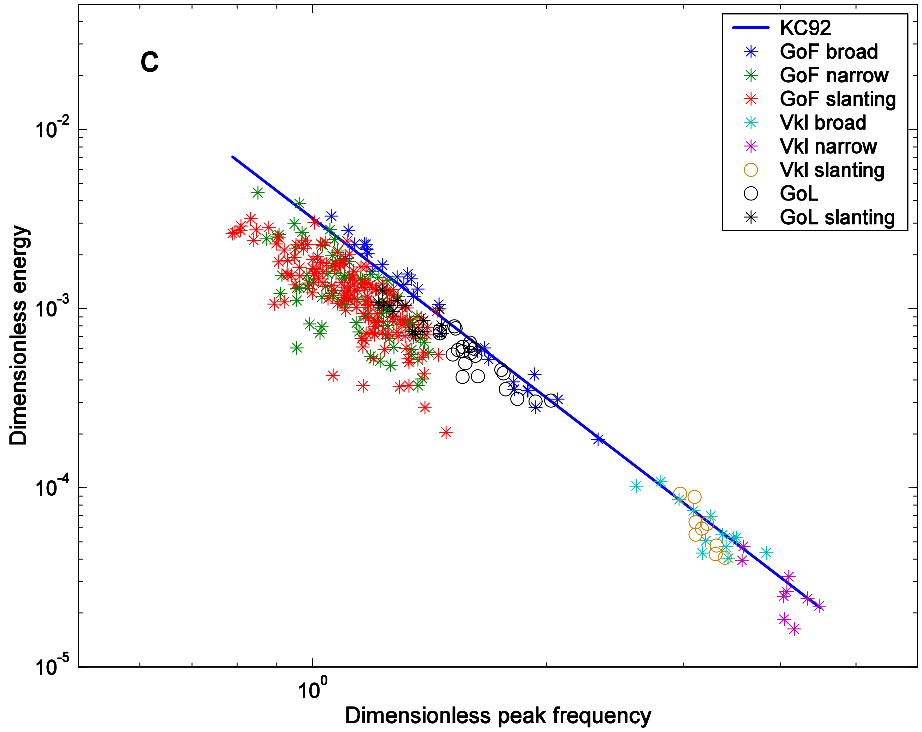



Fig. 2a-c continues.

spectral peak was from southwest-west (Fig. 1 in Paper **III**). The central basin of the Mediterranean Sea opens to the south-southeast. This case behaves very similarly to the Gulf of Finland slanting fetch data, and the broadness of the bay seems to play a minor role in slanting fetch situations.

Like in the dimensionless growth curve analysis in Paper **I**, the atmospheric stratification is not taken into account in the present analysis of the mature waves. In the data sets there were no strongly stable cases, but 10 % of z/L values, where z is the measurement height and L the Monin-Obukhov length, were in the range of 0 ... 0.4. These nearly neutral data form 30 % of the narrow fetch data set and 4 % of the slanting fetch data set for mature waves. As 86 % of the data fall in the z/L range of -1 ... 0.4, all the data has been treated as a composite data set. The division of the data according to the stratification includes also uncertainties because representative air temperature measurements were not available for stations Helsinki in 1990-92 and Hanko in 2001, which cover about 17 % of all the data, and 55 % of the broad fetch data set for mature waves. The influence of the stratification on the results was examined in the limits of the uncertainties in the air temperature, which gave no indications that the stratification, which in this case means two groups, strongly unstable and unstable-near neutral, could explain the differences between the wave growth in the three different fetch geometries. All the short fetch cases from Vanhankaupunginlahti were measured in unstable stratification, and the growth is compared to the KC92 growth curves for unstable stratification in Paper **II**. The deviation from the KC92 unstable growth curve is larger (Fig. 4 in Paper **II** and Fig. 2), but the conclusions remain the same in both cases.

The length of the fetch in this analysis is defined as a mean of the sector in question. Donelan & al. (1985) presented the concept of wave fetch, defined as the length of the fetch in the approach direction of the dominant waves, and scaled with $U_{10}\cos\theta$, where $\theta$ is the angle between the wind and the dominant wave directions. In the broad and narrow data sets the traditional definition, fetch length in the wind direction and $U_{10}$ equals the Donelan & al. (1985) definition. The Donelan & al. (1985) definition restored data from Lake Ontario that include also slanting fetch cases to a universal growth curve (Donelan & al. 1985), but in wave growth along a narrow bay, like in the Gulf of Finland, this approach does not combine the broad and narrow fetch geometry data sets (Paper **I**) and consequently it cannot be regarded as a way to compensate all fetch geometry effects. Here the focus is in the differences between the three fetch geometries, and the fetch in the wind direction is used. In addition, this approach is not as prone to spurious correlation as is the Donelan & al. (1985) definition (Kahma & Calkoen 1992 and Paper **I**), especially when the dimensionless energy is plotted against the dimensionless peak frequency (Fig. 2c).

### 3.2. The frequency spectrum

The dimensionless presentation suggests that the shape of the spectrum cannot be regarded as universal. The shape of the one-dimensional spectrum, the frequency spectrum $S(\omega)$, has been the subject of many studies, especially the slope of the rear face of the spectrum. Since Phillips (1958) suggested that the slope of the saturation range of the spectrum follows a power law of $\alpha\omega^{-5}$, where $\alpha$ is a constant, more evidence of an $\omega^{-4}$ slope has been presented (e.g. Kahma 1981, Forristall 1981, Donelan & al. 1985), and the parameter $\alpha$ can no longer be regarded as a constant (e.g. Hasselmann & al. 1973, Mitsuyasu & al. 1980, Kahma 1981, Donelan & al. 1985).

In Fig. 3 the spectra from the three different fetch geometries is presented in the form used by Donelan & al. (1985). The spectrum $S(\omega)$ is multiplied by $\omega^4$ and divided by the average of $S(\omega)\omega^4$ in the frequency range of $1.5\omega_p < \omega < 3\omega_p$. In all fetch geometries the rear face of the spectrum in this frequency range follows the $\omega^{-4}$ slope. In deep water, and in the absence of swell, the power law of the rear face of the frequency spectrum can be distorted by the Doppler shift caused by currents (Kitaigorodskii & al. 1975). Due to the lack of coincident current measurements or ocean circulation model runs, an analysis of the possible effect of the currents has not been made. It is only stated that the slope of the rear face of the spectrum at frequencies $1.5\omega_p < \omega < 3\omega_p$ in these data is in agreement with the more detailed analysis of the saturation range of the spectrum made by e.g. Kahma (1981) and Donelan & al. (1985).

The mean spectra from the broad fetch geometry data from the Gulf of Finland and Vanhankaupunginlahti, grouped in four inverse wave age $U_{10}/c_p$ classes, are plotted in Figure 3a. These data show only a small increase of the peakedness of the spectrum with $U_{10}/c_p$. This contradicts the results of Donelan & al. (1985), but are in accordance with the results of Kahma (1981). The Vanhankaupunginlahti data that form the highest $U_{10}/c_p$ class, $2.6 < U_{10}/c_p < 3.8$, have some uncertainties as the energy in this data set was smaller than predicted (Paper **II** and section 3.1), but this does not mean that the shape of the spectrum itself is necessarily distorted (Paper **II**). The corresponding mean spectra from the narrow and slanting fetch geometries is plotted in panels b and c of Figure 3. The narrow and slanting fetch geometry data from the Gulf of Finland includes only $U_{10}/c_p$ values of 0.8 ... 1.5, but the data show some evidence of a stronger increase of peakedness with $U_{10}/c_p$. Adding the narrow and slanting fetch geometry data from Vanhankaupunginlahti to the panels suggests that the peakedness of the spectrum is more strongly dependent on the wave age in narrow and slanting fetch geometries than in the broad fetch geometry. The slanting fetch case from Golfe du Lion has $U_{10}/c_p$ values between 1.2 and 1.4, and the normalized mean spectra is little more peaked than the corresponding data from the Gulf of Finland (dashed line in Fig. 3c).

The peakedness of the spectrum can also be presented by the peak enhancement parameter $\gamma$ presented by Hasselmann & al. (1973). The parameter $\gamma$ is defined as the ratio between the maximum of the spectrum and the maximum of the corresponding spectrum for fully developed waves of Pierson & Moskowitz (1964) (Hasselmann & al. 1973). The peak enhancement parameter from the three fetch geometries is plotted against the inverse wave age in Fig. 4a, and as mean values in ten classes of inverse wave age in Fig. 4b. The scatter is large, but the broad fetch data show a very slow decrease with increasing wave age while the decrease is much faster in the case of narrow and slanting fetch data. These latter data approaches the value $\gamma = 1$ as the inverse wave age approaches the Pierson-Moskowitz fully development limit $U_{10}/c_p = 0.79$. The slanting fetch case from Golfe du Lion does not deviate from this interpretation (Fig. 4). There is a gap in the narrow and slanting fetch data between inverse wave ages 1.5 ... 3, but when the waves are younger than that, no differences in peak enhancement can be found in the strongly scattered values.

## 4. DIRECTIONAL SPECTRUM

### 4.1. Directional measurements and parameters

Information about the directional properties of the waves is needed in a variety of applications ranging from air-sea interaction studies to different off-shore activities. Measuring the directional spectrum is not an easy task, and none of the existing sensors today can provide all the data needed for a complete directional spectrum (COST714 WG3 2004). The use of the directional information is further complicated because sensors with different measuring principles sometimes disagree significantly on the directional properties of the wave field, and if data from different wave sensors are combined, the performance of the sensors with respect to each other has to be known (COST714 WG3 2004 and Paper **III**).

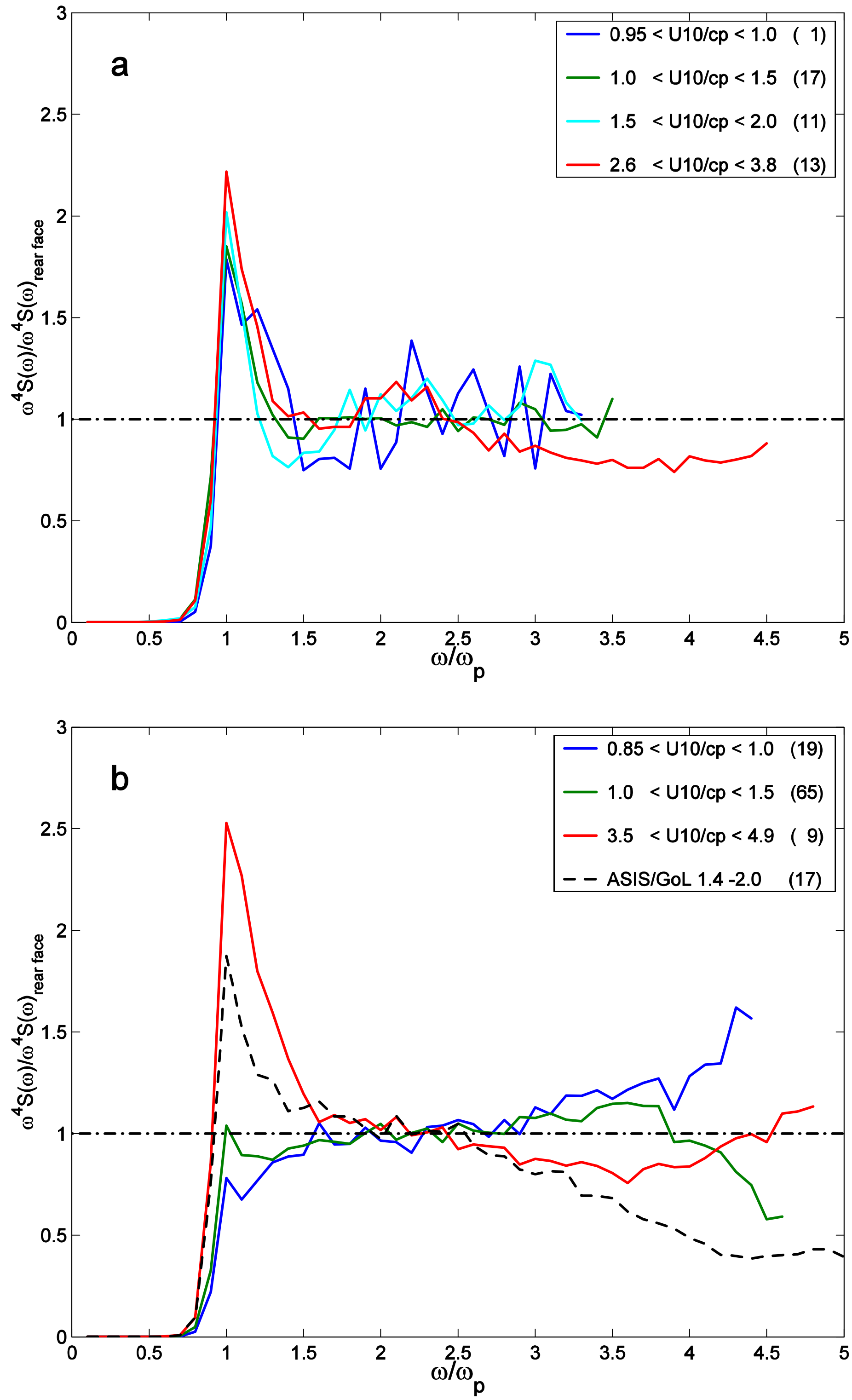



Fig. 3a-c. The normalized spectrum in four inverse wave age classes. Panel a: broad, panel b: narrow and panel c: slanting fetch geometries. The numbers in the parenthesis denote the number of observations in each class. The ASIS and DWR data from Golfe du Lion is denoted by dashed lines in panels b and c, respectively.

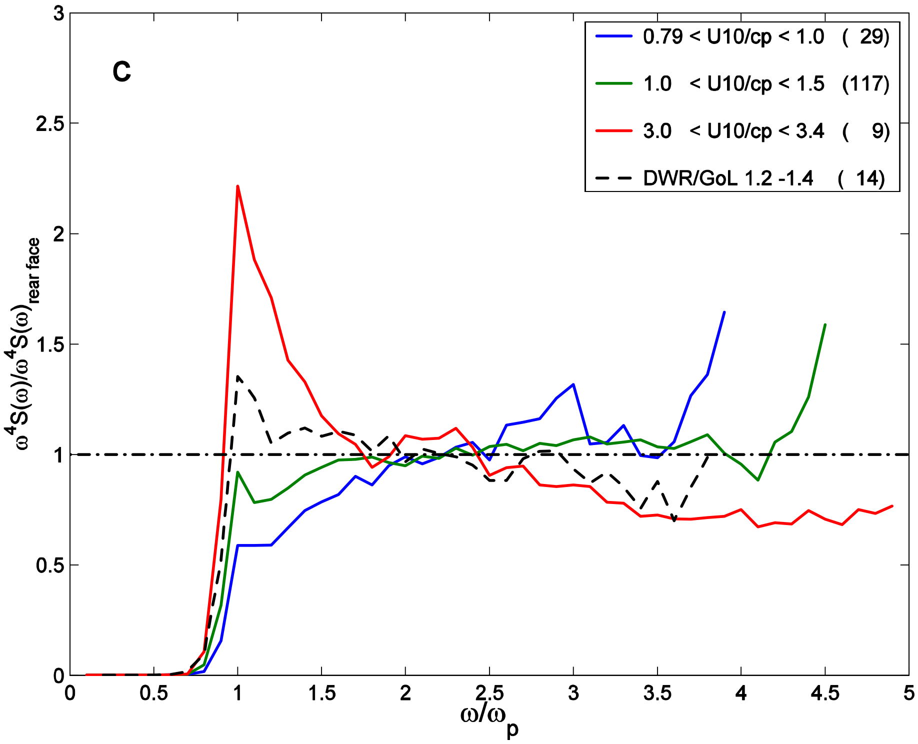



Fig. 3a-c continues.

The data from the Gulf of Finland and the slanting fetch case on 12 April 1998 from Golfe du Lion were measured with Directional Waveriders. This type of buoy measures the surface displacement in three directions, and the directional parameters as function of frequency is calculated on board the buoy by the method presented by Longuet-Higgins & al. (1963). From three displacement time series it is possible calculate the first two pairs of Fourier coefficients

$$a_1(\omega) = Q_{12}(\omega)/\sqrt{(C_{22}(\omega)+C_{33}(\omega))C_{11}(\omega)}$$

$$b_1(\omega) = Q_{13}(\omega)/\sqrt{(C_{22}(\omega)+C_{33}(\omega))C_{11}(\omega)}$$

$$a_2(\omega) = (C_{22}(\omega)-C_{33}(\omega))/(C_{22}(\omega)+C_{33}(\omega))$$

$$b_2(\omega) = 2C_{23}(\omega)/(C_{22}(\omega)+C_{33}(\omega)) ,$$

where $C_{ij}$ and $Q_{ij}$ are the co- and quad spectra of the cross spectrum between the $i$th and $j$th displacement time series in the vertical (1), west (2) and north (3) direction. The centered Fourier coefficients are

$$m_1(\omega) = \sqrt{a_1(\omega)^2 + b_1(\omega)^2}$$

$$m_2(\omega) = a_2(\omega)\cos(2\theta_1(\omega)) + b_2(\omega)\sin(2\theta_1(\omega))$$

$$n_2(\omega) = b_2(\omega)\cos(2\theta_1(\omega)) - a_2(\omega)\sin(2\theta_1(\omega))$$

The mean direction as a function of frequency is

$$\theta_1(\omega) = \arctan(b_1(\omega)/a_1(\omega))$$

and the directional spreading

$$\sigma_1(\omega) = \sqrt{2(1-m_1(\omega))}.$$

The directional skewness and kurtosis are defined as

$$\gamma_2(\omega) = -n_2(\omega)/[0.5(1-m_2(\omega))]^{3/2}$$

$$\delta_1(\omega) = (6-8m_1(\omega)+2m_2(\omega))/[2(1-m_1(\omega))]^2$$

respectively (see e.g. Kuik & al. 1988 for a detailed description).

In order to be able to combine the directional wave data from Vanhankaupunginlahti that were measured with an array of six wave staffs (Paper **II**) to the directional buoy data from the Gulf of Finland, the heave, pitch angle and roll angle time series were calculated from the raw data. The directional parameters were then calculated from the time series using the Longuet-Higgins & al. (1963) method. That the two sensors themselves have different measuring principles is of course an uncertainty that cannot be removed. The consistent behaviour of the directional parameters in Paper **III** gives some confidence on these parameters in general. The comparison in Paper **III** was made between a Directional Waverider, a floating array of six wave gauges ASIS (Graber & al. 2000) and the real-aperture radar RESSAC (Hauser & al. 1992), all of which have different measuring principles. Of these three wave sensors, the ASIS buoy has the same measuring principle as the wave array in Vanhankaupunginlahti.

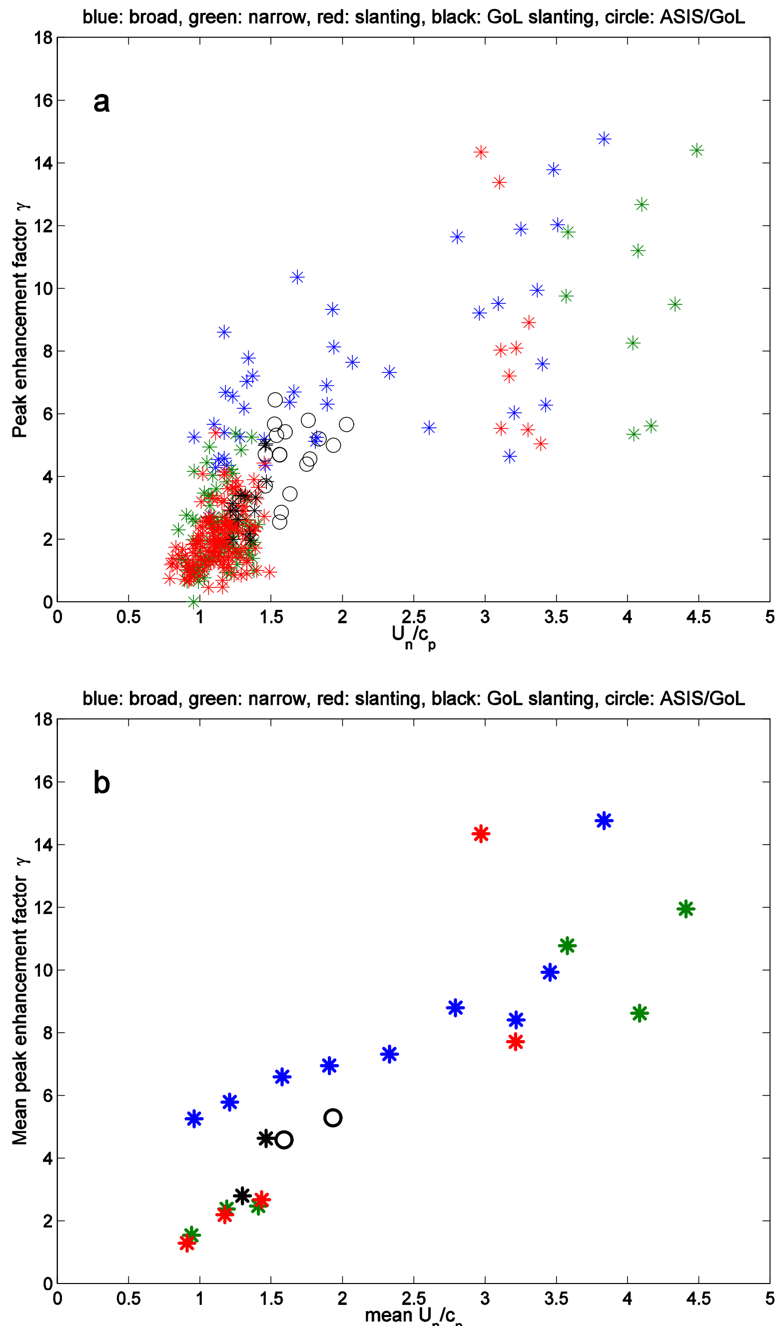



Fig. 4a-b. The peak enhancement factor. Panel a: all data, panel b: mean values. Blue stars denote the data from broad fetch geometry, green stars data from the narrow fetch geometry and red stars the data from slanting fetch geometry. The open circles denote the ASIS data and the black stars the DWR slanting fetch data from Golfe du Lion.

It is also possible to calculate the two-dimensional frequency-direction spectrum from the buoy and wave array data, using e.g. Maximum Likelihood Method MLM (Capon 1969) or Maximum Entropy Method MEM (Lygre & Krogstad 1986). As in the case of wave sensors that measure the two-dimensional spectrum directly (Paper **III**), the Fourier coefficients that give the directional parameters can be calculated from the two-dimensional spectrum according to the basic definitions. Unfortunately the two-dimensional spectra calculated with these two methods can look very different from each other (e.g. Ewans 1998, Kahma & Pettersson 2004), and consequently the directional parameters obtained from the two methods can be expected to differ. This is especially so in the case of the directional spreading, while the mean direction is usually the most reliable parameter obtained from the directional measurements. An example of how the choice of the calculation method influences the results can be seen by comparing Fig. 7 of Paper **II** with Fig. 7b. In the former the directional spreading parameter for the broad and narrow fetch geometries in Vanhankaupunginlahti is calculated from the MLM spectra, and in the latter the same parameter is calculated from the time series of heave, pitch angle and roll angle. The shape of the spreading curves are comparable, but the actual values of the directional spreading are much higher when the parameter is calculated from the MLM spectra. The exact values of the spreading parameter are uncertain, but the relative differences are more useful, provided that the parameters are calculated with the same method. In this thesis the directional parameters are calculated directly from the time series with the Longuet-Higgins & al. (1963) method and the two-dimensional MLM spectrum is used as a qualitative tool in the analysis.

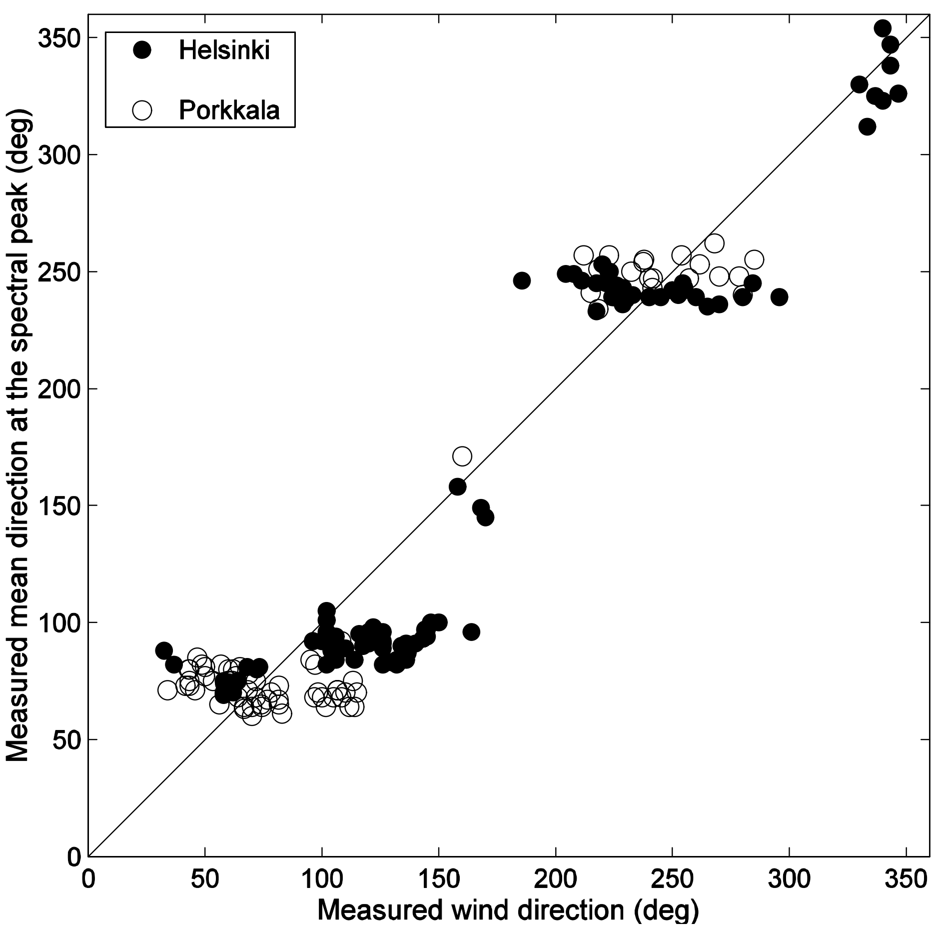



Fig. 5. The mean direction at the spectral peak versus wind direction. The directions indicate the approach directions. Open circle denotes data from station Porkkala and the bullet data from station Helsinki.

## 4.2. Directional properties of waves in a narrow bay

Directional wave measurements from the Gulf of Finland indicate that the fetch geometry has a strong influence on the directional properties of the waves and consequently to the wave climate in the area. In the narrow Gulf of Finland the directions of the dominant waves are concentrated to the directions along the gulf (Pettersson 2001 and Fig. 2 in Paper **IV**). The mean direction at the spectral peak in fetch-limited conditions from stations Helsinki and Porkkala is plotted against the wind direction in Fig. 5. The steering of the wave directions is pronounced at both stations which are situated in the narrow part of the Gulf of Finland (Fig. 1). The distance between the two stations is 50 km, and the sectors in the direction along the bay are a little different for each station (Table 1 and Fig. 1). This difference is visible in Fig. 5: in the southwestern sector there is a 10° difference in the dominant wave directions between the stations and in the southeastern sector the steering of the waves is stronger at station Porkkala, which is situated in the narrowest part of the gulf, while the gulf widens south-eastward of the station Helsinki.

The directional spreading parameter is an indicator of the directional width of the spectrum. It is typically smallest at the peak of the spectrum, growing rapidly at frequencies lower than the peak and more slowly at frequencies higher than the peak. The spreading parameter is the standard deviation by definition and it is sensitive to the uncertainties originating from instrumental factors and from the methods of calculating the directional spectrum. Previous studies on the evolution of the directional width with wave age have given contradictory results. Mitsuyasu & al. (1975) and Hasselmann & al. (1980) reported decreasing spreading with increasing wave age, whereas Donelan & al. (1985) and Ewans (1998) did not find a clear dependence. The directional spreading, grouped in four inverse wave age $U_{10}/c_p$ classes, from the three fetch geometries is plotted in Fig. 6. The data do not show a dependence of the directional spreading on the wave age in any of the fetch geometries. The two lowest $U_{10}/c_p$ classes in the broad fetch geometry data have even slightly higher spreading values than the spectra of the youngest waves. There are some uncertainties in the interpretation of Figure 6, as the narrow and slanting fetch data for mature waves cover only an $U_{10}/c_p$ range of 0.8 ... 1.5. It should also be kept in mind that the measuring principle for the data for young waves was different: they were measured with an array of six wave gauges while the mature waves have been measured with a Directional Waverider. On the other hand, treating an array of wave gauges as a heave, pitch and roll buoy for calculating the directional parameters gave consistent results in Paper **III**, and it is notable that the spreading values of the young wave spectra are so similar to those obtained from a buoy that follows the surface. The slanting fetch case from Golfe du Lion, which is added separately to Figure 6c, is very narrow, but is still inside the scatter of the directional spreading values from the Gulf of Finland slanting fetch data.

The mean directional spreading as a function of frequency in the three fetch geometries from the Gulf of Finland is plotted in Fig. 7a and the young wave data from Vanhankaupunginlahti in Fig. 7b. In both cases, the directional spreading parameter is higher for waves growing in broad fetch geometry, whereas the spreading values for narrow and slanting fetch geometries are nearly comparable, the slanting fetch cases showing a little broader directional distribution. The difference between broad fetch and narrow/slanting fetch geometry is about 10° and constant in the energy containing frequency range of the spectrum.

Finally, a comparison of the two other directional parameters obtained from the first pair of Fourier coefficients is done. The directional skewness $\gamma_2(\omega)$ describes the symmetry of the directional distribution, and Figure 8b tells us that there is some directional skewness present in the narrow and slanting fetch data for the young waves. The directional kurtosis, $\delta_1(\omega)$, plotted in Figure 8c-d, describes the concentration of the energy in directional space. In spite of the uncertainties in calculating these higher order directional parameters (COST714 WG3 2004), a clear difference is found between the broad and narrow/slanting fetch geometries. In the latter case the kurtosis is more peaked around the spectral peak than in the former case. The directional kurtosis of the young waves show a similar behaviour, although the differences are smaller. In general the kurtosis did not change with wave age, except that it was higher for the young waves than for the mature waves in the broad fetch geometry. Kuik & al. (1988) suggested that the directional skewness and directional kurtosis could be used to identify directionally unimodal spectra. Their criteria for unimodal spectrum, based on model simulations and heave, pitch and roll buoy measurements, was that $\delta_1(\omega) > 2 + |\gamma_2(\omega)|$ for $|\gamma_2(\omega)| \leq 4$ and $\delta_1(\omega) > 6$ for $|\gamma_2(\omega)| > 4$. Wyatt (2004) applied the criteria to Directional Waverider measurements and found that the bimodality indicated by the parameters agreed well with the bimodality found in the coincident two-dimensional spectra measured with an HF radar. According to the criteria presented by Kuik & al. (1988), all the data in this study were unimodal and symmetric at the spectral peak (not shown).

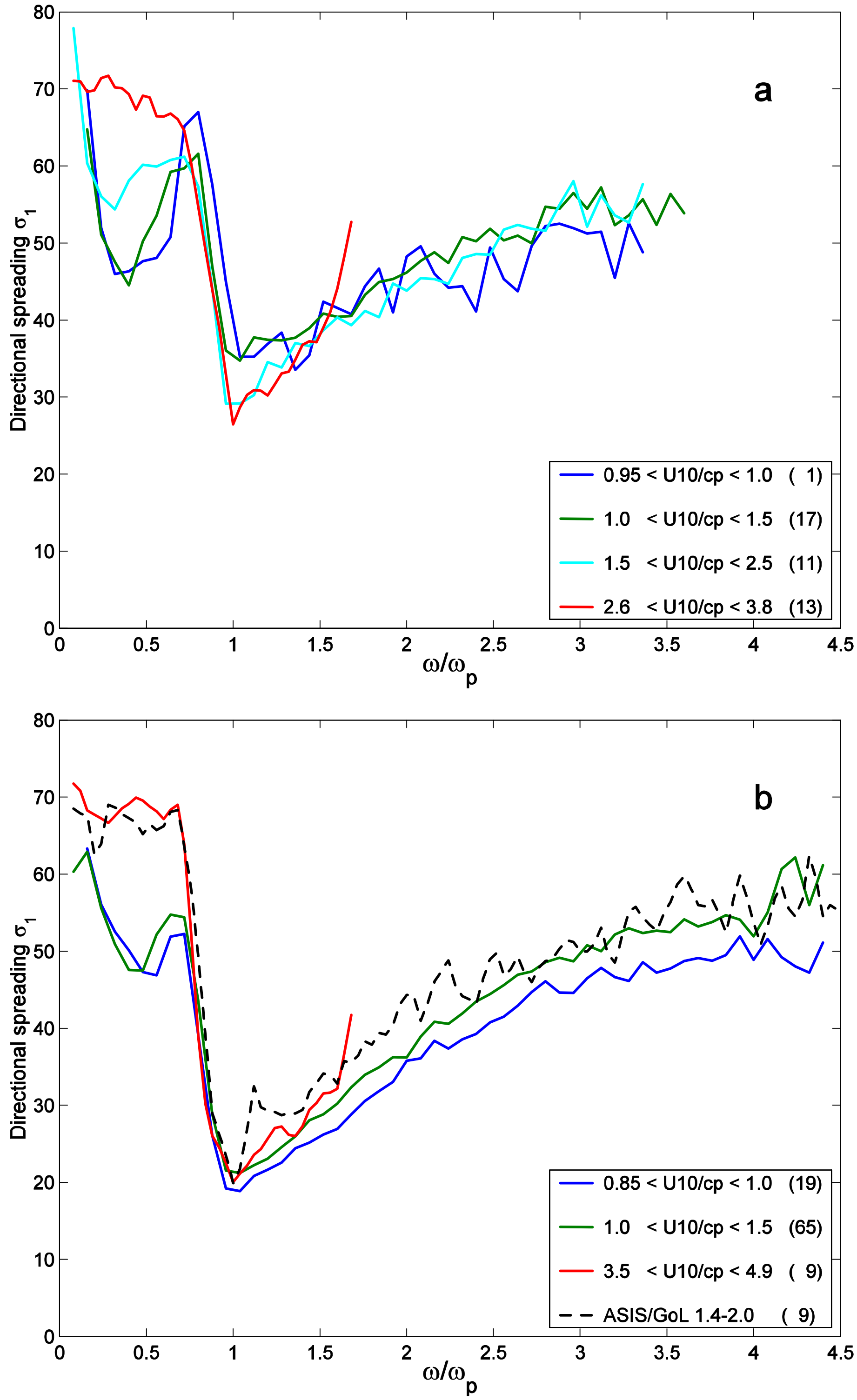



Fig. 6a-c. The directional spreading parameter $\sigma_1(\omega)$ in four inverse wave age classes. Panel a: broad, panel b: narrow and panel c: slanting fetch geometries. The dashed line in panel b denotes the ASIS data, and in panel c the DWR slanting fetch case from Golfe du Lion. The numbers in the parenthesis denote the number of observations in each class.

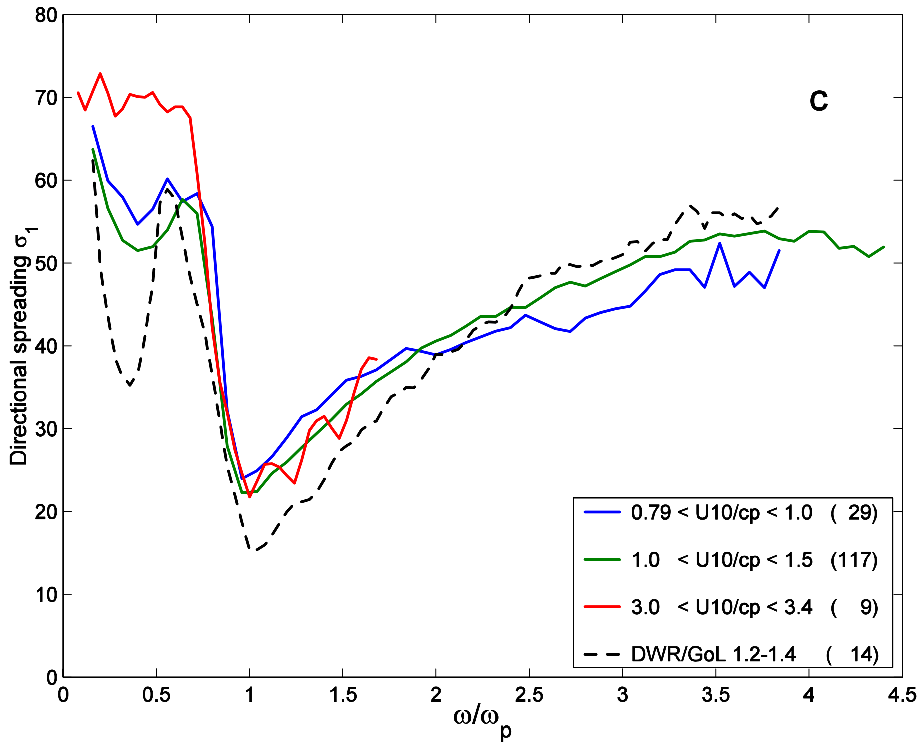
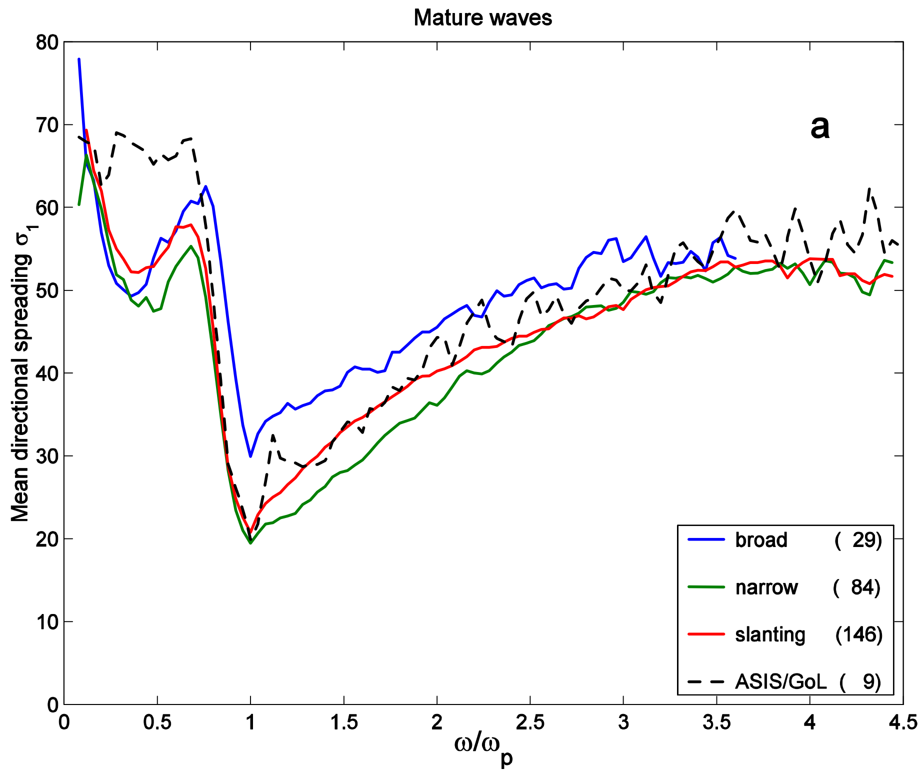



Fig. 6a-c continues.

## 5. THE SLANTING FETCH CASE

The analysis of the directional parameters gave similar results for the narrow and slanting fetch geometries. The two-dimensional distribution of the wave energy is, however, different in these two cases. When the wind is along a narrow bay, the directional distribution is rather symmetric with respect to the wind direction in the whole frequency range. This is not the case in the slanting fetch geometry. The first studies of the directional properties of the waves in slanting fetch geometry were made by Donelan (1980) and Donelan & al. (1985). Their directional wave measurements from Lake Ontario and the stereophotography wave data of Holthuijsen (1983) showed convincingly that in slanting fetch conditions the wave components at higher frequencies were aligned with the wind, while the mean direction at the spectral peak was coming from the direction of a longer fetch component.

Traditionally, the role of the nonlinear transfer has been seen to shape the spectrum to a quasi-equilibrium form and in downshifting the spectral peak (Hasselmann & al. 1973). The analysis of the dimensionless growth curves (Paper **I** and section 3.1) indicate that the nonlinear transfer is not efficient enough to shape the one-dimensional spectrum into a universal form in all fetch-limited growths. The role of the nonlinear transfer in shaping the directional distribution of the waves is still an open question, partly because of the rarity of reliably directional wave measurements. Holthuijsen (1983) applied a directional decoupled model originally suggested by Seymour (1977) and Donelan (1980) presented a parametric method based on the empirical growth curve of the peak period to predict the wave direction. The most developed wave models today, the third generation wave models like WAM (WAMDI 1988, Komen & al. 1994), solve in principle the transport equation without a priori assumptions on the spectral shape. Paper **IV** studies the ability of these three models to predict the wave directions at the spectral peak in the Gulf of Finland. The most demanding situation for the models is the slanting fetch case, which, due to the shape of the gulf, is a frequently observed situation in the area. The parametric method of Donelan (1980, Donelan & al. 1985), where the direction of the dominant waves is defined by searching the pair of wind and fetch components that yields the largest peak period, predicted well the steering of the wave directions. The decoupled model (Seymour 1977, Holthuijsen 1983) was not able to predict the correct response of the wave directions to slanting fetch conditions. The third generation wave model WAM predicted a stronger steering than the decoupled model, but still a smoother than observed steering of the wave directions. The grid size of WAM had a strong impact on



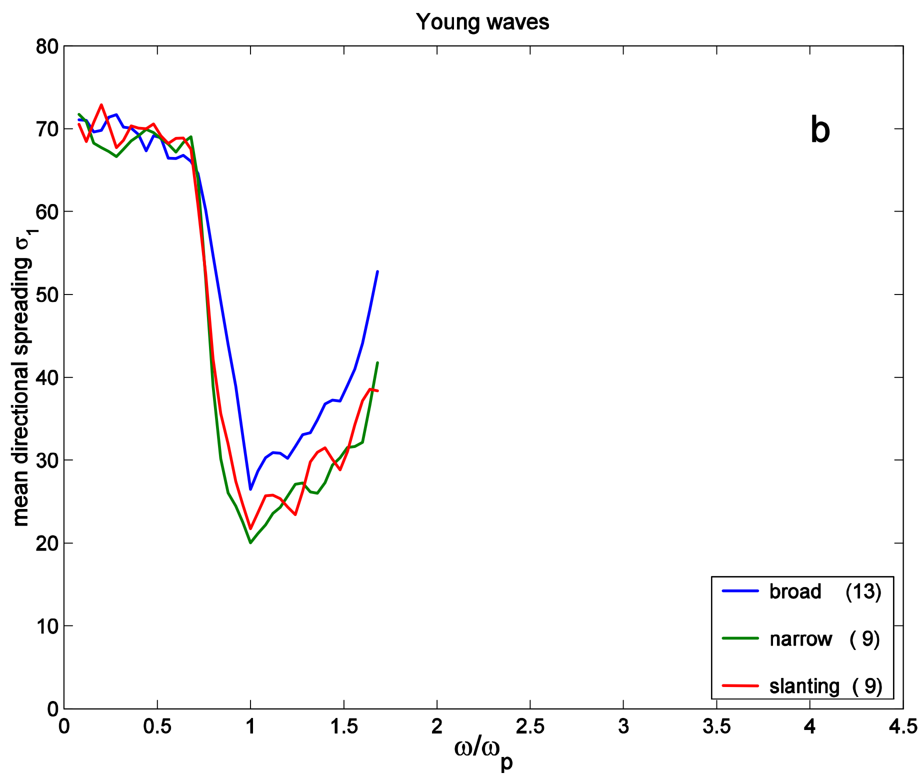




Fig. 7a-b. The mean spreading in broad, narrow and slanting fetch geometries. Panel a shows the mature waves from the Gulf of Finland and the ASIS data (dashed line) from Golfe du Lion and panel b the young wave data from Vanhankaupunginlahti.

the results, and a rather small grid size, 5 km, was required before the model predicted reasonable wave directions in the middle parts of the Gulf of Finland. Assessing the physics of the model is difficult without a detailed analysis of the effects of the numerical solutions (Paper **IV**).

Comparing the results of the three models in Paper **IV** gives an insight to the physical processes involved in a slanting fetch case. Clearly the nonlinear transfer is not strong enough to retain the peak of the spectrum in the direction of the wind, and the directionally decoupled model was unable to produce components in the direction of the longer fetch component that were energetic enough to dominate the spectrum (Figure 5 in Paper **IV**).

Young & al. (1987), van Vledder (1990) and van Vledder & Holthuijsen (1993) have simulated turning wind situations with the third generation model Exact-NL which solves the nonlinear interactions exactly (Hasselmann & Hasselmann 1981, 1985). Because these calculations are very time-consuming, the model has been run only as a one-dimensional model in duration-limited situations. Van Vledder (1990) and van Vledder & Holthuijsen (1993) found that in the early stages of a turning wind situation the turning of the wave direction at the spectral peak was opposed mainly by the dissipation and to a smaller extent by the nonlinear transfer. The nonlinear interactions were transferring energy across frequencies and directions from the new wind direction at higher frequencies towards the components in the old wind direction, thus slowing down the turning of the waves by maintaining the peak in the old wind direction (Fig. 9).

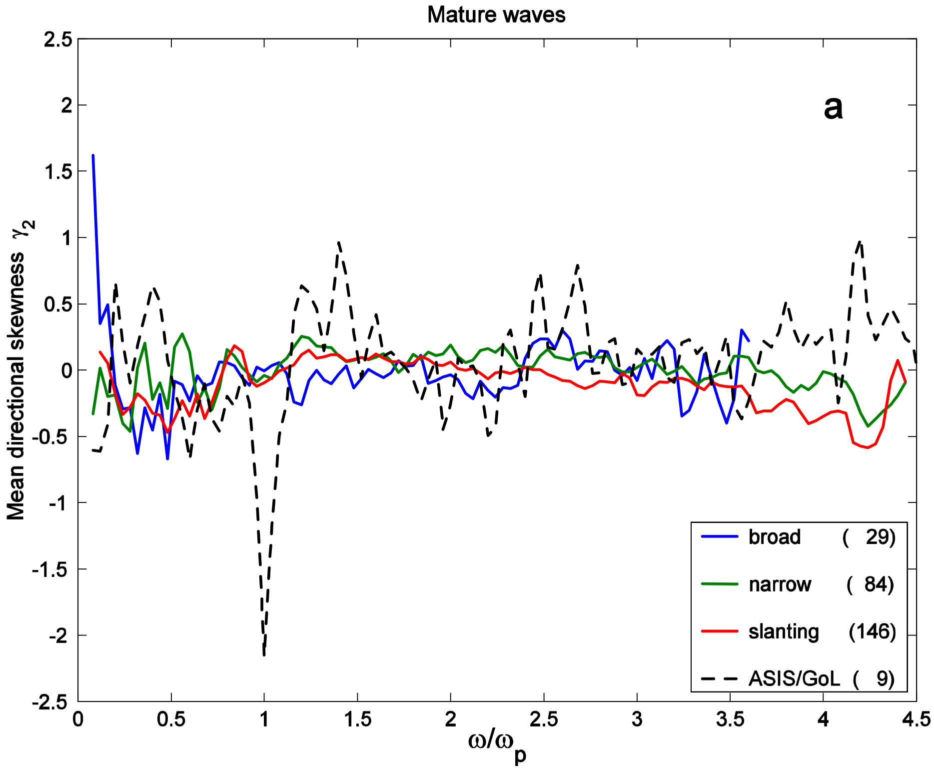
The slanting fetch situation has a resemblance to the turning wind case. Instead of evolving with time and gradually aligning with the new wind direction, the waves are fetch-limited which leads to a frozen image of the early stages in a turning wind situation. Initially, when the wave components that grow over the shorter fetch in the wind direction (wind fetch) reach the fetch-limited stage, the components in the direction of the longer fetch component are still evolving with time. The nonlinear transfer from higher frequencies in the direction of the wind is more effective than in the direction of the longer fetch component, and the wave components in this direction are thus able to evolve rather freely, even if more slowly (Fig. 9). By the time when these components have evolved so much that their frequency becomes lower than that of the components grown over the wind fetch, the role of the nonlinear transfer is after this point the same than in the early stages of a turning wind situation: to transfer energy from higher frequencies towards the components aligned with the bay at lower frequencies and to maintain the spectral peak in this direction.

The parametric method of Donelan (1980) for predicting the direction of the dominant waves was based on the assumption that the wind and fetch components that generate the largest peak period, produce also the main portion of the energy. In the light of the description of the physical processes involved with the slanting fetch case, Donelan's (1980) approach is reasonable, although the shape of the spectrum is not universal, and due to the nonlinear interactions, the dominance of only one wind and fetch component is not necessarily justified in more complicated fetch geometries.

# 6. DISCUSSION

## 6.1. The evolution of waves in a narrow bay

The data available for this study was not complete enough to cover all the stages of the evolution of waves in a narrow bay. One stage of development was absent in the narrow and slanting fetch geometry data, the inverse wave age range of 1.5 ... 3. The separation between the narrow/slanting and broad fetch geometries, especially in the one-dimensional properties, seems to happen in this range. More young wave data of good quality is needed in all the three fetch geometries. The physical processes involved in the evolution of the waves restricted by the fetch geometry should be confirmed by a model that solves the nonlinear interactions exactly in fetch-limited conditions. In spite of these deficiencies, a picture of the evolution of the wind waves in a narrow bay can be sketched. When the waves are young, the influence of the fetch geometry is not clearly visible in the shape of the frequency spectrum nor in the parameters calculated from it, except that the energy is reduced. The fetch geometry manifests itself first in the directional properties of the spectrum: the directional distribution is narrower and the energy is concentrated in directions around the spectral peak. The skewed directional distribution as a function of frequency is visible in slanting fetch conditions. When the waves grow more mature, the directional properties do not evolve much with the stage of development, but the shape of the frequency spectrum and the one-dimensional parameters show changes that evolve with the wave age. The peakedness of the spectrum diminish and the growth of energy and peak period slows down. The nonlinear interactions are most active when the waves are steep and young, but their activity slows down when the waves become more mature (Komen & al. 1994). The waves in narrow and slanting fetch geometries reach this stage in the spectral sense at higher inverse wave age than the waves growing in a broad fetch geometry.



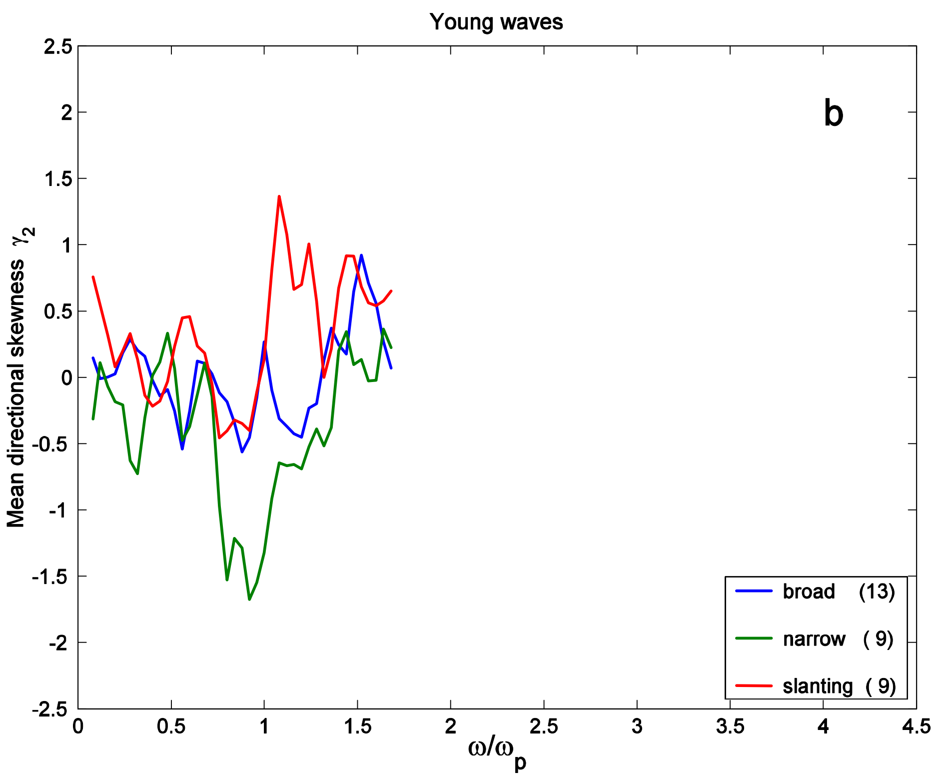




Fig. 8a-d. The mean directional skewness $\gamma_2(\omega)$ in broad, narrow and slanting fetch geometries is shown in panel a for mature waves and in panel b for young waves. Panels c and d shows the mean directional kurtosis $\delta_1(\omega)$ for the mature and young waves, respectively. The ASIS data from Golfe du Lion is denoted by dashed lines in panels a and c.

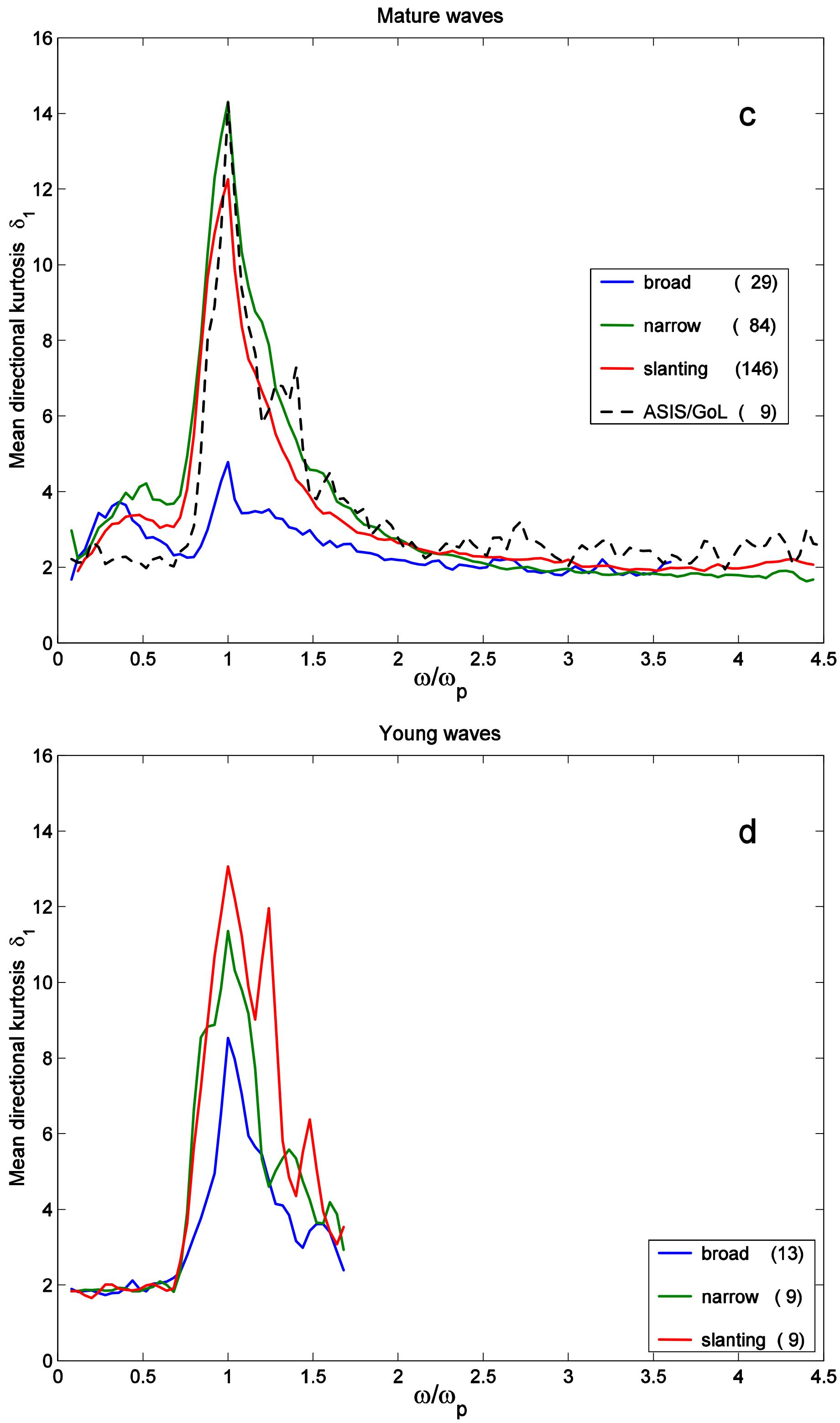



Fig. 8a-d continues.

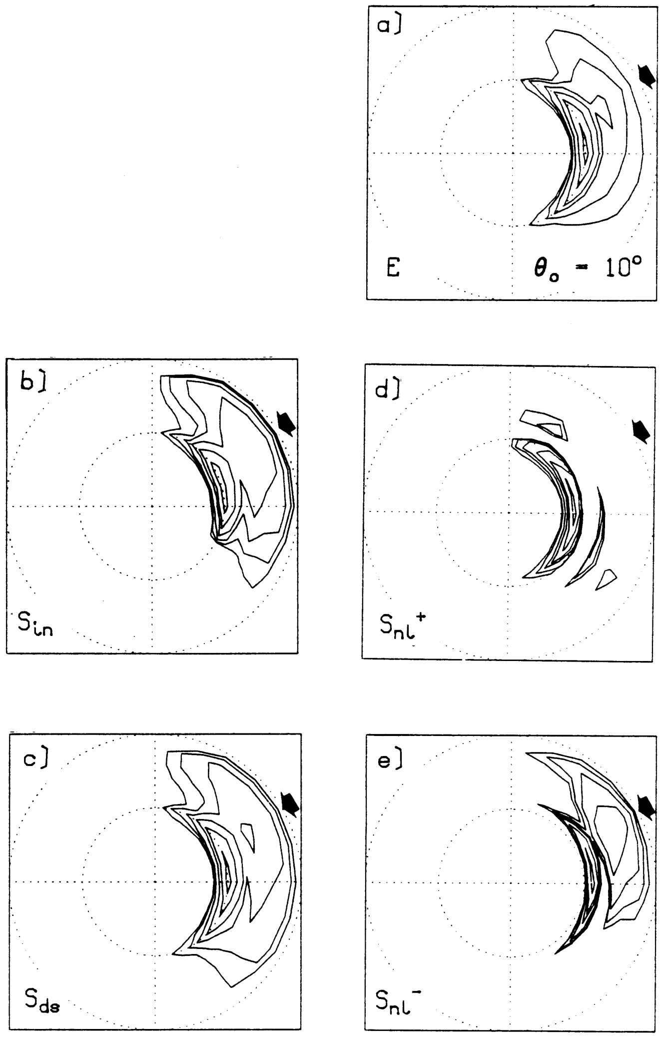



Fig. 9. Nonlinear transfer in the early stages of a turning wind situation calculated with the EXACT-NL model. The panels show the situation after a sudden, 30° shift of the wind direction (wind speed 20 $ms^{-1}$). Panel a: the normalized spectrum, panel b: the wind input and panel c: the dissipation. Panel d shows the gain and panel e the loss of energy due to the nonlinear interactions. The new wind direction is indicated by an arrow. Figure 3.16 from van Vledder (1990), reprinted by the kind permission of Dr. G.Ph. von Vledder, Alkyon, Emmeloord, the Netherlands.

## 6.2. The generality of the results

The influence of the fetch geometry on the spectral properties and on the parameters derived from the directional spectrum is evident in the data presented here. Next the question of whether the results are unique for a narrow bay is studied with the help of wave measurements from the experiment FETCH in the Mediterranean Sea (Hauser & al. 2003 and Paper **III**). The time period of the experiment was chosen to coincide with the expected period of high offshore local winds, Mistral from the north and Tramontane winds from the northwest. Mistrals funnel down to south in the Rhône valley forming a belt of high winds in Golfe du Lion. The position and structure of the wind belt varies, and can even generate a bimodal wave spectrum in the area, like was the case on 24 March 1998 in Paper **III** (see also Hauser & al. 2004). The three fetch-limited cases that are discussed in this section, were measured during events where the Mistral formed a well defined belt over Golfe du Lion. An example of the wind field during one of the fetch-limited cases, 20 March 1998 at 03 UTC, is shown in Figure 10. The wind field is from the atmospheric circulation model Aladin of Météo-France which is run on a 10 km grid (Figure by courtesy of Dr. D. Hauser, Centre d'Etudes Planétaires and Terrestres, Vélizy, France).

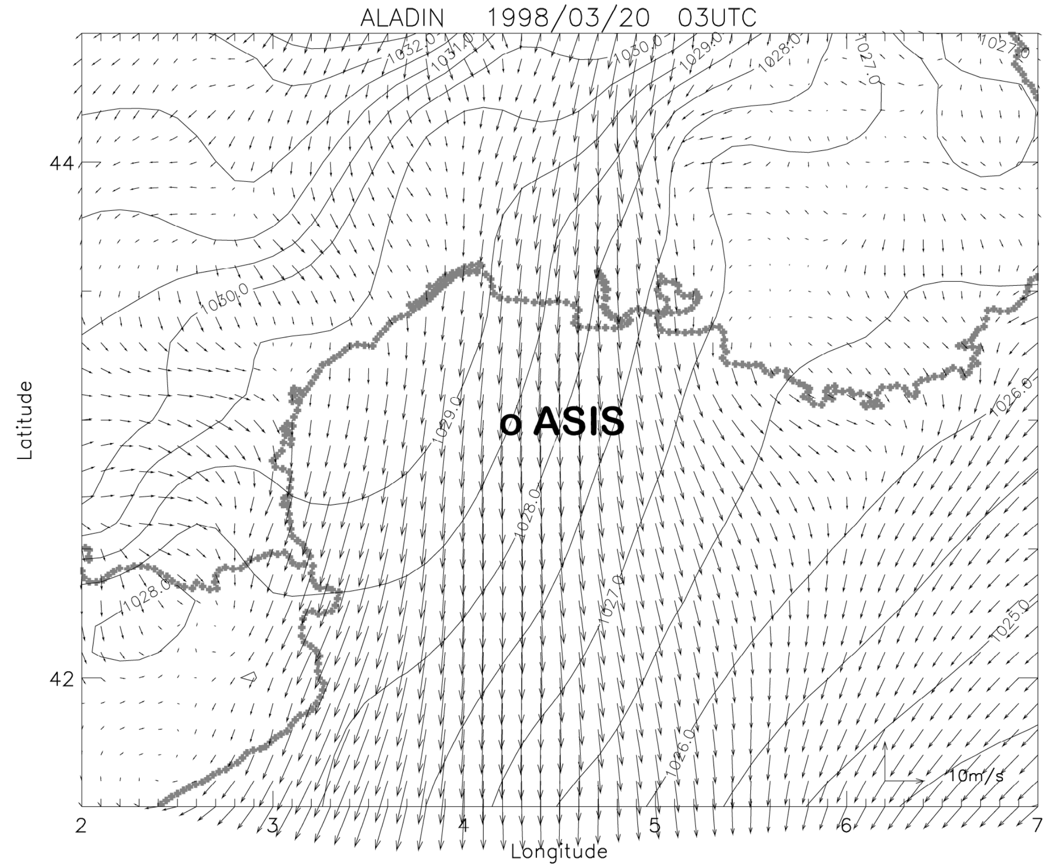



Fig. 10. The wind field in Golfe du Lion during the Mistral event 20 March 1998 at 03 UTC predicted by the atmosphere model Aladin of Météo-France. The position of the ASIS buoy is indicated by a circle. Figure by courtesy of Dr. D. Hauser, CEPT, Vélizy, France.

These Mistral events give an opportunity to study how the width of the area where the wind is steady is affecting the spectral properties of the waves. During the first part of the experiment, a Directional Waverider and the Air-Sea Interaction Spar ASIS (Graber & al. 2000) were deployed side by side for comparing the performance of these two wave sensors with different measuring principles (Paper **III**). The position of the buoys is indicated in Figure 10. Unfortunately there were gaps in the measurements of the Directional Waverider, and only three spectra were available during these three fetch-limited events. The comparison of the directional parameters in Paper **III** show that the compatibility between ASIS and DWR is good, and the ASIS data (by courtesy of Prof. W.M. Drennan, Rosenstiel School of Marine Atmospheric Science, University of Miami) have been used instead.

The ASIS data is denoted by open circles in Figures 2 and 4 and by dashed lines in Figures 3b, 6b, 7a, 8a and 8c. The dimensionless energy is smaller and the dimensionless peak frequency is higher than predicted by the KC92 composite growth curve, but the points are still inside the scatter of the broad fetch geometry data from the Gulf of Finland (Fig. 2). As mentioned in section 2, the difference in width in the eastern and southwestern sectors in the Gulf of Finland is visible in the energy levels. The width of the high wind belt during the Mistrals was about 100 km giving an width-to-fetch-length ratio of 1.4 while the ratios in the Gulf of Finland were smaller, about 0.5 in the eastern and about 0.35 in the southwestern sector. In Figure 3b there is no data from the Gulf of Finland in the corresponding $U_{10}/c_p$ range, 1.4 ... 2.0, and the peakedness of the ASIS spectra is comparable to those of the spectra from the broad fetch geometry in all the $U_{10}/c_p$ classes. On the other hand, the peakedness of the ASIS spectra does not contradict the increasing peakedness observed in the narrow fetch data from the Gulf of Finland and Vanhankaupunginlahti. The same conclusion can be drawn when the peak enhancement factor $\gamma$ calculated from the ASIS spectra is added to the Figure 4: the factor $\gamma$ is smaller for the ASIS data than for the broad fetch geometry data and they fit to the ensemble of the narrow fetch geometry $\gamma$ that is increasing with the inverse wave age.

The directional parameters for ASIS buoy were calculated from the heave, pitch angle and roll angle time series as described in section 4 and Paper **III**. The mean directional spreading from the Mistral cases is denoted by a dashed line in Figures 6b and 7a. These Mistral cases are directionally as narrow as the narrow and slanting fetch spectra from the Gulf of Finland and Vanhankaupunginlahti. The two other directional parameters are also denoted by dashed line in 8a and 8c. The ASIS data is somewhat skewed directionally. Some directional skewness can be expected because the position of the Mistral wind belt with respect to the position of the buoy was not symmetric (Fig. 10) nor constant from case to case. The directional kurtosis (Fig. 8c) has the same pronounced peakedness than the narrow fetch data from the Gulf of Finland and Vanhankaupunginlahti. The directional parameters from the three coincident spectra measured with Directional Waverider during one of the Mistral cases do not contradict with the data from the ASIS buoy (not shown), which gives confidence to the interpretation presented here. The narrowness of a wind field can cause changes in the one-dimensional and directional properties of the spectrum that are comparable to the influence of the fetch geometry in a narrow bay.

## 7. CONCLUSIONS

Directional wave measurements from the Gulf of Finland and from a small bay called Vanhankaupunginlahti in the Baltic Sea have been used to study the influence of fetch geometry on the wave growth and on the spectral properties of the waves. Complementary directional wave measurements were obtained from Golfe du Lion in the western Mediterranean Sea. The data was divided into three categories, representing broad fetch, narrow fetch and slanting fetch geometries, and the one-dimensional and directional properties of the waves in these three groups were compared. The following conclusions are made from the results:

- The growth of mature waves was faster in the broad fetch geometry than in the narrow fetch geometry. The change in the dimensionless peak frequency at the same dimensionless fetch was not as pronounced as in the dimensionless energy, indicating that the shape of the spectrum cannot be regarded as universal. The reduction in the energy was smaller in the slanting fetch geometry than in the narrow fetch geometry, and the evolution of the peak frequency was nearly unchanged when compared to the evolution in the broad fetch geometry.
- When the waves were young, the differences in the dimensionless energy and dimensionless peak frequency between the three fetch geometries were not as pronounced as in the case of mature waves. This can be seen as a consequence of the more efficient nonlinear transfer when the waves are young and steep. The quality of the short fetch data from broad fetch geometry was not the best possible which made it difficult to make definite conclusions. More wave data with inverse wave age $U_{10}/c_p$ over 1.5 is also needed to cover the transition from young waves to mature waves.
- The saturation range of the spectrum had a $\omega^4$ slope in all three fetch geometries. The peakedness of the one-dimensional spectrum decreased much more slowly with increasing wave age in the broad fetch geometry than in the narrow and slanting fetch geometry. No differences in the peakedness could be found when the waves were young, but when the waves were mature, the spectrum at a given wave age was significantly less peaked in the narrow and slanting fetch geometry than in the broad fetch geometry.
- Analysing directional measurements is not a straightforward task. The results may be affected by the inaccuracies caused by the operational principles of the wave sensors or by the method applied to calculate the spectrum. A comparison between two of the wave sensors used in this thesis was done to find out the reliability and compatibility of the directional measurements. The consistent performance of the sensors gives confidence on the quality of the data and on the results obtained from it.
- The directional spreading parameter was about 10° smaller in the narrow and slanting fetch geometry than in the broad fetch geometry. The difference was constant in all energy containing frequencies of the spectrum. The directional spreading parameter did not show a dependence on the wave age in any of the three fetch geometries.
- The higher order directional parameters, the skewness and kurtosis, are not very stable estimates. Even though the directional kurtosis behaved consistently. It was clearly peaked around the spectral peak in narrow and slanting fetch geometries. In broad fetch geometry the kurtosis of the mature waves was nearly flat, but the kurtosis of

the young waves showed a stronger peakedness.

- In the Gulf of Finland the mean direction at the spectral peak is strongly controlled by the fetch geometry. Due to the frequent slanting fetch conditions, the direction of the dominant waves is steered to the directions along the gulf which strongly modifies the wave climate in the area.
- Models with different assumptions on the coupling between the wave components were used to study the physical processes involved in the observed strong steering in the Gulf of Finland. The results suggest that this steering and the skewed directional distribution in the frequency space is a consequence of the nonlinear transfer between the wave components. This transfer across the frequencies and directions from the shorter waves aligned with the wind is maintaining the peak of the spectrum in the direction of a longer fetch component.

## Acknowledgements

When looking back on the past years, I recognize that I will not be able to mention all the persons that have been involved, in one way or another, with the work that has led to my dissertation. The first measurements in the Gulf of Finland were made over twenty years ago, and during the years many persons, some of which I know only by name, have contributed to the measurements and consequently to the progress of this study. Yet one thread is evident through all the years: Dr. Kimmo K. Kahma. I am indebted to him for guiding me in his inspiring way in the interesting and challenging world of wave research and measurements, and for being the supervisor of my thesis. From time to time my route to the thesis has been a slightly winding one, but here we are.

The Finnish Institute of Marine Research has been my professional home since the beginning of my career. I am grateful to the Director of the Institute, Professor Pentti Mälkki for his support and understanding. I wish to thank also Professor Jouko Launiainen. In addition to being the Director of the Department of Physical Oceanography at the Institute, he was Professor in geophysics at the University of Helsinki while I was a student, and his lectures form the basis of my knowledge of physical oceanography. I am grateful to my colleagues and the staff at the Institute for the help and support I have got in a variety of things, and also for some unforgettable joyful events during these years. I have had several discussions with Leena Roine about the peculiarities of life. And now, she, in the role of a technical editor, is wondering the peculiarities of this thesis together with Leena Parkkonen.

The wave measurements would not have been possible without the help of a number of people. I want to thank especially Henry Söderman whose devoted expertise has been irreplaceable in the field work. From changing an antenna to a wave buoy from a rubber boat in the middle of the Gulf of Finland to setting up a receiving station in the middle of a flock of sheep, what wouldn't we do for the buoys? The skillful crew of R/V *Aranda* made the deployments and recoveries of the wave buoys look like an easy task. Juhani Rapo and Hannu Vuori are thanked for contributing to the construction of the wave gauge array. Among the persons that has taken part in the wave array measurements is Hannu Jokinen, who has also taken care of the processing of newest wave buoy data. I wish to express my warm thanks to all the persons who have got their schedules rearranged, have shivered, got wet, hungry and tired in our pursuit of the precious wave data.

The visits to the pilot stations in Harmaja and Porkkala where we had our receiving stations are warmly remembered. The wave measurements at station Helsinki in the new millennium are done in cooperation with the Gulf of Finland Maritime District and the Port of Helsinki. The coastguard of the Gulf of Finland have given valuable help in keeping track of the buoys. The first stages of this study was supported by the Natural Sciences Research Council of the Academy of Finland.

During the FETCH experiment N/O *l'Atalante* of IFREMER took me to the azure waters of the Mediterranean Sea. The scientists and the crew made me feel welcome (vous m'avez fait reprendre mes études de français!). I am grateful to Dr. Danièle Hauser and Dr. Céline Quentin for the discussions we had during the meetings and my visit to CEPT in Vélizy. Thanks to the members of the Working Group 3 of COST Action 714. Being a member of the group made it possible to learn the state of the art in directional wave measurements. I wish to thank also Professor William M. Drennan (RSMAS, University of Miami) for the discussions varying from scientific issues to the quality of chèvre. I am grateful for his encouragement and the comments on my curly English in this summary.

The discussions with Dr. Gerbrant van Vledder (Alkyon, the Netherlands) during his visit to Helsinki were valuable in understanding better the nonlinear interactions and their calculation methods in wave models.

I am grateful to the reviewers of my thesis, Professor Aike Beckmann (University of Helsinki) and Dr. Tarmo Soomere (Tallinn Technical University), for their constructive and encouraging criticism on my work. Professor Matti Leppäranta (University of Helsinki) is thanked for the gentle hustling into getting ready with my thesis.

I am indebted to my parents Bertta and Evald for supporting me on the career I chose and for offering a refuge in our summer house Jaksos in Åva. Thanks to my sisters Maire and Iris and my friends who have patiently tried to remind me that I will not miss the Most Important Wave if I sometimes go to an art exhibition, a party or a concert.

And now forward: there are still plenty of waves in the sea!

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