Wave Directions in a Narrow Bay

HEIDI PETTERSSON, KIMMO K. KAHMA, AND LAURA TUOMI

Marine Research, Finnish Meteorological Institute, Helsinki, Finland

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ABSTRACT

In slanting fetch conditions the direction of actively growing waves is strongly controlled by the fetch geometry. The effect was found to be pronounced in the long and narrow Gulf of Finland in the Baltic Sea, where it significantly modifies the directional wave climate. Three models with different assumptions on the directional coupling between the wave components were used to analyze the physics responsible for the directional behavior of the waves in the gulf. The directionally decoupled model produced the direction at the spectral peak correctly when the slanting fetch geometry was narrow but gave a weaker steering than observed when the fetch geometry was broader. The method of Donelan estimated well the direction at the spectral peak in well-defined slanting fetch conditions, but overestimated the longer fetch components during wave growth from a more complex shoreline. Neither the decoupled nor the Donelan model reproduced the observed shifting of direction with the frequency. The performance of the third-generation spectral wave model (WAM) in estimating the wave directions was strongly dependent on the grid resolution of the model. The dominant wave directions were estimated satisfactorily when the grid-step size was dropped to 5 km in the gulf, which is 70 km in its narrowest part. A mechanism based on the weakly nonlinear interactions is proposed to explain the strong steering effect in slanting fetch conditions.

1. Introduction

Saville (1954) was one of the first to discuss the influence of fetch geometry on the wave growth. He suggested a method based on a boxcar spreading function over either 90° or 180° to define an effective fetch for wave growth along a rectangular basin. As an additional result, his method suggests that the effective fetch is longer than the distance to shore in the wind direction when the wind is not orthogonal to the shoreline but blows from an angle to it. According to the method of Saville (1954), the fetch geometry effects on the wave growth can be accounted for by an effective fetch. This implies an assumption that the shape of the spectrum of growing waves is independent of the fetch geometry.

Some physical justification for the effective fetch concept came from Hasselmann et al. (1973), who concluded that the weak nonlinear interactions between the wave components of actively growing waves control the shape of the one-dimensional spectrum so that the spectrum rapidly reaches a quasi-equilibrium form. Hasselmann et al. (1976) proposed an even stronger assumption of universal spectral shape of actively growing waves. They suggested that the nonlinear transfer also sufficiently controls the directional wave spectrum efficiently so that for practical purposes, the directional distribution of growing waves conforms to a universal form that depends only on the energy and frequency scales of the one-dimensional spectrum. It was recognized, however, that this does not necessarily apply to complex seas generated by rapidly varying winds (Hasselmann et al. 1976, 1985; Janssen et al. 1994). Later it turned out that wave growth along a narrow basin (Kahma and Pettersson 1994; Ataktürk and Katsaros 1999; Pettersson 2004) or in a slanting-fetch geometry (Donelan 1980; Holthuijsen 1983; Donelan et al. 1985) are other examples where the nonlinear transfer is not sufficient to bring the directional wave spectrum into a universal form.

The linear weighting scheme to calculate the effective fetch suggested by Saville (1954) was criticized by Seymour (1977), who argued that no simple effective fetch can be found when the waves are growing in a basin with an irregular coastline. Kahma and Pettersson (1994) arrived at the same conclusion when they applied the method of Saville (1954) to wave growth along the

Corresponding author address: Heidi Pettersson, Marine Research, Finnish Meteorological Institute, P.O. Box 503, FI-00101 Helsinki, Finland.
E-mail: heidi.pettersson@fmi.fi

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narrow and long Gulf of Finland. Seymour (1977) suggested a model in which the wave spectrum is composed of directional segments that do not interact. Each segment depends only on the wind speed, wind direction, and the fetch, which may be different for each direction. The performance of this directionally decoupled model was at that time verified only with one-dimensional wave measurements.

One of the most comprehensive experimental studies of directional wave spectrum in fetch-limited conditions is that of Donelan et al. (1985). Their data from Lake Ontario showed that in slanting fetch conditions the direction at the spectral peak was biased toward the longer fetch components while the shorter waves were aligned with the wind. Donelan (1980) and Donelan et al. (1985) showed that the observed direction at the spectral peak at a given wind speed can be estimated from the empirical growth curve of the peak period by searching the pair of fetch and wind components that yields the largest peak period. This largest peak period was assumed to also have the largest energy. The method of Donelan assumes that all the fetch geometry effects can be accounted for by using the wind and fetch components in the direction the dominant waves are approaching from (i.e., in the direction at the spectral peak). This assumption implies that other directional properties except the mean direction are not affected by the fetch geometry. Walsh et al. (1989) applied the method to their slanting fetch case from the mid-Atlantic coast of the United States and found a good agreement between the model and the measurements. They generalized the method to take into account that the energy is not necessarily maximized in the same direction as the peak period. The Donelan method was also included as a boundary condition to the second-generation hybrid parametric wave model HYPA (Günter et al. 1989), but due to the lack of directional measurements the ability of the HYPA model to produce the correct wave directions in slanting fetch conditions was not confirmed.

Holthuijsen (1983) reported similar directional behavior of waves in slanting fetch conditions as Donelan et al. (1985) and later Walsh et al. (1989) when he studied the directional spectrum in fetch-limited conditions in the southern parts of the North Sea. Holthuijsen (1983) compared his measurements of wave growth from an irregular coastline and in slanting fetch conditions to the results of a model that was based on the principles presented by Seymour (1977). The agreement between the directionally decoupled model and the measurements was found to be good.

On the other hand the Donelan model and Seymour–Holthuijsen directionally decoupled model are based on assumptions that cannot both be true at the same time. The first assumes that waves are strongly directionally coupled, the second that the waves are directionally uncoupled.

Both models have explained well those observations they have been applied to. Before this study they have not been tested using the same experimental dataset. The narrow Gulf of Finland provides frequent and pronounced slanting fetch effects in directional wave spectra, which gives data to test the two methods and to analyze the role of different source terms of the transport equation. For the latter, we mainly use the results of one point exact nonlinear transfer calculations in a turning wind situation (Young et al. 1987; van Vledder 1990; van Vledder and Holthuijsen 1993). The computing task using the exact nonlinear transfer when the fetch geometry is modeled by reasonably high spatial resolution is huge and has turned out to be well beyond the resources available for this study.

We will also study the results of the third generation wave model (WAM) (WAMDI Group 1988; Komen et al. 1994). Because of the limitations of the discrete interaction approximation that is used in WAM, the results mainly serve here as indicators of the numerical aspects involved when the transport equation is solved in narrow bays. They also show that the results of this study have relevance for operational wave modeling.

2. The experimental data

a. Wave measurements

The experimental area is the Gulf of Finland in the Baltic Sea in northern Europe (Fig. 1). The narrow gulf is 300 km long and between 70 and 120 km wide. The northern Finnish coast of the gulf is lowland and covered with forests while the southern coast is formed by steep cliffs open to the sea. The overall topography of the coasts is rather flat, but on a small scale the Finnish coast consists of many rocky hills, a topography that continues into the sea as an archipelago. Wave measurements have been carried out in two locations in the middle parts of the gulf: off Porkkala (59°44′30″N, 24°18′30″E), Finland, in 1993 and off Helsinki (59°57′54″N, 25°14′06″E), Finland, in 1990–91, 1994, and 2002 (Fig. 1).

The directional wave sensors that exist today are not able to measure all the information needed for a full directional spectrum, and different wave sensors sometimes disagree significantly on the directional properties of the spectrum (e.g., Allender et al. 1989; COST714-WG3 2005). Here we focus on the mean direction, which is usually the most reliable directional parameter obtained from the measurements. The sensors used were Directional Waveriders, which means that one of the uncertainties in directional measurements—the

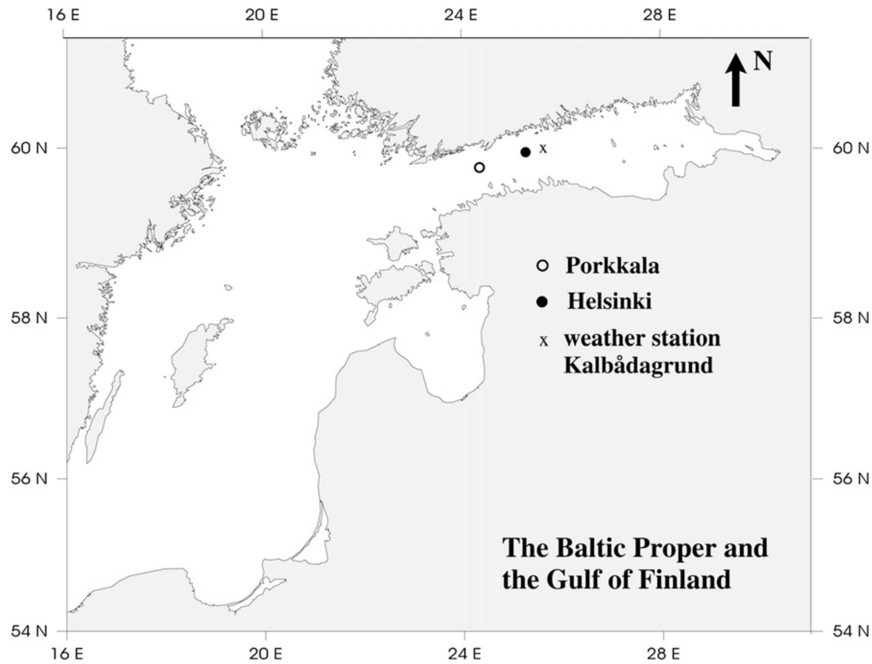

FIG. 1. Wave measuring sites in the Gulf of Finland, Porkkala (open circle) and Helsinki (bullet). The automatic weather station Kalbådagrund is denoted by x.

inconsistencies originating from instrumental differences—was avoided.

The basic parameters are calculated on board the wave buoy from three 1600-s displacement time series (vertical, north, and west) following Longuet-Higgins et al. (1963). The mean direction $\theta_1(\omega)$, as a function of the frequency ω, is calculated from the first pair of the Fourier coefficients $a_1(\omega)$ and $b_1(\omega)$:

$$\theta_1(\omega) = \arctan\left[\frac{b_1(\omega)}{a_1(\omega)}\right]$$

and

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

$$b_1(\omega) = \frac{Q_{13}(\omega)}{\sqrt{[C_{22}(\omega) + C_{33}(\omega)]C_{11}(\omega)}},$$

where C_{ij} and Q_{ij} are the real and imaginary parts of the cross-spectrum between the ith and jth displacement time series in the vertical ($i, j = 1$), west ($i, j = 2$) and north ($i, j = 3$) directions.

The maximum likelihood method (Capon 1969) was applied to obtain the two-dimensional spectra using the code by Drennan et al. (1994). In these latter calculations, 1200 s of displacement data were used. The sampling rate of the time series was 0.78 s.

b. Directional properties of wind waves in the Gulf of Finland

Directional measurements from the years 1990 to 1994 (Pettersson 2001) show that the mean direction of the dominant waves in the Gulf of Finland is controlled by the geometry in narrow sectors in the east and southwest directions; an example is shown in Fig. 2.

When the wind is not straight along the axis, the directional wave spectrum shows a slanting fetch behavior similar to that described by Donelan et al. (1985) and Holthuijsen (1983): the waves at higher frequencies are aligned with the wind while the direction at the spectral peak is determined by a longer fetch component—in our case, that along the axis of the bay. An example of

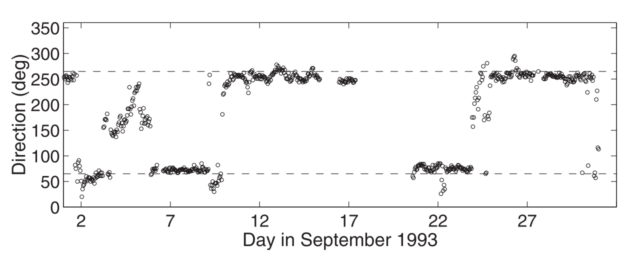

FIG. 2. A typical example of the steering of the wave directions in the Gulf of Finland. The time series shows the mean propagation directions at the spectral peak from station Porkkala in September 1993. The orientation of the axis of the gulf is indicated by dashed lines.

a spectrum in slanting fetch conditions is given (see Figs. 5a,b).

Since the steering of the dominant wave directions caused by the slanting fetch conditions is not the only mechanism that can cause wave and wind directions to differ, a subset of data was selected by the following criteria: (i) the waves are growing in a steady wind, (ii) swell from the Baltic Proper is small compared with the wind sea, and (iii) the peak wave period is short enough that refraction effects are not present.

The wind measurements were made at the automatic weather station Kalbådagrund (59°59′12″N, 25°36′12″E). This caisson lighthouse stands approximately 20 km to the east of station Helsinki and the wind is measured at a height of 32 m (Fig. 1). The steady wind cases were first selected on the basis of these wind measurements. Only the cases where the variation and trend of the wind speed were less than ±30% and 1.6 % per hour, and less than ±30° and 2.5° per hour for the wind direction, were accepted. The steadiness of the wind was further confirmed with meteorological maps and wind measurements from weather stations along the northern coast of the Gulf of Finland and in the Baltic Proper. Finally the cases with swell were excluded, except when the swell was small and its peak frequency clearly separated from the peak frequency of the wind sea.

At the measuring sites the water is deep enough (60 m) that the waves are not locally affected by the bottom. From the northern coast the distance to the 40-m isobath is about 15 km and from the southern coast a couple of kilometers. In the eastern end of the gulf the 40-m isobath is found at about 30 km from the shore. Refraction calculations in the Gulf of Finland (not shown) indicate that for peak frequencies over 0.125 Hz the refraction is not significant. Of the measured fetch-limited peak frequencies in this study, 97% exceeded this value and were accepted to the dataset. In the Gulf of Finland with its u-shaped topography the main effect of the refraction is to turn long waves toward the shores, thus affecting the wave field in the middle of the gulf.

The mean directions at the spectral peak in the selected cases are plotted against wind directions in Fig. 3. The steering effect at the peak of the spectrum is prominent at both locations: when the wind is in a 90° sector around the axis of the bay the dominant waves propagate along the axis independently of wind direction. Comparing the two stations reveals the strong dependence of the mean wave directions at the spectral peak on the fetch geometry: when the wind is from the southeastern sector (propagation directions 250°–300°) the mean wave directions at the spectral peak are more clearly aligned with the axis of the gulf at station Porkkala, which is in the middle of the narrowest part of the gulf, than at station Helsinki where the gulf starts to broaden toward the southeast (Fig. 1).

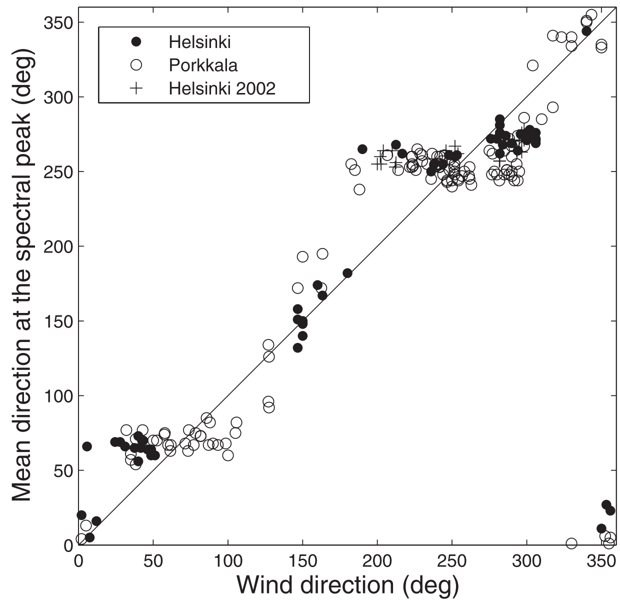

FIG. 3. Wind direction vs mean wave direction at the spectral peak during steady winds in the Gulf of Finland. Bullets denote the data from station Helsinki and open circles the data from station Porkkala. The data from station Helsinki measured in 2002 are indicated by crosses. The wind direction is from the automatic weather station Kalbådagrund. The total number of observations at station Helsinki is 78 and at station Porkkala 127. The directions indicate the direction toward which the waves and wind are propagating–blowing.

3. Seymour–Holthuijsen directionally decoupled wave growth

In his study on the effect of an irregular coastline on the directional properties of wind waves in fetch-limited conditions, Holthuijsen (1983) applied successfully a directionally decoupled model originally suggested by Seymour (1977). When directionally decoupled waves grow from an irregular coast line, the fetch felt by the components from different directions with respect to the wind direction varies. The parameters that control the growth of the waves from a certain direction are the distance to the shore in that direction, X_θ, and the wind speed U. Since the waves traveling in different directions are assumed not to interact, the wave components evolve the same way as they would choosing the fetch as $X_{0\theta} = X_\theta \cos\theta$, where θ is the angle between the wind direction and the direction of the wave component; the segment in the directional spectrum is the same as the segment of a directional spectrum from a straight shoreline at fetch $X_{0\theta}$. The segment of the resulting two-dimensional spectrum in the direction in question determines the corresponding directional components in the final spectrum.

A valuable property of the decoupled model is that it transfers the problem of determining the directional spectrum in complex fetch geometry to determining the directional spectrum in orthogonal fetch. In principle, no parameterization of the spectrum is necessary if sufficient data are available from orthogonal fetch experiments. In practice, measurements from all fetches and wind speeds do not exist and therefore some parameterization of the spectrum in orthogonal fetch growth is needed.

Holthuijsen (1983) used in his decoupled model the Joint North Sea Wave Project (JONSWAP) frequency spectrum and the directional distribution suggested by Hasselmann et al. (1980) with some modifications connected to fully developed sea state. Since then the growth curves have been revised and it has been found that the frequency spectrum has a ω^{-4} tail. We have therefore constructed the model using a new frequency spectrum that has these properties. Compared with the ω^{-4} spectrum of Donelan et al. (1985), our spectrum does not have an extensive undershooting in the rear face and which is not seen in the measured spectra. Our spectrum F as a function of frequency ω has the form

$$F(\omega) = 5.2gU\omega^{-4}\exp\left(\frac{\omega}{\omega_p}\right)^{-4}\gamma,$$

where

$$\gamma = \left\{\left[\frac{(\omega-\omega_p)}{(0.008\omega_p)}\right]^2 + 1\right\}^{0.5}.$$

The peak frequency ω_p is calculated from the dimensionless growth relation given by Kahma and Calkoen (1992):

$$\tilde{\omega}_p = 13.7\tilde{X}^{-0.27},$$

where $\tilde{\omega}_p = \omega_p U_{10}/g$ is the dimensionless peak frequency, $\tilde{X} = Xg/U_{10}^2$ is the dimensionless fetch, U_{10} denotes the wind speed at a height of 10 m, and g is the gravity. The limit for frequency is set at the Pierson–Moskowitz full development level $\tilde{\omega}_p = 0.79$ (Pierson and Moskowitz 1964). For the directional distribution we have used two distributions. The Donelan et al. (1985) distribution is

$$S(\omega, \theta) = 0.5F(\omega)\beta\,\mathrm{sech}^2\{\beta[\theta - \overline{\theta}(\omega)]\},$$

where $S(\omega,\theta)$ is the two-dimensional spectrum and $\overline{\theta}(\omega)$ the mean wave direction. The parameter β has the following frequency dependence:

$$\beta = 2.61\left(\frac{\omega}{\omega_p}\right)^{+1.3}, \quad 0.56 < \frac{\omega}{\omega_p} < 0.95$$

$$\beta = 2.28\left(\frac{\omega}{\omega_p}\right)^{-1.3}, \quad 0.95 < \frac{\omega}{\omega_p} < 1.6.$$

Donelan et al. (1985) gave a constant $\beta = 1.24$ above $\omega/\omega_p > 1.6$. Ewans (1998) has compared different directional distributions to heave–pitch–roll buoy observations and shown that the directional spreading at high frequencies is better described by the formulation presented by Banner (1990). His β was used for the high-frequency part of the spectrum:

$$\beta = 10^{-0.4+0.8393\exp[-0.567\ln(\omega/\omega_p)^2]}, \quad \frac{\omega}{\omega_p} > 1.6.$$

The directional resolution of the spectrum is 10°, the frequency resolution 0.01 Hz, and the fetch is an average over a 30° sector.

The mean wave directions at the spectral peak calculated by this model at the two stations are plotted in Fig. 4. In this figure a wind speed of 20 m s^{-1} was used. Runs with wind speeds of 10 and 15 m s^{-1} gave similar results, except that the steering of the mean wave directions at the spectral peak was slightly weaker in the southwest sector (propagation directions 20°–110°) at the wind speed of 10 m s^{-1}. The model estimates well the directions of the dominant waves that are propagating to the north or south (i.e., from orthogonal and straight shoreline). In slanting fetch conditions, the steering is stronger in propagation directions 25°–100°, where the fetch gradient is large than in propagation directions around 200°–300°, where there are several fetch components of equal length. Because of the fetch distribution, this behavior is best visible when the two stations are compared: at station Helsinki (Fig. 4a) the steering of the mean wave directions at the spectral peak in propagation directions around 200°–300° is weaker than at station Porkkala.

The other directional distribution we used was the $\cos^{2s}(½)\theta$ used by Holthuijsen (1983). Hasselmann et al. (1980) give the following parameterization:

$$s = 6.97\left(\frac{\omega}{\omega_p}\right)^{4.06}, \quad \frac{\omega}{\omega_p} < 1.05,$$

$$s = 9.77\left(\frac{\omega}{\omega_p}\right)^{\mu}, \quad \frac{\omega}{\omega_p} \geq 1.05,$$

and

$$\mu = -2.33 - 1.45\left(U_{10}/c_p - 1.17\right),$$

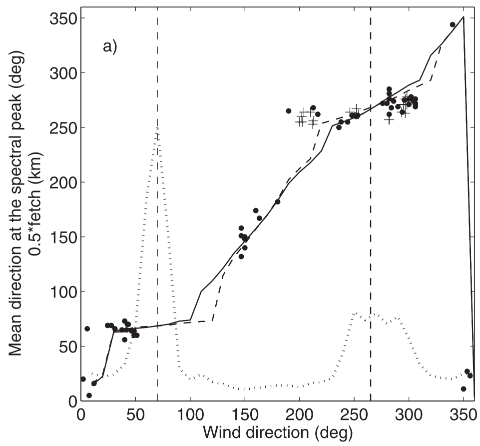

FIG. 4. The mean direction at the spectral peak estimated by the directionally decoupled model. (a) Station Helsinki, (b) station Porkkala. The solid line represents calculated wave directions with the Donelan et al. (1985) directional distribution and dashed lines with the Hasselmann et al. (1980) distribution. The dotted line indicates fetch in kilometers divided by two, and the vertical dashed lines the orientation of the axis of the gulf. The conventions for the measured data are the same as in Fig. 3.

where c_p is the phase speed at the spectral peak. The $\cos^{2s}(½)\theta$ distribution with this parameterization is broader than the $\mathrm{sech}^2\beta\theta$ distribution of Donelan et al. (1985) and it produces a stronger steering effect: the wind direction windows for constant wave directions are 20°–30° broader (dashed lines in Fig. 4). The wave age dependence of the directional spreading in the Hasselmann et al. (1980) distribution did not have influence on the mean direction at the spectral peak. That the decoupled model with $\cos^{2s}(½)\theta$ distribution better estimates the observed mean directions at the spectral peak does not necessarily mean that the distribution is more accurate than other distributions found in the literature to describe the directional shape of the spectrum. Even in the ideal conditions, steady wind blowing from a straight shoreline, the true shape and evolution of a directional distribution has not yet been solved, mostly because of the difficulties in measuring the necessary directional information (Krogstad and Barstow 1999; COST714-WG3 2005).

The steering of the mean wave direction at the spectral peak estimated by the directionally decoupled model is not as strong as observed in the northeastern sector (Fig. 1; and propagation directions around 225° in Fig. 4), where the shoreline forms a well-defined slanting fetch geometry. An example of the two-dimensional spectra in this direction from station Porkkala is given in Fig. 5. In Figs. 5c and 5d the decoupled model has been forced by the wind speed and direction corresponding to the measured fetch-limited situation, 8 m s^{-1} and 30° (propagation direction 210°). The directional distribution used in the decoupled model is the Donelan et al. (1985) distribution. The peak frequency of the hindcast spectrum is higher than the measured one and the hindcast two-dimensional spectrum shows components that propagate along the gulf at frequencies lower than the peak frequency. These components are at the same frequencies and in the same direction as the peak of the measured spectrum. Clearly the directionally decoupled model is not able to produce wave components in the direction aligned with the gulf with enough energy to dominate the spectrum.

The two-dimensional spectrum estimated by the decoupled model with $\cos^{2s}(½)\theta$ distribution had a local maximum at lower frequencies aligned with the gulf, but the mean direction at the spectral peak was only 6° closer to the orientation of the axis of the gulf.

At station Porkkala in the northwest sector (propagation directions around 100° in Fig. 4b), the steering of the dominant wave directions is produced correctly. In this sector the fetch gradient is large and the gulf is narrow so that the components along the gulf have enough energy to dominate the spectrum.

4. The directionally coupled wave growth of Donelan

On the basis of theoretical considerations and the wave measurements from Lake Ontario, Donelan et al. (1985; see also Donelan 1980) suggested a method for determining the wave direction at the spectral peak in a slanting fetch geometry. The relevant parameters in the model are the fetch and the wind components in the direction the waves are approaching from. The pair of these two parameters that yields the largest period will also produce the main portion of the energy and therefore determines the spectral peak and its direction. The equation

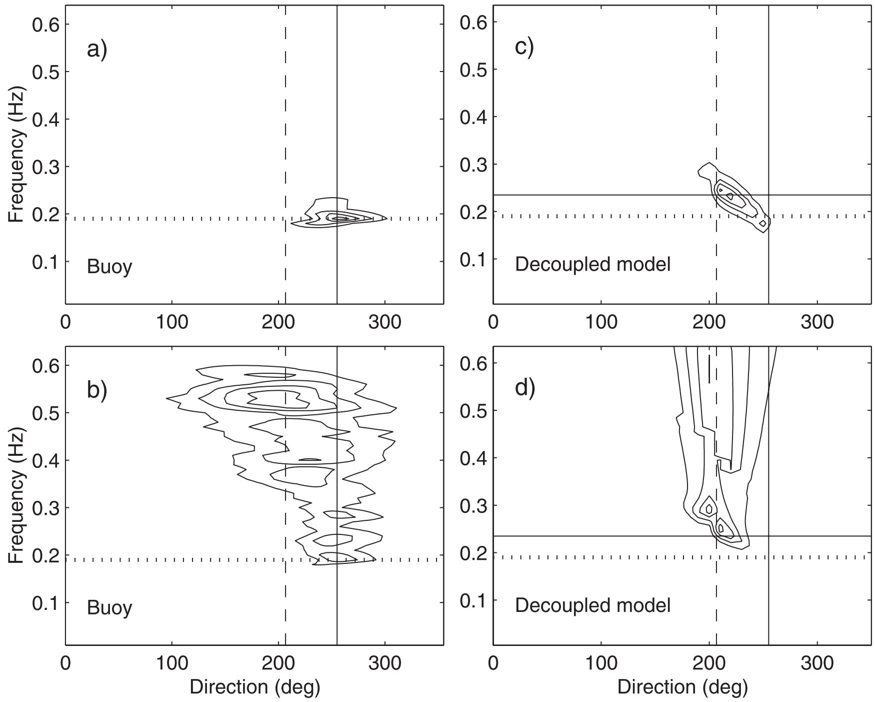

FIG. 5. Two-dimensional spectrum in slanting-fetch conditions from station Porkkala at 0600 UTC 28 Sep. (a) The measured spectrum and (b) the spectrum multiplied by ω^5. (c),(d) The corresponding spectra hindcast by the directionally decoupled model with the Donelan et al. (1985) directional distribution. The solid vertical lines denote the orientation of the axis of the bay and the dashed vertical lines, the direction toward which the wind is blowing. The measured peak frequency is indicated by the dotted lines in each panel and the peak frequency hindcast by the decoupled model by the horizontal solid line in (c) and (d). The energy density is normalized with respect to the peak value and the contour levels are 0.3, 0.5, 0.7, 0.9, and 1.

for the peak period T_p is solved from the empirical growth curve of Donelan et al. (1985):

$$T_p = 0.54g^{-0.77}(U_{10}\cos\theta)^{0.54}X_\theta^{0.23},$$

where $U_{10}\cos\theta$ is the wind component and X_θ the fetch in direction θ from the wind direction.

The wave directions at the spectral peak calculated with the Donelan model at stations Helsinki and Porkkala are plotted in Fig. 6. A wind speed of 20 m s^{-1} is used in this figure. The model gives a stronger steering effect than the directionally decoupled model. On the other hand it gives hardly any waves propagating toward the north, although the fetch is nearly orthogonal.

Donelan et al. (1985) used the wind and fetch component in the approach direction of the dominant waves to include the slanting fetch cases to a universal growth law, so the method should be valid regardless of the growth curve used. The discrepancies between growth relations from different experiments were analyzed in Kahma and Calkoen (1992), who presented growth curves based on three datasets, the JONSWAP data (Hasselmann et al. 1973), the orthogonal Lake Ontario data (Donelan et al. 1985), and the Bothnian Sea data (Kahma 1981). Using their relation, and $U_{10}\cos\theta$ instead of U_{10}, the expression for the peak wave period becomes

$$T_p = 0.459g^{-0.73}(U_{10}\cos\theta)^{0.46}X_\theta^{0.27}.$$

The mean wave directions at the spectral peak calculated using this growth relation are indicated by dashed lines in Fig. 6. The results are almost the same, except that all the northward propagating waves are missing.

In terms of frequencies, a well-defined minimum of the term $1/(X_\theta\cos\theta)^{0.426}$ was not always found in the northern propagation directions. For example, at Porkkala, when the wind is from 160° (propagation direction 340°), the frequencies of eight components is less than 0.01 Hz higher than the minimum value, which in this case is in the wind direction. At station Helsinki, at winds coming from 170° (propagation direction 350°), the minimum is found at a propagation direction of 360°, and two secondary minima (0.006 and 0.009 Hz higher) are found at propagation directions of 310° and 50°. Donelan et al. (1985)

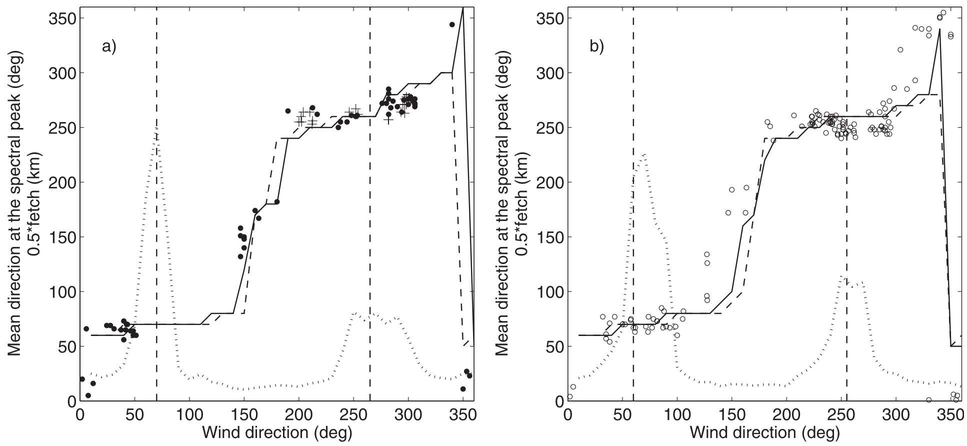

FIG. 6. The mean direction at the spectral peak estimated by the model of Donelan (1980). (a) Station Helsinki and (b) station Porkkala. Solid line represents wave direction obtained using the Donelan et al. (1985) growth curve, and dashed line using the growth curve of Kahma and Calkoen (1992). The dotted line indicates fetch in kilometers divided by 2, and the vertical dashed lines the orientation of the axis of the gulf. The conventions for the measured data are the same as in Fig. 3.

found that the model fits their observations best when the fetch component used for searching the approach direction of the dominant waves was an average over a 30° sector. The corresponding average fetch has been used in Fig. 6. An average over a 10° sector reduces the influence of the longer fetch components, but it did not improve the agreement. The biggest change was at station Porkkala in the propagation direction of 350°. Here two minima were found, in directions of 10° and 30° instead of the 50° in Fig. 6b. The term $1/(X_\theta \cos\theta)^{0.587}$ obtained from the growth curve of Kahma and Calkoen (1992) emphasized the longer fetch components and in some directions the existence of a minimum peak frequency was even less clear. Ignoring the other fetch and wind components that can generate energy at frequencies close to the minimum peak frequency can result in a too strong steering effect, as in the northern propagation directions in Fig. 6.

This was also pointed out by Walsh et al. (1989), who suggested that because of the weakly nonlinear interactions, the components growing from directions other than the direction of the peak frequency cannot be ignored, and that the direction that yields the lowest peak frequency is not necessarily the same that yields the maximum energy. Their method, which maximizes both energy and period, relies, however, on the correctness of the wave directions at the spectral peak estimated by the model of Donelan. Their method allows other growth curves obtained from orthogonal wave data to produce the same wave directions as the growth curve of Donelan et al. (1985) by introducing an additional parameter to the growth curves, V, that describes the effectiveness of the wind, $U_{10}(\cos\theta)^V$. The Donelan et al. (1985) parameterization has $V = 1$; Walsh et al. (1989) obtained $V = 1.63$ from the growth curves fitted to their measurements. The growth curves of Kahma and Calkoen (1992) give $V \approx 1.35$, producing, as they should, the same wave directions as the model of Donelan (solid line in Fig. 6).

When compared to a ''pure'' slanting fetch situation, the narrowness of the Gulf of Finland imposes an additional restriction on the growth of the waves. According to the model of Donelan, the evolution of the peak frequency should be unaffected by the fetch geometry when the wind blows along the gulf. The studies of Kahma and Pettersson (1994) and Pettersson (2004) on the wave growth in steady winds along the Gulf of Finland showed, however, that the evolution of the dimensionless peak frequency was slowed down, but not as much as the growth of the dimensionless energy. The conclusion was that although the influence of the weakly nonlinear interactions was visible, they were not able to shape the spectrum into a universal form. Similar results on the one-dimensional spectrum were also found by Ataktürk and Katsaros (1999) when they analyzed their wave data from the narrow Lake Washington. The above studies suggest that the position of the spectral peak is not entirely determined by only one fetch and wind component.

The model of Donelan gave a stronger steering of the dominant wave directions than the decoupled model. In the well-defined slanting fetch geometry in propagation directions around 225° in Fig. 4, the model produced well the steering of the dominant wave directions. When there were several fetch components of equal length as in the northern propagation directions, the model produced a too strong steering. The model of Donelan provides an efficient tool for determining the wave direction at the spectral peak, provided that a well-defined minimum of the term $1/(X_\theta \cos\theta)^{0.426}$ is found. The assumption made on the universality of the spectral shape, however, is not entirely supported by the Gulf of Finland data.

5. Analysis based on transport equation

The evolution of the wave spectrum in deep water can be described by the transport equation:

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

where $S(\omega, \theta)$ is the two-dimensional wave spectrum, ω the angular frequency, θ the direction of the wave component, and $\mathbf{c}_g$ the group velocity. The weakly nonlinear interactions G_{nl} can be calculated but our knowledge of the other two source terms, the wind input G_{in} and especially the dissipation G_{ds}, is still limited. As a consequence the balance of the source terms is only approximate. In addition, if the exact solution of the nonlinear transfer is used with a sufficiently high grid resolution the computational task becomes huge and is beyond the resources available for this study. Instead we have made use of the fact that the slanting fetch case has a resemblance to the early stages in a turning wind situation when the wave field is horizontally homogeneous. In this case the studies of van Vledder (1990), Young et al. (1987), and van Vledder and Holthuijsen (1993) can be used. They studied the physical processes in turning wind cases with the one-dimensional, third-generation wave model that uses an exact solution of the weakly nonlinear interactions (EXACT-NL; Hasselmann and Hasselmann 1981, 1985). Just after the wind has turned, waves are generated in the new wind direction while the spectral peak at the lower frequencies still remains in the previous wind direction. It was found that in the beginning of a turning wind event the weakly nonlinear interactions are transferring energy from the young growing waves in the new wind direction toward the spectral peak at lower frequencies in the previous wind direction. The nonlinear transfer from the higher frequencies is stronger in the new wind direction than in the direction of the old wind. Figure 3.16 from van Vledder (1990) showing the source terms in a turning wind case is reproduced in Fig. 7.

Instead of gradually turning into the wind direction, the waves growing in a slanting fetch geometry are fetch limited, which leads to a "frozen" image of the early stages of a turning wind case. When waves are growing in slanting fetch conditions in a gulf, they begin to feel the slanting fetch geometry at some distance from the end of the gulf. This can be expected to happen when the fetch component along the gulf is long enough and the wind component in the same direction effective enough to generate components at frequencies below those that have grown over the fetch in the wind direction. The components in the wind direction reach the fetch-limited conditions earlier than the components growing along the gulf. Keeping in mind the analogy with the early stages of a turning wind case, there is a smaller transfer of energy from the high-frequency part in the direction along the gulf than in the wind direction (Fig. 7), which enables a rather independent evolution of the components aligned with the gulf. When these components have grown to a sufficient size, the role of the weakly nonlinear interactions is to maintain the evolution of the spectral peak in the direction of the longer fetch component by transferring energy from the high-frequency part aligned with the wind.

6. Wave directions hindcast by WAM

For computational reasons the weakly nonlinear interactions are not calculated using the exact solution in WAM (WAMDI-Group 1988; Komen et al. 1994). Instead they are solved using the discrete interaction approximation (DIA; Hasselmann et al. 1985). The DIA describes well the main features of the weak nonlinear interactions (e.g., the down shifting of the spectral peak), but it has some shortcomings that demand tuning of the source terms to produce the desired wave growth (van Vledder et al. 2000). The DIA uses only one configuration of the sets of four waves that can exchange energy under resonant conditions, and the mirror image of that quadruple. The configuration of the quadruple is such that the resonance condition actually requires a directional coupling between the waves; and in principle, the use of a mirror image might imply some restrictions to the shape of the spectrum.

Considering the size of the Gulf of Finland, it is evident that the grid resolution of an atmospheric model has to be quite high to avoid the underestimation of the marine winds. Such a model for the Baltic Sea was not available before the end of last century, when a joint project of the Finnish Institute of Marine Research and the Finnish Meteorological Institute to couple the WAM cycle 4 to the atmospheric High Resolution Limited Area Model (HIRLAM; Källén 1996) started. Since 2000 both the models have been run operationally on a grid of 22-km resolution. The grid is rotated with respect to 0° longitude to obtain equally spaced grid steps. In 2002 the models were run fully coupled with a coupling time step of 4 min. WAM is run in a shallow water configuration and the spectra have 24 angular and 25 frequency bands in the range 0.042–0.414 Hz.

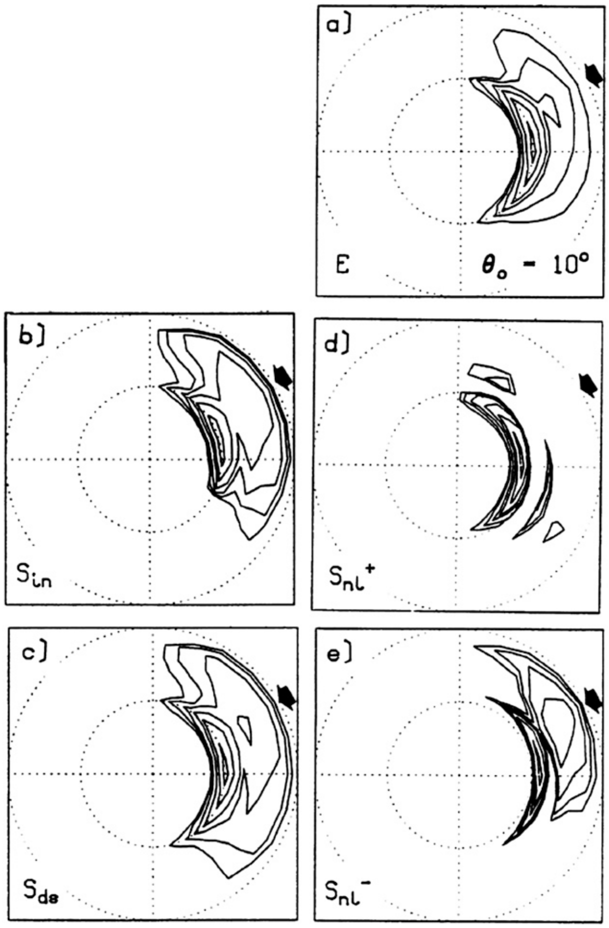

FIG. 7. Nonlinear transfer at the early stages of a turning wind situation calculated with EXACT-NL model. (a) The spectrum, (b) the wind input, and (c) the dissipation. (d) The gain and (e) loss of the energy due to the nonlinear interactions. The spectrum is normalized and the isolines are at relative heights of 0.8, 0.4, 0.2, 0.1, 0.05 and 0.25. The dotted circles are at 0.125 and 0.25 Hz, and the arrow shows the wind direction. Reprinted from van Vledder's (1990) Fig. 3.16.

A period of 10 days in October 2002 was selected for studying the wave directions in a narrow bay calculated by WAM. The wave buoy was deployed at station Helsinki (Fig. 1). In this period there were two events with steady winds according to the criteria presented in section 2b, first from the northeast (9 October) and later from the southeast (14–15 October). These measured steady wind events are denoted by crosses in Figs. 3, 4, and 6. The calculated wind, significant wave height, and peak frequency from the whole period are plotted in Fig. 8 together with observations. The calculated wind speed and direction from the coupled atmosphere wave model agree well with the wind measurements at Kalbådagrund (Figs. 8a,b), but the significant wave height is underestimated and the peak frequency overestimated by WAM (Figs. 8c,d). Despite the fact that the wind is estimated correctly in the middle of the gulf, it is possible that the 22-km grid resolution cannot produce the correct horizontal gradient of the wind speed along the upwind fetch. The stratification during the comparison period was unstable with a bulk Richardson number between -1.03 and -0.3, which may partly explain the smaller values given by WAM, which uses a neutral stratification in the wave growth. Cavaleri and Sclavo (1998) have also pointed out that with the present propagation scheme in the standard WAM there can be unrealistic energy loss close to the coast and when waves propagate parallel to it. In our case, the coasts are on both sides, and not very far.

In this study we are interested in the behavior of the directions of the dominant waves in a slanting fetch geometry, and the mean direction at the peak of the WAM spectrum was calculated from the first pair of Fourier coefficients obtained from the two-dimensional spectrum (see, e.g., Longuet-Higgins et al. 1963; Kuik et al. 1988).

The calculated mean directions at the spectral peak at station Helsinki are denoted by stars in Fig. 9. It is clear that WAM on a grid of 22-km resolution is not able to produce the correct steering of the mean wave directions at the spectral peak, but gives mean wave directions at the spectral peak that are in the middle between the wind direction and the orientation of the axis of the gulf.

As the grid resolution may affect the propagation, which is central for the reproduction of the fetch geometry effects, additional WAM runs with higher grid resolutions, 11 and 5 km, were made. In these runs the winds from the coupled 22-km WAM–HIRLAM were used as a one-way input with a time step of 60 min. The winds were linearly interpolated to the wave model grids with smaller grid-step size. The run on the 5-km grid resolution differs; because of numerical instabilities the model was run in a deep-water configuration. Including the bottom effect is necessary for regions near the shore in the operational model for the whole Baltic Sea, but in the area studied here, and with the wind speed range during the comparison period, the assumption of deep water is sufficient. The calculated parameters of the one-dimensional spectrum, the significant wave height and the peak frequency, did not differ from those calculated by the 22-km WAM (Fig. 8), but the higher grid resolutions had a clear effect on the mean direction at the spectral peak (Fig. 9). The calculated mean wave directions at the spectral peak are much closer to the measured ones when the grid resolution is 5 km, although there is still an offset between the measured and modeled wave directions. Evidently the propagation of the waves is estimated more reliably with a small grid step size. To the northeast from station Helsinki the number of grid points for 22-, 11-, and 5-km grid

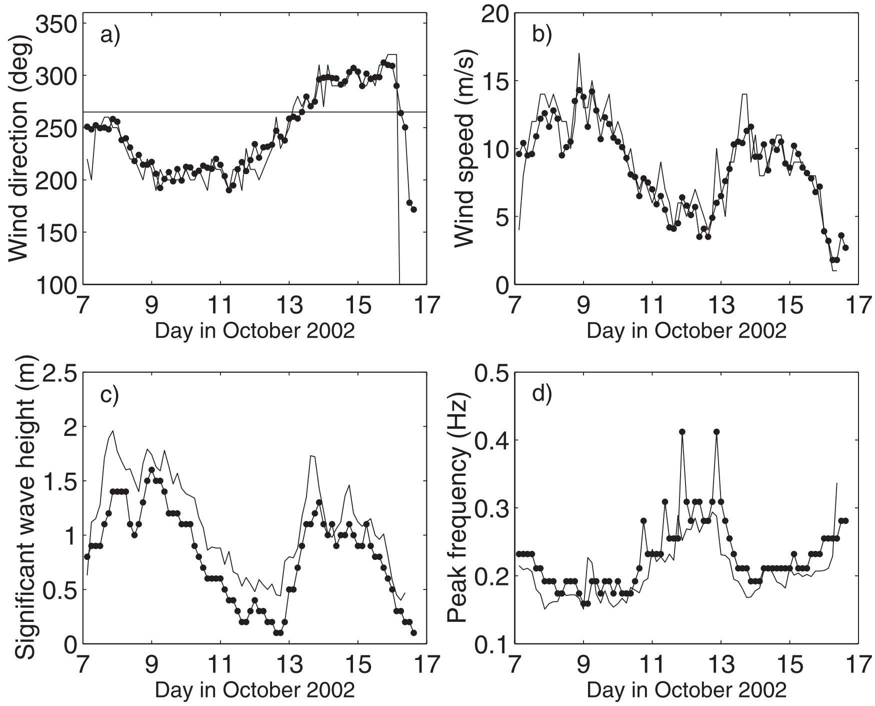

FIG. 8. The time series from the coupled WAM–HIRLAM with a 22-km grid resolution in October 2002 at station Helsinki. The solid line denotes the measured data and the bullets the modeled data. (a) The wind direction, (b) the wind speed at 32 m, (c) the significant wave height, and (d) the peak wave frequency. The orientation of the axis of the gulf is indicated by solid line in (a). The wind has been measured at Kalbådagrund and the directions indicate the directions toward which the wind is blowing.

resolutions was 1, 2, and 4 and to the southeast 6, 14, and 28, respectively.

The directional resolution of the WAM spectrum in the runs discussed above is 15°. To find out how the directional resolution affects the results, a WAM run with 5-km grid and 30° directional resolutions was done. The mean wave directions at the spectral peak calculated with the coarser directional resolution were very similar to those calculated with 15° resolution, denoted by circles in Fig. 9. On the basis of these runs, the directional resolution appears to have a minor role in the accuracy of the calculated wave directions.

With a high grid resolution, the spectral model was able to produce rather realistic wave directions, indicating that WAM with DIA is capable of producing the overall features in a slanting fetch geometry. On the other hand, the strong dependence of the wave directions on the grid resolution suggests that making definite conclusions about the physics of the model is not straightforward. As Tolman (1992) pointed out, while a model may work satisfactorily for practical purposes, knowing the numerical errors in the model is essential for interpreting the physics involved. Evidently the numerical solutions play an important role in modeling the evolution of the waves, and the wind as well, in a rather small-scale narrow bay. In recent years there have been several studies on the numerical solutions in spectral wave models concerning, for example, the deficiencies of the DIA (van Vledder et al. 2000), the advection scheme (Cavaleri and Sclavo 1998), the numerics associated with high spatial resolution (Monbaliu et al. 2000), and the garden sprinkler effect (Lavrenov and Onvlee 1993), all of which can influence the estimation of the directional properties of the waves. A detailed study of the numerical solutions is, however, beyond the scope of the present study.

7. Discussion

To be able to compare the three models in the full range of wind directions, the 5-km WAM was forced by steady, 15 m s^{-1} winds (at the height of 10 m) and the wind direction was changed every 48 h by 10°. At the two stations studied here, the fetch-limited conditions are reached in less than 18 h. The calculated mean wave directions at the spectral peak at the two stations are plotted against the wind directions in Fig. 10 together with the mean wave directions at the spectral peak from the model of Donelan and the decoupled model. The

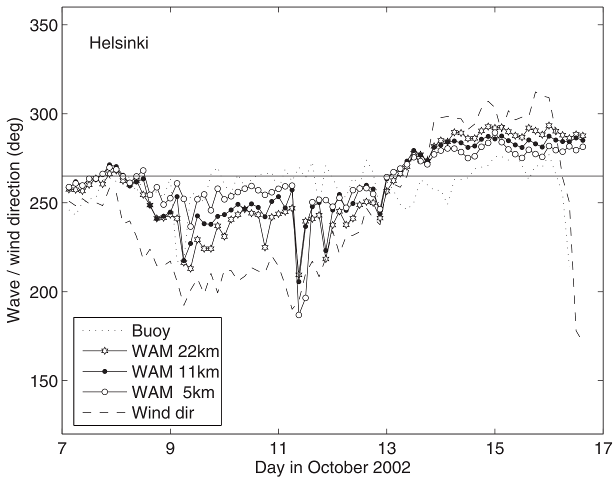

FIG. 9. The time series of the mean directions at the spectral peak at station Helsinki estimated by WAM with three different grid resolutions. The wave directions from WAM with the 22-km grid resolution (stars), 11-km grid resolution (bullets), and 5-km grid resolution (circles). The dashed line indicates the wind direction from the coupled WAM–HIRLAM with the 22-km grid resolution. The measured wave directions are denoted by the dotted line and the solid line indicates the orientation of the axis of the gulf. The directions indicate the direction toward which the waves and wind are propagating–blowing.

northward-propagating waves are better estimated by WAM than by the model of Donelan, which emphasizes the longer fetch components, but in the most clear slanting fetch conditions at propagation directions around 225° WAM is not able to produce as strong a steering effect as observed. On the other hand, the mean wave directions at the spectral peak calculated by WAM show a stronger steering effect than those of the decoupled model. The difference between WAM and the decoupled model with the $\cos^{2s}(½)\theta$ distribution is even smaller (Figs. 4, 10). The slightly stronger steering suggests that the weakly nonlinear interactions are involved in determining the position and direction of the spectral peak. The same conclusion can be drawn when the two-dimensional spectrum given by the decoupled model is compared with the measured two-dimensional spectrum in Fig. 5. The measured position of the spectral peak indicates a stronger steering effect than estimated by the decoupled model, and suggests that the wave components are not entirely decoupled.

Considering the role of the nonlinear transfer, the slanting fetch case has a resemblance to the early stages in a turning wind situation. In section 5 we showed how this can be used to infer the role of the nonlinear transfer in the slanting fetch case. The model of Donelan (1980) was based on the assumption that the position and the direction of the spectral peak are determined solely by one fetch and wind component. The spectral peak and its direction are solved assuming that the wave components are growing directionally decoupled, and only one component will dominate the spectrum at the peak. The one-dimensional spectrum is expected to have a universal shape. This approach is reasonable when the suggested description of the role of the weakly nonlinear interactions in the wave growth in a slanting-fetch geometry is considered.

The evolution of the spectrum along the gulf in slanting fetch conditions can be expected to be highly dependent on the balance of the source terms. Although there were no measurements from station Porkkala during the comparison period in 2002, the mean wave directions at the spectral peak in the area are so predictable (cf. Fig. 2) that we can expect that the dominant waves are propagating along the gulf here also. The mean direction at the spectral peak calculated by WAM on the three different grid resolutions and the calculated wind direction are shown in Fig. 11. Looking from the easterly wind direction, station Porkkala is situated deeper in the narrow part of the gulf, about 50 km from station Helsinki. Comparing the WAM runs on the two higher grid resolutions in Figs. 9 and 11 indicates that the steering of the mean wave directions at the spectral peak is slightly stronger when the distance to the end of the gulf is longer. Some evidence of the stronger steering at station Porkkala is also visible in Fig. 10 at propagation directions 200°–260°. According to the measurements the waves grow in a slanting fetch geometry already at station Helsinki, and intuitively we would expect them to do so at some distance to the east too (Fig. 1). How well a spectral wave model can describe this evolution is not necessarily only a question of the grid step size, but is also dependent on how accurate the balance of the source terms is.

8. Conclusions

The steering of the mean direction at the peak of the spectrum is a frequently observed directional property in the middle parts of the Gulf of Finland. It offers an excellent opportunity to study the influence of the fetch geometry on the spectral shape. We compared the experimental data with three different models that all have different assumptions of directional coupling between wave components and about the spectral shape: Seymour–Holthuijsen directionally decoupled wave growth, the Donelan model, and the third generation WAM cycle 4.

None of the three models reproduce perfectly the observed influence of the fetch geometry on the directional properties. The directionally decoupled model produces well the steering of the mean direction at the spectral peak in slanting fetch directions provided that the bay is narrow and shores are parallel. It also agrees

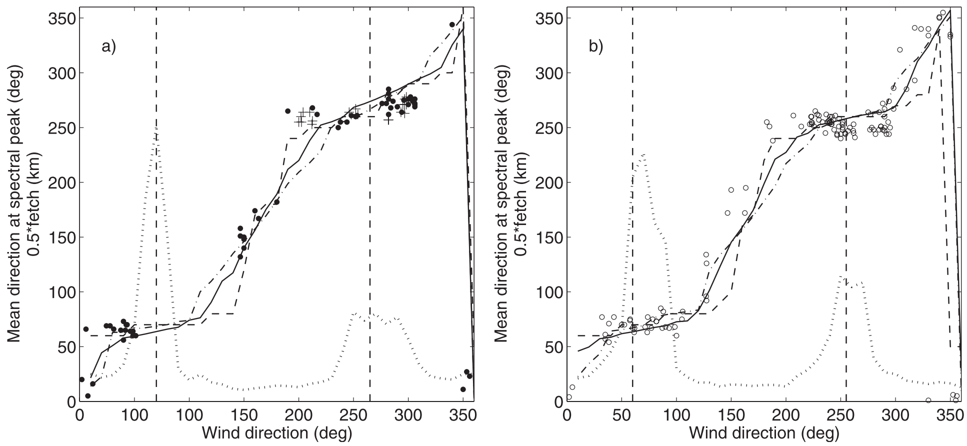

FIG. 10. The mean direction at the spectral peak estimated by the three models. (a) Station Helsinki, (b) station Porkkala. Dashed–dotted line represents the decoupled model using the directional distribution of Donelan et al. (1985), solid line the WAM with the 5-km grid resolution, and dashed line the model of Donelan with Donelan et al. (1985) growth curve. The dotted line indicates fetch in kilometers divided by two, and the vertical dashed lines the orientation of the axis of the gulf. The conventions for the data are the same as in Fig. 3.

well with the observations when the fetch is close to orthogonal. When slanting fetch geometry is broader the steering effect produced by the model is weaker than observed. The directionally uncoupled model is not able to produce the relaxation of the wave direction from the bay direction to the wind direction as the wave frequency becomes higher. These findings suggest that the waves do not grow directionally fully decoupled.

The Donelan model on the other hand estimates the steering of the dominant wave directions well in well-defined slanting fetch conditions, but in other directions the steering is stronger than observed. It fails to estimate correctly the direction when the wind is toward the north from a nearly orthogonal fetch. The Donelan model does not have a mechanism to produce the relaxation of the wave direction from the bay direction to the wind direction as the wave frequency becomes higher. This together with the results of Kahma and Pettersson (1994) and Pettersson (2004) does not support the main assumption of the Donelan method that all fetch geometry effects could be accounted for by using the fetch and wind component in the approach direction of the dominant waves.

WAM with a 22-km grid resolution did not show significant steering of the mean wave direction at the spectral peak along the gulf, which is 70 km wide in its narrowest part. When the grid step size of the model was dropped from 22 to 5 km, the model was able to estimate the direction of the dominant waves better, but still the full extent of steering could not be recovered. The fact that WAM can reproduce the steering effect at all indicates that the phenomenon is covered by the transport equation.

We propose a mechanism explaining how the weakly nonlinear interactions could be able to produce the strong steering effect and the relaxation of the direction from the bay direction to the wind direction as the frequency increases. It is based on the calculations in a homogeneous wave field by van Vledder (1990) and van Vledder and Holthuijsen (1993), and the analogy

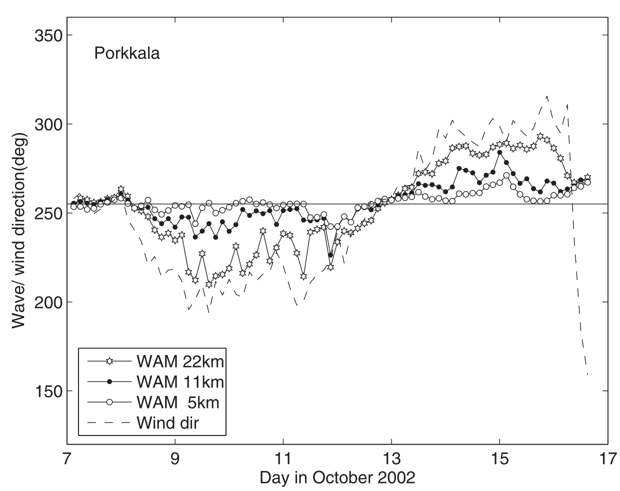

FIG. 11. The time series of the mean directions at the spectral peak at station Porkkala estimated by WAM with three different grid resolutions. The wave directions from WAM with the 22-km grid resolution (stars), 11-km grid resolution (bullets), and 5-km grid resolution (circles). The dashed line indicates the wind direction from the coupled WAM–HIRLAM with the 22-km grid resolution and the solid line indicates the orientation of the axis of the gulf. The directions indicate the direction toward which the waves and wind are propagating–blowing.

between early stages of a turning wind case in a homogeneous wave field and the fetch-limited growth from a slanting fetch. We suggest by this analogous interpretation of the exact transfer calculations that in slanting fetch conditions the weakly nonlinear interactions allow the along-bay components to grow rather independently until they grow larger than the fetch-limited waves in the wind direction. From that point on, nonlinear interactions are maintaining the peak of the spectrum in the direction of the axis of the gulf by transferring energy from the shorter wave components aligned with the wind.

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