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A comparison between measured wave properties and simple wave hindcasting models in shallow water

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A comparison between measured wave properties and simple wave hindcasting models in shallow water

Comparaison entre les caractéristiques mesurées de la houle et son estimation à partir du vent en eau peu profonde

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ABSTRACT
Significant wave heights and wave periods obtained from field measurements in Lake Balaton, Hungary, were compared with two versions of the shallow water wave hindcasting model published by the U.S. Army Corps of Engineers. The version presented in CERC [3, 4] was found to give very good hindcasts of wave height but fall ~20% low on wave period. The model presented in CERC [5] was 15-20% above the earlier version at long fetches and approximately equivalent at shorter fetches.

RÉSUMÉ
On a comparé les hauteurs significatives et les périodes d'une houle mesurée en nature sur le Lac Balaton en Hongrie avec deux versions du modèle d'estimation de la houle à partir du vent conçu par l'U.S. Army Corps of Engineers. Il apparaît que la version présentée au CERC [3, 4] restitue bien la hauteur de houle à partir du vent mais donne des périodes à peu près 20% plus basses. Avec les modèle présenté au CERC [5], on retrouve approximativement les mêmes résultats pour de faibles fetchs et on les majore de 15 à 20% pour de plus grands fetchs.

Introduction

Sediment transport, benthic ecology, water quality and mean circulation in the shallow waters of lakes, sounds and coastal regions may be significantly affected by the presence of locally generated, wind waves [1, 2, 6, 7, 9, 13]. In conjunction with these types of studies it is often very useful to have an easy method for predicting characteristic wave properties. The U.S. Army Corps of Engineers, CERC [3, 4, 5], has published two versions of a simple shallow water wave hindcasting model that have the potential to meet this need. However, there is relatively little field data that has been published demonstrating their accuracy, particularly in the wave height range generally considered to be surface chop (e.g., wave heights ~ 0.5 m or less). This paper presents a comparison of wave hindcasts and wave data measured on Lake Balaton, Hungary, (Fig. 1), which has the largest surface area of any lake in central Europe (700 km^2) but has a mean depth of only 3.2 m.

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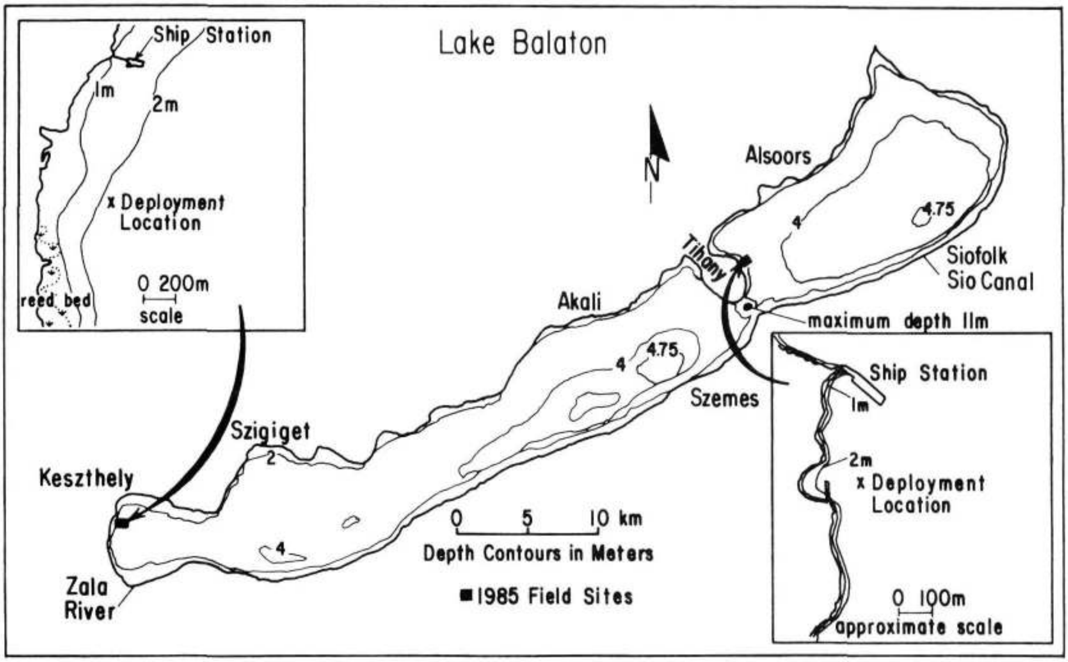

Fig. 1. Lake Balaton, Hungary with detailed drawings of the Keszthely and Tihany field sites.
Le Lac Balaton en Hongrie avec la représentation détaillée des lieux de mesures en nature de Keszthely et Tihany.

Field study and data analysis

Field data were collected using a tripod-based system of instruments at two sites in Lake Balaton, one in 2.2 m deep water 100 m east of the Tihany peninsula and the other in 2.0 m deep water 200 m east of the western end of the lake at Keszthely, (Fig. 1). A more detailed description of the instrumentation system is presented in Luettich et al. [9]. Bottom sediments at the Tihany field site consisted primarily of silty-sand while those at the Keszthely field site were mainly clayey-silt. Frequent dives failed to indicate the presence of appreciable bed forms at either location. Sediments ranged from areas of predominantly silt to areas of predominantly clay along the major fetchs of both field sites.

Data was collected in 6 minute long bursts and the instruments turned off for intervals ranging from 4–54 minutes depending on the ambient conditions. During a burst the sensors were sampled at a rate of 2 Hz.

Wind velocity was recorded using sensors 2 m above the mean water level.

Wave orbital velocities were measured by two BASS velocity meters 28 cm and 94 cm above the bottom at the Tihany side and 24 cm and 85 cm above the bottom at the Keszthely site. These acoustic sensors have a resolution of 0.03 cm/s, an accuracy of about 0.3 cm/s, measure velocity components in all three coordinate directions, and contain no moving parts which might have difficulty following a highly oscillatory flow, Williams [15].

Extensive comparisons between one-dimensional vertical velocity spectra measured by the upper and lower BASS showed that the surface wave band was well defined and that the velocities were accurately described by linear theory for significant wave heights greater than about

4 cm (for smaller waves a reliable separation between wave velocities and turbulent velocities could not be obtained). Therefore, linear wave theory was used to extrapolate the surface wave part of each vertical velocity spectrum measured at the upper BASS into a wave amplitude spectrum at the water surface. The significant wave height, H_s, was determined from the approximate relation,

$$H_s \approx 4\sigma \tag{1}$$

where σ is the standard deviation of water surface elevation in the wave band. Equation (1) is justified theoretically since all of the wave amplitude spectra satisfied the narrow bandedness criteria of Ochi [11] and Longuet-Higgins [8]. It's use with the data sets presented below also agrees with the results of Thompson and Vincent [14 - Fig. 6], regarding the relationship between statistical and energy based wave heights in shallow water.

The wave amplitude power spectra were used to compute the peak frequency, the centroid frequency and the expected zero-crossing frequency, Nath and Yeh [10]. Due to the narrowness of the wave spectra, there was virtually no difference among the three. Wave periods presented below were computed from the centroid frequency. It should be noted that since data was collected at 2 Hz it is theoretically impossible to resolve wave periods smaller than 1 sec and in practice, wave periods near 1 sec will be poorly represented as well. To check whether this was a problem with any of the measured data, the roll off of the measured velocity spectra and the computed wave amplitude spectra in the vicinity of 1 sec were examined. In all cases no indication of aliasing by improperly sampled high frequency waves was found.

Using the horizontal components of velocity it was also possible to estimate the direction of wave propagation ($\pm$ 180°). Occasions that the waves were not closely aligned with the wind are noted in the next.

Wave models

The two versions of the shallow water wave hindcasting model used in this study are summarized in Table 1. Equations (2)-(7) are based on the assumption that a spatially uniform wind has been blowing long enough for the waves to have reached a steady state at the point of interest, (i.e., fetch limited conditions). Dimensionless parameter groupings appear in equations (4)-(7) so that any consistent system of units can be used without changing the coefficient values.

As indicated in Table 1 and discussed below, the two model versions differ in their coefficient values, definitions of wind speed and fetch, and the inclusion of duration limitation.

Model 73 uses the effective fetch, F_e, to account for the loss of wave energy at lateral boundaries in enclosed and partially enclosed water bodies. F_e is computed as a weighted average of the distance from the measurement point to the shoreline at angles up to 45° on either side of the up-wind direction, CERC [3, 4]. The fetch in model 84 is defined simply as the distance between the measurement point and the shoreline in the up-wind direction.

Both models require the wind speed at a height of 10 m above the water surface and therefore it was necessary to adjust the measured windspeeds from 2 m up to 10 m. CERC [5] recommends a power law expression for model 84. No recommendation is made by CERC [3, 4] and therefore the adjustment for model 73 was performed assuming a logarithmic wind profile and the drag coefficient formula of Wu [16]. Wind velocities were smoothed with a 30-minute running average when measurement bursts were made more frequently than twice per hour. This acted to filter out some of the wind fluctuations with periods less than the response time of the wave field, particularly when the wind was oriented along the long axis of the lake.

Table 1. Shallow water wave hindcasting models

$$\frac{gH_s}{W_a^2} = 0.283 \tanh \alpha \cdot \tanh \left[\frac{\gamma}{\tanh \alpha} \right] \tag{2}$$

$$\frac{gT}{W_a} = 2.4\pi \tanh \beta \cdot \tanh \left[\frac{\delta}{\tanh \beta} \right] \tag{3}$$

$$\alpha = 0.530(gh/W_a^2)^{0.75} \tag{4}$$

$$\beta = 0.833(gh/W_a^2)^{0.375} \tag{5}$$

$$\gamma = A(gF/W_a^2)^{\delta} \tag{6}$$

$$\delta = B(gF/W_a^2)^{\varepsilon} \tag{7}$$

Model 1973 - CERC [3, 4]

$A = 0.0125$
$\delta = 0.42$
$B = 0.077$
$\varepsilon = 0.25$
$W_a = W_{10}$ (wind speed measured 10 m above the water surface)
$F = F_e$ (effective fetch)

Model 1984 - CERC [5]

$A = 0.00565$
$\delta = 0.5$
$B = 0.0379$
$\varepsilon = 0.333$
$F = F_{sl}$ (straight line fetch)
$W_a = 0.71 W_{10}^{1.23}$ (adjusted wind speed) (8)

$$\frac{gD}{W_a} = 537 \left(\frac{gT}{W_a} \right)^{2.33} \quad \text{(condition for duration limitation)} \tag{9}$$

Variable definition

H_s = significant wave height
T = wave period
g = acceleration of gravity
h = water depth
D = wind duration

CERC [5] suggests several additional adjustments should be made to convert the 10 m wind speed to W_a for use in model 84. Equation (8) is recommended to account for the nonlinear relationship between wind speed and wind stress and was used to obtain the results presented below. Corrections for the measurement duration and the air-water temperature difference typically canceled each other out, although occasionally up to a 10% increase in W_a was indicated. In all cases that this was significant, however, it decreased the agreement between the model 84 hindcasts and the measured wave data. Therefore neither the duration nor the air-water temperature adjustments were included in the results presented below.

Model 84 attempts to determine if fetch limited (steady state) conditions exist at the point of interest using equation (9). By substituting equation (3) into equation (9) it is possible to compute, for a given fetch, water depth and wind speed, the length of time the wind must blow before fetch limited conditions are reached. Waves produced by winds blowing for lesser periods are duration limited.

Both models were applied using the local water depth at each site as h in equations (4) and (5) due to the very gradual changes in bottom bathymetry that occur throughout most of Lake Balaton.

Results

Model comparisons are presented with two data sets, one from the Keszthely site and one from the Tihany site that were selected based on the presence of periods of reasonably sustained winds.

Keszthely, 8/15–8/18, 1985

Data was collected for a period of about 60 hours. Figs. 2a, b contain the measured wind speeds and directions and indicate the occurrence of three discrete wind events. During the first event the wind speed increased rapidly from near zero to an average of nearly 4 m/s and then diminished gradually over the following 12 hours. The direction remained quite constant throughout the period with winds blowing from the east and therefore nearly aligned with the long axis of the lake. Winds during the second event increased rapidly from near zero to about 3 m/s and fluctuated around this speed for approximately 6 hours before dropping back to zero. For the first half of this event the winds were oriented from the north, across the lake. Thereafter, they rotated 90° to blow from the east. Winds during the final event averaged 5–8 m/s for about 12 hours and blew consistently from the north.

Wave statistics and model hindcasts for the 60 hours of data are shown in Figs. 2c, d. Overall model 73 does a very good job of reproducing the observed significant wave heights both for winds blowing along the lake's long axis and for winds blowing across the lake (Fig. 2c). The waves observed during hours 10–12 immediatey preceding the first wind event, correspond to a period of virtually zero wind at the measurement site and therefore were not locally generated. (Horizontal velocity spectra showed that these waves were aligned in the east-west direction and therefore propagating down the lake ahead of the storm.) Model 73's over-prediction of significant wave height during the first wind event near hour 14 occurs at a time of rapid increase in wind speed and suggests that the waves were probably duration limited rather than fetch limited.

At the beginning of the second event there is also an indication of nonlocally generated waves. When the wind does arrive, model 73 has very little overshoot due to the short fetch length across the lake. The modeled wave height is a little high after the wind switches to the east, suggesting another period of duration limitation.

No noticeable model overshoot in significant wave height occurs during the final event because of the short cross-lake fetch. For the same reason much of the non-steady nature of the observed wave heights is reproduced by the model. The under-prediction between hours 54–56 is due in part to the smoothing introduced by the 30 minute running average applied to the wind measurements. In this case the waves were apparently responding to fluctuations in wind speed at time-scales even less than 30 minutes.

Hindcasts of significant wave height using model 84 were characteristically 15–20% greater then those from model 73 when winds were oriented along the long axis of the lake. For cross-lake winds the model results were virtually the same, (Fig. 2c). Fig. 3 shows comparisons of the time

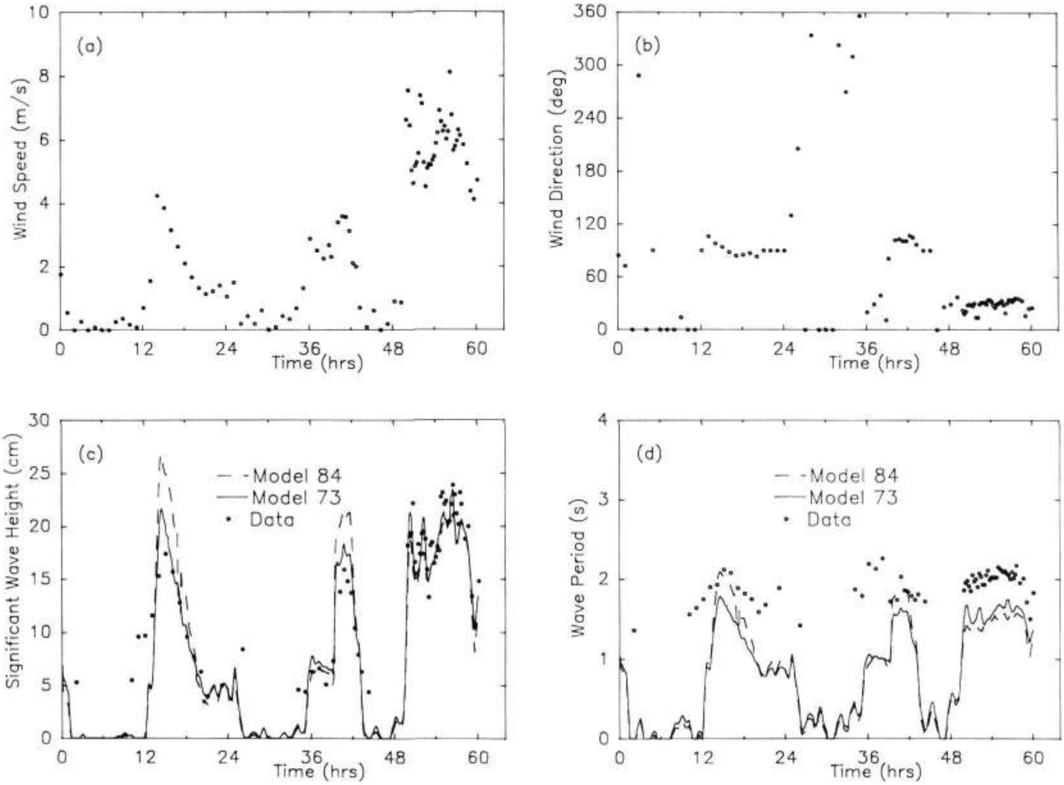

Fig. 2. Comparison between data and model hindcasts from the Keszthely field site for the period 8/15/85–8/18/85.
a. Wind speed 2 m above the water surface
b. Wind direction 2 m above the water surface
c. Measured and modeled significant wave heights
d. Measured and modeled wave periods

Comparaison des mesures en nature avec les résultats obtenus à partir du modèle d'estimation de la houle à partir du vent à Keszthely dans la période du 15/08/85 au 18/08/85.
a. Vitesse du vent à 2 m mètres au-dessus de la surface de l'eau
b. Direction du vent à 2 m mètres au-dessus de la surface de l'eau
c. Hauteurs significatives de la houle mesurée et obtenue par le modèle
d. Périodes de la houle mesurée et obtenue par le modèle

histories of F and W_a used in both models. During periods that the wind blows along the long axis of the lake, the narrowness of Lake Balaton causes F_e (model 73) to be restricted to 8–10 km while F_{sl} (model 84) reaches nearly 25 km (Fig. 3a). These occasions occur at relatively low wind speeds and W_a is nearly the same in each model (Fig. 3b). Therefore the over-prediction of significant wave height by model 84 suggests that some reduction in fetch due to the narrowness of the lake may be appropriate. During periods that the wind blows across the lake there is no appreciable reduction in fetch due to lateral boundaries and F_e and F_{sl} are nearly identical. When this occurs during a period of low wind speed, wave height hindcasts from model 84 are below those from model 73, (e.g., hours 34–36). At windspeeds above about 5 m/s, the nonlinear form of equation (7) causes W_a in model 84 to be greater than in model 73. In this situation the two models predict

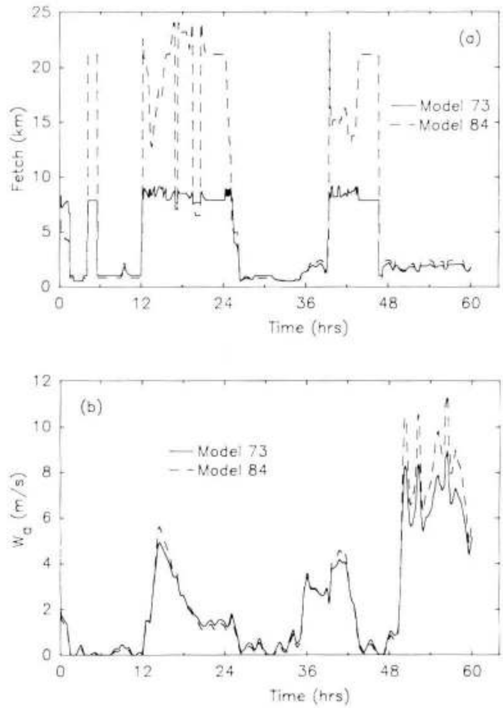

Fig. 3. Time histories of fetch and W_a used in each wave hindcasting model for the data set measured at the Keszthely field site.

Historique du fetch et de W_a mesurés à Keszthely et utilisés dans chacun des modèles d'estimation de la houle à partir du vent.

similar significant wave heights. As the wind speed increases above 8–10 m/s hindcast wave heights from model 84 are again above those from model 73 for the same fetch.

As shown in Fig. 2d wave periods were not reproduced by either of the models as well as wave heights. Model 73 characteristically underpredicted wave periods by about 20% during stretches of reasonably constant winds. A comparison of hindcast wave periods from model 84 with those from model 73 shows essentially the same behavior as it did for wave heights. Model 84 yielded greater periods for the winds aligned with the lake axis and nearly the same periods for the wind blowing across the lake.

Some idea of model 84's ability to predict the time required to reach fetch limited conditions can be obtained by computing D using equation (9). This gives 7.5 hours, 7 hours, and 25 minutes as the times necessary to reach fetch limited conditions in the three wind events, respectively. For cross-lake winds, 25 minutes seems reasonable considering the good dynamic comparison between the modeled and observed wave heights. For the initial two events oriented along the lake, durations of 7–7.5 hours seem rather long based on the observations, although there was no 7 hour period of sustained winds in this direction to fully validate this conclusion.

Tihany, 7/30–7/31, 1985

Figs. 4a, b present measured wind speeds and directions for a period of 12 hours. The average wind speed increased from near zero to approximately 4 m/s over a period of about 1 hour just

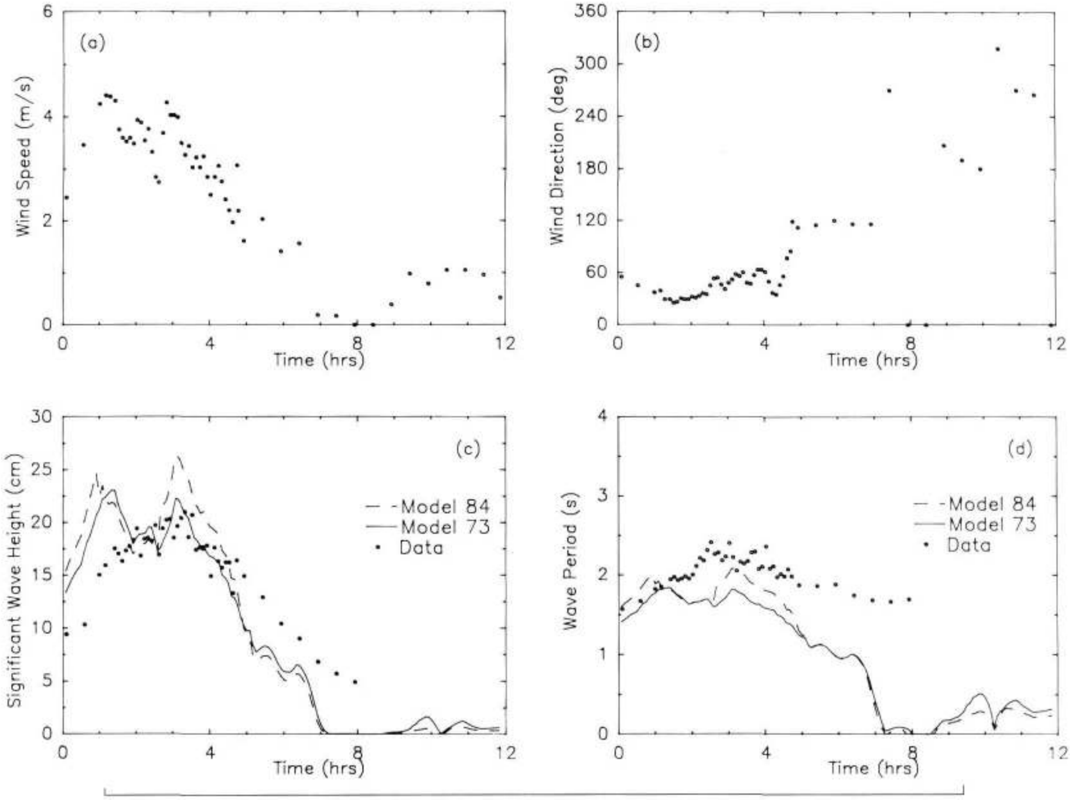

Fig. 4. Comparison between data and model hindcasts from the Tihany field site for the period 7/30/85–7/31/85.
a. Wind speed 2 m above the water surface
b. Wind direction 2 m above the water surface
c. Measured and modeled significant wave heights
d. Measured and modeled wave periods

Comparaison des mesures en nature avec les résultats obtenus à partir du modèle d'estimation de la houle à partir du vent à Tihany dans la période du 30/07/85 au 31/07/85.
a. Vitesse du vent à 2 mètres au-dessus de la surface de l'eau
b. Direction du vent à 2 mètres au-dessus de la surface de l'eau
c. Hauteurs significatives de la houle mesurée et obtenue par le modèle
d. Périodes de la houle mesurée et obtenue par le modèle

prior to and during the initial part of the data. It fluctuated near this intensity for about 2.5 hours and decreased to zero over the following 3.5 hours.

Each of the models exhibited the same characteristic behavior for both significant wave height and wave period as was found for the Keszthely data. Model 73 did the best overall job of matching measured wave heights (Fig. 4c) and was about 20% low with wave period (Fig. 4d). The overshoot occurring in the first 1.5 hours suggests the waves were duration rather than fetch limited. From hour 5 to hour 8 the horizontal velocity spectra in the wave band showed that the waves did not follows the shift in wind direction to S30°E that occurred at hour 5. Rather, these waves were remnants of the N60°E wind. Therefore the local wind measurements are no longer appropriate for modeling the wave properties and the deviation of the model from the data is understandable.

Model 84 again gave predictions of wave height and period that exceeded model 73 by 15–20% at large fetches and more closely matched at shorter fetches.
Equation (9) predicts about 12 hours is necessary to reach fetch limited conditions at the measurement site. The comparison between the model results and the observations suggests this occurred in about 2 hours.

Conclusions

Measurements are presented of wave heights and periods of locally generated wind waves in the very shallow waters that characterize Lake Balaton, Hungary. Despite the fact that these waves fall in the wave height range generally considered to be surface chop, they can be responsible for resuspending large quantities of bottom sediment in Lake Balaton and therefore are quite significant to the water quality of the lake, Luettich et al. [9]. Since there has been virtually no previous field verification of the ability of the shallow water models presented in CERC [3, 4, 5] to predict wave properties under these conditions, a comparison is presented between model hindcasts and the measured data.
The results of this comparison consistently show:

i. The model version in CERC [3, 4] does a very good job of hindcasting significant wave heights but falls about 20% under observed wave period for fetch limited conditions.
ii. The model version in CERC [5] gave hindcasts of wave height and period that were 15–20% above the earlier version for winds directed along the axis of the lake and therefore having relatively long fetches. For short fetches results from the two model versions were nearly the same.
iii. Equation (9) included in CERC [5] gives a value of the time required to reach fetch limited conditions which is consistent with the model/data comparison for short fetches, however, it is significantly longer than is suggested by the model/data comparison at long fetches.

The overprediction of wave height by model 84 at long fetches may be due to its use of the straight line fetch rather than an effective fetch. In abandoning the use of an effective fetch, CERC [5] notes that "There may be a critical fetch width where width becomes important, but this is not known at this time." The results presented above together with the highly elongated shape of Lake Balaton, suggest that this effect may be important for waves generated along the lake's long axis.

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Notations

A	model coefficient
B	model coefficient
D	wind duration required to reach fetch limited conditions
F	fetch used in hindcasting models
F_e	effective fetch
F_{sl}	straight line fetch
g	acceleration of gravity
h	water depth
H_s	significant wave height
T	wave period
W_a	wind speed used in hindcasting models
W_{10}	wind speed measured 10 m above the water surface
δ	model coefficient
ε	model coefficient
σ	standard deviation of the water surface elevation in the wave band

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