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The relative importance of wind and ship waves in the littoral zone of a large lake

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Abstract

Surface waves and their interactions with sediments and benthic organisms are the main hydrodynamic process affecting littoral ecosystems. Here, we present a long-term data set on surface-wave parameters, which was obtained from the analysis of measurements with a pressure sensor. The data set covers a time period of a year and allows for resolving waves with heights down to less than a centimeter and frequencies up to 0.8 Hz. Wind waves and three different types of ship waves were distinguished by their spectral properties. In Lake Constance, ship-generated waves are as important as wind-generated waves and contribute about 41% of the annual mean wave energy flux to shore. In summer, during the most productive time period, ship waves dominate the wave field in terms of the energy flux to shore and also in their frequency of occurrence. Ship waves cause a diurnal and a seasonal pattern in the frequency of occurrence and in the heights of surface waves, whereas in the case of wind waves these parameters do not vary significantly with season or between nighttime and daytime. In contrast to wind waves that occur only sporadically, ship waves propagate into the littoral zone very frequently at regular time intervals. The different pattern of occurrence of ship and wind waves results in a different pattern of disturbance in the littoral ecosystem.

One of the most prominent differences between the littoral and the pelagic zone is the role of surface waves. In the littoral zone, waves interact directly with the sediment surface and biota and thus cause, for example, resuspension, erosion, and transport of particles (Luettich et al. 1990; Hawley and Lee 1999; Håkanson 2005); release of nutrients and methane (Güde et al. 2000; Bussmann 2005); reallocation and stress on zoobenthos affecting zoobenthos diversity (Scheifhacken 2006); abrasion of biofilms from stones (Cattaneo 1990; Peters 2005; Francoeur and Biggs 2006) and aquatic macrophytes (Eriksson et al. 2004); and damage of reed belts (Schmieder et al. 2004). Surface waves also influence the growth and behavior of fish that cannot escape from the fluctuating currents by vertical migration (Stoll pers. comm.), the light regime via the fluctuations in water level and light attenuation by resuspended particles (Stramski et al. 1992; Erm and Soomere 2006), and the riparian plant community (Ostendorp et al. 2004; Kotowski and Piórkowski 2005).

Nevertheless, most descriptions of surface waves are based on studies in marine environments or shelf regions (e.g., Madsen 1976; Le Blond and Mysak 1978; Donelan et al. 2005). In oceans, waves are generated by strong and frequent winds over long fetch lengths and propagate to the coast with large amplitudes. Typical wave heights vary between 0.5 m during calm sea and several meters during storm events, whereas wave periods vary between 5 and 10 s (e.g., Komen et al. 1996; CERC 2002; Brown et al. 2005). In most lakes, winds are infrequent and wind speeds low. In addition, wind forcing at the water surface often varies on small spatial scales, and the effective fetch length is restricted to a few kilometers. Hence, the wave field in most lakes is characterized by waves with small amplitudes and high frequencies and thus differs considerably from the wave field in the ocean.

The ecological effect of wind-generated surface waves in lacustrine environments has been investigated mainly in the Great Lakes (Lawrence and Davidson-Arnott 1997; Meadows et al. 1997; Hawley and Lee 1999). Only a few studies specifically investigated wind waves in smaller lakes (Jin and Wang 1998; Allan and Kirk 2000).

Apart from the wind, commercial and tourist ship traffic causes surface waves. Several studies investigated the properties and the importance of regular ship traffic in rivers and channels or shelf regions (e.g., Sorensen 1973; Stumbo 1999; Bauer et al. 2002) and the relevance of high-speed catamaran ferries in coastal environments (Parnell and Kofoed-Hansen 2001; Soomere 2005), but only few studies focused on ship waves in lakes (Bhowmik 1975; Maynord 2005). Because of their specific generation, ship and wind waves have considerably different properties (e.g., wave form, period, and length) and thus potentially have a different ecological effect in the littoral zone (Bauer et al. 2002; Soomere 2005; Erm and Soomere 2006). However, the hydrodynamic forcing in the littoral zone due to ship waves is often underestimated or even neglected (Bhowmik 1975; Maynord 2005). The purpose of the current study is, therefore, to fill this gap by comparing the relative importance of wind- and ship-generated surface waves in a large lake over a year.

Materials and methods

Study sites—Lake Constance is located in the southwest of Germany and borders Switzerland and Austria. It is the

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second-largest (by surface area) prealpine lake in Europe with a surface area of 536 km^2 and a maximum depth of 254 m (Braun and Schärpf 1990). Lake Constance is not regulated and experiences seasonal water level fluctuations of about 2–3 m (Luft and van den Eertwegh 1991; Jöhnk et al. 2004). The littoral zone, where most of the disturbances due to surface waves occur, covers about 10% of the total surface area (Braun and Schärpf 1990). Measurements were carried out in the western part of Upper Lake Constance at a site called Littoral Garden (LG; 47°41′29″N, 09°12′11″E) (Fig. 1A,B), where intensive biological, chemical, and physical experiments were performed in earlier years (Fischer and Eckmann 1997; Bäuerle et al. 1998; Baumgärtner and Rothhaupt 2005). The shore is sheltered against westerly winds and exposed to northeasterly winds with a fetch of about 3.5 km (Fig. 1A). The study site is close to the ferry crossing from Meersburg to Konstanz-Staad with regular sailings throughout the year (Fig. 1A,B). Additionally, during the tourist season (middle of March to middle of October), large passenger ships travel parallel to the shore line and increase the frequency of occurrence of ship-generated waves.

In addition to the long-term measurements at LG, short-term measurements were carried out in the eastern part of Upper Lake Constance at a site next to the city of Langenargen (LA; 47°35′42″N, 09°31′59″E) (Fig. 1A). This shore is exposed to westerly winds with a fetch of about 20 km. Ferries as well as passenger ships pass the study site nearby.

Meteorological data—A meteorological station 1 km to the west of the study site provided wind speed and wind direction averaged over 20 min during 2005. The anemometer was deployed directly at the shore at 6 m height. The data are corrected to the reference height of 10 m using a parameterized drag coefficient derived for lakes with low wind speeds (Wüest and Lorke 2003; Guan and Xie 2004).

Wave measurements—Wave characteristics and their temporal changes were studied using a pressure sensor (PS) and a NORTEK Vector Acoustic Doppler Velocity Meter (ADV) during 2005. Both devices were deployed close to each other at the study site LG at water depths of about 2 m (PS) and 1–3 m (ADV).

The custom-made PS has a full-scale range of 7 m, an accuracy of 0.1 mbar, and a maximum stand-alone deployment time of 45 d. The sensor was always positioned 1 m above the bottom and about 1 m below the surface (the water height above the sensor did not vary by more than 0.3 m during individual deployment periods). To compensate for the seasonal water level fluctuations (Jöhnk et al. 2004), the sensor was moved to shallower or deeper water depths. Pressure measurements were made at 16 Hz throughout 2005 with some gaps resulting from battery replacements or malfunction. Wave parameters were calculated for burst intervals of 1,024 (~1.1 min) and 4,096 (~4.3 min) samples. The measured time series of subsurface pressure in each burst interval was converted to a time series of surface elevation using the following procedure: In each burst interval, the mean value and linear trend was subtracted from the pressure data before a fast Fourier transform with a Hanning window was applied. The spectral density of the subsurface pressure was transformed to the spectral density of surface elevation by applying the pressure attenuation coefficient calculated for the given sensor position, water depth, and wave frequency using the dispersion relation of surface waves (Krogstad and Arntsen 2000; Tucker and Pitt 2001; Kundu and Cohen 2002). All frequencies in the range between 0.05 and 0.8 Hz were considered, which covers the frequencies expected to be relevant in the field. The inverse Fourier transform of the spectrum of surface elevation and later addition of the mean water depth and the linear trend in water elevation provided an estimate of the water surface elevation as a function of time (Fig. 2A). Note that the technique is based on linear wave theory and assumes sinusoidal waves, which may not be exactly fulfilled for ship waves (Soomere et al. 2005). The accuracy of the sensor and the technique allows for resolving fluctuations of water surface elevation within 1 cm.

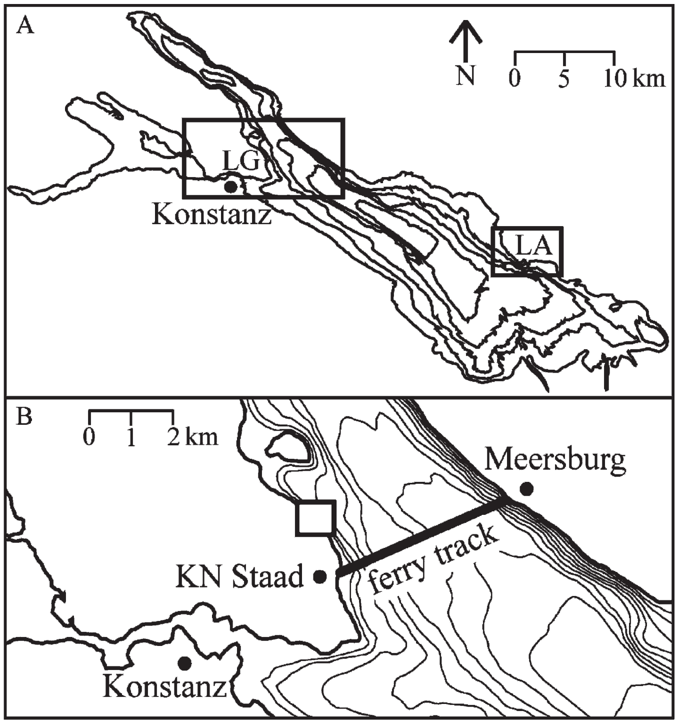

Fig. 1. Study sites. (A) Map of Lake Constance. The upper box shows the section of the main study site Littoral Garden (LG) and the lower box the site near the city of Langenargen (LA). (B) Zoom to the study site LG (indicated by the square), which is situated at Upper Lake Constance close to the ferry crossing from Meersburg to Konstanz-Staad.

Maximum and significant wave heights (H_{max}, H_s) and significant period (T_s) were calculated by using the zero-upcrossing method (IAHR 1989). Within each burst, the wave amplitude was calculated separately for each time period between two consecutive zero upcrossings. The difference between the maximum elevation in this time period and the mean elevation in the burst interval was used as a measure of wave amplitude. Twice the maximum

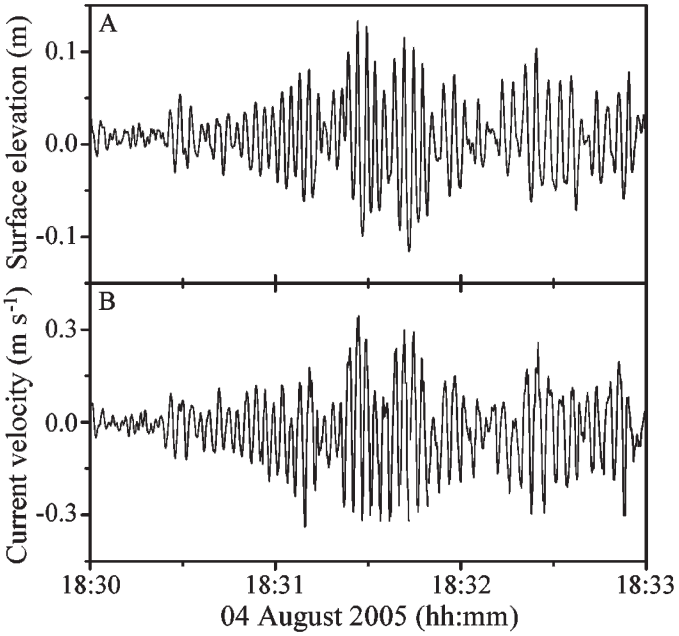

Fig. 2. Train of characteristic ship waves measured simultaneously by pressure sensor (PS) and Acoustic Doppler Velocity Meter (ADV) at ~1 m water depth on 04 August 2005. (A) Surface elevation (wave height) corrected for pressure attenuation. (B) Near-bottom horizontal current velocity (cross-shore velocity).

of all wave amplitudes in the burst interval gave H_{max}. H_s is two times the average of the highest one-third of all amplitudes in the burst interval. The significant wave period T_s is defined as the average of the periods of the highest one-third of wave heights (H_s) in the burst interval (IAHR 1989).

The wind-wave field is usually characterized by the significant wave height H_s. Because of the transient nature of ship waves (Fig. 2), short burst intervals (~1.1 min) were chosen to calculate H_s. However, the maximum current velocity at the sediment surface u_{max} during these short burst intervals is one of the most important consequences of surface waves affecting the ecological conditions in the littoral zone. Because u_{max} is directly related to H_{max} rather than to H_s, H_{max} was used for the comparison between ship and wind waves.

The ADV was attached to a bottom-resting tripod that also supported the data acquisition system. Current velocities were measured within a range of ±0.3 m s^{-1} with an accuracy of 10^{-3} m s^{-1} and a sampling frequency of 8 Hz. The ADV measurements of the near-bottom current velocities were performed simultaneously to the pressure measurements with the PS (Fig. 2B).

Turbidity measurements—Turbidity measurements were carried out using an optical backscatter sensor (Driesen & Kern) deployed during distinct time periods in 2005. Turbidity was measured with an accuracy of 0.01 FTU and a sampling frequency of 0.1 Hz. The sensor was attached to the tripod of the ADV next to the PS 0.2 m above the bottom at ~1 m water depth.

Wave statistics, energy flux, and wave-generated current velocities—Wind and ship waves can be distinguished by their respective periods. As we will show below, wind-generated waves are characterized by wave periods below 2.5 s, whereas ship-generated waves have periods above 2.5 s.

In the statistical analysis of the wave field, we investigate the frequency of occurrence of ship and wind waves and distinguish between daytime (09:00–21:00 h) and nighttime (21:00–09:00 h) on monthly scales. Waves with heights below 0.05 m are excluded from the statistical analysis because they represent mainly ripples with small periods and have a negligible effect on the shallow littoral.

The comparison of wind and ship waves solely by frequency of occurrence, however, does not take into account the different properties of ship and wind waves (e.g., wave length or wave energy) and thus does not adequately consider their different potential for disturbance in the shallow littoral. A more appropriate measure of the ecological relevance of waves is the energy flux to shore associated with the wave motion per unit length of wave crest E_F (W m^{-1}). E_F can be estimated as the product of the group velocity and the wave energy. The latter is solely determined by the wave amplitude. E_F implicitly accounts for the different wave periods of ship and wind waves since the group velocity of surface waves depends on the wave period (Fenton and McKee 1990; Kundu and Cohen 2002):

$$E_F = E \cdot c_g \qquad (\mathrm{W\ m^{-1}}) \qquad (1)$$

$$E = \frac{1}{2}(\rho \cdot g \cdot a^2) \qquad \left(\mathrm{Ws\ m^{-2}}\right) \qquad (2)$$

$$c_g = \frac{c}{2} \cdot \left(1 + \frac{2 \cdot k \cdot h}{\sinh\,(2 \cdot k \cdot h)}\right) \qquad \left(\mathrm{m\ s^{-1}}\right) \qquad (3)$$

$$c = \sqrt{\frac{g}{k} \cdot \tanh\,(k \cdot h)} \qquad \left(\mathrm{m\ s^{-1}}\right) \qquad (4)$$

$$k = \frac{2 \cdot \pi}{\lambda} \qquad \left(\mathrm{m^{-1}}\right) \qquad (5)$$

$$\lambda = \frac{g \cdot T^2}{2 \cdot \pi} \cdot \left\{ \tanh \left[\frac{2 \cdot \pi \cdot \sqrt{\frac{h}{g}}}{T} \right]^{\frac{3}{2}} \right\}^{\frac{2}{3}} \qquad (\mathrm{m}) \qquad (6)$$

where E is the wave energy (Ws m^{-2}), c_g the group velocity (m s^{-1}), a the wave amplitude (m), c the phase velocity (m s^{-1}), k the wave number (m^{-1}), λ the wave length (m), T the wave period (s), g the gravitational acceleration (m s^{-2}), and h the water depth (m). Note that Eq. 6 is an approximation for short and long waves in water of intermediate depth (Fenton and McKee 1990).

The calculation of the monthly mean wave energy flux to shore is performed at a water depth of 2 m, where the PS

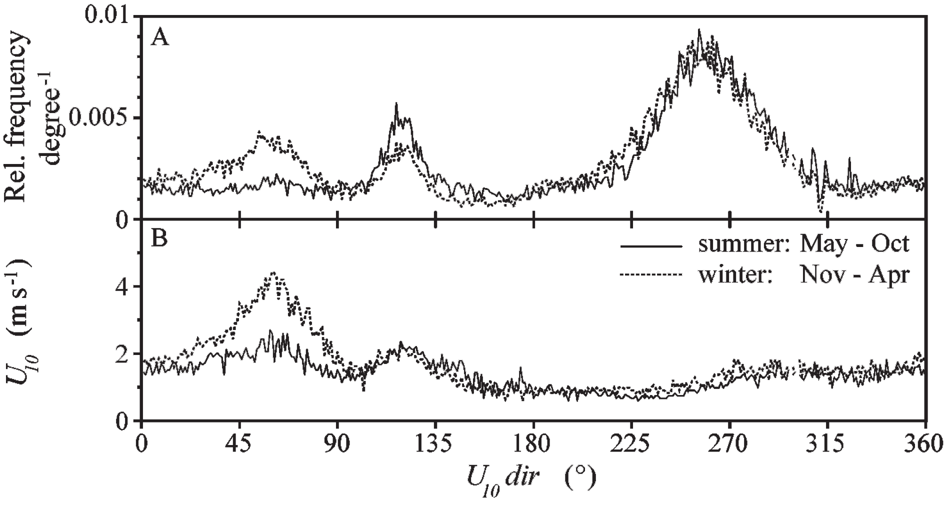

Fig. 3. Wind exposure of the study site Littoral Garden (LG). (A) Relative frequency and (B) wind speed (U_{10}) per degree wind direction (direction where the wind is blowing from) between 2001 and 2005 in summer (solid line) and winter (dotted line). Values are averaged per degree direction.

was deployed. The wave energy and its flux are calculated per individual wave basis, derived from the zero-upcrossing method. The mean wave energy flux for each burst interval (~1.1 min) is determined by weighting the energy flux of each wave by its wave period prior to averaging. Then the energy flux is classified as ship-wave or wind-wave generated, depending on the significant wave period (T_s) for the specific burst; that is, ship waves have periods above and wind waves periods below the threshold period of 2.5 s. Energy fluxes from individual bursts are averaged in order to obtain monthly mean values.

Another parameter that characterizes the impact of surface waves on the littoral zone in terms of bottom shear is the maximum near-bottom current velocity u_{max} (m s^{-1}) (Brown et al. 2005):

$$u_{\max} = \frac{\pi H}{T \cdot \sinh \frac{2\pi h}{\lambda}} \qquad (7)$$

where H denotes the wave height (m), T the wave period (s), h the water depth (m), and λ the wave length (m).

Here we considered u_{max} at a water depth of 1 m. In the calculation we used the appropriate dispersion relation and H_{max} and T_s measured with the PS. Thereby we assumed that H_{max} and T_s do not change significantly between 1 and 2 m water depth. The maximum near-bottom current velocity is calculated for each burst interval (~1.1 min) and classified as wind-wave or ship-wave generated following the same procedure as outlined for the wave energy flux. The relative monthly frequency distribution of u_{max} generated by wind or ship waves is obtained for a constant frequency distribution step size of 0.005 m s^{-1}, where the individual wind and ship wave distribution was normalized by the total number of burst intervals counted in the specific month. Values of u_{max} for waves of heights below 0.05 m are not considered in the statistics.

Results and discussion

Wind exposure—The wind field and hence the wind exposure of the study site changes at a seasonal time scale. Figure 3 shows wind speed and relative frequency of occurrence per degree direction for summer (May–October) and winter (November–April), respectively. Westerly winds are most frequent during the year, but the associated wind speeds at the study site are small. The second most frequent winds come from southeast during summer and northeast during winter. In general, wind speeds averaged per degree direction vary between 1 and 5 m s^{-1} (Fig. 3B), although maximum values can exceed 8 m s^{-1}. At the study site LG, high wind speeds from northeast are most relevant for the generation of wind waves. In 2005 several major wind events could be observed and were slightly more frequent during winter as compared to summer, where strong winds were nearly absent.

Wave spectral properties—The different spectral characteristics of wind and ship waves are exemplified in Fig. 4 for different wind conditions: Whereas the 28 February and 12 May were accompanied by strong on-shore winds (U_{10} = 6–8 m s^{-1}, U_{10} *dir* = 40–60°), the 04 March, 15 May, and 04 August were characterized by nearly no wind (U_{10} = 0–2 m s^{-1}, U_{10} *dir* = 180–270°). In the pressure spectra, four typical peak frequencies or frequency bands can be identified that are assigned to wind- and ship-generated waves (Fig. 4). On all 5 d, the spectra have a clear peak at 0.27 Hz (T = 3.7 s). The occurrence of waves with this frequency correlates with the timetable of the ferry traffic from Meersburg to Konstanz-Staad (Figs. 1, 4, square). The spectral peak at 0.35 Hz (T = 2.9 s) visible in the spectra from 15 May and 04 August when winds were calm can be assigned to passenger ships (Fig. 4, triangle). The broad, wind-generated spectral band of frequencies masks

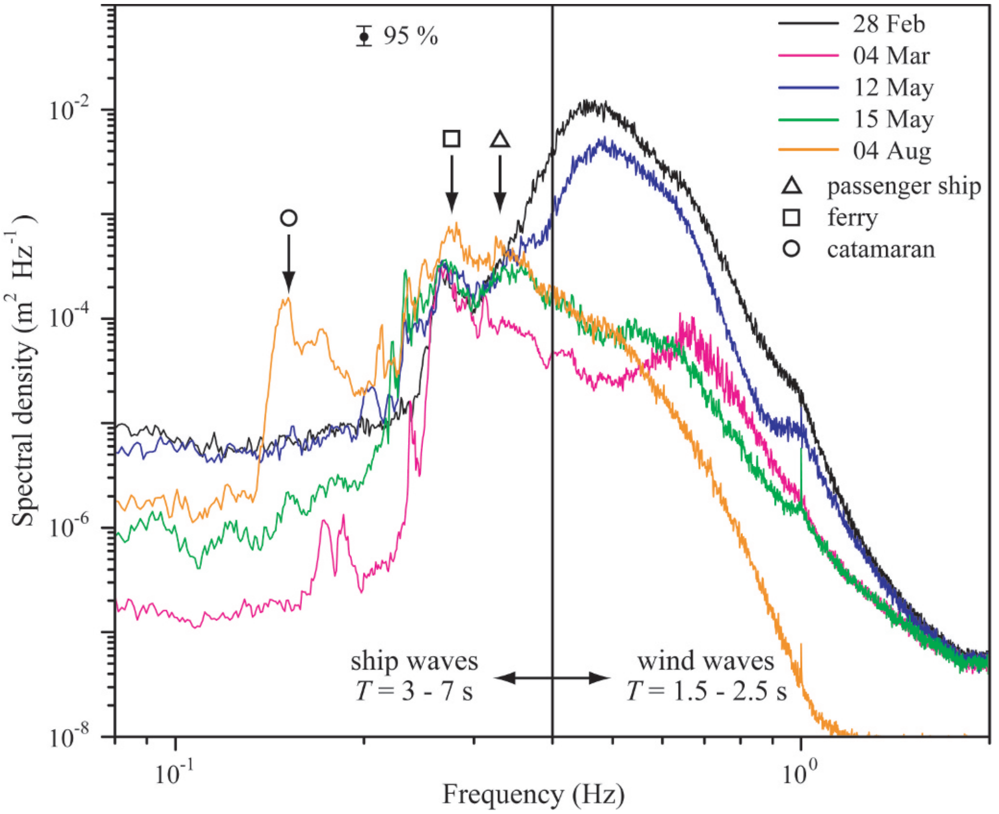

Fig. 4. Wave spectrum (surface elevation) of two wind-wave–dominated days (28 February and 12 May 2005, black and blue) and three ship-wave–dominated days (04 March, 15 May, and 04 August 2005; magenta, green, and orange). The vertical line indicates the threshold frequency of 0.4 Hz (T = 2.5 s) where ship-generated (left-hand side) and wind-generated (right-hand side) waves can be discriminated. The most prominent ship types with their typical wave frequencies are noted by the triangle (passenger ship), square (ferry), and circle (catamaran). The spectrum was estimated from pressure sensor (PS) data on the respective days using 16,384 samples (~17 min), respectively. The spike at 1 Hz is an artifact of the PS.

this peak on 12 May (strong wind event). In winter under calm conditions (represented by 04 March), when passenger ships have stopped their service, their signal cannot be found. On 04 August the spectrum has an additional peak at 0.16 Hz (T = 6.3 s) that was not observed before (Fig. 4, circle). This peak can be assigned to the newly introduced catamaran ferry on Lake Constance. The identification of the three types of ship waves with their typical frequencies was validated by visual observations confirming the linkage between the passage of a specific ship and its typical wave signature (e.g., wave frequency).

As indicated above, the 28 February and 12 May were accompanied by wind-generated wave events that showed no distinct spectral peaks. Wind waves are characterized by a rather broad spectral peak between 0.4 and 0.7 Hz (T = 2.5–1.4 s) (Fig. 4). The spectral density and peak frequency of wind waves is related to the effective fetch length, the wind speed, and the duration of the wind. Although Fig. 4 is not a variance-preserving plot, spectral densities are higher for the data from 28 February than for the data from 12 May at all frequencies. This indicates that the wind-generated wave event on 28 February was slightly stronger than that on 12 May, which fits with the measured wave heights (Fig. 6A,D). Weak and short-lasting winds are typical especially during summer (e.g., mountain vent and local thunderstorms) and cause small-amplitude waves with short periods and wave lengths. A good example for such waves was observed on 04 March between 00:00 and 01:00 h, where a short wind event occurred (Fig. 6A,B,C). The maximum wave height was slightly above 0.1 m, and the frequency ranged between 0.6 and 0.7 Hz. In comparison, higher wind speeds with longer duration on 28 February and 12 May resulted in significant lower frequencies between 0.4 and 0.5 Hz (Figs. 4, 7).

The characteristic spectral properties of wind and ship waves are used to discriminate between wind and ship waves at the threshold frequency of 0.4 Hz (T = 2.5 s). Waves with frequencies above 0.4 Hz are classified as wind waves, below as ship waves. Additionally, the expected significant wave period T_s can be estimated following CERC (2002) by considering an effective fetch length of 3.5 km for winds from the northeast and a maximum wind speed of 10 m s^{-1}, resulting in T_s = 2.0 s. This period is significantly lower than the threshold period of 2.5 s. Both

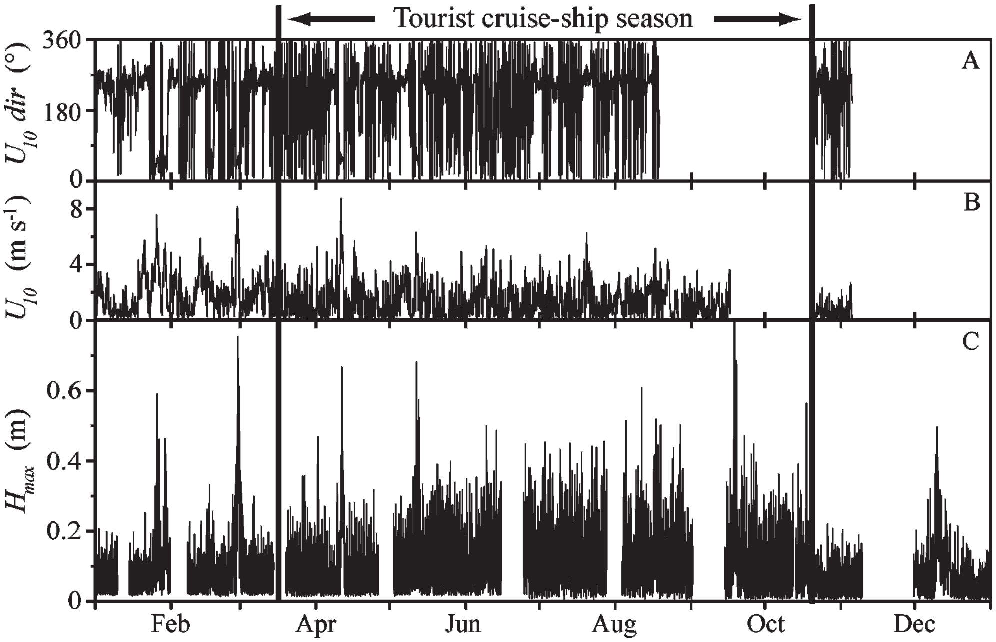

Fig. 5. Wind and wave exposure of the study site Littoral Garden (LG) in 2005. (A) Wind direction (U_{10} dir, direction where the wind is blowing from) and (B) wind speed (U_{10}) averaged over 3 h. (C) Time series of maximum wave height (H_{max}) measured by pressure sensor (PS; burst interval (~4.3 min) = 4,096 samples). Data gaps are due to battery replacement, malfunction, and nondeployment periods, respectively.

spectral analysis and the calculation of the empirical wave properties confirm that the chosen threshold period of 2.5 s is reasonable.

The wind-wave field—The maximum wave heights observed during 2005 are shown in Fig. 5C. In general, wave heights range from about 0.01 to nearly 0.8 m. Wave heights between 0.4 and 0.8 m occur mainly in combination with strong and long-lasting (at least 2 h) northeastern winds (Fig. 5). Maximum wave heights of 0.7–0.8 m seem to be the upper limit at the study site LG and are in agreement with empirical estimations under the given effective fetch length and wind speed (CERC 2002). Such wind-wave events, however, are rare and unevenly distributed over the year. In 2005 about 10 major wind-wave events with maximum heights above 0.4 m could be observed. The relative frequency of occurrence of these events increased slightly during spring, autumn, and winter compared to a single event during summer or even none from June to the end of August, when southeastern and western winds with low wind speeds are dominant (Figs. 3, 5).

The observation of wind waves at the study site LG reflects its specific shelter against western winds (the main wind direction at Lake Constance) and its exposure to northeastern winds (the second most frequent wind direction) with relatively low wind speeds and a short effective fetch because wind waves are generated only in combination with northeastern winds. The wind-wave events around 28 February (winter season) and 12 May (early summer season) illustrate this relation (Fig. 6). Even strong western winds, observed on 14 and 15 May (Fig. 6E,F), did not generate increased wave heights compared to those observed on 12 May (Fig. 6D). Typical wind-wave events last between several hours and more than a day. The wave growth and their subsequent decline last only between 1 and 2 h (Fig. 6A,D; e.g., wind-wave events from 28 February and 12 May). The rapid formation of the wave field is caused mainly by the relatively short effective fetch. This also explains the extremely dynamic wave heights measured during a single event, which follow closely the temporal dynamics of the wind speed (Fig. 6A,C,D,F; e.g., wind-wave events from 28 February and 12 May). Also the wind-wave period follows this behavior. On 28 February during increased wave heights (until 19:00 h), the significant wave period fluctuated between 1.8 and 2.3 s (Fig. 7A,B). In general, the measured wind-generated significant wave periods are between 1.5 and 2.3 s. The upper limit is determined by fetch length and the maximum wind speed (Fig. 7B). The observed wind waves have "deep-water wave lengths," defined here as the wave length obtained from the dispersion relation for deep-water waves and by assuming that the wave period at the measuring site is the same as in deep water, ranging between 2 and 8 m.

The ship-wave field—As indicated above, in addition to the wind-generated wave field, a variety of ship-generated waves could be measured. Spectral analysis of the PS time series shows that ferry, passenger, and catamaran waves can be distinguished by their frequencies (Fig. 4). The individual ship-wave types could be assigned to the distinct peaks in the spectra by considering the time of observation (during a single day or the whole year) in combination with their wave properties (e.g., wave height or length). The high

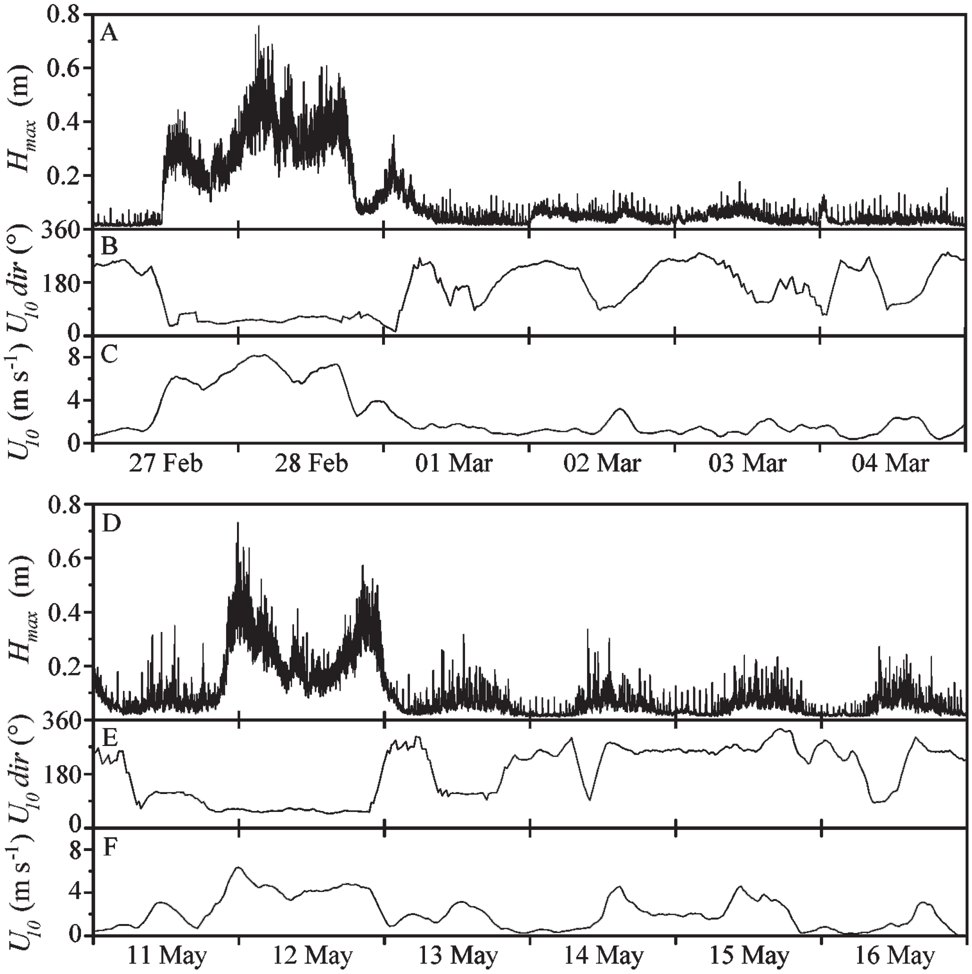

Fig. 6. Maximum wave height (H_{max}) and related wind direction (U_{10} *dir*) and speed (U_{10}). (A–C) In winter (27 February–04 March 2005). (D–F) In summer (11–16 May 2005). Both periods include one major wind event and several windless, ship-wave–dominated days.

temporal resolution of wave properties enabled the identification of individual ships by comparing the time of occurrence of certain spectral peaks in the data with the schedule of the ship traffic and visual observation.

Ship waves generated by the regular car and passenger ferry crossing from Meersburg to Konstanz-Staad are present throughout the whole year. The ferry waves have typical maximum heights of 0.04–0.15 m, periods of about 3.7 s, and deep-water wave lengths of about 20 m (Figs. 4, 5C, 6A,D, 7C,D). These comparatively small-amplitude ship waves become a prominent and important feature of the wave field especially when wind speed is low. The occurrence of ferry waves follows the timetable of the ferries, four to five wakes per hour during daytime (09:00–21:00 h) and once per hour during nighttime (21:00–09:00 h) (Fig. 7C,D). The relative frequency of occurrence of ferry waves does not change throughout the year, but it follows a strong diurnal pattern with many waves during daytime and a few at night (Figs. 5C, 6A,D, 7C,D).

Passenger-ship waves are even more pronounced than ferry waves. These tourist ships cruise all around Lake Constance from the middle of March to the middle of October (“tourist cruise-ship season”; Fig. 5). The passenger-ship waves have typical maximum heights of 0.1–0.5 m, periods of about 2.9 s, and deep-water wave lengths of about 13 m (Figs. 4, 5C, 6A,D, 7C,D). The course of the maximum wave height in Fig. 5C shows a seasonal pattern, which is related to the “tourist cruise-ship season.” In the middle of March, maximum wave heights start to increase, develop at a plateau from the middle of May to the middle of September with maximum values between 0.2 and 0.5 m, and finally decrease until the middle of October to characteristic wave heights generated by ferries. In addition to wave height, the relative frequency of occurrence of ship-generated waves increases significantly during this time period, which is confirmed by statistical analysis (see below). The comparison of two selected time periods when wind waves were absent (01–04 March and 13–16 May) illustrates the seasonal change of the ship-wave field (Fig. 6A,D). Passenger ships further intensify the diurnal pattern in the occurrence of surface waves (as described for ferry waves) by cruising only at daytime (Figs. 6A,D, 7C,D).

A new catamaran passenger ferry was introduced at Lake Constance for fast connection between Friedrichshafen (10 km to the north of site LA; Fig. 1A) and Konstanz

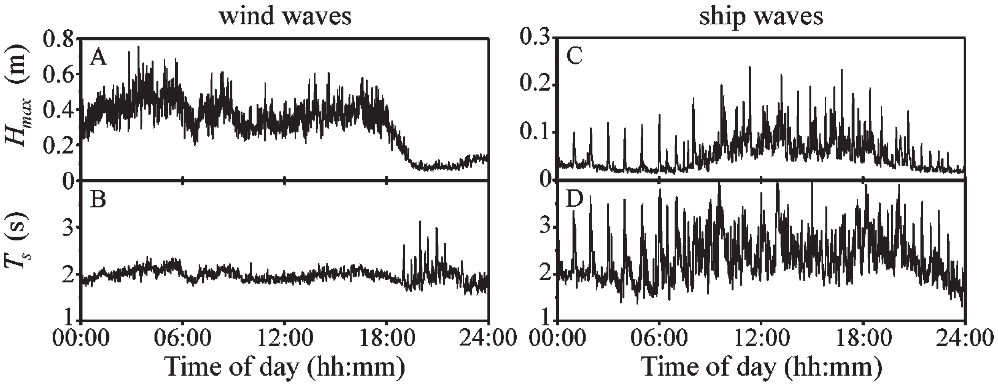

Fig. 7. Course of the maximum wave height (H_{max}) and significant period (T_s) during a single day. (A,B) Wind-wave–dominated day in winter on 28 February 2005. (C) and (D) Ship-wave–dominated day in summer on 15 May 2005.

in July 2005. Between 06:00 and 21:00 h, the catamaran ferry cruises hourly between the two cities during the whole year. Although the catamaran track is more than 10 km away from the study site, catamaran waves can be distinguished from the other wave types by spectral analysis (Fig. 4). The catamaran waves typically have heights of a few centimeters at site LG. The wave periods and deep-water wave lengths of the catamaran waves are about 6.3 s and up to 50 m, respectively. The much longer wave lengths generated by the catamaran compared to the other two ship types implies that shoaling of the catamaran waves has a larger impact on the nearshore region than that of other ship waves with the same wave height. However, this effect is more important at other sites in Lake Constance, where the catamaran waves have larger wave heights than at site LG.

The observed characteristic wave periods, lengths, and heights are related to the specific properties of the three dominating ship types at Lake Constance (e.g., length, width, displacement mass, speed, shape, or the distance of the sailing line to the shore). Most of these properties are summarized in Table 1. Empirical relations describe and approximate wave characteristics (e.g., wave period and height) from ship properties (Sorensen 1973; Stumbo 1999; Maynord 2005). Ferries and passenger ships at Lake Constance do not differ significantly in their properties compared to the catamaran. The main differences between the ferries, passenger ships, and the catamaran on Lake Constance are not primarily the shape but the traveling speed (Table 1) and the distance to shore at which they pass site LG. The wave period of the catamaran waves is about twice the period of the waves generated by the ferries or the passenger ships. The height of ship-generated waves decreases with distance from the sailing line (Sorensen 1973; Bhowmik 1975; Stumbo 1999). This effect contributes to the differences in the wave heights between passenger-ship, ferry, and catamaran waves observed at LG because the distance of the sailing lines of these ships from LG are 1–2 km, 2–3 km, and about 10 km, respectively.

Wave statistics: The relative importance of wind and ship waves—Since wind and ship waves can be distinguished by frequency (period), their relative importance can be quantified in terms of monthly wave distribution and wave energy flux to shore during the whole year 2005 (Fig. 8). To express not only the seasonal but also the diurnal pattern of the wave distribution, daytime and nighttime are considered separately (Fig. 8A,B).

During daytime, the overall proportion of the number of waves greater than 0.05 m is significantly higher in summer (March–October) than in winter (November–February), ranging from 44% to 89% and 23% to 40%, respectively (Fig. 8A). This increase in the number of waves ≥0.05 m from winter to summer is caused by ship waves. Whereas the proportion of wind waves remains almost constant throughout the whole year and accounts for 11–37% of the total number of waves during the day, the proportion of ship waves increases significantly in summer and amounts from 24% in March to 58% in August of the total number of waves. The seasonal pattern of ship waves from March to October follows the "tourist cruise-ship season" of passenger ships. In winter, the proportion of ship waves accounts for only 9–14% of the total number of waves.

The total number of waves ≥0.05 m during nighttime (10–31%) is much lower than during daytime (Fig. 8B) and does not show a seasonal pattern. This is due mainly to the near absence of ship waves during nighttime, when ship waves contribute only 4–12% of the total number of waves. Passenger ships do not cruise at night. The remaining ship

Table 1. Characteristics of commercial ships operating regularly on Lake Constance.

Ship type	Length (m)	Width (m)	Displacement mass × 10^3 (kg)	Speed (km h^{-1})	Passengers	No. of ships
Ferries	55–72	12–13	340–900	22–24	500–700	9
Passenger ships	20–62	4–13	50–510	20–28	50–1,200	~60
Catamaran	33.6	7.6	60	40	182	3

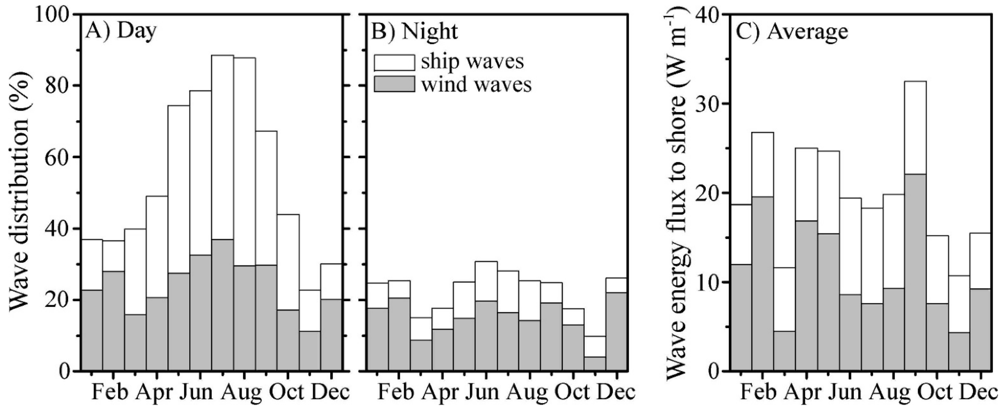

Fig. 8. Wave statistics. Relative wave distribution according to origin: wind-generated (gray bars) or ship-generated (open bars) and time (day: 09:00–21:00 h; night: 21:00–09:00 h) in 2005. (A) At day. (B) At night. (C) Average monthly wave energy flux to shore of wind and ship waves in 2005. Wave heights below 0.05 m were excluded from the data sets (A–C), and are expressed by the missing percentage to 100% (A,B).

waves stem from the ferry crossing from Meersburg to Konstanz-Staad and occasional leisure boats.

The large difference in the number of ship waves between daytime and nighttime causes the pronounced diurnal pattern. The missing percentage to 100% in Fig. 8A,B represents waves below 0.05 m. These small waves are dominant especially during winter and at night, when they contribute between 60–77% and 69–90% of the total number of waves, respectively.

The wave energy flux to shore follows the seasonal pattern caused by passenger ships with highest energy fluxes between June and September, although both daytime and nighttime are considered together (Fig. 8C). In summer, the monthly mean wave energy flux was about 9 W m^{-1} (minimum of about 7 W m^{-1} in March and maximum of about 11 W m^{-1} between June and September), compared to about 6 W m^{-1} in winter (Fig. 8C). Note that the mean wave energy flux of ship and wind waves does not exactly reflect the pattern of their number of occurrence (Fig. 8) because the energy flux depends on wave height as a measure of wave energy and also on wave length affecting the group velocity. Note also that the wave energy flux due to ship waves is larger than that due to wind waves of the same height because at site LG ship waves have a larger wave length than wind waves.

The proportion of the annual mean wave energy flux caused by wind waves is about 50%, compared to 41% of ship waves (Fig. 8C), and only about 9% account for waves with heights below 0.05 m. During the main navigation period in summer, ship waves contribute about 50% and in winter about 35% to the total wave energy flux to shore.

Apart from the seasonal pattern caused by ship waves, the monthly wave energy flux to shore is highly variable, which can be explained mainly by the irregular occurrence of wind-wave events. High wind events are responsible for the high values in February and September, and the absence of high winds explains the low values in March, October, and November (Fig. 8C).

Another measure of the wave forcing in the littoral zone is the maximum near-bottom current velocity (u_{max}) generated by the waves. Figure 9 shows a comparison of the relative monthly frequency distributions of u_{max} generated by wind and ship waves, respectively. The distributions reveal a clear difference between winter (January and February; Fig. 9A,B) and summer months (July and August; Fig. 9C,D). In winter, especially for u_{max} values exceeding 0.1 m s^{-1}, wind waves are dominant. In summer, the situation is the opposite, and ship waves are dominant even at high u_{max} values. Turbidity measurements suggest that at the study site LG, near-bottom current velocities above 0.1 m s^{-1} are required to cause resuspension. Considering a water depth of 1 m, the threshold of $u_{max} > 0.1$ m s^{-1} is exceeded by ship waves, especially in summer (Figs. 2B, 9C,D).

Comparison to other sites and lakes—The wave field at site LG can be regarded as characteristic and representative for most of the southern and southwestern shores at Lake Constance. Along these shores the exposure to wind waves can be expected to be similar. However, the wave heights of the wind waves, which are also determined by the effective fetch lengths, can change slightly from site to site. The exposure to ship waves is similar at all shores because passenger ships travel all around Lake Constance, and ferries travel not only at the ferry crossing Meersburg to Konstanz-Staad but also across the center of Upper Lake Constance between Friedrichshafen (northern shore, Germany) and Romanshorn (southern shore, Switzerland). The ferries are of similar type and have similar timetables (Table 1). Hence, a large proportion of the shores at Lake Constance are highly influenced by a ship-wave–dominated wave field.

To compare the wave conditions at the southern shore of Lake Constance with shores that are exposed to western winds, an additional PS was deployed at a site next to LA (Fig. 1A). Between 06 and 13 April 2006, pressure data were collected simultaneously at stations LG and LA. Figure 10 compares the maximum wave heights during this period at both sites. The main difference between the two time series is due to the exposure to wind. When wind

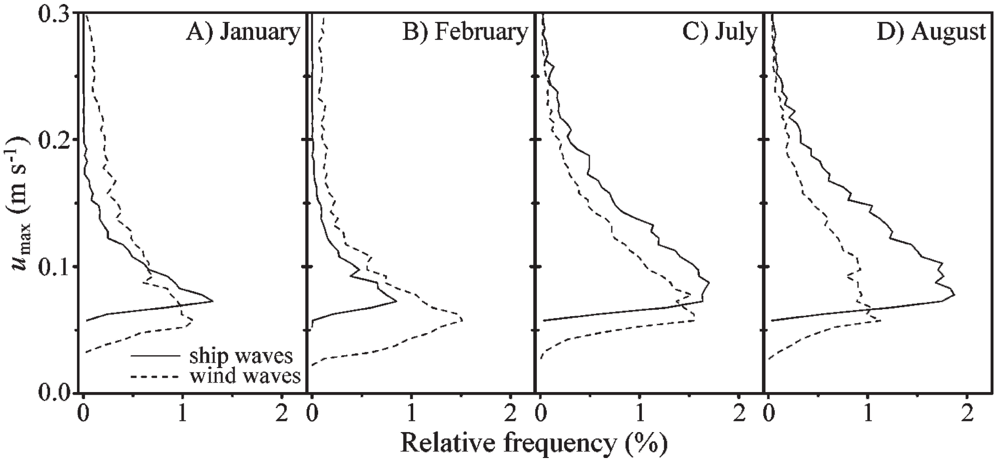

Fig. 9. Relative monthly frequency distribution of the maximum near-bottom current velocity at 1 m water depth generated by wind waves (dashed line) and ship waves (solid line) at the study site Littoral Garden (LG). (A,B) In January and February, representative of the winter months. (C,D) In July and August, representative of the summer months. Wave heights below 0.05 m were excluded from the data sets. The frequency distribution step size of u_{max} is 0.005 m s^{-1} throughout all data sets. The relative frequency distributions of wind and ship waves are normalized by the total number of burst intervals (~1.1 min) counted in the specific month.

waves occur at site LG (e.g., 06 April; Fig. 10A), no wind-wave event can be observed at site LA (Fig. 10B) and vice versa. Wind-wave events at site LA seem to be stronger and more frequent than at site LG. When no wind is present, the wave field is dominated by ship waves, and the characteristic diurnal cycle can be observed at both sites. At site LA, which is typical for shores exposed to western winds at Lake Constance, the importance of ship waves in terms of frequency of occurrence and wave height appears to be somewhat lower than at site LG. However, ship waves still play an indisputable role for the overall wave field and the wave energy flux to shore.

The situation at Lake Constance, where ship waves contribute to a large extent to the wave field and hence the wave energy flux to shore, is representative for many prealpine and alpine lakes in Germany and Switzerland. Because of their morphometric characteristics and geographical exposure (e.g., high length-to-width ratio and shelter of the lake surface from high wind speeds by steep mountain slopes), these lakes have rather short effective fetch lengths and are typically exposed to low wind speeds limiting the wind-generated wave field. On the other hand, these lakes are typically located in highly populated areas with diverse recreational and commercial activities that lead to intensive ship traffic on the lakes. Examples for lakes that have a similar characteristic as Lake Constance are Lake Ammer, Lake Starnberg, and Chiemsee in Germany and Lake Zurich and Lake Lucerne in Switzerland. The types and characteristic properties of passenger ships cruising on these lakes are comparable to those operating on Lake Constance (Table 1, except the catamaran). Hence, it can be expected that on these lakes, ship waves significantly contribute to the overall wave field. However, detailed measurements are still required to confirm this hypothesis.

Forcing and disturbances by ship waves in the littoral zone—The littoral zone of a lake is a highly productive and diverse habitat the abiotic conditions of which are determined by, for example, the substrate structure and distribution, the light climate, the nutrient availability, and the prevailing temperature regime. These factors and mechanisms are influenced by hydrodynamic processes. The strongest forcing and main disturbances are generated by surface waves. Since ship waves can amount to nearly half the annual mean wave energy flux to shore at Lake Constance, the overall hydrodynamic forcing in the littoral zone is significantly enhanced by ship traffic. In addition, ship waves affect the ecosystem at much larger depths than wind waves of the same amplitude because of the differences in wave length. For a given wave height and water depth, the maximum wave-generated near-bottom current velocity is determined by the wave length (Eqs. 6 and 7; Kundu and Cohen 2002). Hence, ship waves having longer wave lengths than wind waves potentially affect a much wider part of the littoral zone. Seasonal water level fluctuations amplify the wave-generated resuspension by exposing different sections of the littoral zone to wave forcing.

Whereas wind waves occur rather sporadically, ship waves can be considered as a frequent hydrodynamic forcing in the littoral zone, at least during daytime in summer (Figs. 6D, 7C, 8A, 10, 11A). Hence, ship and wind waves generate a considerably different pattern of disturbance that may have different consequences for the littoral ecosystem.

A major effect of hydrodynamic disturbances in the littoral zone is sediment resuspension and transport. Our analysis revealed that ship waves dominate the frequency distribution of u_{max} in summer (Fig. 9C,D), which indicates their potential for resuspension. The direct relation between

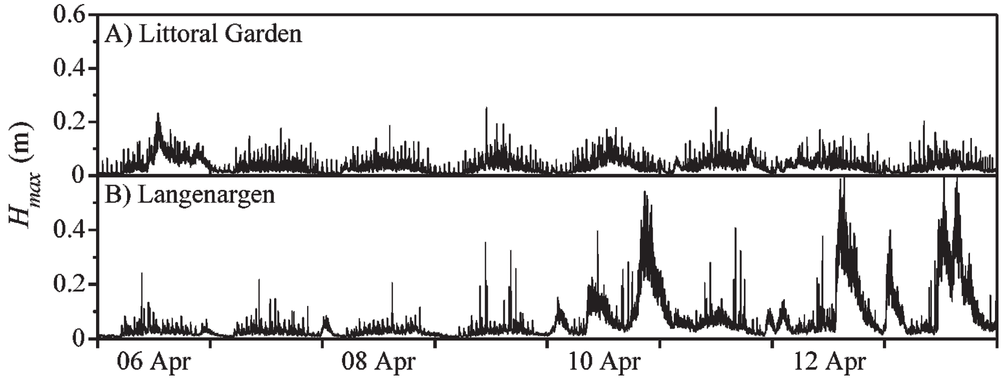

Fig. 10. Course of the maximum wave height (H_{max}) at two different sites between 06 and 13 April 2006. (A) At the study site Littoral Garden (LG), exposed to northern and northeastern winds. (B) At the study site Langenargen (LA), exposed to western winds.

the occurrence of ship waves and suspended particle concentration measured in terms of optical backscatter strength (turbidity) is exemplified in Fig. 11. During the day, distinct peaks in H_{max} generated by ship waves are correlated with peaks in turbidity, which makes it evident that the occurrence of ship waves causes resuspension. Further, ship waves cause an overall increase in turbidity at daytime, which creates a diurnal cycle with high values at daytime and low at nighttime (Fig. 11B). The periodic and regular occurrence of ship waves possibly prevents sediment consolidation and the development of a cohesive upper sediment layer (Dyer 1986; Schoellhamer 1996). The absence of a cohesive upper sediment layer increases the probability of resuspension and leads to strong impulse loads of suspended sediment in the water column mediated by ship waves (Schoellhamer 1996; Lindholm et al. 2001) and hence reduces water transparency (van Duin et al. 2001) and increases turbidity (Fig. 11B). Because ship waves are most frequent during daytime, they particularly affect the availability of light for primary production of phytoplankton and biofilms in the littoral zone. Utne-Palm (2004) showed that turbid water during daytime affects hunting success of fish and may even contribute to a competitive advantage of non–visually oriented compared to visually oriented predators (Schleuter and Eckmann 2006). There is evidence that the specific wave exposure influences the community structure of benthic organisms and fishes (Scheifhacken 2006; Schleuter 2006). Furthermore, ship waves limit or even suppress the growth of macrophytes and biofilms (Eriksson et al. 2004; Francoeur and Biggs 2006). These effects are enhanced by their frequent occurrence, especially during summer.

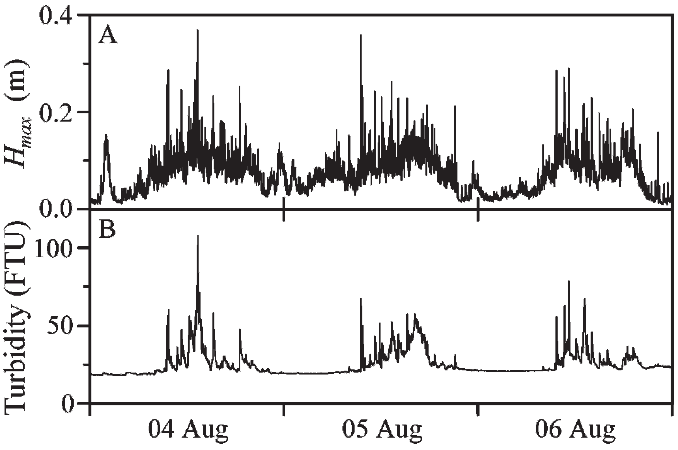

Fig. 11. Wave-generated resuspension. Time series of (A) maximum wave height (H_{max}) and (B) turbidity (optical backscatter strength in FTU) at the study site Littoral Garden (LG) on three consecutive days (04–06 August 2005). The turbidity was measured 0.2 m above the bottom at ~1 m water depth.

The interactions between surface waves, the abiotic conditions, and the biota in the littoral zone are difficult to assess in the field. The regular and "scheduled" occurrence of ship-generated waves, however, provides an ideal natural environment to study the ecological effect of surface waves on the littoral ecosystem in greater detail.

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