

Dances with waves: the KNMI wave follower

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Air-sea interaction • The generation and growth of waves due to wind blowing over water, is a well-known example of air-sea interaction. Momentum transported downwards from the air to the sea causes the waves to grow until equilibrium is reached between input and dissipation of energy. The most obvious manifestation of wave energy dissipation is breaking waves, often visible as whitecaps. If growth or an equilibrium situation cannot be sustained anymore by the input from the wind, the waves decay again. This form of air-sea interaction has a variety of practical consequences, ranging from the design and construction of dikes to the pleasure - or dangers - that surfers or swimmers experience in the surf zone.

But air-sea interaction goes far beyond generation, growth and decay of waves. Air-sea exchange processes, taking place at over two-thirds of the Earth's surface, are of paramount importance to our weather and climate. The exchange of heat, moisture and momentum between the oceans and the atmosphere fuels to a large extent the atmospheric and oceanic circulation. The release of water vapour and cloud condensation nuclei by the oceans affects the formation and distribution of clouds. Trace gases, such as CO₂ and many other natural or anthropogenic constituents are exchanged continuously between the ocean and the atmosphere. This affects the distribution of such substances between atmosphere, hydrosphere, cryosphere, biosphere and lithosphere, and therefore atmospheric trends of, for example, greenhouse gases. On smaller scales air-sea interaction influences the dynamics and chemical and biological processes of the upper ocean.

Thus, any type of coupled ocean-atmosphere model aiming at wave and surge prediction, weather prediction, climate studies or studies of other environmental issues should contain a correct description of air-sea exchange. This in turn requires a fundamental knowledge of air-sea interaction processes.

Wave-turbulence interaction • The exchange of momentum, heat, moisture and gaseous substances between the air and the sea, driven by differences in wind speed, temperature, humidity and concentration, respectively, is predominantly controlled by turbulence. Just above the wavy water surface, the waves interact with the atmospheric turbulence. Wave motions initiate pressure fluctuations and motions in the air, resulting in what we will call wave-coherent features. For example, air is forced upwards if it approaches a wave crest, and flows downwards again if it enters the trough. Thus, while the spatial average of the vertical velocity is approximately zero near the surface, the vertical velocity is in this case on average positive at the backward faces of the crests, and negative at the forward faces. In other words, choosing the wave-phase as the frame of reference, we may anticipate phase-related systematic differences in the vertical velocity. In the case of fixed obstacles (a 'frozen' wave field) such differences would turn out to be systematic, spatial differences. Waves will also induce differences in other quantities, such as horizontal wind speed, pressure and turbulent transport ¹⁾.

The closer to the sea surface, the more intense we expect the interaction between waves and turbulence to be. The atmospheric layer in between and just above the waves, with a noticeable influence of wave motion on turbulence is called the wave boundary-layer (WBL). It is often assumed that the wave-induced motions decrease exponentially with height, but the exact vertical decay function is still uncertain ²⁾.

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Within the WBL, the fluxes are generally assumed to be constant with height. Three mechanisms contribute to the momentum fluxes: viscous, turbulent, and wave-induced transport. The latter mechanism contributes to the flux by wave-induced motions of the air. The relative contribution from the various mechanisms changes with height. At the water surface, the momentum transport is entirely due to viscous transport plus the wave-induced momentum transfer. Above the surface, turbulence soon dominates the viscous transport. The relative contribution from the wave induced transport decreases with height. At the top of the WBL, the influence of the waves has disappeared so that the momentum transport is almost entirely due to turbulence. The

situation for the sensible heat and moisture fluxes is somewhat different. In this case, a direct impact of wave-induced air motions is supposed to be much smaller. However, indirect wave-induced fluxes occur, for example, due to the production of sea spray ²⁾.

The structure of the WBL has important implications for air-sea interaction processes. The wave growth rate can be shown to depend on the turbulent structure of the WBL, as influenced by wave coherent structures ¹⁾. Wave-induced fluctuations in the WBL are considered to be a key parameter in our understanding of the sea surface roughness and in the parameterisation of the air-sea momentum flux as a function of the wave field ^{2,3)}. Wave-turbulence interaction may introduce additional length and velocity scales in the atmospheric surface layer. The almost universally applied Monin-Obukhov similarity theory, describing the structure of this layer, is probably not applicable within the WBL, and, if used, it must be applied above the WBL ⁴⁾. Similarity relations and flux-profile relationships within the WBL will have to be reconsidered ⁵⁾. In a recent modelling study, Kudryavtsev and Makin ⁶⁾ showed that breaking waves can have a significant impact on momentum transport by means of wave-coherent structures induced by airflow separation. The estimated contribution from such structures in the WBL was up to ~40% of the momentum flux, at wind speeds greater than 10 m/s. Breaking waves also generate spray, which affects the heat and moisture fluxes ²⁾. Such effects will be visible mainly within the WBL. Finally, gas transfer might be affected as well.

The need for a wave follower • Fundamental knowledge of the WBL structure is needed to quantify the impact of wave-turbulence interaction on wave growth and turbulent transport. Unfortunately, obvious practical problems have precluded turbulence observations at sea below the level of the wave crests, where wave-turbulence interaction is most intense. Until now, field observations are restricted mainly to estimates of the wave growth due to wave-induced pressure perturbations and to observations at fixed heights, above the wave crests ^{5,7)}. Knowledge about the WBL has therefore been obtained basically from theoretical and model studies, and a few laboratory experiments. Models of the WBL are mostly evaluated using the limited number of data from laboratory experiments, but results from such experiments still need to be confirmed at sea.

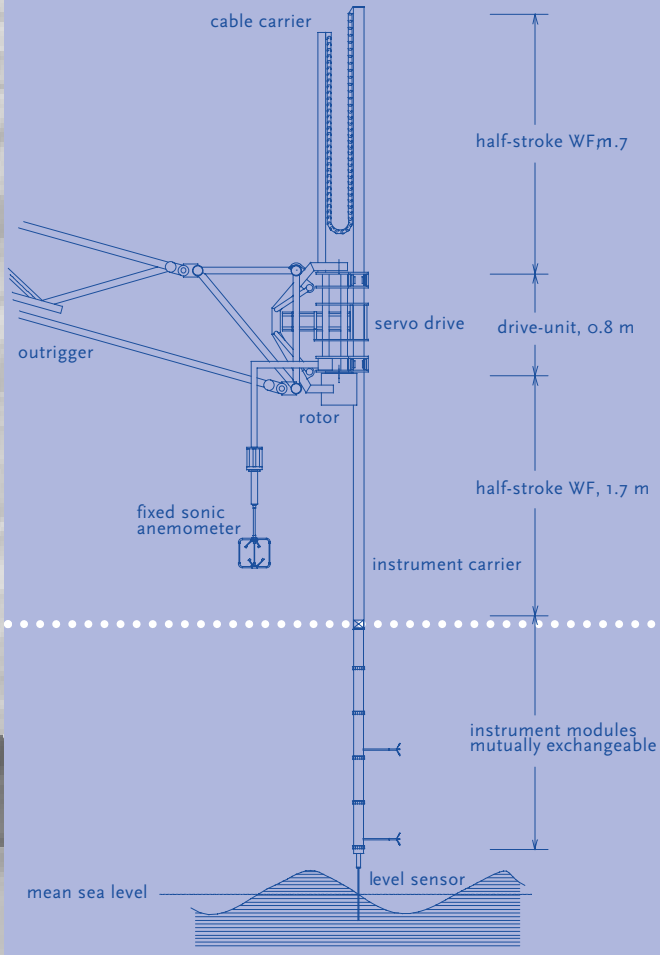
In order to contribute to a fundamental understanding of the WBL, the Oceanographic Research Division decided to develop a wave following system that allows turbulence measurements very close to the sea surface, in between the waves. In the year 2000, the wave follower was used at sea for the first time. This campaign was primarily intended to test and operationalise the wave following system. Furthermore, we wanted to show that it actually is possible to perform high-quality turbulence measurements at sea below the level of wave crests. In the present contribution we describe our wave follower, and present results from a pilot experiment conducted in November 2000.

Basic design and development • The wave follower, shown schematically in Figure 1, consists of a tall vertical pole, on which micrometeorological instruments can be mounted and that can be moved up and down by means of a strong electromotor. A water level sensor at the lower end of the pole detects the position of the system relative to the instantaneous water surface at a sampling frequency of 60 Hz. The signals from the water level sensor are transferred to the digital motion control system, consisting of the electromotor, a PC interface card, and a servo amplifier. These signals are processed by means of a Kalman filter, implemented on the servo system, which predicts the position of the water surface one timestep ahead. The servo system then moves the pole towards a position in accordance with the predicted one, so as to maintain the pole at a fixed distance from the water surface. The cycle is repeated using a new signal from the water level sensor. In this way, instruments mounted on the wave follower are kept at a more or less constant distance from the water surface, as low as some 20 - 30 cm above it, even if the waves are up to three meters high.

The wave follower is attached to a special boom, which in turn is attached to a stable platform (Figure 2). The motion of the wave follower is purely vertical and the area in contact with the water surface is minimal. These characteristics imply great advantages over, for example, a pole supported by a float. The delay in the wave following motion is much smaller, so that the data are obtained in an almost perfect wave following co-ordinate system. Furthermore, the distortion of the local wave field will be much less than the distortion introduced by a floating system. Also, due to the purely vertical motion, no pitch-and-roll corrections to the turbulence data need to be made. Another favourable characteristic is the limited diameter (7.6 cm) of the circular part of the pole that carries the sensors, which minimises flow distortion.

Special provisions • A software package that provides the man-machine interface of the wave follower and the control of the servo system has been developed. It allows to switch between computer control and remote, manual control. A visual interface shows the signal from the level sensor, and the performance of the Kalman filter can be checked. Furthermore, a display of real-time video images from a camera at the lower side of the wave follower boom enables a continuous visual check on the wave follower and the surrounding wave field.

The instrument is designed to follow waves with frequencies less than 1 Hz, and to ignore smaller waves of higher frequencies. It has a vertical stroke of somewhat more than 3 m, and the electromotor is able to move 50 kg at a maximum acceleration of 6 m/s². Although the acceleration of the water surface is usually less, the servo system might not be capable to follow very steep or vigorous, actively breaking waves. Special provisions safeguard the functional use of the wave follower under such adverse conditions. First, the software checks whether or not the water surface approaches either the lower



Discovering the sea surface

Figure 1. Schematic representation of the wave follower (WF) attached to the outrigger at Meetpost Noordwijk.



Figure 2. Photograph of the wave follower in action. The photograph was taken below the main body of Meetpost Noordwijk. The black structures in the foreground are part of the jacket construction that supports Meetpost Noordwijk, and to which the wave follower boom is attached.

or the upper boundary of the measurement range of the water level sensor. Second, a special, small sensor just above the level sensor will detect the presence of liquid water at the lower side of the instrument pole. If any of these conditions occurs, an emergency signal is sent to the servo system and the wave follower is pulled up towards a safe position, using maximum acceleration.

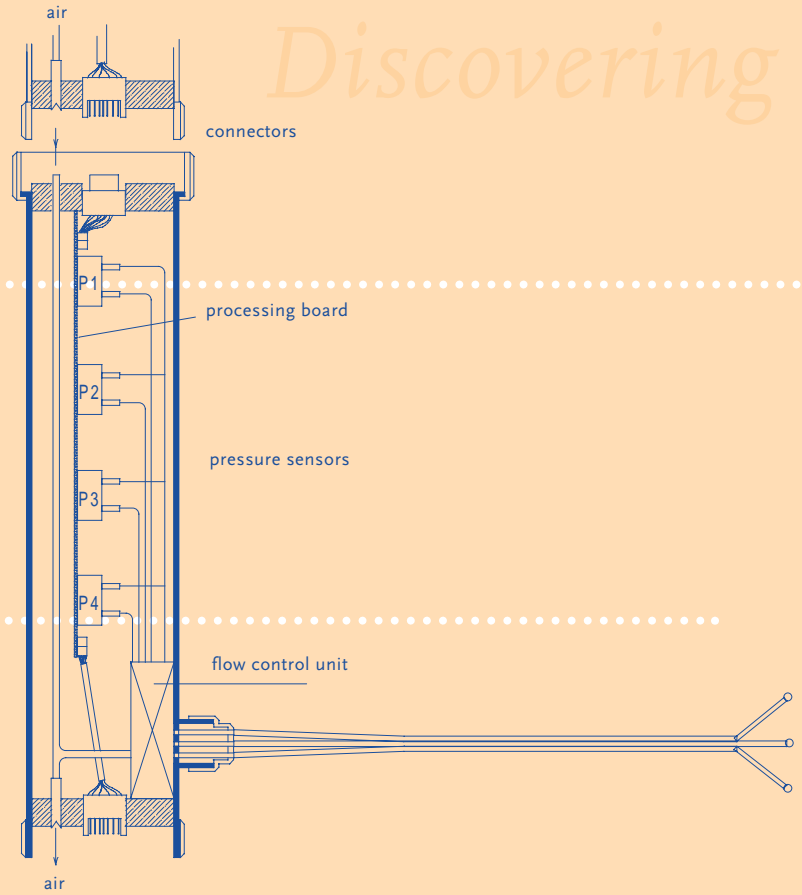
The wave follower is constructed to be deployed at Meetpost Noordwijk (MPN), a research and monitoring platform owned by Rijkswaterstaat (Directorate-General of Public Works and Water Management). The special outrigger on which the wave follower is mounted will always keep the pole in an accurately vertical position. The boom has a length of 12 m and is pointing towards the North. This allows meaningful observations to be made if the wind is blowing from a direction between south-west and north-east, over north (225° - $360^{\circ}/0^{\circ}$ - 45°). For other wind directions, flow distortion by the platform will induce irrecoverable measurement errors. During operation, the wave follower can be aimed at the mean wind direction by means of a rotor, fixed at the end of the outrigger. A small plateau, integrated in the system, provides a stable position for reference measurements without motion. To attach or detach the instrument modules (see below) and for maintenance the boom can be hoisted up, using a winch. The wave follower still maintains its vertical position during this operation.

Mounting the sensors • Micrometeorological instruments are mounted on the wave follower using a modular system of mutually exchangeable hollow tubes. Figure 3 schematically depicts one of these modules, designed to carry a pressure anemometer (see below). Each module, with a length of about 34 cm, has one or two positions where specific instruments can be attached. The inside of the tubes contains processing boards, signal cables, and an air conduit that allows maintaining some overpressure at the specialised anemometers. The connectors integrated in the modules allow signal transfer from one module to the other. At present, the wave follower can carry up to five modules. The set of instrument modules makes up the lower part of the pole. Because the tubes are interchangeable, there is some flexibility in our choice of the actual experimental configuration during field experiments.

The pressure anemometer • For turbulent flux measurements on the wave follower we deploy pressure anemometers (PA's)⁸⁾. It is at present probably the only anemometer that can be used for reliable turbulence measurements as close to the sea surface as desired during a prolonged period of time. Figure 4 shows a photograph of a special version of the PA, designed specifically for use on the wave follower.

The PA is based on the principle that wind exerts a pressure on an object that depends on both the strength and the direction of the wind⁸⁾. The pressure differences between the components of four pairs of flow outlets,

Figure 3. Schematic representation of the anemometer-module, used to mount the pressure anemometer on the wave follower. A thermistor and a pressure probe can be mounted on another, slightly different version of the module.



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Figure 4. Photograph showing a pressure anemometer (PA). The version of the PA shown here was constructed especially for use on the wave follower. The flow outlet tubes can clearly be seen.

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placed in an arrangement that provides the widest possible angle of acceptance, are measured. Combining the signals yields the wind vector. The wind can be sampled at a frequency of 40 Hz. Because the PA is kept under a slight overpressure the sensor is self-cleaning, which is important in particular over the sea. Furthermore, the sample volume of the PA is smaller than that of most wind sensors that are commercially available to date. The small sample volume allows measurements close to the surface without losing a significant part of the contribution of small turbulent eddies to the flux.


Initial tests • The wave follower has now passed through various stages of testing. Initial tests were performed at KNMI. The wave follower was attached to a container, and special simulation devices allowed dry system tests in our laboratory. The first emerging growing pains could be cured.

Hereafter the wave follower was ready to be tested in a wave flume facility. Here, realistic wind-wave spectra can be created, allowing tests under quasi-natural conditions. The first tests in the wave flume facility revealed that the design of software that allows the wave follower to keep track of the water surface is far from trivial. This led to the development of the predictive Kalman filter, a piece of real-time software running on the motion controller, presently in use. Additional tests in the wave flume facility demonstrated the wave follower to be able to follow a realistic wave spectrum, containing waves with heights up to 2.5 m.

The following tests at sea, without micrometeorological sensors, showed that the special provisions at MPN, such as the specialised boom and the mechanical part of the wave follower, the servo system and the rotor, functioned well. Also, the software and the arrangements that safeguard the instrument functioned well. The instrument was now found ready to be tested with instruments mounted.

*Tests in a wave flume facility
showed the wave follower to be ready
for the real waves at sea*

November 2000: a pilot study • A first, orientative field experiment with our wave follower was conducted in November 2000. The primary goal of this pilot experiment was to operationalise the wave follower, and to demonstrate that turbulence measurements within the WBL and in a wave following frame of reference are actually possible. Furthermore, we wanted to get an impression of the behaviour of the sensors on a moving platform and of the effects of motion on the signals.



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We mounted two PA's and a fast thermistor on the wave follower. The instrument modules were placed in a way that put the PA's at 49 and 152 cm above the actual local water surface if the system would follow real waves. The thermistor then was at 134 cm above the sea surface. Reference signals for wind speed and temperature at a fixed position were obtained from a conventional sonic anemometer (Gill, Solent R3A), mounted on the special plateau at the end of the boom. Upon descent of the boom, this instrument was located about 3 m above the mean sea level.

Because of the unfavourable wind conditions (the wind was blowing from the south during most of the experiment, a direction outside the acceptable range), we first conducted measurements with the wave follower well above the mean sea level (~5 m). Some of these runs were performed with the wave follower in a fixed position, while we let the wave follower move independently from the actual surface in other runs. In one set of the latter runs we applied a perfectly sinusoidal motion (about 0.17 Hz). Another set was performed in which we used wave data from an earlier field experiment to drive the wave follower motion.

Some preliminary results on the wind observations from the pilot experiment are presented next.

Results with surface-independent motions • Like we had hoped, the measurements during runs with surface-independent motions revealed that the first-order effect of motion is simply the registration by the sensors of the vertical speed due to the motion of the wave follower, which is a feature that can easily be corrected for. This is illustrated most clearly using the results from runs with the sinusoidal motion, shown in Figure 5. The graph depicts the raw power spectral density of the measured vertical wind speed in this case, along with the one corrected for the wave follower motion, the one obtained with the motionless sonic anemometer, and the observed surface wave spectrum. The large peak in the raw spectrum, at 0.17 Hz, is clearly due to the motion of the wave follower. When the vertical speed of the wave follower was subtracted from the samples, the remaining spectrum of the turbulent motion showed a good correspondence with the one obtained with the fixed sonic anemometer. In both spectra, a small peak at about 0.2 Hz remains, which is presumably due to the influence of the waves, as the peak in the turbulent spectra coincides with the peak in the surface wave spectrum. The smaller peaks at the higher frequencies in the spectrum from the PA are probably due to resonance from the outrigger: in the case of strong wave follower movements concurrent motions from the outrigger were observed. Similar results were found using the wave data from an earlier experiment and for runs in which the actual waves were followed.

An important conclusion from these tests is that it is possible to measure turbulence on the wave follower with reasonable confidence if a simple, first order vertical motion correction is applied. However, some work

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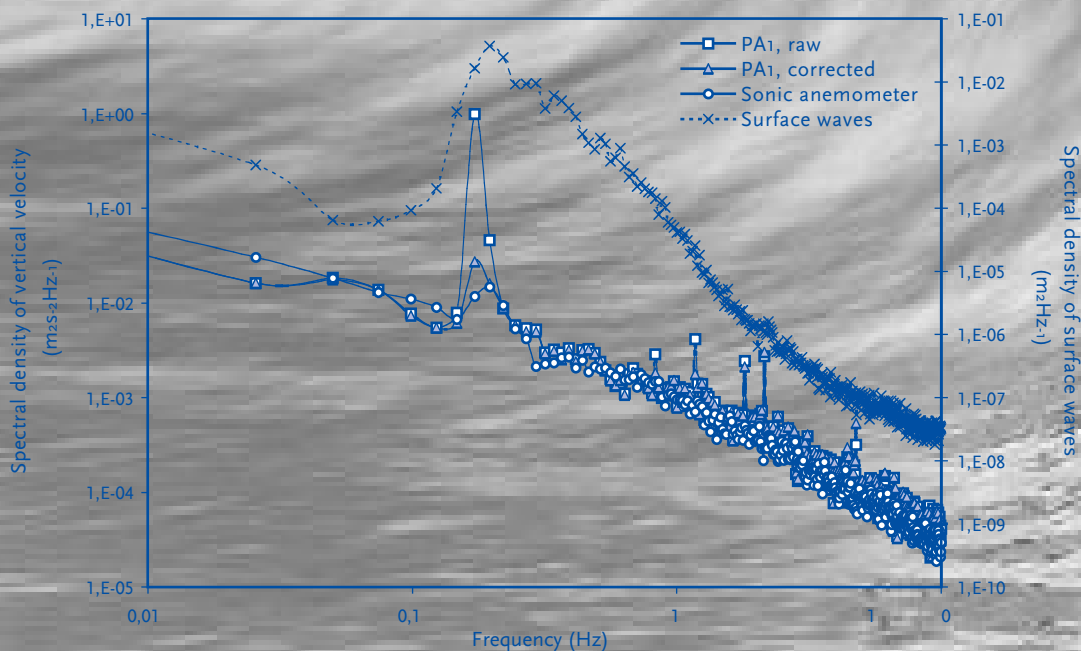


Figure 5. Power spectral density of vertical velocities (left scale) measured by the lower pressure anemometer (PA1), and the stable sonic anemometer attached to the plateau at the end of the outrigger. Also shown is the surface wave spectrum (right scale). For PA1 the raw signal contains the effect of a sinusoidal motion at

0.17 Hz. After correction for the wave follower motion the peak in the velocity spectrum is largely removed. In both the corrected spectrum from PA1 and the spectrum from the sonic anemometer a small peak that coincides with the peak of the surface wave spectrum remains, which suggest an influence of the underlying wave field.

has to be done to stabilise the outrigger. Furthermore, small sensor effects related to motion can not be excluded at present.

Turbulence measurements within the WBL • On the very last day of the experiment music was in the air. The wind turned and started to blow from a favourable direction (west to north-west). Waves reached maximum heights up to 2 m near MPN. Using the instrument configuration described above, the wave follower descended to follow the actual water surface, and measurements were performed well below the level of most wave crests. The average wind speed was about 6 m/s at the level of the wave follower. Occasionally, the wave follower lost track of the water surface due to the strong accelerations upon the approach of a very steep or breaking wave. Furthermore, after some time the signal from the water level sensor was corrupted due to dirt attached to the sensor. It will be attempted to address these problems by substituting the present level sensor by an acoustic one at the end of the outrigger. The measurement range of the sensor will furthermore be extended.

Despite the problems, the first dance with the waves yielded about five 18-minute runs of turbulence measurements deep within the WBL. Afterwards, two of these runs appeared to contain usable information and their data were combined into a 25-minute record for further processing. An important, challenging step in the processing of the data is the extraction of wave-coherent signals. Information induced by waves that are part of a wide spectrum is incorporated in randomly varying turbulent signals. To extract wave-related information buried in turbulence we applied a method proposed by Hristov et al ⁹⁾. Alternative methods to extract wave-coherent information will be tested later.

A challenging step is to extract the wave-coherent signals buried in turbulence

The important first step in the analysis involves the reconstruction of wave-phase information from the measured surface elevation record. This information allows relating the observations to wave-phases, and subsequent averaging over wave-phase bins, so as to obtain the so-called phase-locked signals. The result of the phase averaging of surface elevation can be considered as a definition of the average wave during a run. For our run, this average wave is depicted as the bold line in Figure 6. It can be seen that a nice, smooth average wave is extracted from the wave spectrum. In what follows, it is important to keep in mind that the wave travels from the left to the right in the figure.

Next, we computed the phase-locked vertical wind speed for all three sensors used. The open squares and the pluses show the uncorrected,

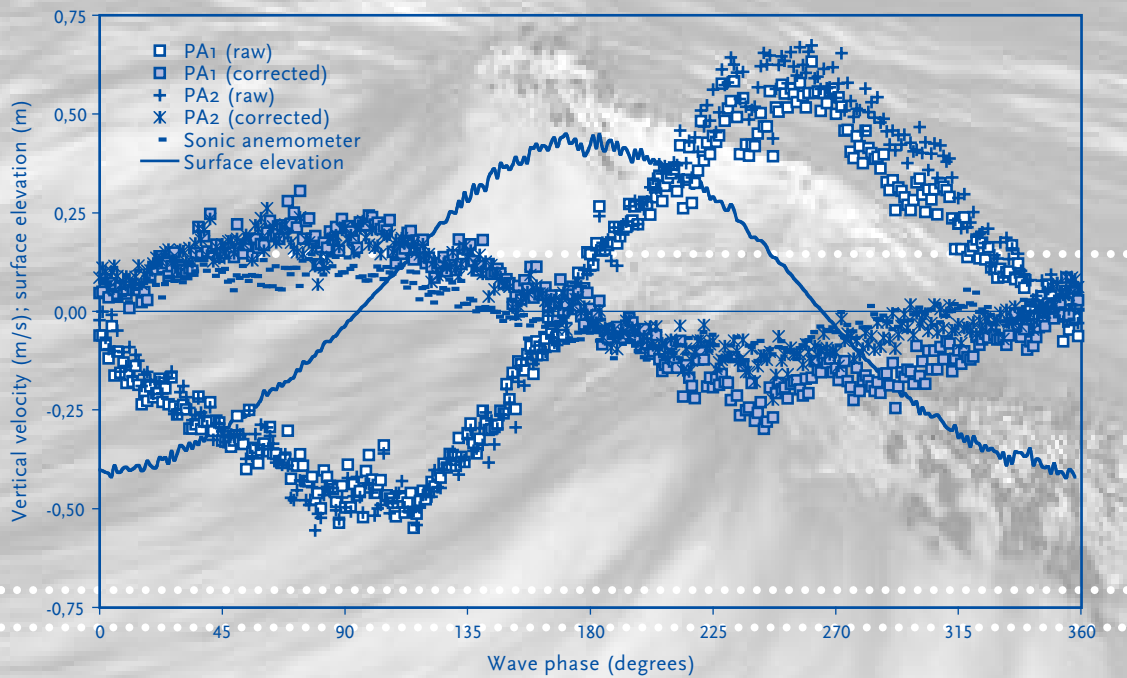


Figure 6. Phase averaged signals of the surface elevation (the 'average wave', travelling from the left to the right), the vertical velocities from the pressure anemometers (PA1 at 49cm above the sea surface and PA2 at 152 cm above the sea surface, respectively), and the sonic anemometer (at 3 m above mean sea level).

The raw signals from the PA's still contain the wave follower movement. After correction, clear phase-locked patterns remain, which are consistent with the phase-locked pattern from the stable sonic anemometer. The patterns suggest that, on average, the air overtakes the waves during this run.



phase-locked vertical wind speed of PA1 (height 49 cm) and PA2 (height 152 cm). These results are included to demonstrate that the algorithm to extract wave-related information works well. The main contribution to these signals comes from the wave follower motion. This motion can clearly be seen. If a wave crest approaches, the wave follower moves upward and it descends again if the wave travels away. As expected, the speed, up or down, is at its maximum over the steepest parts of the surface, while it is about zero right on top of the waves.

Next, we computed the phase-locked, motion-corrected vertical velocity signal of the PA's and that of the vertical speed observed with the stable sonic anemometer. First, it can be seen that the magnitude of the signals is similar, which again demonstrates that the first-order motion correction yields reasonable results. All signals show clear, phase-related differences. This is an indication of wave-coherent motions at all levels. The influence tends to decrease with height, and a phase-shift occurs among the wave-coherent signals. This kind of information is important, because it can be used to check and improve models of the WBL^{1,2}). Such an exercise is beyond the scope of the present contribution.

The present results are consistent with a situation in which air, on average, overtakes the waves: the air moves upward to flow over the crest and moves downward to enter the trough. In principle, an effect on the PA's due to the strong wave follower motions cannot be excluded at present. However, because the stable sonic anemometer revealed similar wave-coherent information, we feel that the results obtained with the PA's truly indicate the presence of wave-coherent fields, and are not an artefact of measurements on a moving platform.

The future • The most important conclusion from the results presented in previous sections is that the wave follower sounds promising. We are able to perform over sea turbulence measurements at heights below the level of the wave crests, in a wave-following frame of reference, and to extract important information about wave-induced processes in the WBL, a so far unprecedented feat.

*We can now obtain at sea
information about wave-induced processes
far below the level of the wave crests*

Possibilities emerge to perform basic tests of crucial assumptions. Can the logarithmic wind profile be extrapolated to a level near the waves in a way that makes sense? Are the fluxes really constant with height and what is

the contribution of wave-induced fluxes? Can we understand wave growth in terms of the WBL structure? How can we improve models of the WBL and parameterisations for wave growth? Is there experimental evidence of airflow separation due to wave breaking at sea and, if so, how often does it occur and what might be the contribution of the resulting wave-coherent structures to the total flux?

The tests revealed some remaining growing pains of the instrument, such as pollution of the level sensor and resonance of the outrigger. We will be working hard to alleviate them. Furthermore, the preliminary results presented above just mark the very beginning of our analysis and learning process at the time of writing. Further analyses of wave-coherent structures will be performed on other signals and their combination. Independent, alternative methods to extract wave-coherent signals will be tested as well. Given the limited number of data from the pilot experiment, the main goal of these analyses will be to check experimental procedures and algorithms. In the spring of 2001, we hope to be ready to perform more extensive and high-quality, near-surface observations during our next measurement campaign at sea, using a unique instrument: the KNMI wave follower.

Acknowledgement • The wave follower research is conducted on a unique facility: Meetpost Noordwijk. We would like to thank the owner of the platform, the North Sea Directorate of the Directorate-General of Public Works and Water Management of the Ministry of Transport, Public Works and Water Management, for granting us permission to install and use the wave follower on the platform.

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