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Mechanistic, empirical and numerical perspectives on wind-waves interaction

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Abstract

A mechanistic theory of wind-wave interaction must rely on verifiable assumptions and offer reproducible observable predictions. For decades, the limited mechanistic grasp on the problem has motivated RANS and LES modeling and has driven a vast empirical effort to describe the interaction in terms of wave-induced modifications of standard statistical characteristics of the wind, such as wind profile, kinetic energy balance or exchange coefficients. Because the mechanistic, empirical and numerical approaches are all concerned with the same phenomenon occurring in the same media, consistency here requires that the assumptions on which the approaches rest and the predictions they generate are compatible with each other and supported by measurements. Recent findings from theoretical analysis and field experiments advanced the understanding of the statistical and dynamic patterns of the wave-coherent flow, which is at the core of the mechanistic description of the wind-wave exchange. The progress prompts reexamining of earlier concepts, efforts and findings to evaluate their suitability, validity and usefulness. For the purpose, this survey traces the development of ideas, methods and results in the study of the wind wave generation.

1. Introduction

’What causes the waves in the ocean?’ is a question that seeks to elucidate an ubiquitous phenomenon and in that sense it stands next to questions such as ’What makes the stars shine?’ or ’What causes the lightning?’. In his thesis advised by Richard Feynman, ”The growth of water waves due to the action of the wind”, Hibbs [22] wondered about *”Why should such a problem still exist, with all the abilities of modern physics and the accomplishments of modern aerodynamics?”.* Indeed, initiated by Kelvin [30], the efforts to reveal the physics behind the wind-generated ocean waves are still ongoing, as evidenced by this meeting. In his influential review on the subject Ursell [63, p. 217] pointed out the key obstacle to understanding the process that is the disconnect between theory and experiment, a disconnect that began to close only recently. Since the times of Ursell [63], however, the lines of inquiry on wind-

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wave interaction have been broadened beyond theory and experiment to include empirical and numerical approaches which, like theory and experiment, have also developed separately and any possible connection between them has stayed unexplored. As all these approaches are concerned with the same phenomenon in the same environment, the results and predictions from different approaches should be consistent with each other. Whether a theory should be about a mechanism or unity, as Poincare [47, p. 177] pondered, this survey pursues both. Because a mechanistic theory on wind-wave interaction should be capable to provide details and physical insight, a summary of a theory is used below to gain an unified mechanistic frame of reference for empirical and numerical approaches and results. For the purpose, here we discuss the corollaries of some recent findings on the problem of waves generation by wind, the analytic and experimental details of which are available in [26], [27] and [24]. To put these findings in perspective and to answer the question raised by Hibbs' [22], we outline the milestones in the early evolution of ideas as they may, justifiably or not, still guide the thinking on the subject.

2. Milestones in the early wind-wave interaction studies

Like Kelvin [30], Jeffreys [29] studied the process of wind waves generation assuming an air flow velocity constant with the distance from the interface. At the time the specific functional form of the wind velocity profile was still unknown and its role in the generation had not been studied and understood. Starting from such unrealistic air flow Jeffreys [29] arrived to unrealistic predictions and incorrectly traced them back to the assumption of irrotational waves. Abandoning that assumption while keeping the unrealistic wind profile, Jeffreys [29] proceeded to hypothesize and prescribe, rather than to derive or otherwise deduce, the physical nature of the interaction. Forty years later Stewart [60, p. S48] found Jeffreys [29] solution of the wind wave generation problem lacking.

The review of Ursell [63] summarized the ideas available at the time, stated the unsatisfactory understanding of the problem, and inspired the works of Phillips [45] and Miles [37]. Phillips [45] built on the work by Eckart [12] and considered a wave generation due to the turbulent air pressure fluctuations as in an oscillator under the action of a random force. Paradoxically, Phillips [45, p. 417] both neglected the wave-coherent motion in the air and found it to be most effective for the generation process: *"Correlations between air and water motions are neglected ... It is found that waves develop most rapidly by means of a resonance mechanism which occurs when a component of the surface pressure distribution moves at the same speed as the free surface wave with the same wavenumber."* For the resonant wave growth to occur, Phillips [45, p. 422] required that *"the pressure distribution contains components whose wave-numbers and frequencies coincide with possible modes of free surface waves"*. Yet, the dispersion of the turbulent motion in a wind with advection velocity U is $U = \omega/k$, also known as Taylor's hypothesis, and the dispersion of surface waves with a phase speed c is $c = g/\omega$, g being the acceleration of gravity. Because for aligned wind and waves same frequency and wave number correspond to different advection velocity U and phase speed c, these dispersions are incompatible for resonance. For a wave mode $\omega(k)$ a resonance may still occur if it propagates obliquely at some angle $\pm\theta$ with respect to the wind, thus predicting a wave field with a bimodal spectral distribution. The observations of Simpson [55, p. 93] detected no bimodal spectrum in the range of the locally generated waves. Longuet-Higgins [34] reported the turbulent air pressure fluctuations to be too small to ensure wave growth rates near the observed, but offered no interpretation. The turbulent pressure fluctuations decay with scale as $k^{-7/3}$ [43, 3], that is faster than the decay rate with scale $k^{-5/3}$ in velocity. As turbulent motion undergoes the energy cascade from integral scales down to the scales of the initiating sea surface ripples, only small magnitude pressure fluctuations are retained. Consequently, the turbulent pressure component on which the random force mechanism relies, is virtually absent, explaining the findings of Longuet-Higgins [34] and causing the reported lack of experimental support for the random forcing mechanism of wave generation [55].

The idea that the generation of wind-driven waves may be viewed as a shear flow instability has its roots in the work of Tollmien [62], published as an obscure technical memorandum for NACA and thus rarely referenced. Its results became available to a broader audience through Lin [33]. Tollmien [62] analyzed the perturbations in laminar shear flows as solutions of the Rayleigh equation and established the dynamic significance of the location where the averaged flow velocity profile matches the phase speed of the perturbation, known as critical layer. In the 1940s and 1950s novel results on flow stability were spreading and igniting interest among fluid dynamicists [41]. Surveying the ideas lying around, Miles [37] postulated that the laminar flow analysis and results of Tollmien [62] apply to the generation of surface waves by a wind that is turbulent. However, Miles [37] offered no physical justification of

the proposition and no testable predictions from it, which greatly influenced the perception, including Miles' own, of that proposition. Sir James Lighthill, at the time already an authority in fluid mechanics and whose life and work are celebrated at this meeting, wrote favorably of Miles [37] and referred to it as 'the Miles theory.' Still, he viewed [37] as a mathematical construct with somewhat tenuous relation to the physical world and hence in [32] he sought an interpretation for it. Like Ursell [63, p. 217], Lighthill [32, p. 385] recognized the agreement between theory and experiment as essential to gaining insight into the wind waves generation. With the observational support still absent, however, Miles [36, p. 1] viewed *'Lighthill's opinion [as] too optimistic'* and cautioned [39, p. 166] that Lighthill's [32] endorsement of the mathematical theory in [37] has been *'interpreted with less reservation than either he or the writer might have wished.'* Miles [40] considered the concept of critical layer in wind-wave interaction only as a *'convenient mathematical notion'*. Uncertain about the suitability of the ideas in the 1957 paper, Miles' later work proceeded with modifications of that paper's concept rather than with its experimental verification, interpretation, potential physical impacts or operational use. Besides Miles, others have explored such modifications, e.g. in specific corners of the parameter space, the work of Sajjadi et al. [52] among the latest.

Miles [37] postulation that the surface waves occur as growing perturbations of the wind profile and are thus described by Rayleigh equation, is now superseded by a derivation that renders moot the gaps and deficiencies in wind input knowledge as perceived by Pushkarev and Zakharov [50, p. 21]. Resting solely on the well-confirmed premise of small slope waves, [27] demonstrated that the Taylor-Goldstein equation describes the wave-coherent component, and thus the wind-wave interaction, in a stratified turbulent wind. Both the Rayleigh and the Taylor-Goldstein equations predict critical layers for a wide variety of wind profiles $U(z)$. The wave-coherent motion there is associated with a kinetic energy production $\langle \tilde{u}\tilde{w} \rangle (\partial U / \partial z)$ that is delivered from the mean flow to the waves and is leading to a wave generation for any of these profiles. Because the logarithmic wind profile $U(z) = (u_* / \kappa) \log(z/z_0)$ is sufficiently representative of the marine atmospheric boundary layer [6, 51, 42, 59], Miles [37] offered numerical estimates for the wave growth rate for the case of that profile. While the key concept in [37] has been only illustrated with a logarithmic profile, that still invites the misinterpretation, e.g. in Pushkarev and Zakharov [50, p. 21], that the concept in [37] requires such profile. It does not. Stratification as well as inhomogeneity and non-stationarity of the marine atmospheric boundary layer may cause departures of the wind profile from its logarithmic shape [27]. While in such cases the wind-wave interaction still occurs through the same physical mechanism of wave-coherent flow with critical layers, the wind-to-wave energy transfer rates may vary substantially from their values obtained for a logarithmic profile. Yet, experimental estimates of the wave growth rates have been compared with theoretical predictions calculated for the case of a logarithmic wind profile. Discrepancies in such comparisons, although not in whole, are related to the unphysical narrowing, as in [50, p. 21], of the theory's scope to a logarithmic wind profile.

Over the decades that followed, review papers have repeatedly described [37] as difficult to understand, interpret, validate or apply [5, 60, 2], and as *"...least well understood because of the less-than-intuitive nature of the theory"* [14]. With such sentiment widely shared, the proposition in [37] has been misconstrued, doubted and dismissed. Regarding the Hibbs' [22] question, that sentiment may have dissuaded close interest in and may have delayed the progress on the wind waves generation problem.

3. Empirical studies of wind-wave interaction

With the mechanistic theory of wind-wave interaction deemed inaccessible, the attention has turned to empirical studies. There, the ocean is treated as a rough aerodynamic surface where the waves of all scales are responsible for the surface roughness and the variability of the surface's drag. Motivated by the need for computational efficiency in large scale models of atmospheric dynamics and ocean circulation, this vast effort has included dozens of experiments in laboratory, over lakes and over the coastal and the open ocean and since the 1960s has produced hundreds of papers. It has been primarily concerned with applied issues, such as establishing empirical relationships between easy-to-measure environmental variables, e.g. wind speed, vertical scalar gradients, etc., and variables of ocean-atmosphere exchange, e.g. fluxes of momentum, heat, species, etc. Among the constraints of this empirical approach is the inability to distinguish between momentum or energy transferred to the waves and those transferred to the currents, leaving a significant blind spot for numerical modeling and forecasting. Among the main interests pursued within this effort have been the empirical estimates of the air-sea exchange coefficients. The scatter of these estimates, however, has not been reduced over time, despite the improved instrumentation and the accumulation of more statistics [8]. The latter

suggests that at the core of the uncertainty is the complex dynamics of the air flow laying outside of the empirical framework, rather than experimental imperfections or isolated statistical aberrations.

A related line of inquiry within the empirical approach on wind-wave interaction and characterization of the marine atmospheric boundary layer has been to seek violations of the Monin-Obukhov similarity theory over the ocean, e.g. in the shape of the wind profiles or in the budgets of momentum flux and kinetic energy, ascribe them to the influence of the surface waves [15, 13, 56, 28, 23], and use these violations to understand and quantify the dynamic wind-waves exchange. The underlying assumption of such studies is that no violations of the Monin-Obukhov similarity theory occur over land, so that any violations of that theory can be interpreted with certainty as a dynamic signature of the surface waves. Once found and their patterns discerned, these violations were to be incorporated in an updated theory, where the universal gradient functions $\{\phi_m(z/L), \phi_h(z/L), \ldots\}$ of the Richardson number (z/L), where L is the Obukhov mixing length, are modified to account for the waves' presence [13]. Such logic, however, ignores multiple reports of discrepancies between the said theory and observations over land [44, 66, 17]. Furthermore, the assumption that the wave influence would depend solely on the Richardson number and be independent of any variables characterizing the sea state, appears unjustified. The research strategy just outlined, has detected no wave signature in the study of Edson and Fairall [15]. Consistent with the report of Charnock [6] and the studies of Ruggles [51], Mitsuyasu and Honda [42], Soloviev and Kudryavtsev [59] and of Bergström and Smedman [4], the Edson and Fairall [15] experiment determined that the kinetic energy balance is virtually unaffected by the presence of waves. Their proposed explanation was that the instruments have been positioned above the layer affected by the wave influence, commonly referred to as the wavy boundary layer (WBL). Sjöblom and Smedman [56] point out that the research strategy produces *"seemingly contrasting results"*, that are circumstantial and inconclusive.

In its broadest formulation the empirical approach would select a statistical characteristic of the atmospheric boundary layer, be that dissipation rate, velocity structure function, velocity spectra, etc., search for differences in that characteristic in measurements over land and over waves and from these differences seek insights into the wind-wave interaction. Schacher et al. [54] have found no detectable wave signature in the rate of kinetic energy dissipation, Van Atta and Chen [64] have failed to identify such signature in the wind velocity structure function. Pond et al. [49, 48], Weiler and Burling [65], Stewart [60], Soloviev and Kudryavtsev [59] have reported no peak at the wave frequency in the wind velocity spectra. All these negative, yet informative results indicate that the mechanical air-sea interaction is both intense and subtle. The size and energy of the waves generated by a storm indicates the interaction's intensity. Yet the interaction does not manifest itself in quantities commonly used to characterize the atmospheric boundary layer (wind profiles, spectra, structure functions, kinetic energy budget, etc.), hence the subtlety. That subtlety may partially hold the answer to the question posed by Hibbs [22]. The negative results listed above suggest that the selected characteristics of the atmospheric boundary layer are insensitive to wave influence and that choosing a different set of informative variables and analysis techniques is essential for gaining a physical insight into the wind-wave coupling.

4. Mechanistic perspective and its observational validation

The generation of ocean waves results from the interaction between two random fields, the air flow and the compliant water surface. Given the surface elevation η, the vertical velocity $\dot{\eta}$, and the atmospheric pressure p_0 at a point of the water surface, the averaged energy exchange rate there is $\langle p_0 \dot{\eta} \rangle$. The latter suggests that the wave-coherent pressure, and generally the wave-coherent motion in the air, carries the interaction. Therefore, the dynamic equations of that motion would be the key to formulating the mechanistic theory, while discerning that motion's dynamic and statistical patterns from field measurements would be key to verifying the theory.

The wave-coherent motion, however, has been perceived as elusive to both define and detect. Phillips [46, p. 108] thought of it: *"In physical space, the induced pressure at any point on the surface of a random wave field is a rather ill-defined functional of both the wind and the wave fields, and it is not easy to separate this from the turbulent contribution."* Hasse and Dobson [20, p. 101] saw experimental challenges: *"This means that in the air above the sea, where there is usually a mean wind many times stronger than the wave-induced flows, the wave-induced motions are hard to detect."*, as did Komen et al. [31, p. 72]: *"The measurement of the energy transfer from wind to waves is, however, a very difficult task, as it involves the determination of the phase difference between the wave-induced pressure fluctuation and the surface elevation signal..."*
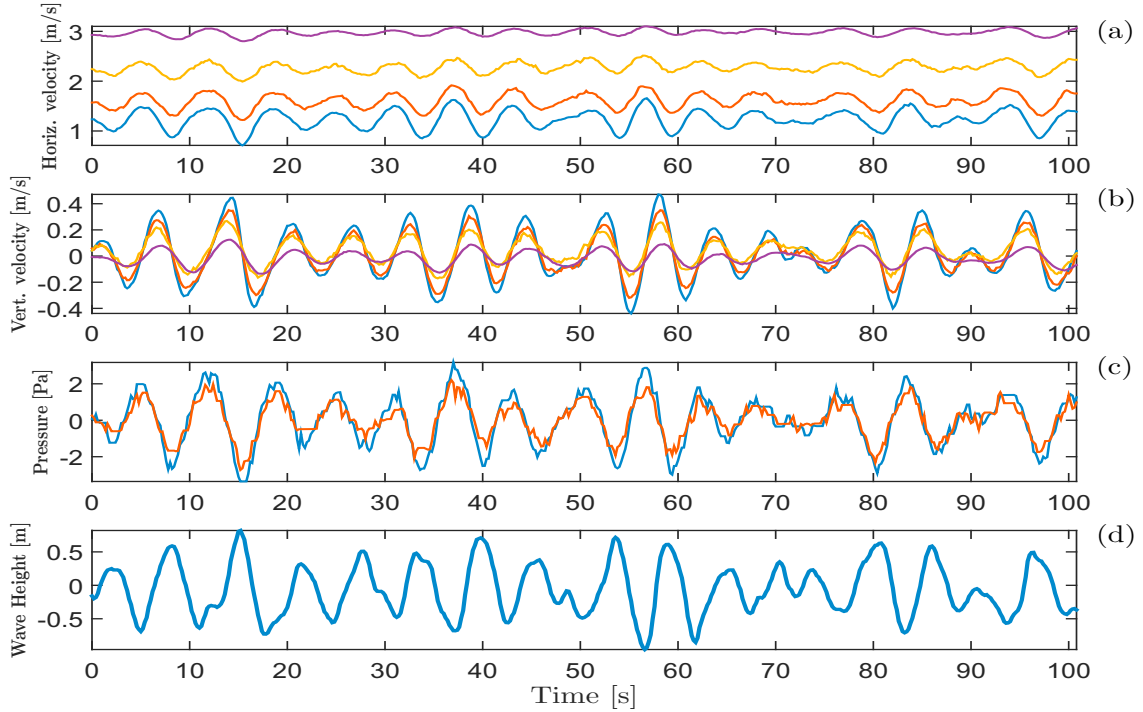
Fig. 1. Wave modulation of the wind during Coupled Boundary Layers Air-Sea Transfer (CBLAST) experiment. (a) Horizontal wind velocity measured by 4 ultrasonic anemometers positioned between 5m and 18m from the surface in the order blue (the lowest), red, yellow, magenta (the highest). (b) Vertical wind velocity, with colors matching the same order of the instruments. (c) Pressure, blue (lower) and red (higher). (d) Surface wave elevation.

When the wind speed and the turbulence intensity in the air are relatively low, the wave-coherent modulation of the wind is directly observable in unprocessed signals of air velocity and pressure (Figure 1). With the increase of wind speed, turbulence begins to dominate and the identification of wave-coherent modulation requires statistical tools [25, 26, 18, 27].

Consider a signal of an air flow variable $u(t)$ that consists of a wave-correlated component $\tilde{u}(t)$ and a uncorrelated component $u'(t)$, so that $u = \bar{u} + \tilde{u}(t) + u'(t)$. Consider a wave signal $\eta(t)$ as consisting of a finite-number narrow-band components $\{\eta_n(t)\}$, i.e. $\eta(t) = \sum_n \eta_n(t)$, for which $\langle \eta_k \eta_l \rangle \sim \delta_{kl}$. Then, the wave-coherent component $\tilde{u}(t)$ can be obtained as a projection of the measured signal $u(t)$ onto the vector space of all wave-coherent signals $W = \text{span}\{\eta_n, \hat{\eta}_n\}$, where $\hat{\eta}_n$ is the in-quadrature counterpart of η_n obtained via the Hilbert transform, i.e.

$$\tilde{u}(t) = \sum_n \left(\frac{\langle u(t)\eta_n(t)\rangle}{\|\eta_n\|^2}\eta_n(t) + \frac{\langle u(t)\hat{\eta}_n(t)\rangle}{\|\hat{\eta}_n\|^2}\hat{\eta}_n(t) \right). \tag{1}$$

The filter $\widetilde{(\cdot)}$ defined this way has the properties $\widetilde{(u)} = \tilde{u}$, $\widetilde{(\tilde{u})} = \tilde{u}$, $\widetilde{(u')} = 0$, and $\langle u'\tilde{u}\rangle = 0$. Such filter both defines and detects wave-coherent fields in the air flow. It is suitable for deriving the dynamic equations for the wave-coherent flow and for retrieving the time series of the wave-coherent variables in measured signals [25, 26, 27].

Referring to [26], [27] and [24] for analytic and experimental details, below we outline the foundations of the theory there, its experimental verification, its predictions, and their implications. Invoking only the assumption of small slope waves, [27] employs the filter (1) to arrive to the dynamic equations for the wave-coherent flow, thus extending the shear flow instability analysis to the interaction of waves with a turbulent wind. As the transfer functions of the wave-coherent fields in the air are invariant with respect to the wave spectrum and can be produced both theoretically and experimentally, they are well suited for validating theory from measurements. Therefore, the wave-coherent flow structure and dynamics can be described through the transfer functions between the waves and the air velocity. Matching analytical and experimental transfer functions would support the theory that predicted them or,

conversely, would explain the experiment that produced them. The theory predicts that at low wind speeds the wave-coherent flow may form a regime with Stokes drift (e.g. as in Figure 1), causing momentum flux from waves to wind, and a regime with critical layers at moderate and high wind speeds [26, 18, 27], causing momentum and energy fluxes from wind to waves. A distinct flow feature is the discontinuity of the velocity's phase at the critical height [26, 24].

Since coastal ocean and laboratory are much more accessible than the open ocean for wind-wave interaction studies, it is pertinent to recognize the constraints of such environments for observing the critical layer signature. The dispersion of waves in finite-depth water $\omega^2 = gk \tanh(kd)$, where g is the acceleration of gravity and d is the water depth, establishes a maximum for the waves' phase speed $c_{max} = (gd)^{1/2}$. When waves transition from deep to shallow water, the refraction may misalign the wind and the waves, requiring that the relative direction is included in estimating the wave age. Furthermore, for the range of wave frequencies $[0, \infty]$, the range of possible phase speeds contracts from $[0, \infty]$ to $[0, \sqrt{gd}]$. For a frequency range $\Delta\omega$ the corresponding phase speed range in deep water Δc_{deep} contracts to a phase speed range in shallow water $\Delta c_{\text{shallow}}$, so that $\Delta c_{\text{shallow}} < \Delta c_{\text{deep}}$. In turn, the range of critical heights $\Delta z_{c,\text{deep}}$ corresponding to the same frequency range $\Delta\omega$, contracts as well to $\Delta z_{c,\text{shallow}}$, i.e. $\Delta z_{c,\text{shallow}} < \Delta z_{c,\text{deep}}$, as does the range of wave ages $\Delta(c/u_*)$. Compressing the critical layer features of a range of wave modes $\Delta\omega$ into a thinner critical heights range and narrower wave age intervals may cause these features to become poorly resolvable, while the increased wave steepness in shallow water may enhance nonlinearities and distort any critical layer signature.

Measurements over deep water waves, conducted during the Marine Boundary Layer Experiment [26, 24] and the High Resolution Air-Sea Interaction Experiment [18, 27], along with the analytic results in [27, 24] established that:

(i) The wind-wave interaction does occur through a wave-coherent flow in the air and the critical layer pattern of phase discontinuity in that flow is sustained, thus identifying the mechanism responsible for wind wave generation, [26, 18, 24].

(ii) A Stokes drift regime is observed at low wind conditions, associated with weak, yet pronounced wave-to-wind momentum flux [27].

(iii) Relying only on the assumption of small slope waves, that is, $k_p \sigma_\eta \ll 1$, where k_p is the wave number of the spectral peak and $\sigma_\eta = \langle \eta^2 \rangle^{1/2}$ is the variance of the sea surface, the analysis in [27] shows that the budgets of second order moments, e.g. kinetic energy and momentum, apply separately to the wave-correlated and wave-uncorrelated motions in the wind. As the phenomenology of the atmospheric boundary layer's kinetic energy budget is the essence of the popular Monin-Obukhov similarity theory (MOST), the separated budgets show how the waves modify the predictions from MOST.

(iv) The key measure of the waves' dynamic influence on the air flow is the ratio of the production terms in the kinetic energy budgets for the correlated $\langle \tilde{u}\tilde{w} \rangle (\partial U / \partial z)$ and uncorrelated $\langle u'w' \rangle (\partial U / \partial z)$ motions, which in turn is expressed as a ratio of the wave-supported $-\langle \tilde{u}\tilde{w} \rangle$ and total $-\langle uw \rangle = u_*^2$ momentum fluxes, i.e. $-\langle \tilde{u}\tilde{w} \rangle / u_*^2$, [27].

(v) At heights available for atmospheric measurements $z \geq 10^4 z_0$, where z_0 is the aerodynamic roughness length of the sea surface, typically between 2×10^{-4}m and 5×10^{-4}m, both theory and experiment find that the ratio $-\langle \tilde{u}\tilde{w} \rangle / u_*^2$ is small, of the order of 5%, [27].

(vi) Consequently, the wave contribution to the sea surface drag coefficient C_D, the wave-induced modification of the kinetic energy budget, the apparent wave-enhanced imbalance between production and dissipation, the wave contribution to the departures from the predictions of the Monin-Obukhov similarity theory and the wave-induced bending of the wind profile are also small and thus virtually undetectable next to other physical influences modifying these characteristics, in agreement with empirical studies, [27].

(vii) The explicit forms of the wave-supported momentum and kinetic energy fluxes indicate that a wave frequency spectrum $\omega^{-\beta}$, through relaxation, converges to a spectral slope $4 \leq \beta \leq 5$, [27].

These findings explain the negative results in the vast body of empirical studies that sought a wave signature in standard characteristics of the flow over waves, such as a wind profile, a dissipation rate, a kinetic energy balance, a momentum flux, or a variation of the drag coefficient with sea state. They show that the predictions of the Monin-Obukhov similarity theory are virtually insensitive to the waves, letting the conclusion that the theory adequately describes the marine atmospheric boundary layer, yet it is a poor instrument for detecting and studying wind-wave coupling. The demonstrated agreement between theory and experiment unifies the mechanistic and empirical perspectives on wind-wave interaction.
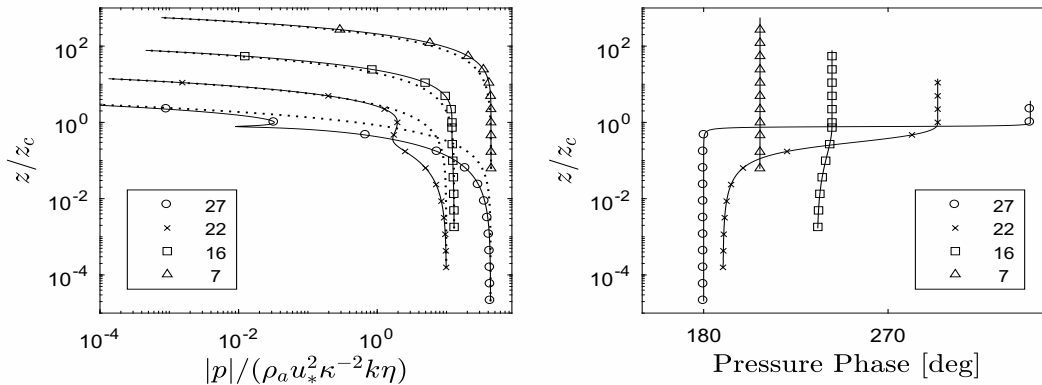
Fig. 2. The normalized magnitude $|p|/(\rho_a u_*^2 \kappa^{-2} k\eta)$ (left), and phase (right) of the wave-coherent pressure vs. the distance from the surface normalized by the critical height z/z_c, obtained from a solution of the Rayleigh equation [26, 27, 24]. The symbols $\circ, \times, \square, \triangle$ distinguish different values of the wave age c/u_*. The dotted lines show exponents that match the pressure magnitude at the endpoints and exhibit a notable departure in the middle.

5. Experimental and numerical studies of wave growth rate and wave energy evolution

Wave growth rate and wave energy evolution under wind forcing are of primary interest for wave modeling and forecasting [50]. The wave growth rate, rather than the air flow pattern, has been central to the thinking and studies of wind waves to the extent that a discrepancy with observed growth rates sufficed for Donelan and Hui [10, p. 228] to dismiss the available theory: *"Thus, our knowledge of the wind input to a spectrum of waves is still rather primitive. The theoretical ideas of the fifties have not been capable of explaining the observed growth rates and no essentially new ideas have followed."* Yet, experimental and numerical estimates of growth rates and of energy evolution depend on the constraints and the uncertainties in the methods used to obtain them. Below, these constraints and uncertainties are outlined for proper interpretation of wave growth rate estimates' relation to a particular theory.

As a wave generation through random force [45] or through shear flow instability [62, 37], would lead to a different growth rate and a different evolution of the wave field's energy, experiments have sought to identify wind-wave generation scenarios through growth rate or energy evolution measurements. Davis [7] noted, however, that the growth rate is a function of the pressure distribution on the surface, yet since the pressure distribution does not uniquely specify the flow structure in the air, it does not determine the mechanism of wind-wave interaction. As for the evolution of the wave field energy observed in an experiment, it depends not only on the wind-wave interaction mechanism, but also on the history and spatial distribution of the variable wind forcing as well as on the action of non-linearity that redistributes the wave energy across the spectrum. Because different wave modes draw momentum and energy from the wind at different rates, a wave field developing with non-linearity may have evolution of its energy significantly different from a wave field developing under the wind forcing alone, i.e. when each mode retains exactly the energy received directly from the wind. Consequently, like the wave growth rate, the observable wave field energy evolution lacks the certainty necessary for identifying the physics of wind-wave interaction.

Multiple experiments [16, 58, 57, 21, 19, 9, 11, 53] have been carried out to measure the wind-to wave energy transfer rate as a correlation between pressure and surface velocity, i.e. $\langle p_0 \dot{\eta} \rangle$ and compare them with predictions from theory. Pressure measurements on the surface risk wetting the sensor or distorting the readings with protective film, etc. Commonly, pressure measurements are conducted at some finite height and later extrapolated to the surface, assuming exponential decay of the pressure's magnitude scaled by the wave number k, i.e. $\propto e^{-kz}$, and no change in phase with height, as in [16, p. 443], [58, p. 508], [57, p. 24], [21, p. 397, p. 405, p. 407-409], [19, p. 1020], [9, p. 190], [11, p. 1174], [53, p. 1334]. However, a theory of wind-wave interaction through wave-coherent flow predicts the wave-coherent pressure from solutions of the Taylor-Goldstein equation [26, 27, 24], which depends on the dimensionless aerodynamic surface roughness $\Omega = y_0 g k^2 / u_*^2$ and the wave age parameter c/u_* rather than on the wave number k, and exhibits a dependence on height that is distinctly different from exponential (Figure 2). The dotted lines in Figure 2 show exponents that match the pressure predicted from the Rayleigh equation at the end points

and notably depart, by up to a factor of 10, from it in the middle. Furthermore, the assumption of phase independent of height does not hold for a range of wave ages. Consequently, an assumption of wavenumber-scaled exponential pressure decay with constant phase is inconsistent with the theory that it is employed to test and distorts the pressure extrapolation to the surface. Along with the random variability of the surface roughness Ω, the distortive pressure extrapolation contributes to observed discrepancies between theoretical and experimental estimates of the wind-to-wave energy transfer rates. Furthermore, the wind-to-wave energy transfer depends on the wind profile shape $U(z)$ through the factor U''/U' [62, 38, 27]. The wind's non-stationarity and spatial inhomogeneity along with atmospheric stratification deform the wind profile [27, p. 3192] and through the factor U''/U' add to the variability of the wave-supported energy flux. Although the available theory explains such variability, that variability has been unaccounted in any of the field experiments listed above.

Since the 1970s, RANS and LES models for the flow over waves have been used evaluate wind-to-wave energy transfer. Such models rely on concepts (eddy viscosity, diffusivity) and tools (closures and sub-grid parametrization schemes) developed for describing turbulent flows. The strong sensitivity of modeling results to the choice of closure [1] and the fact that no second-order closure model has detected any critical layer flow features [35, 61], has led some to question the adequacy of these closures. Phillips [46, p. 117] observed that *"Closure schemes in turbulent shear flow are still rather ad hoc and different methods, which may be reasonably satisfactory in other flows, give very different results when applied to this problem. The situation is not one in which firmly established methods lead to results that one might seek, with some confidence, to verify experimentally. On the contrary, because of sensitivity of results to the assumptions made, the air flow over waves appears to provide an ideal context to test the theories of turbulent stress generation themselves."* As outlined below, the inadequacies in such models extend beyond the deficiencies in closures and sub-grid parametrizations.

Starting from Al-Zanaidi and Hui [1], a number of studies have modeled the flow over a Stokes wave, that is

$$\eta(x) = -a\cos(kx) - (ka^2/2)\sin^2(kx), \tag{2}$$

instead of over a monochromatic wave $\eta = ae^{-i(kx-\omega t)}$. Such studies ascribe to a single mode k the energy flux to two wave modes, k and $2k$, thus producing a spurious enhancement of the wave growth rate.

Contrasting with the widely held views about turbulence, the wave-induced flow is anisotropic at both large and small scales. Its directions of distinct significance are the direction of wave propagation, and the vertical direction, along which the wave signature decays. The critical layers, which both the theory and experiment show to be dynamically essential in wind-wave interaction, create a fine structure in the wind. The wave-induced flow may experience a large variation over a short distance near the distinctly anisotropic critical layer [26, Figure 1e]. The critical layers of different wave modes are densely stacked on top of each other along the vertical coordinate. Closures and sub-grid parameterizations have been proposed with regard to the assumed properties of turbulence and none with regard to the properties of the wave-induced flow, which differs from turbulence in its scales and symmetries. Resolving the wave-induced flow with multiple critical layers [26, Figure 1e] requires a fine spatial grid. The 40 cells along the vertical coordinate used by Al-Zanaidi and Hui [1, p. 234] or LES grids with $\Delta z \geq 1m$ near the surface, [27], define a domain discretization too coarse to capture the wave-induced flow structure just described. Although such coarse grids may resolve the large scale motion of the atmospheric Stokes drift and the associated wave-to-atmosphere momentum transfer, they suppress the critical layers and the concomitant wind-to-wave transfer. This way the grid size selects the elements of wind-wave dynamics that are retained and that are ignored in a LES model.

6. Conclusion

Hibbs [22] contemplated the causes that kept the wind waves generation mechanism as a longstanding open physical problem. Within the century between the pioneering work of Kelvin [30] and Donelan and Hui [10, p. 228] dismissal of the contemporary theory for its inability to explain the experimental growth rates, theoretical, empirical and numerical approaches have been employed inconclusively. Over the last one and a half decade, analytic, numerical and open ocean experimental results [26, 18, 27, 24] have confirmed that the mechanism of wind-wave interaction through wave-coherent flow is indeed active and the critical layer pattern in that flow is persistent and pronounced. Such findings offer a new mechanistic perspective on the constraints and challenges through the evolution of ideas and methods relied on to study the problem. Among these have been:

(i) The lack of physical justification and testable predictions, as well as the *'less-than-intuitive'* [14] analytic details, have made the theoretical ideas to be misconstrued, doubted and dismissed, [5, 60, 39, 2, 10, 40, 36].

(ii) Instead of seeking air flow patterns that uniquely do identify the wind-wave interaction mechanism, the experimental studies [16, 58, 57, 21, 19, 9, 11, 53] have been focused on wave growth rates, that do not [7].

(iii) Improper choice of the wave number k instead of the wave age c/u_* as a governing parameter, distortive exponential extrapolation to the surface, variation of the wind-to-wave energy flux through the factor U''/U' due to deviation of the wind profile from its logarithmic shape, and possibly other experimental imperfections and uncertainties, are contributors to the discrepancy [10] between theoretical and measured wave growth rates.

(iv) Empirical studies have been concerned with air flow characteristics weakly affected by the surface waves, e.g. wind profiles, kinetic energy balance, structure functions and spectra, etc., thus pursuing a wave signature that is virtually undetectable in experiments [15, 27].

(v) The wave-coherent flow (Figure 1), a key to the mechanistic description of wind-wave coupling, has been perceived as elusive to both define and detect in a field experiment [46, p. 108], [20, p. 101], [31, p. 72].

(vi) Numerical studies have relied on concepts, tools and computational grids suitable for turbulent flows. As turbulence differs from the wave-coherent flow in its scales and symmetries, resolving the wave-coherent flow, and by extension the wind-wave interaction, requires computational grids much finer than those used so far in LES [27].

These constraints and challenges may offer at least a partial answer to the question posed by Hibbs' [22], that is, why for more than a century understanding the dynamics of wind-wave interaction has been a tenacious physical problem.

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