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In Memoriam

In March 2008 we lost Ralph Goodman, who
greatly inspired the creation of this
monograph series in underwater acoustics.
His encouragement and support were critical
to the successful development of this
important series.
He will be missed.

Series Preface

The efficacy of sound to penetrate the seas made acoustic systems in the past century the leading tools for sensing objects in and measuring properties of the seas. For over 60 years, the US Office of Naval Research (ONR) has been a major sponsor of undersea research and development at universities, national laboratories, and industrial organizations. Appropriately ONR is the sponsor of this monograph series.

The intent of the series is to summarize recent accomplishments in, and to outline perspectives for, underwater acoustics in specific fields of research. The general field has escalated in importance and spread broadly with richness and depth of understanding. It has also, quite naturally, become more specialized. The goal of this series is to present monographs that critically review both past and recent accomplishments in order to address the shortcomings in present understanding. In this way, these works will bridge the gaps in understanding among the specialists and favorably color the direction of new research and development. Each monograph is intended to be a stand-alone advanced contribution to the field. We trust that the reader will also find that each is a critical introduction to related specialized topics of interest as well.

ONR has sponsored the series through grants to the authors. Authors are selected by ONR based on the quality and relevance of each proposal and the author's experience in the field. The Editorial Board, selected by ONR, has, at times, provided independent views to ONR in this process. Its sole official role, however, is to judge the manuscripts before publication and to assist each author at his request through the process with suggestions and broad encouragement.

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Homer P. Bucker, Ph.D.
Ira Dyer, Ph.D.
Finn B. Jensen, Ph.D.
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Contents

Chapter 1
Introduction

Ambient noise became an active area of research during World War II because of the availability of calibrated instruments and the necessity to understand the ambient noise levels in coastal waters. This wartime research was summarized by Knudsen et al. (1948), and later by Urick and Pryce (1954). After the war, during the 1950s, published ambient noise research waned until the classic paper of Wenz (1962). This work initiated a renaissance of ambient noise as one of the most interesting areas of oceanic acoustic research. The classic paper of Wenz (1962) was notable as it supplied a graphical or schematic spectrum, omnidirectional noise levels versus frequency. This schematic identified sources of ambient noise and resultant omnidirectional levels in frequency bands parameterized by the Beaufort wind force. This metric includes the 10-m wind speed as well as the appearance of the sea. The schematic also identified regions dominated by shipping and regions dominated by rain noise.

Most ambient noise research between 1950 and 1980 was classified; recently, several key experimental papers from this period were published in a special archival issue of the *Journal of Oceanic Engineering*, Carey (2005), and represent important benchmarks of observed noise levels and directionalities. Walkinshaw (2005) presented 4 years of noise measurements in the Norwegian Sea. This work was unique because sensors and recording instrumentation in the period from 1957 through 1961 were rather primitive compared with current technology and the difficulty in performing these measurements cannot be understated. Nichols (2005) obtained noise results between 1951 and 1974 using new specially built barium titanate hydrophones to perform the measurements that stressed transient noise sources (biological, machines, and offshore drilling) compared with the background of wind-driven and shipping noise. He discussed in detail the mysterious 20-Hz/20-cycle sounds correctly attributed to cetaceans. According to Urick (1984), the observation of these sound sequences was so mysterious that their occurrence was highly classified until a 1963 conference on marine bioacoustics and a paper by Walker (1963). Reports and phonographic recordings became available on bioacoustics and marine mammal sounds [Tavolga (1964, 1965), Hills (1968); a knowledge base of these recorded sounds is available from the Historic Naval Ships Association, Smithfield, VA, USA, http://www.hnsa.org].

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The ambient noise problem was a primary focus of the scientists assembled by the Office of Naval Research under a special project called LRAPP (Long Range Acoustic Propagation Project). This aim of this project was first to develop a quantitative understanding of propagation and noise and second to develop predictive techniques for calculating ambient noise levels in worldwide ocean areas. LRAPP was under the direction of Bracket Hersey and Roy Gaul. Many ambient noise discoveries were either directly or indirectly a consequence of this program. In 1974, Bracket Hersey held an "International Workshop on Low Frequency Propagation and Noise" at the Woods Hole Oceanographic Institution and published three volumes of the proceedings. The first two volumes were available to the general public, the third was not. Selected papers from the third volume were reviewed and included in Carey (2005). Vertical directionality of the noise field was considered important and measurements found in Garabed (2005) are of archival interest because of their scope and relevance to the continuing interest in noise levels and vertical directive effects. Garabed's work was in a band between 200 and 380 Hz and most of the LRAPP work was at less than 1 kHz. Several additional vertical noise measurements were made public [see Urick (1984), Carey and Wagstaff (1986)].

By 1976, multiple summaries, bibliographies, and a vast amount of literature (about 1,500 references) had been published on the measurements, theory, and computational methods; and by the 1980s, ambient noise was the second largest area of underwater acoustics. In 1984, Urick (1984) summarized the main features of ambient noise from the unclassified literature but stated that a vast amount of classified literature existed. In this review, Urick commented on the prolific nature of literature concerning theories of sound generation at the sea surface and the measurements of the temporal and spatial spectral characteristics. The idealized spectra suggested by Urick were in agreement with the schematic proposal by Wenz (1962). The spectral characteristics for frequencies greater than 500 Hz were also consistent with the observations of Knudsen (1948) and Wenz's "rule of fives": "In the frequency band between 500 Hz to 5 kHz the ambient sea-noise spectrum levels decrease 5 dB per octave with increasing frequency, and increase 5 dB with each doubling of wind speed from 2.5 to 40 knots; the spectrum level at 1 kHz in deep water is equal to 25 dB (5 × 5) re 0.0002 dyn/cm^2 when the wind speed is 5 knots, and is 5 dB higher in shallow water." This "rule of fives" can be expressed as follows:

$$
\begin{aligned}
NL(f,U) &= 25 - 10 \cdot \log[f^{5/3}] + 10 \cdot \log[(U/5)^{5/3}] \\
&\textit{or} \\
NL(f,U) &= 25 - (5/3) \cdot 10 \cdot [\log[f] - \log[U/5]]
\end{aligned}
$$

where f is frequency (kHz) and U is wind speed (knots). However, Wenz observed in the 10–500-Hz band the measured noise levels were often variable and dominated by shipping noise. The shape of the spectrum was also found to vary from a positive slope to a steep negative slope.

Kerman (1984) showed that "the amalgamated observations of the ambient noise reveal a similarity structure, both in the acoustical spectrum and wind dependency."

For frequencies greater than the local maximum in the 300–500-Hz range, Kerman found that the normalized measured spectral characteristic was proportional to f^{-2} (6 dB/octave). Furthermore, he showed that the noise intensity was proportional to the cube of the friction velocity (u_*^3) prior to a critical friction velocity (u_{*c}), which is determined by the minimum phase velocity of the gravity–capillary waves. Wave breaking was associated with this critical condition, and for $u^* > u_{*c}$ the noise intensity was found to increase with $u_*^{1.5}$. These observations were found to be consistent with a large number of experimental observations by Perrone (1976) and cited by Kerman. He concluded that the two observed regions of ambient noise wind speed dependency indicated the presence of two sound source generation mechanisms or one mechanism that changes sensitivity. Nevertheless, since breaking waves are known to produce bubbles, spray, splash, and turbulence, combinations of these mechanisms may explain the production of sound at frequencies above 500 Hz. Kerman also observed variability in the low-frequency region below 500 Hz. The low-frequency measurements by Whittenborn (1976) with a vertical array of hydrophones above and below the critical depth of the sound channel also showed a dramatic noise level increase associated with breaking waves.

Naval laboratory researchers considered omnidirectional ambient noise a closed subject and the emphasis was on the statistical characterization of noise observed with directional arrays. Ambient noise was simply unwanted random signals to be discriminated. Knowledge of the statistical properties of this noise was required to determine sonar performance, and Dyer (1970) established a fundamental statistical analysis of the shipping component. Following his approach, Wagstaff (1978) conducted experiments with arrays and characterized the beam noise cumulative distribution functions and its persistent directionality. During this period, ambient noise codes were developed that used archival oceanographic and bathymetric data, range-averaged transmission loss, and the uncorrelated plane wave assumption to estimate the omnidirectional noise and directional array response by means of convolution. The response of an array of hydrophones in the noise field was known to be determined by the space-time correlation properties of the field and hydrophone separation. The difficulty in performing large array experiments and the requisite processing analysis necessitated the use of theoretical treatments and simplified analytical models. Cron and Sherman (1962) developed analytical expressions for these correlation functions assuming ergodic random noise sources for volumetric (isotropic) generated noise and surface-generated noise for directional sources. They recognized the noise field was composed of multiple frequency-dependent components such as distant shipping-generated and local wind-generated noise. General agreement with the simplified analytical treatments was found at the higher (above 400 Hz) frequencies. Cox (1973) examined the correlative properties of temporally stationary and spatially homogeneous (ergodic) noise fields. He employed spherical harmonics and their series expansion to describe the cross-spectral density between two sensors and its wavenumber projection. This formulation was found to agree with experimental measurements and to be useful as a basis for optimal array design. These analytical approaches were necessary since acquisition, processing, and beamformer implementation were largely analog. From the mid

1970s to the early 1990s experimental arrays were constructed and experiments conducted to determine the directional response of these systems in the multicomponent noise field. Carey et al. (1997) published results from the early 1980s featuring the response of horizontal arrays in the ambient noise fields of the Mediterranean. The importance of the evolution from analog systems with wide-band tape recorders, to hybrid analog/digital systems with high-density tape recorders, to digital systems and acquisition is central to the development of the understanding of the directional noise field and its correlative properties.

From 1980 to the early 1990s, renewed research focused on the source mechanisms responsible for ambient noise. Between the 1985 Acoustical Society of America meeting in Memphis Farwell 1985) and the 1997 Sea Surface Sound meeting (Leighton 1997), there were six major conferences stressing recent Russian, European, American, and Chinese work (see "Ambient Noise Reviews and Proceedings"). Important new experimental results were reported concerning the sources of noise and the higher-order properties of the noise fields in deep water, shallow water, the Arctic, the Southern Hemisphere, and coastal Asian waters. Breaking waves and the production of splash, microbubbles and clouds were found to have an important role in ambient noise production as well as the scattering of sound from the composite sea surface. The quantification of rain noise was accomplished theoretically and experimentally.

Naval research was directed toward the accurate large-scale noise-field computations to numerically determine the limit ambient noise places on array performance and underwater communication. In addition, a societal interest in the ambient noise background to which marine mammals are exposed developed. This societal interest stresses the importance of accurately summarizing historical as well as current measurements of oceanic ambient noise, especially the contribution of shipping.

The ambient noise schematic produced by Wenz (1962) (Fig. 1.1) provided a qualitative overview of the frequency-dependent ambient noise omnidirectional levels. This conceptual classification by mechanism, frequency, and Beaufort wind force focused much of subsequent ambient noise research along defined frequency ranges and mechanisms.

Even though this paper and schematic have been widely cited and are indeed descriptive of the qualitative ambient noise field, much progress has been made. For example, in the range of frequencies less than 10 Hz, measurements that agree with the theory of the microseismic noise have been made; in the frequency range from 10 Hz to 1 kHz, the non-wind-dependent noise of Wenz and Knudsen has been replaced by the role of shipping and wind-dependent breaking waves; in the frequency region greater than 1 kHz, the roles of bubbles, spray, splash, and rain have been placed on a quantitative basis.

It is important to note that Wenz wisely used the Beaufort wind force as the metric of ambient noise since it not only includes the 10-m wind speed but also includes the appearance of the sea itself. Investigators largely ignored the role of the atmospheric and near-surface boundary layer after his paper, and gradually wind speed alone became the metric. An important contribution would be the quantification of the environmental variables required to be an integral part of future measurements

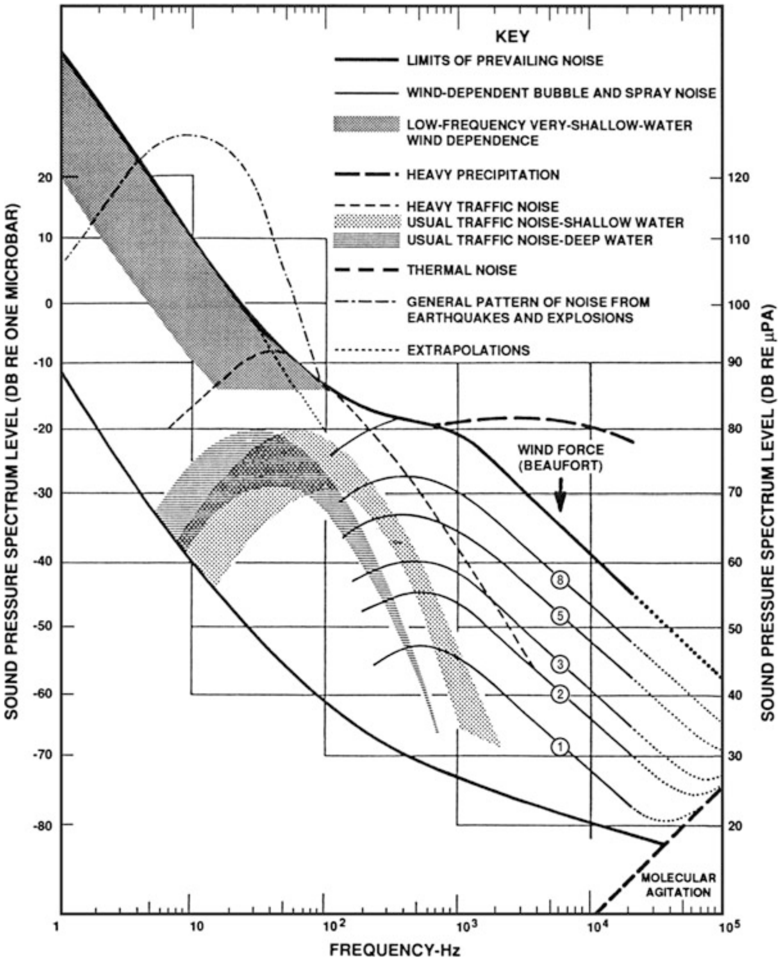

Fig. 1.1 The Wenz curves

necessary to provide quantitative analysis and comparison of experimental results. This is the reason Chapter 2 is on the air–sea interaction zone. The goal was to present a minimal set of parameters to characterize noise measurements. These are the sea state, the Richardson number, and the Reynolds number. It may be possible to use these parameters and satellite observations to provide appropriate environmental knowledge with subsurface noise measurements.

In summary, the literature on this subject is voluminous and beyond the scope of talented scientists to read, understand, and apply. This statement is made in light of the considerable number of and good reviews on this subject of oceanic ambient noise. The questions posed by this state of the art are: "Can a framework be developed for oceanic ambient noise equivalent to the Wenz curve, but based on theoretical descriptions of noise mechanisms supported by experimental evidence?" and "Can the voluminous number of experimental measurements be summarized by a theoretical overview to provide a concise treatment of ambient noise mechanisms?"

This monograph develops a physical understanding of ambient noise mechanisms by coupling analytical treatments of these mechanisms and supporting experimental evidence in a Wenz-like framework of oceanic ambient noise. The air–sea boundary interaction zone and the environmental variables necessary for characterization are treated qualitatively and shown to be important in noise production due to breaking waves. The coherent properties of the ambient noise field are treated on the basis of the radiation from specific mechanisms coupled to the boundary interaction zone. On the basis of the physical realizable mechanisms, the array response, vertical and horizontal, directional noise field characteristics from basin-scale numerical computations presented.

The natural question to be answered is: "What is different in this monograph compared with previous reviews or those works found in conference proceedings?". Certainly an updated Urick (1984) summary would be valuable and necessarily used in developing this monograph. However, this monograph presents not simply a summary of the evidence, but also presents the natural physical-acoustic noise source mechanisms along with the selected but representative experimental results. The ambient noise source mechanisms provide a natural, theoretical framework to discuss and summarize ambient noise measurements. In addition, an example computation of the basin noise field due to surface-generated noise and distributed shipping illustrates the response of an array to the resultant three-dimensional noise field and explains many observed directional noise field characteristics.

The monograph is composed of six chapters followed by ten appendices. The first part of the monograph is written for the acoustical-oceanographer graduate student and researcher. The chapters in this part represent a readable overview of ambient noise measurements and theory focused on natural physical mechanism of noise production. The original monograph was restricted to the archival literature prior to 2000. However, on the recommendation of a reviewer, Chapter 6 was included to discuss contemporary issues in ambient noise research. The importance of bioacoustics and its effects on marine mammals can be found in Richardson and Greene (1995), a detailed treatment of noise impacts, and in Frisk and Bradley (2003), perceived research required to quantify noise impacts

Investigators and students may also be interested in the mathematical basis for many of the phenomena discussed in the first five chapters. These details and derivations are found in the appendices and are included to compensate for the wide-ranging backgrounds of ambient noise researchers. Each appendix contains a separate derivation with appropriate references followed by a summary plate (following the lead of K. Ingard).

For example, the thermal noise limit of the ambient noise simply results from the agitation of the water molecules. The importance of thermal noise to an ambient noise measurement system is first determined by the mean square pressure fluctuation in the water itself and second by the resistive components of the hydrophone amplifier system. The limit of thermal noise is shown in Fig. 1.1. In Appendix F, the thermal noise spectrum is derived by the combination of elemental statistical concepts of the energy density per mode and the density of normal modes in a volume of the ocean. These concepts are related to the literature from statistical physics to room acoustics. This noise places a limit on the detection and measurement of signals in the sea and the minimal detectable plane wave; the result of Mellen (1952) is derived.

Most of the literature on fundamental mechanisms starts with an integral representation of the sources of sound. In Appendix A, these integrals are derived, including the effect of the sea surface (see Appendix G). The application of these source integrals is presented in Chapter 2, where the physical meaning of each is discussed. However, the details are found in the appendices to guide the reader through a general theoretical treatment that encompasses treatments found in the literature.

Appendix B develops from national standards the requisite and the correct quantification of measurements. This appendix was included because there appears to be confusion with the measured noise and its correct reference units. The use of the International System of Units (Système International d′Unités) with logarithmic scales such as the decibel can clarify noise levels in the sea and the societal concern with aquatic life. In short, this appendix answers the question: “What is a deci-bel (decibel)?” Another issue is the correct specification of spectral density and the arcane and inappropriate use of $\sqrt{Hz}$. In preparing this monograph, few changes were made to published results; rather the original figure ordinate and abscissa labels were retained and in several cases clarification is included in the captions.

Sound radiation from splash, that from drops, that from bubbles, and that from bubble clouds are key noise mechanisms at the sea surface. In Appendices C–E and H, suitable expressions are derived to perform calculations and to guide experiments. The result used in the description of these sounds is that they are monopole oscillators below the sea surface, doublets, or point dipoles in the surface. These forms provide a basis for calculations especially when sea surface roughness, sea state, and subsurface microbubble layers are accounted for.

The final two appendices, Appendices I and J, form the basis for computation of the wind-driven noise field and are included to demonstrate the differences in source level determination and representation in computerized codes.

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Chapter 2
The Air–Sea Boundary Interaction Zone

The research problem addressed by ambient noise investigators since the 1950s is the quantitative determination of the sources of sound in the sea. Investigators quickly realized the importance of intermittent sources of sound, compared with the persistent ambient background. Biological noises and nonbiological (including man-made sounds) sources were considered intermittent and predicated on the areas of operation of naval sonar systems. Certainly one would observe a cacophony of noises, grunts, moans, chirps, etc. in shallow water and arctic areas. The crustaceans (shellfish, shrimp), marine mammals (whales, killer whales, and dolphins) and many fish (croakers) produce loud sounds and these can often dominate the ambient noise background (see the suggested bioacoustic references in Chapter 1). Nonbiological sources such as atmospheric storms, seismic disturbances, and the activities of man such as fishing, offshore oilrigs, and airgun surveys have been studied and are also important contributors to the noise field. However, this monograph focuses on the *natural physical mechanisms* of ambient noise that determine the persistent ambient noise background and the properties of the air–sea interaction zone that determine the characteristics of this sound.

The sea–surface interaction zone (Fig. 2.1) is characterized by the wave spectrum, an atmospheric boundary layer, and a subsurface boundary layer. The atmospheric boundary layer, the marine layer, depends on the roughness of the surface determined by the sea state spectrum, thermal stability, humidity flux, and wind speed. The subsurface layer depends on the thermal stability, suborbital wave motions, and turbulence below the sea surface but also on the presence of microbubble layers and clouds. Indeed, this complex situation is difficult to characterize experimentally because of lack of knowledge of the boundary layer characteristics, which are difficult to characterize theoretically. Nevertheless, a qualitative description of this interaction zone is possible.

As shown in Fig. 2.1, the interaction zone basically is composed of two-phase turbulent layers: spray splash and air above, with bubble clouds, critters, and water below. The general problem for the air–sea layer is the characterization of the state of the sea and the velocity profile above the rough moving sea surface. The problem in the subsurface layer is the characterization of the convection and the presence of microbubbles as a function of sea state and water column stability.

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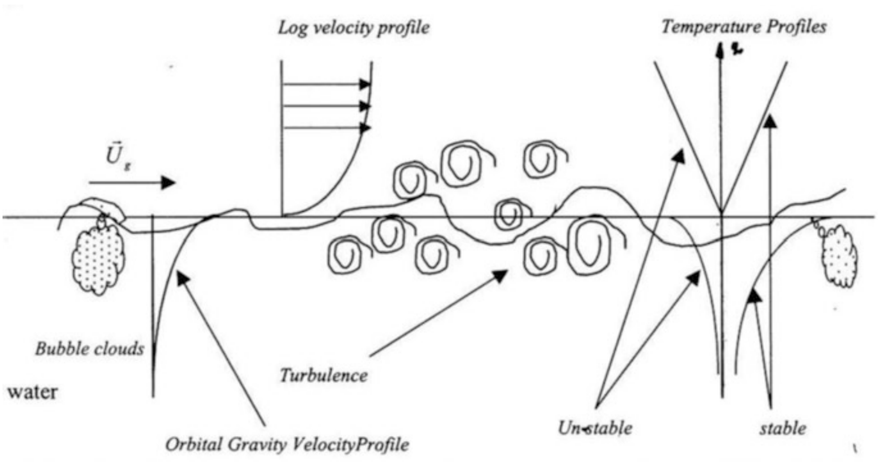

Fig. 2.1 The air–sea interaction zone

The Marine Boundary Layer

The state of the sea has long been a subject of interest for the mariner. Table 2.1 shows the Beaufort scale along with the Hydrographic Office and international scales. Bowditch's *The American Practical Navigator* (Bowditch (1966)) has been widely used in this regard. A key feature of the Beaufort scale is the combination of the visual appearance of the sea surface as well as the wind speed. The visual observations reflect the understanding that the sea state spectrum, fetch, and various near-surface conditions can have a drastic effect on the real state of the sea. Needless to say, the judgment as to the state of the sea can vary from one observer to the next and consequently one would prefer a standard measurement such as wind speed, water temperature, air temperature, or humidity.

As stated previously, the air–sea interaction zone is composed of two turbulent layers, each layer containing multiple unique features. The basic question is what simplification can be made to characterize the complex zone to adequately parameterize the production of sound; can an analytical model with measured parameters describe the state of this zone and parameterize the production of sound? Wenz in his classic paper wisely chose the Beaufort scale (Table 2.1) with its reliance on wind speed, wave height, and appearance of the sea surface, as the parameterization. This choice incorporates the combined effects of mass, momentum, and heat transfer.

One choice is the selection based on empirical evidence of the logarithmic velocity profile of the marine surface layer. Would a measurement of the wind speed at a reference height, 10 m, and a logarithmic velocity profile be an adequate parameterization of this complicated interaction zone? Experience shows to first order that wind speed is a good descriptor and is widely used; but could the exclusive use of the wind speed descriptor also account for much of the noise variability observed?

Table 2.1 The Beaufort scale

Beaufort number	Wind speed				Seaman's term	World Meteorological Organization (1964)	Estimating wind speed	
	knots	mph	meters per second	km per hour			Effects observed at sea	Effects observed on land
0	under 1	under 1	0.0–0.2	under 1	Calm	Calm	Sea like mirror.	Calm; smoke rises vertically.
1	1–3	1–3	0.3–1.5	1–5	Light air	Light air	Ripples with appearance of scales; no foam crests.	Smoke drift indicates wind direction; vanes do not move.
2	4–6	4–7	1.6–3.3	6–11	Light breeze	Light breeze	Small wavelets; crests of glassy appearance, not breaking.	Wind felt on face; leaves rustle; vanes begin to move.
3	7–10	8–12	3.4–5.4	12–19	Gentle breeze	Gentle breeze	Large wavelets; crests begin to break; scattered whitecaps.	Leaves, small twigs in constant motion; light flags extended.
4	11–16	13–18	5.5–7.9	20–28	Moderate breeze	Moderate breeze	Small waves, becoming longer; numerous whitecaps.	Dust, leaves, and loose paper raised up; small branches move.
5	17–21	19–24	8.0–10.7	29–38	Fresh breeze	Fresh breeze	Moderate waves, taking longer form; many whitecaps; some spray.	Small trees in leaf begin to sway.
6	22–27	25–31	10.8–13.8	39–49	Strong breeze	Strong breeze	Larger waves forming; whitecaps everywhere; more spray.	Larger branches of trees in motion; whistling heard in wires.
7	28–33	32–38	13.9–17.1	50–61	Moderate gale	Near gale	Sea heaps up; white foam from breaking waves begins to be blown in streaks.	Whole trees in motion; resistance felt in walking against wind.
8	34–40	39–46	17.2–20.7	62–74	Fresh gale	Gale	Moderately high waves of greater length; edges of crests begin to break into spindrift; foam is blown in well-marked streaks.	Twigs and small branches broken off trees; progress generally impeded.
9	41–47	47–54	20.8–24.4	75–88	Strong gale	Strong gale	High waves; sea begins to roll; dense streaks of foam; spray may reduce visibility.	Slight structural damage occurs; slate blown from roofs.
10	48–55	55–63	24.5–28.4	89–102	Whole gale	Storm	Very high waves with overhanging crests; sea takes white appearance as foam is blown in very dense streaks; rolling is heavy and visibility reduced.	Seldom experienced on land; trees broken or uprooted; considerable structural damage occurs.
11	56–63	64–72	28.5–32.6	103–117	Storm	Violent storm	Exceptionally high waves; sea covered with white foam patches; visibility still more reduced.	Very rarely experienced on land; usually accompanied by widespread damage.
12 13 14 15 16 17	64–71 72–80 81–89 90–99 100–108 109–118	73–82 83–92 93–103 104–114 115–125 126–136	32.7–36.9 37.0–41.4 41.5–46.1 46.2–50.9 51.0–56.0 56.1–61.2	118–133 134–149 150–166 167–183 184–201 202–220	Hurricane	Hurricane	Air filled with foam; sea completely white with driving spray; visibility greatly reduced.	

To examine this question, a discussion of the logarithmic profile and its application to the marine boundary is required.

The Viscous Sublayer

Flow over a smooth plate requires the velocity of the fluid to be zero at the surface of the plate. The change in average fluid velocity, $\bar{u}(z)$, with distance from the plate must be determined by the tangential shear stress. Newton's law of molecular viscosity states

$$\tau = \mu\, d\bar{u}(z)/dz = \rho\, \nu\, d\bar{u}(z)/dz. \tag{1}$$

At the interface this stress is referred to as the wall shear stress, τ_w, and one can readily see by use of a Taylor series since $\bar{u}(o) = 0$ that

$$\bar{u}(z) = \bar{u}(o) + (\partial\bar{u}/\partial z)_o z + \ldots\ldots \approx (\partial\bar{u}/\partial z)_o z = (\tau_w/\rho)(z/\nu) = u_*^2\, \delta_\nu. \tag{2}$$

In this expression u_* is the friction velocity at the surface and δ_ν is the thickness of the viscous sublayer. The relative importance of this viscous sublayer to the marine boundary layer can be determined by use of the Reynolds number (R_e), the ratio of the inertial forces (mechanical turbulence in the layer) to the viscous forces. This number can be expressed as $R_e = L_c\bar{u}/\nu$, where L_c is the height of the marine layer (about 10–50 m), $\bar{u}$ is the mean velocity of the air at a distance of (10 m) from the air–sea interface, and ν is the fluid viscosity (about 0.002 m^2/s); the resulting Reynolds number is 5×10^4, indicating turbulent flow. Since the corresponding viscous boundary layer thickness is (10^{-3} m) much less than L_c, simple flat plate theory will by itself not be useful in describing the marine layer. However, the presence of mechanical, buoyancy, heat transport and mass transport, and sea surface motion effects can alter the near-surface profile.

Mechanical Turbulence

One may account for the mechanical turbulence by using a coefficient of eddy viscosity, K_m, and treating the region between a reference distance near the interface, z_o, and the observed height of the turbulent layer.

$$\tau = \rho(\nu + K_m)d\bar{u}(z)/dz \cong \rho K_m d\bar{u}(z)/dz \qquad z_o < z < L_c \tag{3}$$

The resulting shear stress at the z_o reference condition becomes $\tau_o = \rho K_m(\partial\bar{u}/\partial z)_{z_o}$.

The coefficient of eddy viscosity is known as the "austausch" or exchange coefficient, $A=\rho\, K_m$. Since the goal is to find the velocity profile, observe that $d\bar{u}/dz$ depends on the parameters ν, z, ρ, and τ_o. The π theorem states that with these five dimensional parameters and three fundamental dimensions, two nondimensional ratios can be derived as follows:

$$\begin{gathered} u_* = \sqrt{(\tau_o/\rho)},\ \textit{the friction velocity and the nondimensional ratios} \\ (d\bar{u}/dz)(z/u_*) \quad and \quad zu_*/\nu. \\ \textit{Dimensionless analysis yields} f_o((d\bar{u}/dz)(z/u_*), zu_*/\nu) = 0 \\ or \quad d\bar{u}/dz = (u_*/z)f_1(zu_*/\nu). \end{gathered} \tag{4}$$

The friction velocity, u_*, is necessary to determine the velocity profile. When the distance to the interface is small, such that all roughness elements are less than the reference distance $z_{o\nu}$, (see Fig. 2.2), the viscous effects determine the profile, and R_e is of order 100, then $z_{o\nu}$ is of order 1 mm and can only represent a smooth surface or completely still water. When the surface roughness is much larger than $z_{o\nu}$, z_o is chosen sufficiently large enough to contain the surface roughness, as shown in Fig. 2.2; the larger-scale mechanical eddies dominate and the quantity f_1 needs to be determined. Recognizing the weak dependence of f_1 on zu_*/ν when the reference distance (z_o) is larger than the roughness (h_s) of the interface, one takes the f_1 function to be a constant, $1/\kappa$, where κ is von Kármán's constant. It then follows that

$$\begin{aligned} & d\bar{u}/dz = (u_*/z)(1/\kappa) \\ & \rightarrow \quad u(z) \cong (u_*/\kappa)ln(z/z_o); \ \ \bar{u}(z_o) = 0 \quad h_s < z_o < z < L_c \end{aligned} \tag{5}$$

In Eq. (5), the no-slip condition has been applied at the reference distance, $\bar{u}(z_o) = 0$, with $z_o > h_s$, the roughness distance. With a slight modification of the logarithmic argument, $((z-h_s)/h_s)$, the no-slip condition can be applied at the actual interface, but the distance, z_o, is small compared with the height of the marine layer and this modification has no practical importance.

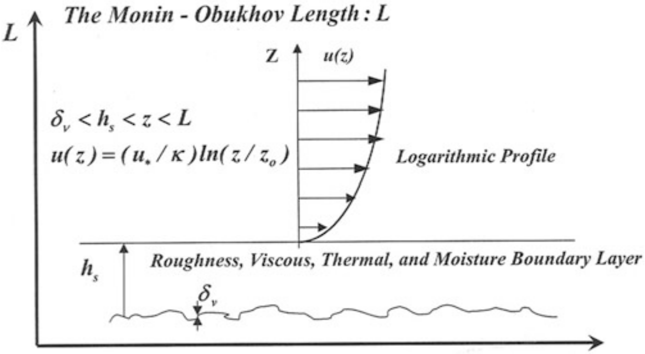

Fig. 2.2 The marine boundary layer for turbulent flow over a rough sea surface

The Effect of Buoyancy

The viscous sublayer and the mechanical turbulence discussed thus far should be augmented by the incorporation of buoyancy effects. Mechanical turbulence is, by its nature, adiabatic, whereas buoyancy, by its nature, is diabatic and dependent on the vertical temperature variation, the lapse rate. When an air parcel is vertically displaced adiabatically, its volume will change in agreement with the ideal gas law, the adiabatic lapse rate. The buoyancy force for such a displacement is the difference between the parcel mass, $M_{p,}$ and the displaced mass, $M_{a,}$ times the gravitational acceleration (g):

$$\begin{aligned} &F_b = g(M_a - M_p) = gV(\rho_a - \rho_p) = a_b M_p \\ &where\ \rho_a, \rho_p \text{ are the densities and } p/\rho = RT. \\ &\rightarrow a_b = g(\rho_a - \rho_p)/\rho_p = g(T_p - T_a)/T_a \end{aligned} \tag{6}$$

The buoyancy force yields buoyancy acceleration, a_b, the sign of which determines whether the force is positive, that is, upward, or negative, that is, downward. The adiabatic lapse rate, $\mathit{\Gamma}$, is thus the temperature change required by the decrease in pressure to maintain neutral buoyancy. The diabatic lapse rate, γ, is determined by the change of temperature resulting from volume change and heat exchange with the surrounding air. Expanding the temperatures in the above expression in a Taylor series about an equilibrium condition gives

$$a_b = g(\partial T_p/\partial z - \partial T_a/\partial z)\Delta z/T_a = g(\gamma - \mathit{\Gamma})\Delta z/T_a. \tag{7}$$

This equation shows the importance of the adiabatic lapse rate, Γ; when one has an adiabatic condition $\gamma = \mathit{\Gamma}$, a characteristic of the temperature stratification. When a diabatic lapse rate, γ, exists and normally it does, the buoyancy force can strongly affect the turbulence that occurs in the atmosphere when the production of turbulent energy by the wind stress is just large enough to counter the consumption by the buoyancy force.

This ratio of the consumption of turbulent energy by the buoyancy force to the production of turbulent energy by the wind stress is the Richardson number, R_i. If $\Delta z=1$, then

$$a_{bd} = g(\gamma - \Gamma)/T_a = (g/T_a)d\Theta/dz \tag{8}$$

and one has four fundamental quantities – $d\bar{u}/dz$, $d\Theta/dz$, g, and T_a – with three fundamental dimensions, so one nondimensional variable can be formed:

$$R_i = (g/T_a)\cdot\frac{d\Theta/dz}{(d\bar{u}/dz)^2} = (g/T_a)\cdot\frac{(\gamma - \Gamma)}{(d\bar{u}/dz)^2} \quad . \tag{9}$$

The importance of the adiabatic lapse rate and the relative importance of the diabatic lapse rate are observed. The quantitative values of the lapse rates are not as important