Table 17.3 Neutral Drag Coefficients over the Ocean[a]

Source	Wind speed range (m s^{-1})	$C_{DN}(10)$ range ($\times 10^3$)	Comments
A. Miller (1964)	17–52	1.0–4.0 (linear)	Hurricanes Donna and Helene—ageostrophic
B. Hawkins and Rubsam (1968)	23–41	1.2–3.6 (discontinuous)	Hurricane Hilda—ageostrophic
C. Riehl and Malkus (1961)	15–34	2.5	Held constant to achieve angular momentum balance
D. Palmén and Riehl (1957)	5.5–26	1.1–2.1 (linear)	Composite Hurricane data—ageostrophic
E. Kunishi and Imasoto (see Kondo, 1975)	14–47.5	1.5–3.5	Wind flume experiment
F. Ching (1975)	7.5–9.5	1.5	Vorticity and mass budget at BOMEX

a. Taken from the literature, for hurricane and vorticity-mass-budget data analyses. Also included are wind flume data of Kunishi and Imasoto (see Kondo, 1975). [After Garratt (1977), who compiled and evaluated the source material.]

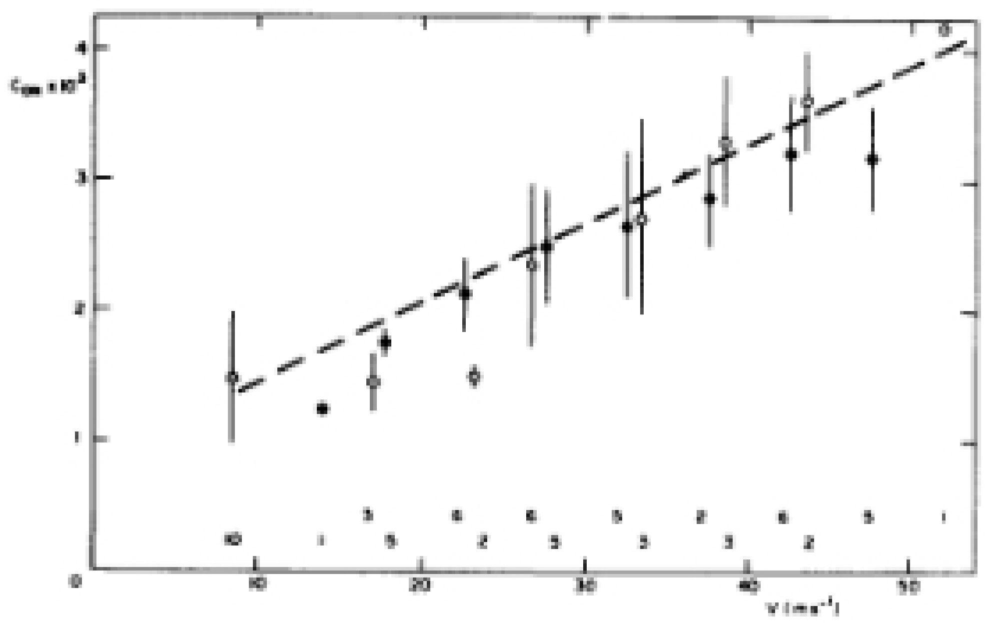

Figure 17.3 Mean values of the neutral drag coefficient as a function of wind speed at 10-m height for 5-m-s^{-1} intervals, based on individual data from hurricane studies (○), wind flume experiment (●), and vorticity mass budget analysis (△)—see table 17.3. Vertical bars as in figure 17.2. The number of data contained in each mean is shown below each mean value, and immediately above the abscissa scale. The dashed curve represents the variation of $C_{DN}(10)$ with V based on $z_0 = \alpha u_*^2/g$ with $\alpha = 0.0144$. (Garratt, 1977.)

Although our knowledge of the complicated processes in the interfacial layer is very unsatisfactory, we can, by using similarity theory and empirical knowledge of z_0, z_θ, etc., derive formulas from which the surface fluxes can be estimated from ships' observations in the near-surface layer of, say, temperature, humidity, and wind speed at a known height, together with sea-surface temperature. The errors in such estimates will be considerable, but they are more likely to be due to the errors in the ships' observations than to deficiencies in the formulas.

Calculations of the fluxes from climatological data [Jacobs (1951), Privett (1960), Budyko (1956), and more recent work by Bunker (1976) and Saunders (1977)] are of great value even though their accuracy is limited by the low precision of the ships' observations and by lack of uniformity of their cover of the ocean. They are thought unlikely to provide estimates from which the poleward heat transport by the ocean can be deduced, but will be useful in attempts to interpret the work of Oort and Vonder Haar (1976).

17.4 Waves

The most obvious effect of the wind on the sea is the generation of waves. They have been much studied, for there is no doubt of their economic importance: the design of ships, of harbors, and of sea defenses all need estimates of the waves to be encountered, to say nothing of the questions raised by the reflection of sound and light at the sea surface.

What is less obvious is how they fit into the coupled mechanics of the ocean and the atmosphere—how the winds and currents would differ if by some magic device the surface waves were eliminated. The drag coef-

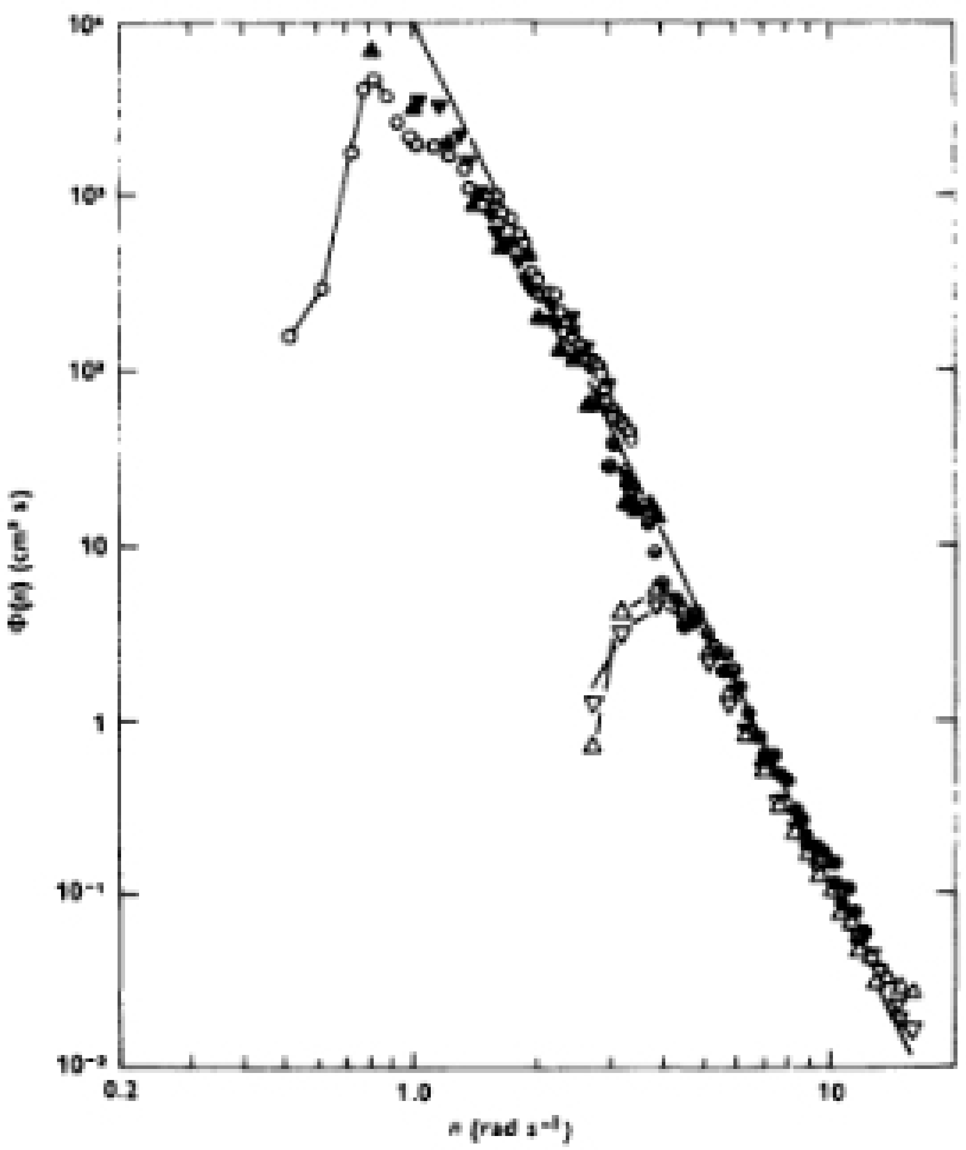

Figure 17.5 The equilibrium range of the frequency spectrum of wind-generated waves. The logarithmic vertical scale covers six decades. The shape of the spectral peak is included in only three cases; otherwise only the saturated part of each spectrum is shown. Key to measurements:

○	Stereo-Wave Observation Project (Pierson, 1960)	floating wave spar	1 spectrum
▲	Longuet-Higgins et al. (1963)	accelerometer	1 spectrum
▼	DeLeonibus (1963)	inverted fathometer	Mean of 6 spectra
△	Kinsman (1960) November series	capacitance probe	Mean of 16
▽	Kinsman (1960) July series	capacitance probe	Mean of 16
●	Burling (1959)	capacitance probe	Mean of 11
⊖	Walden (1963)	probe and cinematograph	1 spectrum

[After Phillips (1977a), who compiled and plotted the original observations.]

that it grew faster than would be expected, for the spectrum as a whole, from linear theory.

The frequency of the spectral peak is clearly an important descriptor of the wave field. Its value for Burling's, the JONSWAP, and other observations is shown in figure 17.7 (from Phillips 1977a). The values are again plotted in the nondimensional form suggested by Kitaigorodskii. It is perhaps worth noting that if L_0, the wavelength at the spectral peak, be given by $L_0 n_0^2 = 2\pi g$, then

$$L_0 = 1.3 u_*(X/g)^{1/2}$$
$$\approx 100\zeta, \qquad (17.18)$$

consistent with the bulk of the energy being in the equilibrium n^{-5} range.

As a result of the many observations of waves we now have reasonably clear information on the evolution of the surface wave field in deep water, at least so far as the frequency spectrum is concerned. Directional spectra are more difficult to measure and information is correspondingly sparse.

17.4.2 The Energy and Momentum Balance of the Wave Spectra

The main purpose of the JONSWAP project was to determine the source function in the spectral equation for the energy balance

$$\frac{\partial E}{\partial t} + v_{gi}\frac{\partial E}{\partial x_i} = S. \qquad (17.19)$$

E is the wave energy and v_{gi} the component of the appropriately generalized group velocity in the direction of coordinate x_i. The basic result is shown schematically in figure 17.8, where the source function S is seen to have a characteristic positive-negative shape.

The source function at a particular frequency is made up of three components—the energy transferred to the waves by the wind, the energy dissipated, and the energy transferred from other regions of the spectrum.

The spectral representation used is based on a superposition of sinusoidal waves traveling independently. But the hydrodynamic equations are nonlinear and the linear approximation is only valid when the wave slope is small, i.e., when the accelerations are small relative to the acceleration of gravity.

To treat the nonlinear terms, one substitutes the linear solution into the nonlinear terms, to get a second-order solution with terms in the wave slope. Higher-order solutions have terms in $(\text{slope})^2$, $(\text{slope})^3$, and so on. The primary waves are sinusoidal and the second approximation has sharper crests and flatter troughs. One gets terms involving products of pairs of primary waves, which produce secondary waves at their sum and difference frequencies.