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Turbulence Measurements of Wind, Temperature and Humidity Over the Ocean

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ABSTRACT

Turbulent properties of wind velocities, air temperature and humidity were measured onboard the R/V Ocean Researcher III over the southern Taiwan Strait and on an offshore platform in shallow waters near Taichung. The longitudinal wind turbulence level and gust factor were found to remain constant at different wind speeds, but these values appeared to increase as the surface roughness increased. Thermal and humidity turbulence levels under unstable conditions depended on the stability parameter $|Z/L|$, where Z is the measurement height and L the Monin-Obukhov length. Spectra of wind speed, air temperature and humidity fluctuations showed the existence of an inertial subrange. Wind stress derived using the inertial-dissipation method was somewhat larger than that obtained using the eddy-correlation method. Transfer coefficients of momentum, heat and water vapor, were found to be functions of wind speed and stability parameter, and their empirical formulae and relationships are presented in this paper.

Key Words: turbulence level, stability parameter, transfer coefficient

I. Introduction

Wind is a widespread and important phenomenon for mankind. This topic deserves more attention especially in monsoon prevalent areas such as the island of Taiwan. The knowledge of turbulent wind characteristics and spectra of wind fluctuations in the atmospheric surface layer are required in studies of aircraft safety and the design of large buildings, bridges, power lines and marine structures. Similarly, temperature and humidity fluctuations also play an important role in determining the optical refractive index and, consequently, the performance of microwave communication systems. Extensive research has been conducted on the turbulent properties of wind over land during the past several decades, and the results were nicely reviewed by Liu (1991). On the other hand, studies on turbulent properties and the spectra of wind, temperature and humidity over the sea have been rather scarce (Shiotani, 1975; Smith and Anderson, 1984). Whether turbulent wind properties over a sea behave differently from those over land surfaces remains an open question, and more experimental data are definitely needed.

Turbulent fluxes of momentum (wind stress), heat and water vapor are produced by joint interaction of a vertical wind component and the corresponding properties of longitudinal wind velocity, temperature and humidity. Turbulent fluxes across a sea surface are of great importance to various aspects of physical oceanography and ocean engineering. For instance, wind stress is the main driving force of the coupled ocean-atmosphere model and is closely associated with sea-surface dynamics, such as wind-drift surface currents, microwave remote sensing of the ocean surface and the dispersion of pollutants in marine environments (Kraus and Businger, 1994).

In this study we have obtained measurements of turbulent properties of wind, temperature and humidity onboard a research vessel over open ocean and on an offshore platform over shallow coastal waters. The measurements enable us to study the seasonal variations of wind characteristics and turbulent fluxes over the ocean, and comparisons of the results of this study with previously published results over land and sea surfaces can also be made.

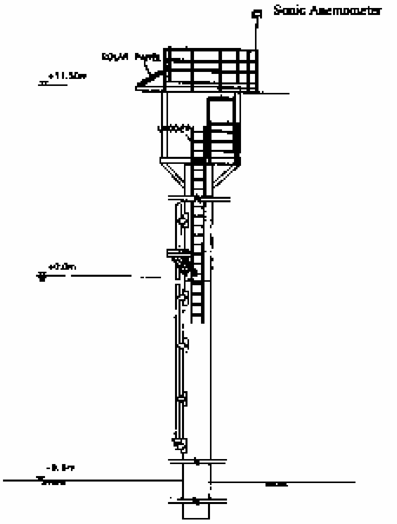


Fig. 1. Plan view of the Taichung research platform and the instrumentation.

II. Experiments

1. Offshore Platform

A stable research platform, about 2 km from the shore, is located in coastal waters off Taichung harbor. At the location of the platform, the mean water depth is about 8m, and the tidal range is 4~5m. Three-dimensional wind speed fluctuations and air temperature were measured using a fast-response Solent sonic anemometer. The sonic probe head, mounted on the rail of the platform, had an elevation of 12.2 m above the mean sea surface (Fig. 1). The sea-surface temperature was measured using a nearby moored current meter. Analog signals from the sonic sensor were digitized by an A/D converter at a sampling rate of 10 Hz. The signals were then converted to frequencies and transmitted by radio telemetry to an onshore receiving station. The data were collected and stored in a PC in runs of 20-minute duration every 2 hours. During the winter season, this site is strongly influenced by a prevailing northeastern monsoon; therefore, the platform is exposed to the maximum upwind fetch for winds ranging in direction from northwesterly to northeasterly. Similarly, this platform is also influenced by a prevailing southwestern monsoon during the summer season. Five series of data sets from December 1994 to November 1995 were analyzed and are presented in this paper (Table 1).

Table 1- Taichung Platform Data

series	period	number of runs
1	Dec. 1994	76
2	May 1995	84
3	June 1995	[illegible]
4	Oct. 1995	241
5	Nov. 1995	214

2. Ship Measurements

Turbulence measurements of wind, temperature and humidity were extended to more open ocean conditions in a second experiment conducted from the R/V Ocean Researcher III during its four patrols in the southern Taiwan Strait from June 1995 to March 1996. A sonic anemometer (Kaijo, DA-600) was used to measure the three-dimensional wind speed, direction and air temperature. The water vapor density was measured using an infrared differential absorption hygrometer (Analytic Applications, M100). Both sensors were mounted at 9.5m above mean sea level on a mast fixed over the ship's upperdeck (Fig. 2). The mean air-temperature and relative humidity were also logged using a hand-held psychrometer during the cruise. Sea temperatures were obtained from bucket thermometer readings.

Analog signals from the sonic anemometer and the hygrometer were low-pass filtered at 22 Hz and then recorded at a 40 Hz sampling rate in a PC. The duration of the data runs was 16 minutes. The most useful data were obtained as the ship steamed into the wind at <3 knots. In such cases, the winds were over the bow, indicating that the ship did not seriously distort the mean flow. Data from four cruises were used in this paper (Table 2): the first data set (June 1995) was obtained mostly in stable atmospheric conditions and the others were obtained in unstable conditions. The experiment in each cruise lasted two days.

III. Results and Discussion

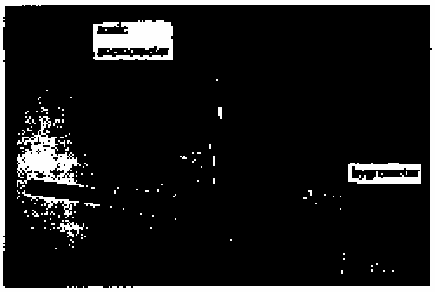
1. Gust Factor and Turbulence Level

A gust is a rapid fluctuation or instantaneous velocity of wind. Peak gusts of short duration are important in designing the wind load of large structures

Table 2. Ship Data

series	period	number of runs
1	June 1995	45
2	Nov. 1995	36
3	Jan. 1996	44
4	March 1996	71

(a)



(b)

Fig. 2. (a) R/V Ocean Researcher III. (b) sensors above the instrumentation mast.

over an ocean. The shorter the gust duration, the higher the peak gust velocity will be (Liu, 1991). The gust factor, defined as the ratio of the gust speed based on a 1-second average to the mean wind speed, is shown in Fig. 3 in relation to the mean wind speed for three different conditions. In shallow waters over the Taichung platform, the gust factors during the summer monsoon (Fig. 3(a)) and the winter monsoon (Fig. 3(b)) appear to be independent of the wind speed and have an average value of about 1.21. Over more open ocean conditions from ship measurements during the winter

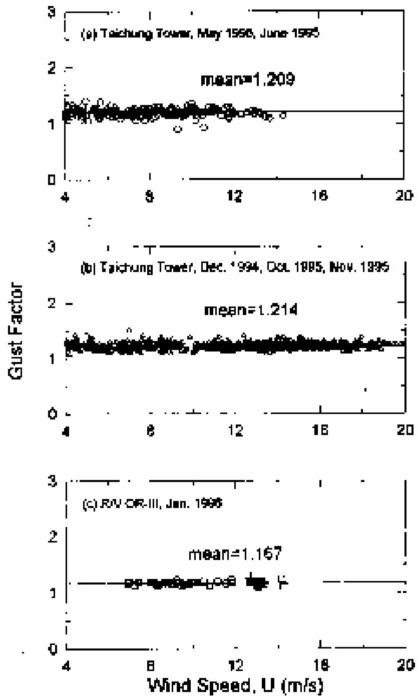


Fig. 3. Variation of the gust factor with wind speed for cases of (a) platform experiments, May and June 1995. (b) platform experiments, Dec. 1994, Oct. and Nov. 1995. (c) ship measurements, Jan. 1996.

monsoon (Fig. 3(c)), the gust factor is slightly smaller (~1.17). Note that the mean wind speed is based on a 20-minute average and a 16-minute average, respectively, for the Taichung platform and ship wind experiments. The average gust factor in Fig. 3(c) will increase somewhat if the record length is corrected from 16 minutes to 20 minutes (Myers *et al.*, 1969) and can be considered as being no different from those factors in Fig. 3(a) and (b). The roughness length Z_0 calculated from the flux-profile relationship of the wind speed is approximately 0.1 cm–0.5 cm from our data. Liu (1991) and Ashcroft (1994), on the other hand, also reported that for smooth, open terrains (Z_0~3.5 cm), the gust factor is on the order of 1.5 and that for rough terrains such as urban and large cities, the gust factor should be even greater. This is consistent with the

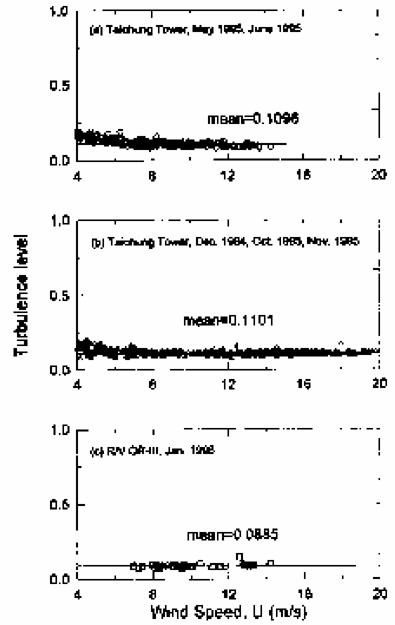


Fig. 4. Variation of the turbulence level with wind speed for cases of (a) platform experiments, May and June 1995, (b) platform experiments, Dec. 1994, Oct. and Nov. 1995, (c) ship measurements, Jan. 1996.

conclusion of Ashcroft (1994) that the gust factor increases with increasing terrain roughness. The present study which was conducted over the ocean provides valuable data set and greatly extends Ashcroft's curve (Ashcroft, 1994) of Fig. 7 to regions of smaller roughness length. However, the effects of thermal stability and the weather system on the gust factor should also be examined before any firm conclusions can be reached.

The turbulence level or relative intensity of turbulence, defined as the root-mean-square value of the longitudinal wind speed u' (the primed symbol represents fluctuations about a mean value) divided by the mean wind speed, is plotted against the mean wind speed in Fig. 4 for three different conditions as in Fig. 3. Similar conclusions can be drawn from Fig. 4 compared to those from Fig. 3. The turbulence level has a higher value (~0.11) in shallow waters over the Taichung platform (Fig. 4(a) and (b)) and a slightly lower value (~0.09) over the open ocean (Fig. 4(c)); both are smaller than that in inland terrain (~0.133) where the roughness is larger (Liu, 1991).

In the case of smaller wind velocities and larger sea-air temperature differences, the marine atmosphere is in unstable conditions, and the buoyancy effect is more significant. Free convection tends to occur more easily in this case. Smith and Anderson (1984) have investigated thermal and humidity turbulence levels in an unstable atmospheric surface layer over a beach near the waterline during periods of onshore winds. They have found that their experimental data agreed well with the free-convection laws:

$$\sigma_T/T_* = -\alpha_t(-Z/L)^{-1/3}$$

$$\sigma_Q/Q_* = -\alpha_q(-Z/L)^{-1/3}, \qquad (1)$$

where σ_T and σ_Q are thermal and humidity turbulence intensities, respectively, T_* and Q_* are surface scales corresponding to the fluxes of temperature and humid-

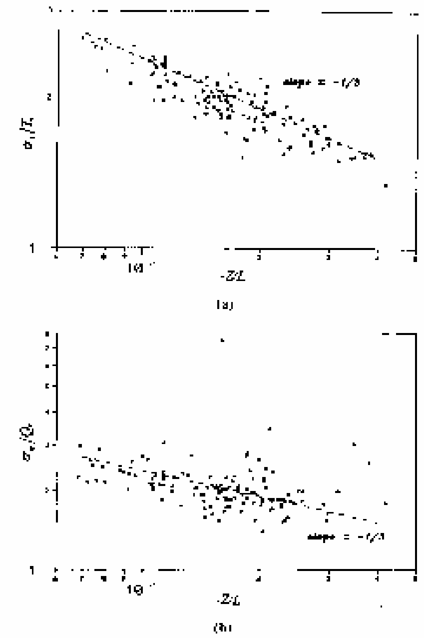


Fig. 5. (a) Thermal turbulence level σ_T/T_* and (b) humidity turbulence level σ_Q/Q_* as a function of stability Z/L for ship data under unstable conditions. Dotted line is Eq. (1).

ity, a_t and a_q are constants to be determined from experimental data. Z is the measurement height and L is the Monin-Obukhov length, defined as $L=-u_*^3 T_v(\kappa g \overline{w't_v'})^{-1}$, where u_* is the friction velocity, T_v is the virtual temperature of the air, κ=0.4 is the von Karman constant, g is the gravitational constant and w is the vertical wind speed component (Hsu, 1988). We have plotted in Fig. 5 σ_T/T_* and σ_Q/Q_* with respect to the stability parameter $|Z/L|$ for ship data with unstable atmospheric conditions. The constant a_t determined from Fig. 5(a) is 1.07±0.07, which is similar to that reported by Smith and Anderson (1984). On the other hand, the data points in Fig. 5(b) are somewhat scattered. The constant a_q determined in this study is 1.14±0.33, which is somewhat greater than that reported by Smith and Anderson (1984). Since there have been relatively few studies on humidity spectra and humidity turbulence levels over oceans, more research in this area is needed to clarify this difference.

2. Spectral Characteristics

Wind, temperature and humidity data were demeaned, and spectral analysis was performed on 8192 and 32768 samples for platform and ship data, respectively. The spectral estimates were averaged in logarithmically spaced frequency bands between 0.0012 Hz and the Nyquist frequency (5 and 20 Hz for platform and ship experiments, respectively). Figure 6(a)-(d) show typical examples of platform wind spectra, ship wind spectra, ship temperature spectra and ship humidity spectra, respectively. Note that the ship data were low-pass filtered before digitization to avoid energy folding back from the higher frequency part of the spectra while platform data were not low-pass filtered due to limitations on the equipment and power supply available on the platform. It can be seen in Fig. 6 that a frequency band of the inertial subrange exists which has a spectral slope of −5/3. The inertial subrange is less clearly visible in the platform wind spectra owing to the lack of a low-pass filtering process as mentioned earlier. The portion of the spectrum with constant $f^{5/3}\Phi_u(f)$ (or $\Phi_t(f)$, $\Phi_q(f)$) typically occurs above 0.5 Hz for ship data and above 0.05 Hz for platform wind data, where f is the frequency and Φ is the spectral values. In the spectra of ship data, there was often a wave-frequency peak at 0.1~0.3 Hz due to dominant waves or ship motion. The temperature spectra from the platform experiments did not show the existence of an inertial subrange for reasons which remain unclear, and the results will not be discussed in this paper.

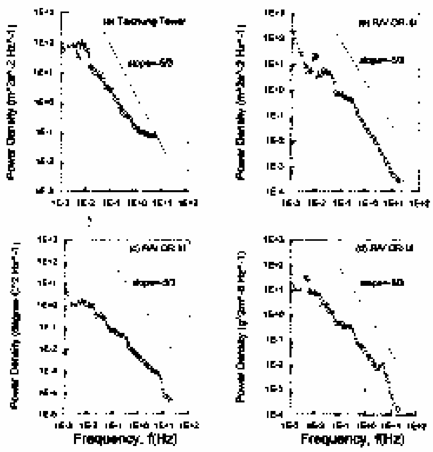


Fig. 6. Typical examples of (a) wind spectra, platform experiment, (b) wind spectra, ship measurement, (c) temperature spectra, ship measurement, (d) humidity spectra, ship measurement. The line is the $f^{-5/3}$ slope.

3. Stress Estimates and Transfer Coefficients

In this study, we used the eddy-correlation method, the inertial-dissipation method and the bulk method to estimate turbulent fluxes. A brief description of these methods follows. The eddy-correlation method is the most direct method for flux estimation. In the surface layer, the turbulent fluxes of the momentum τ, sensible heat H_S and latent heat H_L are nearly independent of height and can be expressed as (Hsu, 1988)

$$\tau=-\rho\overline{u'w'}$$

$$H_s=\rho C_p\overline{w'T'}$$

$$H_L=L_E\overline{w'q'}\,, \qquad (2)$$

where ρ is the air density, C_P is the specific heat of air and L_E is the latent heat of vaporization. The overbar symbol denotes the time averaging process.

The inertial-dissipation method can be further extended to moving and unsteady platforms such as ships and buoys. Assuming isotropic turbulence, it is then argued from the Kolmogoroff hypothesis that there is an inertial subrange of frequencies where a cascade of turbulent energy exists between a source region (lower frequencies) and a dissipation region (higher frequencies). It is then possible to obtain the rate of molecular dissipation of turbulent kinetic energy (ε), the diffusive dissipation rate of the temperature variance (N_t) and water vapor density variance (N_q) from $\Phi_u(f)$, $\Phi_t(f)$ and $\Phi_q(f)$. Assuming that the vertical divergence terms in the equations of the scalar variance budgets can be neglected, Large and Pond (1981) found that eddy fluxes were given by

$$-\overline{u'w'}=(\kappa Z\varepsilon)^{2/3}[\phi_m(Z/L)-Z/L]^{-2/3}$$

$$\overline{w't'}=[\kappa Z u_* N_t/\phi_t(Z/L)]^{1/2}$$

$$\overline{w'q'}=[\kappa Z u_* N_q/\phi_q(Z/L)]^{1/2}, \quad (3)$$

where $\phi_m(Z/L)$, $\phi_t(Z/L)$ and $\phi_q(Z/L)$ are the dimensionless vertical gradient of wind speed, temperature and humidity, respectively. The expressions of Large and Pond (1982) are adopted in this study:

$$\phi_m(Z/L)=\phi_t(Z/L)=\phi_q(Z/L)=1+7Z/L \quad \text{stable, } Z/L>0$$

$$\phi_m(Z/L)=(1-16Z/L)^{-1/4} \quad \text{unstable, } Z/L<0$$

$$\phi_t(Z/L)=\phi_q(Z/L)=(1-16Z/L)^{-1/2} \quad \text{unstable, } Z/L<0. \quad (4)$$

Because the vertical component of the wind speed was accurately measured in the Taichung platform experiments, it is thus possible to apply the eddy-correlation method to estimate the momentum flux. Figure 7 compares the results of $-\overline{u'w'}$ for 56 runs in December 1994 from the platform experiments derived by means of the inertial-dissipation method with the results obtained using the eddy-correlation method. The momentum fluxes obtained using the dissipation technique are found to be somewhat greater than those obtained using the eddy-correlation technique, but the correlation between them is still high. Since the eddy-correlation method is generally regarded as the most accurate method for flux estimation, the comparison of Fig. 7 further validates the accuracy and feasibility of the dissipation method as well.

The turbulent fluxes can be parameterized with the mean or bulk quantities:

$$-\overline{u'w'}=C_D U_Z^2$$

$$\overline{w't'}=C_T U_Z \Delta\theta$$

$$\overline{w'q'}=C_E U_Z \Delta Q. \quad (5)$$

where $\Delta\theta=T_S-\theta_Z$, $\Delta Q=Q_S-Q_Z$, θ is the potential temperature, and the subscripts S and Z stand for those quantities at the sea surface and a height Z, respectively. The nondimensional transfer coefficients C_D, C_T and C_E are the drag coefficient, Stanton number and Dalton number, respectively. They are functions of height and stability and are commonly evaluated in the equivalent neutral case at a 10 m height as

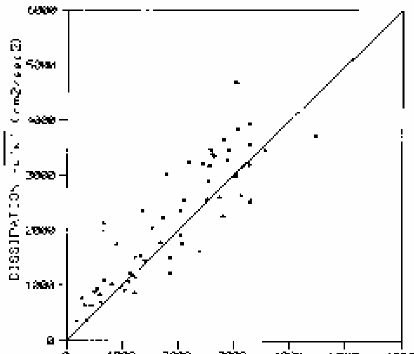


Fig. 7. Comparison of momentum fluxes derived using the inertial-dissipation method with eddy-correlation fluxes.

$$C_{DN}=\kappa^2/[\ln(10/Z_0)]^2$$

$$C_{TN}=\kappa^2/[\ln(10/Z_0)\ln(10/Z_t)]$$

$$C_{EN}=\kappa^2/[\ln(10/Z_0)\ln(10/Z_q)], \quad (6)$$

where Z_0, Z_t and Z_q are the corresponding roughness lengths in meters.

The inertial-dissipation method was then extended to the ocean cruises of the R/V Ocean Researcher III to cover more open-ocean and various atmospheric stability conditions. The roughness lengths Z_t and Z_q, derived from the corresponding integrated flux-profile relationship, are in an order of magnitude of 10^{-4} m~ 10^{-5} m. Figure 8 shows the calculated transfer coefficients of momentum, heat and evaporation from Eq.(6) under neutral conditions at a 10 m height, C_{DN}, C_{TN} and C_{EN}, with respect to the 10 m height wind speed U_{10N} for all four ship patrols. Note that data obtained under light wind conditions (U_{10N}<3 m/s) were not used in this study. The drag coefficient C_{DN} was found to increase with increasing wind speed for U_{10N}>5 m/s. A linear-regression line from the data points is also plotted in Fig. 8(a), which gives 10^3C_{DN}= 0.62+ $0.052U_{10N}$. The regression lines from Large and Pond

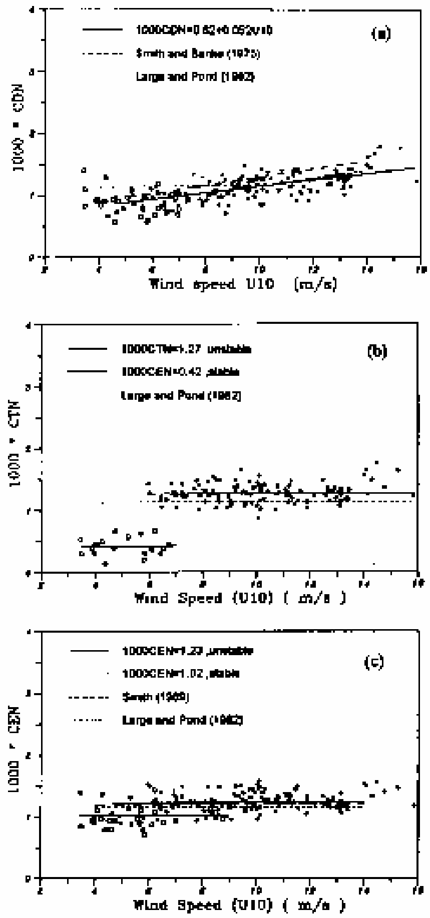


Fig. 8. The neutral transfer coefficients of (a) C_{DN}, (b) C_{TN} and (c) C_{EN} from ship measurements as a function of wind speed for both stable (squares) and unstable (stars) atmospheric conditions.

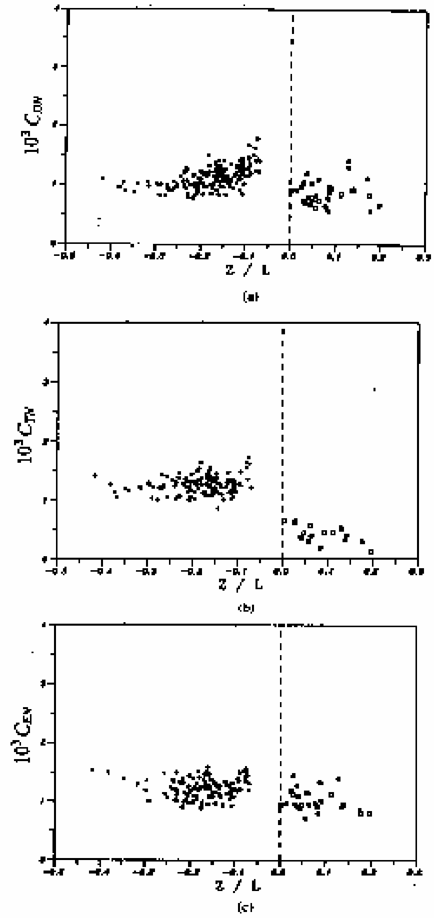


Fig. 9. The neutral transfer coefficients of (a) C_{DN}, (b) C_{TN} and (c) C_{EN} from ship measurements as a function of stability Z/L for both stable (squares) and unstable (stars) atmospheric conditions.

(1982) and Smith and Banke (1975) are also shown in this figure and appear to be consistent with our results. Figure 8(b) clearly indicates that the data points of C_{TN} versus U_{10N} can be divided into two groups; each has markedly different values of C_{TN} but is independent of wind speed. Under stable atmospheric conditions and $U_{10N}<7$ m/s, $C_{TN}=(0.42\pm0.14)\times10^{-3}$, while $C_{TN}=(1.27\pm0.15)\times10^{-3}$ under unstable atmospheric conditions and $U_{10N}>5$ m/s. The constant value of C_{TN} reported by Large and Pond (1982) is slightly smaller than our results. It can be seen in Fig. 8(c) that C_{EN} remains constant for various speeds. The average value of C_{EN} is $(1.06\pm0.21)\times10^{-3}$ for stable atmospheric conditions and $(1.23\pm0.16)\times10^{-3}$ for unstable atmospheric conditions.

In order to further identify the relationship between transfer coefficients and atmospheric stability conditions, Fig. 9 shows variations of C_{DN}, C_{TN} and C_{EN} with Z/L for all four ship patrols. The range of Z/L for our ship experiments was from -0.417 to 0.197. Our results indicate that the transfer coefficients were higher in unstable atmospheric conditions and were lower in stable atmospheric conditions. This trend is particularly evident for the heat flux coefficient C_{TN}. It should also be emphasized that $C_{TN} \approx C_{EN}$ under unstable atmospheric conditions, and that $C_{TN} < C_{EN}$ under stable atmospheric conditions. These results do not show any significant deviations from the previous results of Large and Pond (1982).

IV. Conclusions

In-situ turbulence observations of wind, temperature and humidity over the ocean have been reported in this paper. The experimental program covered various wind speeds and atmospheric stability conditions conducted from both a shallow-water platform and open-ocean ship patrols. The gust factor and the turbulence level of the longitudinal wind speed remained constant for various wind speeds and were slightly lower in open-ocean than in shallow-water conditions; both were lower than those on island terrains where the roughness is much larger. Thermal and humidity turbulence levels were found to depend on $|Z/L|$ and agreed with the free-convection laws. Wind, temperature and humidity spectra over the sea all verified the existence of an inertial subrange.

From the obtained results, it was found that momentum fluxes derived using the dissipation method were only slightly greater than those obtained using the eddy-correlation method. The dissipation-derived transfer coefficients from four ship patrols indicated that C_{DN} increased linearly with increasing wind speed while C_{TN} and C_{EN} remained constant for different wind speeds, but their values were higher under unstable conditions.

Acknowledgment

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References

Ashcroft, J. (1994) The relationship between the gust ratio, terrain roughness, gust duration and the hourly mean wind speed. *J. Wind Eng. Ind. Aerodyn.*, **53**, 331-355.

Hsu, S. A. (1988) *Coastal Meteorology*. Academic Press, San Diego, CA, U.S.A.

Kraus, E. B. and J. A. Businger (1994) *Atmosphere-Ocean Interaction*. Oxford University Press, New York, NY, U.S.A.

Large, W. G. and S. Pond (1981) Open ocean momentum flux measurements in moderate to strong winds. *J. Phys. Oceanogr.*, **11**, 324-336.

Large, W. G. and S. Pond (1982) Sensible and latent heat flux measurements over the ocean. *J. Phys. Oceanogr.*, **12**, 464-482.

Liu, H. (1991) *Wind Engineering*. Prentice Hall, Inc., Englewood Cliffs, NJ, U.S.A.

Myers, J. J., C. H. Holm, and R. F. McAllister (1969) *Handbook of Ocean and Underwater Engineering*. McGraw Hill, Inc., New York, NY, U.S.A.

Shiotani, M. (1975) Turbulence measurements at the sea coast during high winds. *J. Meteor. Soc. Japan*, **53**, 340-354.

Smith, S. D. and R. J. Anderson (1984) Spectra of humidity, temperature, and wind over the sea at Sable Island, Nova Scotia. *J. Geophy. Res.*, **89**, 2029-2040.

Smith, S. D. and E. G. Banke (1975) Variation of the sea surface drag coefficient with wind speed. *Quart. J. Roy. Meteor. Soc.*, **101**, 665-673.

海洋上的風速、氣溫與溼度之紊流觀測

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摘　　要

本文利用海研三號研究船行駛於台灣海峽南部以及在台中外海的一座淺水平台上觀測風速、氣溫和溼度的紊流特性。結果發現水平順風的紊流強度和阻曳係數均不隨風速而改變，卻似乎隨著表面粗糙長度的增加而遞增。在不穩定的大氣條件下，熱和溼度紊流強度為穩定參數Z/L的函數，其中Z為儀器高度，L為莫寧-歐布霍夫長度。由風速、氣溫與溼度變動量之能譜分佈可證實慣性領域的存在，以慣性消散法求得之風應力略大於渦流相關法所求得之值。本文所導到的動量、熱量和水汽傳送係數隨著風速和穩定度而變，並提出了一些經驗公式和數值。