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Wind Estimation for Coastal Modeling Applications

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ABSTRACT

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Winds near the water surface are influenced by a variety of physical processes ranging from synoptic scale variations in atmospheric pressure to very localized interactions with coastal landforms. The U.S. Army Corps of Engineers (CE) requires wind information for estimating waves, water levels, and circulations at coastal locations varying from small reservoirs to the ocean shore. The broad scope of natural processes affecting winds over water and the present CE estimation procedures are reviewed.

ADDITIONAL INDEX WORDS: *Coastal engineering, hurricanes, numerical modeling, surface winds, computer programs.*

INTRODUCTION

Wind has a strong influence on processes in coastal waters. The waves which grow and propagate across the continental shelf and break at the shore are generated by wind. Surface currents and, in relatively shallow depths outside the surf zone, full 3-dimensional circulation patterns are often dominated by wind stresses. Onshore storm winds can dramatically increase water level at the coast. A maximum water level rise of five meters at the coast is not unusual during a severe hurricane.

The U.S. Army Corps of Engineers' (CE) concerns with the effects of wind on the coast fall into two general categories: design and operation. CE project motivations and designs are often based upon significant historical or projected wind-driven events, and include as design goals some quantitative ability to withstand the battering of severe storms affecting the area. For design purposes, wind estimates are needed to quantify the most damaging waves and water levels which attack a region or facility during a project lifecycle. Operational considerations include the navigability of channels, operation of dredges, operation of protective structures, sediment transport issues, and harbor response.

The objectives of this paper are to provide a broad overview of terminology, natural processes, and CE estimation procedures relative to winds affecting the ocean, lacustrine, and general coastal environment. References to detailed descriptions of procedures are provided. The following section summarizes processes including large scale atmospheric flows and processes localized in the boundary layer adjacent to the earth's surface. The next section focuses on CE procedures for estimating winds which are based on research within and outside the CE, seasoned with decades of CE experience in both design and operation of coastal projects. While the goal is to discuss wind processes to provide driving stresses for hydrodynamic applications embodying wind effects on waves, water levels, and currents, this paper will not present hydrodynamic applications. Wind estimation procedures are discussed in terms of three general categories: large (synoptic) scale events such as large winter storms, small (meso) scale events such as hurricanes, and areas strongly influenced by the presence of land. The last category includes lakes, reservoirs, and protected coastal areas which are not subject to waves generated in

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open water, such as much of southeast Alaska. The final section provides a summary.

PROCESSES

Synoptic Scale Processes

Synoptic scale processes operate over a large geographic area. They can be observed with spot measurements at intervals on the order of 100–1,000 km. Atmospheric flows well above the earth's surface are driven by pressure gradients, Coriolis force, and, to a lesser extent, centrifugal forces arising from flow along a curved path. These flows are sometimes referred to as the *free air wind.*

Geostrophic winds represent a balance between atmospheric pressure gradient and Coriolis force. In the geostrophic approximation, air is assumed to flow in a straight, horizontal path without internal or boundary layer friction. The equation for geostrophic wind can be written as

$$U_g = \frac{1}{\rho_a f} \frac{\partial p}{\partial n} \tag{1}$$

where

U_g = geostrophic wind speed,
ρ_a = air density,
$\partial p/\partial n$ = magnitude of pressure gradient normal (perpendicular) to the isobars,
f = Coriolis parameter, $2\omega \sin \phi$,
ω = earth's angular rate of rotation (7.292×10^{-5} radians/sec)
ϕ = latitude.

Pressure gradient normal to the isobars is equal to the vector sum of pressure gradients in the x- and y-directions. The magnitude of the pressure gradient normal to the isobars is given by

$$\left(\frac{\partial p}{\partial n}\right)^2 = \left(\frac{\partial p}{\partial x}\right)^2 + \left(\frac{\partial p}{\partial y}\right)^2 \tag{2}$$

Wind direction for the geostrophic approximation is perpendicular to the pressure gradient. In the northern hemisphere, the wind flows parallel to isobars such that high pressure is always to the right side and low pressure to the left when facing the direction toward which the wind is blowing. The reverse is true in the southern hemisphere.

Beyond the geostrophic assumption, air motions usually follow a curved, rather than straight path with respect to the earth's surface, an effect caused by centrifugal force. When this effect is included in the balance of forces, the resultant wind is referred to as the *gradient wind.* In mid-latitude synoptic systems, the gradient wind differs from the geostrophic wind by a maximum of several percent.

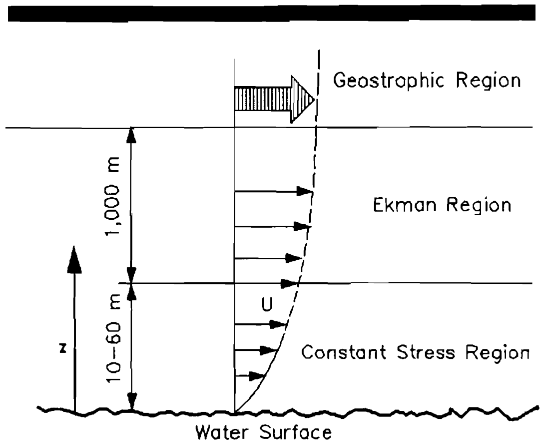

Figure 1. Idealized atmospheric boundary layer over water.

Boundary Layer Processes

Concept of a Boundary Layer. Wind characteristics near the earth's surface differ significantly from the geostrophic wind. In the lower elevation atmospheric regions, winds are strongly influenced by friction and temperature variations resulting in much more turbulent flow regimes. This zone near the earth's surface is termed the *planetary boundary layer* (PBL) (Figure 1) and extends on the order of 1 km above the earth's surface, although the thickness is quite variable.

Coastal hydrodynamic modeling applications require estimates of wind conditions influencing and interacting with the water surface, hence greater interest is focused on the lowest elevations of the PBL. Standard practice is to estimate a *surface wind* at an elevation sufficiently near the water surface to have a direct relationship to processes at the air-sea interface, but high enough to be above storm wave crests and other near-surface ambiguities. Surface wind is usually estimated at 10-m elevation.

Two major approaches are utilized to quantify atmospheric conditions within the PBL. One approach is to consider in detail the 2- or 3-dimensional motions and thermodynamics of the PBL processes. This involves solving differential or integral form conservation and state equations concerning momentum, heat, and moisture fluxes. This approach is powerful, resolving spatial and temporal details of air flow evolution and air-sea interaction with reasonable fidelity at considerable computational expense. Generally, this detailed approach is feasible at only a few major weather centers possessing extensive scientific and computing resources.

A more tractable, but less detailed approach is to approximate the structure of the PBL with a small number of well-chosen parameters and relatively simple generalizations of the boundary layer physics. In the parameterized PBL, low-level winds are assumed to exist in a region characterized as exhibiting relatively constant horizontal stress. Above the *constant stress region* is the *Ekman layer*, where the additional forces of Coriolis, pressure gradient, viscous stress, and convectively driven vertical mixing are also considered. Similarity theory yields parameterizations and relationships for the constant stress region and the full boundary layer (constant stress region and Ekman layer combined). Estimates using this useful concept of the PBL are more easily obtainable and have been widely used in CE studies.

A recent and comprehensive review of the scientific aspects of coastal meteorology is provided by the NATIONAL RESEARCH COUNCIL (1992). A brief discussion of some key variables and processes considered within or concurrently with the parameterized PBL approach follows:

Elevation Considerations. Wind speed generally increases with elevation above the land/water surface, especially in the constant stress region. The wind magnitude increase with elevation is roughly approximated by a logarithmic law of the form

$$U_{10m} = \left(\frac{10}{Z}\right)^{\frac{1}{7}} U_Z \qquad (3)$$

where

U_{10m} = wind speed at 10-m elevation,
Z = elevation of another wind speed estimate,
U_Z = wind speed at elevation Z.

This is the simplest approximation of wind profile as a function of elevation only, and is directly soluble. As more processes are considered (such as air-sea temperature gradients, or other forces considered in the Ekman region), the expression evolves into more transcendental forms. Even with a parameterized PBL approach, additional relationships requiring simultaneous solution mandate numerical techniques for solution.

Air-Sea Temperature Difference Effect. Temperature differences between near surface air and water can have a pronounced effect on boundary layer processes. When the air is cooler than the water, vertical mixing is intensified and momentum transfer from wind to water is enhanced. When the air is warmer than the water, a stable layer of air develops adjacent to the water surface and air-water transfers are inhibited. Inclusion of such stability effects involves expansion of the parameterized PBL equations with mixing theory relationships solved in simple forms. Iterative solutions of simultaneous relationships are employed in CE treatments of these effects.

Averaging Time Considerations. Highly deterministic methods for estimating wave growth or circulation patterns require temporal and spatial-distribution estimates of wind speeds and directions over the water domain. For such analyses, continuous wind-driven events are usually discretized at some time interval. Simpler diagnostic techniques assume winds to be constant in magnitude and direction for some average time interval. For example, a wind speed may represent an average over a 1-minute sample. Another often-used statistic from measurements is the *fastest mile wind speed*, which is the highest value in a wind record averaged over a time equivalent to a 1-mile travel distance. When dealing with maximum wind speed values, the speed decreases as averaging time increases. Typical averaging times for hydrodynamic modeling applications are from 10 minutes to several hours. In CE procedures, averaging time adjustments are made externally to PBL computations and are treated as separate considerations.

Overland/Overwater Effect. Friction and temperature characteristics differ significantly between land and water surfaces with resultant differences in effects upon wind processes in those regions and at land-sea boundaries. Thus, winds blowing in offshore or onshore directions at the coast will be transitional and have different characteristics. The influence of land effects on the surface wind gradually disappears with increasing distance over water. Land effects can be essentially disregarded at sea distances from the coast on the order of 20 km.

Orographic Processes. The deflection, channeling, or blocking of air flow by high-relief land forms (mountains, cliffs, high islands, etc.) is called the *orographic effect.* It has a pronounced impact on many localized coastal ares. A related process, the *katabatic wind,* is caused by topographically-channelled downhill flow of cold air off high ground. Katabatic winds, which can easily exceed hurricane strength, are strongest and most common in high latitudes. Such processes require separate consideration from parameterized PBL approaches.

Sea Breeze. Abrupt differences in surface temperature and heat flux between water and adjacent land cause air circulations commonly termed *sea breeze.* Since land temperatures fluctuate on a daily cycle, the sea breeze has a characteristic diurnal behavior. When it occurs, the sea breeze is a significant feature at the coast and extending several 10's of kilometers seaward and landward from the coastline. Peak wind speeds are typically less than 10 m/sec.

Wave Effect. Since surface wind is influenced by surface roughness, the characteristics of surface waves have some feedback impact on wind. This effect may be related to wave height, wave steepness, and wave direction, particularly when waves generated by onshore winds have been turned by refraction.

Meso Scale Processes

Meso scale events are significant weather features which are too compact to be well represented in synoptic scale modeling. The relevant processes in these events also differ significantly from those considered in synoptic scale systems. Meso scale features extend over distances of about 5 to 1,500 km. Hurricanes are the most important meso scale events in CE applications. Hurricanes are a vital part of the design wave and water level conditions at U.S. Gulf and Atlantic (south of New England) coast locations. Hurricanes are typically small, extremely intense storm systems. The distance from the center, or eye, to the point of maximum wind is typically several 10's of kilometers. Hurricanes have a consistent structure and are amenable to being characterized by a small number of parameters (Table 1). In addition to being small and powerful, hurricanes occur infrequently. Only a few hurricanes have strong impact on the U.S. coast in an average year. Areas with heavy damage are typically very localized. Thus, the climatological record of hurricane occurrences at a specific site contains at most a few severe events. It is likely to be a rather poor representation of the statistical possibilities which could occur.

Table 1. *Key hurricane parameters.*

Symbol	Description
p_o	Central pressure
p_n	Peripheral pressure
R	Radius of maximum winds
V_f	Forward speed
θ	Track direction
ϕ	Inflow angle

ESTIMATION PROCEDURES

Synoptic Scale Events

The CE applies two basic approaches to estimate winds on a synoptic scale. The first approach requires the development of synoptic scale atmospheric pressure fields using weather maps and other historical data. Surface pressure fields are developed on a large scale grid over the area of interest at regular time intervals, typically 6 hours (Figure 2). A numerical model is used to develop gradient wind fields, typically at 3-hr intervals, from the pressure fields. At each grid point and time step, a parameterized PBL model based on similarity theory is used to estimate surface wind (RESIO *et al.*, 1982). Improvements to the model were added by FARRAR (unpublished) and LEENKNECHT *et al.*, (1992).

The second approach consists of the acquisition of surface wind fields from a major forecasting center. Global synoptic scale forecasting systems are routinely operated by the U.S. Navy (HOGAN and ROSMOND, 1991) and the U.S. National Weather Service (KALNAY *et al.*, 1990). Spatial resolution of these systems is on the order of 1 degree of latitude and longitude. Both referenced systems include simulation of boundary layer processes. Products from these sources are discussed by DEMIRBILEK *et al.*, (1993). It should be recognized that both systems are designed for forecasting functions and not specifically for generating a historical data base. However, the data base is a natural by-product, if the massive files can be saved efficiently and the data matches actual events adequately. This approach is generally preferred in CE modeling for the recent time periods covered by available data.

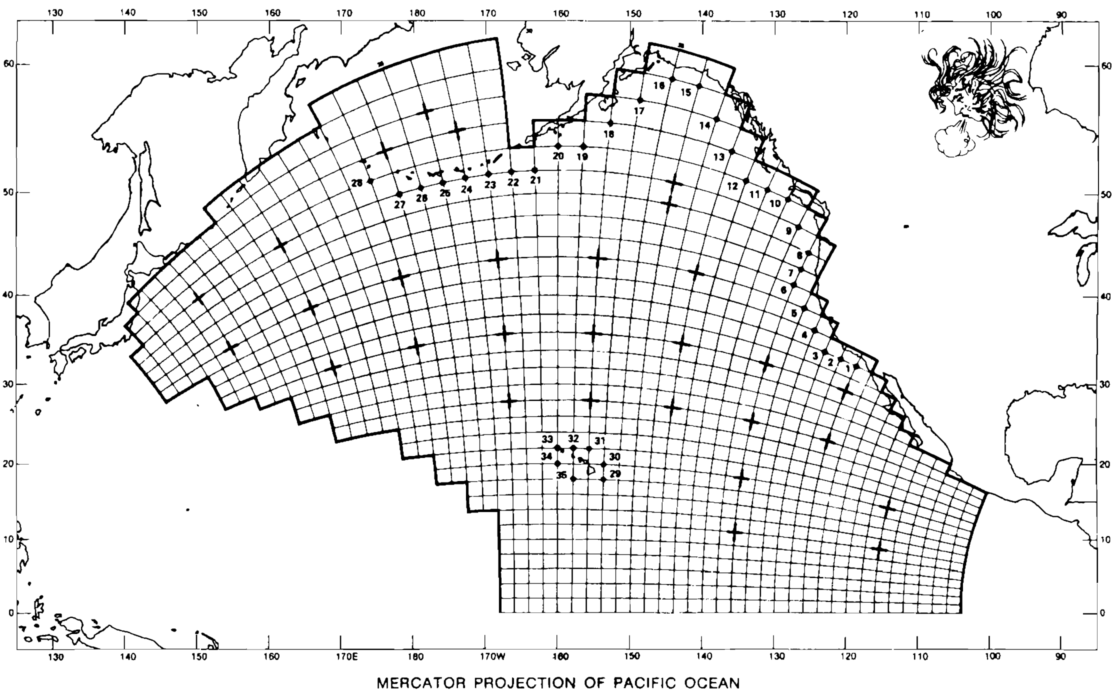

Figure 2. Synoptic scale grid for surface pressure and wind fields over the north Pacific (from CORSON *et al.*, 1986).

Meso Scale Events

Hurricane events are treated by a variety of methods in CE practice. Two numerical models (SPH and another PBL model) estimating the intense cyclonic windfields resulting from these events are routinely employed for design purposes and are briefly described below. As mentioned earlier, the parameters often used to characterize hurricanes are summarized in Table 1.

The *Standard Project Hurricane* (SPH) model was developed to provide a simplified, consistent and systematic approach for hurricane wind estimation (SCHWERDT *et al.,* 1979). The SPH is defined as a hurricane having a severe combination of values of meteorological parameters that will give high sustained wind speeds reasonably characteristic of a specified coastal location. SPH parameters are specified along U.S. Atlantic and Gulf coasts in terms of values for the parameters listed in Table 1. The SPH model can be used for deterministic modeling of a suite of hurricanes to estimate project design conditions. Alternatively, with proper choice of parameters, it can be used to replicate historical storms.

An alternative model for hurricane wind fields has also received extensive CE use (CARDONE *et al.*, 1992). The modeling approach based on a PBL concept is more comprehensive and flexible than the SPH. It incorporates a vortex model developed originally by CHOW (1971). The model computes a sequence of steady state snapshots of the hurricane wind field. The model computational grid embodies a series of nested meshes which move with the storm track. The grid is always centered on the hurricane eye, with highest resolution in the vicinity of the eye and decreasing resolution with distance from the eye. Results are interpolated onto a user-specified output grid fixed in space. An example output wind field is given in Figure 3. The model includes options for specifying a spatial distribution of surface roughness characteristics, at grid point locations. This aspect of the model has not been fully validated, and the open water option is used in most CE applications. A more detailed overview of the SPH and hurricane PBL models is given by THOMPSON and DEMIRBILEK (1992).

The SPH and hurricane PBL models are numerical tools for the representation of specific storms. An alternative approach to evaluating hurricane generated coastal impacts embodies the use of results from a family of historical storms used to develop statistical information for a site such as frequency-of-occurrence relationships for maximum surge elevation, shoreline erosion, or dune recession (SCHEFFNER *et al.*, 1993). The procedure uses the statistics of past storm events and coastal responses to develop many statistically correct samples of possible events. Mean-value frequency relationships with confidence intervals are then computed.

The increase in the quantity and quality of hurricane wind measurements in recent years has led to another procedure for developing wind fields commonly called *kinematic analysis techniques* (POWELL, 1982; POWELL *et al.*, 1991). As a hurricane passes by a fixed measurement site, such as a buoy moored on the continental shelf, data are obtained at a variety of positions relative to the eye. Often it is reasonable to assume that the storm structure changes little as the storm passes the offshore or coastal gauge. With proper correction, all measurements can be composited with reference to the eye location to reconstruct a cross section of the wind field. If a disperse network of gauges records the storm and those data are supplemented by aircraft wind measurements corrected to represent surface winds (POWELL and BLACK, 1989), a rather accurate wind field can be reconstructed. Kinematic analysis is a labor-intensive, tedious procedure which is applied only to hurricanes of special interest. Aspects of kinematic analysis are becoming more automated, and it may increasingly become a more practical tool.

Other meso scale events of interest to the CE include small, transient, but intense disturbances such as thunderstorms and squalls. These events cause operational concerns, but are not considered as design events. They are not easily or effectively modelled and the CE has no standard procedures for estimation.

Areas Strongly Influenced by Land

The procedures for estimating winds due to synoptic and meso scale events give little or no consideration to interaction of the wind with land. The land effect cannot be ignored in some situations, such as reservoirs, lakes, estuaries, and even open coast sites with offshore winds, yet such situations often present very difficult challenges for estimating wind fields. A wide variety of surface roughness regimes may be involved, ranging from marsh grass to forest to city buildings. Strong orographic effects may be present, as in the sinuous coastal waterways bounded by mountainous islands in southeast Alaska. In enclosed or semi-enclosed areas less than about 50 km across, much of the wind over water may be in a transition regime between the overland boundary layer and the fully developed marine boundary layer.

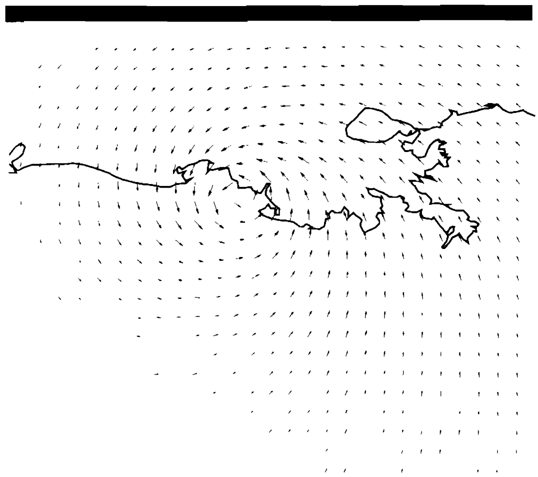

Figure 3. Example wind field from hurricane PBL model, Hurricane Andrew crossing the Louisiana coast.

Simplistic methods fail to properly represent the complex interactions between wind, land, and water in close proximity. More sophisticated and elaborate modeling approaches embodying current knowledge of the physics are presently inadequate for estimating this process. Direct measurements of over water surface wind are very valuable; however, they must be carefully interpreted and applied. Data at a single point in a wind field containing spatial and temporal variations may not adequately represent, for example, the integrated wind effect along a fetch for wave growth.

Wind measurements over water are rarely available at sites affected by land. Often measurements or other estimates over land are employed instead. The estimates must be corrected to give reasonable approximations to winds over water. This approach was preferred even in water bodies as large as the Great Lakes (*e.g.*, HUBERTZ *et al.*, 1991).

Computing Environments and Manual Guidance

Among several numerical tools developed by the CE, the Automated Coastal Engineering Sys-

Table 2. *Character and action for wind observations in ACES.*

Observation Type	Initial Action	Solution Domain
Over water (non-ship obs.)	None	Constant stress layer
Over water (ship obs.)	Adjusted	Constant stress layer
At shoreline (onshore winds)	None	Constant stress layer
At shoreline (offshore winds)	Geostrophic wind estimated	Full PBL model
Over land	Geostrophic wind estimated	Full PBL model
Geostrophic wind	None	Full PBL model

tem (ACES) is a convenient broadly-used PC-based software package which embodies some of the present CE technology for wind estimation (LEENKNECHT *et al.*, 1992). One specific ACES application is aimed at windspeed adjustment and wave growth. Adjustments are included for elevation, air-sea temperature difference, averaging time, and overland/overwater effects. The types of input observation and ACES treatment are summarized in Table 2. A PBL model similar to that used with the CE synoptic scale model is used as needed to estimate surface wind. The PBL model implemented within ACES is described in detail in the Appendix.

Other CE numerical tools mentioned in this document are utilized on large centralized computing facilities within the Coastal Modeling System (CMS) (CIALONE *et al.*, 1993). In the future, some of these more computationally intense tools will likely be utilized on engineering workstations as desktop computing capabilities increase.

The CE also publishes manual guidance on wind estimation (THOMPSON, 1988; U.S. ARMY CORPS OF ENGINEERS, 1989). The manual guidance is similar to that in ACES except that, being based on charts, graphs, and simple empirical equations, it does not embody some of the processes and refinements in ACES.

SUMMARY

Winds near the water are influenced by a variety of physical processes ranging from synoptic scale variations in atmospheric pressure to very localized interactions with coastal landforms. The CE requires wind information for estimating waves, water levels, and circulations at locations varying from small reservoirs to the ocean coast. A broad scope of CE applications and estimation procedures is discussed.

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APPENDIX—BOUNDARY LAYER WIND REPRESENTATION

Constant Stress Region

The major features of the constant stress region can be summarized as follows:

—The constant stress region is confined to the lowest few meters of the boundary layer.
—Wind flow is assumed parallel to the water surface.
—The wind velocity is adjusted so that the horizontal frictional stress is nearly independent of height.
—The stress remains constant within the layer and is characterized by the friction velocity U_*.

The wind profile within the constant stress region is described by the following equations:

$$U_z = \frac{U_z}{k}\left[\ln\left(\frac{z}{z_o}\right) - \Psi\left(\frac{z}{L'}\right)\right] \qquad \text{(A-1)}$$

where

U_z = wind velocity at elevation z

k = von Karman's number = 0.4

z_o = surface roughness length

$$= \frac{c_1}{U_*} + C_2 U_*^2 + C_3 \qquad \text{(A-2)}$$

$$\left(C_1 = 0.1525, \quad C_2 = \frac{0.0144}{980}, \quad C_3 = -0.00371\right) \qquad \text{(A-3)}$$

Ψ = universal similarity function KEYPS formula (LUMLEY and PANOFSKY, 1964)

L' = Monin-Obukov stability length

$$= 1.79\frac{U_*^2}{\Delta T}\left[\ln\left(\frac{z}{z_o}\right) - \Psi\left(\frac{z}{L'}\right)\right] \qquad \text{(A-4)}$$

ΔT = air-sea temperature difference

$$\left.\begin{array}{ll} \Psi = 0 & \Delta T = 0 \\ \Psi = C_4\dfrac{z}{L'}, \quad C_4 = -7.0 & \dfrac{z}{L'} > 0 \\ \Psi = 1 - \phi_u - 3\ln\phi_u & \\ \quad + 2\ln\left(\dfrac{1+\phi_u}{2}\right) + 2\tan^{-1}\phi_u & \\ \quad - \dfrac{\pi}{2} + \ln\left(\dfrac{1+\phi_u^2}{2}\right) & \dfrac{z}{L'} \le 0 \end{array}\right\} \qquad \text{(A-5)}$$

$$\phi_u = \frac{1}{1 - 18R_i^{1/4}} \qquad \text{(A-6)}$$

$$R_i = \frac{z}{L'}(1 - 18R_i)^{1/4} \qquad \text{(A-7)}$$

The origin of the constant 1.79 in Equation A-4 is explained on pp. 50–51 of CARDONE (1969). It represents the ratio of mean potential temperature of the air (taken as 280 °K or 44 °F) to k^2g, where g is the acceleration due to gravity. The value of C_4 in Equation A-5 is given on p. 44 of CARDONE (1969) with reference to PAULSON (1967).

Full Boundary Layer

The following additional relationships describe the full PBL from water surface level to geostrophic level:

$$\ln\frac{|U_g|}{fz_0} = A - \ln\frac{U_*}{|U_g|} + \sqrt{\frac{k^2|U_g|^2}{U_*^2} - B^2} \quad \text{(A-8)}$$

$$\sin\theta = \frac{BU_*}{k|U_g|} \quad \text{(A-9)}$$

where

U_g = geostrophic wind
f = Coriolis parameter
A, B = nondimensional functions of stability
μ = dimensionless stability parameter

$$\left.\begin{array}{l} A = A_0[1 - e^{(0.015\mu)}] \\ B = B_0 - B_1[1 - e^{(0.03\mu)}] \end{array}\right| \quad \mu \leq 0 \quad \text{(A-10)}$$

$$\left.\begin{array}{l} A = A_0 - 0.96\sqrt{\mu} + \ln(\mu + 1) \\ B = B_0 + 0.7\sqrt{\mu} \end{array}\right| \quad \mu > 0 \quad \text{(A-11)}$$

$$\mu = \frac{kU_*}{fL'} \quad \text{(A-12)}$$

A_0, B_0, B_1 = constants
θ = angle between U_g and the surface stress

The wind speed required for hydrodynamic applications is the wind at the desired elevation under conditions of neutral stability ($\Delta T = 0$). This equivalent neutral wind speed U_e is obtained from equation A-1 as

$$U_e = \frac{U_*}{k}\left[\ln\frac{z}{z_0}\right] \quad \text{(A-13)}$$

where U_* embodies the effect of the actual difference in temperature.

Turning of the wind between geostrophic level and the desired surface level is estimated according to the relative decrease in wind speed in the PBL by matching solutions for the wind in the constant stress and Ekman layers. This friction-induced turning, often called the Ekman spiral, introduces a component of wind motion toward low pressure. The following equation (taken from equation 8-29, p. 276 of HALTINER and WILLIAMS, 1980) is used:

$$\cos\alpha_s - \sin\alpha_s = \frac{U_e}{U_g} \quad \text{(A-14)}$$

where α_s = change in wind direction between geostrophic level and desired surface level. This equation is solved iteratively. The limiting values of α_s are 0 and 45 degrees at the geostrophic and water surface levels, respectively.