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# Boundary Layer Processes in Coastal Meteorology: Prospects for Remote Sensing Applications

C.W. Fairall

**Abstract**. Recent advances in observing systems and models have led to a renewed interest in the special problems of coastal meteorology. In this report the boundary layer aspects of the coastal regime are examined. The current state of understanding is assessed for homogeneous boundary layers, surface interactions, internal boundary layers, and various inhomogeneous conditions. The inhomogeneities can be due to topography, land-ocean contrast, land-surface horizontal variations, or clouds. Surface-based remote sensing systems are ideal for studying the boundary layer on coastal scales. Six recently developed systems are described and their prospects for coastal studies discussed.

## 1. BACKGROUND

The boundary layer is that part of the lower troposphere which, through turbulent transport processes, interacts directly with the surface. Because a coast defines the boundary between two drastically different surfaces, a coastal region has by definition an inhomogeneous surface. In any such region, we expect that boundary layer interactions will be of primary importance in determining the nature of dynamical processes and the evolution of atmospheric structure. The boundary layer can also be viewed as a buffer zone that interacts both with the "free" tropospheric flow at its upper interface (through entrainment processes) and with the surface (through surface exchange processes).

Past studies of the atmospheric boundary layer (ABL) have greatly emphasized certain idealized, near-equilibrium, and horizontally homogeneous boundary layer regimes (Wyngaard, 1988). For example, Stull's (1988) comprehensive reference on boundary-layer meteorology devotes only about 5% of its discussion to geographic effects. In fact, many common ABL conditions are still poorly understood, even for homogeneous surfaces. The horizontally inhomogeneous and rapid temporal forcing conditions typical of coastal regions dictate consideration of problems that to date have rarely been investigated. Furthermore, even those aspects of the physical processes that are generally regarded as being well understood (e.g., bulk parameterization of surface fluxes) must be reconsidered for application to coastal environments.

In this report we examine the current state of understanding of boundary layer processes and identify some important deficiencies. Following the introductory material on sources of knowledge about boundary layers, we examine generic problems in boundary layer processes. Then we consider special coastal problems involving surface fluxes, internal boundary layer growth, baroclinicity, and a variety of phenomena that are either inherently inhomogeneous or associated with inhomogeneous forcing. Finally, we discuss several mature surface-based remote sensing technologies and their potential impact on coastal boundary layer research problems.

## 2. CURRENT UNDERSTANDING AND CHALLENGES

The ABL has been extensively investigated and certain aspects are considered to be well understood. This understanding has developed from a combination of information sources: (1) laboratory models (e.g., Willis and Deardorff, 1974; Deardorff and Willis, 1982), (2) three-dimensional, primitive equation large eddy simulations (e.g., Deardorff, 1974; Deardorff, 1980; Moeng, 1984), and (3) atmospheric measurements with aircraft and tethered balloons (e.g., Lenschow, 1973; Kaimal et al., 1976; Lenschow et al., 1980; Brost et al., 1982; Nicholls, 1984).

A variety of models of ABL behavior are now available. Because a model represents the reduction of a problem to its important components, it not only is a useful tool but also can serve as an expression of our understanding of the physics. Linear regression and crude parameterizations often imply little or no understanding. Today a hierarchy of complexity is available in atmospheric models. Similarity models are the simplest but typically are applicable only to idealized situations. One index of our understanding is the existence of simplified conceptual models and useful scaling laws. By this measure, the cloud-free, convective ABL is clearly the best understood regime.

Numerical solutions to systems of physical equations form the basis of the more sophisticated models commonly used in meteorology. Two approaches are used, depending on whether solutions are sought for the **ensemble** average or **volume** average atmospheric budget and state equations. Ensemble average models are often referred to as higher-order closure models and volume average models are usually referred to as large eddy simulations (LES). These approaches are fundamentally different; an LES model produces an explicit simulation of a single realization of a three-dimensional, time-dependent atmospheric structure whereas an ensemble average model predicts or describes the relationships between the moments of the atmospheric variables (the first moments are the averages of the variables and the second moments are the variances and fluxes). LES are currently used strictly for research purposes (such as developing parameterizations); ensemble average models have a variety of practical as well as research applications.

## 2.1. The Generic ABL

Scaling theories have their origins in dimensional analysis; important variables of the problem are selected and other properties are calculated from dimensionally consistent combinations of those variables. Modern ABL similarity theories are now based on arguments about the relative variability and magnitude of the various terms in the mean and turbulent budget equations. In the ABL the similarity regimes are broken down by the vertical scale, assuming that the horizontal fields are statistically homogeneous. Historically, this process has proceeded from the ground up. Figure 1 depicts schematically the typical mean structure of the ABL under convective, well-mixed, horizontally homogeneous conditions in a synoptic regime having sufficient subsidence to ensure the presence of a capping inversion. Compared to the ABL, the overlying free troposphere can be considered essentially nonturbulent.

Surface layer similarity theory is based on scaling parameters obtained from surface fluxes (Wyngaard, 1973). The theory is considered valid in the region near the surface where various terms (particularly the gradients) in the turbulent kinetic energy (TKE) and scalar variance budget equations are considerably more dependent on height than are the fluxes. Thus, the assumptions on which the theory is based are generally valid in the lowest 10% of the ABL. For the convective ABL, we also have mixed-layer similarity (Moeng and Wyngaard, 1984) and inversion region similarity (Wyngaard and LeMone, 1980). For the stable ABL, no mixed layer exists; rather there is a gradual transition from the surface layer to the inversion layer. A local similarity theory (Nieuwstadt, 1984) has been proposed for a stable ABL in steady state or slowly evolving conditions. This theory has, however, exhibited shortcomings in general application.

In terms of simple models, the present "state of understanding" of the generic ABL can be crudely stated. Given the complexity of ABL dynamics, it is natural to classify the conditions under dynamical regimes of increasing complexity: cloud free, convective; cloud free, shear driven; baroclinic; stable; stratocumulus; tradewind cumulus; and broken clouds. Coastal meteorology encompasses all seven of these regimes. Cloud-modified and stable boundary layers are still essentially unsolved problems. A general similarity theory that can handle all possible cloud regimes does not exist. Higher-order closure models have yet to demonstrate detailed agreement for even the simplest cases (Holt and Raman, 1988) and recent LES studies (Moeng and Wyngaard, 1989) have called into question the transport and dissipation closures used in most second-order models. Transport and dispersion properties of the ABL are strongly dependent on the characteristics of coherent structures and the higher-order moments (Weill, 1990). These are properties that are only now being studied for the homogeneous, convective ABL (Moeng and Wyngaard, 1989; Moeng and Rotunno, 1990). Although there are areas where we believe we do have some understanding of the generic ABL, our understanding in the inhomogeneous situations typical for the coastal region is extremely limited. For example, Fig. 2 shows coastal atmospheric profiles that obviously deviate substantially from the idealized situation depicted in Fig. 1.

## 2.2. Surface Interactions

Surface fluxes can be measured in homogeneous and moderately inhomogeneous terrain using the eddy correlation technique (Businger, 1986; Wyngaard, 1988; McMillen, 1988). It is considered to be the measurement standard. In numerical models (or when the direct method is not available or applicable), bulk transfer coefficients and surface-layer similarity are used to relate the fluxes to the near-surface mean meteorological variables and the surface properties. This approach is often quite successful over the open ocean (in the absence of significant sea surface temperature anomalies) but cannot be straightforwardly applied over land where terrain, soil and plant canopy interactions greatly complicate the physics (Priestly and Taylor, 1972; Sellers et al., 1986). That is the situation for the local coastal climatology where the intensity of the land-sea breeze circulation is, relatively, much stronger with dry, lightly vegetated coastal lands (Segal et al., 1988).

Inhomogeneous surfaces cause special problems because it is difficult to relate the point measurements used to characterize the surface to the larger scale mean fluxes (Schuepp et al., 1990). Also, the bulk expressions are intended to relate the average flux to the average bulk variables. Since an ABL-scale eddy turnover time is about 15 minutes, it takes about a 1-h average over ABL variability to obtain a representative sample. In that hour, a parcel of air in the ABL can easily travel horizontally about 20 km. Thus, another related critical issue is our reliance on Monin-Obukhov similarity expressions that are obtained from 1-h averages of field measurements over homogeneous terrain in models with 1-min time steps applied over 10 x 10 km horizontal grids. For example, Beljaars and Holtslag (1991) found that to characterize momentum transfer on horizontal scales of a few kilometers required an "effective" roughness length considerably greater than the local value. The situation for moisture and sensible heat transfer is even more difficult. To quote Beljaars and Holtslag (1991), "More complicated land surface schemes are certainly available to describe the physics in more detail, ... however, it is not clear whether all the parameters that specify the land surface in such models can easily be determined." There is also a distinction between a patchy surface that is statistically homogeneous and a "nonstationary" situation where the average properties vary with position and time. The applicability of surface-layer similarity and the implications for the bulk transfer coefficients for these conditions are virtually unexplored.

On the ocean side of a coastal region we are also faced with special problems in interfacial transfer. For the open ocean, a reasonable set of bulk transfer coefficients (e.g., Smith, 1988) is available that appears adequate for many applications. These coefficients represent air-sea transfer processes for average surface wave conditions as a function of mean wind speed. Wind speed, the wave spectrum, and bulk transfer coefficients have been related theoretically (Geernaert et al., 1986; Huang et al., 1986), but field measurements in coastal regions (e.g., Geernaert et al., 1987; Smith et al., 1990) have demonstrated greatly increased drag coefficients in shallow water (Fig. 3).

It is clear that fetch and shallow water effects upset the normal, equilibrium wind-wave relationships. Fetch is primarily an issue for offshore wind conditions but the distortion of the open ocean directional wave spectrum in coastal shallow regions is important, regardless of wind regime and becomes increasingly important as wind speeds increase. The effects on the heat fluxes and gaseous fluxes are also unknown. See Geernaert (1990) for a comprehensive review of these concepts. Because the evolving wave field is influenced by the wind stress but the stress vector produced by a given wind field is dependent on the directional wave field, predictions of wind and wave fields on the continental shelves are strongly coupled. Significant and unexplained differences between the mean wind direction and the mean stress direction have been observed in coastal regions (Geernaert, 1990). Substantial hydrostatic stability modulation of stress and of surface wind fields has also been observed in association with sea surface temperature variations typical of coastal regions. A comprehensive theoretical and experimental study of wind/wave/stress/scalar flux relationships on the continental shelves should be an important component in a coastal meteorology research program.

### 2.3. Internal Boundary Layers

Air that is modified by flow over an abrupt change in surface properties is said to be confined to an internal boundary layer (IBL). Here we are concerned with the effects of a boundary between two different but individually homogenous surfaces, as opposed to the boundary layer effects of more general forms of inhomogeneity discussed in Section 2.4. When the surface heat flux changes at such a boundary, a thermal internal boundary layer (TIBL) (Lyons, 1975; Garratt, 1987) is formed on the downwind side. The growth in the depth of the IBL is usually parameterized in terms of the downwind distance from the interface. Typically, the form is that of a power law, but a profusion of different formulas are available. Convective conditions promote rapid growth; thus, the IBL depth quickly reaches the existing capping inversion. In this case IBL considerations are important only close to the transition. Stable, convection-suppressing conditions downwind of the transition result in slow IBL growth, and the tendency is to form a permanent surface-based inversion (Mulhearn, 1981). The situation is similar to the afternoon-evening transition for the overland convective ABL (Zeman and Lumley, 1979). In this case any turbulence above the new surface-based inversion will be cut off from the surface source of energy and will, in the absence of other sources, begin to decay. In an LES study of the decay of convective turbulence, Nieuwstadt and Brost (1986) found that the ABL depth divided by the convective mixing velocity formed a characteristic decay time scale, but the behavior of various turbulent variables was not easily parameterized.

Currently, the standard approach to describe near-surface meteorological profiles is to use surface similarity expressions with one set of scaling parameters for the IBL, a second set for the old ABL above, and the constraint that the profiles must match continuously at the IBL interface. This approach assumes that the dynamics above the IBL are unaffected by the formation of the IBL. This approximation can be valid only fairly close to the transition region. More sophisticated model studies (e.g., Claussen, 1987) have shown that substantial mean vertical motions are also induced by the transition, even outside of the IBL. Because the IBL exists for such a short distance in convective conditions, the formation and growth of the stable IBL are more critical. Here a key issue is the physics of the entrainment processes at the top of the IBL and the associated induced vertical velocity fields.

### 2.4. The Inhomogeneous ABL

Understanding ABL development and evolution in regions of abrupt or gradual changes of surface properties (coastal zones, ice-to-water surface transitions, ocean surface temperature fronts, etc.) involves consideration of horizontal advection, baroclinic forcing, nonequilibrium turbulence effects (e.g., the time derivative of the TKE is not negligible), the special influence of local clouds, and fully three-dimensional dynamical processes.

A simple way to view this three-dimensional problem is to break it down into a conceptual model consisting of a surface grid with each surface point occupied by a mean and turbulence profile governed by one-dimensional turbulent mixing processes. Adjacent grid points are coupled in the normal manner through horizontal advection and horizontal pressure gradients. This approach has enjoyed some success with mixed-layer models (Stage and Businger, 1980; Steyn and Oke, 1982; Overland et al., 1983; Davidson et al., 1984; Reynolds, 1984) and higher-order closure models (Bennett and Hunkins, 1986; Wai and Stage, 1990; Tjernstrom, 1990). However, decoupling of the turbulence dynamics from the horizontal structure is a simplifying assumption that has never been tested. Clearly, similarity approaches (e.g., mixed-layer models) that are tuned to quasi-equilibrium conditions must have limits of applicability in inhomogeneous conditions. However, these limits have not been established. It may be that the techniques used in highly inhomogeneous urban boundary layer models (e.g., Uno et al., 1989) are adaptable to coastal problems.

Both land-sea breeze cycles and cold-air outbreaks have been examined with models, but a comprehensive and extensive program to compare the model results with measurements has not been attempted. Baroclinic effects associated with a sloping inversion (Brost et al., 1982; Overland et al., 1983) are known to be substantial, especially in west coast regimes, but they too are virtually unstudied.

The relative lack of experimental studies of boundary layer physics in coastal zones is not the only reason to question our dependence on present day boundary layer models. A recent LES study (Moeng and Wyngaard, 1989) of second-order closure parameterizations suggests that their rather modest successes in homogeneous conditions (e.g., Holt and Raman, 1988) are not expected to carry over to the coastal regime because homogeneous conditions do not severely test the parameterizations. To quote Moeng and Wyngaard (italics added for emphasis), "Most observational and model studies show that *in the absence of abrupt changes in boundary conditions,* the heat flux profile is indeed essentially linear in the mixed layer. Thus, given the proper boundary conditions, second-order models will tend to have the correct vertical profile of buoyant production rate within the mixed layer, *regardless of the fidelity of their closure parameterizations.*" Moeng and Wyngaard also point out that, under homogeneous conditions, the mean value of the rate of dissipation of TKE in the mixed layer is also nearly independent of closure approximations.

## 2.5. Boundary Layer Clouds

Clouds within the ABL greatly complicate the physical processes because they represent a form of vertical inhomogeneity, significantly affect the dynamics, and couple strongly with atmospheric radiation. It is well known that the structure and dynamics of the ABL are modified by radiative processes associated with cloud development. For example, marine stratocumulus clouds may play a role in varying stress divergence within the lower part of the ABL due to effects of the radiative heating. During the day, if the cloud layer warms faster than the subcloud layer, the cloud may become decoupled with a corresponding increase in wind stress and heat flux divergence between the top of the subcloud layer and the surface (Hignett, 1991; Koracin and Rogers, 1992).

Stratiform clouds are persistent features of cool, upwelling coastal regions, such as along the west coast of the United States, and cool climate regions, such as the Arctic. Recent studies of the global radiation budget have highlighted the possible role of stratiform clouds as an ameliorating influence on the warming of the atmosphere by high altitude clouds (Ramanathan et al., 1989). Although a number of experiments have provided, and continue to provide, considerable insight into the processes that control the development and dissipation of stratiform clouds (Randall et al., 1984), the effect of the variability of the coastal ocean, topography, and the marine ABL on these clouds has received much less attention. The effect of coastally trapped waves on the depth of the marine layer may also play an important role in the persistence of these clouds; the effect of the sea breeze on subsidence and the mesoscale pressure gradients may also be an important mesoscale process that controls the lifecycle and fractional coverage of coastal stratus. In turn, the stratus clouds can substantially modulate the sea-breeze cycle by moving ashore and reducing inland solar-induced convection. Skupniewicz et al. (1991) have presented the only measurement and model examination of the diurnal evolution of the coastal stratocumulus cloud edge and its dramatic effect on sea breeze front dynamics.

## 2.6. Gravity Waves

Gravity waves can exist in regions of the atmosphere that are hydrostatically stable. Gravity waves are generated by vertical displacements of the flow associated with terrain and convection. They may also receive energy from the mean flow in regions of significant velocity shear through Kelvin-Helmholtz instability; the flow becomes unstable to the growth of wave disturbances when the Richardson number, Ri, becomes less than the critical value of 0.25. Above the ABL, the atmosphere is, on average, stable and a significant fraction of free atmospheric variability is thought to be due to a broad spectrum of gravity wave disturbances (VanZandt, 1982). It has been suggested that the persistent background of small scale turbulence in the free atmosphere is caused by local, intermittent breaking of these waves (VanZandt et al., 1979; Fairall et al., 1991).

Gravity waves have received little consideration in traditional turbulence-oriented treatments of the ABL. The dominant features of the vertical structure and dynamics of the convective ABL can be described and simulated with no consideration of gravity waves. For example, in a recent case study of a convective ABL that included observations of gravity waves (Zhou et al., 1985), the authors do not even mention these waves in their conclusions. However, the interaction of the convective ABL with the overlying inversion and the growth of the ABL (i.e., the entrainment process) may require consideration of gravity wave interactions, particularly in the presence of wind shear. One-dimensional entrainment closure models often initially include a term to account for energy lost from the inversion layer by gravity wave radiation (e.g., Tennekes and Driedonks, 1981); this term is later set to zero because its value is unknown and, therefore, assumed small. Carruthers and Moeng (1987) point out that convectively-generated gravity waves with buoyancy frequencies between that of the free atmosphere and the inversion will be trapped in the inversion layer. They use LES to show that these waves can substantially increase the vertical velocity variance of other turbulence moments in the inversion layers. Numerous remote sensing observations of the convective ABL inversion region indicate breaking gravity waves (e.g., Merrill and Grant, 1979) and imply that the entrainment process is very intermittent under these conditions (Carruthers and Hunt, 1986).

Observations of stable boundary layers give ample evidence of the presence of gravity waves (e.g., Gossard et al., 1985; Neff, 1987; Cheung, 1991). In fact, examination of a randomly selected 24-hr backscatter facsimile from an over land acoustic sounder (sodar) is almost certain to reveal wave disturbances of elevated scattering layers at night. Measurements of turbulence in stable conditions typically show highly intermittent events dominate the fluxes. A few studies have explicitly linked this intermittency to breaking gravity waves (Sethuraman, 1980). This intermittency is thought to be one explanation for the frequent break down of surface-layer similarity in stable conditions. Most numerical models of the ABL treat gravity wave processes implicitly. Simple first-order models accomplish this through turbulence length scale and diffusivity parameterizations that depend on Ri in stable conditions. Second-order closure models often have closure constants selected to yield a critical Ri on the order of 0.25 (e.g., Duynkerke, 1988). For these 1-dimensional models gravity-wave dynamics is ignored - turbulence magically appears when Ri is less than the critical value. One problem with this approach is that the vertical scale of the disturbance is often many times the scale of the region with Ri less than 0.25 and the time scale for the growth and breakdown of the disturbance is finite. This implies nonlinearities that are being ignored.

Gravity waves and Kelvin-Helmholtz instabilities can appear explicitly in 2-dimensional and 3-dimensional models (e.g., Sykes and Lewellen, 1982). The most striking demonstration of the importance of these processes for coastal meteorology is contained in the recent 2-dimensional model simulation of a sea/land breeze by Sha et al. (1991). Their simulations indicated that the structure and variability of the ABL near the sea breeze front was dominated by ABL-scale horizontal vortices caused by Kelvin-Helmholtz instability. Frictional force caused by the induced turbulent mixing significantly retarded the inland penetration of the front. The wavelength of these structures was between 0.5 and 3.0 km, suggesting that their effects must be parameterized in coarser-scale models.

## 3. SURFACE-BASED REMOTE SENSORS

A variety of surface-based remote sensors are now being used for meteorological research. All are appropriate for coastal studies. Recent massive increases in minicomputer and microprocessor computational capabilities have led to explosive growth in surface-based remote sensing technologies. There have been order of magnitude improvements in spatial and temporal resolution, height coverage, and the number of atmospheric variables that are detectable. A broad inventory of systems has been developed and maintained at government laboratories (NCAR, NOAA, NASA) and the atmospheric science and engineering departments at roughly a dozen major universities.

Remote sensors are usually classified as active or passive. Passive sensors simply detect radiation emitted by the environment. Active sensors emit their own radiation and detect echoes scattered from the environment (Lenschow, 1986). Both acoustic and electromagnetic radiation are used. The usable parts of the electromagnetic spectrum include visible and infrared light and microwave and shortwave radio wavelengths. The most commonly used active remote sensors are radar and the lightwave (lidar) and soundwave (sodar) analogs. In general, the shorter the wavelength, the smaller the atmospheric entity that dominates scattering of the radiation. Thus, scattering is primarily from refractive index turbulence for shortwave radars and sodar, precipitation for microwave radars, cloud particles for millimeter wavelength radars, and atmospheric aerosols for lidar. In addition to yielding concentration profiles of the scattering entity, active systems can be given Doppler capability to provide wind information. Such systems can have volume scanning capabilities or yield only profiles. A special form of Doppler radar (called codar) can provide two-dimensional maps of ocean surface currents and wave spectra by scattering from ocean surface waves. Passive remote sensors include microwave, infrared, and visible light radiometers. Such systems can yield only integral properties of the atmosphere (e.g., total precipitable water vapor) or can yield some information about vertical distribution by mathematical inversion of multiwavelength radiances.

In this short report we do not attempt to describe all possible remote sensing technologies (see Kaimal, 1990, for more information), but we do highlight a few that can dramatically improve future coastal field programs. The systems we have chosen to highlight are

(1) Scanning radars of centimeter wavelength (operated in dual mode)
(2) High frequency (915 MHz), high resolution ABL wind profilers
(3) Doppler lidar
(4) Millimeter wavelength cloud radar
(5) Multichannel microwave radiometers (moisture and temperature)
(6) Codar

### 3.1. Scanning Radars

Although scanning radars of 1-10 cm wavelength have been used primarily for research on deep convection and precipitating storms, they also have great potential for ABL and coastal meteorological research. Studies of the ABL can use naturally occurring scatterers (pollen, insects, etc.) or chaff dispersed by aircraft. Single systems can provide considerable information on ABL turbulence and dynamics (Kropfli, 1986a), and dual systems can provide volume scans of horizontal winds on scales of tens of kilometers with resolution as fine as 150 m. Figure 4 shows an example of a coastal application of a dual-Doppler system in the Santa Barbara Channel (Kropfli, 1986b). Note the clear definition of a small scale eddy in the center of the volume. This is the only known application of the dual-Doppler radar technique specifically for a coastal meteorology research project.

### 3.2. Wind Profilers

A recent innovation in radar technology is the development of continuously operating Doppler "clear-air" (i.e., able to detect scattering from refractive index fluctuations not associated with clouds or precipitation) radars capable of providing measurements of wind and turbulence profiles on 1-min time scales (Balsley and Gage, 1982). Because of the great value of the around-the-clock wind data, these systems have been given the generic name of wind profilers. The higher frequency (915 MHz) systems (Ecklund et al., 1988) have sufficient vertical resolution (60 m) to be useful for ABL-scale studies. Their relatively low cost and transportability suggest that 10 to 20 units could be deployed in a coastal mesoscale meteorology field program. Such a network combined with a mesoscale numerical model would represent two orders of magnitude improvement in definition of the coastal wind structure. Figure 5 shows an example of diurnal wind speed variations observed in a coastal experiment with a 404 MHz radar. The radar was sited at San Nicolas Island (about 100 km west-southwest of Los Angeles, California). The strong wind jet feature at 400 m height occurred just before midnight local time and was associated with a minimum in the ABL depth. When combined with an appropriate acoustic source, the Doppler spectra can be processed to yield temperature profiles with the same resolution as the wind information. This radio acoustic sounding system (RASS) is a new innovation in wind profiler technology and is still being evaluated, but it suggests that wind profilers can continuously monitor the wind and thermodynamic structure in both the ABL and the free troposphere immediately above it.

### 3.3 Lidars

Through various techniques, lidars are capable of providing profile information on winds, temperature, moisture, and concentration of aerosols and trace gases such as $O_3$, $SO_2$, and $NO_2$ (Schwiesow, 1986). Both airborne and surface-based Doppler systems hold great promise for coastal meteorological research. The LAnd/Sea Breeze EXperiment (LASBEX), held in Monterey, California, in 1987 is the only use to date of a land-based Doppler lidar in a coastal region (Olivier et al., 1991). Figure 6 shows a four hour period with a transition from a land-breeze regime to a sea-breeze regime in the late morning (sunrise is at about 1400 UTC). Note that in this example the land breeze ceases first over the land and the sea breeze is most intense right at the coast. The LASBEX lidar offer a unique picture of the small-scale structure of the land/sea breeze system. The major advantage of lidar over the centimeter-wavelength radar discussed above is the ubiquitous presence of atmospheric aerosols; thus, chaff are not needed even in very clean marine environments. Lidars are also capable, at least in principle, of significantly better resolution than the centimeter-wavelength radars. The major disadvantage of lidars is their inability to penetrate clouds. Therefore, the application is best suited for cloudfree or subcloud studies. A combined lidar and millimeter wavelength radar program would be an excellent way to study coastal stratocumulus regimes.

### 3.4. Cloud Radars

Millimeter-wavelength radars are able to detect scattering from water droplets in clouds and are often referred to as cloud radars. Early work was done with derivatives of military surplus systems at 35 GHz (8.6 mm wavelength). A few 35 GHz systems have been constructed specifically for meteorological research (Pasqualucci et al., 1983), and in the last 5 years three 94 GHZ (3.2 mm wavelength) systems have been constructed (Lhermitte, 1986), but only the most preliminary results have been published. Because of the extremely short pulse lengths and narrow beams of these systems, spatial resolution of about 3m is practical. This permits us to study small-scale cloud processes, such as entrainment, that are usually impossible to observe with conventional methods. Because cloud radars are quite new and only a few systems are available, they have not yet seen extensive use in meteorological field programs. They have not yet been used in coastal work. However, their unique ability to examine details of cloud dynamical and microphysical processes suggests they are very well suited for studies of coastal cloud.

### 3.5. Microwave Radiometers

Microwave radiometers capable of providing limited resolution profiles of temperature and humidity are standard on meteorological satellites. A few upward-looking systems have been constructed specifically for ground-based use. Dual channel systems can provide integrated water vapor (precipitable water) and liquid (Hogg et al., 1983) on 1-min time scales. Multichannel systems in the 60 Ghz atmospheric oxygen absorption bands can provide temperature profiles, although with limited resolution. Figure 7 shows an example of a time series of integrated cloud liquid water content for coastal stratocumulus clouds at San Nicolas Island (Albrecht et al., 1990). The measured time series is compared with values computed using the adiabatic relationship employed in most stratocumulus cloud models. Other periods (not shown) had significant departures from the adiabatic relationship, indicating that cloud decoupling and drizzle processes were important. These data were also used in a unique study of cloud-radiation parameterizations (Fairall et al., 1990) in the coastal zone.

### 3.6. Codars

Radio waves scattered from the sea surface at wavelengths of about the ocean wavelengths produce a characteristic Doppler spectrum often referred to as the Bragg scattering spectrum. This spectrum can be evaluated to estimate the radial component of the sea surface current. Two independent systems separated by tens of kilometers will give two-dimensional maps of the surface vector current. This technique is called the coastal ocean dynamics applications radar (codar). This technology (Frisch and Weber, 1982) was developed in the late 1970s and early 1980s but it has seen only limited application in coastal oceanographic and meteorological research programs in the United States. With the recent appearance of commercially available systems, this should change. Figure 8 shows an overlay of two codar derived surface current vector maps taken 2-h apart. A tidally driven gyre is evident in the center of Monterey Bay. Tidal rotation of the current vectors can be seen at a number of locations. Once the tidally driven currents are removed, the codar-derived surface currents will be a sensitive indicator of air-sea wind coupling. The Bragg spectrum can also be processed to obtain the ocean directional wave spectrum. This, however, is much more complicated than simply deducing the surface current. Codar has the potential to become a powerful tool for observing the modification and evolution of directional ocean wave spectra in the coastal zone.

## 4. SUMMARY AND CONCLUSIONS

Our understanding of coastal boundary layer processes will, to some extent, be improved by general advances in boundary layer science. However, some problems are more specific to the coastal regime and require immediate study. Theoretical developments, modelling studies, and field measurements programs are required. Surface-based remote sensors are well suited for application to many aspects of these problems and are expected to play a major role in this research. A summary of the coastal ABL issues discussed in this report is given below:

*Fundamental work on ABL properties for inhomogeneous and non-equilibrium conditions including suitable surface flux and mixed-layer similarity parameterizations and the general relationships of the ensemble average first and higher-order turbulence variables.

*Fundamental theoretical relationships between the ocean wave spectrum, the surface fluxes, and bulk properties.

*The physical process of the growth of the top of the stable IBL, both entrainment and induced mean vertical velocity effects, and decay processes of turbulence above a newly formed IBL.

*Coastal marine stratocumulus and overland fair weather cumulus cloud regimes and their influence on land/sea breeze cycles.

*The role of gravity waves and Kelvin-Helmholtz instability.

The theme of all of these issues is centered on a break with the simple homogeneous mixing concepts that have been the basis of most of our thinking in micrometeorology and boundary-layer meteorology. This attitude is reflected in the inside joke, "Micrometeorologists are like Dorothy, they always want to go back to Kansas." Patchy surfaces, broken cloud structures, and three-dimensional dynamics have led us to repudiate the Dorothy viewpoint, even for Kansas. For the coastal regime, we must go back and re-examine all conventional wisdom for dealing with boundary layers.

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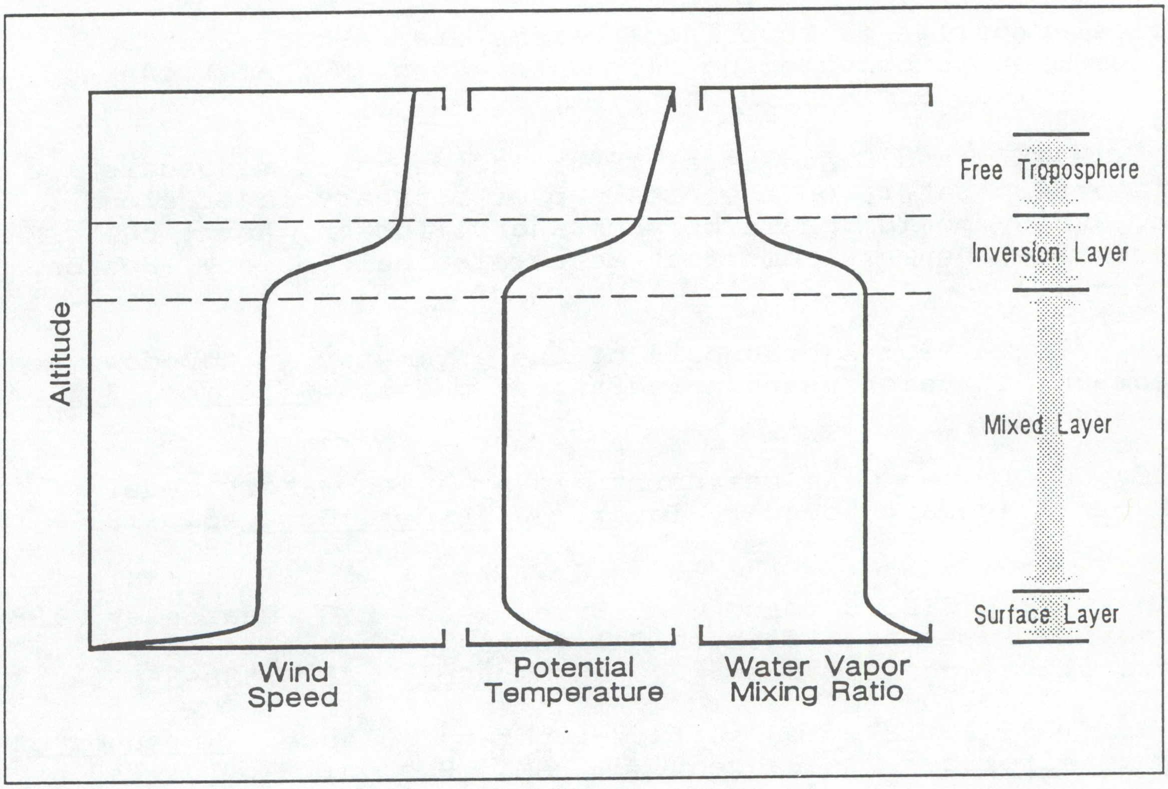



Fig. 1. Schematic of a typical convectively mixed ABL (from Fairall et al., 1982). Wins speed ($u$), water vapor mixing ratio ($q$) and potential temperature ($\theta$) are shown as a function of height. The turbulent ABL occupies the region below the upper dashed line.

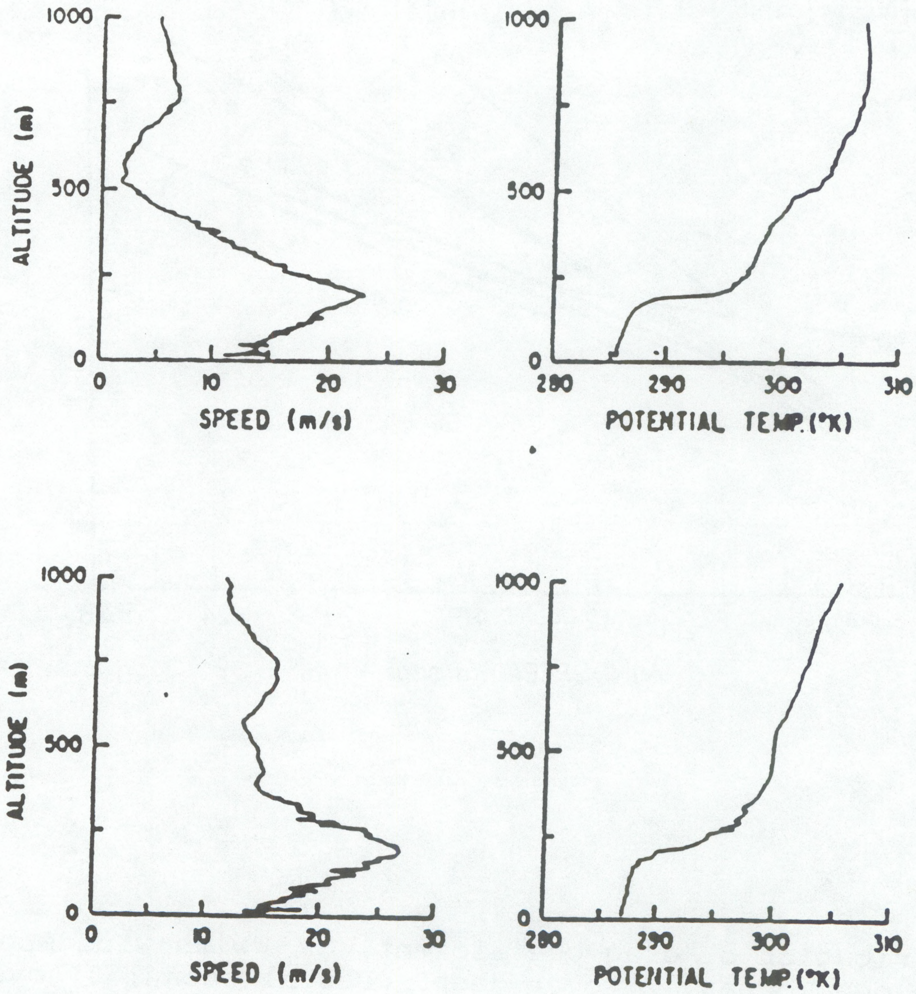



Fig. 2. Vertical profiles of wind speed and potential temperature at two different locations along the North Coast of California (Winant et al., 1988). Note the strong low-level inversion in potential temperature at approximately 250 m altitude, coincident with the maximum in wind speed. Contrast these profiles with the simple mixed-layer structure depicted in Fig. 1.

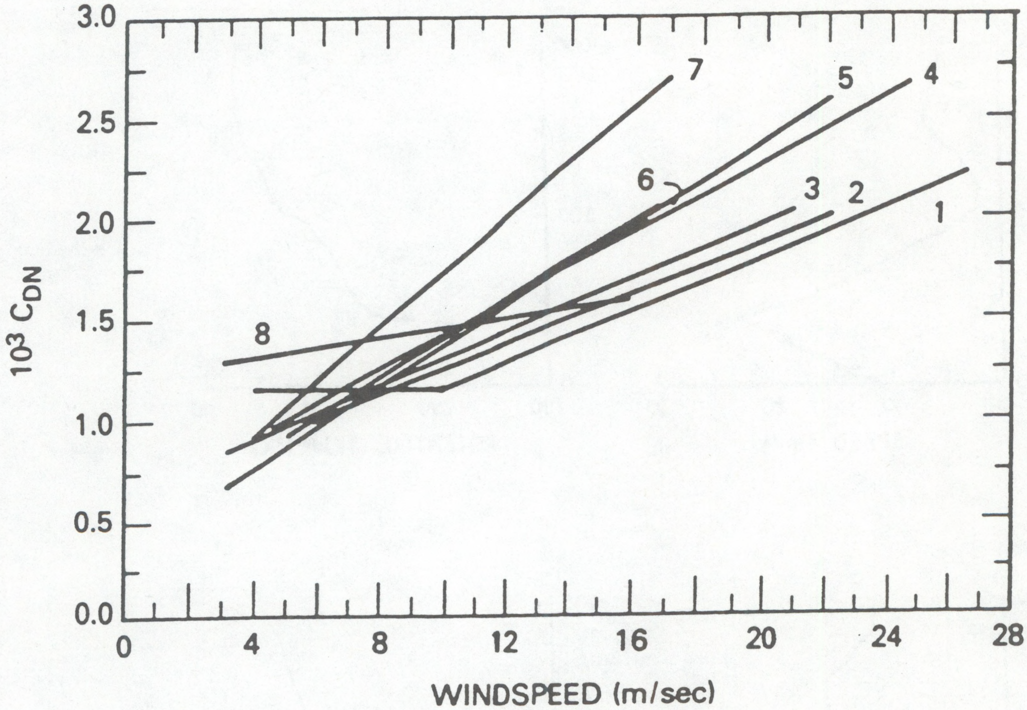



Fig. 3. Distribution of drag coefficient, $C_{dn}$, with wind speed: 1) over deep open ocean; 2) over deep, coastal ocean; 3) over deep water; 4) North Sea depth of 30 m; 5) North Sea depth of 16 m; 6) Lough Neagh depth of 15 m; 7) Lake Ontario depth of 10 m; 8) Lake Geneva depth of 3 m (from Geernaert, 1990).

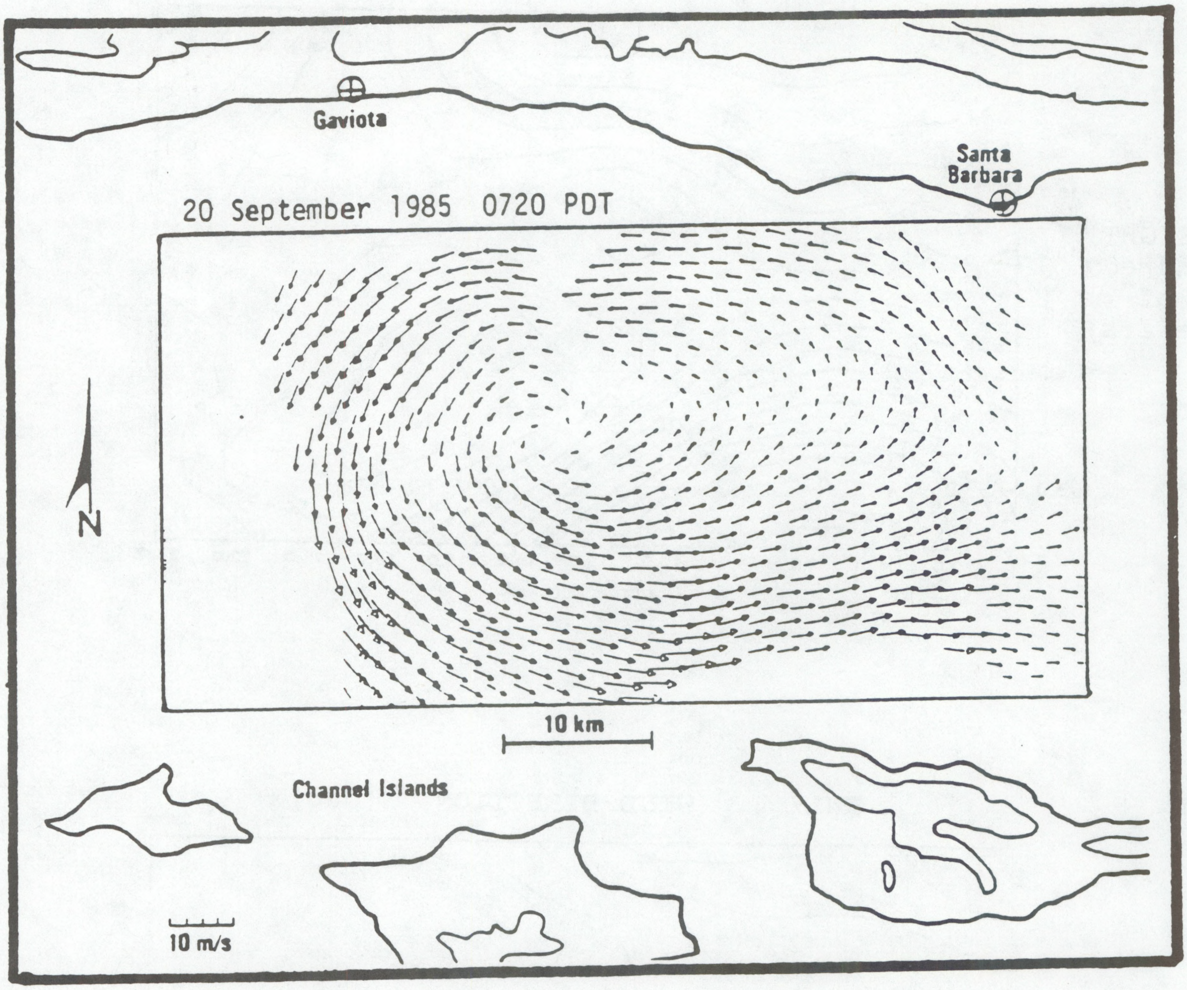
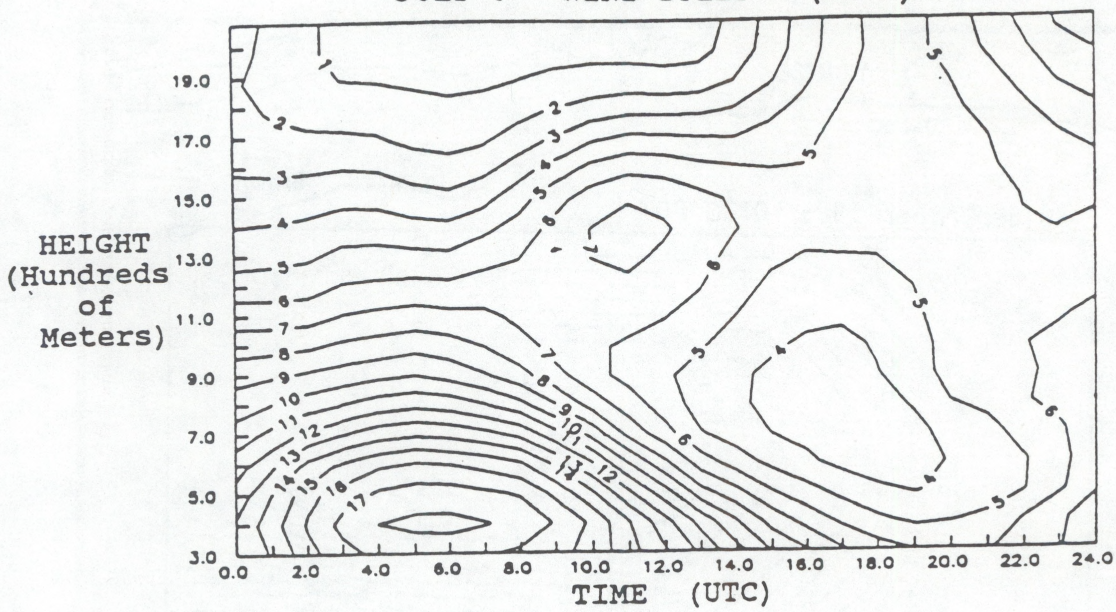


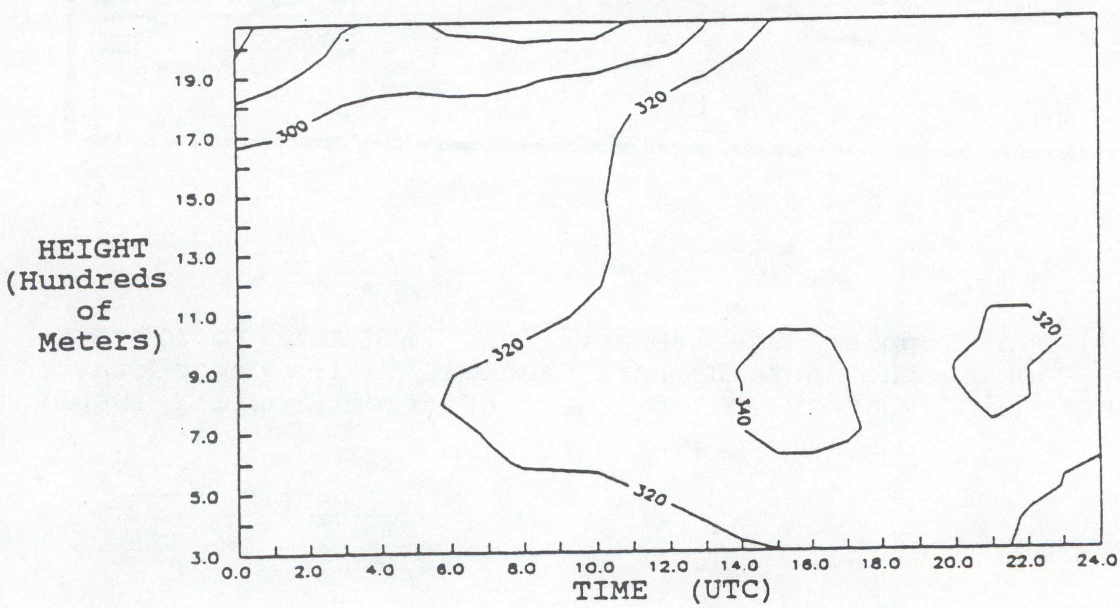

Fig. 4. Dual-Doppler radar observations with the NOAA/WPL X-band systems in the Santa Barbara Channel. A 1-h composite of horizontal wind vectors in the lower ABL (from Kropfli, 1986b).

JULY 4 WIND SPEED ($ms^{-1}$)




(a)

JULY 4 WIND DIRECTION (deg)




(b)

Fig. 5. Wind speed and direction contours for the day July 4, 1987 at San Nicolas Island as measured by a 404 MHz wind profiler (from Syrett, 1988).

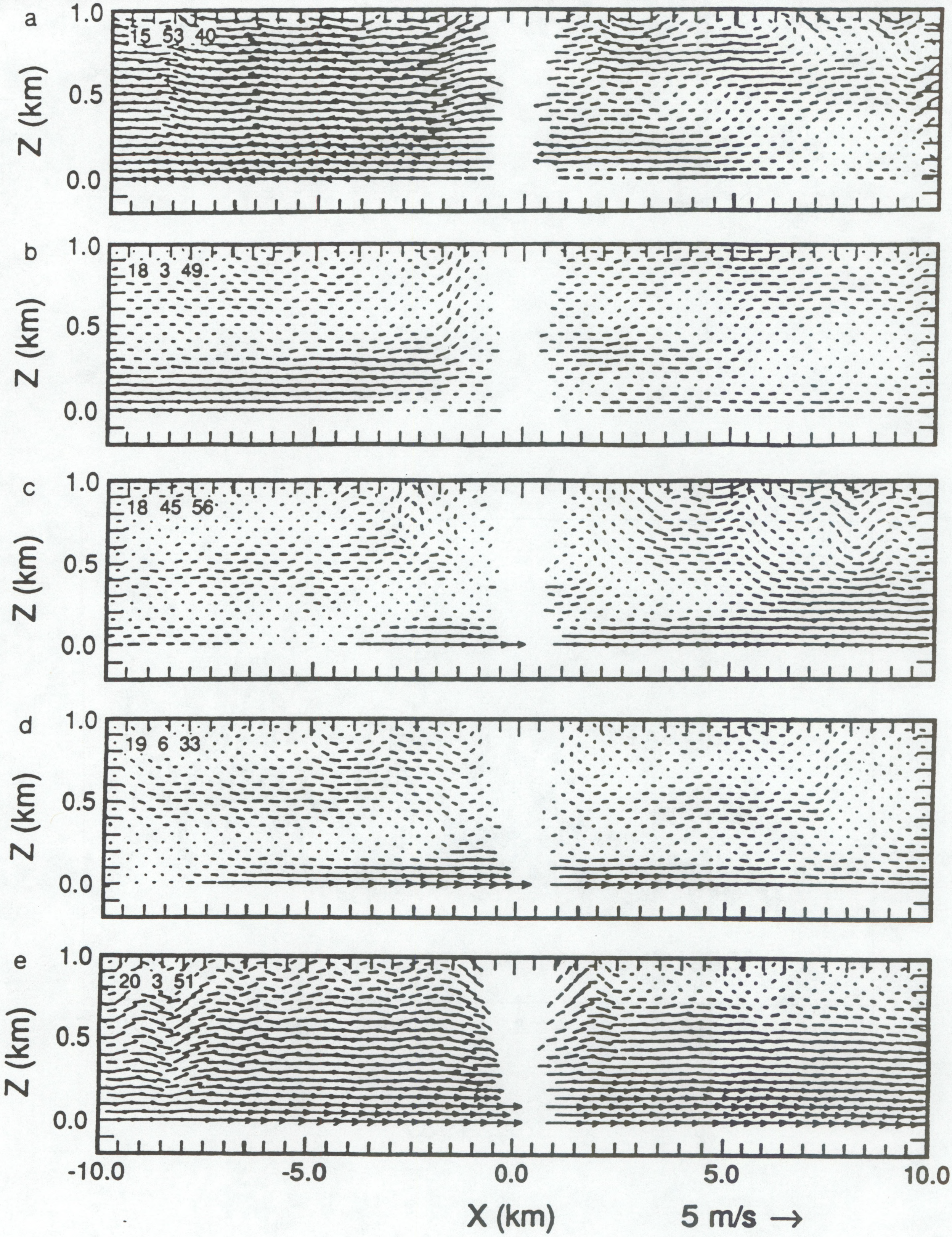



Fig. 6. Doppler lidar wind vector measurements in a plane perpendicular to the coast near Monterey, California, depicting a 4 hour period in the transition from a land breeze to a sea breeze (sunrise is about 1400 UTC). The lidar is located at (0,0) 1.5 km inland, Monterey Bay is to the left, and land is to the right (from Olivier et al., 1991).

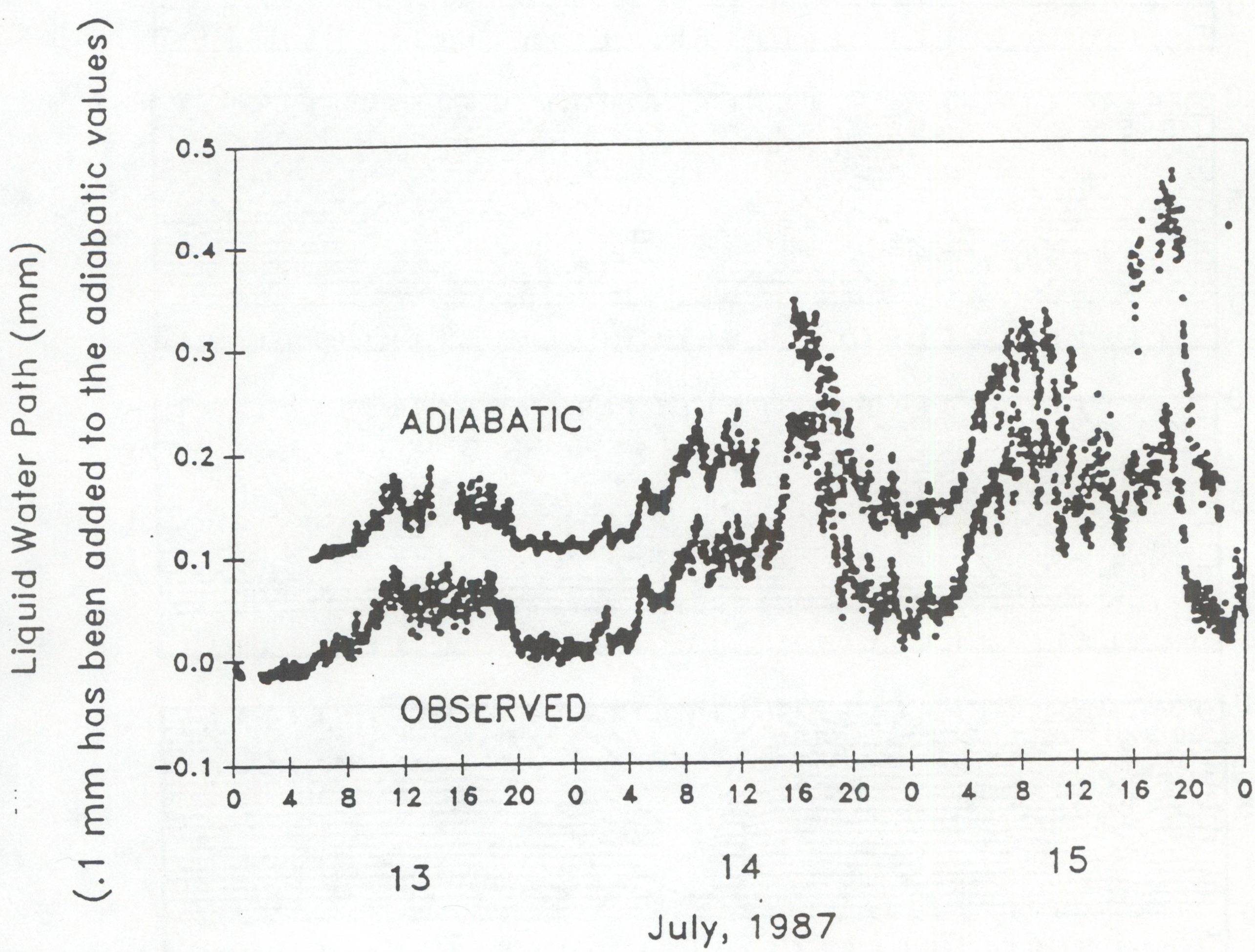



Fig. 7. Time series of the observed integrated cloud liquid water from a microwave radiometer and the adiabatic value calculated with ceilometer measurements of cloud base height and sodar measurements of cloud top height. Each point represents a 2-min average. The adiabatic values are offset vertically by a constant 0.1 mm to aid in the visualization (from Albrecht et al., 1990).

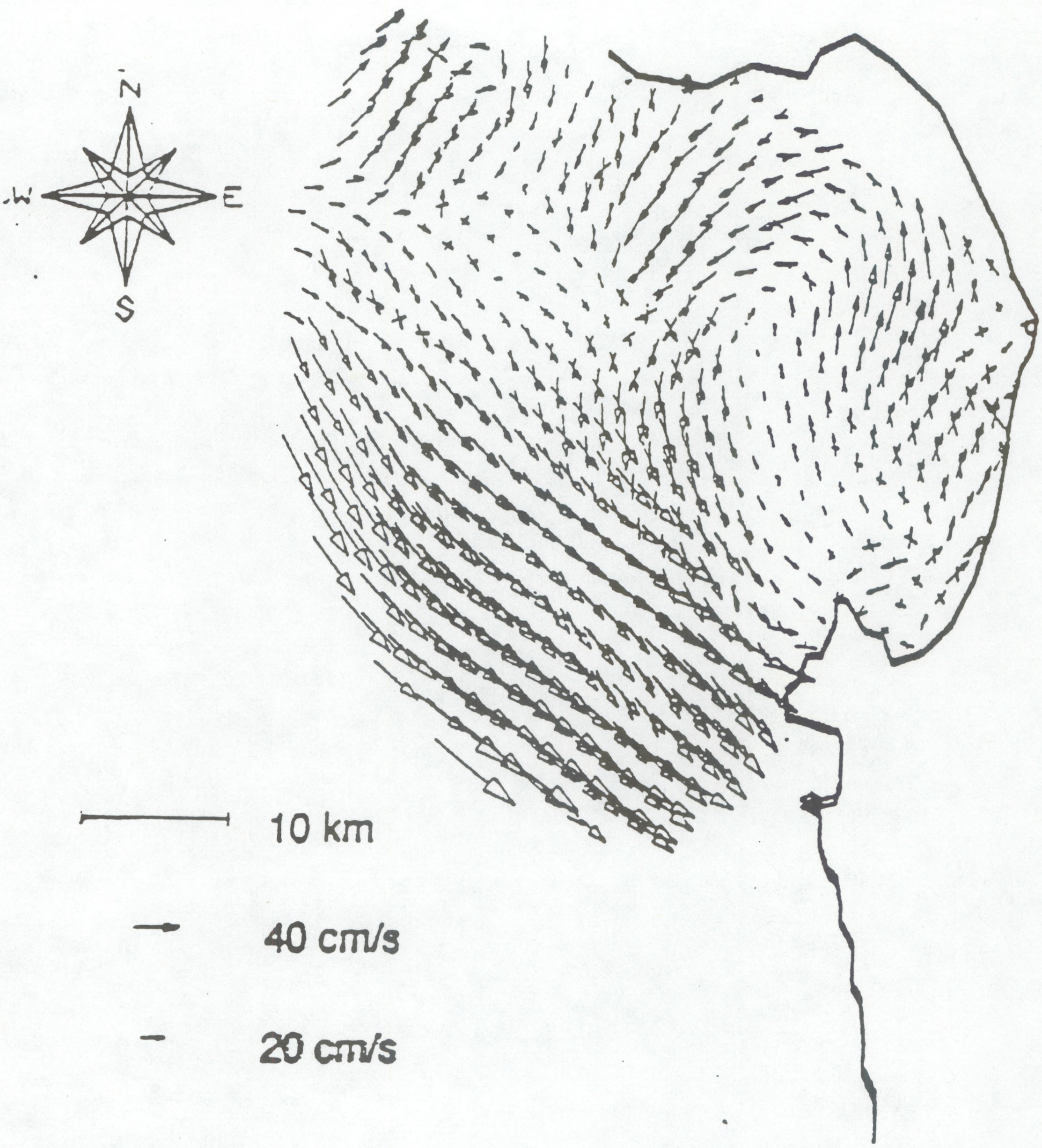



Fig. 8. An overlay of two codar surface current vector maps taken 2 h apart on July 4, 1991, in Monterey Bay, California. Data courtesy of D. Barrick, Codar Ocean Sensors, Ltd., Mountain View, CA.



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