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Atmospheric Transport and Diffusion Mechanisms in Coastal Circulation Systems

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Prepared by R. J. Kaleel, D. L. Shearer, B. L. MacRae/TRC

TRC Environmental Consultants, Inc.

Pacific Northwest Laboratory
Operated by
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Commission

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Coastal Circulation Systems Diffusion Mechanisms in Atmospheric Transport and

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EXECUTIVE SUMMARY

The study being reported here was sponsored by the U.S. Nuclear Regulatory Commission (NRC). It has been directed toward defining the cyclical and cellular atmospheric processes that are of key importance to the NRC with respect to predicting transport and diffusion of radionuclide emissions from nuclear power generating facilities located in coastal regions. This was done to provide a firm basis for design of new measurement programs which the NRC plans to conduct to derive information from which to improve current predictive methods.

The following conclusions are made from this analysis:

- o The sea breeze portion of the cyclical coastal phenomena has been studied, both empirically and theoretically, more than its land breeze counterpart. The transition periods between the two have essentially not been investigated at all.
- o Atmospheric processes occurring within the thermal internal boundary layer (TIBL) during sea breezes are reasonably well understood.
- o The factors controlling transport and diffusion in coastal regions are largely local scale factors. Because these controlling factors are localized, dispersion conditions are highly complex and site specific, and are not often amenable to generalization.
- o Considerable efforts have been devoted to the development of modeling techniques which are capable of simulating atmospheric processes in coastal zones. Such efforts are ongoing, but the models that have been developed are probably not yet ready to be utilized in an operationally predictive mode.
- o Gaussian models cannot provide a rigorous description of transport and dispersion mechanisms in coastal regions, but may provide useful guidance when quick response is necessary. Because of the complexity of coastal atmospheric dynamics, the guidance provided by Gaussian models should be interpreted carefully by experienced personnel.
- o Numerical models do provide reasonably accurate descriptions of atmospheric processes, and may be quite useful for many applications. However, because of the

substantial computer resources required by numerical simulations, they may be inappropriate during situations when quick response is necessary.

- o A rigorous validation of existing modeling techniques has not been performed to date. The validation efforts conducted thus far have utilized data of unknown quality and provide, at best, an incomplete representation of the coastal atmosphere.

The following recommendations are provided to ensure that future research efforts in coastal regions are directed towards aspects that have yet to be documented or studied extensively:

- o A thorough meteorological monitoring program, which addresses all aspects of coastal circulations, should be undertaken. Such a program should be designed to measure the entire diurnal cycle, but, at a minimum, should address the land breeze portion of the cycle, and the transition between the land breeze and the sea breeze.
- o Because the factors which control the evolution and development of coastal circulations are largely local scale factors, meteorological monitoring programs should be conducted in a number of locations and terrain types.
- o Improved techniques to measure meteorological phenomena offshore, with accuracies comparable to on-shore measurements, need to be developed.
- o Efforts to develop modeling techniques applicable to coastal regions should be maintained. Gaussian models incorporating dispersion coefficients representative of various coastal zones and terrain types, and an algorithm, such as that proposed by Lyons, which can simulate continuous fumigation conditions should be developed. Numerical models, such as Pielke's Numerical Mesoscale Model, should be expanded to simulate not only transport processes, but turbulent diffusion processes as well.
- o A detailed model validation program should be undertaken to evaluate and improve simulated results. The performance of the various models for predicting circulation elements and pollution concentrations probably cannot be evaluated with existing data bases.

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1.0 INTRODUCTION

During recent months TRC has completed a critical review of historical studies on atmospheric dispersion conducted in coastal regions (Shearer and Kaleel, 1982). TRC then compiled a compendium of coastal dispersion coefficient values from the data assembled for the Critical Review (MacRae, Kaleel, Shearer, 1983). These studies were performed on behalf of the U.S. NRC to provide an assessment of existing information about atmospheric dispersion in coastal regions and to extract and develop dispersion coefficients from these existing data. The overall intent has been to restrict attention to application of the information to the field behavior of radionuclides that may be emitted from nuclear power generation facilities which are located or are planned to be located in coastal regions.

During the course of these above-described studies it has become abundantly clear that although numerous data sets do exist, and much needed information can be derived from these data, some aspects of atmospheric dispersion in coastal environments are yet to be documented by measurements or to be extensively studied. One aspect that is yet to be rigorously pursued is the primary emphasis of this present report--that of the cyclical aspects of coastal atmospheric circulations and in particular, the transition periods of those cyclical phenomena.

We have seen that most of the dispersion studies conducted in coastal regions have, by design, been conducted during periods of near-steady-state conditions. This being the case, those periods of transition from within the cyclical phenomena have essentially gone unstudied. As a result there exists a biased data base wherein the transition periods for all intents and purposes are unrepresented. Likewise, methods to predict the processes of atmospheric transport and diffusion during those transition periods do not exist. Further, since the transitions are not represented in current predictive techniques, the full cycle of land/sea breezes including the recirculation considerations are not represented by current transport and diffusion predictive methods.

It is the intent of this study and the main objective of this report to define the cyclical aspects of coastal atmospheric behavior that are important to the transport and diffusion (dispersion) of radionuclides. Further, it is intended that this report summarize the level of knowledge and identify the unknowns relating to atmospheric dispersion during those special periods.

This summary document is prepared at this time to serve the NRC as a point of reference. It is intended that this document will, in part, provide a firm basis for the design of new measurement programs which the NRC is conducting to develop better and more complete methods of predicting the field behavior of emissions from nuclear power generating facilities located in coastal regions.

The sources of information employed in this analysis consisted largely of the historical data base assembled for the Critical Review referenced above. To this data base have been added several recent works which were unavailable at the time of the Critical Review. Most notable of the added references is the Proceedings of the Workshop on Coastal Atmospheric Transport Processes which was held at Brookhaven National Laboratory, July 13-15, 1982. This Workshop comprised an extensive summary of recent work on atmospheric processes that occur in coastal regions.

This report is developed around discussions of the meteorological dynamics of the cyclical (and cellular) atmospheric coastal phenomena and the atmospheric transport/diffusion mechanisms along with an assessment of the measurements accompanying both. Further, the efforts directed to modeling both the atmospheric and transport/diffusion processes are summarized and evaluated. Lastly, the review is summarized through a set of conclusions about the current level of understanding of coastal atmospheric phenomena. Recommendations are offered which identify certain aspects of local scale cyclical coastal phenomena that are important to the NRC.

2.0 METEOROLOGICAL PROCESSES

2.1 DYNAMICS OF THE COASTAL ATMOSPHERE

By comparison with land surfaces, large water bodies exhibit several different features which are important for atmospheric dispersion. These differences fall into two general categories: energy exchange and surface roughness. Solar radiation can penetrate a water body, while energy exchange is confined to the surface for a land mass. Water also conducts heat more readily than land. Both of these factors result in much slower surface heating in the presence of incident solar radiation for a water surface than for land. Evaporation/condensation processes also tend to moderate surface heating and cooling. The highly convective conditions which can occur over land with intense solar radiation are therefore unlikely to be experienced over water.

Surface roughness over water especially during periods of land/sea breeze conditions is generally much less than over land. When wave action is not pronounced, the surface is quite uniform. For air moving over the water surface, friction is low and turbulence produced by surface roughness is also low. The variation of wind speed with height is, in most cases, less over water than over land, due to the lower frictional effect. Unlike the land surface, however, a water surface has variable roughness due to wave action. Dispersion over water may therefore depend upon the sea state (which in turn may vary with wind speed and direction). This variation though is normally small at ambient wind speeds characteristic of the cyclical coastal regimes which are of the most concern here. Another factor which can influence the variation of wind speed with height is the presence of a shallow stable layer which frequently occurs over the water. This stable layer, which forms when air temperatures are warmer than sea-surface temperatures, can effectively decouple the lowest layer of the atmosphere over water from the winds aloft, resulting in a significant vertical wind shear.

The difference in atmospheric dynamics also produces a difference between mixing heights over water and over land. During the day, mixing heights over land commonly extend up to thousands of meters as the result of increased surface heating and convective activity. Over water, with greatly reduced heating and convection, mixing heights are frequently much lower.

Coastal dynamics at the land/water interface add considerable complexity to dispersion behavior. Under intense solar radiation, the land surface heats more rapidly than the water surface. The resulting temperature differential produces convective activity over the land, but not over the water. A local sea breeze circulation pattern can develop, with onshore flow at the surface and a compensating offshore flow aloft. The atmospheric turbulence behavior will also change abruptly at the land-water interface. With onshore flow, the relatively stable (low turbulence) conditions over water will change to convective (highly

turbulent) conditions over land. The region where this transition from stable to unstable behavior occurs is bounded by a zone termed the "thermal internal boundary layer (TIBL)." The height of the TIBL will increase with onshore distance, as the convective activity becomes more pronounced.

The physical characteristics of internal boundary layers have serious consequences with respect to diffusion conditions in coastal regions. Characteristics of internal boundary layers are determined primarily by wind speed, temperature, and roughness differences over the coastal discontinuity. Vertical mixing within boundary layers is enhanced due to both thermodynamic and aerodynamic changes from the over water fetch to the onshore conditions and is inhibited above the boundary layer because of a thermally stable layer aloft. Diurnal changes in coastal internal boundary layer heights are generally smaller than the mixing heights at inland locations. Consequently, prolonged periods of constant diffusion conditions can be expected in coastal regions.

Effluents emitted above the boundary layer (as would be the case with stack emissions from a plant located at the shoreline) into onshore flow may become entrained into the TIBL and as a result be transported to ground level rapidly and persist for prolonged periods during fumigation conditions. This aspect of coastal dispersion has been studied by several investigators and is graphically illustrated in Figure 1. Emissions from elevated stacks which are entrained into the boundary layer during onshore flow can result in higher concentrations because of rapid vertical mixing beneath the TIBL. Emissions from stacks during offshore flow may remain above the shallow internal boundary layer, but may result in

Figure 1. The relationship between internal boundary layer and plume fumigation under gradient onshore wind condition (Lyons and Cole, 1973).

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fumigation if the flow passes over another land mass. Hence, the potential for adverse effects from effluent emissions is greater in coastal areas than inland sites because of the existence of the coastal internal boundary layer and the persistent nature of the wind flow.

It is apparent that the meteorological processes involved with the internal boundary layer are important to the diffusion of effluents in coastal regions. Raynor, et al (1979) describes how internal boundary layers affect the character of dispersion in coastal regions. Overall, the presence of boundary layers cause ground-level concentrations from effluent releases in coastal regions to be higher than at inland areas primarily due to the vigorous downward mixing which takes place below the TIBL. Additionally, persistent winds normally associated with the TIBL tend to exacerbate the situation by confining pollutant impact areas to restricted regions for extended periods of time.

Although internal boundary layers are an important aspect of coastal meteorology and resultant dispersion conditions, the diurnal and cellular aspects of coastal circulation regimes are also important with respect to the dispersion potential. An often ignored aspect of the land and sea breezes is their potential for recirculating pollutants. The cellular structure of either the sea or land breeze circulation system creates the possibility that pollutants emitted into such a system could cycle back to or nearby the source region. The half-life of radionuclides is generally much longer than one day. Such effluents emitted into a sea or land breeze could impact populated areas even though the transport winds do not appear to be directed towards those areas. This potential can be seen in Figures 2 and 3. These figures describe a lake breeze and land breeze which are essentially inland versions of the sea/land breeze. This aspect of coastal dispersion should be of particular interest to NRC.

The sea breeze, responding to uneven heating of the surface, is the stronger and most persistent of the two portions of the circulation. The sea breeze is also larger spatially than the land breeze. Hsu (1970) reported that the sea breeze has been observed to extend onshore for distances of tens of kilometers along the Gulf coast of southern Texas. In cases where the gradient wind flow is in the same direction as the sea breeze, the onshore winds may extend even further (Ettenheim, 1967; Smith, 1963). Topographic features affect the distance that a sea breeze extends inland. Where mountains are oriented parallel to the coastline, such as those occurring in southern California, the sea breeze generally does not extend beyond the topographic feature. Not only do the mountains present a physical barrier to the wind flow, but they also serve as a perturbation mechanism for convective activity. This perturbation acts to establish the return flow aloft thereby cutting off the inland extent of the onshore flow.

The sea breeze circulation system also extends offshore for significant distances. The California coastal sea breeze has been

Figure 2. Characteristics of the Lake or Sea Breeze (from Keen and Lyons, 1978).

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Figure 3. Characteristics of the Land Breeze (from Keen and Lyons, 1978).

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observed as far seaward as San Clementi Island, some 90 kilometers from the coast (Prophet, 1961). Prophet also reports that in cases where mountains located near the shoreline limit the inland extent of the sea breeze, the sea breeze tends to extend for greater distances offshore. Prophet noted cases where the sea breeze has been observed as far offshore as 125 miles.

The vertical extent of the circulation systems are largely determined by the density differentials of the air over the cool and warm surfaces. The sea breeze may extend vertically from 500 meters in depth to as high as 3,000 meters (Hsu, 1970). By contrast, the land breeze circulation is shallower, weaker, and of shorter duration than the sea breeze cell and in some cases the return flow aloft is completely absent.

The diurnal cycle from a sea breeze to a land breeze and vice versa has a great potential for the recirculation of airborne pollutants back to a source region. Typically a sea breeze, as it develops, has an initial direction normal to the coastline, but then begins to shift because of the effect of the Coriolis force. Haurwitz (1947) and Staley (1957) constructed hodograms, both from a theoretical approach and from observations, which show that the rotation of sequential hourly wind vectors is usually (but not always) in a clockwise direction. In fact, when examined for an entire daily cycle, through both the sea and land breeze portions of the cycle, the hodograms typically took elliptical forms, with the degree of ellipticity determined largely by frictional effects. Hence pollutants emitted from a coastal location at night may be transported towards the sea by a land breeze only to be carried back to shore the next day as the sea breeze develops.

Diurnal coastal circulations are affected by synoptic scale gradient winds. When the gradient wind is from the same direction as the sea breeze it will tend to enhance the circulation by increasing the speed of onshore flow and the distance that the cellular flow will extend inland. However, the return flow portion of this circulation will be weakened or suppressed. The same processes will be seen in reverse when the gradient wind flow is in the same direction as the land breeze. When gradient wind flows oppose the land or sea breeze flow, the diurnal circulations will be weakened or destroyed depending on the strength of the gradient flow. When the gradient wind is at some angle to the normal diurnal circulation, the sea breeze (or land breeze) and the return flow aloft can be redirected depending on the strength and the off angle of the gradient wind. Bush (1980) attributed observed along shore transport of effluents emitted near the land/water interface to off angle gradient winds.

Several investigators have observed unusual flow patterns to exist within diurnal cyclical flow regimes. One that is particularly noteworthy because of its potential pollutant impact is the helical trajectory form. The helical flow pattern can take two forms. One form involves both the sea breeze onshore flow and the return flow aloft. The

second consists of a smaller scale helical form caused by dynamical forces but is imbedded in the onshore flow or in the flow over open water. The above reference to along shore transport of effluents by Bush (1980) was as a result of off angle gradient flow. The off angle gradient wind flow caused the effluents that were being transported onshore by the sea breeze to be carried at a small downshore angle. As the return flow carried the effluents back out over the water, the return flow was also turned to a small downshore angle. As the effluents were carried through the full sea breeze cycle, they were brought back to the surface level and carried onshore at a location downshore from the original emission (see Figure 4). The track of this circulation describes a helical form.

Figure 4. Helical trajectory resulting from off-angle gradient winds and involving the sea breeze as well as the return flow.

The second form of the helical trajectory is far less understood and has been observed on fewer occasions but also warrants study due to the potential impact on NRC areas of concern. Hallanger (1962) described a helical form of trajectory as the onshore wind lifted over bluffs located at the shoreline. The resulting trajectory was of sufficient amplitude that it lifted atmospheric tracer material being used for diffusion experiments off the ground and later brought it back to the

ground level at distances greater than one kilometer downwind (see Figure 5). Pack (1962) observed two tetrons released simultaneously. The tetrons were caught up in adjacent vortices and executed full helical cycles in opposite directions. Smith (1963) observed downward velocities of atmospheric tracers released aloft (500 to 1,000 feet MSL) at the shoreline to be 50 to 100 feet/minute during some tracer experiments. He concluded that such downward velocities occurred in isolated locations during isolated periods and were probably caused by a form of helical trajectory. Smith also noted that such a helical trajectory could be experienced during conditions consisting of: 1) widespread uniform lifting of the air at the surface layers (coastline topographic perturbation); 2) near-neutral temperature lapse rates; 3) a more stable layer aloft (in the range of a half kilometer altitude); and 4) a moderate wind velocity to organize the motion longitudinally into a helical pattern. Woodcock (1942) observed what appears to be the same form of helical trajectory pattern over the open water. He observed from bird soaring patterns that such a trajectory existed under certain conditions. He suggested that when water temperatures are 2° to 3°C warmer than air temperatures during moderate wind speeds, convection can take the form of helical vortices rather than the classical localized form seen over land.

Figure 5. Helical trajectory within a sea breeze.

In more recent investigations, Lyons and Olsson (1973) observed a helical trajectory form during their mesoscale study of dispersion in the Chicago lake breeze. In a numerical model simulation McNider and Pielke (1979) saw a helical trajectory develop in a solution to their modeling study of a sea breeze/return flow circulation over southern Florida.

There appears to be ample evidence that helical trajectories can and do occur. However, as Smith (1963) notes, such occurrences are difficult to observe quantitatively without unusual preparation and unusual techniques. The end result of such helical trajectories can be that emissions caught up into such a structure could be lifted above the ground surface and later brought back down to the surface at a location not only downwind but also off the angle of the expected trajectory. This occurrence would of course have a profound effect on predictions of effluent footprint patterns.

Topographical features and condition of land and sky affect the occurrence, direction, intensity, and extent of land and sea breezes. Gently rising hills and valleys tend to reinforce the diurnal circulations because of upslope and drainage flows associated with such topographical features. Irregularly shaped coastlines and shallow waters of bays and lakes cause variations in sea and land breeze directions and intensities (Hsu, 1970). Numerous investigators have observed that coastlines having peninsular shapes can lead to intensified sea breezes due to the convergence of onshore winds and enhanced convective activity. Neumann, et al, (1974) studied the same processes over large and small islands and Pielke (1974) modeled and observed similar phenomena at the southern tip of Florida. Conversely, coastlines having shapes in the form of bays can experience diverging sea breezes and less intense convection. Likewise, uniform coastlines such as Florida tend to cause more uniform, reproducible flows (Van Der Hoven, 1967). The frequency and duration of sea breezes is greater in lower latitudes because of more available insolation and weaker synoptic gradient flows. Clear skies and dry, vegetation-free land allow the greatest insolation as well as radiational cooling, creating conditions favorable for strong land and sea breezes.

Variations in the diurnal cyclical wind flow patterns can be seen as a function of the season (Schacher, 1982). This variation is in large part due to the energy balance as it varies from season to season. During summer months when incoming solar radiation is at its maximum for the longest time, and land/water temperature differences also are at their maximum, the sea breeze can be expected to experience its earliest onset and persist the longest into the evening. During the summer period the land breeze occurs for only a short period of time. Conversely, during the winter months when solar insolation is at its yearly minimum the sea breeze may still occur but it persists for a shorter period of the day. The land breeze during this season occurs for a longer period and in some cases is the dominant of the two halves of the diurnal cycle.

2.2 EVALUATION OF COASTAL MEASUREMENT PROGRAMS

A review of field measurement programs conducted in coastal regions was completed as part of the previously referenced Critical Review. The major programs conducted in recent years were portrayed graphically by a map showing the locations of those measurement programs and by listings in a table. The map and table are reproduced here as Figure 6 and Table 1 to reiterate the extent of historical meteorological measurement programs. It was concluded in the Critical Review that measurement programs conducted in coastal zones have been primarily concerned with the structure of the sea/land breeze circulation system, and in particular the sea breeze cell. As a result, such studies were usually of short duration (from several days to a month or two), and were typically conducted in daylight hours during the spring and summer months when gradient winds were light and air-water temperature differences were at a maximum. Because the structure of the sea breeze has been the major topic of concern, other aspects of the coastal regime have not been studied extensively. The land breeze portion of the diurnal cycle has not received as much attention as its daytime counterpart. This is due to the fact that population densities are low over water, and also owing to the obvious difficulties in making accurate measurements over water. Additionally, the transition periods between the sea and land breeze have gone essentially undocumented by measurements. This, of course, leads to a complete lack of knowledge regarding the nature of atmospheric trajectories during the time period between the two portions of the diurnal flow.

In light of the conclusions of various researchers that the reversal of the land breeze to a sea breeze can cause pollutants emitted at night to be transported back over land, the full diurnal cycle is undoubtedly of interest to the NRC and should be represented by extensive measurements. Similarly, summertime measurements allow the collection of data during periods when the land is warmer than the water. However, during the winter months, especially in the Great Lakes region, the water temperatures are higher than over land. This results in very unstable atmospheres over water, and can set up a persistent land breeze when gradient winds are light. With the exception of Phillips (1972) and Lenschow (1973), this area of coastal meteorology has received very little investigation.

Bornstein and several collaborators (1977, 1981, 1982) including Fontana (1979), and Anderson (1979, 1980) have studied a special aspect of atmospheric circulation patterns at and near the land/sea interface. They have been primarily concerned with the influences of a large urban area (New York City) on the atmospheric processes within the coastal zone. They have studied the sea breeze front and the effects of the urban area on various aspects of it. Additionally, they investigated the effects of heat and moisture emissions into the urban atmosphere. In doing this they have employed a very extensive data base collected in the New York City area during the period 1964 - 1969. This data base will

FIGURE 6: Location of Meteorological Measurement Programs Conducted in Coastal Regions

TABLE 1: LISTING OF METEOROLOGICAL MEASUREMENT PROGRAMS CONDUCTED IN COASTAL REGIONS

GROUP	IDENTIFIER/ LOCATION	INVESTIGATOR(S)	DATE OF MEASUREMENTS	MEASUREMENTS PERFORMED
WEST COAST	NAVAL POSTGRADUATE SCHOOL - [CEWCOM-76] - Monterey to San Diego	Schacher, Davidson, and Fairall	- October 1976	From Boat: (T _a , T _w , WD _s , IH, H)
	- [CARB] - Los Angeles Basin		- July 1977	
	- [CEWCOM-78] - San Nicholas Island		- May 1978	
	- [MABLES] - San Francisco Bay		- July 1978	
	- [CTQ] - Monterey Bay		- June 1979	
	UNIVERSITY OF CALIFORNIA - Los Angeles Basin	Edinger	- Summer 1957	From Aircraft: (T _u , P, H, IH)
	- San Fernando Valley		- Summer 1957	(WD _u , WS _u) From PIBALS-
	- Santa Clara Valley		- July 1961	(San Fernando only)
	POINT ARGUELLO, CA	Cramer, Dumbauld, Record, and Swanson	Continuous 1962 - 1965	From 300' Tower: (T _a , T _u , WD _s , WS _s , WD _u , WS _u) IH [Method Unknown]
	METRO-MONITORING	Kauper	Summers of 1975 - 1976	From Aircraft: (T _u , IH) Also: (WD _u , WS _u) From PIBALS
	BRITISH COLUMBIA	Miyake, Stewart, Pond, and Others	Summers of 1962 - 1968	From Vertical Mast Over Water (Height Unknown): (T _a , T _u , WD _s , WS _s , WD _u , WS _u , H)
	COASTAL UPWELLING EXPERIMENTS (CUE) - Oregon	O'Brien	Summers of 1972 - 1973	(WD _s , WS _s) Method Unknown Note: Other measurements performed but are not identified in report.

TABLE 1: LISTING OF METEOROLOGICAL MEASUREMENT PROGRAMS CONDUCTED IN COASTAL REGIONS (Continued)

GROUP	IDENTIFIER/ LOCATION	INVESTIGATOR(S)	DATE OF MEASUREMENTS	MEASUREMENTS PERFORMED
GULF COAST	UNIVERSITY OF TEXAS - Upper Texas Coast	Echols, Wagner, Yu	- June 1968	From 8 Inland and 1 Offshore (Drilling Platform): (Ta, WD _s , WS _s , H)
	FORT WALTON BEACH, FL	Hsu	- May 1970	From 2 Towers (1-10m, 1-100m) (Ta, Tu, WD _s , WS _s , WD _u , WS _u)
ATLANTIC COAST	BROOKHAVEN, NY	Raynor and Others	Intermittent 1972 - 1977	From Coastal Site and 1 Offshore Site (Buoy): (Ta, Tw, WD _s , WS _s) Note: Measurements performed on land at other sites, from aircraft, and boat in support of diffusion studies. See "Tracer Studies".
	LONG ISLAND, NY	Di Vecchio and Others	May - July 1974	From 2 Coastal 120 meter Towers: (Ta, Tu, Ts, WD _s , WS _s , WD _u , WS _u)**
	MASSACHUSETTS BAY, MA	Craig and Others	Summer - Autumn 1944	From Boat and Aircraft: (Ta, Tu, Tw, WD _s , WS _s , H, IH)* Also: (WD _u , WS _u) from PIBALS
	NEW YORK CITY, NY	Frizzola and Fisher	- June 1960	(WD _u , WS _u) from PIBALS**
	BLOCK ISLAND, RI	Fisher	- August 1958	From Aircraft: (Tu, IH) Also: (WD _u , WS _u) from PIBALS (Tw) - Method Unknown
	ATLANTIC CITY, NJ	Angell and Pack	- July 1964	(WD _u , WS _u) from Tetrooms*
	NEW YORK AIR POLLUTION PROJECT, NY	Bornstein and others	1964 - 1969	WD _s , WS _s , WD _u , WS _u , Ta, Tu, H, P, IH, Heat, Moisture, others

TABLE 1: LISTING OF METEOROLOGICAL MEASUREMENT PROGRAMS CONDUCTED IN COASTAL REGIONS (Continued)

GROUP	IDENTIFIER/ LOCATION	INVESTIGATOR(S)	DATE OF MEASUREMENTS	MEASUREMENTS PERFORMED
ATLANTIC COAST (CONT'D)	WALLOPS ISLAND, VA (NASA)	Parsons and Williams	Summers of 1977 - 1978	Note: Parameters measured on Wallops Island not specified in report.
	SAVANNAH, GA	Blanton and Others	February - September 1977	From Offshore Tower (Navigational Light Tower 27 meters high) (T_a , T_w , WD_s , WS_s , P)
	KENNEDY SPACE CENTER, FL	Record and Others	Summers of 1966 - 1967	From 150 meter Tower: (T_a , T_w , WD_s , WS_s , WD_u , WS_u) From Radiosondes: (T_u , IH, WD_u , WS_u , H, P) Note: Tetroons also used on selected days.
GREAT LAKES	UNIVERSITY OF WISCONSIN - Lake Michigan	Lyons and Others	Summers of 1967, 1970, 1974	From Aircraft: (T_u , IH, WD_s , WS_s , H, P)** From Boat: (T_a , T_w) Also: (WD_u , WS_u) From PIBALS and Tetroons
	METEOROLOGICAL SERVICE OF CANADA - Lake Huron - Lake Erie - Lake Ontario	Munn, Richards and Others	Summers of 1960 - 1967 (Intermittent)	From Surface Stations (Some using tethered balloons): (T_a , T_u , WD_s , WS_s) Also: (WD_u , WS_u) from PIBALS From Boats: (Using tethered balloons): (T_a , T_u , T_w , WS_s)
	ARGONNE - Lake Michigan	Sheih and Others	(Reported 1979)	(WD_u , WS_u) from neutral balloons

TABLE 1: LISTING OF METEOROLOGICAL MEASUREMENT PROGRAMS CONDUCTED IN COASTAL REGIONS (Continued)

GROUP	IDENTIFIER/ LOCATION	INVESTIGATOR(S)	DATE OF MEASUREMENTS	MEASUREMENTS PERFORMED
GREAT LAKES (Cont'd)	NCAR - Lake Michigan - Lake Huron	Lenschow	November 1970	From Aircraft: (T _u , IH, T _w , WS _u , H)
	AES - Lake Ontario	Phillips	Winters of 1965 - 1969	From Ships: (T _a , T _w , WD _s , WS _s) *
	UNIVERSITY OF MICHIGAN	Moroz	Summer of 1964	From Surface Stations: (T _a , H) From Ships: (T _w) From Aircraft: (T _u , IH, H) Also: (WD _u , WS _u) from PIBALS

FOOTNOTES:

* Data base supplemented with surface observations from the National Weather Service.

** Data base supplemented with both surface and upper air (radiosonde) observations from the National Weather Service.

LEGEND FOR TABLE 1

T _a	Air Temperature At Surface	WD _u	Upper Level Wind Direction
T _u	Upper Level Air Temperatures	WS _u	Upper Level Wind Speed
T _w	Water Surface Temperature	IH	Inversion Height
WD _s	Surface Wind Direction	H	Humidity
WS _s	Surface Wind Speed	P	Pressure

undoubtedly play an important role as further investigations are performed to define coastal phenomena.

A recently initiated measurement program has generated meteorological and dispersion data which are expected to be quite useful in further describing the meteorological dynamics as well as the dispersion environment. This program known as the California Coastal Offshore Transport and Diffusion Experiment is currently in progress under sponsorship of the Minerals Management Service (formerly Bureau of Land Management). Detailed meteorological measurements as well as gaseous tracer measurements have been collected at two sites in southern California at Ventura and Pismo Beach. To date, reporting is not complete, however some information is available regarding these experiments. Schacher, et al (1980, 1981, 1981) and Aerovironment (1980) described the first set of experiments carried out near Ventura, California and Schacher, et al (1982) described the experiments carried out near Pismo Beach, California. Schacher (1982) also indicates more analyses on these experiments will be forthcoming from Aerovironment, Inc., SRI International, Energy Resources Company, Meteorology Research, Inc., Brookhaven National Labs, and North American Weather Consultants.

During 1982 the NRC initiated a field measurement program to study coastal circulation processes. This program is identified as the Shoreline Environment Atmospheric Dispersion Experiment (SEADEx). SEADEx-1 was conducted during early summer 1982 on the west coast of Lake Michigan in Wisconsin. Reports on the findings of that experimental effort are not available as yet, however it is expected this program will provide further detail about the onshore flow portion of the coastal circulation process.

3.0 TRANSPORT AND DIFFUSION MECHANISMS

Transport and diffusion within the cyclical phenomena found in coastal regions can be influenced by numerous complicating factors--the results of which can be that both the trajectories of pollutant emissions and the local pollutant concentrations can be much different than have been seen in the classical cases of straightline flow during steady-state conditions. The causes for the departures from the classical conditions are largely related to the dynamics of atmospheric behavior at and near the coastline and their variations during the diurnal cycles. The meteorological dynamics of these situations have been discussed at length in Section 2 above. By-and-large the main factors affecting this special area of transport and diffusion are: land and sea breeze circulations, the TIBL, coastal terrain roughness, coastal shape factors, presence or absence of large urban areas, and land-sea temperature differences.

Transport and diffusion over water and in coastal regions involve meteorological processes that differ substantially from those inland. The parameters of wind speed, wind direction, and atmospheric turbulence are all functions of the air-sea and air-land interfaces in coastal regions. More importantly, the manner in which these parameters affect transport and diffusion are made more complex by the temperature and roughness discontinuity at the land-water interface. Consequently, parameters (such as dispersion coefficients) derived to describe transport and diffusion processes at inland areas are likely to be inadequate to describe the same processes in coastal regions.

The roughness lengths associated with land and water surfaces result in turbulence and wind speed profiles unique to each surface. The wind speed profile in the vertical over water does not vary as much as over land because of the relative smoothness of the water. However, the roughness element over water is variable, changing with the state of the sea. Slade (1962) compared horizontal turbulence (σ_θ) and mean wind speed during on and offshore wind flow on Chesapeake Bay. He found horizontal turbulence was reduced 50 percent and wind speed was increased 25 percent after the air flow had traveled 11 kilometers over water.

A study at Brookhaven National Laboratory (Raynor, et al, 1978) revealed that at higher wind speeds, the differences in wind speed over water and over land are greater. For wind speeds of 2 meters per second, there was no difference between wind speeds at inland locations and at coastal locations. However, when speed increased to 8 meters per second at the coastal site, the inland site experienced only 4 meters per second. Similar differences were found in turbulence intensities. Raynor, et al, (1978) reported that the horizontal component of turbulence measured at a coastal site on Long Island averaged 85 percent less than the intensity measured 9 kilometers inland (annual average $\sigma_\theta = 1.3^\circ$ at the coastal site versus 8.7° at the inland site). The vertical component of turbulence experiences similar reductions over water. Subsequently, for overwater transport, turbulent diffusion

generally decreases, while at the same time, transport speed increases, implying that a pollutant plume could travel great distances over water and remain virtually intact.

The heating and cooling rates of the sea and land surfaces cause distinct differences in the thermal stability over each surface. Since solar energy penetrates the water surface, thermal energy is distributed through a relatively deep layer, so water surfaces are therefore slow to heat and cool. Evaporation and condensation processes associated with water surfaces also tend to moderate the heating and cooling process. For these reasons, the temperature of the water surface tends to remain relatively constant. Subsequently, low level thermal stability is quite common over water surfaces, regardless of wind speed, sky conditions, or time of day. Conversely, solar radiation heats a much shallower surface layer over land and, subsequently, the land heats (and cools) more rapidly than water. Thus, the daytime heating generally leads to neutral or unstable thermal stability over land, while stable conditions generally persist at night. These of course are the mechanisms that drive the local circulations in the coastal region but they also profoundly affect the transport and diffusion mechanisms.

The character of the terrain in the coastal region serves to establish the diffusion environment, not only through the energy balance and the surface roughness, but where surface topographic features are of sufficient size and orientation, they will serve to determine effluent transport through channeling or redirection of the flow in the near surface layers. Conversely, the flow and resulting effluent transport over water is much less complex due to the relative homogeneity of the water surface. Overall, topographic features can influence the orientation of onshore flow, and the inland extent of onshore flow, and therefore relative pollutant concentrations.

The character of the coastal atmospheric circulation systems are profoundly affected by the presence or absence of urban areas. Since more urban areas are located in coastal regions than at inland locations this factor becomes a legitimate concern. Many details about the influence exhibited by a coastal urban area (New York) have been described by Bornstein, et al, (1977, 1981, 1982). The authors specifically studied the behavior of emissions of SO_2 , heat, and moisture by iterative three-dimensional analyses of their distributions. Fontana and Bornstein (1979) found that the onshore rate of movement and extent of movement of the sea breeze front was related to the roughness element of the urban area. Anderson (1980) determined that the slope of the sea breeze front was dependent on the character of the urban area. Bornstein, et al, (1981) then observed that pollutant distributions varied according to spatial and temporal changes in sea breeze fronts. All of these factors discussed by Bornstein and collaborators indicate that transport and diffusion of pollutants emitted in the coastal zone display complex characters when influenced by the presence of significantly-sized urban areas.

All of the above-discussed factors combine to result in a very complex transport/diffusion environment in coastal regions. Since the coastal transport/diffusion mechanisms are controlled largely by local features, those mechanisms are likely to be highly specific to a given region and are thus less likely to be amenable to generalized predictive methods.

Measurements of transport and diffusion processes in coastal areas were summarized in the above-referenced Critical Review. It was pointed out that a number of dispersion field measurement programs have been conducted during the past two or three decades. However specific attention to the diurnal cyclical aspect or specific attention to the cellular aspect has not been the central issue motivating the historical measurement programs. Rather, the majority of the programs were conducted in coastal regions because of the occurrence of persistent, steady, onshore winds induced by the sea breeze portion of the cyclical cellular phenomenon. This being the case, the transport and diffusion aspects of the cyclical cellular phenomena that are unique to coastal regions are represented in incomplete fashion at best. The portions that are not represented by transport/diffusion measurements are the same as are discussed in the meteorological measurement section above, namely the land breeze portion of the diurnal cycle, and the transition periods between the sea breeze and the land breeze.

4.0 REVIEW OF MODELING TECHNIQUES

Significant differences between dispersion over water and dispersion over land lead to the need for predictive models to represent the meteorology and effluent behavior in each case. Even more complex though is the in-between zone--the coastal zone itself, where the effects of significant discontinuities formed by the water/land interface lead to characteristic localized and diurnal circulations that develop as a result of the dynamical differences found at the interface. These localized atmospheric circulations extend both inland and offshore to differing distances depending on local features of the land, the synoptic weather influence, and the solar energy balance. Predictive models developed to represent atmospheric dispersion conditions within the coastal discontinuity zone to be fully responsive to NRC's requirements, must be able not only to represent the over land and the over water portions of dispersion but also must be able to account for the transition periods between onshore flow and the offshore flow which is experienced as a cyclical feature. The accounting for these vastly different features through predictive modeling must be accomplished in a manner such that effluent materials (emitted from nuclear power generating facilities) that are transported during one portion of the cyclical phenomena can be tracked or accounted for through the transition and return portion of the cycle.

The understanding and quantification of the unique aspects of coastal meteorology have provided considerable challenges to theoretical and dynamic meteorologists. Not surprisingly, this subject has received attention from many researchers using a variety of techniques. Shearer and Kaleel (1982) have reviewed a number of such studies, which range from simplified, statistical descriptions of the various elements of the coastal atmosphere to detailed numerical solutions of the equations of motion. From that initial review, the authors have identified a smaller selection of works which are, in their opinion, most applicable to the current needs of the NRC.

The selection and review of appropriate modeling techniques included in this report was accomplished using three basic criteria. First, the models must be computerized to ensure that the numerical solutions to the complex equations of motion have already been tested, and any computational instabilities resulting from them have been identified and, when possible, filtered out. Second, the models should be three-dimensional to provide for an adequate description of transport mechanisms unique to different geographical locations. Finally, the models should have been applied to the specific problem of the transport and dispersion of airborne effluents. Since the prediction of downwind concentrations of air pollutants is dependent upon both the transport mechanisms and turbulent diffusion processes, the selected models should be capable of quantifying both. Unfortunately, none of the models that have been identified completely satisfy all three criteria, so the inclusion of models for this review may have ultimately been subjective

to some degree. Using these criteria, it is hoped that the identified models will be most applicable to the objectives of the NRC, and will ensure that future developments sponsored by the NRC will build on the experiences of previous investigators rather than duplicating their efforts.

The above-listed criteria would seem to exclude the use of Gaussian models for application in coastal regions. Given the complex wind flows and thermal structures which result from the abrupt discontinuity in surface heating and roughness characteristics represented by a coastline, the use of statistical approaches hardly appears to be adequate. However, depending upon the intended application, Gaussian models have a number of advantages over the more complicated numerical models. Such models are comparatively simple, both in terms of input requirements and execution; they are relatively inexpensive to run; and they provide quick turnaround. These advantages make Gaussian models most attractive for use in emergency situations when quick response is crucial.

There are many Gaussian models currently available, most of which have been developed for or by the Environmental Protection Agency. It is not the intent of this paper to review these models, since their development and application is not specifically geared toward the coastal environment. However, Gaussian models for coastal applications should, at a minimum, incorporate dispersion coefficients which are representative of the geography and topography of the specific location in question. A review and compilation of such dispersion coefficients has been prepared by MacRae, Kaleel, and Shearer (1983).

The primary disadvantage of Gaussian models (which for many applications is also their primary advantage) is their simplicity. The complex flows and circulations which occur in the coastal atmosphere cannot be described accurately by statistical approaches. However, numerical models, based upon the equations of motion, have been successfully employed by a number of researchers to simulate complex coastal circulations, and, in that respect, are superior to Gaussian models. Numerical models are more expensive to execute than Gaussian models, requiring vastly greater computer resources, but for applications where a detailed description of coastal circulations is important, numerical models are the most appropriate.

A number of numerical modeling approaches have been proposed by a variety of researchers. Some of the primary works include those of Estoque (1961, 1962), Fisher (1961), Neumann and Mahrer (1971), Mak and Walsh (1976), Neumann (1977), and Anthes (1978). The models developed by these authors were, for the most part, used to describe the causes and structure of the sea breeze circulation cell. Being simplified solutions to the basic equations of motion, these models were generally linear (i.e., they did not account for advection of heat) and two-dimensional (i.e., they assumed straight or idealized shorelines). Because of these limitations, these models are probably most appropriate as research

tools, and not for the specific application to air pollution concentration estimates.

Probably the first three-dimensional sea breeze model to achieve wide recognition was the algorithm developed by McPherson (1970). His model was an expansion of Estoque's (1961, 1962) two-dimensional model, and was applied to test the dynamic effects of an irregular coastline on the development of the sea breeze. The model is nonlinear and hydrostatic, and uses two levels to describe the vertical structure of the atmosphere. The first layer, up to 50 meters in height, is the boundary or contact layer, which serves as a buffer between the surface and the air aloft. The transition layer, which extends from 50 meters above the ground to a height of almost 4 kilometers, is the region for which the numerical calculations are performed. The model was used by the author to simulate an 18-hour period to describe the evolution of a sea breeze circulation in the vicinity of an idealized bay. In his original publication, McPherson did not attempt to execute the model through the transition from the sea breeze to the land breeze. Also, the modeled results were not verified using actual measurements. Finally, the author was not concerned with the transport of airborne effluents, and therefore did not incorporate a method for computing downwind pollutant concentrations in the presence of a sea breeze. For these reasons, McPherson's model probably cannot be directly applied to the problems faced by the NRC.

Tingle (1971) developed a numerical model that was very similar to that developed by McPherson. The model was again based on the work of Estoque (1961, 1962) and incorporated two vertical layers, the boundary layer below 50 meters and the transition layer up to about 3 kilometers. The model was hydrostatic, but was originally only two-dimensional. Tingle's initial results were compared to the observed circulation elements measured on the eastern shore of Lake Michigan.

Tingle and Dieterle (1976) expanded Tingle's earlier work to describe the recirculation of pollutants within the sea breeze in three dimensions. The authors incorporated Sklarew's (1971) Lagrangian "Particle-In-Cell" technique, which defines the total wind component as the sum of the transport wind velocity vector and the turbulent flux velocity vector. Hence, both the transport and diffusion of airborne pollutants could be simulated. The model was run for a 6-hour period to examine the distribution of pollutants from an instantaneous, ground-level emission source in a well-developed sea breeze circulation cell. Zero gradient flow conditions were assumed. The results indicated that recirculation of pollutants from a source located at the shoreline can occur during sea breeze conditions, although these results were not verified by actual measurements.

Dieterle and Tingle (1976) utilized the same model to examine the effects of the larger scale, gradient flow on the development of the sea breeze. A continuously emitting area source was assumed to exist at the

shoreline, but at a height of 50 meters corresponding to the top of the "contact layer" used by the model. Three cases were examined: the first assumed no gradient flow; the second assumed an initial flow parallel to the shoreline; the third case utilized an initial gradient offshore flow perpendicular to the shoreline. The model was executed to simulate the evolution of a sea breeze during a twelve-hour period. The results indicated that the highest onshore ground-level concentrations and the greatest degree of pollutant recirculation were predicted to occur with an offshore gradient wind that is perpendicular to the coast. Since the model assumed idealized boundary layer conditions, no verification of the results with actual measurements was performed.

Probably the most rigorous sea breeze modeling technique that has been assembled to date is the algorithm developed by Pielke (1974). The model, originally designated the University of Virginia Mesoscale Model (UVMM) then later the Numerical Mesoscale Model (NMM), is a three-dimensional, hydrostatic, primitive equation model which describes the vertical structure of the sea breeze circulation at eight levels. The model is capable of handling a variety of initial boundary layer and synoptic conditions. Pielke originally developed the model to define the convergence zones in southern Florida resulting from the combination of sea breezes from both sides of the peninsula. The simulated development of the convergence zones, and resulting vertical velocities, compared favorably with the observed development of convective thunderstorms.

McNider and Pielke (1979) utilized the wind flows computed by the UVMM over southern Florida to predict expected particle trajectories. An interesting finding of this analysis was the prediction of the helical flow pattern described in Section 2 of this report. The authors also demonstrated the versatility of the model by examining expected particle trajectories in a noncoastal, idealized deep valley terrain situation.

Pielke, McNider, Segal, and Mahrer (1982) have expanded the UVMM (or NMM) to predict downwind pollutant concentrations in coastal flows. Turbulent velocity fluctuations were parameterized statistically to quantify turbulent diffusion processes affecting plumes emitted from point and line sources. A three-dimensional advection-diffusion equation was applied for emissions from large, area sources. The model was employed to describe hourly carbon monoxide concentrations that were observed in the vicinity of the Chesapeake Bay, but only preliminary comparisons of the observed and predicted concentrations were attempted.

Pielke's model has also been applied by Lyon's, Schuh, and McCumber (1979) to describe the wind fields observed during a lake-breeze event on Lake Michigan. The authors concluded that the mesoscale model exhibited considerable skill in describing the characteristics of the lake-breeze circulation.

Keen, Lyons, and Schuh (1979) recognized that most numerical models could not provide sufficient resolution required for detailed air

pollution applications. Such models typically compute wind vector fields at horizontal grid intervals of several kilometers, which are too coarse to define the impacts of localized pollutant sources. The above authors developed the Kinematic Diagnostic Model (KDM) to predict trajectories with greater resolution than existing numerical techniques. From a detailed set of measurements performed during a lake-breeze event on the western shore of Lake Michigan, the authors employed the KDM to interpolate the horizontal wind components over a fine grid (one kilometer intervals), and then calculate the vertical wind components using a divergence equation. By introducing particles with different settling velocities, detailed trajectories were obtained. The results of the various analyses performed using the KDM identified recirculation patterns of various sized particles, and an apparent sorting of the particles according to their settling velocities.

Because of the large amount of input data required by the KDM it is probably not feasible to execute the model by itself on a real-time basis. However, when used in conjunction with a numerical model which can compute the coarse elements of a coastal circulation, the KDM may be a practical method for defining the small scale features which would affect effluent plumes. In fact, at the time of this writing, Lyons and his collaborators were working towards the development of just such a model, by combining the KDM with the mesoscale model developed by Pielke.

A number of modeling techniques have been developed to quantify the effects on air quality of continuous fumigation conditions which can occur frequently in coastal environments. Unlike the morning breakup of nocturnal inversions when the depth of the mixing layer increases rapidly, the depth of the TIBL changes relatively slowly causing fumigation of plumes emitted near the coastline to persist for several hours. Such events can have obvious effects on air quality in localized areas or "fumigation spots."

Possibly one of the first coastal fumigation models was the Air Quality Short Term Model (AQSTM) developed by the Illinois Environmental Protection Agency (1976). The model requires that the user specify the height of the TIBL at a number of locations for each hour of meteorological input. A Lagrangian interpolation scheme was applied to compute the TIBL height for each grid point, and then Turner's (1970) fumigation technique was used to compute downwind pollutant concentrations. Since this model assumes very idealized boundary layer conditions, and cannot predict the characteristics of the TIBL, its applications are somewhat limited. It may be useful, though, as a screening tool or for applications when the TIBL height is known.

Lyons, et al, (1981) developed a model which is capable of predicting TIBL characteristics and its effects on the dispersion of effluent plumes. The GLUMP II (Great Lakes University of Wisconsin Mesometeorology Project) model is three dimensional, multi-layered vertically, and incorporates a number of plume rise and dispersion

coefficient options. The basic dispersion equations, for both undisturbed flow and fumigation conditions, are based on Turner's (1970) techniques. The TIBL predictions performed by the GLUMP II model were evaluated using aircraft observations at two locations on the western shore of Lake Michigan. The authors found that the model demonstrated considerable skill in predicting the characteristics of the TIBL.

The Environmental Protection Agency and the U.S. Geological Survey are working independently on models capable of addressing dispersion conditions in coastal zones. Both projects are based on one of EPA's UNAMAP models--the single source CRSTER algorithm. The EPA is currently modifying the CRSTER model to simulate continuous fumigation conditions by incorporating Lyons' fumigation (GLUMP II) technique. The USGS is using EPA's Shoreline Coastal Dispersion (SCD) model and modifying it to simulate offshore pollutant transport. Their approach will include not only a fumigation algorithm, but also a scheme for modifying the dispersion coefficients depending upon air-water temperature differences. Since these efforts are underway at the time of this writing, these models are probably not yet available.

It is evident from the discussion provided in this section that a wide range of modeling approaches--from simple Gaussian models to complex numerical formulations--have been developed by a number of researchers to simulate the complex atmospheric flows and structures that are unique to coastal zones. The Gaussian models are simple, inexpensive to execute, and provide quick results but demonstrate little skill in describing the transport processes that effect airborne effluents in coastal regions. A number of numerical approaches have been identified that can simulate the characteristics of the coastal atmosphere quite well, but these can be quite cumbersome to operate and require substantial computer resources. Of the numerical approaches identified, it is noted that very few have been applied to describe the full diurnal cycle. As a result, it has yet to be determined whether they can accurately predict the transport and dispersion of air pollutants through the transition from the sea breeze to the land breeze or vice versa.

Perhaps more fundamentally, few if any of the models developed have been subjected to a rigorous validation (evaluation) exercise. Such efforts are a significant missing step in the assessment of model performance. Detailed validation studies have been conducted of models used for noncoastal applications. For example, the Electric Power Research Institute is currently studying the performance of a number of dispersion models in a variety of terrain types. In pursuing this effort the EPRI has already developed much of the model performance criteria and methodologies that would be required by the NRC if it were to conduct a similar program. In the authors' opinion future work is still necessary, in both model development and validation, before an adequate modeling approach is available that will satisfy the needs of the NRC.

5.0 CONCLUSIONS AND RECOMMENDATIONS

In the preceding sections of this report, the meteorological processes which affect the transport and diffusion of airborne effluents in coastal regions have been defined. Emphasis has been placed on describing the cyclical and cellular nature of the dynamic elements of the coastal atmosphere, as such discussions are apparently lacking in historical research efforts. Meteorological measurement programs that have been conducted in the past by a number of investigators concerned with coastal atmospheric phenomena have been identified, reviewed, and summarized. A synopsis of existing modeling techniques that have been or might be employed to describe transport and diffusion processes in coastal zones has also been prepared. From the efforts described in this report, the following conclusions and recommendations regarding the state-of-knowledge of the coastal atmosphere are provided:

- o The sea breeze portion of the cyclical coastal phenomena has been studied, both empirically and theoretically, more than its land breeze counterpart. The transition periods between the two have essentially not been investigated at all.
- o Atmospheric processes occurring within the thermal internal boundary layer (TIBL) during sea breezes are reasonably well understood.
- o The factors controlling transport and diffusion in coastal regions are largely local scale factors. Because these controlling factors are localized, dispersion conditions are highly complex and site specific, and are not really amenable to generalization.
- o Considerable efforts have been directed toward the development of modeling techniques which are capable of simulating atmospheric processes in coastal zones. Such efforts are ongoing, but the models that have been developed are probably not yet ready to be utilized in an operationally predictive mode.
- o Gaussian models cannot provide a rigorous description of transport and dispersion mechanisms in coastal regions, but may provide useful guidance when quick response is necessary. Because of the complexity of coastal atmospheric dynamics, the guidance provided by Gaussian models should be interpreted carefully by experienced personnel.
- o Numerical models do provide reasonably accurate descriptions of atmospheric processes, and may be quite useful for many applications. However, because of the

substantial computer resources required by numerical simulations, they may be inappropriate during situations when quick response is necessary.

- o A rigorous validation of existing modeling techniques has not been performed to date. The validation efforts conducted thus far have utilized data of unknown quality and provide, at best, an incomplete representation of the coastal atmosphere.

The following recommendations are provided to ensure that future research efforts in coastal regions are directed toward aspects that have yet to be documented or studied extensively:

- o A thorough meteorological monitoring program, which addresses all aspects of coastal circulations, should be undertaken. Such a program should be designed to measure the entire diurnal cycle, but, at a minimum, should address the land breeze portion of the cycle, and the transition between the land breeze and the sea breeze.
- o Because the factors which control the evolution and development of coastal circulations are largely local scale factors, meteorological monitoring programs should be conducted in a number of locations and terrain types.
- o Improved techniques to measure meteorological phenomena offshore, with accuracies comparable to onshore measurements, need to be developed.
- o Efforts to develop modeling techniques applicable to coastal regions should be maintained. Gaussian models incorporating dispersion coefficients representative of various coastal zones and terrain types, and an algorithm, such as that proposed by Lyons, which can simulate continuous fumigation conditions should be developed. Numerical models, such as Pielke's Numerical Mesoscale Model, should be expanded to simulate not only transport processes, but turbulent diffusion processes as well.
- o A detailed model validation program should be undertaken to evaluate and improve simulated results. The performance of the various models for predicting circulation elements and pollution concentrations probably cannot be evaluated with existing data bases.

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