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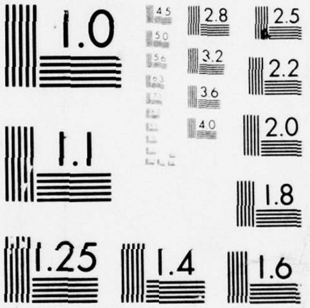
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Coastal Studies Institute
Center for Wetland Resources
Louisiana State University
Baton Rouge, Louisiana 70803

Technical Report No. 229

ATMOSPHERIC DISPERSION CHARACTERISTICS IN THE LOUISIANA COASTAL ZONE

By S. A. Hsu

This research was supported by the Office of Naval Research through Contract N00014-75-C-0192, under Project NR 388 002.

February 1977

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
(3) Coastal Studies Inst~~itute~~ ✓
(1) Louisiana State Univ~~ersity~~
(2) Baton Rouge, ~~Louisiana~~ 70803

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP
Unclassified

3. REPORT TITLE
(6) ATMOSPHERIC DISPERSION CHARACTERISTICS IN THE LOUISIANA COASTAL ZONE

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
(9) Technical rept.,

5. AUTHOR(S) (First name, middle initial, last name)
(10) S. A. Hsu

(12) 32p.

6. REPORT DATE
(11) Feb~~ruary~~ 1977

7a. TOTAL NO. OF PAGES
29

7b. NO. OF REFS
30

8a. CONTRACT OR GRANT NO.
(15) N00014-75-C-0192 ✓

b. PROJECT NO.
NR 388 002

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
Technical Report No. 229 ✓
(14) TR-229

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES
Published originally as:
Center for Wetland Resources, Sea Grant
Publication No. LSU-T-76-011 (CZM series)
November 1976.

12. SPONSORING MILITARY ACTIVITY
Geography Programs
Office of Naval Research
Arlington, Virginia 22217

13. ABSTRACT

Atmospheric dispersion characteristics in the coastal zone are unique in that physical processes of air, sea, and land combine at the shoreline to create motions on many scales which differ in important respects from processes over land or over water. Some of these differences in coastal Louisiana are reviewed. Synoptic-scale characteristics indicate that the coastal zone is superior to areas farther inland for dispersing pollutants. However, mesoscale and microscale studies reveal that diurnal circulation of land-breeze and sea-breeze systems and the development of an internal boundary layer because of aerodynamic roughness changes across the shoreline may actually increase pollution concentration in the nearshore region. Specific studies on these scales of atmospheric motion in relation to the optimum siting for industrial plants are outlined and recommended.

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DD FORM 1 NOV 65 1473 (PAGE 1)
S/N 0101-807-6811

Unclassified
Security Classification

A-31409

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Louisiana Louisiana coastal zone coastal zone management atmospheric dispersion pollution						

DD FORM 1 NOV 65 1473 (BACK)
S/N 0101-807-6821

Unclassified
Security Classification

A-31409

Coastal Studies Institute
Center for Wetland Resources
Louisiana State University
Baton Rouge, Louisiana 70803

Technical Report No. 229

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Acknowledgment

Efforts toward implementation of coastal zone management in Louisiana have enlisted the interest and participation of many public agencies and institutions. As a cornerstone for this program, scientific information from every available source is being compiled and digested in a series of Coastal Zone Management reports. The collection is ultimately intended as an authoritative central reference source for persons involved in administration of an operational CZM program.

The information presented in this report has been synthesized from research efforts performed mainly under a contract with Geography Programs, Office of Naval Research, and the Center for Wetland Resources of Louisiana State University. Editorial, manuscript, and publication services were provided by the Louisiana Sea Grant Program, sponsored cooperatively by the NOAA Office of Sea Grant, U.S. Department of Commerce, and by the state of Louisiana.

Special acknowledgment is made to Drs. William G. McIntire, Associate Dean, and Jack R. Van Lopik, Dean, Center for Wetland Resources, Louisiana State University, Baton Rouge.

Abstract

Atmospheric dispersion characteristics in the coastal zone are unique in that physical processes of air, sea, and land combine at the shoreline to create motions on many scales which differ in important respects from processes over land or over water. Some of these differences in coastal Louisiana are reviewed. Synoptic-scale characteristics indicate that the coastal zone is superior to areas farther inland for dispersing pollutants. However, mesoscale and microscale studies reveal that diurnal circulation of land-breeze and sea-breeze systems and the development of an internal boundary layer because of aerodynamic roughness changes across the shoreline may actually increase pollution concentration in the nearshore region. Specific studies on these scales of atmospheric motion in relation to the optimum siting for industrial plants are outlined and recommended.

Introduction

In the design, planning, and determination of the location of industrial plants and urban developments for a given region, the dispersion characteristics of the atmosphere must be considered. This aspect is particularly important in the coastal zone as compared to inland or offshore areas because the atmosphere behaves differently as a result of the triple air-sea-land interactions. The role of the atmospheric sciences in the Texas coastal zone has been discussed by Jehn (1974). Knecht (1975) has outlined data needed for coastal zone management.

Many atmospheric models have been proposed, depending on specific need (see, e.g., Hosler, 1975). However, there is no one model that is superior in all statistics (Turner et al., 1972). General collections of data on air-pollution meteorology and related subjects can be found elsewhere (e.g., Smith, 1968; Slade, 1968; Turner, 1970; World Meteorological Organization, 1972; American Meteorological Society, 1975). Some specific topics related to the coastal region have been discussed by Hsu (1975), Lyons (1975), and Raynor et al. (1975). It is not the purpose of this report to review various models, theories, or specific experiments. Rather, it is directed toward the general understanding of the atmospheric dispersion characteristics in the coastal zone of Louisiana. Some recommendations are also made to further our knowledge in coastal meteorology as a means of improving coastal zone management.

Basic Concentration Formulas

Since one of the major onshore impacts of offshore oil and gas development is the optimum siting of energy-related industry such as refineries, the most frequent pollutants, sulfate dioxide and particulate matter, should be considered simultaneously. Among various existing models the Climatological Dispersion Model (CDM) is generally regarded as the most adequate and is widely used by existing refineries. CDM computes long-term (seasonal or annual) quasi-stable pollutant concentrations at any ground level receptor, using average emission rates from point and area sources and a joint frequency distribution of wind direction, wind speed, and stability for the same period. A user's manual for CDM was prepared by Busse and Zimmerman (1973); it contains companion papers by Calder (1971) on the technical details of the model and by Turner et al. (1972) on validation.

The basic concentration formula consists of contribution by both point and area sources. The total concentration for the averaging period is the sum of concentrations of the point and area sources for that averaging period.

The average concentration $\overline{C}_A$ due to area sources at a particular receptor is given by

$$\overline{C}_A = \frac{16}{2\pi} \int_0^\infty \left[\sum_{k=1}^{16} q_k(\rho) \sum_{\ell=1}^{6} \sum_{m=1}^{6} \phi(k,\ell,m) S(\rho,z;U_\ell,P_m) \right] d\rho \qquad (1)$$

where k = index identifying wind direction sector

$q_k(\rho) = \int Q(\rho,\theta)\, d\theta$ for the k sector

$Q(\rho,\theta)$ = emission rate of the area source per unit area and unit time

ρ = distance from the receptor to an infinitesimal area source

θ = angle relative to polar coordinates centered on the receptor

ℓ = index identifying the wind speed class

m = index identifying the class of the Pasquill stability category

$\phi(k,\ell,m)$ = joint frequency function

$S(\rho,z;\ U_\ell,P_m)$ = dispersion function defined in Equations 3 and 4

z = height of receptor above ground level

U_ℓ = representative wind speed

P_m = Pasquill stability category

For point sources, the average concentration $\overline{C}_p$ due to n point sources is given by

$$\overline{C}_p = \frac{16}{2\pi}\sum_{n=1}^{n}\sum_{\ell=1}^{6}\sum_{m=1}^{6}\frac{\phi(k_n,\ell,m)G_nS(\rho_n,z;U_\ell,P_m)}{\rho_n} \qquad (2)$$

where

k_n = wind sector appropriate to the nth point source

G_n = emission rate of the nth point source

ρ_n = distance from the receptor to the nth point source

If the receptor is presumed to be at ground level, that is, $z = 0$, then the functional form of $S(\rho,z;\ U_\ell,P_m)$ will be

$$S(\rho,0;U_\ell,P_m) = \frac{2}{\sqrt{2\pi}\,U_\ell\sigma_z(\rho)}\exp\left[-\frac{1}{2}\left(\frac{h}{\sigma_z(\rho)}\right)^2\right]\exp\left(\frac{-0.692\rho}{U_\ell T_{1/2}}\right) \qquad (3)$$

if $\sigma_z(\rho) \leq 0.8\ L$ and

$$S(\rho,0;U_\ell,P_m) = \frac{1}{U_\ell L} \exp \frac{-0.692\rho}{U_\ell T_{1/2}} \qquad (4)$$

if $\sigma_z(\rho) > 0.8$ L. New terms in Equations 3 and 4 are defined as follows:

$\sigma_z(\rho)$ = vertical dispersion function, i.e., the standard deviation of the pollution concentration in the vertical plane

h = effective stack height of source distribution, i.e., the average height of area source emissions in the k^{th} wind direction sector at radial distance ρ from the receptor

L = the afternoon mixing height

$T_{1/2}$ = assumed half life of pollutant, hours

The possibility of pollutant removal by physical or chemical processes is included in the model by the decay expression exp $(-0.692\rho/U_\ell T_{1/2})$.

Some important characteristics of the atmospheric diffusion related to the parameters listed above are discussed in the following sections.

Synoptic Scale Characteristics

Three major dispersion characteristics in the synoptic scale are the atmospheric mixing height, the representative wind speed averaged through this mixing layer, and the frequency of inversion. Equation 4 shows that the concentration is, among other things, inversely proportional to the product of these two parameters, namely the ventilation factor. Based primarily upon regular measurements of temperature and winds aloft at 62 National Weather Service stations throughout the 48 contiguous states, Holzworth (1972) has compiled some needed information on mixing height and wind speed which is shown in Figures 1 through 5.

It is clear that on an annual basis (Fig. 1) the ventilation factor is larger in the coastal region than farther inland. Therefore, the concentration should be smaller for the former than for the latter. Further examination of the seasonal and diurnal variations in the coastal zone (Figs. 2 through 5) reveals that the ventilation factor is larger in the afternoon in winter and spring than in the morning and that the reverse is true in summer and autumn. Moreover, this factor decreases from autumn, to summer, to spring, to winter. An autumn morning has the least concentration of pollutants and a winter morning has the greatest concentration in the Louisiana coastal region.

Atmospheric stability also plays an important role in estimating pollution concentration. The worst stability condition is usually associated with stagnation of anticyclones, which can be represented by the combination of low surface wind speed and the least amount of cloud cover, particularly during nighttime. Some examples are shown in Figures 6 and 7. The data were taken from Hosler (1961). It can be seen that the frequency of dispersion of pollutants is superior in a nearshore region such as Galveston, Texas, to that which occurs in areas some distance inland, such as Lake Charles, Louisiana. This prediction is further supported by a comparison between Burrwood, Louisiana (Fig. 8), which is located near the mouth of the Mississippi River, and Lake Charles, Louisiana (Fig. 9), particularly during the nighttime.

Mesoscale Characteristics

Although synoptic-scale characteristics indicate that the coastal region should have less pollution concentration than areas farther inland, mesoscale atmospheric phenomena in certain coastal regions play a dominant role in dispersion characteristics. Among the most important such phenomena in the Gulf coastal are land-breeze and sea-breeze systems (Hsu, 1970, 1973). On the basis of observations of the Texas Gulf Coast land breeze/sea breeze from a mesoscale station network between Galveston and Port Arthur (summers of 1965-1967), Hsu (1970) synthesized a model of the coastal air circulation system (Fig. 10). Onshore and offshore wind components are shown at 3-hourly intervals during the day. The lower portion of the onshore flow is the sea breeze, and that of the offshore flow is the land breeze. The maximum wind speed and its approximate height in each current are depicted by arrows. The elliptical shapes in the figure illustrate the horizontal and vertical extent of the land-breeze/sea-breeze circulation.

A brief explanation of this coastal air-circulation system follows the sequence shown in Figures 10a-10h. For more detail see Hsu (1970). At 0900 LST the air temperature over land is cooler than that over the sea, and the land breeze is blowing. By 1200 LST the land has become warmer than the water, and the circulation has reversed. A line of small cumulus clouds may mark the sea-breeze front. At 1500 LST the sea breeze is fully developed, and rain showers may be observed at the convergence zone, 30 to 40 km inland. Because of low-level velocity divergence, there is pronounced subsidence near the coast. Note that this sea-breeze-induced mesoscale subsidence inversion is different from the synoptic subsidence inversion discussed previously. At 1800 and 2100 LST the sea breeze is still clearly present but is gradually weakening in intensity. By 0000 LST the sea breeze is barely evident aloft and the surface wind is nearly calm over land. Temperature inversion in the atmospheric surface layer and occasionally fog appear over land. After the land again becomes cooler than the water, a land breeze develops (by 0300 LST) and reaches its maximum intensity near 0600 LST. A weak land breeze convergence line and associated line of cumulus clouds develop offshore near sunrise. The land breeze continues until midmorning, when the sea-breeze cycle starts over.

Large lakes also are affected by pronounced land-sea breeze circulation. Figure 11 summarizes the various features associated with a typical lake breeze near the shore of Lake Michigan (Lyons and Olsson, 1973). The generalized streamlines of a well-developed circulation cell (Fig. 11A) are shown for a lake-breeze cell that has penetrated 15-20 km inland by midafternoon. Potential temperature patterns (Fig. 11B) usually reveal three inversion surfaces over the lake. The highest is a slightly depressed synoptic-scale inversion. A mesoscale subsidence inversion is found near the top of the inflowing layer, overlying a surface-based conduction inversion, the strength of which depends on the air-water temperature contrasts.

Because the internal boundary layer is important, it is treated in the next section. Smoke patterns associated with well-developed lake breezes are sketched in Figure 11C. Frequently, a wall of smoke marks the inland-rushing wind shift line, or the sea-breeze frontal zone. The trajectories of gases and various-sized aerosols are shown in Figure 11D. More research is required to determine the fraction of gases and particulates actually recirculated within the cell. This alternation of flow occurs also with sea breezes and land breezes, which move air back and forth across the shoreline. For example, in Los Angeles (Neiburger, 1969) the air moved inland rapidly in the afternoon, slowed and reversed in the evening, and gradually moved inland the following morning. During its slow back-and-forth movement over the areas of heavy traffic and industrial activity, accumulation of high concentrations of pollution was observed (Neiburger, 1969).

Microscale Characteristics

There are many microscale characteristics associated with pollution dispersion, but the most important parameter concerning the coastal region is the internal boundary layer. Because the coastline constitutes a discontinuity in terms of the roughness of the underlying surface, the wind must readjust as it passes such areas. The flow does not immediately adapt itself at all levels to the local surface roughness but does so only in the layer adjacent to the surface. The height of the layer in which the influence of the new roughness is felt, the so-called internal boundary layer, increases with distance downwind from the point of change in roughness (see, e.g., Blom and Wartena, 1969). Measurements of the boundary layer have been made by Hsu (1971) on a beach and by Panofsky and Peterson (1972) on a narrow peninsula surrounded by bays of varying widths.

The thickness of the internal boundary layer is greater under the influence of sea breeze, owing to stronger solar radiation (Hsu, 1973), than that of synoptic onshore wind (e.g., gradient wind) (Fig. 12). The relationship between the internal boundary layer and plume fumigation is vividly illustrated in Figure 11 for sea breeze and in Figure 13 for gradient onshore wind conditions. Thus, over land influenced by onshore wind, mixing depths are considerably reduced but greatly variable and are eminently favorable for day-long, continuous fumigation of pollutants. Most recently, a diffusion model which takes into account the effect of the internal boundary layer was developed by Hsu and Whelan (1976).

A Diffusion Nomograph for Offshore Operations

For various offshore operations such as waste burning by an incinerator ship or oil-well burning resulting from an accident, a simplified model for quick estimation of the concentration downwind is needed. Figure 14 shows a nomograph specifically developed for these purposes. According to Roll (1965), Kraus (1972), and Hsu (1974), offshore weather conditions related to diffusion may be classified into three categories:

Condition 1 (daytime): Wind speed ≤ 5 m/sec and cloud cover $\leq 3/8$ cloudiness;

Condition 2 (day and night): Wind speed ≤ 5 m/sec, cloud cover $\geq 4/8$ cloudiness; wind speed >5 m/sec, disregard cloud cover;

Condition 3 (nighttime): Wind speed $\leq$ 5 m/sec and cloud cover $\leq 3/8$ cloudiness.

Note that conditions 1, 2, and 3 are equivalent to the overland Pasquill stability categories C, D, and E, respectively (e.g., Slade, 1968). Figure 14 shows the relationship between this classification and effective emission height in order to estimate the distance from an elevated source to the point of maximum ground-level concentration, χ_{max}, and values of maximum ground-level concentration. This calculation was made by proper analytical arrangement of Equations 3 and 4. For more detail, see Hsu (1975).

Summary and Recommendations

For the coastal zone of Louisiana where potential sites for industrial plants and other structures are located, along with other considerations such as geology, economics, availability of cooling waters, etc., proper measurement of pertinent meteorological conditions should be made. The measurement program should include all microscales, mesoscales, and synoptic scales because of their varying temporal and spatial ranges.

On the basis of the dispersion characteristics discussed in the report, it is possible to select an area where those adverse effects are minimal. Some criteria are recommended as follows:

1) Places where there is a pronounced diurnal coastal air circulation system should be avoided.
2) The upwind nearshore region should be relatively flat in order to minimize the development of an internal boundary layer and a terrain-induced vortex.
3) Spacing between storage tanks for oil and natural gas should be at least 5 to 10 times the height of the tanks themselves to minimize hydrocarbon concentration.
4) Extra care must be given to design criteria in locations where hurricanes, cyclones, water spouts, or other catastrophic meteorological phenomena may occur.
5) If the potential site is on the route of a storm track, the offshore bottom slope should be gentle and bathymetrically uniform to attenuate storm surges and wave effects.
6) Last but not least, experienced coastal meteorologists should participate actively as integral members of interdisciplinary scientific and engineering teams striving for better understanding and utilization of coastal and marine environments to best advantage.

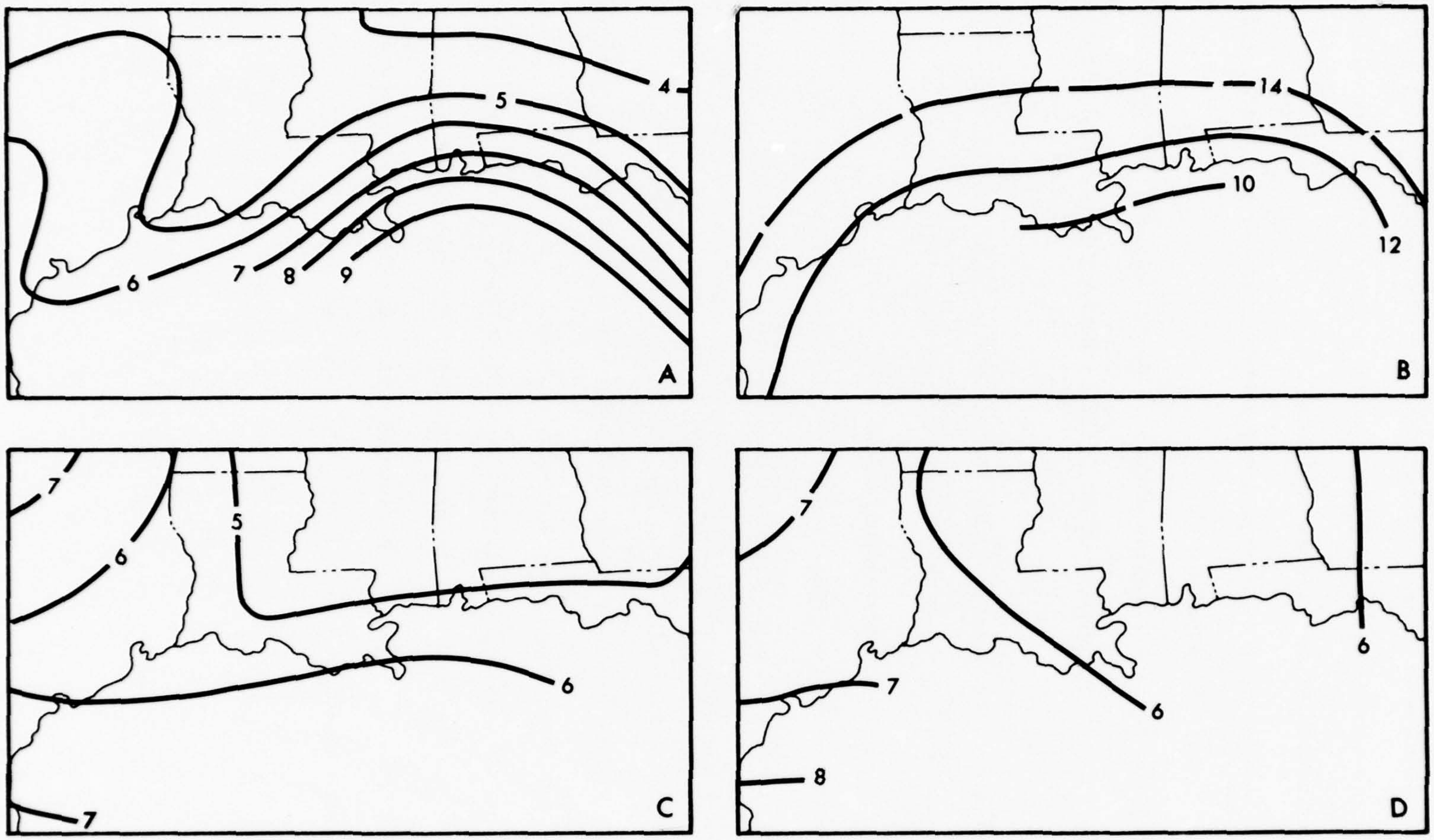


Fig. 1. A, Isopleths (m x 10^2) of mean annual morning mixing height; B, same as A except that it shows afternoon mixing height; C, isopleths (m sec^{-1}) of mean annual wind speed averaged through the morning mixing layer; D, same as for C except that an afternoon mixing layer is shown.

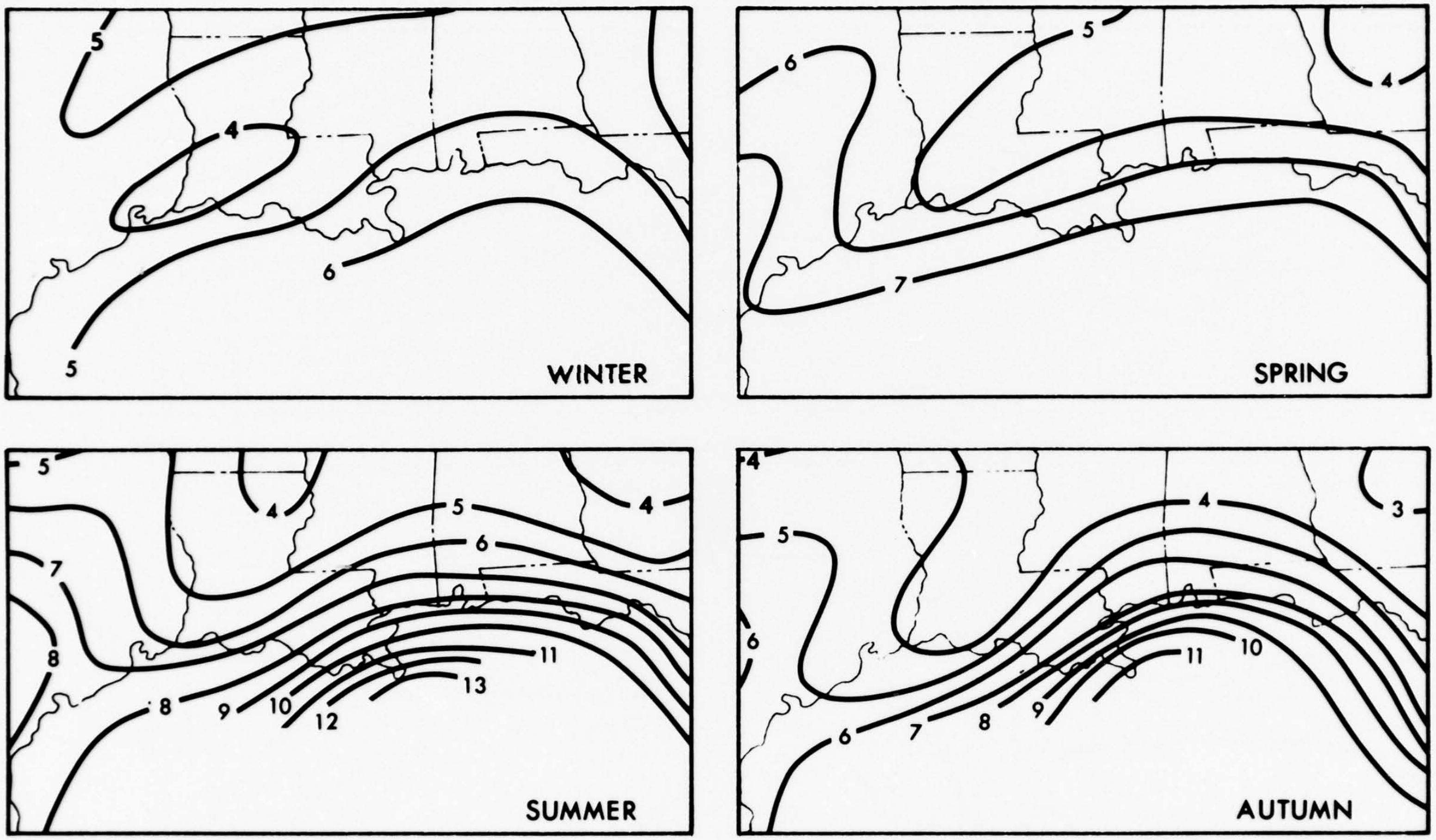


Fig. 2. Isopleths (m x 10^2) of mean winter, spring, summer, and autumn morning mixing heights.

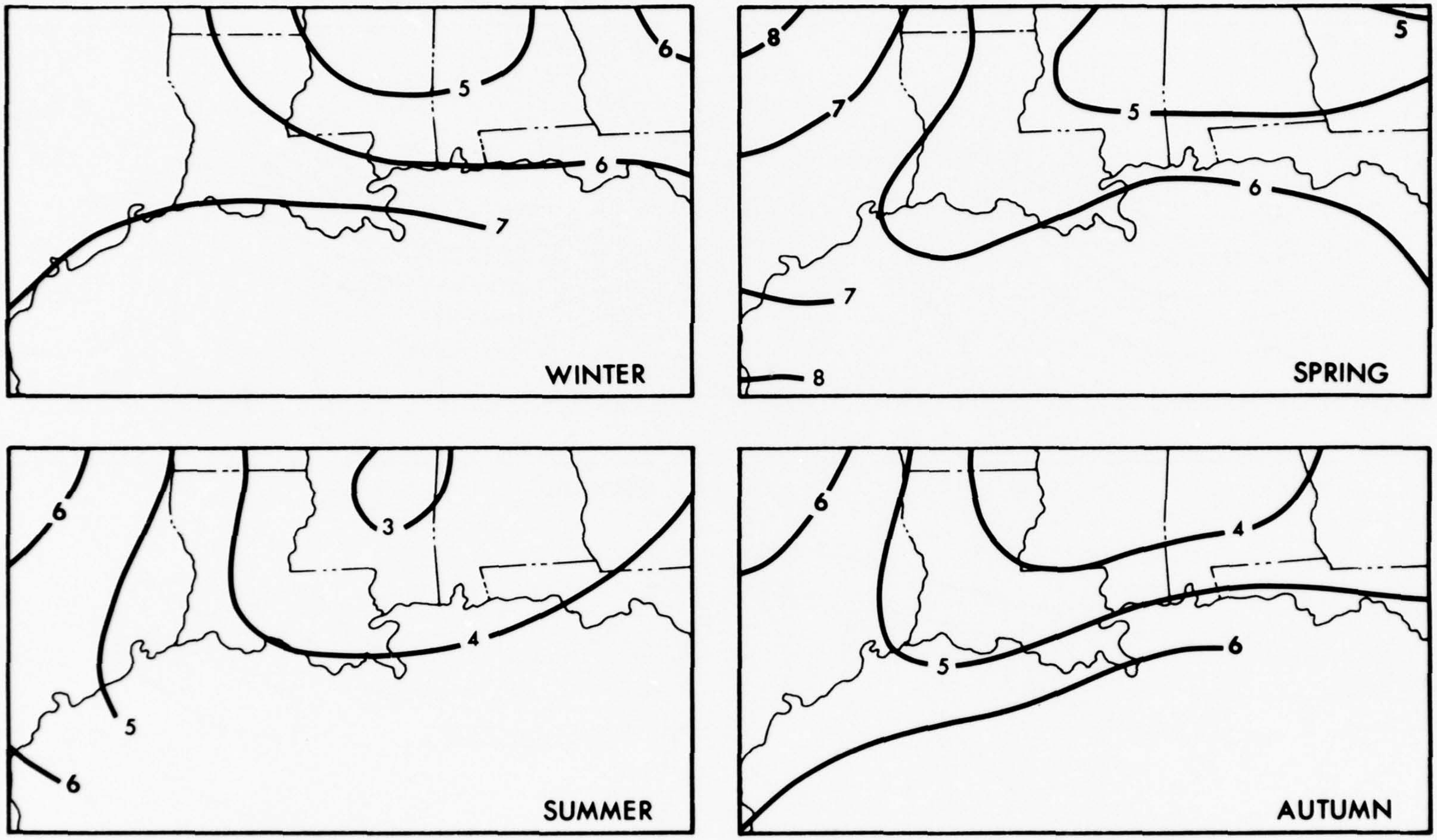


Fig. 3. Isopleths (m sec^{-1}) of mean winter, spring, summer, and autumn wind speeds averaged through the morning mixing layer.

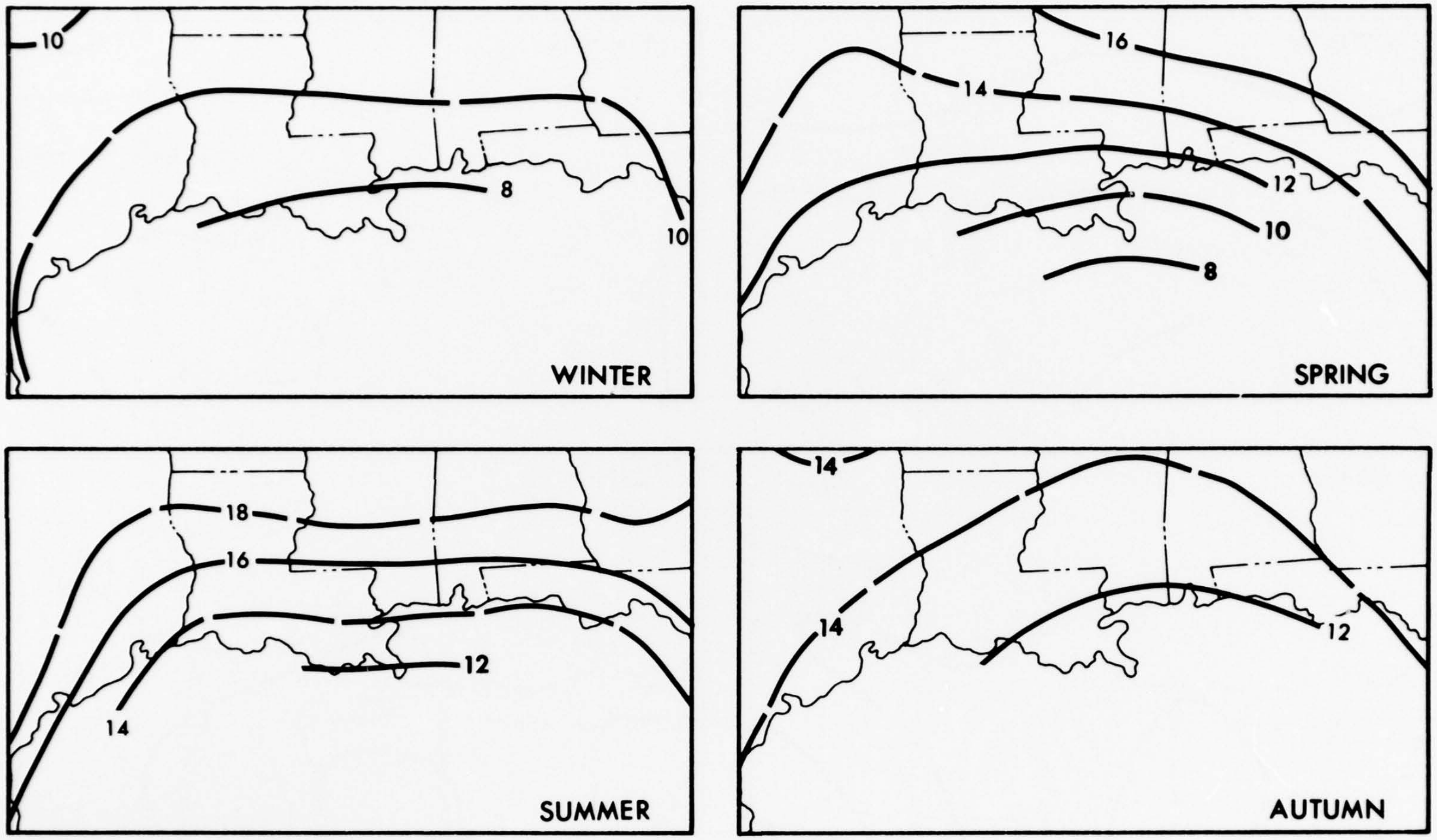


Fig. 4. Isopleths (m x 10^2) of mean winter, spring, summer, and autumn afternoon mixing heights.

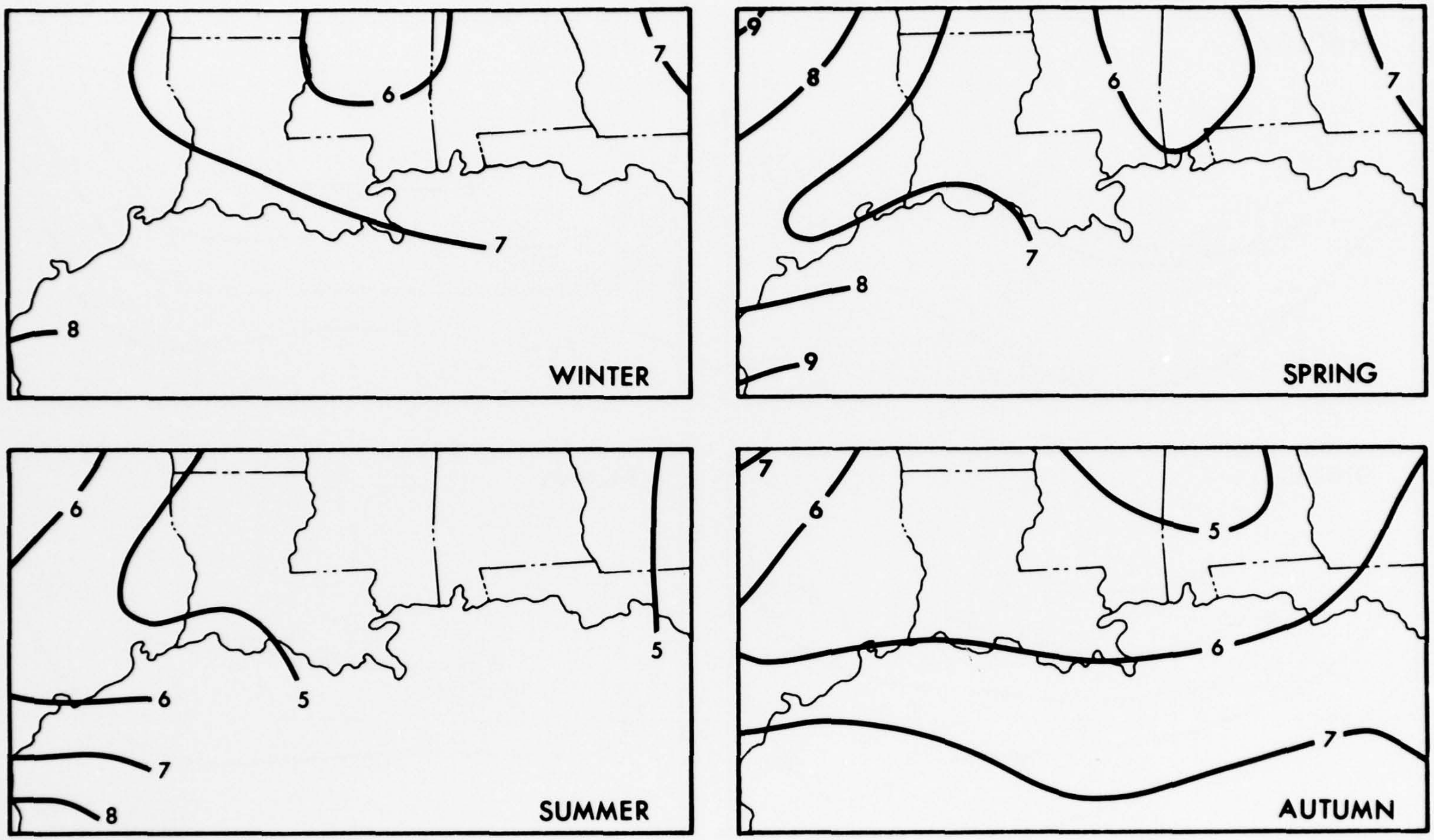


Fig. 5. Isopleths (m $\sec^{-1}$) of mean winter, spring, summer, and autumn wind speed averaged through the afternoon mixing layer.

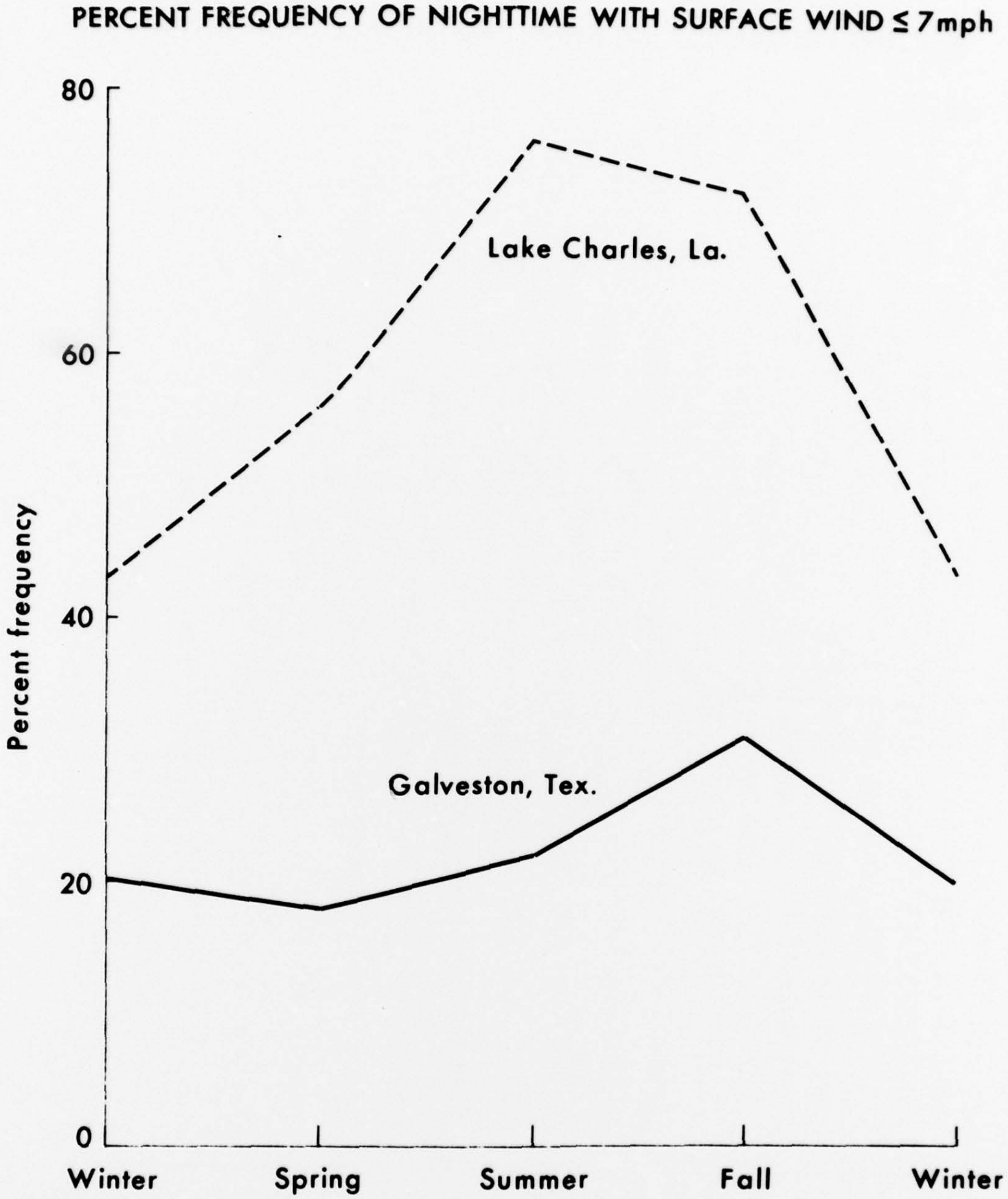


Fig. 6. Percentage of frequency of nighttime with surface wind ≤ 7 mph at Lake Charles, Louisiana, and Galveston, Texas.

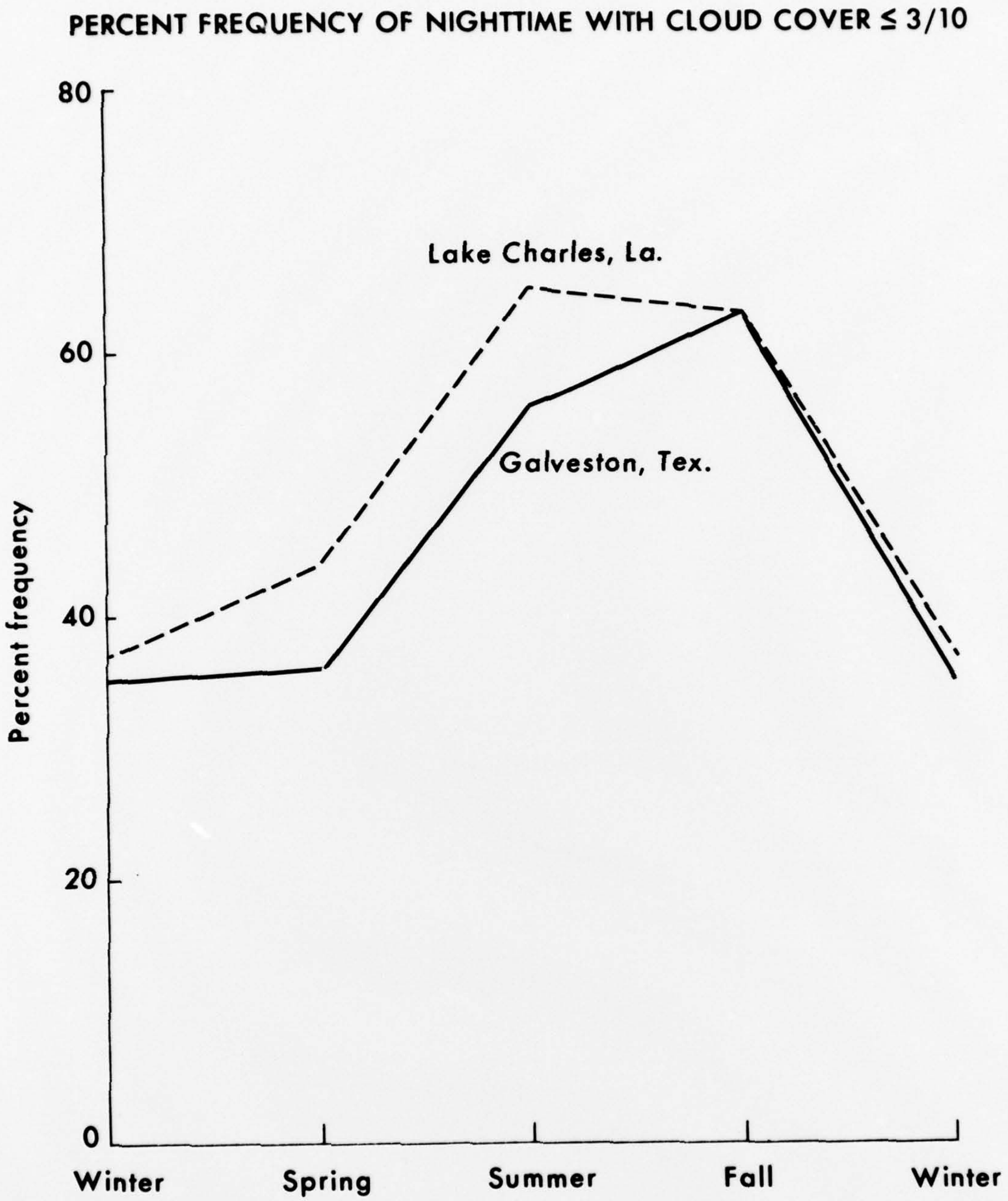


Fig. 7. Percentage of frequency of nighttime with cloud cover ≤3/10 at Lake Charles, Louisiana, and Galveston, Texas.

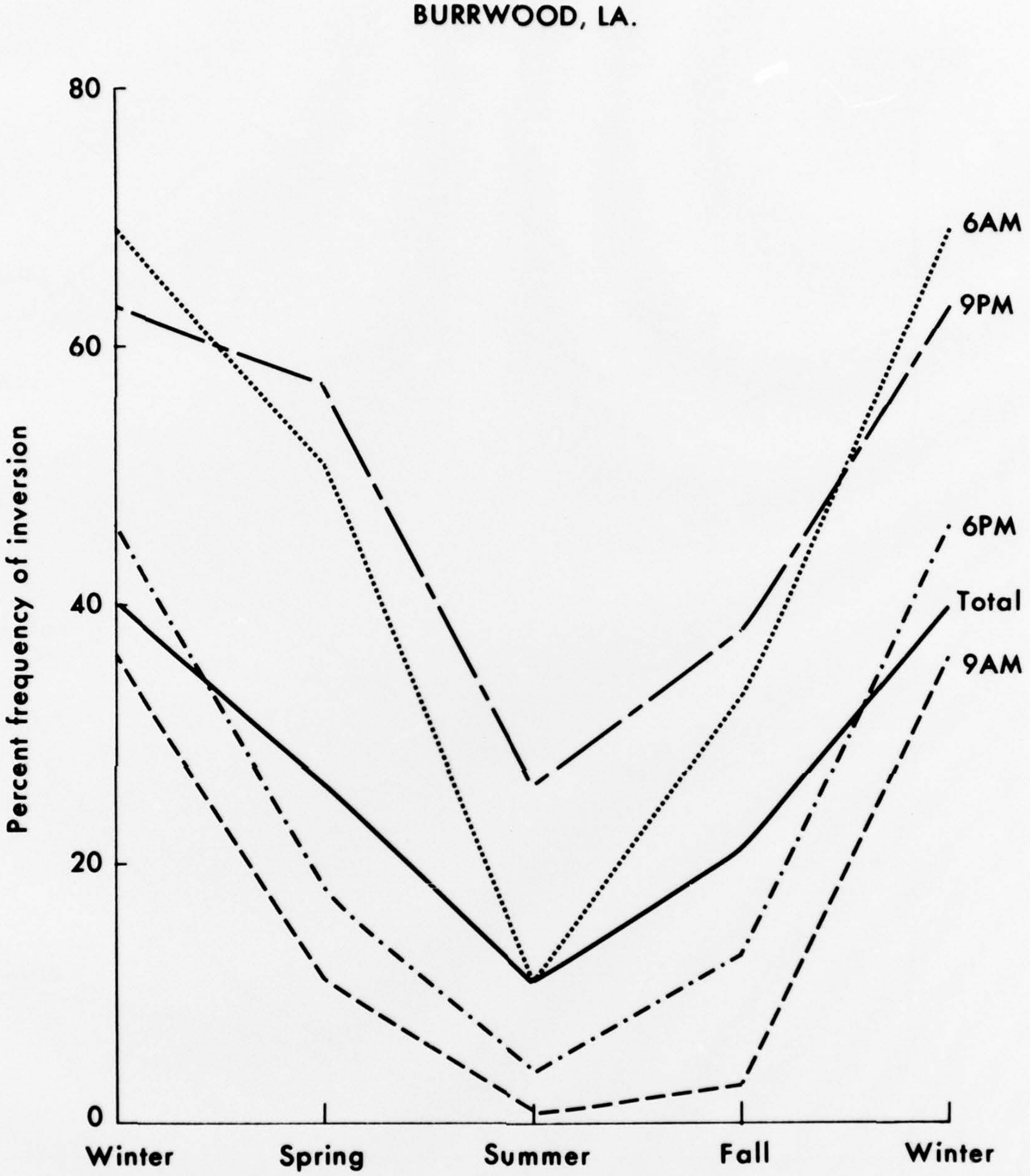


Fig. 8. Percentage of frequency of inversion at Burrwood, Louisiana.

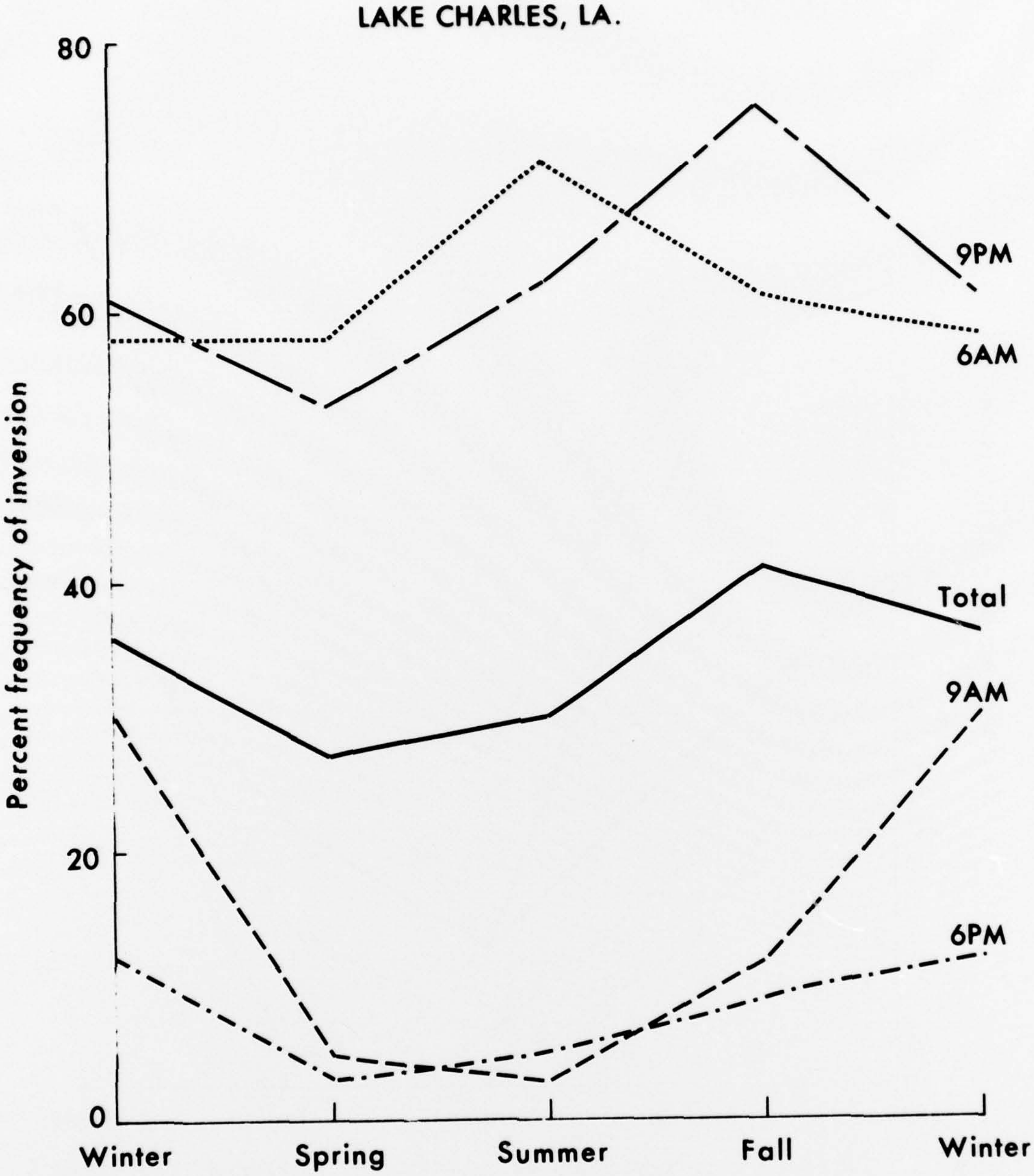
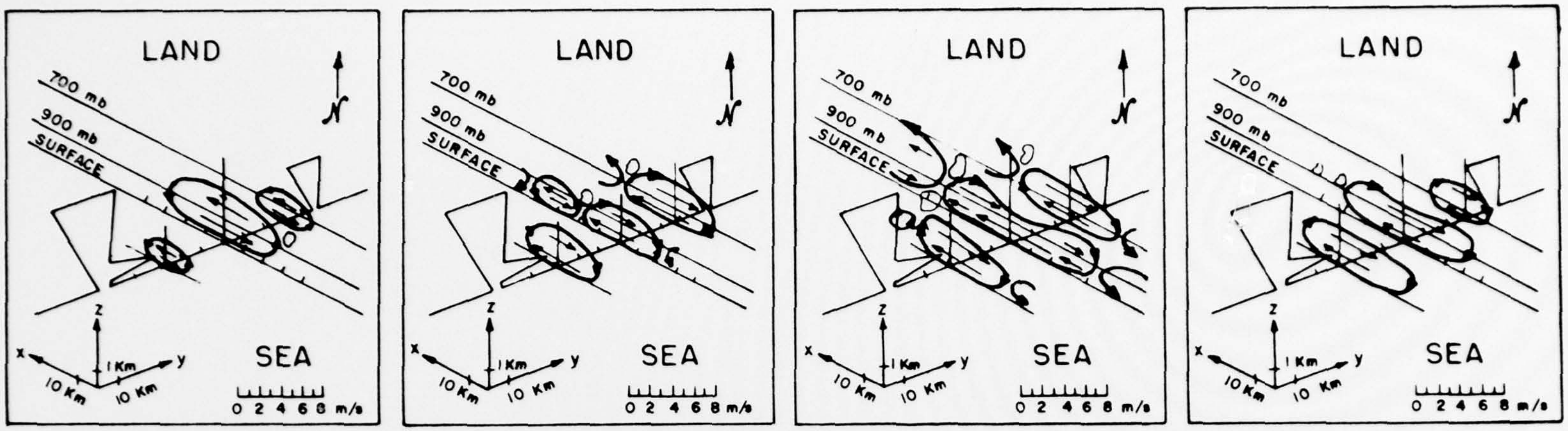
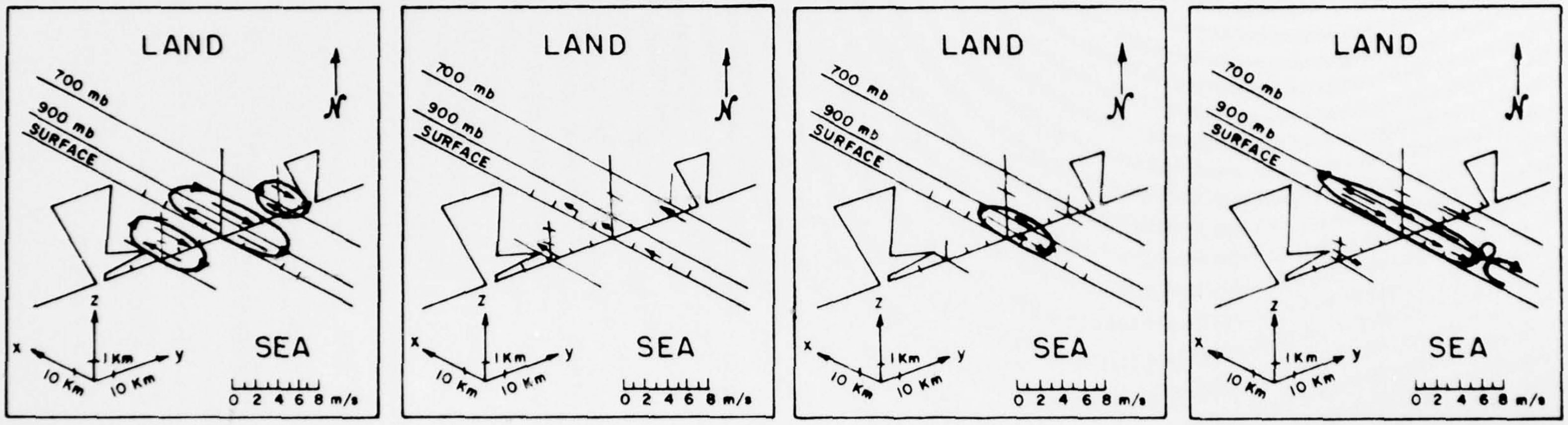


Fig. 9. Percentage of frequency of inversion at Lake Charles, Louisiana.



(a) 0900 Local time (b) 1200 Local time (c) 1500 Local time (d) 1800 Local time



(e) 2100 Local time (f) 0000 Local time (g) 0300 Local time (h) 0600 Local time

Fig. 10. Synthesized empirical model of the coastal air-circulation system on the Texas coast between Galveston and Port Arthur (Hsu, 1970).

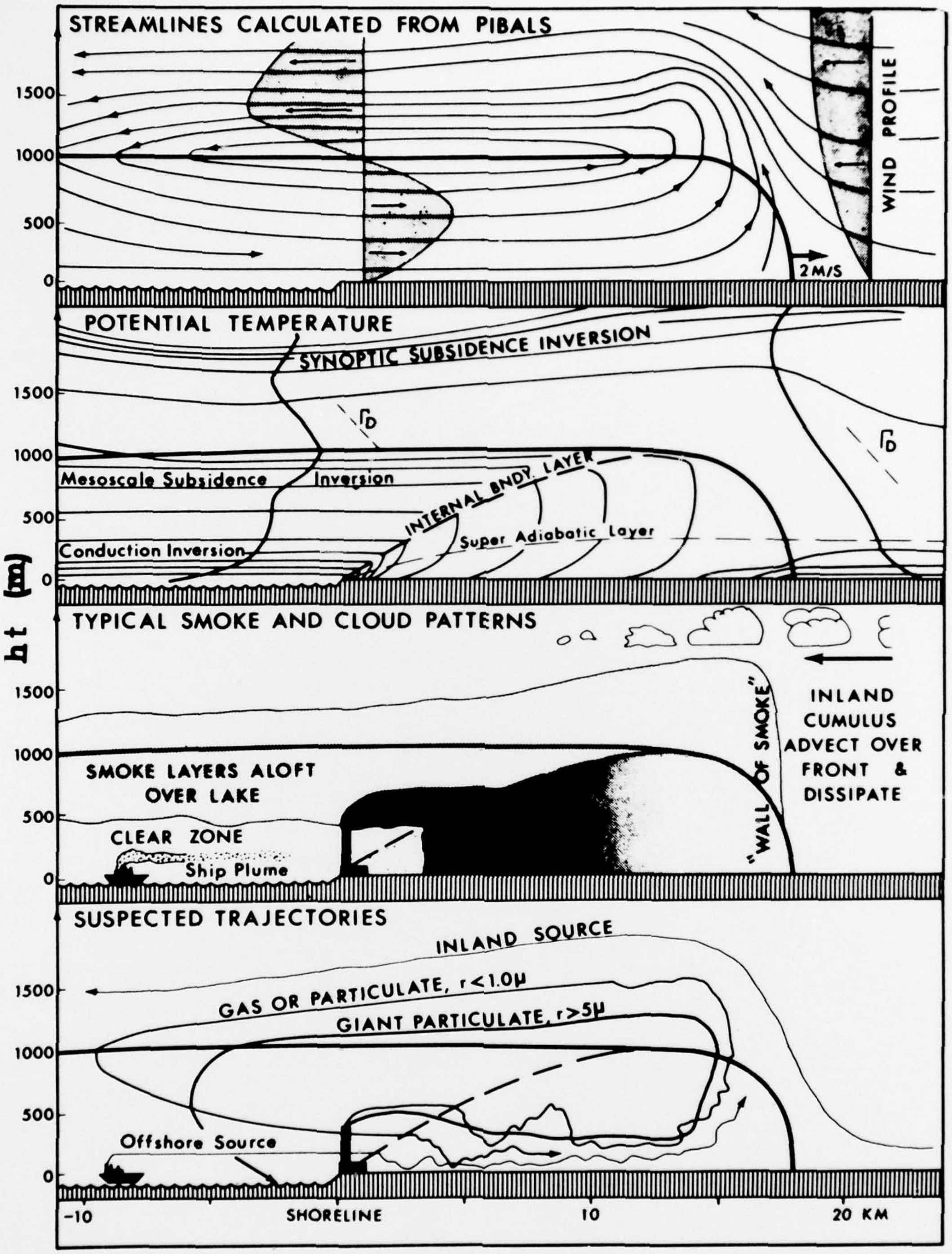


Fig. 11. Summary of the (A) streamline, (B) potential temperature, (C) smoke and cloud, and (D) trajectory patterns associated with the typical land breeze near the shore of Lake Michigan (Lyons and Olsson, 1973).

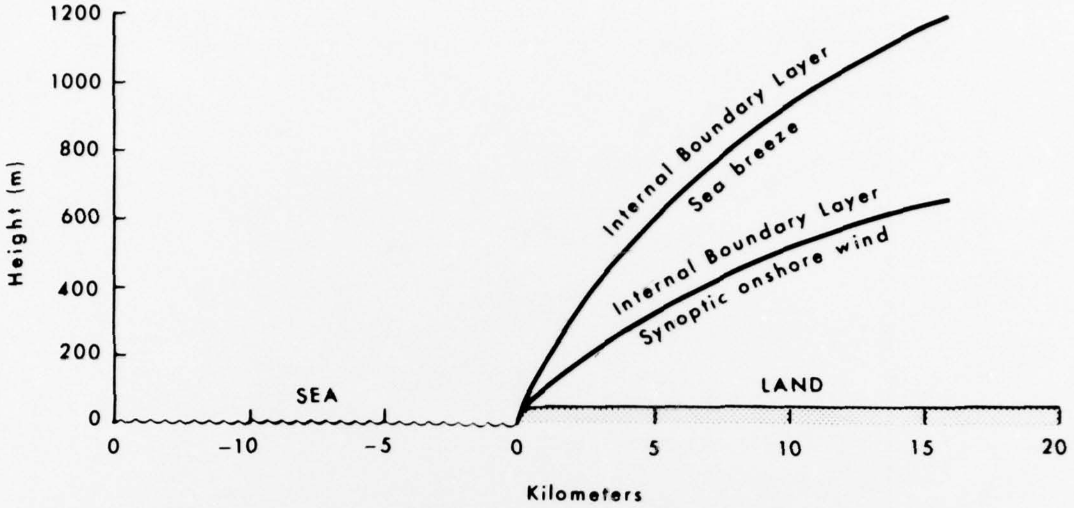


Fig. 12. Examples of the development of the internal boundary layer under sea breeze and synoptic onshore wind influences on the shore of Lake Michigan (Lyons and Olsson, 1973; Lyons and Cole, 1973).

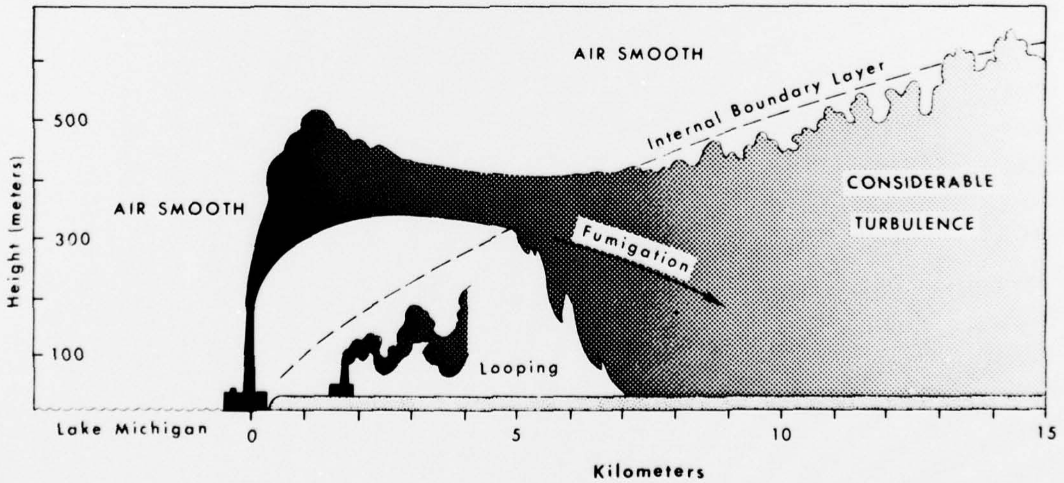


Fig. 13. The relationship between internal boundary layer and plume fumigation under gradient onshore wind condition (Lyons and Cole, 1973).

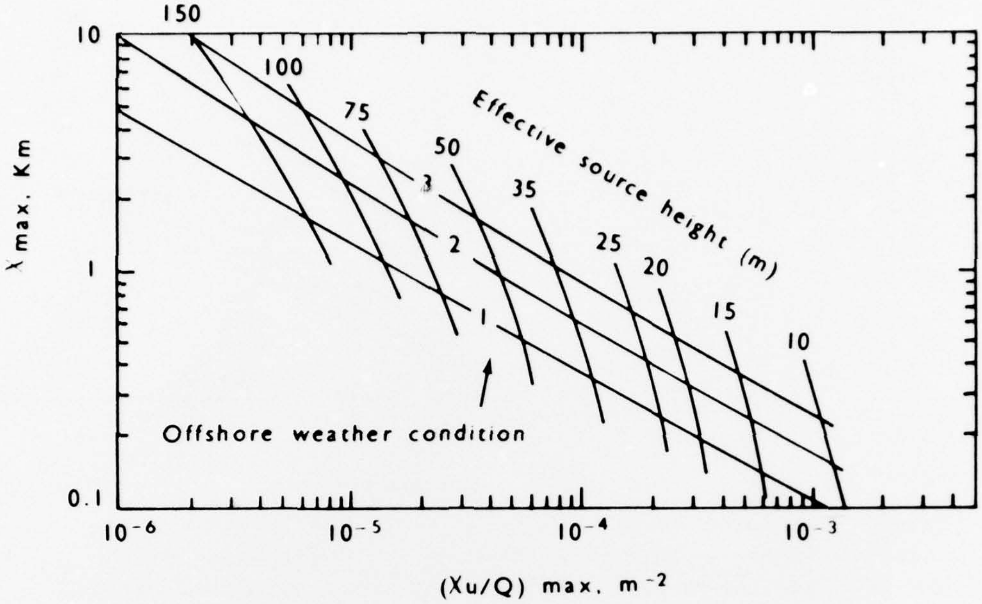


Fig. 14. Distance from an elevated continuous source to point of maximum ground-level average concentration, χmax, and value of maximum ground-level concentration for various effective source heights and offshore weather conditions (modified from Martin, 1965) for offshore operations (Hsu, 1975).

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Revised 1/11/77