Meteorological Aspects of Oil Spills on the Open Ocean

FINAL REPORT

Contract No. T-35429

Techniques Development Laboratory
National Weather Service
National Oceanic and Atmospheric Administration
Silver Spring, Maryland

by

K. H. Jehn, N. K. Wagner, and R. W. Miksad
Co-Principal Investigators
Atmospheric Science Group
Civil Engineering Department
The University of Texas at Austin
Austin, Texas 78712

August 1978

DISCLAIMER:

Publication of this technical report does not constitute official Government approval of the report findings and/or conclusions. The contents reflect the views of the contractor who is responsible for the facts and accuracy of the results presented herein, and do not necessarily reflect the views or policy of the Government.

ABSTRACT

The initial year of work under the terms of the subject contract has been a three-pronged attack on the problem of meteorological aspects of oil spills on the open ocean. The synoptic scale effort has been directed toward producing a geostrophic wind at the site of the spill (the Gulf of Mexico, for example), as input to an atmospheric boundary layer model. Objective analysis, weather types, and forecast sea-level pressures were investigated.

In the atmospheric boundary layer research, a Rossby-number similarity theory approach was used. The direction and magnitude of the surface stress acting on an oil slick was obtained through modifications applicable to a baroclinic, diabatic boundary layer, utilizing input geostrophic wind and other variables from the synoptic scale analysis.

The ocean surface turbulence studies were based on the premise that the dispersive spread of oil slicks is due to the action of random stresses on the surface of the slick, and that the action of these stresses can be related to the kinematics of the ocean surface layer turbulence. The research utilized an apparatus for laboratory-scale measurements of relative dispersion in the uppermost layer of water in a specially designed and constructed tank.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

The problem of oil spills on the open ocean has become a major one in recent years, with important energy and environmental implications. Much work has been done on handling the clean-up of the oil, particularly in coastal areas. On the open ocean, the concern has been with anticipating the movement and ultimate dispersion of the oil, with some concern for environmental degradation, especially in shallower parts of the ocean. Very little effort has thus far been devoted to the trajectory problem. The objective of the research reported herein is to provide an analysis of the atmospheric contribution to the trajectory problem. Ocean current studies are contributed by others; however, an important part of the research contributed by the Atmospheric Science Group is in the dispersion of the oil at the atmosphere-ocean interface by turbulent motions.

The University of Texas investigation is a closely coordinated three-part study of oil slick movement and natural dispersion: (1) the synoptic-scale atmospheric motions are seen as moving the oil slick by means of a stress at the interface which is a function of the geostrophic wind and atmospheric boundary layer characteristics; (2) the atmospheric boundary layer is modelled in such a way as to predict the magnitude and direction of the surface stress from an input geostrophic wind; and (3) the dispersive spread of the slick at the air-sea interface is seen as a consequence of turbulent motions, predominantly in the uppermost ocean layer.

Each of these investigations is handled by a separate principal investigator; the previous work in each case, and the reporting of current research, will be handled in three separate sections of the report to follow.

The research reported here covers the initial contract work only; the study is continuing under a second contract between NOAA and The University of Texas Atmospheric Science Group.

II. SYNOPTIC SCALE ANALYSIS (K. H. Jehn)

II-A. Objectives and Scope of Research

The primary objective of the synoptic scale research has been to produce a geostrophic wind of acceptable accuracy at the site of the hypothetical or actual oil spill, as input to the atmospheric boundary layer model being devised by Dr. N. K. Wagner. This objective of the first year of contract work has been accompanied by several peripheral objectives: (1) to evaluate the usefulness of existing or devised "weather types" in specifying geostrophic wind vectors; (2) to evaluate the usefulness of 24h forecasts of sea level pressure pattern (LFM) in specifying geostrophic wind vectors; and (3) to make direct correlations of anemometer-level winds at coastal and off-shore locations. These points will be considered in turn.

II-B. Data Analysis and Results of Research

II-B.1. Weather Types

In view of the expected scarcity of over-water meteorological data, the original proposal anticipated the need for using existing or devised "weather types" for specifying synoptic scale pressure patterns. This problem was investigated early in the contract period.

The selection of a suitable weather type in a given situation requires an analysis of the available sea level pressure data over the (large) area of interest, and a comparison of the analyzed pattern with the weather type catalog (Sabin, et al, 1974). This was done for seven (7) winter cases. All available sea level pressures for the so-called "Texas window" were plotted, and an isobaric analysis performed by hand.

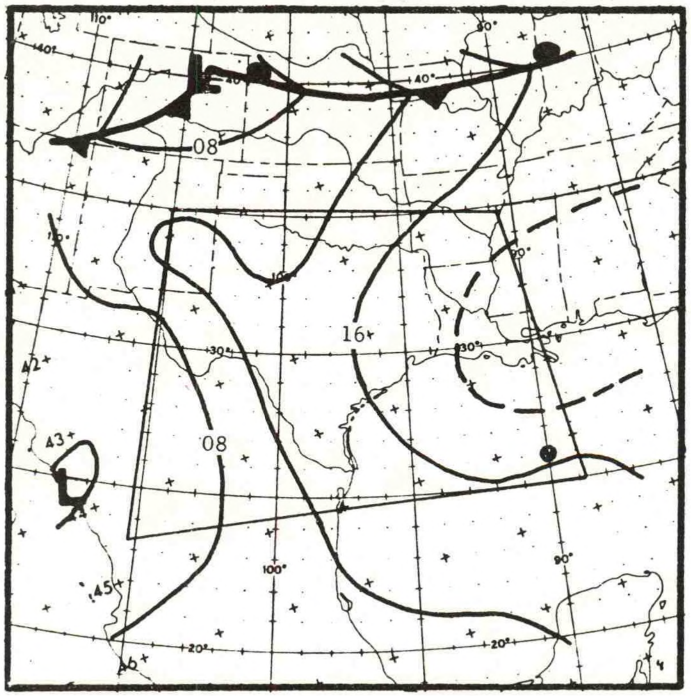
To make feasible the correlation of the sea level pressure pattern with the appropriate weather type, the pressure data were then objectively analyzed, utilizing a technique reported by Barnes (1964), with slight modifications. The fourteen weather types of the Texas "window", based on a 25-year data sample, and obtained by applying a map-pattern classification technique first developed by Lund (1963), were then correlated with each analyzed pressure pattern. The results of this analysis for 23 January and 16 February 1977 are shown in Table 1.

Table II-1. Correlation Coefficients for 14 Weather Types, Two Cases.

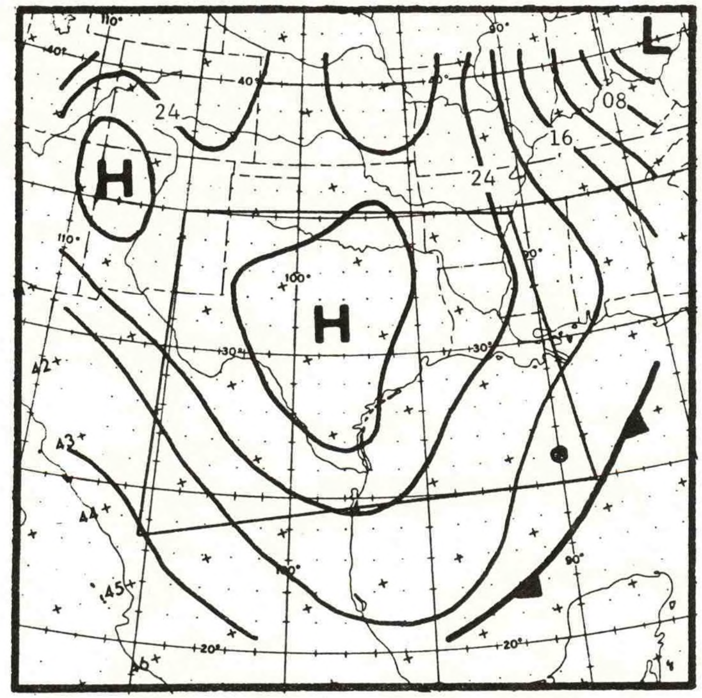
	23 Jan 77	16 Feb 77
Weather Type*	Correlation Coefficient	Correlation Coefficient
1	0.90 ←	-0.14
2	0.06	0.01
3	0.58	0.37
4	0.53	-0.36
5	0.61	-0.52
6	-0.76	0.33
7	-0.16	0.60 ←
8	0.60	0.56
9	0.47	-0.31
10	-0.69	-0.43
11	0.77	0.37
12	0.39	-0.79
13	0.37	-0.21
14	0.39	-0.81

*Sabin, et al, 1974.

The weather types with the largest positive correlations were #1 on 23 January 1977 (90%), and #7 on 16 February 1977 (60%), marked with arrows in the table. The type patterns are shown in Fig. 1. These are, respectively, fairly characteristic onshore and offshore flow patterns in the Gulf of Mexico area, the former (A) usually representative of maritime tropical air, or possibly returning polar air in winter, the latter (B) usually characteristic of polar air



(A) Map Type 1



(B) Map Type 7

Figure II-1 Map types (Sabin, et al, 1974) of the Texas window which correlate with objectively analyzed sea level pressure data (see text).

invasions of the Gulf.

Since the objective of the synoptic scale research is to produce an acceptable geostrophic wind as input for the atmospheric boundary layer model, a comparison is made in Table 2 for the two cases displayed above, at a location in the Gulf chosen to correspond to a reporting point (the buoy located at 26°N 90°W, marked with ⊗ in Figure 1).

Table II-2. Geostrophic Wind (V_g), Calculated (Barnes) vs. Weather Type (Sabin) at 26°N 90°W, and Observed Surface Wind at Same Location

	Wind Speed (ms^{-1})	Wind Direction (degrees true)
23 January 1977		
V_g, Barnes	8.0	103
V_g, Weather Type #1	5.2	90
Surface Wind	2.6 ± 1.3	100
16 February 1977		
V_g, Barnes	7.7	58
V_g, Weather Type #7	11.5	23
Surface Wind	5.2 ± 1.3	360

For the 23 January case, geostrophic wind directions are in good agreement (within 13 degrees), although the weather type wind is only 65% of the objectively analyzed magnitude (from sea level pressure data). The measured surface wind is properly smaller in magnitude than either V_g, although the direction should be more like 80 degrees to more closely agree with geostrophic direction. For the 16 February case, the measured surface wind is more in line with the weather type geostrophic wind (both speed and direction) than with the objectively analyzed sea level pressure data. It should be mentioned that the buoy location is near the southern edge of the data analysis area.

It became evident in this research that the weather types were generally not worth the considerable effort, including computer time, to obtain the correlations. If there were sufficient data for the objective analysis to give confidence in the weather type correlations, then the correlations themselves were unnecessary, since the pressure pattern is already well defined. In fact, sea level pressure data from the vicinity of any oil spill should be given a high priority, since this will improve the initial pressure pattern, and give an important first step in anticipating the direction and speed of movement of the resulting oil slick.

II-B.2. LFM Patterns

At this point in the research, it seemed worthwhile to investigate already available sea level pressure patterns, rather than to undertake objective analyses of surface data. At the time, the initial sea level pressure fields from the Limited-Area Fine-Mesh Primitive Equation Model (LFM) of the National Meteorological Center (NMC) were not available at The University of Texas. The LFM prognostic panels were available, however, so a study was undertaken of the LFM 24-hour prognosis of the sea level pressure field over the Gulf of Mexico area. The chief advantage of this choice was that a preliminary evaluation of the 24h forecast could be made, with some indication of the use of the prognostic series in specifying synoptic-scale air trajectories useful in forecasting oil slick movement.

The preliminary results of this research reported at the contractors' meeting in Silver Spring on 4 August 1977 are shown in the following two tables. As before, the buoy location in the central Gulf was chosen for the comparison. Table 3 compares observed vs. predicted sea level pressure and its standard deviation; computed geostrophic wind and its standard deviation; and the root-mean-square error in geostrophic wind direction and speed. The "observed" values were extracted from the verifying surface pressure charts, and the "predicted" values were extracted from the 24h LFM panels. The first 80 cases spanned a period from winter to spring, so a shorter winter period (38 cases) was selected to match the available summer period (38 cases).

Table II-3. Comparison of Observed and Predicted (24h LFM) Sea Level Pressure and Geostrophic Wind At Buoy 26°N 90°W

		Sea Level Pressure		Geostrophic Wind		RMS Error		
Dates	Data Set	$\bar{P}_o$ (mb)	S.D. (mb)	$\bar{V}_g$ (ms^{-1})	S.D. (ms^{-1})	Direction (deg)	Speed (ms^{-1})	No. of Cases
5 Jan to 8 Apr 77 (12Z only)	Obs.	1017.4	5.42	10.43	4.43	41.7	5.31	(80)
	Pred.	1015.9	6.04	11.46	5.47			
11 Jan to 16 Feb 77 (12Z)	Obs.	1019.5	4.47	10.99	4.75	33.7	5.46	(38)
	Pred.	1018.2	5.28	11.46	5.59			
14 Jun to 23 Jul 77 (00Z & 12Z)	Obs.	1018.2	1.10	6.06	2.04	50.1	2.68	(38)
	Pred.	1015.2	1.46	4.77	1.99			

There was reasonable agreement between observed and predicted geostrophic wind magnitude in all three periods, but standard deviations were relatively large, compared to the mean magnitudes of the computed geostrophic winds, except perhaps in summer, when winds over the Gulf are steadier. Moreover, root-mean-square (RMS) errors (comparisons between observed and predicted) were probably too large to be tolerated in producing oil spill trajectories. Of course, the worst cases make the largest contribution to RMS errors, and the number of cases is not large in this sample.

To examine another aspect of this situation, the period 11 Jan - 16 Feb 1977 was selected for resolving the derived geostrophic winds into components, with auto- and cross-correlations run on the resulting matched time-series. The results are shown in Table 4.

Table II-4. Comparison of Observed and Predicted (24h LFM) Geostrophic Wind Components at Buoy 26°N 90°W, and Correlation Coefficients, 11 Jan - 16 Feb 77 (12Z)

a. Components

Data Set	East -- West Wind		North -- South Wind	
	$\bar{u}_{g}$ (ms^{-1})	S.D. u_g (ms^{-1})	$\bar{v}_{g}$ (ms^{-1})	S.D. v_g (ms^{-1})
Obs.	-7.56	7.73	0.03	5.14
Pred.	-5.34	9.69	0.26	6.34

b. Autocorrelation Coefficient

	u_g	v_g	
Obs.	0.28	0.27	(Just about significant at the 0.1 level)

c. Cross-correlation Coefficient

	u_g	v_g	
Obs/Pred.	0.82	0.76	(Significant at a level very much higher than 0.001)

Note that the agreement is reasonable on geostrophic components, and that the cross-correlation coefficients are significant at a level well above 0.001. Standard deviations are still large, however, compared to mean values of geostrophic components.

Since the contractors' meeting in August 1977, the synoptic scale research on LFM patterns has continued, with a view to obtaining additional cases, thus improving the statistical significance of the comparisons. Additionally, the LFM was tested over the eastern Gulf of Mexico near Tampa, FL (in the Alabama "window"), where data density was greater.

Table 5 summarizes the central Gulf data. Some information in the preceding tables is repeated; in general, the number of cases has been significantly increased.

Table II-5. 24h LFM Verification at $26^{o}N$ $90^{o}W$ (Buoy in Central Gulf of Mexico)

1977 dates	No. of cases	Mean Sea Level Pressure ($\bar{p}_o$) Pred. (mb)	Stand. Dev. (mb)	Obs. (mb)	Stand. Dev. (mb)	Mean Geostrophic Wind ($\bar{V}_g$) Pred. (ms^{-1})	Stand. Dev. (ms^{-1})	Obs. (ms^{-1})	Stand. Dev. (ms^{-1})	RMS Error Azimuth (degrees)	RMS Error Speed (ms^{-1})
5 Jan-8 April (Winter)	80	1015.9	6.04	1017.4	5.42	11.46	5.47	10.43	4.43	41.7	5.31
12Z only		(Obs) - (Pred) = 1.5 mb				(Obs) - (Pred) = -1.03 ms^{-1}					
14 June-7 Sept (Summer)	113	1013.9	1.80	1016.0	2.70	5.06	1.96	6.50	4.03	48.5	4.03
00Z & 12Z		(Obs) - (Pred) = 2.1 mb				(Obs) - (Pred) = 1.44 ms^{-1}					
14 June-7 Sept (Hurricane	97	1014.3	1.66	1016.9	1.70	4.73	1.78	5.46	2.15	45.2	2.39
Days Removed)		(Obs) - (Pred) = 2.6 mb				(Obs) - (Pred) = 0.73 ms^{-1}					
10 Sept-4 Nov (Fall)	88	1014.4	2.78	1015.3	2.69	6.93	3.07	5.86	2.70	34.9	3.04
00Z & 12Z		(Obs) - (Pred) = 0.9 mb				(Obs) - (Pred) = -1.07 ms^{-1}					
10 Sept-23 Nov (Fall)	118	1015.1	3.63	1015.9	3.69	7.27	3.36	6.65	3.21	36.9	3.00
(More cases)		(Obs) - (Pred) = 0.8 mb				(Obs) - (Pred) = -0.62 ms^{-1}					

Mean predicted sea level pressure is too low in all seasons, with the largest difference in summer, compared to observed. Standard deviation of sea level pressure, as expected, is smallest in summer, largest in winter. Predicted geostrophic wind from the LFM tends to be too large in the cold seasons, too small in summer, compared to observed. Root-mean-square (RMS) errors in direction are largest in summer, but RMS errors in magnitude are a minimum in the summer period with hurricane days removed (Anita and Babe occupied the Gulf area successively during the period 29 August through 6 September 1977). This finding is not unreasonable, since RMS direction errors range only between 35 and 45 degrees (neglecting summer hurricane days), and RMS speed errors would be expected to parallel the standard deviation in geostrophic wind speed.

Table 6 makes the same comparisons for the eastern Gulf of Mexico area centered near Tampa, FL. The number of cases is roughly the same. Here, LFM predicted sea level pressure is also too low in all seasons, with a maximum departure in summer, compared to observed. Standard deviations of sea level pressure follow expected patterns. With geostrophic winds, departures are negative in the cold seasons (predicted winds too strong), and positive in summer (predicted winds too weak). Standard deviations of geostrophic wind follow expected patterns. Root-mean-square errors in geostrophic wind direction are larger in summer, and RMS speed error is larger in winter, as in the central Gulf case. However, the RMS direction errors are larger near Tampa than in the central Gulf in summer, possibly because Tampa is located nearer to the center of the Bermuda-Azores anticyclone than is the buoy at 26^{o}N 90^{o}W.

Table II-6. 24h LFM Verification at 28°N 83°W (near Tampa, FL)

		Mean Sea Level Pressure ($\bar{p}_o$)				Mean Geostrophic Wind ($\bar{V}_g$)					
1977 dates	& No. of Cases	Pred. (mb)	Stand. Dev. (mb)	Obs. (mb)	Stand. Dev. (mb)	Pred. (ms^{-1})	Stand. Dev. (ms^{-1})	Obs. (ms^{-1})	Stand. Dev. (ms^{-1})	RMS Error Azimuth (degrees)	RMS Error Speed (ms^{-1})
5 Jan- 8 April (Winter) 12Z	80	1018.5	5.31	1019.5	4.48	11.05	4.65	8.52	3.47	44.6	4.82
		(Obs) - (Pred) = 1.0 mb				(Obs) - (Pred) = -2.53 ms^{-1}					
14 June- 7 Sept (Summer) 00Z & 12Z	114	1015.7	1.66	1018.0	1.88	4.41	2.16	5.61	3.54	53.9	3.27
		(Obs) - (Pred) = 2.3 mb				(Obs) - (Pred) = 1.20 ms^{-1}					
14 June- 7 Sept (Hurricane Days Removed)	98	1015.8	1.60	1018.4	1.71	4.11	2.05	4.68	2.49	56.6	2.42
		(Obs) - (Pred) = 2.6 mb				(Obs) - (Pred) = 0.57 ms^{-1}					
10 Sept- 4 Nov (Fall) 00Z & 12Z	86	1015.6	2.79	1016.4	2.41	5.77	3.15	5.79	3.07	49.1	2.31
		(Obs) - (Pred) = 0.8 mb				(Obs) - (Pred) = 0.02 ms^{-1}					

Except for this, the patterns displayed by pressure and geostrophic wind statistics are much the same at the two locations. One can infer that in 1977, at least, 24h LFM behavior at sea level over the Gulf of Mexico is well portrayed by these statistics.

Because of the seasonal variability in the LFM statistics, and the rather large RMS errors in geostrophic winds, it was decided to count predicted LFM geostrophic winds during each of the three seasons (winter, summer, fall) within pre-set limits as follows: approximately 70% in speed, and 20^{o} in direction, compared to observed. The results are summarized in Table 7.

Table II-7. Comparison of 24h LFM With Observed Geostrophic Wind at 26^{o}N 90^{o}W

1977 Dates	No. of Cases	Percent of Cases: Predicted V_g ≥ 70% of Observed Speed	Predicted V_g ≤ 20^{o} in Direction	Predicted V_g ≥ 70% of Observed Speed and ≤ 20^{o} in Dir.
Winter				
5 Jan-8 Apr	80	55	51	31
Summer				
14 June-7 Sept (Hurricane days removed)	97	62	62	32
Fall				
10 Sept-4 Nov	88	59	57	35

It would appear that through much of 1977, the probability of having a predicted geostrophic wind in the central Gulf of Mexico amounting to 70%

or more of the observed geostrophic wind speed and within 20 degrees in direction amounted to about 1 in 3, a rather dismal percentage for the particular arbitrary limits set. There is a factor of a little less than 2 to 1 involved when the limits are applied separately. There is no obvious seasonal variation in the percentages shown in the table. The longest string of days with both limits satisfied was four, February 7 through 10 1977. Lesser strings appeared in summer and fall.

These results of the examination of LFM 24h forecasts of sea level pressure and geostrophic wind are encouraging in the sense that the LFM produces very few geostrophic wind forecasts which are more than 90° off in direction (less than 5 percent) and less than 50% of the observed speed (less than 20%). For both limits simultaneously, the cases drop to less than 2% of the total number of comparisons.

II-B.3. Correlations of Surface Winds, Land vs. Ocean Stations

The initial synoptic scale proposal indicated that correlations would be sought between land-based and over-water winds, on the grounds that plentiful data from land stations could be used to advantage to obtain over-water data. This is shown by the work of Resio and Vincent (1977) and Overland and Gemmill (1977), among others. But in all cases, atmospheric boundary layer characteristics are heavily involved. Nonetheless, some linear correlations of anemometer level winds were attempted, using Galveston (GLS) as the land station, and the offshore oil rig at 28°N 93°W as the ocean station. The separation between the two observation points is approximately 230 kilometers. Because diurnal variations in correlation were anticipated, as well as effects of off-shore and onshore flow, the data were stratified as shown in Table 8. Seasonal stratification was not feasible, since the total number of cases available was too small for further subdivision.

The number of onshore cases exceeded the number of offshore cases by a factor ranging from 2 at 12Z to 3 at 18Z to 7 at 00Z, evidence of a sea-breeze type circulation operating at Galveston, since the Galveston data were used to separate onshore from offshore cases. As expected, mean surface wind speed at the oil rig exceeded that at Galveston for all offshore cases, although the difference was small at 12Z, when the number of cases was largest. During onshore flow, mean surface winds at Galveston and the rig were nearly the same in magnitude, except at 12Z, when the average effect of a sea-breeze type circulation might account for the 1.1 ms^{-1} smaller wind at Galveston.

The mean absolute difference in direction of the wind at Galveston and the oil rig was consistently larger for the offshore cases than the onshore cases, and with a pronounced diurnal variation in the onshore cases, smallest at 12Z.

It was anticipated that the wind would veer or back from the rig to Galveston in individual cases, because of expected isobaric curvature. There was a pattern in the statistics, as seen in the table, where the number of cases of veering (clockwise turning of the wind from the oil rig to Galveston) during onshore flow exceeded the number of veering cases during offshore flow by a large margin, especially at 00Z. The definition of veering applies always <u>from</u> the oil rig <u>to</u> Galveston, so veering in onshore flow suggests anticyclonic isobaric curvature, and veering in offshore flow suggests cyclonic isobaric curvature.

Table II-8. Comparisons of Surface Wind at Galveston (GLS) and the Oil Rig at 28^{o}N 93^{o}W [19 March - 8 December 1977 (267 cases)]

	Time	Flow Pattern	No. of Cases	$\bar{V}$(GLS) (ms^{-1})	$\bar{V}$(Rig) (ms^{-1})	Diff. (GLS)-(Rig) (ms^{-1})	Mean Absolute Difference Speed (ms^{-1})	Mean Absolute Difference Dir. (deg.)	No. of Cases Veer	Mean Diff. Veer (degrees)	No. of Cases Back	Mean Diff. Back (degrees)	Corre. Coeff. (GLS) vs (Rig)
(a)	12Z	(offshore flow)	33	4.2	4.6	0.4	1.9	59	21		11		0.57
		(onshore flow)	59	4.5	5.6	1.1	2.0	33	43		10		0.53
		(total)	92							49		-45	
(b)	18Z	(offshore flow)	16	4.5	6.6	2.1	3.1	55	12		3		0.63
		(onshore flow)	51	5.7	5.3	-0.4	2.5	40	34		12		-0.03
		(total)	67							45		-58	
(c)	00Z	(offshore flow)	13	5.3	7.4	2.1	4.3	55	9		4		0.09
		(onshore flow)	95	5.1	4.9	-0.2	2.4	54	66		25		0.31
		(total)	108							54		-59	
(d)	Combined Statistics, 268 cases												
	Offshore		62	4.5	5.7	1.2	2.7	57	42	61	18	-58	0.52
	Onshore		206	5.1	5.2	0.1	2.3	44	144	46	47	-53	0.28

Similarly, there was a pattern in the backing cases (wind turning counterclockwise from the oil rig to Galveston), although the difference was noticeable only at 18Z and 00Z. As to the angles involved in veering and backing, the number of cases was too small to subdivide into offshore and onshore flow at the three times (12Z, 18Z, 00Z), so an average veering and backing angle is given for each time, with offshore and onshore cases combined. Since the average veering and backing angles range only from 45 degrees to 60 degrees, approximately, it was thought worthwhile to do a set of combined statistics (12Z, 18Z, and 00Z) as part (d) of the table. The combined statistics eliminated the diurnal variations noted in (a), (b), and (c), but emphasize the offshore versus onshore flow pattern already mentioned. Additionally, it is seen that the offshore veering angle (cyclonic curvature) exceeds the onshore veering angle, a not unexpected finding in view of the cyclonic storms which move across the northern Gulf. The backing angles are nearly alike in both offshore and onshore flow, suggesting that onshore cyclonic flows differ little in curvature from offshore anticyclonic flows in the region between Galveston and the oil rig some 230 km to the southeast, although the average angle is rather large, especially in offshore flow, between the surface wind directions at the two locations.

Surprisingly, correlation coefficients for surface wind speeds in offshore flow exceeded those in onshore flow, except at 00Z. Overall, the offshore correlation coefficient significantly exceeded the coefficient for onshore flow.

III. ATMOSPHERIC BOUNDARY LAYER STRUCTURE (N. K. Wagner)

In the idealized situation, a given synoptic scale atmospheric structure will be associated with a unique planetary boundary layer configuration. This in turn will produce surface water movement in response to the tangential stresses at the air-ocean interface. The planetary boundary layer is essentially driven by the "external" synoptic scale and transfers momentum to (or on rare occasions, from) the oceanic lower boundary. In what follows it is assumed that the synoptic scale structure is known and that a prediction of the direction and speed of the surface water (or oil) movement will be obtained from appropriate atmospheric boundary layer, air-ocean interface, and oceanic models.

Equations for the structure of the horizontally homogeneous, steady-state planetary boundary layer can be obtained from Rossby-number similarity theory. Assuming a linear variation of geostrophic wind ($\vec{V}_{go}$) with height and a height scaling parameter u_*/f gives equations (1) and (2) for the diabatic, baroclinic planetary boundary layer [see Hess (1973) and Clarke and Hess (1974)] where μ is a dimensionless stability parameter involving the von Karmán constant k, friction velocity u_*, Coriolis parameter f, and the Obukhov length L; T, ρ and c_p are the temperature, density and specific heat capacity at constant pressure of air, g is the acceleration of gravity, and Q_H is the vertical heat flux.

$$\ln R_o = A(\mu, \hat{S}_x, \hat{S}_y) - \ln (u_*/|\vec{V}_{go}|) + [k^2|\bar{V}_{go}|^2/u_*^2 - B^2(\mu, \hat{S}_x, \hat{S}_y)]^{\frac{1}{2}} \qquad \text{(III-1)}$$

$$\text{Sin } \theta = (Bu_*)/(k|\vec{V}_{go}|) \qquad \text{(III-2)}$$

where

$$\mu = ku_*/fL, \qquad L = -(u_*^3\ T\ \rho\ c_p)/(k\ g\ Q_H), \qquad R_o = |\vec{V}_{go}|/(f\ Z_o)$$

$$\hat{S}_x = \frac{k^2}{f}\frac{\partial u_g}{\partial z} \doteq -\frac{k^2 g}{f^2 T}\frac{\partial T}{\partial y}$$

and

$$\hat{S}_y = \frac{k^2}{f}\frac{\partial v_g}{\partial z} \doteq \frac{k^2 g}{f^2 T}\frac{\partial T}{\partial x}$$

Dimensionless baroclinic parameters are given by $\hat{S}_x$ and $\hat{S}_y$ where the x-axis is in the direction of the surface wind, R_o is the surface Rossby number, and the angle θ is measured positive from the surface geostrophic wind to the surface stress.

The functions A and B are presumably universal functions to be evaluated experimentally. Because the amount of field data suitable for this type of evaluation is very limited, several researchers have analyzed essentially the same data with somewhat differing results [Clarke and Hess (1974), Arya (1975), Arya and Wyngaard (1975) and others.] Many of these have been summarized recently by McBean (1976). The magnitude of the diabatic function μ should never be very large over the open ocean, that is generally $|\mu| \leq 90$. For a rough comparison, $\mu = 90$ would be associated with an air-ocean temperature difference of about 10C^o. Hence, the cubic term of Arya (1975) may be neglected. Taking some liberties in adjusting the remaining coefficients and utilizing the baroclinic coefficients given by Clarke and Hess (1975) yields equations (3) and (4).

$$A(\mu, \hat{S}_x, \hat{S}_y) = A(\mu) + 0.20\ \hat{S}_x - 0.04\ \hat{S}_y \qquad \text{(III-3)}$$

$$B(\mu, \hat{S}_x, \hat{S}_y) = B(\mu) - 0.32\ \hat{S}_x + 0.33\ \hat{S}_y \qquad \text{(III-4)}$$

where $A(\mu) = A_o - 0.10\mu - 0.001\mu^2$

$B(\mu) = B_o + 0.13\mu + 0.001\mu^2$

except when $\mu < -50$, then $A(\mu) = A(-50) = 3.50$ and $B(\mu) = B(-50) = 1.00$. Neutral barotropic values of $A_o = 1.00$ and $B_o = 5.00$ will be used in later examples. These are close to those determined by Arya (1975).

Equations (1) and (2) can be solved for the expected range of values for A and B. From equation (1) a family of B curves can be obtained as a function of $\ln R_o - A$ on abscissa and $u_*/|\vec{V}_{go}|$ on ordinate. This was done by Clarke and Hess (1974). All values have been recomputed and plotted in slightly different form in Figure III-1. Equation 2 can also be displayed in graphical form. A family of B curves appears in Figure III-2 with $u_*/|\vec{V}_{go}|$ as the abscissa and θ as the ordinate.

For barotropic, adiabatic conditions these graphs provide a quick and convenient means for obtaining surface stress (i.e. u_*) and the cross-isobaric angle of the surface wind. For example, with $\vec{V}_{go} = 10\ ms^{-1}$, $f = 10^{-4}\ s^{-1}$, $A_o = 1.0$, $B_o = 5.0$, and a site roughness $Z_o = 1cm$, then $R_o = 10^7$, and $\ln R_o - A = 15.12$. From Figure 1, $u_*/|\vec{V}_{go}| = 0.031$ or $u_* = 31\ cm\ s^{-1}$. From Figure 2 it is then found that $\theta = 23^o$. Thus, for an air density of $1.2 \times 10^{-3}\ gm\ cm^{-3}$, a surface stress of 1.15 dynes cm^{-2} is determined, directed at an angle of 23^o across the isobars toward lower pressure.

Application of this scheme to the open ocean for neutral barotropic conditions presents a slight additional complication since the surface roughness may be a function of surface stress. For illustrative purposes, a friction velocity-roughness parameter relation is assumed of the form proposed by Charnock (1955) and given by equation (5), where m is a constant.

$$Z_o = \frac{m}{g} u_*^2 \doteq (1.63 \times 10^{-5}\ cm^{-1}\ s^2)\ u_*^2 \qquad \text{(III-5)}$$

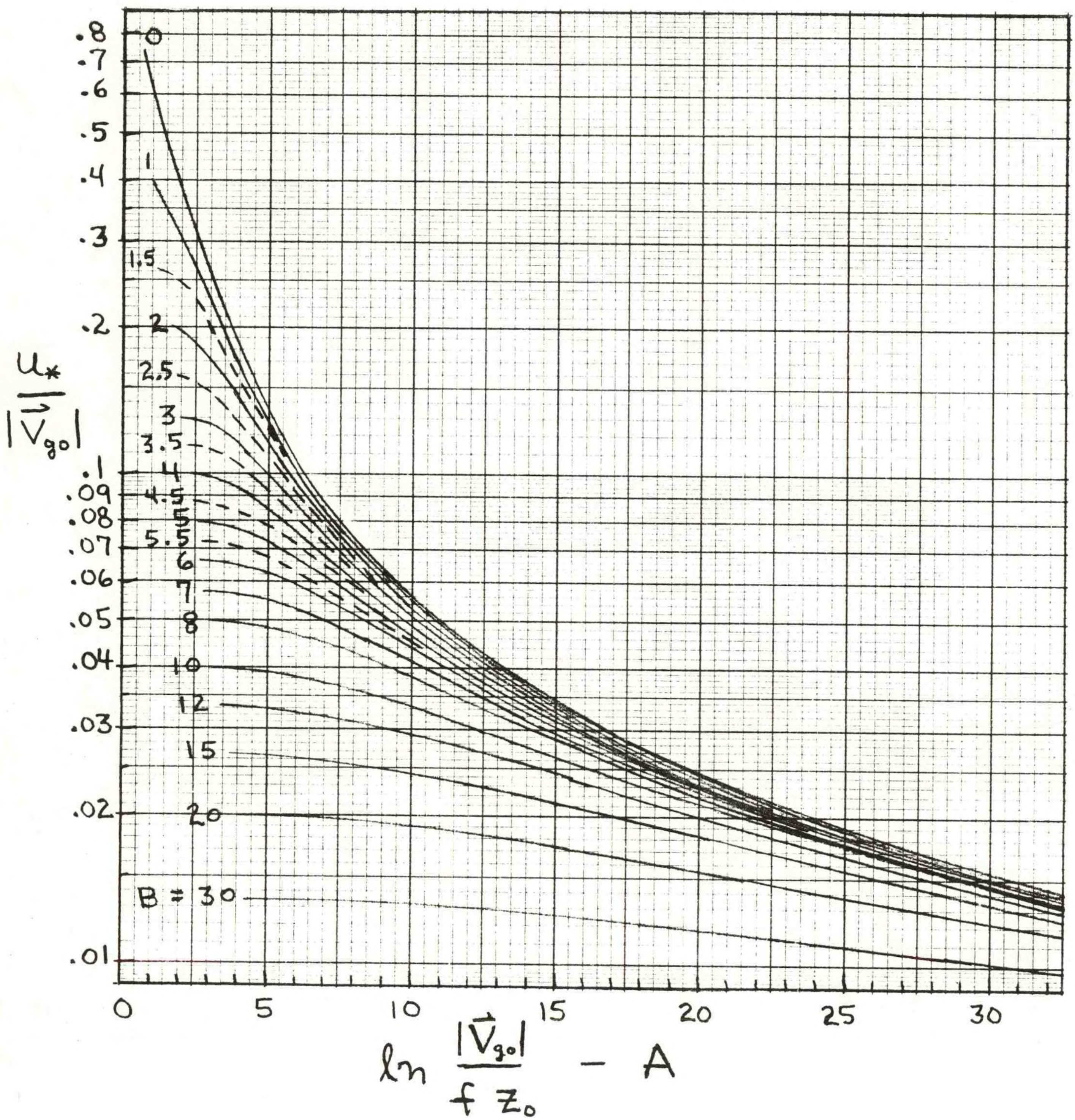


Figure III-1: Rossby-number similarity relation for $u_*/|\vec{V}_{go}|$ and A from equation 1 plotted for various values of B. Note that equation 1 is quadratic in B, hence the lines apply to both positive and negative values of B.

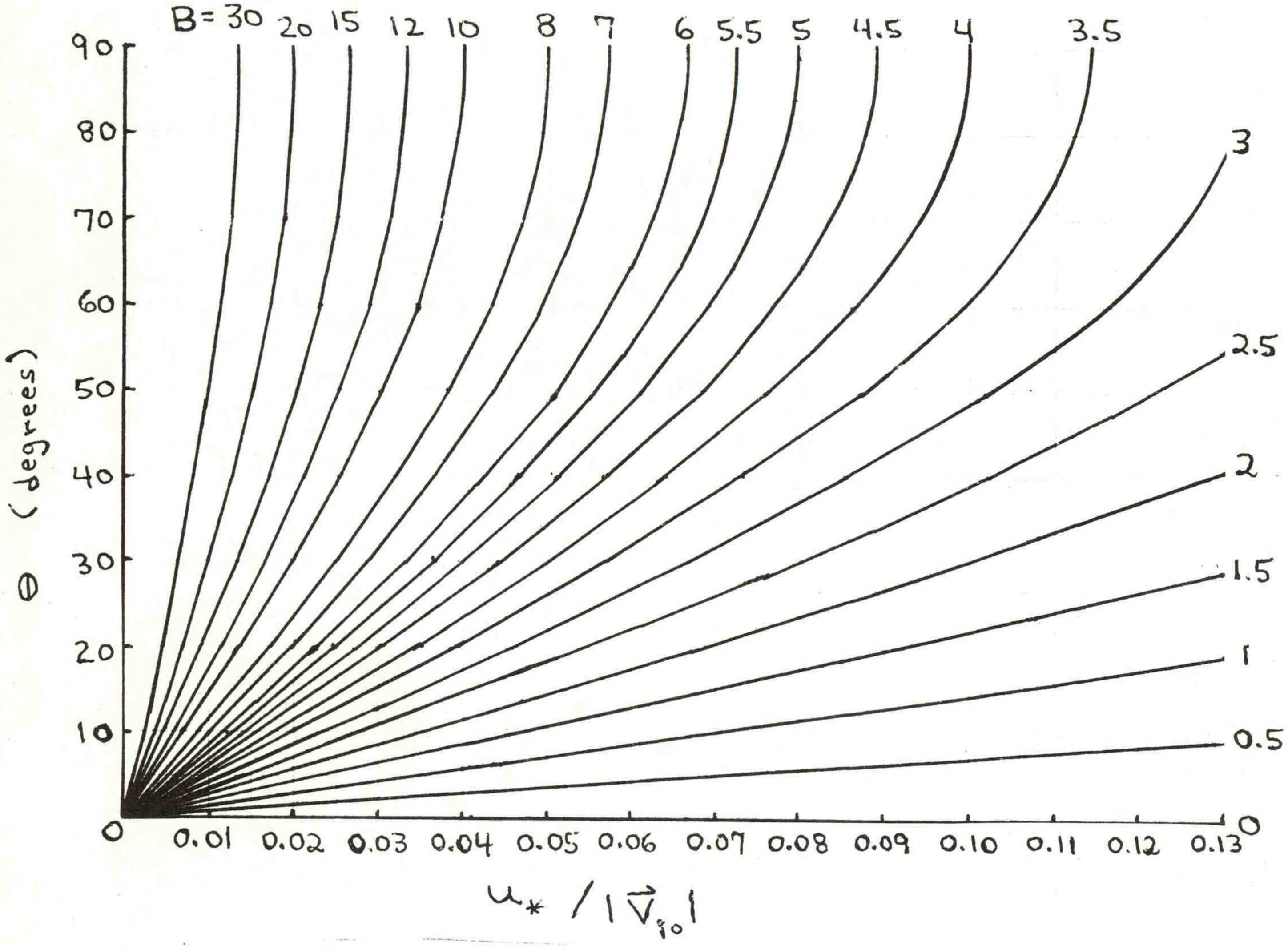


Figure III - 2: Rossby-number similarity relation for the angle Θ between the surface wind and the surface geostrophic wind (equation 2) plotted for various values of B. The quantities B and Θ will have the same algebraic sign.

A value of m = 0.016 is used [Wu (1969), Hicks (1972, 1975)]. Because Z_o is assumed to be a function of the friction velocity, Figure 1 now requires iteration. A first guess Z_o gives a first guess surface Rossby number, which in turn provides an associated u_*. This u_* is used to give a new value for Z_o by equation 5, a new Rossby number and hence a new u_*. Convergence is rapid with any reasonable Z_o first guess. Once the value of u_* is obtained, θ can be determined from Figure 2 as before. Using the same initial values as in the previous example, it is found over the water that $u_* = 23$ cm s^{-1} with $Z_o = 0.0086$ cm and $\theta = 17^o$. It should be pointed out that this iterative step is necessary only if the surface roughness is assumed to be a function of the external forcing functions, in this case u_* through the geostrophic wind speed. If Z_o is assumed constant, then no iteration is necessary, and the solution proceeds as in the first example. The evaluation of surface roughness over the ocean is still a subject of lively debate and represents an area that deserves additional study.

The next level of complication includes diabatic effects. Much of the time the air over the open ocean is in nearly neutral stratification, and hence the adiabatic assumption employed in the previous two examples would be valid. However, important exceptions occasionally occur; for example, air may flow over cold or warm ocean currents, or cold or warm fronts may move through the area. In diabatic conditions the stability parameter μ is required. Sufficient accuracy for the vertical heat flux can probably be obtained by bulk transfer methods such as discussed by Hicks (1975) and Haase and Dunckel (1974). The main requirement is information on the air-sea temperature difference, which presumably would be obtained by ship reports or from satellite data.

Notice that since μ is a function of u_*, it will have to be included in the friction velocity iteration loop. Selecting a first guess Z_o, the friction velocity is computed from equation 5 and used to calculate μ. This μ is then used to determine $A(\mu)$ and $B(\mu)$. Figure 1 is then utilized to obtain a "better" u_* and new values for μ, A, B, and Z_o. Figure 1 is then used again as needed. Once convergence is reached to a sufficiently precise value for u_* and B, these values can be used to determine θ from Figure 2. Increasing stability ($\mu > o$) gives $A < A_o$ and $B > B_o$. This results in decreased u_* (from Figure 1) and increased θ (from Figure 2) as compared to neutral conditions [see for example, Clark (1975)]. Unstable conditions ($\mu < o$) are associated with $A > A_o$ and $B < B_o$ and yields increased u_* from Figure 1 and decreased θ from Figure 2.

In neutral baroclinic conditions, $\mu = 0$ but $\hat{S}_x$ and $\hat{S}_y \neq 0$. Following Clarke and Hess (1974), the following difficulty is encountered: The x-axis is defined by the direction of the surface wind. But to know the direction of the surface wind (or equivalently, θ), values of the Rossby number similarity functions A and B must be known. But A and B depend on $\hat{S}_x$ and $\hat{S}_y$. Hence the direction of the x and y axes needs to be known before A and B can be explicitly computed.

Solution to this problem again involves iterative techniques. A first estimate of the x direction can be obtained from the barotropic model. The first estimates of the baroclinic functions $\hat{S}_x$ and $\hat{S}_y$ are then computed and used to calculate new values for A and B. These are used in Figures 1 and 2 to obtain a better estimate of the orientation of the x-axis, and so on. Convergence is anticipated for all reasonable combinations of the various quantities. Consider the following example: Assume $f = 10^{-4}\ s^{-1}$ and $\vec{V}_{go} = 10\ ms^{-1}$ from 315^o (i.e. the surface isobars are oriented northwest-southeast with lower pressure toward the northeast). The mean isotherms in the boundary layer are oriented perpendicular to the flow with colder air to the northwest. The temperature gradient is taken to be $3^{o}C$ per degree latitude (or $2.7 \times 10^{-5}\ {}^{o}C\ m^{-1}$). For a mean temperature of $7^{o}C$ ($280^{o}K$) and $g = 9.81\ ms^{-2}$ this gives $|\frac{\partial \bar{V}g}{\partial z}| = 9.46 \times 10^{-2}\ s^{-1}$ and $|\hat{S}| = [\hat{S}_x{}^2 + \hat{S}_y{}^2]^{\frac{1}{2}} = 15.14$. The barotropic solution gives $Z_o = 0.0086$ cm, $u_* = 23\ cm\ s^{-1}$ and $\theta = 17^{o}$. Using this value of θ yields $\hat{S}_x = 4.68$ and $\hat{S}_y = 14.40$; then $A(\hat{S}_x, \hat{S}_y) = 1.36$ and $B(\hat{S}_x, \hat{S}_y) = 8.25$. Iteration on u_* and Z_o eventually results in a friction velocity of $23.3\ cm\ s^{-1}$ and a value of θ slightly less than 26^{o}. This represents an additional nearly 9^{o} of backing due to the baroclinity of the atmospheric boundary layer.

A flow diagram for performing computations for all the preceding cases as well as the most general diabatic-baroclinic case is shown in Figure III-3. A computer program for this flow diagram has been written.

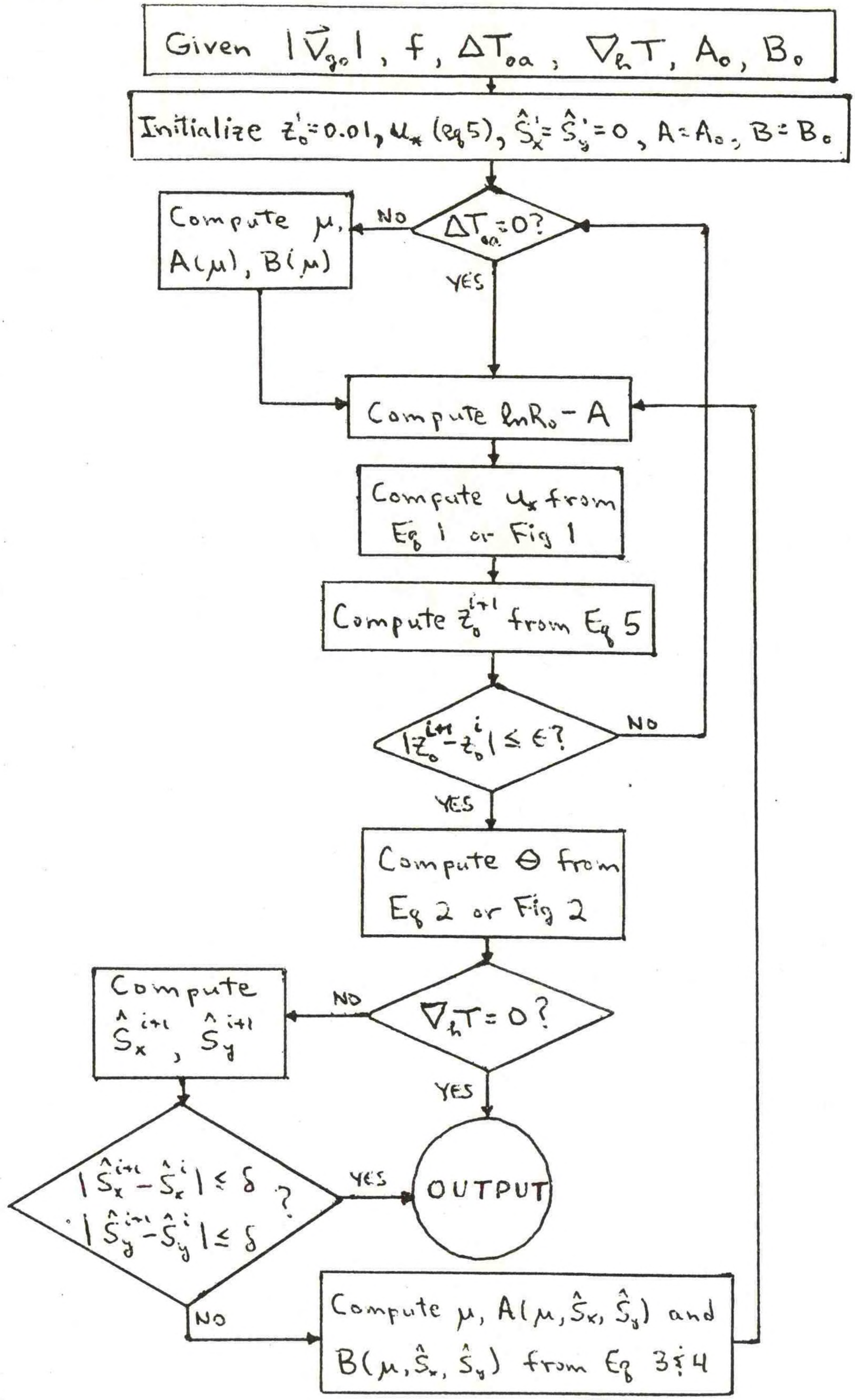


Figure III-3: Flow diagram for evaluating the magnitude and direction of the surface stress for the diabatic, baroclinic, steady-state atmospheric boundary layer.

IV. OCEAN SURFACE TURBULENCE STUDIES (R. W. Miksad)

IV-A. Research Topic Background

The spread of oil on the ocean is customarily viewed as being due to the action of forces arising from either the properties of the slick itself (i.e. density differences and surface tension) or from external influences such as turbulent stresses due to random ocean movements. Spreading due to slick properties will be referred to as "dynamic spreading", while spreading caused by random external influences will be referred to here as "dispersive spreading."

Existing models of "dynamic spreading" have not taken oceanic turbulence effects into account. The most popular models are due to Fay (1969) and Hoult (1972) and assume a quiescent laminar water layer on which a constant-property oil spill spreads, the spreading being due either to gravity or surface tension, and inhibited by inertia or viscous drag. Fay and Hoult find that four basic spreading stages exist; viz.,

SPREADING FORCE	RETARDING FORCE	CHARACTERISTIC SLICK LENGTH VARIATION WITH TIME	SLICK AREA VARIATION WITH TIME
Gravity	Inertia	$l \sim (\frac{\Delta\rho}{\rho} g \forall)^{\frac{1}{4}} t^{\frac{1}{2}}$	$A \sim t$
Gravity	Dynamic Pressure	"	$A \sim t$
Gravity	Viscous Drag	$l \sim (\frac{\Delta\rho}{\rho} \frac{g\forall^2}{\nu^{\frac{1}{2}}})^{1/6} t^{\frac{1}{4}}$	$A \sim t^{\frac{1}{2}}$
Surface Tension	Viscous Drag	$l \sim (S_{o/w}^2/\rho^2\nu)\ t^{3/4}$	$A \sim t^{3/2}$

where l = characteristic slick length

$\Delta\rho = \rho_{H_2O} - \rho_{oil}$ (density difference)

$\forall$ = slick volume

ν = kinematic viscosity of the oil

$S_{o/w}$ = surface tension spreading coefficient of oil on water

For deep ocean situations, (where several days to several weeks may elapse before a spill reaches shore or sinks due to weathering), it is the long time behavior of slick spreading which is of primary concern. As pointed out by Fay (1969), the time of residence in the inertial and viscous stages of spreading depends on the volume of spilled oil, while the residence time in the final surface tension stage depends on the rate at which the net surface tension characteristics of the slick change with time. For very large spills, such as the 20,000 ton Torrey Canyon discharge, it may take a day or so for a slick to enter the final surface tension stage. For smaller spills, the surface tension stage may be reached within hours after release. In the Fay-Hoult formulation, the surface tension stage is the final stage of spread, and slick area should increase as $t^{3/2}$. As can be seen in Fay's data and in subsequent work discussed by Stolzenbach et al (1977), dynamic spreading theory consistently underpredicts final spill size growth rates and eventual final spill size areas. The failure of dynamic spreading models to predict long-time slick behavior is apparently due to their neglect of dispersive spreading induced by oceanic turbulence. This neglect becomes more important as time progresses and the slick grows larger.

"Dispersive spreading" is produced by the effects of shear stresses exerted on the oil slick surface by random water movements. Dispersive spreading is basically a problem in relative diffusion (i.e. diffusion relative to the slick center of mass), and should be viewed in a coordinate frame that moves with the center of mass (Csanady, 1973). Also, although dispersive spreading is produced by the action of random stresses, its complexity forces us to view it in terms of turbulent kinematics. By kinematics, we mean that passive particles (tracers) in a turbulent field will spread with time, and this spreading can be related to the kinematics of the turbulent flow field. Of course, unless an oil slick breaks up into many smaller patches it cannot be considered as a collection of discrete tracers, and the general relation between the spreading of a continuous slick and that of a collection of passive tracers has yet to be established.

However, recent measurements of turbulent spreading of oil by Murray (1972), and Drapeau _et al_ (1974) indicate that a direct connection may indeed exist between the spreading of oil slicks at long times, and the turbulent spreading rates of passive tracers in the water column beneath the spreading oil slick. Drapeau's measurements are of most interest since they involved relatively small releases (370 and 500 liters) of Venezuelan crude oil. The small releases insured a relatively short stay in the inertial and gravity stages of dynamic spreading. Furthermore, measurements of dissolution of the oil with time indicated that the higher spreading rate, more volatile constituents, left the slick within a short period of time after release. Thus, the net surface tension coefficient of the residual was reduced very quickly, and the final stage of dynamic spreading, which is due to surface tension, was limited in duration and intensity, if indeed it was able to occur at all. However, Drapeau's measurements showed extensive long term spreading. Since this long term spreading was apparently not driven by surface tension, it must have been due to surface turbulence. Thus, Drapeau's data seem to provide an excellent example of turbulence-induced spreading. According to Drapeau's data, the area of his measured slicks increased with time as

$$A \sim t^n \qquad \text{where } 2.65 < n < 3.15$$

which is a much more rapid time dependence than the $t^{3/2}$ rate predicted by Fay (1969) for the final surface tension stage of dynamic spreading, and significantly greater than the rates predicted for either of the earlier gravity or inertial dynamic spreading stages.

We can gain some insight into the meaning of Drapeau's results for continuous slicks if we consider existing experimental data and theory on the spread of passive tracers in the turbulent ocean surface layer. The variance σ^2 of a dye patch, or discrete tracer cluster, is a reasonable measure of the area of coverage.

Batchelor (1952) has shown that the variance and hence the area of coverage of passive tracers in a horizontally homogeneous turbulent field undergoing relative diffusion should theoretically grow as

$$\sigma^2 \sim t^{3.00}$$

when the characteristic cluster or patch scale is larger than the Kolmogoroff eddy scale but smaller than that of the energy-containing eddies, (i.e. in the so-called inertial sub-range of turbulence). Experimental confirmation of this relative dispersion time dependence can be found in various oceanic spreading measurements, analyzed by Okubo (1974) which show that over some 10 decades of oceanic scales, passive surface tracers spread as

$$\sigma^2 \approx t^{2.34}$$

while on a local scale (i.e. one to two decades) they spread somewhat faster, as

$$\sigma^2 \approx t^3$$

The area spreading rates found by Drapeau for a continuous oil slick agree quite well with that expected from theory and experiment for the turbulent spreading of discrete passive tracers and continuous dye patches in the water column beneath the slick. Thus, there is good reason to suspect that in the final stage of oil slick spreading, the spreading forces exerted on a continuous slick are due to oceanic turbulent stresses and that the final rates of dispersive slick spreading are related to the rate at which passive tracers disperse in the oceanic surface layers. Furthermore, if a slick does break up into a cluster of smaller slicks, then the net spread of this cluster relative to its center of mass will also be due to oceanic surface turbulence and should be governed by the same relative dispersion constraints.

IV-B. Contract Activity

The premise of this portion of the funded research program is that the dispersive spread of an oil slick is due to the action of random stresses on its surface, and that the action of these stresses can be related to the kinematics of the ocean surface layer turbulence.

The objectives of this first year's research effort have been:

(1) To construct an experimental research apparatus which can be used to study surface layer relative dispersion under controlled conditions.

(2) To conduct experiments to study the dispersive spreading of passive surface tracers in order to verify the relative dispersion characteristics of our apparatus vis à vis oceanic behavior of clusters of discrete surface tracers.

(3) To lay the ground work for subsequent experiments (to be conducted during the second year of this contract) to study the connection between the spread of continuous oil slicks, and the dispersive spread of passive tracers within the turbulent water layer acting on the slick.

Contract activity to date has proceeded along two complementary lines.

First, a literature study has been made of oil slick characteristics, and of existing measurements on the influence of oceanic turbulence on oil spill spreading rates. This information has been analyzed in the context of theories and experiments on relative diffusion to aid us in the design of our laboratory experiments. A combined bibliography of selected literature is attached to this final report.

Secondly, laboratory experiments have been conducted, specifically designed to study the relation between slick spreading rates (due to oceanic turbulence) on the one hand, and passive tracer spreading (due to turbulent kinematics) on the other.

In order to study dispersive spreading, a facility has been constructed to generate a horizontally homogeneous turbulent field in a water surface layer. Experiments have been conducted in an 89 x 89 cm square by 46 cm deep water tank. A horizontally homogeneous turbulent field is generated by vertically oscillating a horizontal grid of 1 cm square plexiglass bars placed beneath the water surface, at precisely controlled frequencies and distance of travel [Thompson and Turner (1975)]. The spacing of bars in the grid is 5 cm on centers.

The experiments are progressing through five stages:

I. Flow visualization of the surface layer turbulence generated by an oscillating grid.

II. Measurements of the kinematics of two-particle relative diffusion in the surface layer.

III. Measurements of the kinematics of particle cluster spreading in the surface layer.

IV. Quantitative measurements of the turbulent field spectral characteristics.

V. Measurements of oil spill equilibrium lens spreading due to surface layer turbulence.

Contract activity during the first year has been placed on stages I, II, and III. The guiding principle is to understand the basic behavior of each stage before proceeding to the next. One need only consider the general lack of understanding of the turbulent spreading of discrete passive tracers to appreciate the need for establishing the nature of the turbulent behavior of this experiment before one proceeds to the even less understood problem of the spread of a continuous slick of oil.

As is common in most experiments, a significant portion of the first year effort has been expended in designing, machining, fine tuning, and calibrating the apparatus so that it functions properly and produces a physically meaningful representation of oceanic conditions. Considerable effort has been expended in finding the proper combination of grid oscillation frequency, grid throw, and water depth above the grid, to insure the generation of a reasonably horizontally homogeneous turbulent field in the water surface layer.

Experiments have been conducted to check the dispersive nature of surface layer turbulence generated in the tank. The results of two-point relative dispersion measurements were reported on at the contractors' meeting in August 1977. Spreading in the apparatus follows the so-called 4/3-power law dependence of turbulent diffusivity on patch size that is characteristic of the inertial sub-range of turbulent theory, and apparently representative of spreading on the ocean surface (Okubo, 1974). Subsequent experiments have studied the relative dispersion of clusters of passive particles in the turbulent surface layer. The results of these experiments have established that the basic dispersion of passive surface tracers in the apparatus does indeed follow the 4/3-power law. This work on cluster spreadings formed the basis of a Master of Science thesis by Mr. K. Zimmerman, and is included as an Appendix to this final report.

V. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK.

The synoptic scale analysis during the contract period has accomplished the main objectives of the research for the first year, including sea level pressure analyses for the Texas and Alabama "windows," and the correlation of surface wind velocity between coastal stations and offshore oil platforms.

The pressure analyses have specified geostrophic wind vectors at two locations, one in the central Gulf of Mexico (a data-sparse area), the other near Tampa, FL in the eastern Gulf of Mexico. Still needed is a specification of the accuracy of geostrophic wind input needed for the boundary layer model to function effectively, compared to the accuracy of geostrophic wind possible from sea level pressure analyses at initial time. Part of this problem can be addressed by specifying geostrophic winds from the LFM initial panels for the Gulf of Mexico area. The remainder will involve a sensitivity analysis of the atmospheric boundary layer model. Both of these aspects will be addressed in the contract renewal period.

Comparison of surface winds at Galveston and the offshore oil rig 230 km to the southeast of Galveston has revealed some interesting relationships which may have value in near-shore spills. The linear correlation coefficients, however, have not been particularly useful, mostly because stratification by boundary layer characteristics has not been attempted. Data for such an analysis are not readily available, so it is unlikely that this problem will be seriously pursued in the contract renewal period. Our attention should really be centered on techniques for producing the best possible geostrophic wind vector over the open Gulf, and in supplying the necessary analyses to give other inputs to the diabatic and baroclinic boundary layer model.

The Technique Development Laboratory has provided computer tapes of initial sea level pressure analyses at 00Z and 12Z for the period December 1976 through December 1977, plus prognostic fields out to 48 hours, for the Gulf of Mexico and adjacent areas of the southeastern U.S. These data tapes should prove useful in removing some of the uncertainties still present in the statistics displayed in Tables 3 through 7 in Section II of this report. Beyond that, it would be worthwhile to assess the value of LFM geostrophic wind forecasts at 12, 24, 36, and 48 hours for use in constructing geostrophic trajectories, as well as their value as direct input to the atmospheric boundary layer model and the resulting surface air trajectories.

As to the atmospheric boundary layer itself (Section III), many shortcomings are contained in the present model. The work currently in progress seeks to reduce these shortcomings. For example, it is necessary to couple the atmosphere to the ocean. This has been done by Spillane (1971), Clark and Hess (1975), and Hess (1975). Their results need to be examined critically in the context of the oil spill problem, and improved to the extent possible.

The significance of acceleration of the mean wind in the boundary layer should also be examined. Recent investigations by Mahrt (1974, 1975) and Augstein and Heinricy (1976) may be of value. Short term accelerations associated with gusty winds could also contribute to enhanced dispersion of the oil.

Even a perfect planetary boundary layer model will be of little value if either the synoptic conditions or the oceanic coupling is inadequately or inaccurately specified. Put another way, there is little point in having a boundary layer model any more complicated than necessary to be consistent with the synoptic input and oceanic coupling output. Continued research in all three areas is required.

The air-sea interaction research has successfully utilized a piece of laboratory apparatus which generates a turbulent surface layer field which can be used to study the turbulent spreading of oil slicks under controlled conditions. Experiments have been successfully conducted to check the relative dispersion of passive surface tracers in the apparatus. The experimental results agree with theoretical conjectures on relative diffusion. More importantly, they also agree with previous experimental measurements of dispersion in the ocean at larger scales. The necessary ground-work has thus been laid for the second year study which will investigate the direct connection between continuous spill spreading, and dispersive discrete particle spreading.

Detailed discussions of the experimental apparatus and methodology, data accumulation and analysis techniques, and relevance of the laboratory results to those of other research on oceanic spreading can be found in the attached Appendix.

BIBLIOGRAPHY

A. References Cited in the Report

Arya, S.P.S. and J.C. Wyngaard, 1975: Effect of Baroclinicity on Wind Profiles and the Geostrophic Drag Law for the Convective Planetary Boundary Layer, J. Atmos. Sci., 32(4), 767-778. BL*

Arya, S.P.S., 1975: Geostrophic Drag and Heat Transfer Relations for the Atmospheric Boundary Layer, Quart. J. Roy. Meteor. Soc., 101 (427), 147-161. BL

Augstein, E. and D. Heinricy, 1976: Actual and Geostrophic Wind Relationships in an Accelerated Marine Atmospheric Boundary Layer, Beiträge Physik der Atmos., 49(1), 55-68. BL

Barnes, S.L., 1964: A Technique for Maximizing Details in Numerical Weather Map Analysis, J. Applied Meteor., 3(4), 396-405. SS

Batchelor, G.K., 1952: Diffusion in a field of homogeneous turbulence, II. The relative motion of particles. Proc. Cambridge Phil. Soc., 48, 345-362. A/S

Charnock, H., 1955: Wind Stress on a Water Surface, Quart. J. Roy. Meteor. Soc., 81(350), 639-640. BL

Clarke, R.H. and G.D. Hess, 1974: Geostrophic Departure and the Functions A and B of Rossby-Number Similarity Theory, Boundary-Layer Meteor., 7(3), 267-287. BL

Clarke, R.H., 1975: Note on Baroclinicity and the Inverse Behaviour of Surface Stress and Wind Turning in the Boundary Layer, Beiträge Physik der Atmos., 48(1), 46-50. BL

Clarke, R.H. and G.D. Hess, 1975: On the Relation Between Surface Wind and Pressure Gradient, Especially in Lower Latitudes, Boundary-Layer Meteor., 9(3), 325-339. BL

Csanady, G.T., 1973: Turbulent Diffusion in the Environment, D. Reidel Publ. Co., p. 248. A/S

Drapeau, G., W. Harrison, W. Bien and P. Leinonen, 1974: Oil Slick Fate in a Region of Strong Tidal Currents, Proc. Fourteenth Coastal Engineering Conference, Copenhagen, III, 2245-2259. A/S

*BL= boundary layer; SS= synoptic scale; A/S= air/sea interaction.

Fay, J.A., 1969: The Spread of Oil Slicks on a Calm Sea, in Hoult, D.P. (ed.), Oil on the Sea, Plenum Press, 53-63. A/S

Hasse, L. and M. Dunckel, 1974: Direct Determination of Geostrophic Drag Coefficients at Sea, Boundary-Layer Meteor., 7(3), 323-329. BL

Hess, G.D., 1973: On Rossby-Number Similarity Theory for a Baroclinic Planetary Boundary Layer, J. Atmos. Sci., 30(8), 1722-1723. BL

Hess, G.D., 1975: Determination of the Sea Surface Stress and Drift Current by Similarity Theory, Annual Report Atmospheric Physics Section, Argonne National Laboratory, 112-119. BL

Hicks, B.B., 1972: Some Evaluations of Drag and Bulk Transfer Coefficients over Water Bodies of Different Sizes, Boundary-Layer Meteor., 3(2), 201-213. BL

Hicks, B.B., 1975: A Procedure for the Formulation of Bulk Transfer Coefficients over Water, Boundary-Layer Meteor., 8(3/4), 515-524. BL

Hoult, D.P., 1972: Oil Spreading on the Sea, in Annual Review of Fluid Mechanics, 4, M. Van Dyke, W.G. Vincenti, and J.F. Wehausen (eds.), 341-368. A/S

Lund, I.A., 1963: Map-pattern Classification by Statistical Methods, J. of Applied Meteor., 2(1). SS

Mahrt, L., 1974: Time-Dependent Integrated Planetary Boundary Layer Flow, J. Atmos. Sci., 31(2), 457-464. BL

Mahrt, L., 1975: The Influence of Momentum Advection on a Well-Mixed Layer, Quart. J. Roy. Meteor. Soc., 101(427), 1-11. BL

McBean, G.A., 1976: The Influence of Surface Roughness, Vertical Thermal Stability and Wind on the Boundary Layer Fluxes of Momentum, Heat and Water Vapor: A Review, Final Report Appendix C, WMO Commission for Atmos. Sci., Working Group on Atmospheric Boundary-Layer Problems, First Session, Potsdam, 20-24 April 1976. BL

Murray, S.P., 1972: Turbulent Diffusion of Oil in the Ocean, Limnology and Oceanography, 27(5), 651-660. A/S

Okubo, A., 1974: Some Speculations on Oceanic Diffusion Diagrams. Rapp. P.v- Reún. Cons. int. Explor. Mer, 167, 77-85. A/S

Overland, J.E. and W.H. Gemmill, 1977: Prediction of Marine Winds in the New York Bight, Monthly Weather Review, 105(8), 1003-1008. SS

Resio, Donald T. and C. Linwood Vincent, 1977: Estimation of Winds over the Great Lakes, J. Waterway, Port, Coastal and Ocean Division, Proc. ASCE, 103(WW2), 265-283. SS

Sabin, R.C., R.L. Nieman, and H.W. Wold, 1974: Map Type Catalog for the Texas Window, Report 12WS TP 74-4, Map Typing Project Office, 12th Weather Squadron, Ent AFB, Colorado. (Other Reports in the same format cover the following Windows: Alabama, Florida, Carolina, D.C., Maine, California, Washington.) SS

Spillane, K.T., 1971: Movement of Oil on the Sea Surface, Austr. Meteor. Mag., 19(4), 158-177. BL

Stolzenbach et al, 1977: A Review and Evaluation of Basic Techniques for Predicting the Behavior of Surface Oil Slicks, Ralph M. Parson Laboratory Report 222, M.I.T., Cambridge, Mass. A/S

Thompson, S.M., and J.S. Turner, 1975: Mixing across an interface due to turbulence generated by an oscillating grid, J. Fluid Mech. 67, Part 2, 349-368. A/S

Wu, J., 1969: Wind Stress and Surface Roughness at Air-Sea Interface, J. Geophys. Res., 74(2), 444-455. BL

BIBLIOGRAPHY

B. Additional References (Not Cited in the Report)

Adamson, A.W., 1967: Physical Chemistry of Surfaces, Interscience Publishers, New York, p. 629.

Agee, E.M., T.S. Chen and K.E. Dowell, 1973: A Review of Mesoscale Cellular Convection, Bull. Amer. Meteor. Soc., 54(10), pp. 1004-1012.

Agee, E.M. and K.E. Dowell, 1974: Observational Studies of Mesoscale Cellular Convection, J. Applied Meteor., 13(1), pp. 46-53.

Alofs, D.J. and R.L. Reisbig, 1972: An experimental Evaluation of Oil Slick Movement Caused by Waves, J. Physical Oceanogr., 2(4), 439-443.

Arya, S.P.S., 1975 : Comments on 'The Influence of Geostrophic Shear on the Cross-Isobar Angle of the Surface Wind', Boundary-Layer Meteor., 8(2), 239-242.

Barger, W.R., W.D. Garrett, E.L. Mollo-Christensen and K.W. Ruggles, 1970: Effects of an Artificial Sea Slick upon the Atmosphere and the Ocean. J. Applied Meteor., 9(3), 396-400.

Batchelor, G.K., 1950: The Application of the Similarity Theory of Turbulence to Atmospheric Diffusion, Quart. J. Roy. Meteor. Soc., 76, 133.

Bauer, E., 1974: Dispersion of Tracers in the Atmosphere and Ocean: Survey and Comparison of Experimental Data, J. Geophysical Res., 79(6), 789-795.

Bernstein, A.B., 1973: Some Observations of the Influence of Geostrophic Shear on the Cross-Isobar Angle of the Surface Wind, Boundary-Layer Meteor., 3(3), 381-384.

Berridge, S.A., R.A. Dean, F.G. Fallows and A. Fish, 1968: The Properties of Persistent Oils at Sea, J. Institute of Petroleum, 54(539), 300-309.

Berridge, S.A., M.T. Thew and A.G. Loristen-Clarke, 1968: The Formation and Stability of Emulsions of Water in Crude Petroleum and Similar Stocks, J. Institute of Petroleum, 54(530), 333-357.

Bhumralkar, C.M., 1975: Parameterization of the Planetary Boundary Layer in Atmospheric General Circulation Models - A Review, Rand Corporation Report R-1654-ARPA, March 1975, 43 pp.

Blackadar, A.K. and H. Tennekes, 1968: Asymptotic Similarity in Neutral Barotrophic Planetary Boundary Layers, J. Atmos. Sci., 25(6), 1015-1020.

Blokker, P.C., 1964: Spreading and Evaporation of Petroleum Products on Water, Proc. 4th International Harbor Conference, Antwerp.

Blumer, M. and J. Sass, 1972: Oil Pollution: Persistence and Degradation of Spilled Fuel Oil, Science, 176(4039), 1120-1122.

Bowden, K.F., D.P. Kranel and R.E. Lewis, 1974: Some Features of Turbulent Diffusion from a Continuous Source at Sea, in Advances in Geophysics, 18A, Academic Press, 315-329.

Bretherton, F.P. and M. Karweit, 1975: Mid-Ocean Mesoscale Modeling, in Numerical Models of Ocean Circulation, National Academy of Sciences, 237-249.

Brosin, H-J., 1974: Photogrammetric Investigations on Turbulent Diffusion with Discrete Particles. Rapp. P.v- Reún. Cons. int. Explor. Mer, 167 222-224.

Brown, R.A., 1974: Matching Classical Boundary-Layer Solutions toward a Geostrophic Drag Coefficient Relation, Boundary-Layer Meteor., 7(4), 489-500.

Brümmer, B., 1976: The Coefficients of the Mechanical Resistance Law over the Tropical Oceans, Beiträge Physik der Atmos., 49(4), 299-305.

Bryant, G.W. and K.A. Browning, 1975: Multi-level Measurements of Turbulence over the Sea During the Passage of a Frontal Zone, Quart. J. Roy. Meteor. Soc., 101(427), 35-54.

Buckmaster, J., 1973: Viscous-gravity Spreading of an Oil Slick, J. of Fluid Mechanics, 49 Part 3, 481-491.

Burt, Wayne V. and Ernest M. Agee, 1977: Buoy and Satellite Observations of Mesoscale Cellular Convection During AMTEX 75, Boundary-Layer Meteor., 12(1), 3-24.

Businger, J.A., 1975: Interaction of Sea and Atmosphere, Reviews of Geophysics and Space Physics, 13(3), 720-726.

Caldwell, D.R. and W.P. Elliott, 1971: Surface Stresses Produced by Rainfall, J. Physical Oceanogr., 1(2), 145-148.

Canevari, G.P., 1969: The Role of Chemical Dispersants in Oil Cleanup. Oil on the Sea, D.P. Hoult ed., Plenum Publ., 29-51.

Chew, F. and G.A. Berberian, 1972: Neighbor Diffusivity as Related to Lateral Shear in the Florida Current., Deep-Sea Res., 19(7), 493-506.

Ching, J.K.S. and J.A. Businger, 1968: The Response of the Planetary Boundary Layer to Time Varying Pressure Gradient Force, J. Atmos. Sci., 25(6), 1021-1025.

Clarke, R.H., 1970: Recommended Methods for the Treatment of the Boundary Layer in Numerical Models, Austr. Meteor. Mag., 18(2), 51-73.

Clutter, D.W., A.M.O. Smith, and J.M. Brazier, 1959: Techniques of Flow Visualization using Water as the Working Medium. Report No. ES-29075, Douglas Aircraft Co., El Segundo, CA.

Cochran, R.A. and P.R. Scott, 1971: The Growth of Oil Slicks and Their Control by Surface Chemical Agents, J. Petroleum Technology, 781-787.

Cogan, J.L. and J.H. Willand, 1976: Measurement of Sea Surface Temperature by the NOAA 2 Satellite, J. Applied Meteor., 15(2), 173-180.

Csanady, G.T., 1967: On the "Resistance Law" of a Turbulent Ekman Layer, J. Atmos. Sci., 24(5), 467-471.

Csanady, G.T., 1972: Frictional Currents in the Mixed Layer at the Sea Surface, J. Physical Oceanogr., 2(4), 498-508.

Csanady, G.T., 1974: The 'Roughness' of the Sea Surface in Light Winds, J. Geophys. Res., 79(18), 2747-2751.

Csanady, G.T., 1974: Turbulent Diffusion and Beach Deposition of Floating Pollutants, in Advances in Geophysics, 18A, Academic Press, 371-381.

Davidson, K.L., 1974: Observational Results on the Influence of Stability and Wind-Wave Coupling on Momentum Transfer and Turbulent Fluctuations over Ocean Waves, Boundary-Layer Meteor., 6(1/2), 305-331.

Deacon, E.L., 1973: Geostrophic Drag Coefficients, Boundary-Layer Meteor., 5(3), 321-340.

Deacon, E.L.,1973: The Wind Profile under Low U_* Conditions, Quart. J. Roy. Meteor. Soc., 99(420), 391-393.

Deardorff, J.W., 1976: Discussion of 'Thermals over the Sea and Gull Flight Behavior' by A.H. Woodcock, Boundary-Layer Meteor., 10(2), 241-246.

Deutsch, M., A.E. Strong and J.E. Estes, 1977: Use of Landsat Data for the Detection of Marine Oil Slicks, Preprint, Offshore Technology Conference, paper OTC 2763, 311-317.

Denman, K.L. and M. Miyake, 1973: Behavior of the Mean Wind, the Drag Coefficient, and the Wave Field in the Open Ocean, J. Geophys. Res., 78(12), 1917-1931.

Dorman, C.E. and E. Mollo-Christensen, 1973: Observation of the Structure of Moving Gust Patterns Over a Water Surface ("Cat's Paws"), J. Physical Oceanogr., 3(1), 120-132.

Dunckel, M., L. Hasse, L. Krugermeyer, D. Schriever and J. Wucknitz, 1974: Turbulent Fluxes of Momentum, Heat and Water Vapor in the Atmospheric Surface Layer at Sea During AMTEX, Boundary-Layer Meteor., 6 (1/2), 81-106.

Ebbesmeyer, C.C., 1975: Computing Current Shear from Dye Observations Using One of Okubo's Advective-Diffusive Models., J. Physical Oceanogr. 5(1), 191-193.

Ebbesmeyer, C.C. and A. Okubo, 1975: Variance Relations Between Variable Shear-Diffusion and Radially Symmetric Turbulent Diffusion., Deep-Sea Res., 22, 441-445.

Fallah, M.H. and R.M. Stark, 1976: Literature Review: Movement of Spilled Oil at Sea, M.T.S. Journal, 10(1), 3-18.

Fallah, M.H. and R.M. Stark, 1976: A Probabilistic Approach for Dispersion of Oil at Sea., Ocean Engng., 3, 145-156.

Fallah, M.H. and R.M. Stark, 1976: Random Drift of an Idealized Oil Patch, Ocean Engng., 3, 83-97.

Fiedler, F., 1972: The Effect of Baroclinicity on the Resistance Law in a Diabatic Ekman Layer, Beiträge Physik der Atmos., 45(2), 164-173.

Frankenfeld, J.W., 1973: Factors Governing the Fate of Oil at Sea; Variations in the Amounts and Types of Dissolved or Dispersed Materials During the Weathering Process, Proc. Joint Conf. on Prevention and Control of Oil Spills, API, 485-495.

Garratt, J.R., 1973: Studies of Turbulence in the Surface Layer over Water (Lough Neagh). III. Wave and Drag Properties of the Sea-Surface in Conditions of Limited Fetch, Quart. J. Roy. Meteor. Soc., 99(419), 35-47.

Garratt, J.R., 1977: Review of Drag Coefficients over Oceans and Continents, Monthly Weather Review, 105(7), 915-929.

Gifford, F.A., Jr., 1968: An outline of theories of diffusion in the lower layers of the atmosphere. Meteorology and Atomic Energy, ed. D.H. Slade, U.S. Atomic Energy Comm., 83-94.

Gill, A.E., 1968: Similarity Theory and Geostrophic Adjustment, Quart. J. Roy. Meteor. Soc., 94(402), 586-588.

Golder, D., 1972: Relations Among Stability Parameters in the Surface Layer, Boundary-Layer Meteor., 3(1), 47-58.

Grassl, H., 1976: The Dependence of the Measured Cool Skin of the Ocean on Wind Stress and Total Heat Flux, Boundary-Layer Meteor., 10(4), 465-474.

Gurka, J.J., 1976: Satellite and Surface Observations of Strong Wind Zones Accompanying Thunderstorms, Preprint Vol., 6th Conference on Weather Forecasting and Analysis; May 10-14, 1976; Albany, NY, American Meteor. Soc., 252-258.

Hardy, C.D. and E.R. Baylor, 1975: Surface Tension Reductions and Urban Wastes in the New York Bight., J. Geophysical Res., 80(18), 2696-2699.

Hasse, L. and V. Wagner, 1971: On the Relationship Between Geostrophic and Surface Wind at Sea, Monthly Weather Review, 99(4), 255-260.

Hasse, L., 1974: Note on the Surface-to-Geostrophic Wind Relationship from Observations in the German Bight, Boundary-Layer Meteor., 6(1/2), 197-201.

Hasse, L., 1974: On the Surface to Geostrophic Wind Relationship at Sea and the Stability Dependence of the Resistance Law, Beiträge Physik der Atmos., 47(1), 45-55.

Hay, J.S. and F. Pasquill, 1959: Diffusion from a Continuous Source in Relation to the Spectrum and Scale of Turbulence, Adv. in Geophysics, 6, 345 ff.

Houk, D. and T. Green, 1976: A Note on Surface Waves Due to Rain, J. Geophysical Res., 81(24), 4482-4484.

Hoxit, L.R., 1974: Planetary Boundary Layer Winds in Baroclinic Conditions, J. Atmos. Sci., 31(4), 1003-1020.

Hsu, S.A., 1974: A Dynamic Roughness Equation and Its Application to Wind Stress Determination at the Air-Sea Interface, J. Phys. Oceanogr., 4(1), 116-120.

Hsu, S.A., 1974: On the Log-Linear Wind Profile and the Relationship Between Shear Stress and Stability Characteristic over the Sea, Boundary-Layer Meteor., 6(3/4), 509-514.

Hsu, S.A., 1976: Determination of the Momentum Flux at the Air-Sea Interface under Variable Meteorological and Oceanographic Conditions: Further Application of the Wind-Wave Interaction Method, Boundary-Layer Meteor., 10(2), 221-226.

Ichiye, T., 1973: Hydrodynamic Problems Concerning Oil Spillage in the Ocean., In Report TAMU-SG-73-201, Texas A & M University.

Katsaros, K.B., 1976: Effects of Precipitation on the Eddy Exchange in a Wind-Driven Sea, Dynamics of Atmos. and Oceans, 1(2), 99-126.

Knight, Doyle, 1977: Turbulent Flow over a Wavy Boundary, Boundary-Layer Meteor., 11(2), 205-222.

Kolpack, R.L., 1977: Priorities in Fate of Oil Spill Research, 1977 Oil Spill Conference preprints, New Orleans, LA, 8-10 March 1977, sponsored by American Petroleum Institute.

Kondo, J., 1976: Parameterization of Turbulent Transport in the Top Meter of the Ocean, J. Physical Oceanogr., 6(5), 712-720.

LaValle, L. and P. DiGirolamo, 1975: Determination of the Geostrophic Drag Coefficient, Tellus, 27(1), 87-92.

Lee, R.A.S., 1971: A Study of the Surface Tension Controlled Regime of Oil Spread, M.S. Thesis, Mechanical Engineering, M.I.T.

Leibovich, S., 1975: A Natural Limit to the Containment and Removal of Oil Spills at Sea., Ocean Engineering, 3, 29-36.

Leibovich, S., 1975: Hydrodynamic Problems in Oil Spill Control and Removal, Proc. Seventh Annual Offshore Tech. Confr., paper OTC 2198.

Leibovich, S., 1976: Oil Slick Instability and the Entrainment Failure of Oil Containment Booms., Trans A.S.M.E., J. of Fluids Engineering, March, 98-105.

LeMone, M.A., 1973: The Structure and Dynamics of Horizontal Roll Vortices in the Planetary Boundary Layer, J. Atmos. Sci., 30(6), 1077-1091.

LeMone, M.A., 1976: Modulation of Turbulence Energy by Longitudinal Rolls in an Unstable Planetary Boundary Layer, J. Atmos. Sci., 33(7), 1308-1320.

LeMone, M.A., and W.T. Pennell, 1976: The Relationship of Trade Wind Cumulus Distribution to Subcloud Layer Fluxes and Structure, Monthly Weather Review, 104(5), 524-539.

Lewis, J.L. and T.H. Grayson, 1972: The Adjustment of Surface Wind and Pressure by Sasaki's Variational Matching Technique, J. of Applied Meteor. 11(4), 586-597.

Lin, C.C., 1960: On a theory of dispersion by continuous movements. Proc. Natl. Acad. Sci., 46, 566-570.

Lissauer, I.M., J.C. Bacon and M.C. Miller, 1977: A Computer Simulation Technique for Oil Spills off the New Jersey-Delaware Coastline, 1977 Oil Spill Conference preprints, New Orleans LA, 8-10 March 1977, sponsored by American Petroleum Institute.

Lo, A.K., 1977: Boundary Layer Flow over Gentle Curvilinear Topography with a Sudden Change in Surface Roughness, Quart. J. Roy. Meteor. Soc., 103(435), 199-209.

Logan, E. and G.H. Fichtl, 1975: Rough-to-Smooth Transition of an Equilibrium Neutral Constant Stress Layer, Boundary-Layer Meteor. 8(3/4), 525-528.

Long, Robert R. and Larry J. Guffy, 1977: Drag and Heat Transfer Relations for the Planetary Boundary Layer, Boundary-Layer Meteor., 11(3), 363-373.

Luna, R.E. and H.W. Church, 1972: A Comparison of Turbulence Intensity and Stability Ratio Measurements to Pasquill Stability Classes, J. Applied Meteor., 11(4), 663-669.

Mallinger, W.D. and T.P. Mickelson, 1973: Experiments with Monomolecular Films on the Surface of the Open Sea, J. Physical Oceanogr., 3(3) 328-336.

Manton, M.J., 1971: Wave Generation on the Air-Sea Interface, Boundary-Layer Meteor., 2(2), 152-160.

McGrath, J.R. and M.F.M. Osborne, 1973: Some Problems Associated with Wind Drag and Infrared Images of the Sea Surface, J. Physical Oceanogr., 3(3), 318-327.

McLeish, W. and G.E. Putland, 1975: Measurements of Wind-Driven Flow Profiles in the Top Millimeter of Water, J. Physical Oceanogr., 5(3), 516-518.

McLeod, W.R., J.H. Kennedy and D.T. Hodder, 1977: Modeling of Oil Spill Trajectories using Sequential Satellite Imagery, Preprint, Offshore Technology Conference, paper OTC 2764, 319-324.

Melgarejo, J.W. and J.W. Deardorff, 1974: Stability Functions for the Boundary-Layer Resistance Laws Based upon Observed Boundary-Layer Heights, J. Atmos. Sci., 31(5), 1324-1333.

Molinari, R. and A.D. Kirwan, Jr., 1975: Calculations of Differential Kinematic Properties from Lagrangian Observations in the Western Caribbean Sea, J. Physical Oceanogr., 5(3), 483-491.

Munk, W.H. and J.D. Woods, 1973: Remote Sensing of the Ocean, Boundary-Layer Meteor., 5 (1/2), 201-209.

Murray, S.P., 1975: Wind and Current Effects on Large-Scale Oil Slicks, Preprint, Offshore Technology Conference paper OTC 2389, 523-533.

Murty, T.S., M.L. Khandekar, and G.V. Rao, 1974: The Movement of Oil Slicks, Rapp. P.v- Reún. Cons. int. Explor. Mer, 167, 66-74.

Needler, G.T. and R.A. Heath, 1975: Diffusion Coefficients Calculated from the Mediterranean Salinity Anomaly in the North Atlantic Ocean, J. Physical Oceanogr., 5(1), 173-182.

Nordberg, W., J. Conaway, D.B. Ross and T. Wilheit, 1971: Measurements of Microwave Emission from a Foam-Covered, Wind Driven Sea, J. Atmos. Sci., 28(3), 429-435.

O'Brien, J.A., 1970: Wind Tunnel Experiments on Oil Slick Transport. Naval Civil Engr. Lab Report 71-1. Port Hueneme, Calif.

Okubo, A., 1971: Oceanic Diffusion Diagrams, Deep-Sea Res., 18, 789-802.

Panofsky, H.A., H. Tenneker, D.H. Lenschow and J.C. Wyngaard, 1977: The Characteristics of Turbulent Velocity Components in the Surface Layer Under Convective Conditions, Boundary-Layer Meteor., 11(3), 355-361.

Pendergast, M.M. and T.V. Crawford, 1974: Actual Standard Deviations of Vertical and Horizontal Wind Direction Compared to Estimates from Other Measurements, Preprints, Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, Calif., 9-13 Sept. 1974, Amer. Meteor. Soc., 1-6.

Peterson, E.W., 1972: Relative Importance of Terms in the Turbulent-Energy and Momentum Equations as Applied to the Problem of a Surface Roughness Change, J. Atmos. Sci., 29(8), 1470-1476.

Phillips, C.R. and V.M. Groseva, 1975: Separation of Multicomponent Hydrocarbon Mixtures Spreading on a Water Surface, Separation Science, 10(2), 111-118.

Pierson, W.J. and V.J. Cardone, 1977: Ocean Surface Winds from Seasat-A, Preprint, Offshore Technology Conference, paper OTC 2762, 303-308.

Plate, E.J., 1971: Aerodynamic Characteristics of Atmospheric Boundary Layers, U.S. Atomic Energy Commission Critical Review Series, 190 pp.

Pollard, R.T., 1973: Wind Driven Mixing and Deepening of the Oceanic Boundary Layer, Quart. J. Roy. Meteor. Soc., 99(422), 772-773.

Rao, K.S., J.C. Wyngaard, and O.R. Cote, 1974: The Structure of the Two-Dimensional Internal Boundary Layer over a Sudden Change of Surface Roughness, J. Atmos. Sci., 31(3), 738-746.

Raynor, G.S., P. Michael, R.M. Brown and S. SethuRaman, 1975: Studies of Atmospheric Diffusion from a Nearshore Oceanic Site, J. Applied Meteor., 14(6), 1080-1094.

Richardson, L.F., 1926: Atmospheric Diffusion Shown on a Distance-Neighbor Graph, Proc. Roy. Soc., 110(A), 707-737.

Richardson, L.F. and H. Stommel, 1948: Note on Eddy Diffusion in the Sea, J. of Meteor., 5(5), 238-240.

Richardson, P.L., A.E. Strong and J.A. Knauss, 1973: Gulf Stream Eddies: Recent Observations in the Western Sargasso Sea, J. Physical Oceanogr., 3(3), 297-301.

Riley, J.J. and S. Corrsin, 1974: The Relation of Turbulent Diffusivities to Lagrangian Velocity Statistics for the Simplest Shear Flow, J. Geophysical Res., 79(12), 1768-1771.

Ruggles, K.W., 1970: The Vertical Mean Wind Profile Over the Ocean for Light to Moderate Winds, J. Applied Meteor., 9(3), 389-395.

Sanders, F., 1972: Meteorological and Oceanographic Conditions During the 1970 Bermuda Yacht Race, Monthly Weather Review, 100(8), 597-606.

SethuRaman, S., 1976: Air Mass Modification Due to Change in Surface Characteristics, Monthly Weather Review, 104(8), 1040-1043.

SethuRaman, S., R.M. Brown and J. Tichler, 1974: Spectra of Atmospheric Turbulence over the Sea During Stable Stratified Conditions, Preprints, Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, Calif. 9-13 Sept. 1974, Amer. Meteor. Soc., 98(415), 175-186.

SethuRaman, S. and G.S. Raynor, 1975: Surface Drag Coefficient Dependence on the Aerodynamic Roughness of the Sea, J. Geophys. Res., 80(36), 4983-4988.

Sheu, P.J. and E.M. Agee, 1977: Kinematic Analysis and Air-Sea Heat Flux Associated with Mesoscale Cellular Convection during AMTEX 75, J. Atmos. Sci., 34(5), 793-801.

Shir, C.C., 1972: A Numerical Computation of Air Flow over a Sudden Change in Surface Roughness, J. Atmos. Sci., 29(2), 304-310.

Shukla, D.K. and R.M. Stark, 1974: Random Movement of Oil Patches, The Science of the Total Environment, 3, 117-25.

Smith, C.L., E.J. Zipser, S.M. Daggupaty and L. Sapp, 1975: An Experiment in Tropical Mesoscale Analysis, Monthly Weather Review, 103(10),878-903.

Smith, F.B. and J.S. Hay, 1961: The Expansion of Clusters of Particles in the Atmosphere, Quart. J. Roy. Meteor. Soc., 87, 82-101.

Smith, J.E., 1968: Torrey Canyon Pollution and Marine Life, Cambridge University Press.

Smith, S.D. and E.G. Banke, 1975: Variation of the Sea Surface Drag Coefficient with Wind Speed, Quart. J. Roy. Meteor. Soc., 101(429), 665-673.

Stewart, R.W., 1974: The Air-Sea Momentum Exchange, Boundary-Layer Meteor., 6(1/2), 151-167.

Stommel, H., 1949: Horizontal Diffusion Due to Oceanic Turbulence, J. Marine Res., 8(3), 199-225.

Suchman, D. and D.W. Martin, 1976: Wind Sets from SMS Images: An Assessment of Quality for GATE, J. Applied Meteor., 15(12), 1265-1278.

Swinback, W.C., 1974: The Geostrophic Drag Coefficient, Boundary-Layer Meteor., 7(1), 125-127.

Taylor, G.I., 1921: Diffusion by Continuous Movements, Proc. of the London Mathematical Society,Ser.2, 20, 196-212.

Teeson, D., F.M. White and H. Schenck, Jr., 1970: Studies of the Simulation of Drifting Oil by Polyethylene Sheets, Ocean Engng., 2, 1-11.

Thompson, R.O.R.Y., 1974: The Influence of Geostrophic Shear on the Cross-Isobar Angle of the Surface Wind, Boundary-Layer Meteor. 6(3/4), 515-518.

Thompson, S.M., 1969: Turbulent interfaces generated by an oscillating grid in a stably stratified fluid. PhD. thesis, Emmanual College, University of Cambridge.

Turner, J.S., 1968: The Influence of Molecular Diffusivity on Turbulent Entrainment Across a Density Interface, J. Fluid Mech., 23, 639.

Vughts, H.F. and J.A. Businger, 1977: Air Modification due to a Step Change in Surface Temperature, Boundary-Layer Meteor., 11(3), 295-305.

Waldman, G.D., T.K. Fannelop and R.A. Johnson, 1972: Spreading and Transport of Oil Slicks on the Open Ocean, Preprint, Offshore Technology Conference paper OTC 1548, Vol. 1, 353-364.

Warner, J., 1972: The Structure and Intensity of Turbulence in Air over the Sea, Quart. J. Roy. Meteor. Soc., 98(415), 175-186.

Warner J. L., J.W. Graham and R.G. Dean, 1972: Prediction of the Movement of an Oil Spill on the Surface of the Water, Preprint, Offshore Technology Conference, paper OTC 1550, Vol. 1, 381-388.

Wesley, M.L., 1974: Magnitudes of Turbulent Fluctuations in the Atmospheric Surface Layer, Preprints, Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, Calif., 9-13 Sept. 1974, Amer. Meteor. Soc., 15-18.

Whitman, J. and R. Golob, 1975: First Generation Directory of Spills, Center for Short-Lived Phenomena, Cambridge, Mass.

Wieringa, J., 1973: Gust Factors over Open Water and Built-up Country, Boundary-Layer Meteor., 3(4), 424-441.

Wieringa, J., 1974: Comparison of Three Methods for Determining Strong Wind Stress over Lake Flevo, Boundary-Layer Meteor., 7(1), 3-19.

Wippermann, F., 1972: Baroclinic Effects on the Resistance Law for the Planetary Boundary Layer of the Atmosphere, Beiträge Physik der Atmos., 45(3), 244-259.

Wippermann, F., 1972: A Note on the Parameterization of the Large-Scale Wind Stress at the Sea-Surface, Beiträge Physik der Atmos., 45(3), 260-266.

Wippermann, F., 1974: The Parameterization of the Large-Scale Wind Stress at the Sea-Surface (Second Note), Beiträge Physik der Atmos., 47(4), 227-234.

Wippermann, F., 1974: The Influence of Nonstationarity on the Surface-Stress Determined by the Resistance Law, Izvestiya, Atmos. and Oceanic Physics, 10(6), 646-647.

Woodcock, A.H., 1975: Thermals over the Sea and Gull Flight Behavior, Boundary-Layer Meteor., 9(1), 63-68.

Wright, J.W., 1976: The Wind Drift and Wave Breaking, J. Physical Oceanogr., 6(3), 402-405.

Wu, J., 1975: Effects of Pulsating Wind on Velocity Profiles and Microstructures, J. Physical Oceanogr., 5(4), 782-789.

Wu, J., 1975: Sea Surface Drift Currents, Preprint, Offshore Technology Conference, paper OTC 2294, 477-484.

Wyngaard, J.C., 1975: Progress in Research on Boundary Layers and Atmospheric Turbulence, Reviews of Geophysics and Space Physics, 13(3), 716-720.

Yeh, G.T., 1973: The Effect of Thermal Stratification and Evaporation on Geostrophic Drag Coefficient in the Atmospheric Boundary Layer, Monthly Weather Review, 101(8), 617-623.

Yordanov, D., 1974: Influence of Baroclinicity on the Drag Law, Izvestiya Atmos. and Oceanic Physics, 10(6), 647-649.

Yordanov, D. and F. Wippermann, 1972: The Parameterization of the Turbulent Fluxes of Momentum, Heat, and Moisture at the Ground in a Baroclinic Planetary Boundary Layer, Beiträge Physik der Atmos., 45(1), 58-65.

Young, J.A., 1973: A Theory for Isallobaric Air Flow in the Planetary Boundary Layer, J. Atmos. Sci., 30(8), 1584-1592.