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LAKE TO LAND COMPARISON OF WIND, TEMPERATURE AND HUMIDITY ON LAKE ONTARIO DURING THE INTERNATIONAL FIELD YEAR FOR THE GREAT LAKES (IFYGL)

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1 INTRODUCTION

Defining the magnitude and variability of climatological parameters over the water area of the Great Lakes has interested many scientists during the past two decades. A network of climatological stations, often of great density in urbanized areas, exists over the land portion of the Great Lakes basin. But, the lakes themselves remain virtually devoid of climatological sampling.

Except for some lighthouse stations, located on points of land and on the larger islands, and which operate only during the navigation season, no information from fixed locations is available on over lake air temperature, humidity and wind.

Due to this scarcity of over-lake data, investigators have used in their studies observations taken from commercial vessels operating on the Great Lakes, and in a few cases, specially equipped research ships. Ships' observations have undeniably enriched the over lake data log. However, for obvious reasons, ships could not fulfill the need for continuous in situ acquisition of data over extended periods.

The lack of permanently fixed observing platforms on the Great Lakes has directed investigators to seek alternate solutions to the problem. Much scientific effort and data acquisition have been concentrated on the development of techniques for adjusting over land data to synthesize over lake conditions. This procedure involves the comparison of ships' observations with simultaneous observations over land. The paired observations yield adjustment factors for wind, temperature, and humidity that subsequently can be applied to over land data, in order to extrapolate conditions over the lakes.

During IFYGL, extensive lake data were collected from many different observing platforms, such as buoys, towers, islands, ships, and airplanes. More significantly, data collection extended over 12 months, giving a fairly good seasonal distribution to the sampling rate. Thus, IFYGL provided a unique opportunity for re-examination of the methods used in synthesizing an over lake climatology.

The value of a knowledge of climatological fields over the Great Lakes can be easily appreciated by noting the numerous applications which can be made of accurate estimates. For example:

1. Improved estimates of wind, temperature, and restrictions to visibility in marine weather forecasts would benefit both commercial shipping and small pleasure craft. With the trend towards year-round navigation on the Great Lakes, it is important to have over lake temperature and wind data for forecasting the movement, formation, and decay of ice.

2. Knowledge of over lake conditions would aid in forecasting mesoscale weather phenomena, such as lake-effect snowstorms, lake- and land-breeze circulations, and pollution-trapping inversions.

3. Specification of over lake wind is crucial in modelling lake currents, predicting storm surges, and calculating wind stress, all of which are useful in understanding such dynamic processes as shoreline erosion, water-level fluctuations, and wave generation.

4. Knowledge of wind, atmospheric stability, and energy exchange rates are important in evaluating the dispersion of discharges of oil and other toxic substances, and in monitoring the dissipation of thermal pollution from conventional and nuclear power plants and assessing the consequences of waste heat on biota.

2 PREVIOUS STUDIES

A number of earlier studies approached the problem of data paucity over the lakes by averaging land data near the perimeter of the lake, or by computing differences between upwind and downwind stations, or island and shoreline stations. A more rigorous approach, which has proven to be quite popular, consists of establishing empirical relationships between observations, collected from research vessels on the lake, and simultaneously-observed data from the land.

2.1 Wind Ratio R_w (lake wind/land wind)

Hunt (1958) is credited with being the first to employ the wind ratio to compute short-period set-up and seiches on Lake Erie. He established the importance of air mass stratification in determining over water wind speed and described how R_w varied with the seasons and time of day. Bruce and Rodgers (1962) compared simultaneous meteorological readings observed at Toronto International Airport and aboard the CCGS Porte Dauphine on Lake Ontario. The data were combined regardless of the type of weather, intervening frontal weather systems, time of day, season, wind direction, or ship's location. Their results confirmed on Lake Ontario what Hunt had found for Lake Erie. Lemire (1961) combined new data collected from the Porte Dauphine with data from Bruce and Rodgers to evaluate wind ratios for each of the months from March through November. Richards (1964) completed the calculations for the remaining months: December, January, and February. Table 1 is a listing of the various monthly and seasonal wind ratios compiled by these authors. A later study was undertaken by Richards in co-operation with Dragert and McIntyre, (1966) to quantify the effect of atmospheric stability and fetch on winds as they move from land to lake. Five years of paired observations were accepted, and were used to compute average ratios for different groups of: a) stability (defined as land air temperature minus water temperature), b) over water fetch, and c) land wind speed. Because of the limited amount of coincident data available to these early researchers, it was not possible to produce wind ratios in sufficient detail to describe the regional variation in the wind field. Moreover, rigorous testing of their statistical significance was precluded.

2.2 Humidity Difference ΔT_d (land dew point - lake dew point)

Several researchers have considered the effect of large lakes on humidity when calculating evaporation losses from large bodies of water. Rodgers and

TABLE 1

ESTIMATES OF WIND RATIO R_W FOR THE GREAT LAKES

	Author: Hunt (1958)	Lemire (1961)	Richards (1964)	Richards Dragert and McIntyre (1966)	Phillips and Irbe (1977) (This Study)
January			1.96		1.31
February			1.94		1.57
March		1.88			1.39
April		1.81			1.30
May		1.71			1.15
Spring	1.35	1.38			
June		1.31			1.20
July		1.16			1.27
August		1.39			1.49
September		1.78			1.61
Fall	1.82	1.87			
October		1.99			
November			2.09		1.93
December			1.98		1.78
Average	1.56	1.63	1.66	1.56	1.53

Anderson (1961) chose climatological differences from opposite shorelines to arrive at a mean dew point, representative of conditions over the water. Richards and Fortin (1962) computed humidity ratios by pairing lake/land vapour pressure for approximately 700 observations over the Great Lakes. Monthly values varied from 0.86 in May to 1.33 in January, with a 12-month average of 1.14. Phillips (1973) used the same number of observations to derive regression equations for five stability groups in order to predict over lake dew point, when given a corresponding land value, surface water temperature, and over water residence time.

2.3 Air Temperature Difference ΔT_a (land air temperature - lake air temperature)

Studies of air temperature modification over the Great Lakes have received much less attention. Rodgers and Anderson (1961) examined weather observations from ships and found that air temperatures at 2 m were much closer to surface water temperature than the temperatures measured at land stations. For this reason the over lake air temperature for summer conditions was arbitrarily taken as:

$$T_{AW} = T_W + \tfrac{1}{4}(T_{AL} - T_W) \qquad (1)$$

where T_{AW} is air temperature over water (^{o}C)

T_W is surface water temperature (^{o}C)

T_{AL} is air temperature over land (^{o}C)

Phillips (1972) used a step-wise regression technique to derive equations for five stability classes, with over lake air temperature as the dependent variable. The resultant models based on 700 observations explained 80 per cent of the variance and had a standard error of approximately 1.5 degrees C. The over lake data were obtained entirely from ship observations and were not adjusted to a common observing height.

3 PURPOSE OF STUDY

The purpose of this study was to re-evaluate earlier studies of differences of air temperature and humidity, and wind data observed over-land and over Lake Ontario. IFYGL archives of data from buoys and ships, and meteorological stations received from the Atmospheric Environment Service (AES) in Canada and the National Weather Service (NWS) in the United States were the principal sources of data used to calculate new values of R_w, ΔT_a, and ΔT_d.

The results of the study are presented in three different ways, in order to accommodate various applications ranging from broad estimates of climatological means to complex modelling techniques. The data were sorted and analysed to provide the following:

1. simple monthly averages

2. values of R_w, ΔT_a and ΔT_d grouped for different classes of stability, fetch distance, and land wind speed

3. regression equations suitable for modelling, with the capability to predict variables at specific locations, for all situations, and with a known degree of accuracy.

4 DESCRIPTION OF OVER LAKE DATA

Reliable meteorological observations from Lake Ontario were obtained from Canadian and American IFYGL buoy networks and from research vessels. A detailed description of the systems is given in Data Acquisition Systems, IFYGL Technical Plan, Volume 2 (IFYGL Project Office, 1972).

The Canadian buoys had a sampling interval of ten minutes, the U.S. buoys, six minutes. The buoys were instrumented to measure air temperature, dew point temperature (or relative humidity), wind speed and direction, and lake surface temperature. In addition, some buoys measured atmospheric pressure, total incoming radiation, and current speed and direction, but these parameters were not considered in this study.

All atmospheric parameters were normalized to a common level of 3 m, relative to the calm water surface, by logarithmic interpolation. Water temperature, measured within the top 1 m, was assumed to approximate closely the surface temperature. Measurements of relative humidity were converted to equivalent dew point temperatures by using the existing air temperatures.

Observations taken aboard three Canadian scientific vessels operated by the Canada Centre for Inland Waters were also incorporated into the study. In the case of ships' observations, wind speeds were normalized to the standard 3 m height by using the power-law equation:

$$U_2 = U_1\left[\frac{z_2}{z_1}\right]^{1/7} \qquad (2)$$

where U_2 = wind speed at height level two

U_1 = wind speed at height level one

z_2 = height level two

z_1 = height level one

However, no height corrections were imposed on temperature or humidity readings. It was assumed that even the greatest height difference between ships and land stations would require a negligible correction, when compared to possible discrepancies in readings introduced by variability in exposures.

5 PAIRING OF LAND/LAKE OBSERVATIONS

The over lake observations were paired with over-land observations recorded at seven first order meteorological stations located around Lake Ontario. The land stations used were: Toronto International, Trenton, Kingston, Watertown, Syracuse, Rochester, and Niagara Falls (NY), all airports (see Figure 1). Several other land stations were initially considered for inclusion in the study, but these were discarded because they did not have a full 24-hour observing schedule.

FIGURE 1

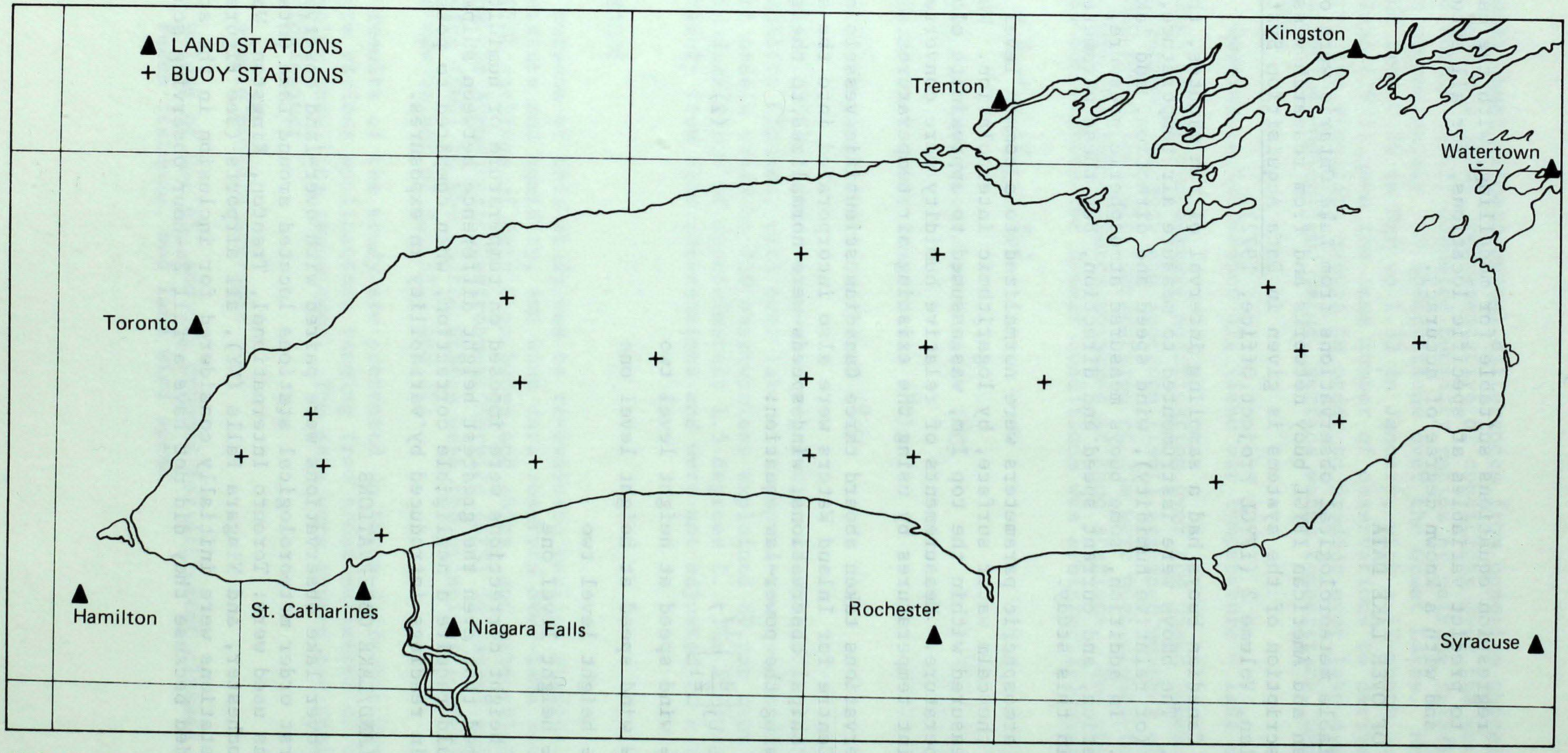

FIGURE 1 - Location of stations used in paired simultaneous weather observations over land and lake during IFYGL

One of the major tasks in this study was to devise a technique that would ensure reliable pairing of land and lake observations. Lake Ontario occupies an area approximately 300 by 100 km. Changes in wind direction, either of geostrophic or localized nature, are inevitable over a region of this size. Unless the entire wind field is known in detail, the confidence with which land/lake observations can be paired decreases rapidly with distance.

Ideally, pairing of simultaneous land and lake observations requires examination of the general weather situation and streamline analysis. This procedure, however, is too time-consuming when dealing with a large volume of data, as in this study. Therefore, a compromise method was devised in which specific limits were established for determining the upwind land station, fetch, and allowable divergence in wind direction with respect to each buoy location. In the case of ships' observations, similar limits were devised for geographical sectors of Lake Ontario.

Fetches were measured upwind to the shore along the wind direction observed at the buoy or ship. For ships' observations the fetch distance had to be measured in each individual case; for the 20 buoys, distances were pre-determined for 36 compass points. A 30-degree difference in wind direction was allowed between the over land and over lake observations in the pairing process.

Pairing of observations was carried out for each synoptic hour. A quick scan of all available wind directions was sufficient in most cases in order to decide whether or not a uniform circulation existed over the lake. If the flow was well established, data selection could proceed smoothly with the aid of the limits described above.

If the winds appeared to be variable over the region, observations were paired with more caution, after examination of synoptic weather maps. Often land/lake pairs with matching wind directions were rejected, due to the nature of the general circulation. In other cases, although the land/lake wind directions differed by more than 30 degrees, paired data were accepted if the synoptic situation revealed an unmistakable geostrophic flow pattern over the basin.

This method of data selection functioned reliably for the majority of paired observations. However, certain shortcomings and difficulties remained in this quasi-systematic approach. Two situations, in particular, arose frequently, causing uncertainties in matching of land/lake observations:

1. Due to the orientation of Lake Ontario, difficulties were experienced in selecting land stations under westerly and easterly wind regimes. Frequently, any one of two or three possible upwind stations and appropriate fetches could be chosen.

2. Under light winds, wind directions at near-shore buoys often diverged considerably from directions over land, probably due to shoreline and local eddying effects; while winds at buoys located further in the lake conformed to the general direction of flow.

   In these instances it was difficult to ascertain which over lake observations, if any, could be paired with land station data.

Once the data set was created and placed on computer tape a further screening of data was performed. Computer computations were prepared of the difference in air temperature and dew point temperature, and the wind ratio for each of the paired observations. The results of these calculations were grouped and printed chronologically. A check was then made to identify erratic values that departed significantly from the range of the group. For these suspected values, synoptic weather maps and, in some cases, wind plots, were then consulted to verify whether the paired data were still acceptable.

That all of the remaining pairs are valid matches is not guaranteed. It is hoped, however, that a statistical analysis of a large sample of observations will tend to minimize the effects of a few incongruous values and yield reasonably stable results.

6 RESULTS AND INTERPRETATION

6.1 Presentation of Results

More than 11,000 hourly observations were initially considered for pairing. Of the total, 3800 were rejected because wind speed was calm, lake/land wind directions did not agree within 30 degrees, or no station was located within the upwind sector. An additional 300 observations were discarded after the final screening process. In all, 6926 observations were deemed usable, having met all the necessary requirements. Table 2 is the summary of the number of paired observations by month, stability, synoptic hour, and by ship number and buoy number.

The Canadian buoys accounted for 82% of the selected data, evenly divided among the 11 buoys. There was also a tendency for most of the ships' paired observations to come from the Canadian side of Lake Ontario. For the most part, there was no definite bias to any synoptic hour, although usable records from 12Z were more common, constituting 28% of the total. Unfortunately, there was a serious shortage of winter-time observations, with only 8% of the total falling within the December to March period.

Monthly averages of R_w and results obtained by previous investigators are listed in Table 1. Considering that the estimates were based on data from different periods of time, for various lengths of record, and were arrived at by different techniques, the results are in good agreement.

The three parameters governing the magnitude of R_w, ΔT_a and ΔT_d are: atmospheric stability (defined as air temperature on land, minus surface water temperature), wind speed over land, and over lake fetch. In order to assess the relative effects of each of these parameters, the R_w, ΔT_a, and ΔT_d values obtained in this study were sorted according to five categories of atmospheric stability, four classes of land wind speed, and four fetch groups. The results of these analyses are shown in detail in Tables 3 to 5 and in Figures 2 to 5.

While the results obtained in past investigations appear theoretically sound and have been shown to be useful for estimating wind speed and air temperature over the lake, it was decided to undertake a rigorous statistical analysis to detect the association between over water and over land data. A stepwise multiple linear regression program was used to formulate the best predictive model of over lake wind speed, air temperature, and dew point temperature. Included in the list of meteorological parameters, both measured and derived, were:

TABLE 2

TOTAL NUMBER OF OBSERVATIONS BY MONTH

J	F	M	A	M	J	J	A	S	O	N	D	YEAR
90	25	84	444	388	902	871	849	1033	1033	927	280	6926

TOTAL OBSERVATIONS BY HOUR

00Z	06Z	12Z	18Z	TOTAL
1721	1842	1944	1419	6926

OBSERVATIONS BY BUOY/SHIP NUMBER

BUOY (CANADIAN)		SHIP		BUOY (AMERICAN)	
1	570	12	283	15	15
2	592	13	360	16	31
3	538	14	145	17	17
4	556			18	171
5	468	TOTAL	788	19	29
6	422			20	16
7	529			21	49
8	510			22	91
9	441			23	54
10	481				
11	558			TOTAL	473
TOTAL	5665				

OBSERVATIONS BY STABILITY

VERY STABLE	478
STABLE	1685
NEUTRAL	2695
UNSTABLE	1687
VERY UNSTABLE	381
TOTAL	6926

STABILITY CLASS	TEMPERATURE DIFFERENCE °C (AIR-WATER)
VERY STABLE	⩾10.5
STABLE	3.5 to 10.4
NEUTRAL	-3.4 to +3.4
UNSTABLE	-10.4 to -3.5
VERY UNSTABLE	⩽-10.5

wind, air temperature, humidity, atmospheric pressure, surface water temperature, over-water fetch, residence time, air/water stability and air mass modification.

Only those variables which contributed a significant percentage of the explained variance were included in the final equations. Table 6 shows the equations, together with results of statistical tests that describe their effectiveness in predicting over lake conditions.

6.2 Diurnal and Seasonal Variations

The data were sorted into four synoptic hours for each stability class and plotted for each month to give an indication of the daily and seasonal variation (see Table 7 and Figures 6 and 7). It is evident that there is a substantial variation in R_W over the period of a day within each stability group. There is also a large variation from stability to stability, although less variation occurs at 18Z than at any other synoptic hour.

The highest value of R_W occurs near midnight and the lowest shortly after noon. The existence of this diurnal change can be attributed to the unequal heating and cooling rates of the land and lake surfaces. Winds display a marked response to diurnal temperature changes of land surfaces. This effect is greatly reduced over water surfaces, where diurnal temperature variations are relatively small. For all synoptic hours, identical land winds produce, in unstable conditions, over water winds that are 80 to 100 per cent stronger than in stable situations.

Monthly estimates of R_W range from a peak in November (1.9) to a low in May (1.2). The controlling factor here is also stability: the more stable the air, the lower the wind speed over the lake. R_W increases slowly during the spring months. The trend changes abruptly in July, when R_W begins to increase very rapidly to the November peak. During the winter months R_W remains high. In March the ratio starts a decrease to the May low. The low value of R_W in January is due to above normal wind speed in January, 1973 (Phillips, 1974). Given strong prevailing land winds, R_W can be expected to be lower. The average R_W of 1.28 in spring and 1.81 in the fall agree well with Hunt's seasonal ratios of 1.35 and 1.82 respectively (Figure 7).

Temperature differences between air over the lake and air over the land (ΔT_a) are greatest at midday (3 degrees C at 18Z), and least from 03Z to 12Z, when over lake air temperatures begin to exceed those over the land. Land-lake air temperature differences are the greatest in February and May, -5 degrees C and +5 degrees C, respectively. From September through March ΔT_a is negative. ΔT_d remains negative throughout the day with little diurnal variation, although humidity differences are slightly less near midday. Dew point temperatures over land exceed those over the lake only in May and June. Richards and Fortin (1962) also found that lake/land vapour pressure ratios were less than unity during these two spring months.

6.3 Effects of Land Wind Speed, Stability, and Fetch on R_W, ΔT_a and ΔT_d.

6.3.1 Wind Ratio R_W

As stated before, data were sorted into several classes of stability, fetch, and land wind speed, in order to assess the relative influence of each of these parameters on the modification of air, as it moves from land out to the lake. The class ranges were made to correspond closely to those used by Richards et al (1966).

Generally, the results obtained are similar to Richards'. R_w values were less erratic and their standard deviations were significantly less in this study, compared to the earlier work. However, with $3\frac{1}{2}$ times as many observations than in Richards' study, these results are to be expected. In addition, the observations were taken primarily from meteorological buoys with narrow error windows.

Several conclusions can be reached with respect to R_w by inspecting Table 3 and Figures 2 and 3.

1. The average value of R_w for all data is 1.53. This compares well with the R_w of 1.56 obtained by Hunt (1958) and Richards et al (1966).

2. R_w increases as stability decreases, being 1.15 for very stable situations and 2.38 for very unstable ones.

3. For stability groups neutral through very unstable, R_w increases with fetch. An exception to this situation occurs in the very unstable case with a fetch of 25 to 40 nautical miles. For this stability/fetch class R_w is 2.1, whereas for shorter and longer fetches R_w is 2.6. Richards et al (1966) reported a similar decrease in R_w for the same stability/fetch class. No physical explanation is readily available for this apparent anomaly. The 89 paired observations, falling within the very unstable/fetch of 25-40 n mi groups, were examined for a possible sampling bias. There is a preponderance of observation pairs from Kingston A/Buoy #11 and Toronto International A/Buoy #4 in this group, constituting roughly 1/3 of the sample. The above bias has a logical explanation. Most very unstable situations (water temperature exceeding air temperature by 10.5 degrees C, or more) occur with strong northerly winds. Due to the configurations of Lake Ontario and the network of buoys, and with northerly winds, pairing for this fetch of 25-40 n mi was often restricted to the above-named land stations and buoys.

Upon further investigation it was found that, in a northerly flow, winds at Kingston A are approximately 1 ms^{-1} stronger than at other stations along the north shore of Lake Ontario. Exposure of the land station could be a factor here. Similarly, the location of Buoy #4 near the western shore of the lake could have influenced the results. The proximity of the Niagara escarpment could induce local turbulence here, thus disrupting a northerly wind flow.

If the observation pairs in question are removed from the group, the R_w value calculated from the remaining pairs becomes 2.83. This value conforms better with others in the very unstable class. However, the possibility that there is a physical reason for the low R_w in this stability/fetch class cannot be excluded on the basis of the above speculations. This problem bears further investigation, preferably on another of the Great Lakes and in a more favourable exposure setting.

TABLE 3a

EFFECT OF FETCH ON R_W
(OVER LAKE/OVER LAND WIND SPEED)
TABULATED ACCORDING TO ATMOSPHERIC STABILITY

FETCH (n mi)

STABILITY	0-6	7-14	15-24	25-40	≥ 41	All Fetches
	1.07	1.01	1.10	0.97	1.54	1.15
Very Stable	29	86	113	134	116	478
	0.65	0.94	0.65	0.60	1.18	
	1.06	1.04	1.04	1.14	1.21	1.10
Stable	95	369	458	368	395	1685
	0.50	0.55	0.52	0.59	0.56	
	1.27	1.33	1.39	1.60	1.67	1.47
Neutral	225	619	704	603	544	2695
	0.73	0.75	0.77	0.93	0.94	
	1.65	1.83	1.96	2.07	2.15	1.96
Unstable	125	470	448	378	266	1687
	0.98	0.89	0.97	1.12	1.09	
	2.12	2.35	2.62	2.12	2.57	2.38
Very Unstable	36	89	108	89	59	381
	1.23	1.04	1.96	0.99	2.29	
All Ranges	1.37	1.45	1.49	1.58	1.66	1.53
	510	1633	1831	1572	1380	6926

Mean
Number of Observations
Standard Deviation

TABLE 3b

EFFECT OF WIND SPEED ON R_w (OVER LAKE/OVER LAND WIND SPEED) TABULATED ACCORDING TO ATMOSPHERIC STABILITY

	WIND SPEED CLASSES (ms^{-1})						
STABILITY	< 2.1	2.1-4.0	4.1-6.0	6.1-8.0	8.1-10.0	⩾10.1	All Speeds
Very Stable	2.69 54 1.57	1.35 117 0.57	0.98 140 0.37	0.66 125 0.22	0.68 33 0.26	0.65 9 0.12	1.15 478
Stable	1.84 170 0.68	1.30 436 0.55	1.00 517 0.42	0.82 415 0.31	0.79 123 0.33	0.89 244 0.24	1.10 1685
Neutral	2.37 464 1.36	1.47 827 0.61	1.22 885 0.48	1.10 368 0.40	1.17 89 0.36	0.96 62 0.33	1.47 2695
Unstable	3.03 378 1.42	1.88 452 0.65	1.62 531 0.50	1.47 209 0.38	1.29 72 0.36	1.01 45 0.12	1.96 1687
Very Unstable	3.55 129 2.25	2.11 107 0.61	1.63 83 0.51	1.46 48 0.32	1.47 11 0.33	.91 3 0.28	2.38 381
All Ranges	2.64 1195	1.56 1939	1.27 2156	1.03 1165	1.01 328	.96 143	1.53 6926

Mean
Number of Observations
Standard Deviation

TABLE 3c

EFFECT OF FETCH AND WIND SPEED ON R_W
(OVER LAKE/OVER LAND WIND SPEED)
TABULATED BY FETCH, WIND SPEED, AND ATMOSPHERIC STABILITY

WIND SPEED CLASSES (ms^{-1})

STABILITY	< 2.1	2.1-4.0	4.1-6.0	6.1-8.0	8.1-10.0	≥10.1	All Speeds
FETCH: 0-6 n mi							
Very Stable	1.10 1	1.85 7 0.89	0.88 15 0.26	0.61 5 0.25	0.76 1	 0	1.07 29 0.65
Stable	1.31 10 0.80	1.12 24 0.52	1.08 29 0.45	0.87 22 0.33	1.05 8 0.22	0.67 2 0.06	1.06 95 0.50
Neutral	1.95 40 1.29	1.22 71 0.43	1.09 80 0.38	0.96 22 0.34	1.26 5 0.24	1.06 7 0.24	1.27 225 0.73
Unstable	3.03 24 1.32	1.54 38 0.53	1.24 43 0.37	1.22 13 0.24	0.89 4 0.03	0.83 3 0.11	1.65 125 0.98
Very Unstable	3.41 12 1.25	2.03 8 0.52	1.30 11 0.30	1.04 4 0.22	 0	0.63 1	2.12 36 1.23
All Ranges	2.37 87 1.44	1.36 148 0.57	1.12 178 0.40	0.96 66 0.35	1.06 18 0.24	0.91 13 0.25	1.37 510
FETCH: 7-14 n mi							
Very Stable	2.49 6 2.73	1.28 19 0.40	0.90 29 0.24	0.68 26 0.22	0.67 4 0.15	0.66 2	1.01 86 0.94
Stable	1.91 33 0.72	1.28 91 0.58	0.87 111 0.31	0.79 96 0.26	0.87 32 0.27	0.90 6 0.21	1.04 369 0.55
Neutral	2.13 106 1.21	1.27 171 0.51	1.13 213 0.44	1.09 90 0.34	1.17 20 0.30	0.85 19 0.34	1.33 619 0.75
Unstable	2.75 103 1.27	1.76 133 0.59	1.56 134 0.42	1.44 68 0.29	1.22 17 0.28	0.98 15 0.15	1.83 470 0.89

TABLE 3c (CONT'D)

WIND SPEED CLASSES (ms-1)

STABILITY	< 2.1	2.1-4.0	4.1-6.0	6.1-8.0	8.1-10.0	≥10.1	All Speeds
FETCH: 7-14 n mi (cont'd)							
Very Unstable	3.07 39 1.06	2.18 21 0.57	1.61 20 0.38	1.28 7 0.20	1.19 2 0.11	0	2.35 89 1.04
All Ranges	2.46 287 1.31	1.47 435 0.62	1.19 507 0.48	1.04 287 0.40	1.03 75 0.33	0.90 42 0.21	1.45 1633
FETCH: 15-24 n mi							
Very Stable	2.36 12 0.83	1.37 30 0.44	0.95 24 0.27	0.67 33 0.19	0.75 11 0.31	0.73 3 0.18	1.10 113 0.65
Stable	1.79 43 0.53	1.20 112 0.55	0.96 142 0.42	0.79 122 0.26	0.76 33 0.31	0.87 6 0.22	1.04 458 0.52
Neutral	2.23 116 1.23	1.37 211 0.54	1.18 243 0.46	1.06 94 0.39	1.12 21 0.37	0.90 19 0.31	1.39 704 0.77
Unstable	3.02 100 1.26	1.95 120 0.64	1.61 143 0.50	1.43 59 0.39	1.18 14 0.34	1.00 12 0.16	1.96 448 0.97
Very Unstable	3.70 46 2.55	2.14 27 0.56	1.54 21 0.50	1.63 10 0.24	1.93 3 0.06	0.63 1	2.62 108 1.96
All Ranges	2.64 317 1.58	1.51 500 0.65	1.24 573 0.52	1.00 318 0.43	0.96 82 0.43	0.92 41 0.30	1.50 1831
FETCH: 25-40 n mi							
Very Stable	2.06 8 1.05	1.31 36 0.58	0.86 38 0.33	0.65 42 0.23	0.75 6 0.26	0.55 4 0.05	0.97 134 0.60
Stable	1.85 47 0.66	1.30 103 0.51	1.05 113 0.44	0.78 80 0.34	0.67 21 0.29	0.72 4 0.29	1.14 368 0.59
Neutral	2.62 108 1.40	1.63 211 0.64	1.28 186 0.49	0.99 70 0.35	1.02 19 0.32	1.14 9 0.24	1.60 603 0.93

TABLE 3c (CONT'D)

WIND SPEED CLASSES (ms^{-1})

STABILITY	< 2.1	2.1-4.0	4.1-6.0	6.1-8.0	8.1-10.0	⩾10.1	All Speeds
FETCH: 25-40 n mi (cont'd)							
Unstable	3.24 91 1.52	2.04 94 0.63	1.61 130 0.47	1.48 33 0.41	1.35 20 0.34	1.08 10 0.18	2.07 378 1.12
Very Unstable	3.32 20 1.12	2.04 34 0.65	1.68 14 0.49	1.36 15 0.26	1.41 5 0.20	1.48 1	2.12 89 0.99
All Ranges	2.73 274 1.43	1.64 478 0.67	1.29 481 0.53	0.95 240 0.44	1.01 71 0.42	0.99 28 0.30	1.58 1572
FETCH: ⩾41 n mi							
Very Stable	3.12 27 1.35	1.29 25 0.53	1.26 34 0.43	0.67 19 0.18	0.58 11 0.18	0	1.54 116 1.18
Stable	1.94 37 0.62	1.48 106 0.50	1.10 122 0.41	0.90 95 0.35	0.76 29 0.39	1.07 6 0.14	1.21 395 0.56
Neutral	2.71 94 1.46	1.69 163 0.65	1.36 163 0.53	1.27 92 0.45	1.31 24 0.36	1.04 8 0.24	1.67 544 0.94
Unstable	3.21 60 1.61	2.00 67 0.70	1.92 81 0.51	1.67 36 0.40	1.45 17 0.36	1.07 5 0.55	2.15 266 1.09
Very Unstable	5.06 12 4.00	2.18 17 0.58	1.95 17 0.57	1.67 12 0.25	0.96 1	0	2.57 59 2.29
All Ranges	2.89 230 1.80	1.68 378 0.66	1.41 417 0.58	1.16 254 0.50	1.04 82 0.49	1.05 19 0.34	1.66 1380

Mean
Number of Observations
Standard Deviation

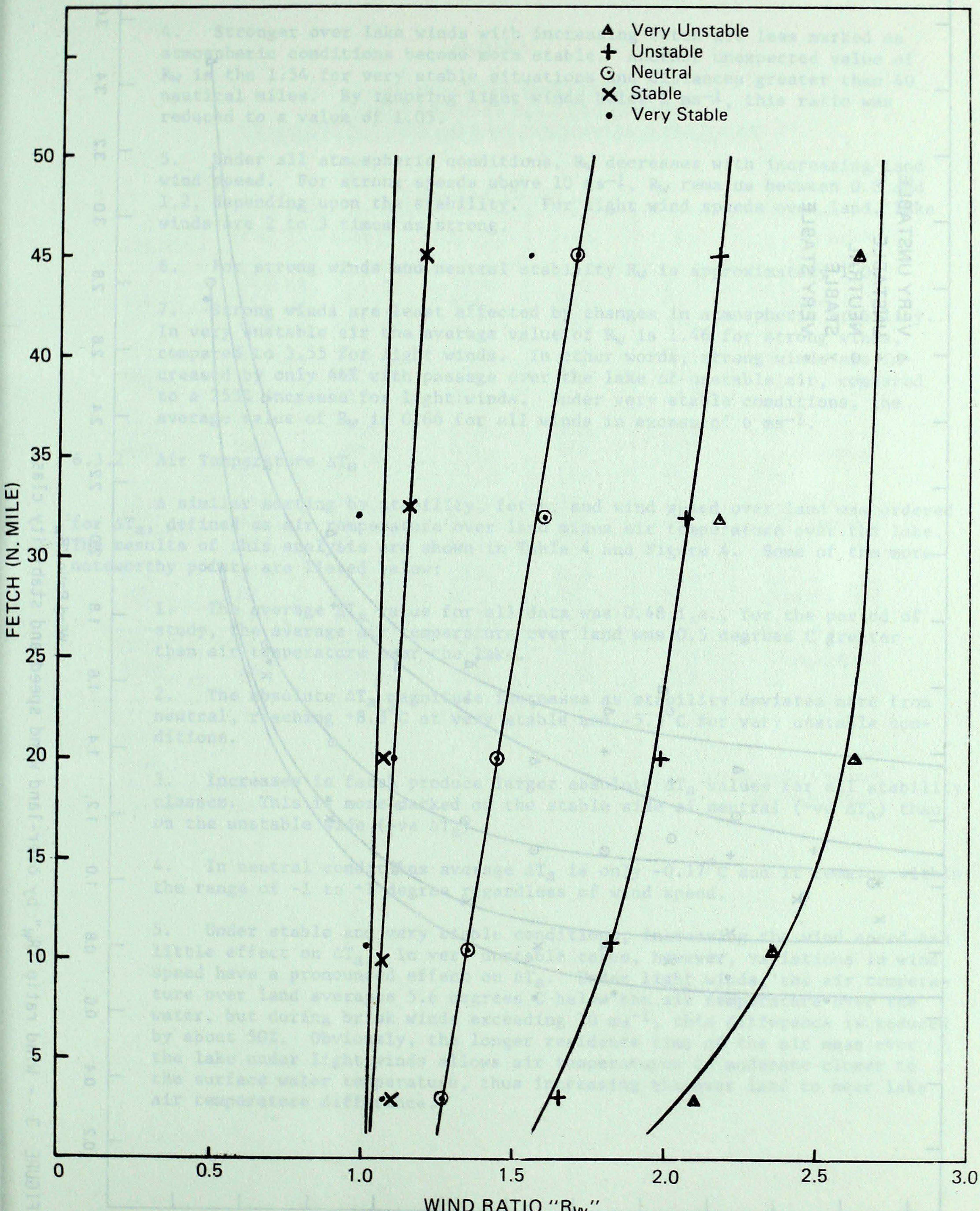

FIGURE 2 - Wind ratio "R_W" by fetch distance and stability class

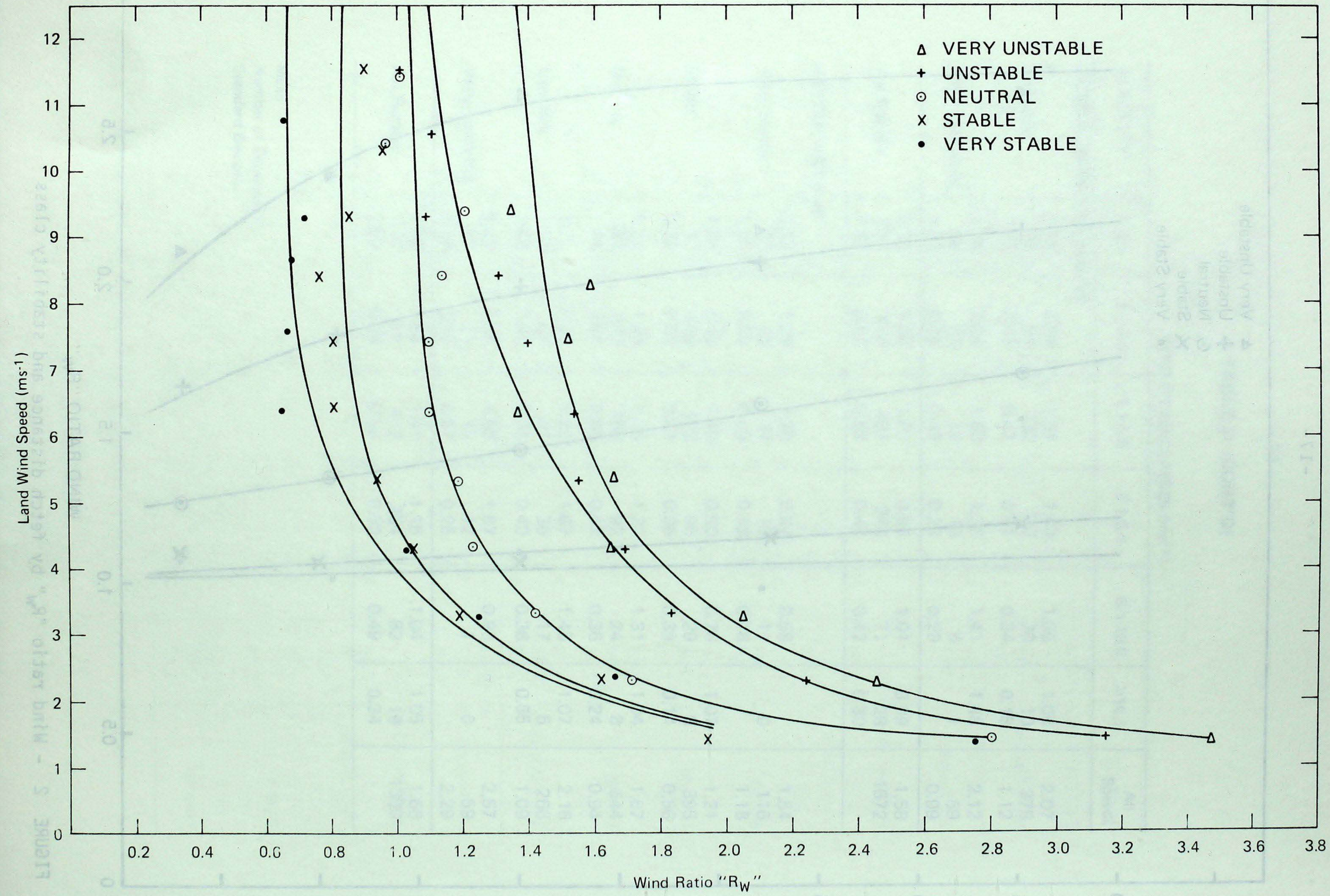

FIGURE 3 - Wind ratio "R_W" by over-land wind speed and stability class

4. Stronger over lake winds with increasing fetch are less marked as atmospheric conditions become more stable. Another unexpected value of R_w is the 1.54 for very stable situations and distances greater than 40 nautical miles. By ignoring light winds below 2 ms^{-1}, this ratio was reduced to a value of 1.05.

5. Under all atmospheric conditions, R_w decreases with increasing land wind speed. For strong speeds above 10 ms^{-1}, R_w remains between 0.8 and 1.2, depending upon the stability. For light wind speeds over land, lake winds are 2 to 3 times as strong.

6. For strong winds and neutral stability R_w is approximately 1.0.

7. Strong winds are least affected by changes in atmospheric stability. In very unstable air the average value of R_w is 1.46 for strong winds, compared to 3.55 for light winds. In other words, strong winds are increased by only 46% with passage over the lake of unstable air, compared to a 255% increase for light winds. Under very stable conditions, the average value of R_w is 0.66 for all winds in excess of 6 ms^{-1}.

6.3.2 Air Temperature ΔT_a

A similar sorting by stability, fetch, and wind speed over land was ordered for ΔT_a, defined as air temperature over land minus air temperature over the lake. The results of this analysis are shown in Table 4 and Figure 4. Some of the more noteworthy points are listed below:

1. The average ΔT_a value for all data was 0.48 i.e., for the period of study, the average air temperature over land was 0.5 degrees C greater than air temperature over the lake.

2. The absolute ΔT_a magnitude increases as stability deviates more from neutral, reaching $+8.8^{o}C$ at very stable and $-5.3^{o}C$ for very unstable conditions.

3. Increases in fetch produce larger absolute ΔT_a values for all stability classes. This is more marked on the stable side of neutral (+ve ΔT_a) than on the unstable side (-ve ΔT_a).

4. In neutral conditions average ΔT_a is only $-0.17^{o}C$ and it remains within the range of -1 to +1 degree regardless of wind speed.

5. Under stable and very stable conditions, increasing the wind speed has little effect on ΔT_a. In very unstable cases, however, variations in wind speed have a pronounced effect on ΔT_a. Under light winds, the air temperature over land averages 5.6 degrees C below the air temperature over the water, but during brisk winds exceeding 10 ms^{-1}, this difference is reduced by about 50%. Obviously, the longer residence time of the air mass over the lake under light winds allows air temperatures to moderate closer to the surface water temperature, thus increasing the over land to over lake air temperature difference.

TABLE 4a

EFFECT OF FETCH ON ΔT_a (LAND-LAKE AIR TEMPERATURE °C) TABULATED ACCORDING TO ATMOSPHERIC STABILITY

	FETCH (n mi)					
STABILITY	0-6	7-14	15-24	25-40	⩾ 41	All Fetches
	5.77	7.68	8.47	9.42	9.90	8.78
Very Stable	29	86	113	134	116	478
	3.16	2.68	2.70	2.58	2.38	
	1.75	3.00	3.51	4.37	4.58	3.74
Stable	95	369	458	368	395	1685
	1.74	1.77	1.80	1.91	1.91	
	-0.47	-0.36	-0.23	-0.10	0.17	-0.17
Neutral	225	619	704	603	544	2695
	1.38	1.41	1.58	1.67	1.78	
	-2.41	-2.69	-2.70	-2.96	-3.18	-2.81
Unstable	125	470	448	378	266	1687
	1.71	1.77	1.79	1.75	1.88	
	-4.06	-4.33	-4.83	-6.02	-7.05	-5.26
Very Unstable	36	89	108	89	59	381
	2.10	2.05	1.87	2.04	2.42	
	0.43	0.06	0.37	0.74	1.30	0.48
All Ranges	510	1633	1831	1572	1380	6926

Mean
Number of Observations
Standard Deviation

TABLE 4b

EFFECT OF WIND SPEED ON ΔT_a (LAND-LAKE AIR TEMPERATURE °C) TABULATED ACCORDING TO ATMOSPHERIC STABILITY

WIND SPEED CLASSES (ms^{-1})

STABILITY	< 2.1	2.1-4.0	4.1-6.0	6.1-8.0	8.1-10.0	⩾10.1	All Speeds
	8.88	8.90	8.32	9.04	8.93	9.49	8.78
Very Stable	54	117	140	125	33	9	478
	3.15	2.50	3.16	2.71	2.33	1.97	
	3.76	3.96	3.59	3.68	3.97	2.34	3.74
Stable	170	436	517	415	123	24	1685
	1.94	2.02	1.98	1.97	2.06	1.61	
	-0.66	-0.12	-0.13	0.33	-0.12	-0.59	-0.17
Neutral	464	827	885	368	89	62	2695
	1.76	1.63	1.53	1.46	1.31	1.11	
	-3.83	-3.09	-2.30	-2.03	-2.09	-2.20	-2.81
Unstable	378	452	531	209	72	45	1687
	1.88	1.90	1.53	1.33	1.09	1.20	
	-5.67	-5.91	-4.87	-4.05	-3.11	-2.56	-5.25
Very Unstable	129	107	83	48	11	3	381
	2.11	2.14	2.49	1.98	1.62	1.75	
	-1.14	0.33	0.59	1.85	1.79	0.02	0.48
All Ranges	1195	1939	2156	1165	328	143	6926

Mean
Number of Observations
Standard Deviation

TABLE 4c

EFFECT OF FETCH AND WIND SPEED ON ΔT_a (LAND-LAKE AIR TEMPERATURE °C) TABULATED BY FETCH, WIND SPEED, AND ATMOSPHERIC STABILITY

WIND SPEED CLASSES (ms^{-1})

STABILITY	<2.1	2.1-4.0	4.1-6.0	6.1-8.0	8.1-10.0	≥10.1	All Speeds
FETCH: 0-6 n mi							
Very Stable	0.34 1	6.72 7 2.76	4.59 15 2.51	7.73 5 1.89	12.31 1	 0	5.77 29 3.16
Stable	2.21 10 1.79	1.93 24 1.79	1.48 29 1.71	1.77 22 1.65	1.55 8 1.04	1.76 2 1.10	1.75 95 1.74
Neutral	-1.03 40 1.37	-0.35 71 1.35	-0.43 80 1.37	0.11 22 1.15	-0.48 5 0.78	-0.85 7 0.78	-0.47 225 1.38
Unstable	-2.84 24 1.55	-3.08 38 1.96	-1.73 43 1.32	-1.94 13 1.43	-1.51 4 0.24	-3.22 3 1.22	-2.41 125 1.71
Very Unstable	4.81 12 1.65	5.32 8 1.17	-3.10 11 2.11	-2.66 4 2.01	 0	-1.11 1	-4.06 36 2.10
All Ranges	-1.66 87 2.42	-0.61 148 3.01	-0.17 178 2.46	0.67 66 2.95	0.91 18 3.14	-1.01 13 1.42	-0.43 510
FETCH: 7-14 n mi							
Very Stable	6.43 6 4.12	7.72 19 2.08	7.76 29 2.57	7.89 26 2.51	7.58 4 1.93	7.30 2	7.68 86 2.68
Stable	2.96 33 1.78	3.01 91 1.51	2.77 111 1.78	3.30 96 1.78	3.07 32 1.77	3.42 6 2.31	3.00 369 1.77
Neutral	-0.85 106 1.60	-0.20 171 1.42	-0.35 213 1.35	-0.02 90 1.22	-0.65 20 0.64	-0.43 19 1.07	-0.36 619 1.41
Unstable	-3.80 103 1.86	-3.14 133 1.76	-2.13 134 1.43	-1.75 68 1.11	-1.69 17 1.19	-1.64 15 1.23	-2.69 470 1.77

TABLE 4c (CONT'D)

WIND SPEED CLASSES (ms^{-1})

STABILITY	< 2.1	2.1-4.0	4.1-6.0	6.1-8.0	8.1-10.0	≥10.1	All Speeds
FETCH 7-14 n mi (cont'd)							
Very Unstable	-5.05 39 2.09	-4.45 21 1.82	-3.65 20 1.72	-2.71 7 0.70	-1.37 2 0.25	0	-4.33 89 2.05
All Ranges	-1.89 287 3.27	-0.28 435 3.32	0.20 507 3.06	1.33 287 3.27	1.12 75 2.91	-0.13 42 2.53	-0.06 1633
FETCH: 15-24 n mi							
Very Stable	8.41 12 2.54	9.05 30 2.79	8.12 24 3.05	8.10 33 2.16	8.21 11 2.37	10.66 3 1.59	8.47 113 2.70
Stable	3.42 43 1.72	3.68 112 1.95	3.39 142 1.66	3.43 122 1.72	4.06 33 1.67	1.93 6 1.12	3.51 458 1.80
Neutral	-0.90 116 1.78	-0.16 211 1.65	-0.11 243 1.44	0.33 94 1.26	-0.40 21 1.09	-0.88 19 1.06	-0.23 704 1.58
Unstable	-3.84 100 1.79	-2.93 120 1.83	-2.28 143 1.48	-1.64 59 1.32	-1.87 14 0.81	-1.95 12 1.02	-2.70 448 1.79
Very Unstable	-5.27 46 1.67	-5.42 27 1.78	-4.47 21 1.69	-2.59 10 1.05	-2.89 3 0.28	-4.61 1	-4.83 108 1.87
All Ranges	-1.52 317 3.75	0.30 500 3.86	0.40 573 3.18	1.87 318 3.31	2.21 82 3.72	-0.03 41 3.59	0.37 1831
FETCH: 25-40 n mi							
Very Stable	8.87 8 2.52	8.99 36 1.66	9.36 38 2.95	10.19 42 2.64	7.55 6 1.15	9.72 4 2.44	9.42 134 2.58
Stable	4.16 47 1.68	4.60 103 1.94	4.17 113 1.85	4.28 80 1.86	5.22 21 2.16	3.80 4 1.15	4.37 368 1.91
Neutral	-0.46 108 1.77	-0.37 211 1.66	0.10 186 1.61	0.47 70 1.35	0.68 19 1.55	-0.08 9 1.03	-0.10 603 1.67

TABLE 4c (CONT'D)

STABILITY	WIND SPEED CLASSES (ms-1) <2.1	2.1-4.0	4.1-6.0	6.1-8.0	8.1-10.0	≥10.1	All Speeds
FETCH: 25-40 n mi (cont'd)							
Unstable	-3.84 91 1.91	-2.93 94 1.77	-2.28 130 1.59	-1.64 33 1.14	-1.87 20 0.99	-1.98 10 1.05	-2.70 378 1.75
Very Unstable	-7.55 20 1.40	-6.36 34 1.78	-5.10 14 1.84	-5.03 15 1.63	-3.97 5 1.91	-1.97 1	-6.02 89 2.04
All Ranges	1.04 274 5.09	0.47 478 4.52	0.93 481 4.32	2.66 240 4.06	1.45 71 4.46	0.90 28 1.84	0.80 1572
FETCH: ≥41 n mi							
Very Stable	9.96 27 2.27	10.08 25 2.33	9.43 34 2.47	10.01 19 2.43	10.59 11 1.44	0	9.90 116 2.38
Stable	4.79 37 1.85	4.90 106 1.74	4.52 122 1.88	4.35 95 1.98	4.63 29 1.69	2.16 6 0.67	4.58 395 1.91
Neutral	-0.24 94 1.86	0.41 163 1.70	-0.01 163 1.70	0.62 92 1.83	-0.01 24 1.34	-0.70 8 0.91	0.17 544 1.78
Unstable	-4.18 60 1.88	-3.49 67 2.19	-2.55 81 1.57	-2.61 36 1.20	-2.62 17 1.10	-2.98 5 0.28	-3.18 266 1.88
Very Unstable	-6.99 12 2.44	-7.87 17 2.08	-7.74 17 2.24	-5.29 12 1.87	-2.99 1	0	-7.05 59 2.42
All Ranges	-0.39 230 5.09	1.24 378 4.52	1.27 417 4.32	1.98 254 4.06	2.48 82 4.46	-0.42 19 1.84	1.30 1380

Mean
Number of Observations
Standard Deviation

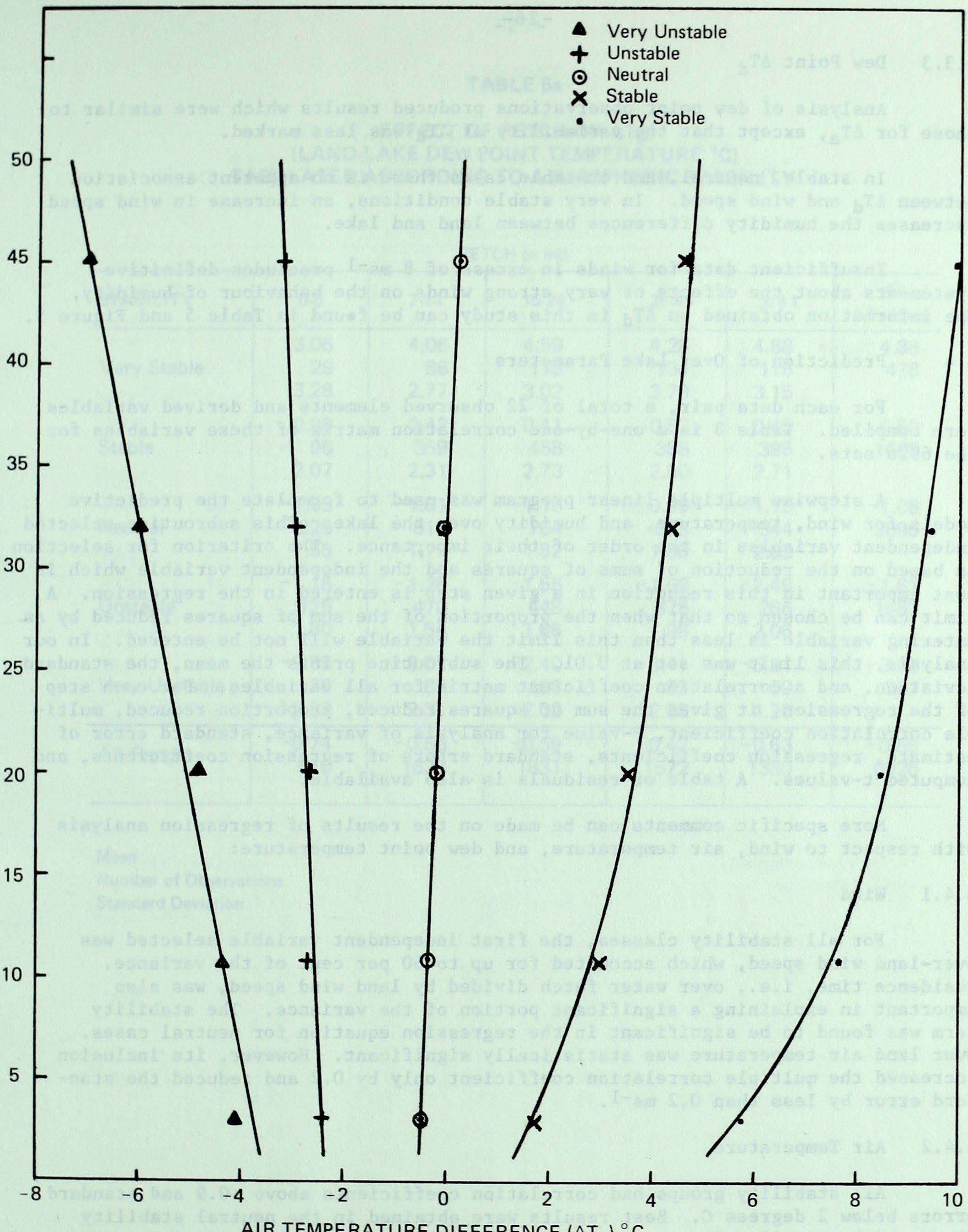

FIGURE 4 - Air temperature difference °C by fetch distance and stability class

6.3.3 Dew Point ΔT_d

Analysis of dew point observations produced results which were similar to those for ΔT_a, except that the variability of ΔT_d was less marked.

In stable, neutral, and unstable cases there is no apparent association between ΔT_d and wind speed. In very stable conditions, an increase in wind speed increases the humidity differences between land and lake.

Insufficient data for winds in excess of 8 ms^{-1} precludes definitive statements about the effects of very strong winds on the behaviour of humidity. The information obtained on ΔT_d in this study can be found in Table 5 and Figure 5.

6.4 Prediction of Over Lake Parameters

For each data pair, a total of 22 observed elements and derived variables were compiled. Table 8 is a one-by-one correlation matrix of these variables for the 6926 sets.

A stepwise multiple linear program was used to formulate the predictive models for wind, temperature, and humidity over the lake. This subroutine selected independent variables in the order of their importance. The criterion for selection is based on the reduction of sums of squares and the independent variable which is most important in this reduction in a given step is entered in the regression. A limit can be chosen so that when the proportion of the sum of squares reduced by an entering variable is less than this limit the variable will not be entered. In our analysis, this limit was set at 0.01. The subroutine prints the mean, the standard deviation, and a correlation coefficient matrix for all variables. For each step of the regression, it gives the sum of squares reduced, proportion reduced, multiple correlation coefficient, F-value for analysis of variance, standard error of estimate, regression coefficients, standard errors of regression coefficients, and computed t-values. A table of residuals is also available.

More specific comments can be made on the results of regression analysis with respect to wind, air temperature, and dew point temperature:

6.4.1 Wind

For all stability classes, the first independent variable selected was over-land wind speed, which accounted for up to 60 per cent of the variance. Residence time, i.e., over water fetch divided by land wind speed, was also important in explaining a significant portion of the variance. The stability term was found to be significant in the regression equation for neutral cases. Over land air temperature was statistically significant. However, its inclusion increased the multiple correlation coefficient only by 0.2 and reduced the standard error by less than 0.2 ms^{-1}.

6.4.2 Air Temperature

All stability groups had correlation coefficients above +0.9 and standard errors below 2 degrees C. Best results were obtained in the neutral stability class, with $r = .99$ and a standard error of 1.2 degrees. Over land air temperature is an important parameter in explaining the variance in all stability classes.

TABLE 5a

EFFECT OF FETCH ON ΔT_d (LAND-LAKE DEW POINT TEMPERATURE °C) TABULATED ACCORDING TO ATMOSPHERIC STABILITY

	FETCH (n mi)					
STABILITY	0-6	7-14	15-24	25-40	≥ 41	All Fetches
	3.06	4.06	4.59	4.28	4.88	4.38
Very Stable	29	86	113	134	116	478
	3.28	2.77	3.02	3.79	3.15	
	0.20	0.42	0.41	0.82	0.45	0.50
Stable	95	369	458	368	395	1685
	2.07	2.31	2.73	2.60	2.71	
	−1.05	−1.01	−1.18	−0.99	−1.15	−1.08
Neutral	225	619	704	603	544	2695
	1.58	1.79	1.82	1.80	2.03	
	−1.16	−1.28	−1.55	−1.69	−2.49	−1.63
Unstable	125	470	448	378	266	1687
	1.80	1.54	1.66	1.98	2.06	
	−2.85	−2.07	−2.40	−3.41	−5.51	−3.08
Very Unstable	36	89	108	89	59	381
	2.82	2.31	2.02	2.88	4.28	
All Ranges	−0.74	−0.56	−0.59	−0.42	−0.63	−0.56
	510	1633	1831	1572	1380	6926

Mean
Number of Observations
Standard Deviation

TABLE 5b

EFFECT ON WIND SPEED ON ΔT_d (LAND-LAKE DEW POINT TEMPERATURE °C) TABULATED ACCORDING TO ATMOSPHERIC STABILITY

WIND SPEED CLASSES (ms^{-1})

STABILITY	<2.1	2.1-4.0	4.1-6.0	6.1-8.0	8.1-10.0	≥10.1	All Speeds
	5.60	5.37	4.12	3.48	4.38	0.95	4.38
Very Stable	54	117	140	125	33	9	478
	3.68	3.28	3.26	3.07	1.75	1.79	
	1.35	0.87	0.61	-0.18	-0.30	1.12	0.50
Stable	170	436	517	415	123	24	1685
	2.30	2.75	2.59	2.37	2.47	2.00	
	-1.04	-0.91	-1.14	-1.22	-1.21	-1.74	-1.07
Neutral	464	827	885	368	89	62	2695
	1.84	1.88	1.83	1.77	1.65	1.58	
	-1.74	-1.66	-1.41	-1.63	-2.06	-2.12	-1.62
Unstable	378	452	531	209	72	45	1687
	1.84	1.93	1.76	1.64	1.69	1.85	
	-2.44	-2.82	-3.87	-4.02	-3.27	-2.86	-3.18
Very Unstable	129	107	83	48	11	4	382
	2.55	2.28	4.11	3.37	1.67	0.80	
All Ranges	-0.77	-0.41	-0.55	-0.53	-0.56	-1.25	-0.56
	1195	1939	2156	1165	328	143	6926

Mean
Number of Observations
Standard Deviation

TABLE 5c

EFFECT OF FETCH AND WIND SPEED ON ΔT_d (LAND-LAKE DEW POINT TEMPERATURE °C) TABULATED BY FETCH, WIND SPEED, AND ATMOSPHERIC STABILITY

STABILITY	WIND SPEED CLASSES (ms-1) < 2.1	2.1-4.0	4.1-6.0	6.1-8.0	8.1-10.0	≥10.1	All Speeds
FETCH 0-6 n mi							
Very Stable	3.28 1	4.86 7 3.29	1.99 15 2.95	4.26 5 1.37	7.06 1	0	3.06 29 3.28
Stable	1.05 10 1.59	0.30 24 2.05	0.12 29 2.48	-0.37 22 1.41	0.34 8 1.17	1.75 2 0.18	0.20 95 2.07
Neutral	-1.27 40 1.32	-0.74 71 1.61	-1.17 80 1.56	-1.53 22 1.85	-0.47 5 0.49	-0.62 7 0.66	-1.05 225 1.58
Unstable	-0.85 24 1.54	-1.42 38 1.54	-0.72 43 1.42	-2.64 13 2.73	-0.44 4 0.64	-1.40 3 3.15	-1.16 125 1.80
Very Unstable	-3.39 12 2.78	-3.75 8 3.13	-2.03 11 2.69	-1.92 4 1.46	0	-1.76 1	-2.85 36 2.82
All Ranges	-1.20 87 2.03	-0.64 148 2.42	-0.64 178 2.19	-0.95 66 2.55	0.31 18 1.88	-0.57 13 1.72	-0.74 510
FETCH: 7-14 n mi							
Very Stable	4.44 6 3.54	4.71 19 2.89	4.42 29 2.35	3.38 26 2.51	3.03 4 2.24	2.49 2	4.06 86 2.77
Stable	1.28 33 2.09	0.67 91 2.55	0.23 111 2.44	0.09 96 1.82	0.11 32 1.97	2.25 5 2.09	0.42 369 2.31
Neutral	-0.94 106 1.71	-0.74 171 1.63	-1.20 213 1.90	-1.13 90 1.98	-0.56 20 0.78	-1.55 19 1.00	-1.01 619 1.79
Unstable	-1.46 103 1.65	-1.48 133 1.55	-1.06 134 1.52	-1.00 68 1.18	-1.76 17 1.24	-0.90 15 1.54	-1.28 470 1.54

TABLE 5c (CONT'D)

STABILITY	WIND SPEED CLASSES (ms^{-1}) < 2.1	2.1-4.0	4.1-6.0	6.1-.80	8.1-10.0	≥10.1	All Speeds
FETCH: 7-14 n mi (cont'd)							
	-2.11	-2.36	-1.84	-1.52	-2.42		-2.07
Very Unstable	39	21	20	7	2	0	89
	2.11	1.67	3.22	1.88	0.40		2.31
	-0.92	-0.51	-0.55	-0.29	-0.40	-0.58	-0.56
All Ranges	287	435	507	287	75	42	1633
	2.23	2.39	2.46	2.25	1.94	2.14	
FETCH: 15-24 n mi							
	6.38	5.52	4.67	3.46	4.28	0.96	4.59
Very Stable	12	30	24	33	11	3	113
	2.28	3.18	2.55	3.01	1.13	0.53	3.02
	1.58	0.89	0.66	-0.44	-0.70	0.48	0.41
Stable	43	112	142	122	33	6	458
	2.52	2.90	2.56	2.42	2.66	1.98	2.73
	-1.15	-1.00	-1.15	-1.35	-0.85	-2.44	-1.18
Neutral	116	211	243	94	21	19	704
	1.83	1.96	1.72	1.67	0.88	1.86	1.82
	-1.77	1.43	-1.41	-1.56	-1.72	-2.23	-1.55
Unstable	100	120	143	59	14	12	448
	1.68	1.69	1.67	1.33	1.25	1.58	1.66
	-2.04	-2.26	-3.24	-2.36	-3.28	-3.36	-2.40
Very Unstable	46	27	21	10	3	1	108
	2.06	1.32	2.44	1.98	0.48	—	2.02
	-0.82	-0.39	-0.60	-0.57	-0.34	-1.72	-0.60
All Ranges	317	500	573	318	82	41	1831
	2.67	2.85	2.49	2.61	2.65	2.19	
FETCH: 25-40 n mi							
	4.11	5.80	3.97	3.83	3.17	0.18	4.28
Very Stable	8	36	38	42	6	4	134
	4.77	3.43	3.88	3.28	1.47	2.21	3.79
	1.09	0.87	1.30	0.01	0.18	1.75	0.82
Stable	47	103	113	80	21	4	368
	2.23	2.86	2.32	2.60	2.16	0.74	2.60
	-0.74	-1.11	-0.95	-1.00	-1.20	-1.24	-0.99
Neutral	108	211	186	70	19	9	603
	1.68	1.78	1.81	1.70	2.26	1.09	1.80

TABLE 5c (CONT'D)

WIND SPEED CLASSES (ms^{-1})

STABILITY	< 2.1	2.1-4.0	4.1-6.0	6.1-8.0	8.1-10.0	≥10.1	All Speeds
FETCH: 25-40 n mi (cont'd)							
Unstable	-1.76 91 1.90	-1.42 94 1.90	-1.57 130 2.09	-2.27 33 1.43	-1.76 20 1.53	-3.10 10 1.86	-1.69 378 1.98
Very Unstable	-3.00 20 2.78	-2.81 34 2.54	-3.28 14 2.74	-5.25 15 3.23	-4.09 5 1.91	-3.16 1	-3.41 89 2.88
All Ranges	-0.79 274 2.54	-0.34 478 3.05	-0.27 481 2.84	-0.26 240 3.35	-0.78 71 2.59	-1.36 28 1.74	-0.42 1572
FETCH ≥41 n mi							
Very Stable	6.28 27 3.05	5.23 25 2.85	4.59 34 3.05	2.63 19 2.92	5.41 11 1.19	0	4.88 116 3.15
Stable	1.53 37 2.18	1.16 106 2.61	0.38 122 2.74	-0.25 95 2.47	-0.81 29 2.76	-0.00 6 0.31	0.45 395 2.71
Neutral	-1.28 94 2.18	-0.70 163 2.09	-1.25 163 1.98	-1.26 92 1.51	-2.23 24 1.67	-2.01 8 1.16	-1.15 544 2.03
Unstable	-2.47 60 2.00	-2.93 67 2.56	-2.11 81 1.49	-1.98 36 1.81	-3.39 17 1.86	-3.83 5 0.63	-2.49 266 2.06
Very Unstable	-3.13 12 3.74	-3.87 17 2.43	-8.74 17 4.35	-6.02 12 3.51	-0.85 1	0	-5.51 59 4.28
All Ranges	-0.35 230 3.63	-0.32 378 3.22	-0.77 417 3.41	-0.92 254 3.76	-0.92 82 3.37	-1.85 19 1.76	-0.63 1380

Mean
Number of Observations
Standard Deviation

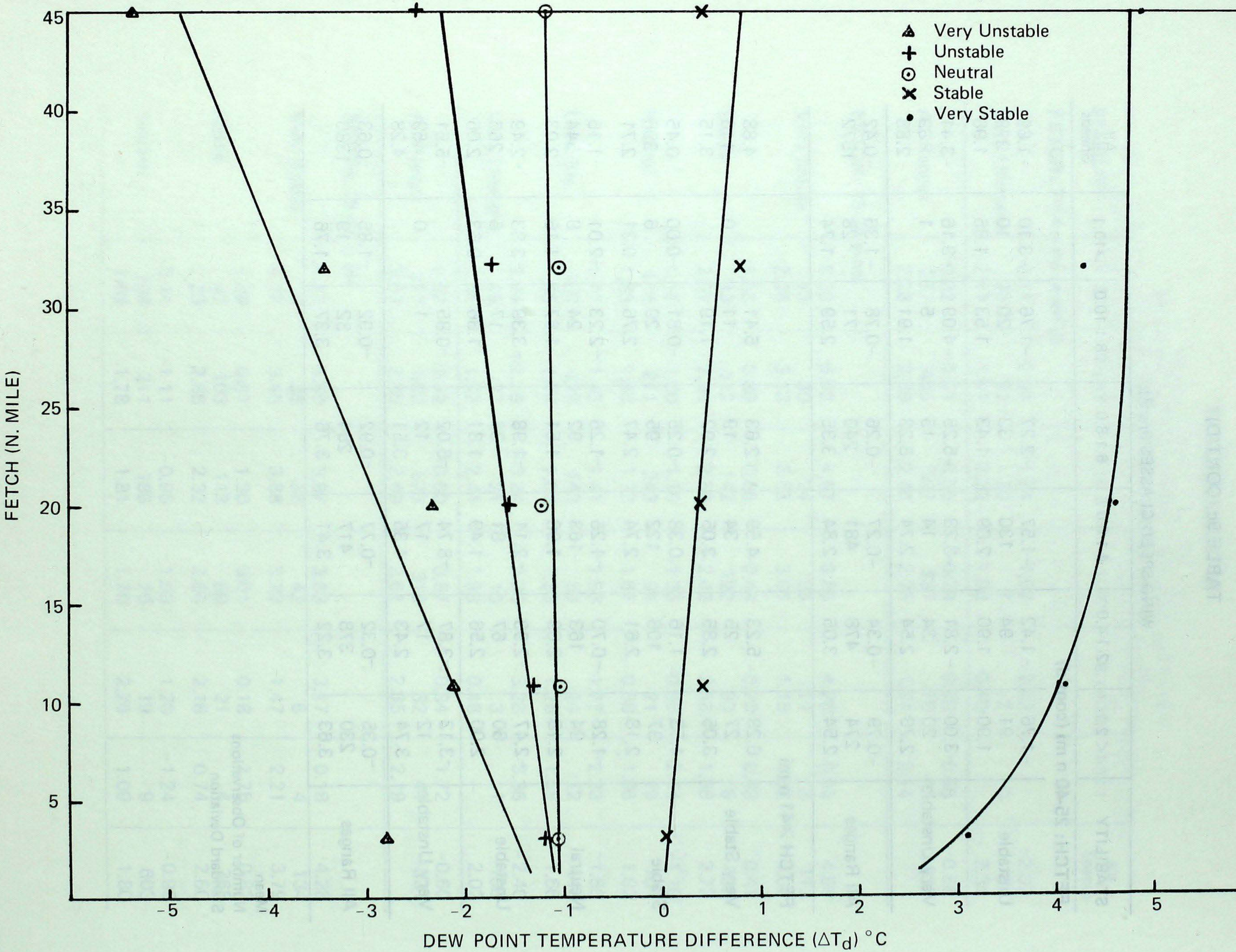

FIGURE 5 - Dew point difference (°C) by fetch distance and stability class

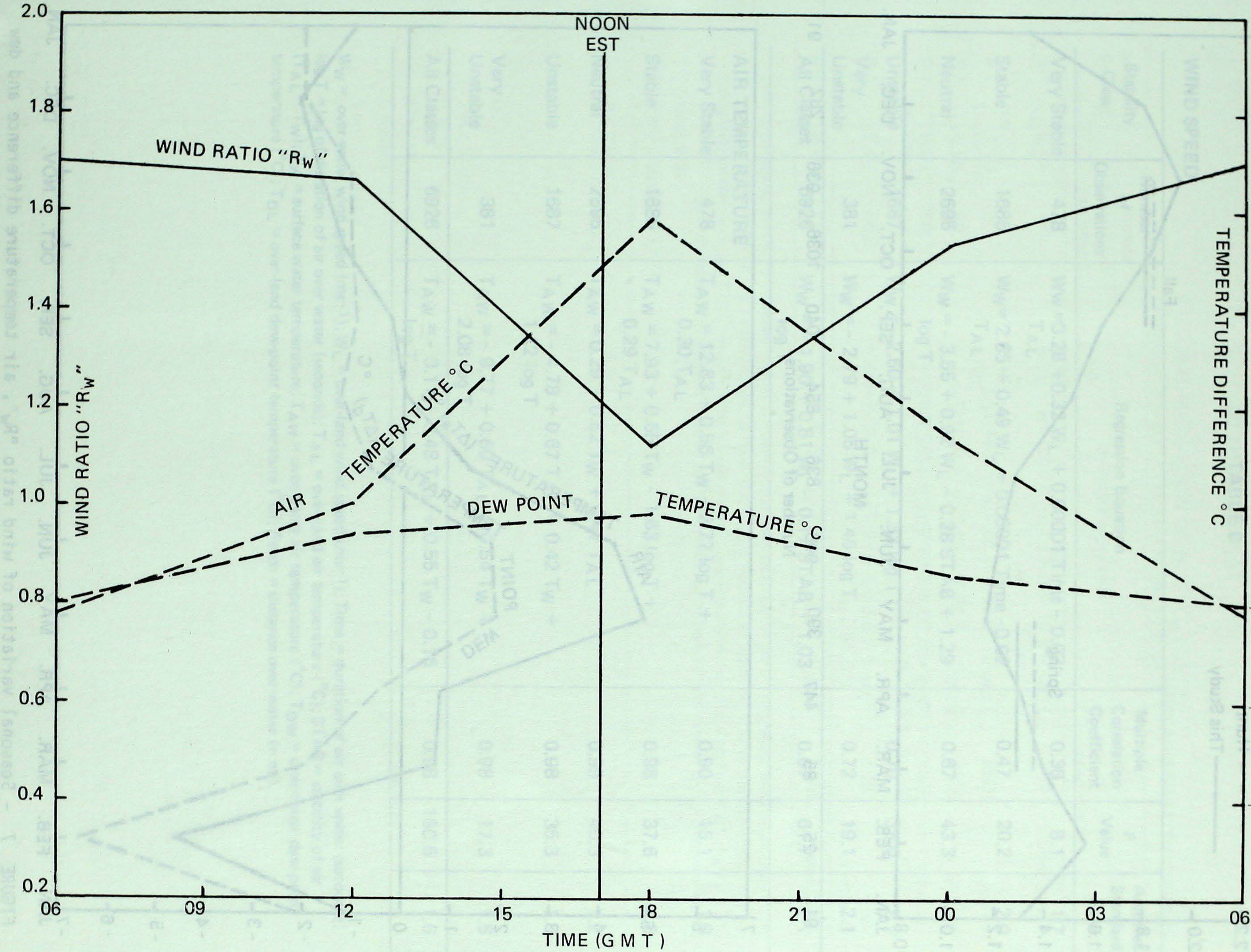

FIGURE 6 - Diurnal variation of wind ratio "R_W", air temperature difference and dew point temperature difference

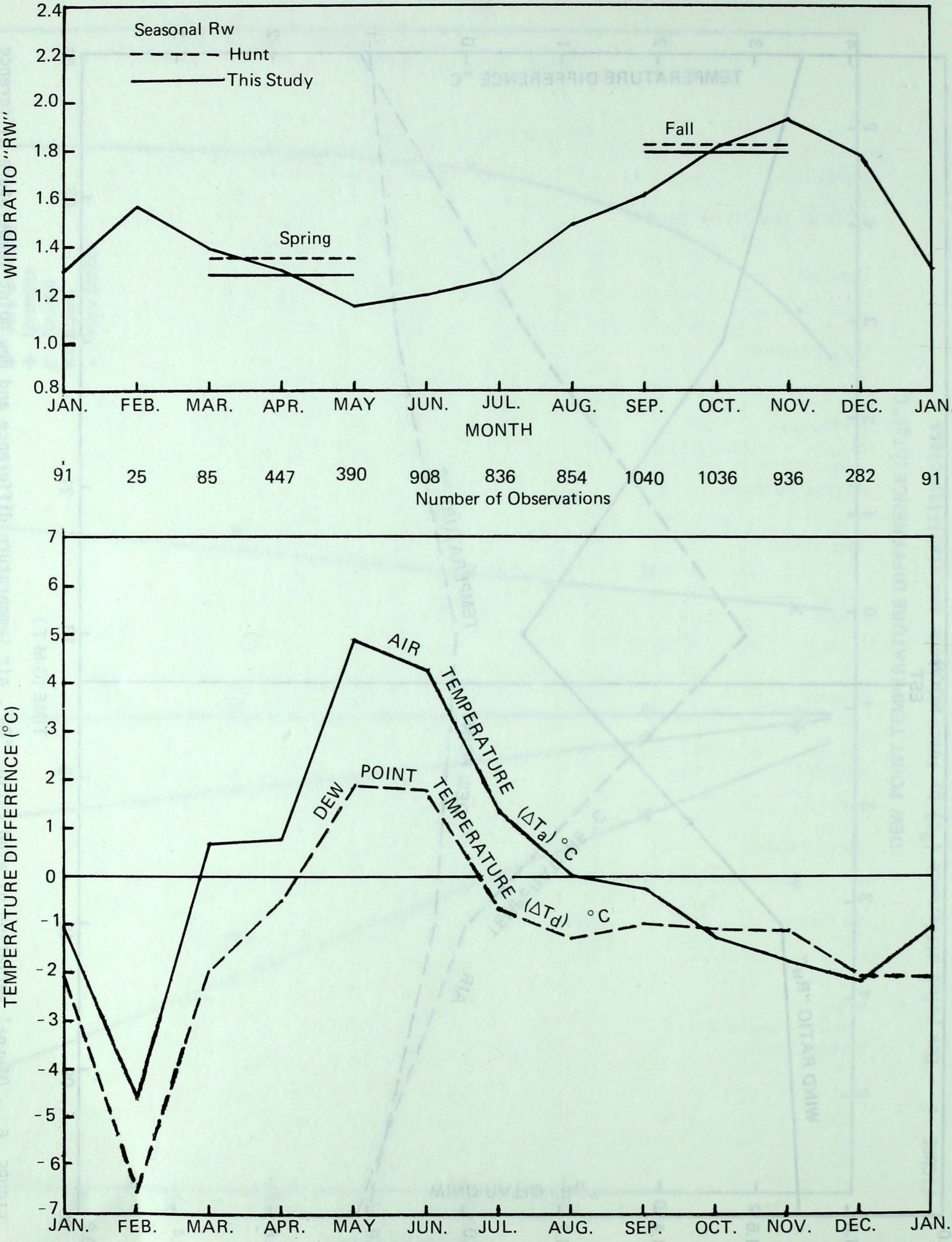

FIGURE 7 - Seasonal variation of wind ratio "R_W", air temperature difference and dew point temperature difference

TABLE 6

WIND SPEED

Stability Class	Number of Observations	Regression Equation	Multiple Correlation Coefficient	F Value	Adjusted Standard Error
Very Stable	478	$W_W = 3.28 + 0.32\,W_L + 0.00001\,Time - 0.02\,T_{AL}$	0.36	8.1	1.7
Stable	1685	$W_W = 2.65 + 0.49\,W_L + 0.00001\,Time - 0.02\,T_{AL}$	0.47	20.2	2.0
Neutral	2695	$W_W = -3.55 + 0.92\,W_L - 0.28\,STAB + 1.29\log T$	0.67	43.3	2.0
Unstable	1687	$W_W = -2.50 + 1.01\,W_L + 1.33\log T$	0.70	38.0	2.1
Very Unstable	381	$W_W = -2.79 + 1.05\,W_L + 1.46\log T$	0.72	19.1	2.1
All Classes	6926	$W_W = -1.90 + 0.81\,W_L - 0.17\,STAB + 1.03\log T$	0.67	61.7	2.1

AIR TEMPERATURE

Stability Class	Number of Observations	Regression Equation	Multiple Correlation Coefficient	F Value	Adjusted Standard Error
Very Stable	478	$T_{AW} = 12.83 + 0.56\,T_W - 2.77\log T + 0.30\,T_{AL}$	0.90	15.1	1.9
Stable	1685	$T_{AW} = 7.93 + 0.65\,T_W - 1.63\log T + 0.29\,T_{AL}$	0.98	37.6	1.3
Neutral	2695	$T_{AW} = 0.29 + 0.52\,T_W + 0.47\,T_{AL}$	0.99	40.3	1.2
Unstable	1687	$T_{AW} = -4.78 + 0.67\,T_{AL} + 0.42\,T_W + 1.12\log T$	0.98	35.3	1.5
Very Unstable	381	$T_{AW} = -9.77 + 0.60\,T_{AL} + 0.54\,T_W + 2.08\log T$	0.98	17.3	1.6
All Classes	6926	$T_{AW} = -0.11 + 0.48\,T_{AL} + 0.55\,T_W - 0.16\log T$	0.98	160.5	1.6

W_W = over-water wind speed (ms^{-1}); W_L = over-land wind speed (ms^{-1}); Time = duration of air over water (seconds); log T = log of duration of air over water (seconds); T_{AL} = over-land air temperature (°C); STAB = stability of air ($T_{AL} - T_W$); T_W = surface water temperature; T_{AW} = over-water air temperature (°C); T_{DW} = over-water dew-point temperature (°C); T_{DL} = over-land dew-point temperature (°C); Fetch = distance over-water (n mi).

TABLE 6 (CONT'D)

DEW POINT TEMPERATURE

Stability Class	Number of Observations	Regression Equation	Multiple Correlation Coefficient	F Value	Adjusted Standard Error
Very Stable	478	$T_{DW} = 8.07 + 0.43\ T_{DL} + 0.53\ T_W - 2.04 \log T$	.91	20.9	1.9
Stable	1685	$T_{DW} = -0.16 + 0.55\ T_W + 0.44\ T_{DL}$	.98	57.1	1.4
Neutral	2695	$T_{DW} = -0.35 + 0.72\ T_{DL} + 0.31\ T_W$	.98	77.8	1.5
Unstable	1687	$T_{DW} = 0.03 + 0.94\ T_{DL} + 0.02\ \text{Fetch} + 0.11\ T_W$	.97	59.8	1.7
Very Unstable	381	$T_{DW} = -5.64 + 0.56\ T_{DL} + 0.05\ \text{Fetch} + 0.46\ T_W$	0.95	14.2	1.9
All Classes	6926	$T_{DW} = -1.31 + 0.70\ T_{DL} + 0.35\ T_W$	0.97	192.6	1.9

W_W = over-water wind speed (ms^{-1}; W_L = over-land wind speed (ms^{-1}); Time = duration of air over-water (seconds); log T = log of duration of air over water (seconds); T_{AL} = over-land air temperature (°C); STAB = stability of air ($T_{AL} - T_W$); T_W = surface water temperature; T_{AW} = over-water air temperature (°C); T_{DW} = over-water dew-point temperature (°C); T_{DL} = over-land dew-point temperature (°C); Fetch = distance over-water (n mi).

TABLE 7

DIURNAL VARIATION OF R_w, ΔT_a, and ΔT_d TABULATED BY ATMOSPHERIC STABILITY

R_w	00Z	06Z	12Z	18Z
Very Stable	1.24	1.30	1.25	0.97
Stable	1.18	1.23	1.13	0.92
Neutral	1.47	1.58	1.51	1.17
Unstable	1.98	2.02	2.18	1.45
Very Unstable	2.43	2.32	2.62	1.47
All Cases	1.53	1.70	1.66	1.12
ΔT_a				
Very Stable	8.8	7.7	8.4	9.4
Stable	3.3	2.9	3.6	4.7
Neutral	-0.1	-0.8	-0.2	0.9
Unstable	-2.9	-3.6	-3.0	-0.9
Very Unstable	-5.0	-5.7	-5.5	-2.7
All Cases	0.7	-1.1	-0.0	2.9
ΔT_d				
Very Stable	4.6	5.3	5.4	3.3
Stable	-0.1	1.1	1.6	0.1
Neutral	-1.6	-1.2	-0.7	-0.8
Unstable	-1.4	-2.1	-1.6	-1.0
Very Unstable	-3.4	-3.0	-3.2	-2.4
All Cases	-0.7	-1.0	-0.3	-0.1

TABLE 8

ONE-BY-ONE CORRELATION MATRIX OF THE VARIABLES CONSIDERED FOR THE REGRESSION ANALYSIS.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	1.00	-0.06	-0.28	-0.31	-0.14	0.11	0.11	-0.43	0.00	0.51	-0.33	-0.34	0.25	0.19	-0.31	0.04	0.00	-0.25	-0.22	0.29	-0.13	-0.16
2		1.00	-0.16	-0.12	-0.24	0.06	0.05	0.08	0.01	0.01	-0.09	-0.11	-0.10	-0.30	0.10	-0.02	-0.01	0.05	0.09	-0.05	0.05	0.04
3			1.00	0.96	0.87	-0.01	0.02	0.16	0.00	-0.07	0.91	0.90	-0.23	-0.32	0.41	-0.03	0.02	0.09	-0.09	-0.15	0.01	0.05
4				1.00	0.80	0.03	0.06	0.21	0.08	-0.09	0.91	0.95	-0.31	-0.35	0.48	-0.03	0.01	0.11	-0.14	-0.17	0.04	0.09
5					1.00	-0.29	0.00	0.08	-0.06	-0.13	0.67	0.69	0.08	-0.16	-0.03	-0.26	0.03	0.06	-0.01	0.00	0.02	0.07
6						1.00	0.87	0.71	0.04	0.01	0.04	0.02	-0.13	-0.02	0.09	-0.01	-0.00	0.36	0.06	0.09	0.66	0.73
7							1.00	0.82	0.04	0.01	0.08	0.06	-0.14	-0.03	0.10	-0.02	-0.01	0.33	0.07	0.09	0.57	0.84
8								1.00	0.04	-0.24	0.24	0.22	-0.26	-0.13	0.25	-0.03	-0.00	0.53	0.16	-0.11	0.57	0.82
9									1.00	0.02	0.07	0.12	-0.15	-0.11	0.15	0.02	-0.01	0.02	0.04	-0.06	-0.02	0.01
10										1.00	0.02	-0.08	-0.18	0.06	0.15	0.03	0.00	-0.09	-0.35	-0.46	-0.39	-0.50
11											1.00	0.94	-0.62	-0.46	0.72	-0.03	0.01	0.13	-0.09	-0.27	0.01	0.04
12												1.00	-0.48	-0.50	0.62	-0.04	0.01	0.11	-0.14	-0.19	0.04	0.08
13													1.00	0.44	-0.90	0.01	0.02	-0.13	0.04	0.36	0.01	-0.01
14														1.00	-0.46	0.02	-0.02	-0.07	-0.05	0.10	-0.05	-0.06
15															1.00	-0.01	-0.02	0.02	-0.11	-0.37	-0.01	-0.01
16																1.00	-0.00	-0.02	-0.02	-0.01	-0.04	-0.03
17																	1.00	0.00	0.00	-0.00	-0.00	-0.00
18																		1.00	0.07	-0.12	0.32	0.33
19																			1.00	0.16	0.17	0.23
20																				1.00	0.46	0.40
21																					1.00	0.75
22																						1.00

Variable Number	Variable Name
1	wind speed over water
2	atmospheric pressure over water
3	air temperature over water
4	dew point temperature over water
5	surface water temperature
6	fetch distance
7	log of fetch distance
8	log of residence time from lake wind
9	cloud cover over land
10	wind speed over land
11	air temperature over land
12	dew point temperature over land
13	air temperature difference (lake-land)
14	dew point temperature difference (lake-land)
15	stability (land air temperature – surface water temperature)
16	(%) actual/potential air temperature modification; variable 13/variable 15
17	(%) actual/potential dew point temperature modification; variable 14/variable 15
18	residence time over water from lake wind
19	atmospheric pressure over land
20	ratio of lake/land wind speed
21	residence time over water from land wind
22	log of residence time over water from land wind

However, its order of significance varies, being first in unstable cases and third in stable ones. Water temperature was included as an independent variable in all stability classes; there was an increase in over lake air temperature with increasing surface water temperature. Residence time was also included in the final equation. Under stable conditions, the longer residence times decrease over lake air temperatures, bringing them closer to the surface water temperature. In unstable conditions a reverse effect is produced. It was found that expressing residence time in logarithmic form gave a better fit in the regression equation for air temperature, as well as for wind and dew point temperature.

6.4.3 Dew Point Temperature

Again, statistical results for estimating over lake dew point are similar to those for estimating air temperature. The multiple correlation coefficient r is 0.97 and the average standard error is 1.9 degrees C. The statistical results are better than those obtained by Phillips (1973) for the same stability classes. The improvement in this study is likely due to the larger sample size. Residence time was not considered for the stable and neutral stability classes in the final analyses, since this term did not explain additional variance. Moreover, its inclusion resulted in a small increase in standard error.

6.4.4 Summary of Regression Analyses

Figures 8, 9, and 10 are a collection of scatter diagrams which depict estimated versus measured wind speed, air temperature, and dew point temperature over Lake Ontario during IFYGL. The graphs show a one-to-one correlation line and the least-squares regression line resulting from the plotted points.

Figure 8 shows that for land wind speeds between 3 and 8 ms^{-1} the estimated over-water speeds agree well with the observed. For winds below and above these limits, estimated speeds tend to diverge from observed at progressively increasing rates, underestimating the low speeds and overestimating the high ones. Over 75% of the data occurred within the rather narrow land wind speed group of 3 to 8 ms^{-1}. Graphical presentation of the existing relationships became difficult with so many data points clustered in a narrow range. A clearer picture of the land/lake wind relationship was obtained by sorting the data into one metre per second land wind speed classes, averaging the observed lake wind speeds in each class, and plotting the results, as in Figure 11. It can be seen that the relationship between the variables is curvilinear. The correlation coefficient of the grouped and averaged data is 0.93. This figure compares with a coefficient of 0.53 when all data points are considered individually. The regression equations for the grouped and ungrouped data are almost identical.

7 APPLICATION AND VERIFICATION OF THE REGRESSION MODELS

Since data from only synoptic hours were used to develop the climatological relationships, there were ample observations for independent verification. Considering the number of data sets which were used to formulate the equations, it was not surprising that almost identical coefficients were computed when the analysis was performed on only half the data.

Another means of verification was sought, which would demonstrate the application of the regression models. The mass transfer method of computing evaporation has been adapted successfully where meteorological data are readily

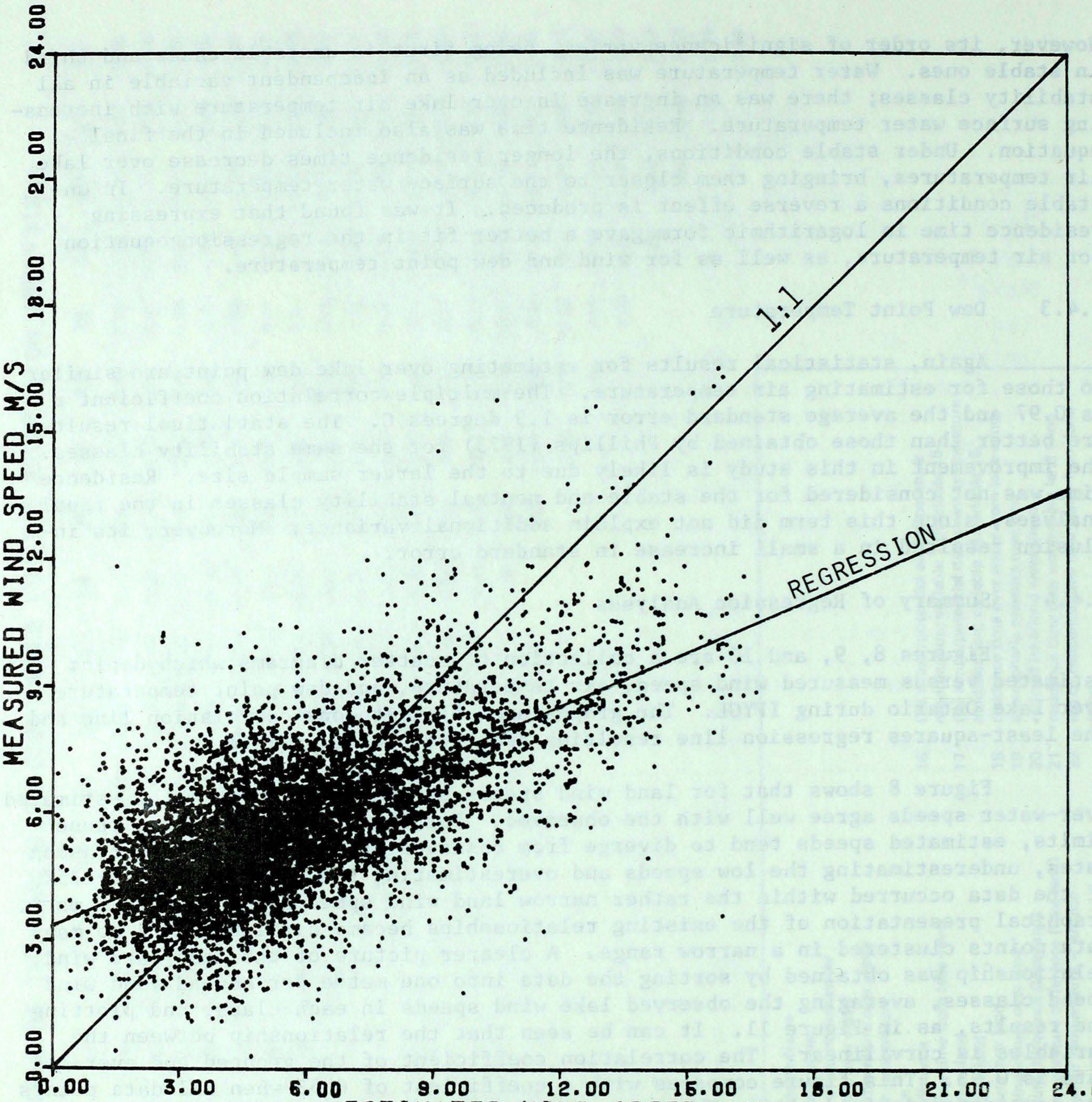

FIGURE 8 - Comparison of estimated and measured wind speed (m/s) over Lake Ontario for all paired observations

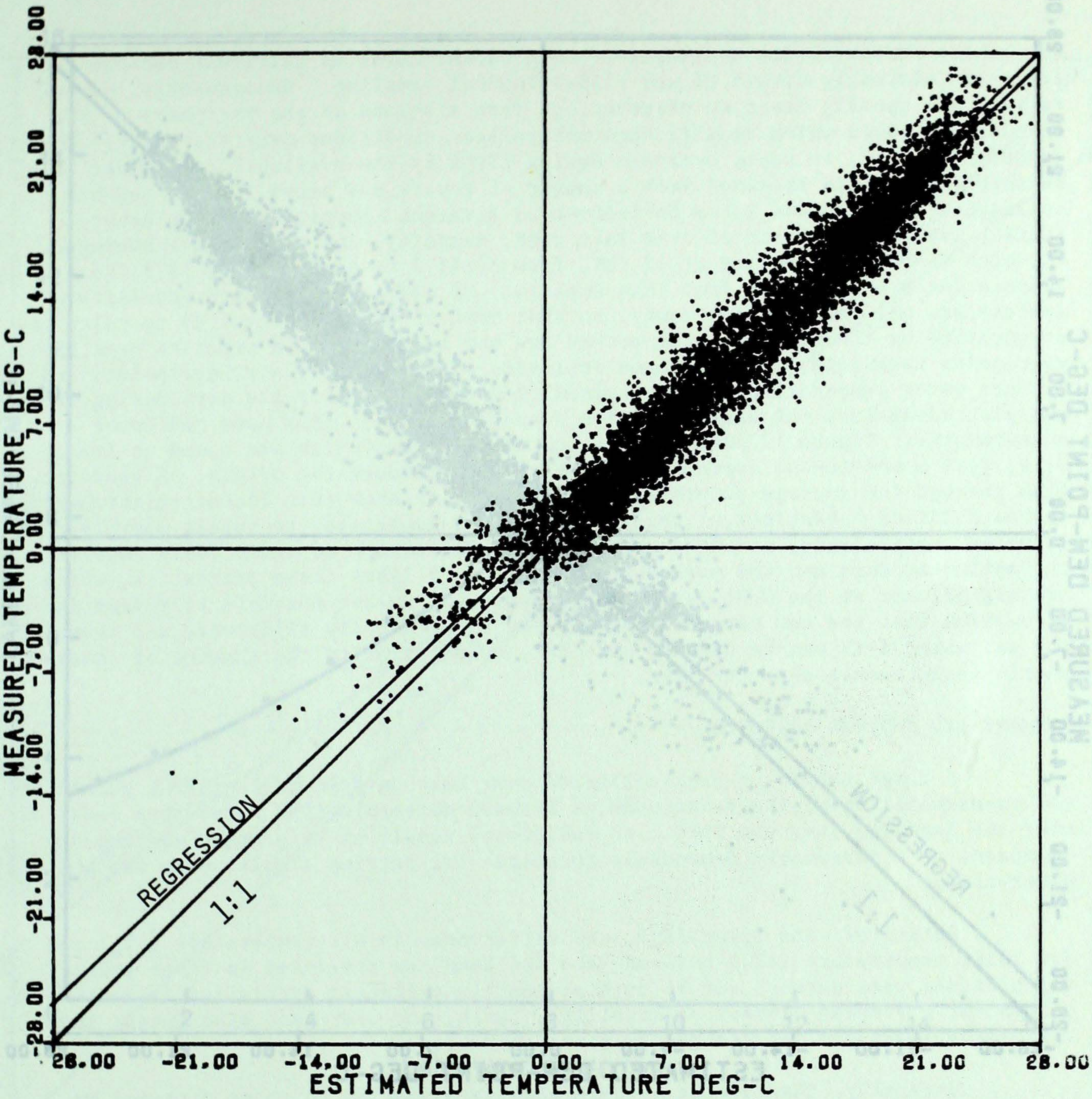

FIGURE 9 - Comparison of estimated and measured air temperature (°C) over Lake Ontario for all paired observations

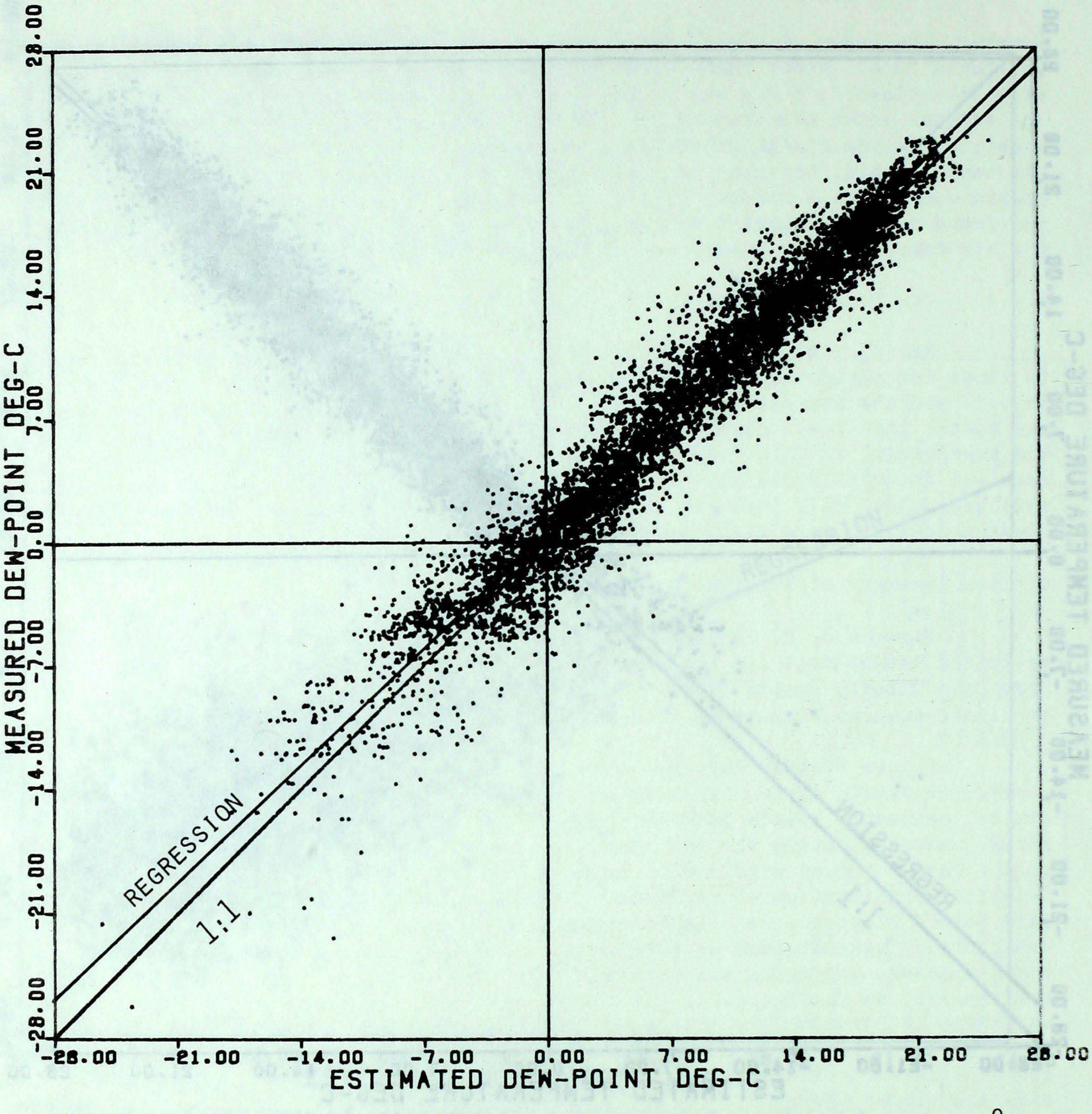

FIGURE 10 - Comparison of estimated and measured dew point temperature (^{o}C) over Lake Ontario for all paired observations

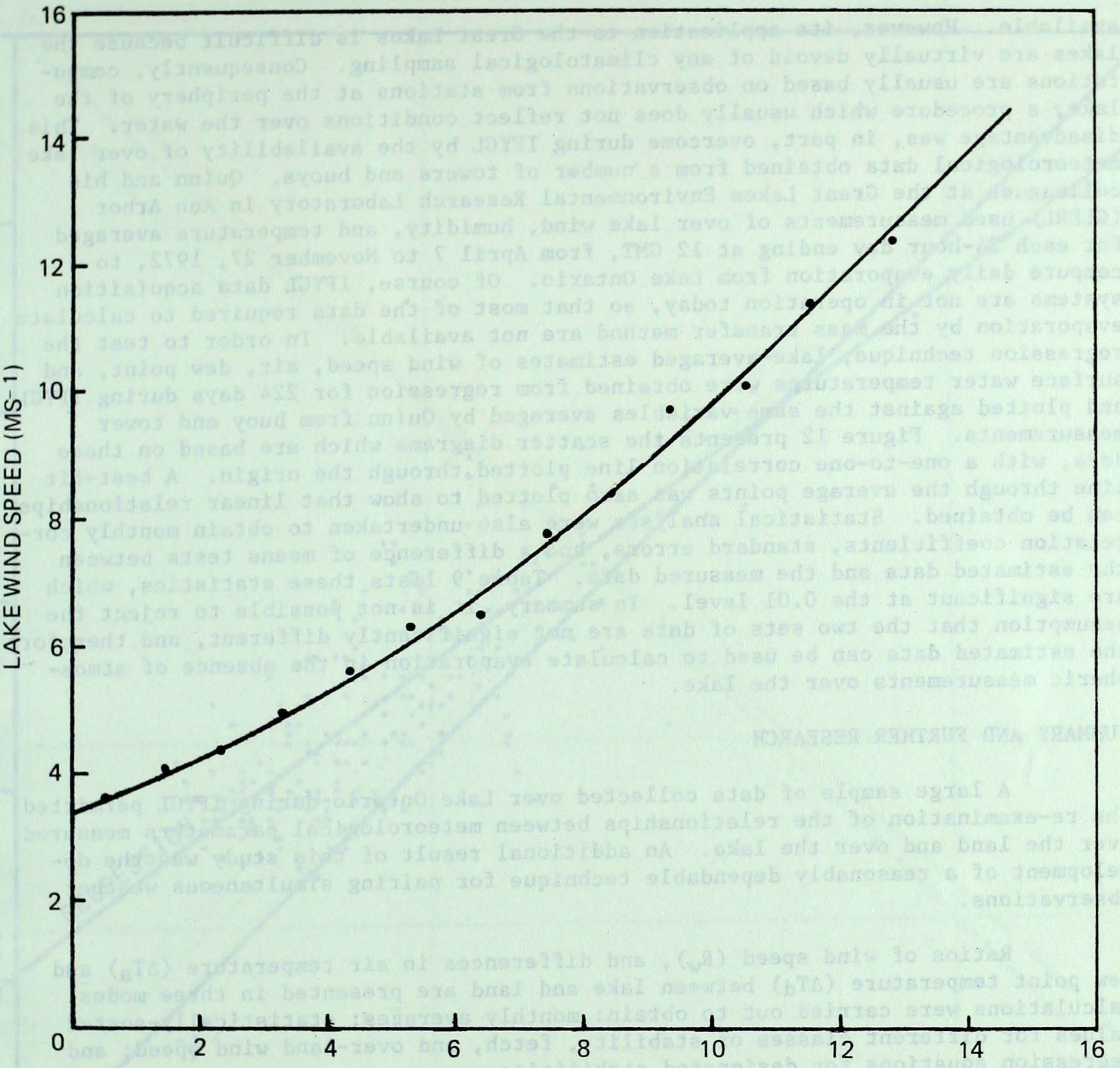

FIGURE 11 - Comparison of land wind speed by one metre sec^{-1} intervals and the average lake wind speed corresponding to each interval

available. However, its application to the Great Lakes is difficult because the lakes are virtually devoid of any climatological sampling. Consequently, computations are usually based on observations from stations at the periphery of the lake, a procedure which usually does not reflect conditions over the water. This disadvantage was, in part, overcome during IFYGL by the availability of over lake meteorological data obtained from a number of towers and buoys. Quinn and his colleagues at the Great Lakes Environmental Research Laboratory in Ann Arbor (GLERL) used measurements of over lake wind, humidity, and temperature averaged for each 24-hour day ending at 12 GMT, from April 7 to November 27, 1972, to compute daily evaporation from Lake Ontario. Of course, IFYGL data acquisition systems are not in operation today, so that most of the data required to calculate evaporation by the mass transfer method are not available. In order to test the regression technique, lake-averaged estimates of wind speed, air, dew point, and surface water temperatures were obtained from regression for 224 days during IFYGL and plotted against the same variables averaged by Quinn from buoy and tower measurements. Figure 12 presents the scatter diagrams which are based on these data, with a one-to-one correlation line plotted through the origin. A best-fit line through the average points was also plotted to show that linear relationships can be obtained. Statistical analyses were also undertaken to obtain monthly correlation coefficients, standard errors, and a difference of means tests between the estimated data and the measured data. Table 9 lists these statistics, which are significant at the 0.01 level. In summary, it is not possible to reject the assumption that the two sets of data are not significantly different, and therefore the estimated data can be used to calculate evaporation in the absence of atmospheric measurements over the lake.

8 SUMMARY AND FURTHER RESEARCH

A large sample of data collected over Lake Ontario during IFYGL permitted the re-examination of the relationships between meteorological parameters measured over the land and over the lake. An additional result of this study was the development of a reasonably dependable technique for pairing simultaneous weather observations.

Ratios of wind speed (R_w), and differences in air temperature (ΔT_a) and dew point temperature (ΔT_d) between lake and land are presented in three modes. Calculations were carried out to obtain: monthly averages; statistically-sorted values for different classes of stability, fetch, and over-land wind speed; and regression equations for designated stabilities.

Generally, the results of this study are similar to those obtained by previous investigators, although the new values are less erratic and their standard deviations are smaller, compared to earlier works. The wind ratio (R_w), with an average value of 1.53 for all data, was found to have a strong dependence on stability, fetch distance and land wind speed.

Average ΔT_a and ΔT_d were 0.48 and -0.56 degrees C, respectively. Final multiple regression equations formulated from a potential list of 20 independent variables explained as much as 98% of the variance. Independent testing of the regression equations was done on a sample of data collected from buoys and towers during IFYGL.

It is doubtful whether additional pairing of meteorological observations obtained on Lake Ontario during IFYGL, more rigorous statistical analyses will

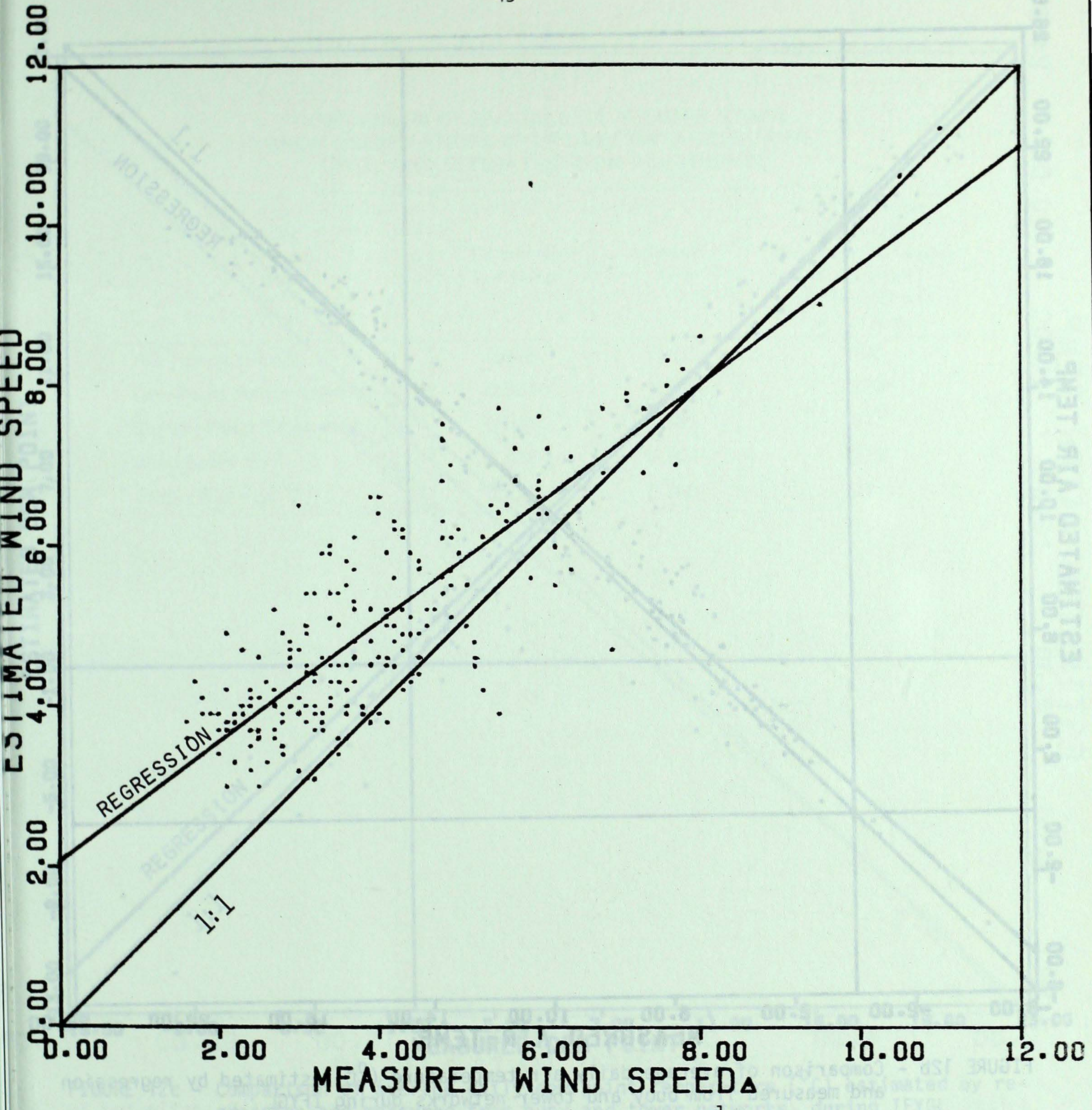

FIGURE 12a - Comparison of average daily wind speed (ms^{-1}) estimated by regression and measured from buoy and tower networks during IFYGL

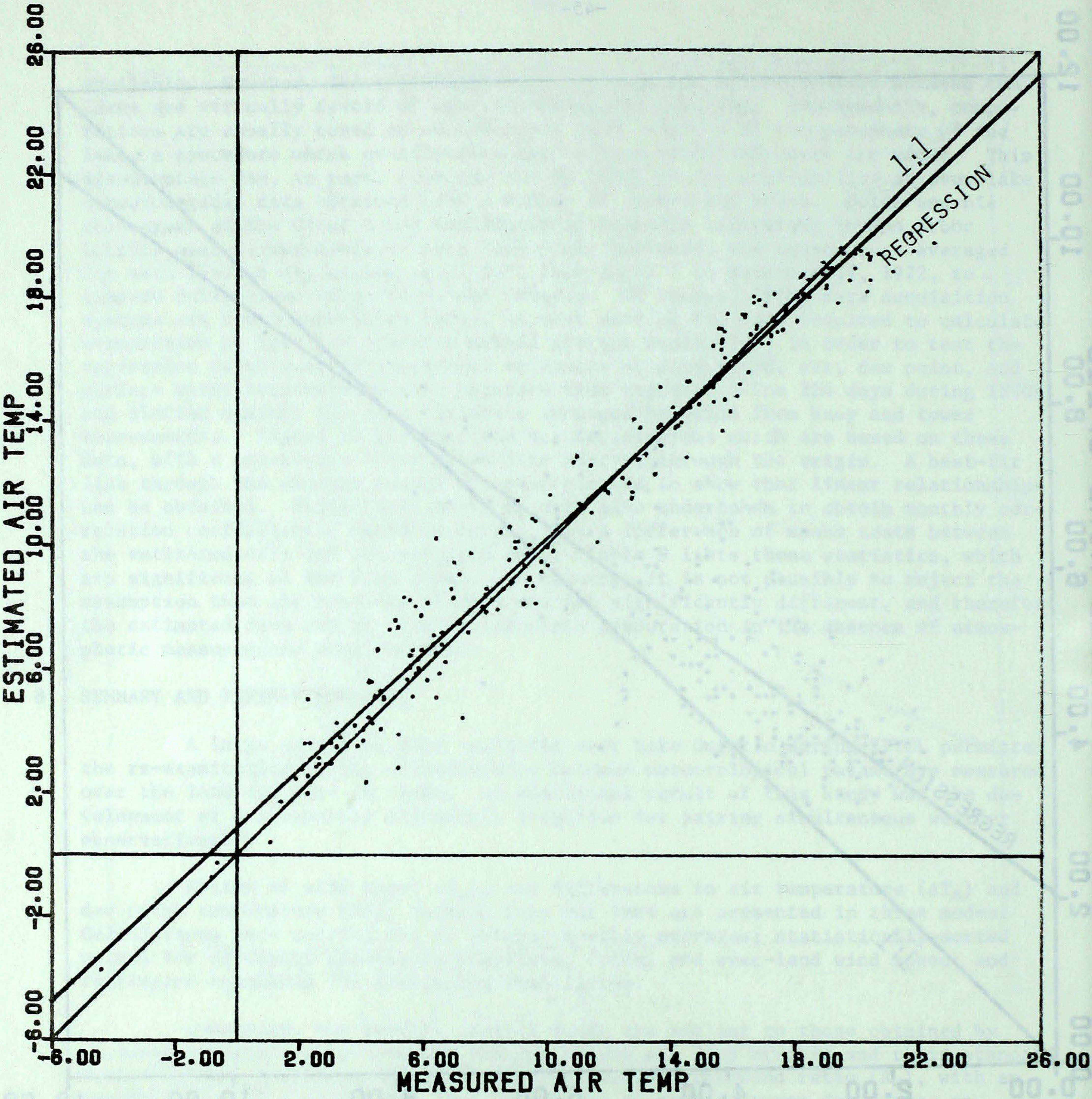

FIGURE 12b - Comparison of average daily air temperature (^{o}C) estimated by regression and measured from buoy and tower networks during IFYGL

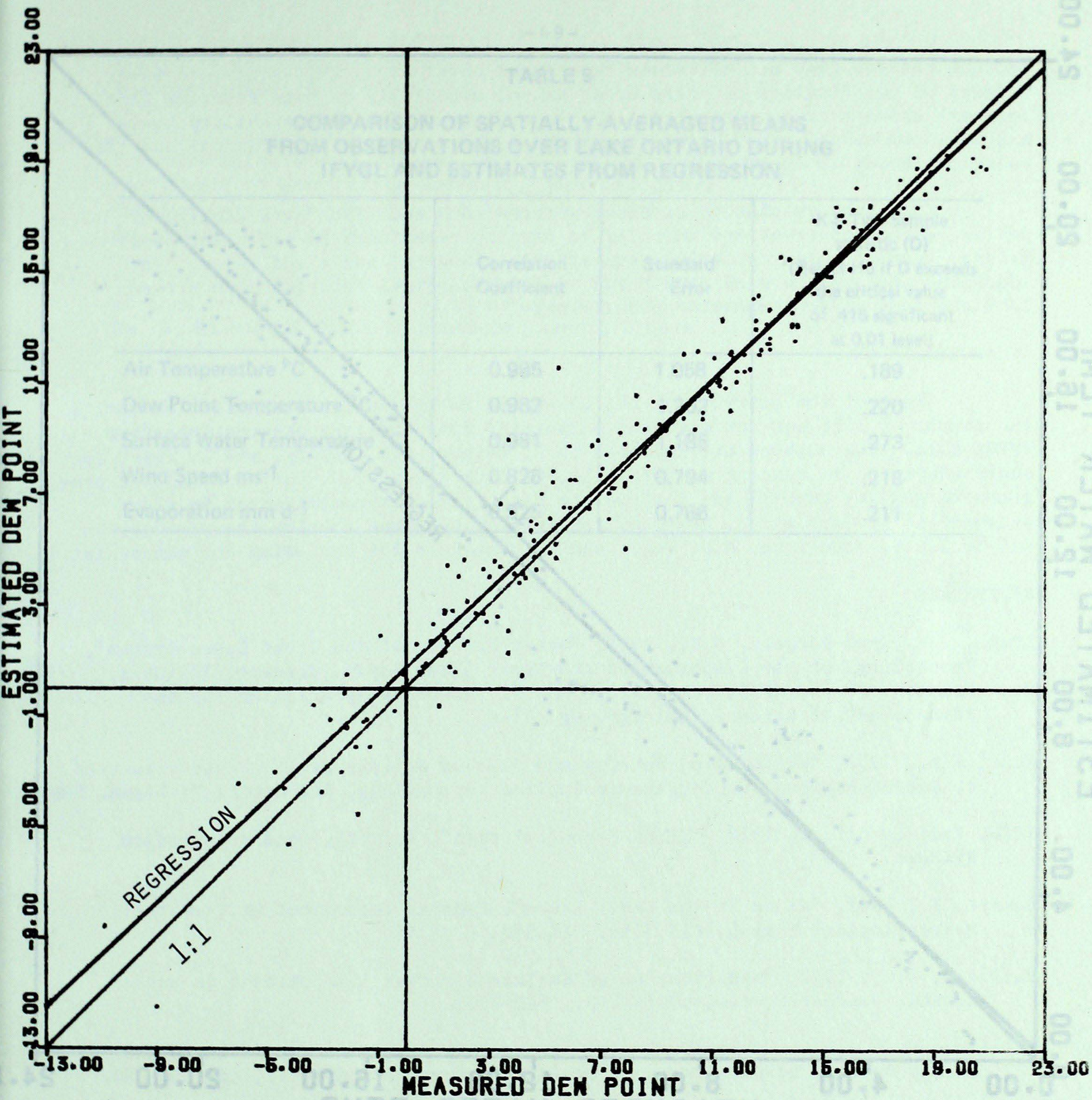

FIGURE 12c - Comparison of average daily dew point temperature (^{o}C) estimated by regression and measured from buoy and tower networks during IFYGL

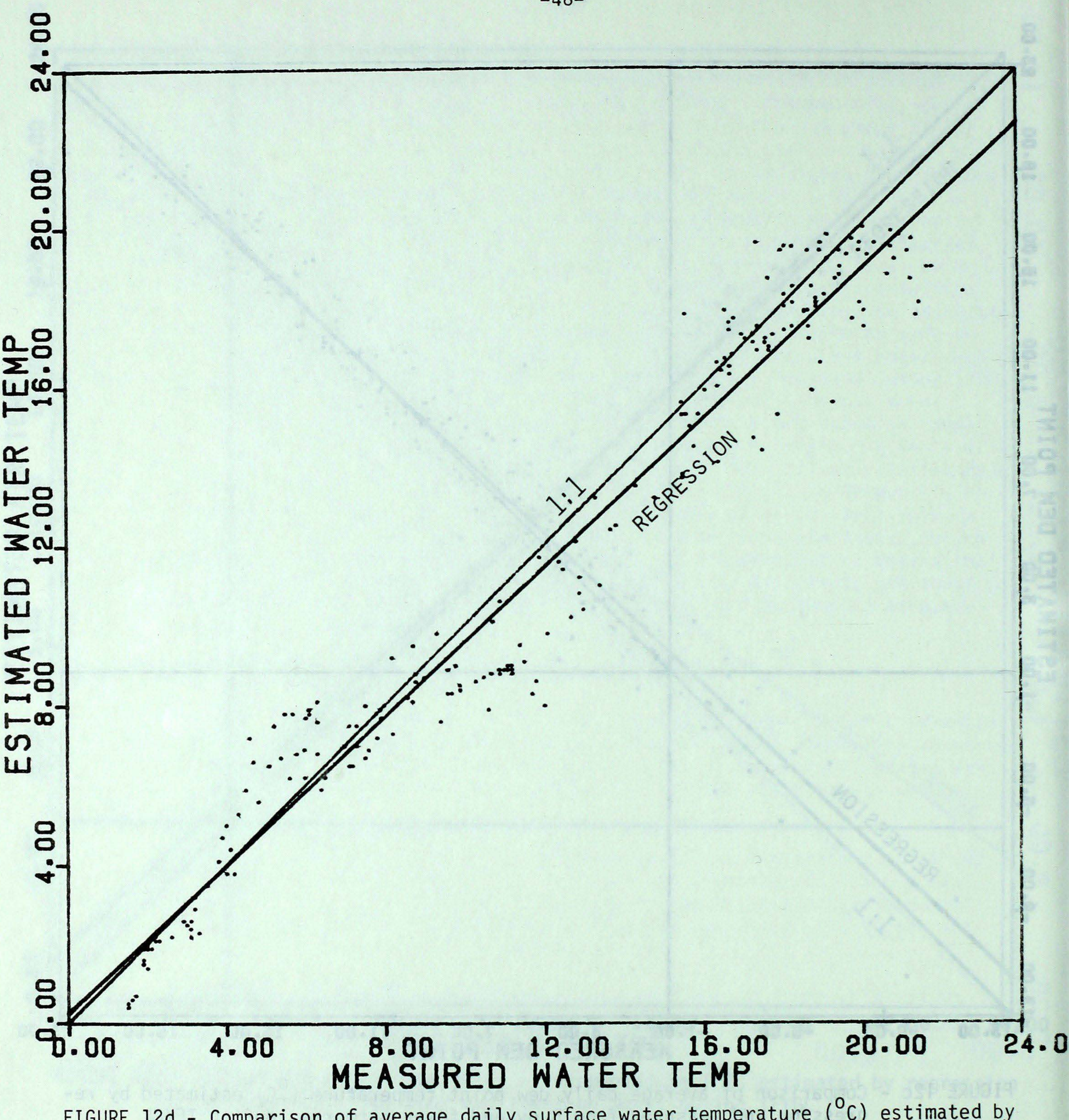

FIGURE 12d - Comparison of average daily surface water temperature (^{o}C) estimated by ART analysis and measured from buoy and tower networks during IFYGL

TABLE 9

COMPARISON OF SPATIALLY-AVERAGED MEANS FROM OBSERVATIONS OVER LAKE ONTARIO DURING IFYGL AND ESTIMATES FROM REGRESSION

	Correlation Coefficient	Standard Error	K-S Two Sample statistic (D) (Reject Ho if D exceeds the critical value of .415 significant at 0.01 level)
Air Temperature °C	0.985	1.058	.189
Dew Point Temperature °C	0.982	1.262	.220
Surface Water Temperature °C	0.981	1.185	.273
Wind Speed ms^{-1}	0.826	0.794	.218
Evaporation mm d^{-1}	0.925	0.766	.211

produce results that are different from those obtained in this study. However, testing of the findings on other Great Lakes, especially on Lake Superior (the largest) appears to be warranted. The technology of limited-capability buoys has advanced to the point where year-round deployment of meteorological and limnological buoys is feasible.

The authors plan to continue working with the IFYGL data archive of paired weather observations in order to develop relationships for other parameters, such as solar radiation, atmospheric pressure, and cloud cover. In addition, analyses have already begun of climatological relationships between lake and land under light-wind situations.

9 ACKNOWLEDGEMENTS

Much of the activity of the Lakes and Marine Applications Section during the summer of 1976 was concentrated on pairing land and lake observations from IFYGL data. The authors are indebted to E. Veinot, D.G. Massey, and L. Tozer for their adeptness in testing more than 10,000 data sets. T.H. Cutler developed programs to quality control and analyze the data file. Acknowledgement is also extended to D. Carr and J. Donegani for writing routines to plot the many graphs and to J.A.W. McCulloch, M.S. Webb, and S. Venkatesh for reviewing the manuscript.

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