FORECASTING THE LAKE BREEZE AT CLEVELAND HOPKINS INTERNATIONAL AIRPORT

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1. INTRODUCTION

The prediction of a lake breeze is important to several areas of meteorology. The aviation forecaster can alert the aviation community of impending wind changes. The marine forecaster can let recreational boaters and fishermen know if the winds are likely to become onshore (Munn 1966), and the public forecaster can use the information to make adjustments to the wind and temperature forecasts.

2. BACKGROUND

Forecasting a lake breeze can be a dilemma for meteorologists. Because of the many factors involved, and the lack of a mesoscale observing system, the task becomes difficult. The problem basically boils down to the question: "Will the mesoscale forces be strong enough to overpower the synoptic scale forces?"

Cleveland Hopkins International Airport (CLE) is about 6 miles from the Lake Erie shoreline, which is well within the normal range of a lake breeze penetration (Humphreys 1929). Once the lake breeze sets in, temperatures begin to fall, usually by about 5°F, depending on the time of year and strength of the lake breeze. The lake breeze always hits downtown Cleveland first since it is located right on the shoreline. There is often a difference of 5-10°F between the city (which is colder) and the airport until the lake breeze reaches the airport. Hence, the zone forecast during the spring will often read "cooler near the lake" when a lake breeze is expected.

At Hopkins, the main runway, R05/23, is 9000 feet long and is used most of the time. However, when the winds blow from north northwest to north northeast at speeds greater than 12 knots, runway R18/36 is used. This runway is only 6400 feet long. According to the local FAA, when R18/36 is used the FAA personnel in the Tower and Approach control (TRACON) must "thin the traffic out." This may cause some minor delays for arrivals and departures. Flying conditions are almost always VFR for these situations, except for possibly some cumulus clouds based at 2,000 to 3,000 ft, and/or visibilities 3-5 miles in haze.

3. METEOROLOGICAL CONDITIONS

The lake breeze most frequently occurs during the spring, when the temperature gradient along the lakeshore can become quite strong. The lake temperature starts

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off at 33°F in early spring, rises to around 60°F by the end of spring, and into the mid 70's by the middle of summer. At the same time, air temperatures over the land can be significantly warmer. These temperature gradients are usually strongest when high pressure is over or just east to southeast of Lake Erie.

The synoptic scale conditions are usually such that a surface high is located east to southeast of Ohio with a weak pressure gradient across the lake, skies are mostly sunny, and the gradient winds are southeast to southwest and less than 15 knots. These conditions cause the nearshore landmass to warm considerably, resulting in a heat source, while the lake acts as a heat sink (Hess 1959). The warmer air over the land expands, bending the isobaric surfaces upward, and air flows out over the lake from the upper surface of the expanding air. This shallow layer of air is then cooled by the colder lake causing it to sink and drift toward land (Haurwitz 1941). The effect of this partial convectional circulation is a decrease of pressure over the land, and an increase of pressure over the lake (Haltiner 1957). The mesoscale flow from the surface high over the lake to the inland surface low is the lake breeze (Figure 1). This phenomena generally extends 10 to 25 miles inland, depending on the strength of the circulation (Humphreys 1929).

The circulation theorem can be used to describe a lake breeze. Circulation is simply a parameter which measures the rotational tendency of a fluid, or in this case, the atmosphere (Hess 1959). The theorem describes relationships between cyclonic (anticyclonic) rotation and convergence (divergence). These relationships can be applied to the lake breeze.

The potential wind speed of the lake breeze can be computed by use of the circulation theorem and the ideal gas law (Holton 1979) as follows:

$$\frac{dC}{dt} = -\oint RT \ln P$$

where C represents the circulation around a circuit; R is the gas constant; T is the temperature; and P is the pressure. Integrating the right hand side of this equation yields:

$$\frac{dC}{dt} = R \ln\left(\frac{P_0}{P}\right)(\overline{T_2} - \overline{T_1})$$

where P_o is the surface pressure; P is the pressure at some height h; $\overline{T_1}$ is the mean temperature over the land; and $\overline{T_2}$ is the mean temperature over the lake. If $\overline{V}$ is the mean tangential velocity along the circuit in Figure 1, then,

$$\frac{d\overline{V}}{dt} = \frac{R \ln(P_0/P)}{2(h+L)}(\overline{T_2} - \overline{T_1})$$

where L is the distance between the center of convergence over the land and the center of divergence over the lake. V at CLE usually ranges between 10 and 15 knots.

The circulation of the lake breeze is usually no more than 800 to 1200 feet deep, and extends inland 10 to 30 miles. Knowing the depth of this circulation cell could be important to the small aircraft (Cessna's, Piper's, etc.) making approaches and departures from the airport. The change in wind direction usually does not affect larger jet aircraft, since the mean velocities within the circulation are only around 15 knots. This information can be made readily available to the TRACON units. The depth of the lake breeze cell can be calculated by using the equation of state, and making certain assumptions.

If ϱ is the density of the air, then,

$$-dP = \varrho g h$$

From the equation of state,

$$P = \varrho RT$$

Substituting for ϱ :

$$-dP = \frac{Pg}{RT}dh, \quad or \quad -\frac{dP}{P} = \frac{g}{RT}dh$$

Integrating from (P_0,h_0), where h_0 equals zero, to (P,h), and as a first approximation, assuming T is independent of height:

$$-\int_{P_0}^{P}\frac{dP}{P} = \frac{g}{RT}\int_0^h dh, \quad or \quad \ln\frac{P}{P_0} = -\frac{gh}{RT}$$

But the lake breeze ceases at the level where the barometric pressure above the land is the same as that above the water, or where dP = 0 when h is constant. This height, or top of the lake breeze circulation can be found by differentiating the previous equation. Thus,

$$dP = dP_0\left(\frac{P}{P_0}\right) + \left(\frac{Pgh}{RT^2}\right)dT$$

Solving for h yields:

$$h = -\left(\frac{dP_0}{dT}\right)\left(\frac{RT^2}{gP_0}\right) \quad or \quad h \approx \left(\frac{|\Delta P_0|}{|\Delta T|}\right)\left(\frac{RT^2}{gP_0}\right)$$

But what we really want to know is: "At what level above the airport does the wind direction change?" As an approximation, we assume that the change in direction would usually occur at around 1/2h.

4. DISCUSSION

Data were collected from 118 days from 1987 through 1990 for synoptic situations that appeared to be conducive for lake breeze development. This was a subjective determination based upon past observations and experience. The data consisted of air and water temperatures, and sea level pressures, from the buoy in western Lake Erie, the surface temperatures and sea level pressures at Cleveland (CLE) and Detroit (DTW), and the sea level pressure at Pittsburgh (PIT).

Of the 118 cases, 78% produced a lake breeze, most of which occurred when the pressure gradient between Detroit and Pittsburgh was less than 2.5 mb, while 22% of the cases produced no lake breeze.

As a first guess to the problem and solution, an empirical approach was taken by plotting CLE's air temperature at the time the lake breeze commenced, against the corresponding lake temperature (Figure 2). The data points were clustered in such a way that some form of a regression equation seemed to be the obvious solution. The method of least squares was used to determine the best fit (Neter 1974), and the resulting regression equation was:

$$T_A = 1.08T_L + 9.93$$

where T_L represents the lake temperature, and T_A represents the air temperature at CLE when the lake breeze commences. The correlation coefficient was .94, and the standard deviation was about $\pm5°F$.

As a second step, a multiple regression was performed by using the pressure gradient between DTW and PIT as another variable. This was done theorizing that the lake breeze would initiate at a lower temperature when a smaller pressure gradient existed, and vice versa. This scenario was observed on many occasions, but not all of the time. There were cases when the pressure gradient was less than one half millibar, but the lake breeze didn't commence until an air temperature greater than the mean air temperature generated from the regression equation, T_A, was reached. The resulting multiple regression equation was

$$T_A = 1.06T_L + 2.57\Delta P_{DTW/PIT} + 8.46$$

The correlation coefficient for this equation was .95, or only about a 1% improvement over the single linear regression equation. The standard

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deviation turned out to be the same. Based upon these results, the more straight forward, single variable linear regression equation could be used operationally. The average time of occurrence of the lake breeze was 1700 UTC.

Almost all (93%) of the lake breeze cases occurred when the pressure gradient between DTW and PIT was less than 2.5 mb. There were only a few cases (7%) where a lake breeze occurred when the pressure gradient between DTW and PIT was greater than 2.5 mb, and less than 4.5 mb. When the pressure gradient between DTW and PIT was less than 2.5 mb, and no lake breeze occurred, the surface winds remained southerly at 8 to 12 knots. The reason for this remains unclear. When the pressure gradient between DTW and PIT approached 3 mb, the synoptic scale forces usually dominated the mesoscale forces. Lake breezes were not observed at CLE when the pressure gradient between DTW and PIT was greater than 4.5 mb. The mean pressure gradient along the regression line was 1.2 mb.

The benefits of knowing if a lake breeze is going to occur are threefold. First, the aviation forecaster can prepare the terminal forecast by incorporating the wind shift for the terminals close to the lake (e.g., CLE and possibly Erie, PA). This would alert the towers and approach control personnel of the impending situation so they could make any adjustments necessary for air traffic control into and out of the airports. Second, the public forecaster would be able to make adjustments for the afternoon high temperatures. For example, suppose the lake temperature is 50°F, and MOS (Carter et al. 1989) provides a forecast high of 75°F, the pressure gradient between DTW and PIT is less than 2 mb, and the surface winds are light and southerly on the backside of a high pressure area. The situation is conducive to a lake breeze which, from looking at Figure 2, would commence when the air temperature at CLE reached 62°F (±5°F). Thus, the max temperature is not likely to be much greater than 67°F. The forecaster can then go below MOS and make a better forecast (as well as improved verification scores), since the temperature usually remains constant or drops a few degrees once the lake breeze sets in. Third, the marine forecaster will be able to use the information to adjust the Nearshore Marine Forecast, if necessary, for the development of onshore winds.

Therefore, if a high pressure area is over, or just to the east of the Ohio Valley producing a pressure gradient less than 2.5 mb between DTW and PIT, one can assume there is a 78% chance that a lake breeze will occur. The public forecaster can enter Figure 2 at the current lake temperature, and go across to the regression line to determine what the air temperature at CLE will be (±5°F) when the lake breeze commences. This information can then be used to make adjustments to the forecast. The aviation forecaster can enter the windshift into the CLE FT, and the marine forecaster can put onshore winds in the nearshore marine forecast.

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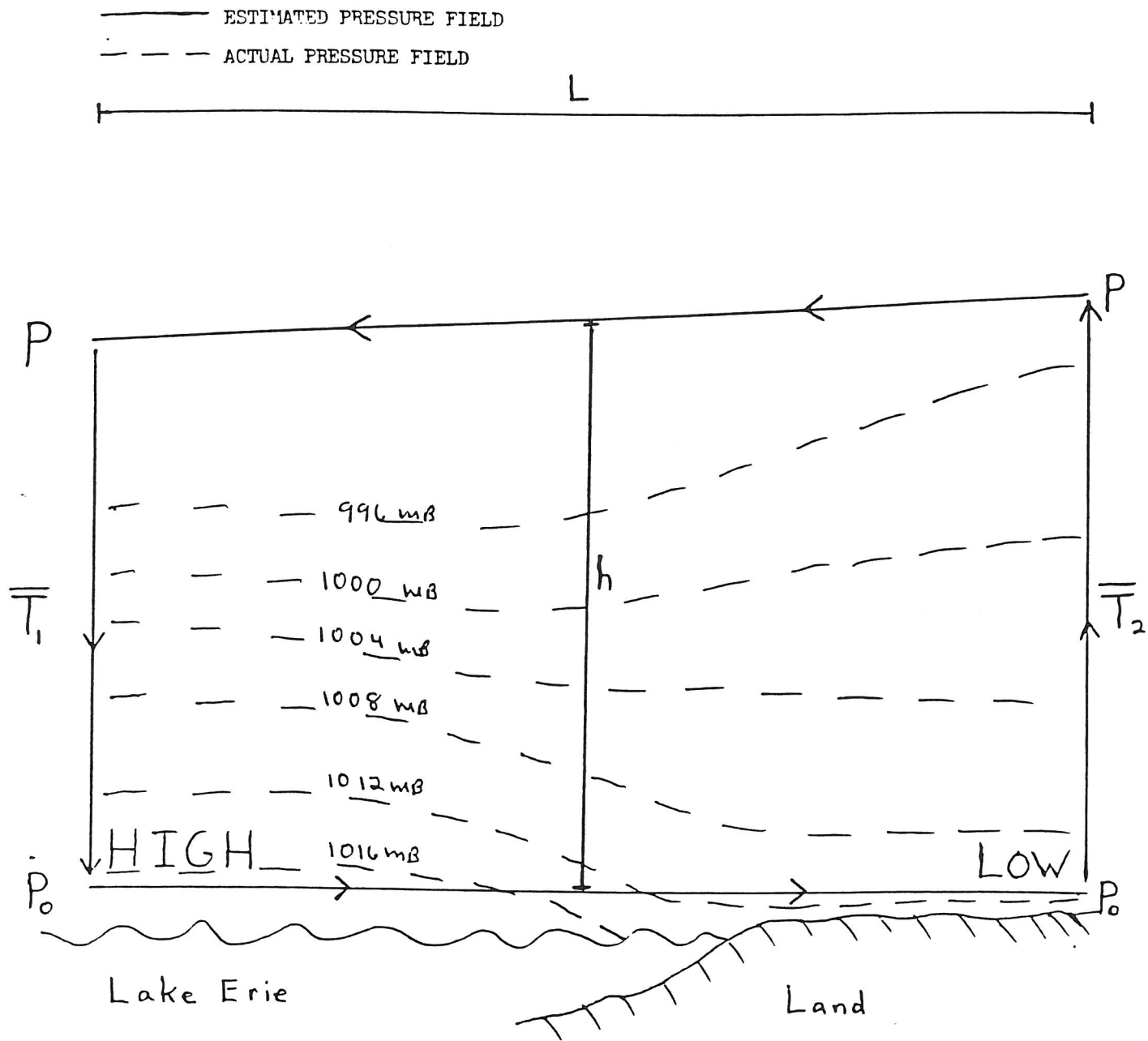
L

P   P

996 mB

1000 mB

$\overline{T_1}$ h $\overline{T_2}$

1004 mB

1008 mB

1012 mB

HIGH   1016 mB   LOW

P_o P_o

Lake Erie   Land

Figure 1. Schematic mesoscale lake breeze circulation (adapted from Holton 1979).
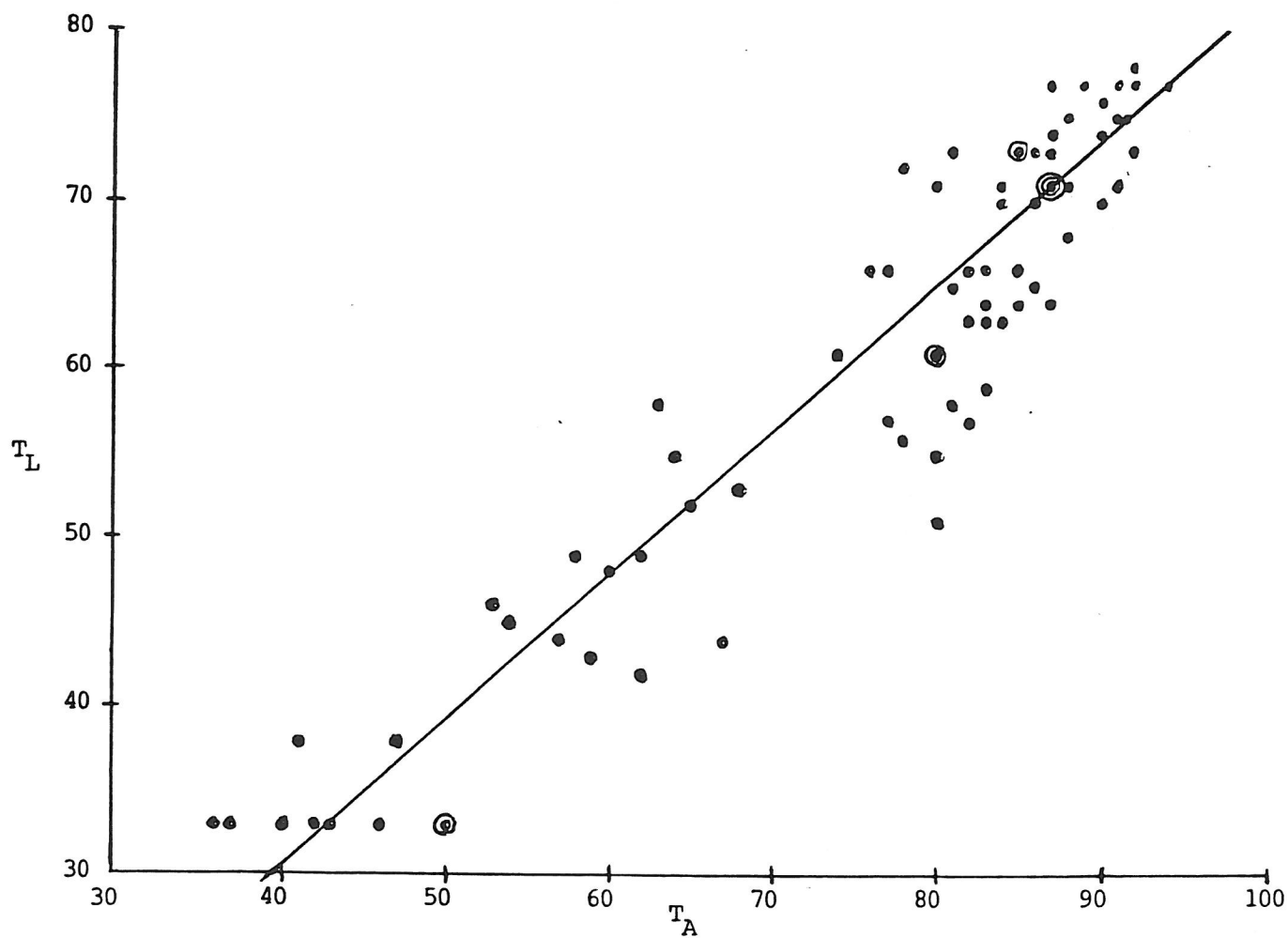
Figure 2. Observed lake temperature (T_L) vs. the corresponding air temperature (T_A) when the lake breeze commences (1987-1990).