Diurnal Patterns in Lifted Index and the Prediction of Severe Weather

Jay Anderson (1)
Pacific Weather Centre
200-1200 W 73rd Ave
Vancouver, B.C.
Canada, V6P 6H9

ABSTRACT

The combination of hourly surface data and model-derived upper air temperatures can be used to construct lifted indices with a greater temporal and spatial resolution than that offered by the radiosonde network. These indices have a diurnal and seasonal variation which suggests considerable utility in the prediction of severe convection, with a lead time of several hours.

Monthly and seasonal means were calculated from lifted indices collected at three hour intervals across central Canada during the 1985 summer convective season. Statistical tests showed a significant difference between means for days with and without severe weather. The percent of variance explained by the index peaked in the mid afternoon, at which time the index was significantly correlated with the frequency of thunderstorms with large hail and tornadoes. Similar relationships can be derived for other climatic regions to provide operational meteorologists with a valuable tool for monitoring the potential for hazardous thunderstorms.

1. INTRODUCTION

Atmospheric stability can be quickly characterized by the use of indices, some of which have found wide acceptance by operational forecasters. Among the most commonly used is the lifted index (2), which has shown some success in marking those environments which give rise to severe thunderstorms (3, 4, 5, 6). However the use of all indices has, until recently, been closely tied to the upper air observation network which provides the profiles of atmospheric temperature and moisture necessary for their calculation. This network is limited by its coarse spatial and temporal resolution, with stations many hundreds of kilometres apart making observations at 12 hour intervals. Actual and predicted lifted indices have been available from operational numerical models for a number of years as well, but these are not generally available at frequencies greater than every six hours, and tend to show a smoother field and more conservative values than those calculated from actual surface data, though they do have significant predictive value (3, 4, 6).

One method of ameliorating these limitations is to use hourly surface data in combination with model-derived upper air data to construct higher resolution maps of surface-based lifted indices. Similar maps in use at the National Severe Storms Forecast Center have been described by McCann *et al* (7), using advective rather than model-derived 500 millibar temperatures. To the operational forecaster, the difference between the two approaches is likely small in view of the smoothness of the temperature field in the middle troposphere.

The surface-based lifted index is particularly suited for a detailed look at instability as it can take advantage of the higher time and space density of surface observations of temperature and dewpoint. Indices such as the Total Totals, which uses only upper level data, are less useful in this respect since even with model data the resolution remains relatively low.

Once a higher resolution index is available, the temporal and spatial behaviour of the instability can be monitored by the operational forecaster. Several questions about the behaviour of the index then become of considerable interest to the user. When, for instance, does the instability decrease the most, and at what point should additional attention be directed to the most unstable regions? At what time does the index provide the most reliable indication of severe weather, and how well can the threat be followed through the rest of the day? This study attempts to provide a quantitative answer to these and other questions based on a systematic study of one summer's data.

2. NUMERICAL TECHNIQUE

The model output for this study was provided by the Spectral model developed at the Canadian Meteorological Centre (CMC) in Montreal (8, 9), and used operationally by Canadian forecasters. The model supplies grid point data at a 381 kilometre spacing across North America every six hours. This compares with a mean radiosonde spacing of 530 kilometres over the Canadian Prairies.

500 mb temperatures, and 850 and 1000 mb heights were linearly interpolated from the grid point data to the time of each surface observation. This was followed by interpolation in space to the location of the observation using Bessel's central difference formula (10, p. 252). Linear interpolation was then used to derive surface pressures from the 850 and 1000 mb heights. Interpolation using the hydrostatic equation would have been more precise, but errors were only 1 to 3 millibars as a result of the simpler approach (11). The use of altimeter settings to calculate actual surface pressures was rejected because Canadian automatic stations do not report them.

The index was calculated by lifting a surface-based parcel adiabatically to 500 mb with no mixing, and then subtracting the derived parcel temperature from the model environmental temperature at that level. The resulting calculations were displayed in a map format for 72 observing sites across western Canada and the north central United States (Fig. 1). The process could be initiated at any time by the operational forecaster; each new chart was available about 20 minutes past the hour when the surface data collection was complete.

New model data became available approximately 3-h after the 0000 and 1200 GMT synoptic hours, so that the old model run was used out to 15-h before being supplanted by the new. Some measure of the accuracy of the technique was obtained by comparing the indices calculated from the new and old model runs during the overlap. After 12-h, the Spectral model proved to have a small bias toward instability, giving lower lifted indices with the older model run than with the new. This was likely due to biases in the 500 mb temperature field, as surface pressure errors would have had to be unrealistically large to result in a trend of the calculated magnitude.

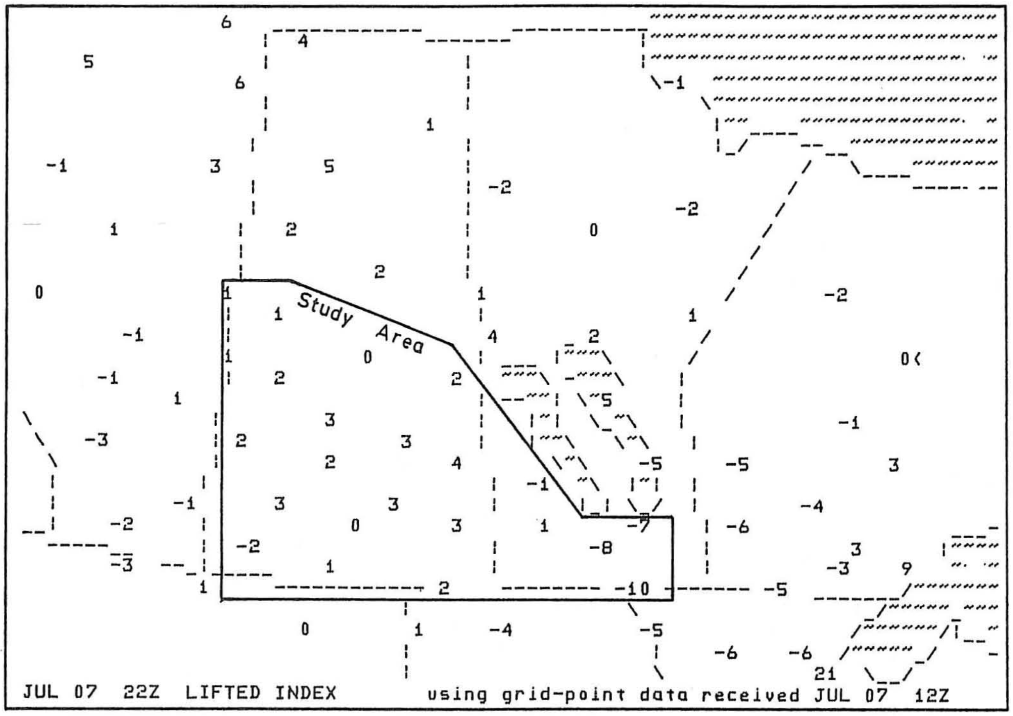

Fig. 1. Hourly lifted index chart for July 7, 1987. In this example +4 would be selected as the stable sample and −10 as both the unstable and severe weather sample.

The mean difference between the old and the new model runs after 12-h was −0.7°C, with no significant distinction between the means at 0000 and 1200 GMT. One-third of the differences were zero, and 81 percent were within 1 degree Celsius.

3. DATA COLLECTION AND ANALYSIS

Lifted indices were calculated, mapped and archived at three hour intervals from mid-May to the end of August 1985 (regardless of the occurrance of convection) to determine the diurnal behaviour of the instability and its relationship to severe weather. The sample size ranged from a low of 80 at 0900 GMT to 105 at 1200 GMT, being dependant on the successful receipt of grid point data, and the frequency at which operational staff ran the analysis. Areal coverage was generally confined to southern Saskatchewan and Manitoba, a relatively homogenous prairie regime within the area of responsibility of the Prairie Weather Centre in Winnipeg. Stations near the Manitoba lakes, where temperatures are influenced by the proximity of water (Fig. 1), were excluded.

To the operational forecaster, the behaviour of the lowest lifted indices was of primary interest, since it was expected that these would be most closely associated with the development of significant convective weather. In contrast, areas with high indices were the least likely to undergo deep convection. The mean value of the hourly lifted index of all 72 of the stations in the sample did not describe either of these regimes well, tending to hide the daily rise and fall of stability in the areal variation of lifted index across the two provinces.

For these reasons, only the highest and lowest lifted indices were collected from within the study boundary every three hours. These were respectively referred to as the stable and unstable samples. In Fig. 1, for example, the value selected for the unstable sample would have been the −10 over southern Manitoba, while that for the stable sample would be the +4 over eastern Saskatchewan (though the time in Fig. 1 is not one at which data were collected for this study).

Lifted indices for severe weather episodes were extracted by following the associated area of instability forward to 0600 GMT and backward to 0900 GMT and selecting the most unstable value from the area at each 3-h time period. The area associated with each severe weather report was determined subjectively after isopleths of lifted index had been drawn. This tracking of severe weather regions was possible because the areas of high and low lifted indices had a remarkable degree of temporal continuity, and in most cases could be readily followed as they moved from the western to the eastern side of the study area. The diurnal variation in lifted index tended to strengthen or weaken the values within a particular area, but did not create new stable or unstable regions which could not be traced to an earlier time.

On a few occasions, the lowest index values in an area associated with a severe weather report were located at stations outside of the study boundary. These values were accepted for inclusion in the severe weather sample, in contrast to those in the stable and unstable samples which were restricted strictly to the study area. In all cases, the severe weather event had to occur in southern Saskatchewan or southern Manitoba. In Fig. 1, the −10-value in southern Manitoba was associated with an occurrence of golf-ball sized hail and was thus incorporated into the severe weather sample (the value was −10 at 2100 GMT). Had the −10-value occurred at Grand Forks, North Dakota (−5 in Fig. 1), it would still have been accepted for inclusion in the severe sample, but then would not have been included in the unstable sample. It must be emphasized that the severe weather did not have to occur at the station with the lowest index, but only in association with the minimum in the lifted index field.

The relaxation of the boundary constraint meant that severe and unstable samples were collected from two regions which were not exactly coincident. This carried the risk that the underlying population for each of the samples was dissimilar enough that the difference between severe and unstable regimes found in this study was merely a reflection of the climatology of the two areas. This seems unlikely however, since only a few points at a few hours were selected from outside the boundary, and always from stations very close to the border. On a few occasions a low lifted index outside the boundary was later found to represent the environment within, but between reporting stations. This became apparent when indices fell at downstream stations as the area of instability moved onto them.

Reports of severe weather were collected from the synoptic station data, an extensive severe weather watcher network, from regional and local newspapers, and by forecaster initiated telephone calls to areas of concern identified on radar and satellite imagery. This "multi-media" collection system probably resulted in the identification of most of the damaging thunderstorm weather which occurred in the summer of 1985, though a residual sample of unreported events must certainly exist. Such limitations are a continuing problem in studies of severe convective weather.

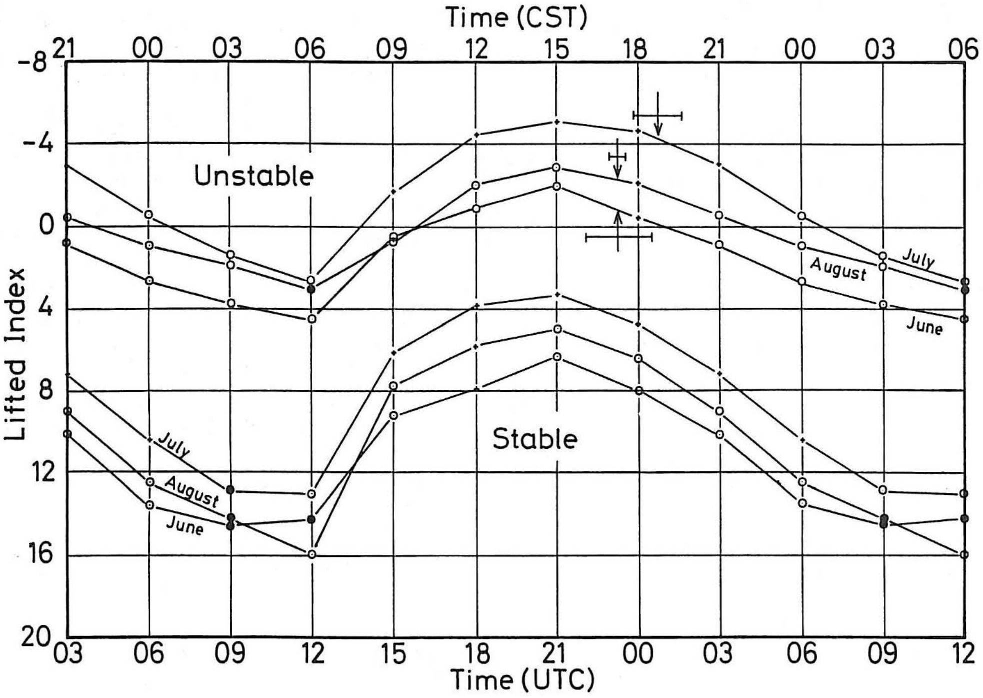

Fig. 2. Diurnal variation in lifted index by month. The unstable curves show the monthly means of the lowest lifted index values while the stable curves indicate the highest. Arrows mark the mean time of the first report of large hail or tornadoes for the severe weather days of each month. Error bars show +/− one standard deviation for the time of first report.

A total of 33 severe events (hail of golf ball size or large (20 mm), or tornadoes) were identified. Multiple events within the same area of instability were counted once, reducing the severe weather sample to 21 episodes. The time of each was confirmed by examination of the archived radar data, where such was available, and adjusted if necessary. In the case of multiple reports the onset time was that of the earliest event.

One severe weather event was rejected from the sample when its associated minimum blended with a second more unstable area which gave rise to its own severe weather event. The weaker area of instability could then no longer be identified by a separate closed lifted index isopleth. By the rules of selection used in this study, the same minimum would have to be associated with both events though they were separated by 500 kilometres in distance and 90 minutes in time. While a particular value for the weaker instability area could be extracted from the analysis, it was felt that such a value would be subject to an unwelcome amount of subjective interpretation and so it was excluded from the statistics.

Seasonal mean lifted indices for the severe and unstable samples were compared using a t-test (12), with significance accepted at p = .05. Lifted indices for days with severe weather were removed from the unstable sample in order to maximize the independence of the two groups. A simple Fourier analysis (12) was performed on the mean lifted indices for severe weather days to determine the time of day at which the index was most unstable. Results are presented in the following section.

4. RESULTS

Fig. 2 presents the diurnal pattern of stability for June, July and August. July was the most unstable month, followed by August and June. This pattern is mostly a reflection of the hours of daylight, the warming of the lower atmosphere through summer, and the advection of moisture northward as southerly winds become more established through the troposphere.

The stable sample had a larger amplitude of variation than the unstable, possibly because of the increased cloudiness which would tend to accompany convective areas and reduce the diurnal swings in temperature. Stability decreased most between 1200 and 1500 GMT (6 to 9 am CST), allowing threat areas to be recognized by mid morning when initial outlooks for the day were issued from the Prairie Weather Centre in Winnipeg.

The plot symbols used in Fig. 2 indicate whether or not the sample means were significantly different from each other at each time period. A cross indicates that the point in question was significantly different (at p = .05) from the other two points, an open circle that it was significantly different from one of its neighbors, and a solid circle that no significant difference was found with either of the other points. The exact relationship of each mean to the others can be ascertained by inspection of the graph; at 2100 GMT for instance, August and June were not significantly different, while July was, on average, significantly more unstable than the other two.

Arrows along the unstable curves show the mean time of the first report of hail or tornadoes for the severe weather days of each month. Errors bars associated with each arrow are +/− one standard deviation.

Fig. 3 shows the diurnal trend in stability for all months combined, as well as that for areas of instability which resulted in severe weather. The mean lifted index for severe weather days was significantly different from the unstable sample means at the p = .02 level for all hours. This result, along with the temporal continuity in the pattern of lifted indices outlined earlier, suggests that areas of severe weather potential may be identifiable through much of the day, though with less success in the morning hours than in the afternoon. The percent of variance between the two samples which was explained by the lifted index (determined by eta-squared, the strength-of-association statistic used with t-tests (13)) varies from a high of 32% at 2100 GMT (3 pm CST) to a low of 7% at 0900 GMT. Since the data for severe weather days was removed from the sample for unstable conditions, eta-squared in effect measured the ability of the lifted index to distinguish between unstable areas with severe weather and those without.

Fourier analysis of the severe weather means showed a peak just before 2200 GMT (4 pm CST) for the first harmonic, and a corresponding minimum before 1000 GMT. This confirms speculation by David and Smith (3) that 0000 GMT is not the best time of day for the lifted index. The mean time of the beginning of severe weather is shown by the arrow just after 0000 GMT (Fig. 3), suggesting that an hourly lifted index could offer a few hours lead time in the forecasting of hazardous thunderstorms over the Canadian Prairie.

Since the greatest resolution between areas of instability which did and did not produce severe weather occurs at 2100 GMT in the data collected for this study, it was selected to test the predictive abilities of the hourly lifted index. Fig. 4 is a plot of the frequency of severe weather versus 2100 GMT lifted index. No values above −2 were associated with reports of large hail or tornadoes. Lifted indices lower than −8 were recorded on 6 occasions, of which 5 resulted in a severe weather report. The remaining event was associated with damaging winds in North Dakota, outside of the study boundary. Since wind speeds are difficult to quantify from public reports, they were excluded from consideration in this study.

The straight line on the graph is the least squares fit to the data. While a straight line fit is uncomfortable in that it predicts both a zero and 100 percent probability of severe weather, a second-order polynomial fit had a nearly identical explained variance, and a third-order curve had a tendency to turn sharply downward at low lifted indices. A straight line fit was the most appropriate for the limited sample in this study.

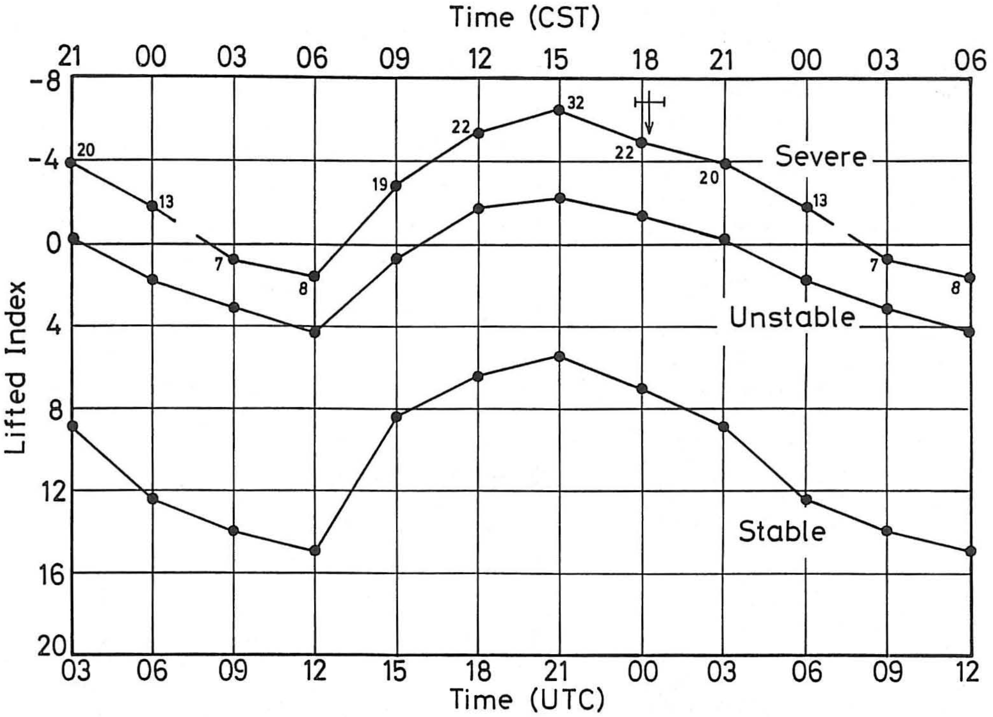

Fig. 3. Diurnal variation in lifted index for the 1985 convective season. The severe curve indicates the occurrence of large hail or tornadoes followed forward to 0600 GMT and backward to 0900 GMT. The unstable and stable curves are similar to those in Fig. 2 except that severe weather days, have been removed from the unstable sample. The arrow marks mean time of first report of occurrence, with error bars showing +/− one standard deviation. Numbers are the percent of variance between the severe and unstable curves explained by the lifted index.

5. FORECAST IMPLICATIONS

The area used in this study was large enough that it almost always contained at least one region of closed isopleths of low lifted indices. The results and techniques above allow the severe weather potential for those regions to be quickly assessed, with a degree of certainty which depends on the time of day. It need not be limited to severe weather potential: with an appropriate database one could assess the potential for the development of convection, the amount of lightning, or any other stability-related meteorological parameter. While the percent of variance explained is rather low, it should be noted that this study attempts to identify the potential for severe weather between areas which already have considerable instability. Had the statistics been developed on samples which included the stable areas, the explained variance would have been considerably greater, at the expense of the utility of the information on the forecast desk. The ability of only three of the many parameters which make up the severe weather environment (low level moisture, and low and mid level temperature) to explain one-third of the variation in the samples is an encouraging measure of the value of greater time and space resolution of critical fields.

Fig. 4 suggests that a 2100 GMT lifted index of −6 to −7 is associated with a severe weather probability of 50% on the Canadian Prairies, provided the sample collected in 1985 was an accurate reflection of the climatology of severe weather events in other years. A prudent forecaster would probably consider the possibility of a severe weather watch at this point, if other factors were favourable. Severe weather warnings could be issued when the index reaches −9 or −10, if the forecaster was faced with corroborating evidence such as radar or satellite imagery. The watch or warning should not be removed when the lifted index begins to fall, but held for at least three hours if other factors remain strong. Prairie Weather Centre forecasters had a number of successful watches and warnings with generous lead times during the late part of the 1985 severe weather season when these relationships became apparent.

The hourly lifted index is not a panacea for the ills of severe weather meteorology. The site of the event was often not at the station with the lowest index, though usually nearby. Trough lines, fronts, moisture, and other triggers remain critical to the successful forecasting of the severe weather environment. These statistics were based on a regional sample for only one year, and can only be used with confidence on the northern plains. Other climatic regimes would have to develop a comparable data set of their own. The significant differences between monthly mean lifted indices for many hours (Fig. 2) suggest that seasonal graphs may have to be developed for best resolution of the severe weather threat.

Nevertheless, a higher resolution lifted index allows the duty meteorologist to monitor the severe weather potential quickly in a work environment which requires attention to many other tasks. When presented as a map, it draws attention to critical areas, or areas in which the instability is changing rapidly. The diurnal trends presented here can be used to predict the behaviour of the lifted index in succeeding hours, and identify areas which are becoming more stable or unstable than the normal climatological pattern.

6. SUMMARY AND POTENTIAL

Operational numerical models in use in Canada and the United States can be partnered with surface observations to provide more timely lifted indices for short range forecasting. Such indices are capable of distinguishing between areas of severe weather potential and those of more benign temperament.

Scatter diagrams were readily developed to reflect the probability of severe weather events. Such diagrams would have to be tuned to the season and the model used, but offer a ready method of following the movement and development of threat areas (a potential available only from geostationary satellite sounding data at present). Lead times of several hours are possible.

The combination of model and actual data can be greatly extended by merging data at many more levels than the surface and 500 mb, particularly since high vertical-resolution models have recently become operational in Canada and the United States. Reasonable soundings through the depth of the atmosphere can be constructed, and factors such as positive area, hail size potential, tropopause penetration, and the strength of the capping inversion can be calculated and mapped, all at the scale of the surface observation network, for each hour of the day. Such work has been suggested by Stone (14) and is now underway at the Prairie Weather Centre. When combined by multiple regression or similar statistical ensembles, it holds promise of a greatly enhanced ability to predict the short term development of severe thunderstorms.

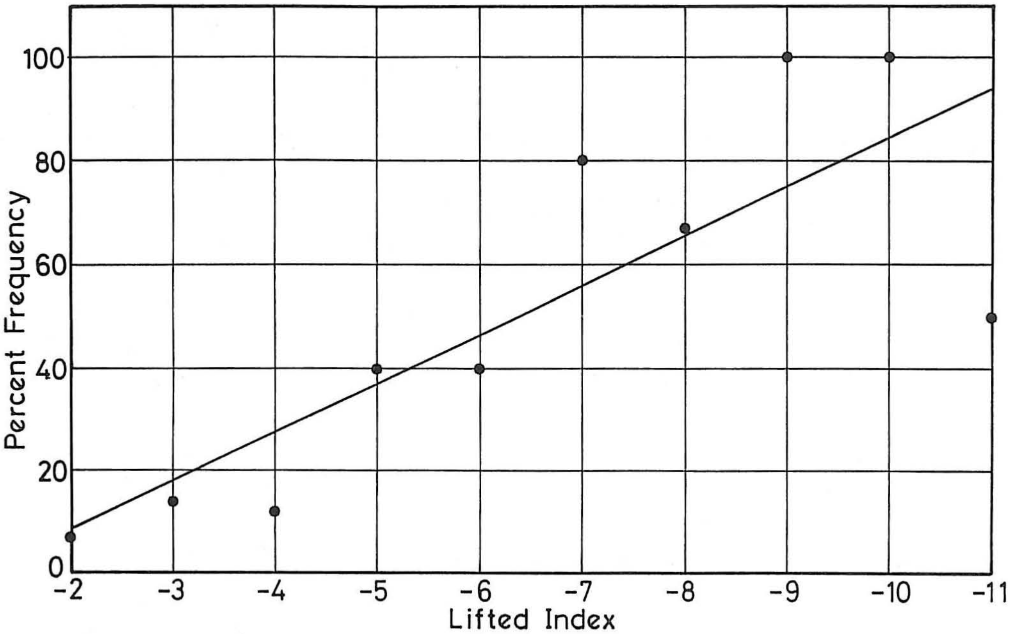

Fig. 4. Percent frequency of weather as a function of 2100 GMT surface lifted index. The straight line is the least square fit to the data; its equation is freq. = −.100 − .094 (LI). The correlation coefficient is .81.

ACKNOWLEDGEMENTS

I would like to thank Dave Patrick at the Prairie Weather Centre, who did the programming to extract the lifted indices from the model grid-point data, and who provided useful comments during the development of this study. Rick Raddatz provided many useful suggestions to improve the first draft of the paper.

NOTES AND REFERENCES

1. Jay Anderson is a physics and astronomy graduate of the University of British Columbia and is currently employed as a meteorologist at the Pacific Weather Centre in Vancouver. Prior to his move to Vancouver, he worked for 11 years as a meteorologist at the Prairie Weather Centre in Winnipeg. During the summer of 1985 he was a severe weather forecaster in Winnipeg. He has been a member of the NWA since November 1985.

2. Galway, Joseph G., 1956: The lifted index as a predictor of latent instability. Bull. Amer. Meteor. Soc., *37, 528–529.*

3. David, Clarence L. and John S. Smith, 1971: An evaluation of seven stability indices as predictors of severe thunderstorms and tornadoes. Preprint Volume, 7th Conference on Severe Local Storms, *(Kansas City, MI), Amer. Meteor. Soc., Boston, pp. 105–109.*

4. Anderson, Jay, 1985: The climatology of severe thunderstorms over Central Canada in 1985. Preprint Volume, First Workshop on Operational Meteorology, *(Winnipeg, MB), Atmos. Environ. Service/Cdn. Meteor. and Oceanog. Soc., Winnipeg, MB, pp. 123–130.*

5. Taylor, G. E. and G. L. Darkow, 1983: The unique structure of the atmosphere in areas of subsequent tornado bearing storm development. Preprint Volume, 13th Conference on Severe Local Storms *(Tulsa, OK), Amer. Meteor. Soc., Boston, pp. 296–299.*

6. Stone, Hugh M., 1986: A comparison among various thermodynamic predictors of convection. Preprint Volume, 11th Conference on Weather Forecasting and Analysis, *(Kansas City, MO), Amer. Meteor. Soc., Boston, pp. 241–246.*

7. McCann, Donald W., Edward L. Ferguson, Melvin D. Mathews, Steven J. Weiss, Anthony L. Siebers, and Jeffrey L. Hobson, 1983: Recent technical advances at the National Severe Storms Forecast Center that will improve short term aviation advisories. Preprint Volume, 9th Conference on Aerospace and Aeronautical Meteorology, *(Omaha, NE), Amer. Meteor. Soc., Boston, pp. 101–105.*

8. Daley, Roger, Claude Girard, John Henderson, and Ian Simmonds, 1976: Short-term forecasting with a multi-level spectral primitive equation model. Part I—Model formulation. Atmosphere, *14, 98–116.*

9. Daley, Roger, Claude Girard, John Henderson, and Ian Simmonds, 1976: Short term forecasting with a multi-level spectral primitive equation model. Part II—Hemispheric prognoses and verification. Atmosphere, *14, 117–134.*

10. Haltiner, G. J., 1971: Numerical Weather Prediction. *John Wiley and Sons, Inc., New York, 317 pp.*

11. Patrick, David, 1986: Private communication. Atmospheric Environment Service, Prairie Weather Centre, 900-266 Graham Ave., Winnipeg, MB, Canada, R3C 3V4.

12. Panofsky, Hans A., and Glenn W. Brier, 1968: Some Applications of Statistics to Meteorology. *Earth and Mineral Sciences Continuing Education, The Pennsylvania State University, University Park, PA, 224 pp.*

13. Linton, Marigold and Philip S. Gallo, Jr., 1975: The Practical Statistician: Simplified Handbook of Statistics. *Brooks/Cole Publishing Co., Monterey, CA, 384 pp.*

14. Stone, Hugh M., 1984: The energy index for stability. Preprint Volume, 10th Conference on Weather Forecasting and Analysis, *(Clearwater Beach, FL), Amer. Meteor. Soc., Boston, pp. 550–554.*