ITWS MICROBURST PREDICTION ALGORITHM PERFORMANCE, CAPABILITIES AND LIMITATIONS*‡

Robert G. Hallowell[†], Marilyn M. Wolfson, Richard L. Delanoy, Barbara E. Forman,
Margita L. Pawlak, Peter D. Smith and Michael P. Moore

MIT/Lincoln Laboratory
Lexington, Massachusetts

1. INTRODUCTION

Lincoln Laboratory, under funding from the Federal Aviation Administration (FAA) Terminal Doppler Weather Radar program, has developed algorithms for automatically detecting microbursts. While microburst detection algorithms provide highly reliable warnings of microbursts, there still remains a period of time between microburst onset and pilot reaction during which aircraft are at risk. This latency is due to the time needed for the automated algorithms to operate on the radar data, for air traffic controllers to relay any warnings and for pilots to react to the warnings. Lincoln Laboratory research and development has yielded an algorithm for accurately predicting when microburst outflows will occur. The Microburst Prediction Algorithm is part of a suite of weather detection algorithms within the Integrated Terminal Weather System (ITWS; Evans and Ducot, 1994).

This paper details the performance of the Microburst Prediction Algorithm over a wide range of geographical and climatological environments. The paper also discusses the full range of the Microburst Prediction Algorithm's capabilities and limitations in varied weather environments. This paper does not discuss the overall rationale for a prediction algorithm or the detailed methodology used to generate predictions. For a detailed discussion of these issues, see Wolfson, et al. (1994).

2. ALGORITHM PERFORMANCE

The ITWS Microburst Prediction Algorithm (MBPredict) was tested in a real–time operational setting during 1994 and 1995 in Memphis, Orlando, and Dallas, (Klingle–Wilson, 1995). The results of these tests are described in this section.

Because of the safety–oriented operational use of the Microburst Prediction Algorithm, the performance must meet very strict false prediction criteria. The ITWS Functional Requirement for the Microburst Prediction Algorithm performance accuracy states that, while it would be acceptable if MBPredict issued predictions for only one third of the expected microburst events, the predictions that are issued must be accurate at least 90% of the time. This ensures that any issued predictions will be highly reliable.

Table 1 shows the scoring results of each demonstration site. The ITWS Microburst Prediction Algorithm description (Lincoln Laboratory, 1995) was written to allow two modes of operation via a simple parameter change. The first mode is called "restricted" mode. This conservative mode reduces the chances for false predictions by allowing only predictions which have an underlying, confirming wind shear detection (15 to 29 knots) to be sent to the Situation Display. The second mode is called "unrestricted" mode. This mode allows both wind shear and microburst strength predictions to be sent to the Situation Display. Operating in "restricted" mode reduces the probability of falsely predicting a wind shear (PFP_{ws}) to zero (since, by definition, wind shear with loss ≥ 15 knots must be present), but it also reduces the number of microbursts predicted and the lead time for those that are predicted. In some regional storm environments, MBPredict may be able to run with limited false predictions in unrestricted mode, providing longer lead time and increased awareness of new wind shear events. Therefore, the results in Table 1 were calculated for both the restricted and unrestricted modes at each site.

The Probability of Prediction (POP) is the number of microburst (MB) events correctly predicted by the algorithm divided by the total number of events that should have been predicted. Subjective truth entered by an experienced meteorologist was used to determine the number of events that should have been predicted. POP is calculated on a event–by–event basis

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[†] *Corresponding author address:* Robert G. Hallowell,
MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA
02173–9108;
e–mail <bobh@ll.mit.edu>

Table 1. MB Prediction Scoring Results by Site and Mode of Operation (25 microburst events per site.)

SITE	PROBABILITY OF PREDICTION (%)		PROBABILITY OF FALSE WS PREDICTION (%)		PROBABILITY OF FALSE MB PREDICTION (%)		AVERAGE LEAD TIME (sec)	
	UNRE-STRICTED	RE-STRICTED	UNRE-STRICTED	RE-STRICTED	UNRE-STRICTED	RE-STRICTED	UNRE-STRICTED	RE-STRICTED
Memphis	80	80	33	0	50	22	246	126
Orlando	64	56	19	0	29	24	205	58
Dallas	64	64	23	0	30	17	360	102
AVERAGE	69	67	27	0	36	21	270	95

and only considers truth events which reach microburst strength (≥ 30 knots). The analyst searches up to 9 minutes ahead in time to find matching events when scoring the algorithm. A prediction can only match one microburst event. If a microburst is predicted at least once for an event, it is considered a correct prediction. Generally, a 25% overlap of the predicted and true regions was required, but very small predictions (< 1 km radius) within 1 km of true events were also considered hits.

The Probability of False WS Prediction (PFP_{ws}) is the number of false predictions issued by the algorithm divided by the total number of predictions issued. This is calculated on a minute-by-minute basis by comparing the predictions issued with truth events which reached at least wind shear strength (15 knots). Thus, a single MB event can be falsely predicted for several minutes, leading to several false predictions. The PFP_{ws} corresponds to the probability of false prediction criterion specified in the ITWS Functional Requirements.

The Probability of False MB Prediction (PFP_{mb}) is the number of predictions issued which did not match a truth event with a microburst strength outflow (≥ 30 knots) divided by the total number of predictions issued. This value is a more stringent criteria than PFP_{ws} and is shown here to indicate that MBPredict has considerable skill at precisely predicting events which will reach true microburst strength.

3. LEAD TIME OF PREDICTIONS

MBPredict is capable of predicting outflows from 1 to 8 minutes in advance of microburst strength winds. As shown in Table 1, while the POP does not change significantly between restricted and unrestricted modes of operations, the average lead time triples from 1.5 to 4.5 minutes. This increased margin of safety is one of the primary benefits of operating in unrestricted mode. Figure 1 illustrates the distribution of lead times based on individual alerts generated by MBPredict. [Note that the Situation Display does not indicate the timing, i.e. when the outflow is predicted to occur. MB predictions are depicted exactly as MB detections are on the Situation Display.]

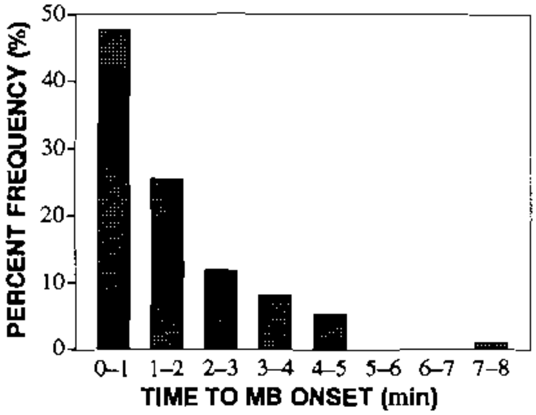


Figure 1. Distribution of lead times for individual prediction alerts. Data presented are for all three test sites in restricted mode.

4. THE NATURE OF FALSE PREDICTIONS

The Microburst Prediction Algorithm is, at its core, a downdraft detector. Many of the features which are used to find potential microburst regions are designed to detect the rise and fall of water and moisture associated with thunderstorm updrafts and downdrafts. Because the algorithm accurately charts downdrafts, any prediction region will correspond to a region which (a) has significant liquid water associated with it and (b) has a downdraft which could cause an aircraft airspeed loss. The only question is whether the surface outflow will become strong enough to become an aviation hazard.

Upon examining the false predictions which occurred at each of the three test sites, we found they fell into four categories. Figure 2 illustrates the various types of false predictions using charts of wind shear strength versus time. (The dashed line indicates MB strength or 30 knots). Referring to this figure, the false prediction types are:

A. During–After False Predictions, or predictions which occur during (hits) but which persist after a truth event has ended.

B. After False Predictions, or predictions which occur only after a true MB event.

C. Weak False Predictions, or predictions which match truth events with a peak strength less than 30 knots.

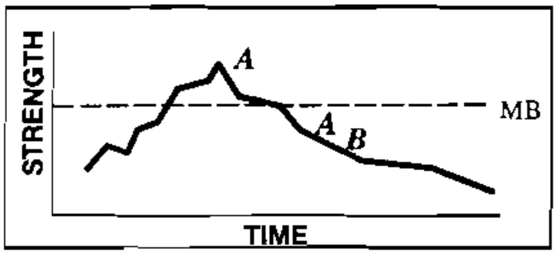
D. Location Offset False Predictions, or predictions which are false due to location errors.

Table 2 shows the breakdown of false prediction types by their relative frequency of occurrence in restricted and unrestricted modes.

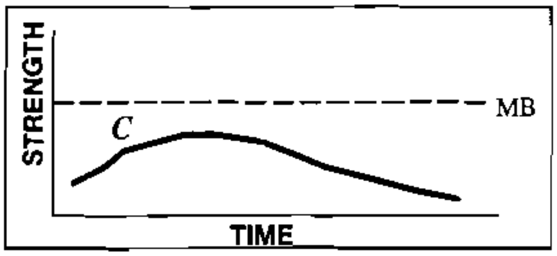
False prediction type (A) can possibly be eliminated by simply correlating microburst detections and predictions with time. MBPredict was specified in the ITWS Microburst Prediction Algorithm description to allow tracking of the underlying matching detection. This will hopefully make it fairly simple to remove type A false predictions once a sensible removal process has been developed.

False prediction type (B) is more difficult to remove because there is no time continuity between the detectable event and the predicted event.

The weak (C) false predictions are dependent upon the quality of the thermodynamic information used in the algorithm (discussed later in this paper.) Over one–quarter of the type C falses are predictions which matched detected wind shears between 15 and 30 knots.



(a) Showing type A (during–after) and B (after).



(b) Showing type C (weak).

Figure 2. Illustration of three types of False Predictions

Finally, location offset errors (D) are problematic because they are related to radar data quality problems which the algorithm itself has little control over. Fortunately, these location errors account for a very small fraction of the overall false predictions.

Table 2. Relative frequency of false prediction types in restricted and unrestricted mode (Data presented are derived from Dallas scoring results.)

FALSE PREDICTION TYPE	RE-STRICTED	UNRE-STRICTED
DURING–AFTER (*A*)	84%	34%
AFTER (*B*)	16%	34%
WEAK (*C*)	N/A	25%
LOCATION OFFSET (*D*)	N/A	7%

Note that 93% of the "false" predictions actually matched a confirming, but weak, wind shear outflow. In addition, if all the "after" false predictions were removed from the scoring analysis shown in Table 2, the PFP for unrestricted mode would meet the ITWS Functional Requirement level of $\leq 10\%$.

5. OPERATIONAL CAPABILITIES AND LIMITATIONS

The Microburst Prediction Algorithm is designed to accurately predict microburst outflows with a very low probability of false predictions in a wide range of thermodynamic environments. This requirement demands a fairly complex set of checks and balances within MBPredict. Operationally, the algorithmic features which make the algorithm work have physical limitations. While the Microburst Prediction Algorithm has proven to be reliable and effective, it is important to understand the limitations of the techniques used within MBPredict. In developing the Microburst Prediction Algorithm, steps were taken to incorporate software and adjustable parameters which would help mitigate any limitations.

Sections 5.1 and 5.2 describe how, by understanding the physical forcing of microburst outflows and characterizing the overall microburst environment, the Microburst Prediction Algorithm is able to achieve a high probability of detection. Just as important as the algorithm's ability to predict microbursts is its ability to control false predictions. As shown in Table 2, only one–quarter of the false predictions are due to over–estimations of the peak outflow strength. The remaining sections detail the controlling methodology of the algorithm. They also discuss ways in which false predictions could occur along with the POP tradeoffs involved in controlling the PFP.

5.1. Overview

Wolfson (1990) showed that the primary forcing mechanisms of thunderstorm outflows were the amount of upper level water and ice within the storm and the amount of evaporation and melting of the water and ice as it was pulled downward by gravity (as shown below.)

$$\underset{\textit{Downdraft Strength}}{\frac{dw}{dt}} \simeq \underset{\textit{Buoyancy}}{\frac{\Delta T}{T}} - \underset{\textit{Water Loading}}{g\,(water+ice)}$$

As an illustration, Figure 3 shows that the surface reflectivity associated with Orlando and Denver microbursts are extremely different. However, as shown in Figure 4, the corresponding distribution of peak outflow strengths is quite similar. The moisture profile in Denver is much drier than that of Orlando, reducing Denver's potential water–load forcing. The thermodynamic forcing in Denver, however, is much greater than that of Orlando. Environmental factors such as the temperature and humidity structure in the atmosphere determine the negative buoyancy generated by the melting of frozen precipitation and the evaporation of rain. Because water phase changes are usually not discernible in radar reflectivity, explicit consideration of the atmospheric temperature and humidity profile are needed to develop a reliable and accurate Microburst Prediction Algorithm.

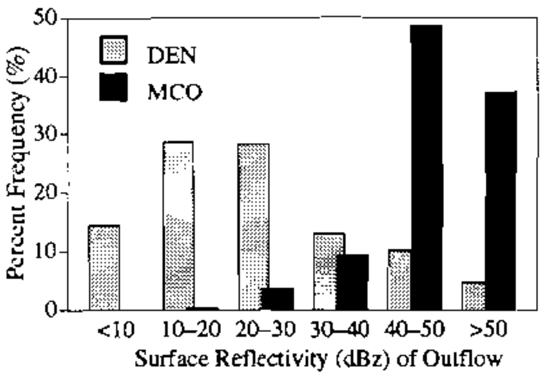


Figure 3. Comparison of the surface reflectivity measurements associated with wind shear outflows. The grey histogram shows the distribution for Denver(DEN), CO (a "dry" MB environment), and the black histogram shows the distribution for Orlando(MCO), FL (a "wet" MB environment).

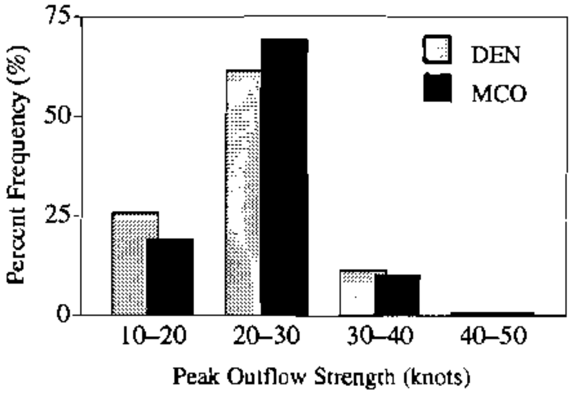


Figure 4. Comparison of the peak outflow strength distribution for the same events characterized in Figure 3

5.2. The Microburst Environment

The ability of MBPredict to estimate the buoyancy and water–load downdraft forcing, allows it to operate year–round in widely varying environments. The thermodynamic "microburst environment" is determined via a combination of three sounding profile parameters:

A. Freezing Level, the height at which the ambient temperature first drops to 0° C.

B. Full Lapse Rate, the change in temperature with height from the surface to the freezing level.

C. Low–level Lapse Rate, the change in temperature with height from the surface to 3/4 of the freezing level height.

Negative buoyancy in the downdraft is primarily generated below the freezing level; thus the height of the freezing level is a measure of the depth of the downdraft. The full lapse rate is a measure of how much negative buoyancy the water–saturated air can gain through melting and evaporation. Finally, the low level lapse rate is a measure of sub–cloud evaporation and discontinuities at low levels. A low–level lapse rate that is significantly lower than the full lapse rate indicates possible temperature inversions which will dampen outflow strengths. The reverse case is an indication of enhanced outflows from extreme low level evaporation (typical of dry MB environments).

Figure 5 shows the wide range of lapse rates under which the Microburst Prediction Algorithm operates. The stable region indicates an environment where thermodynamic forcing is so low that impossible amounts of water and ice are needed to force an outflow. The operating region of the curve is an environment where microbursts may occur and MBPredict is able to perform with a low probability of false predic-

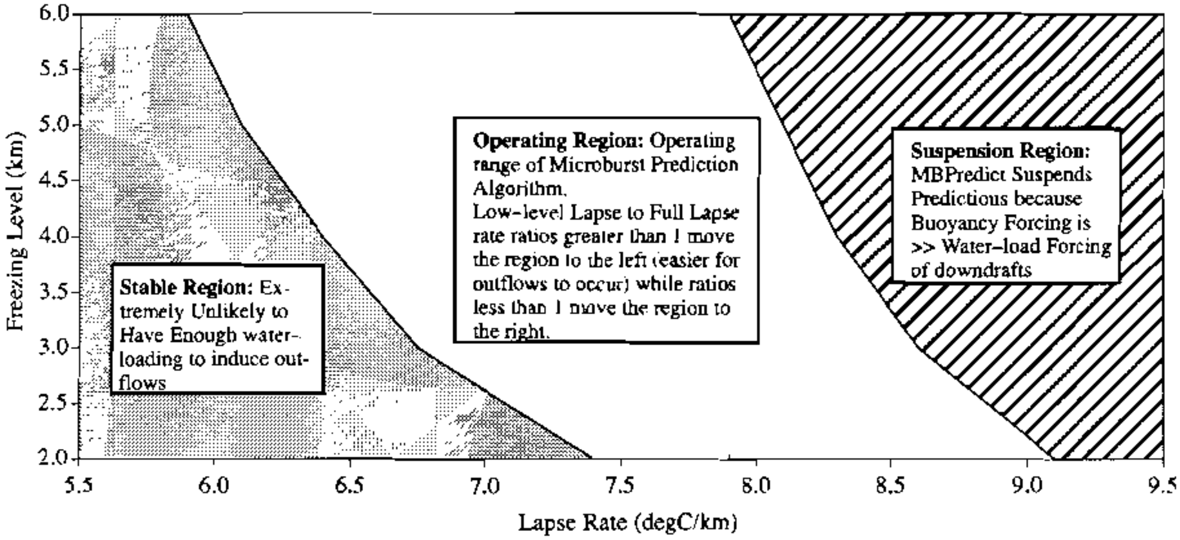


Figure 5. Illustrates the regions of thermodynamic forcing for microbursts. The regions shown assume a low–level lapse rate equal to the full lapse and that MBPredict is attempting to predict outflows greater than 25 knots.

tion. The suspension region indicates an environment where the buoyancy forcing far outweighs the water–loading forces, and suspension of the algorithm predictions is necessary to limit false predictions.

5.3. Detecting Potential Dry Microburst Environments

MBPredict is designed to recognize whether or not it is operating in an environmental regime where it will likely have a high probability of false prediction. The suspension region in Figure 5 depicts environments under which MBPredict (left unchecked) would potentially have a high PFP. Semi–arid microburst environments, for example, are problematic for the Microburst Prediction Algorithm. Buoyancy forcing is so large in these environments that MBPredict predicts that any amount of water loading will result in a microburst strength outflow. Dry microbursts tend to occur in regions where the lapse rate is approaching or greater than dry adiabatic (9.76 °C/km). By utilizing the sounding parameters discussed above, MBPredict is able to detect dry environments where the algorithm will have difficulty accurately predicting microbursts.

Once a dry environment is detected, MBPredict will suspend predictions until the thermodynamic environment changes. While this is a limitation of the Microburst Prediction Algorithm's ability to predict outflows, it is an asset in that it eliminates the chances for severe over–warning and false predictions.

5.4. Sounding Quality and MBPredict Feedback

Soundings are created by combining RUC (Rapid Update Cycle) model data, automated aircraft reports via MDCRS (Meteorological Data Collection and Reporting System), and NWS surface observations. The model data provides a good approximation of the sounding profile, but the large scale smoothing removes any localized sounding features. The surface observations and MDCRS reports are used to capture these smaller scale features. Not all aircraft automatically report meteorological data, and during slow traffic periods (i.e. overnight) reports are very sparse. In many cases, there are an insufficient number of MDCRS reports at heights under 5 km to accurately represent the thermodynamic profile.

The scarcity of aircraft measurements and large–scale smoothing of model data can cause the sounding to be an inaccurate measure of the thermodynamic environment. Because MBPredict relies heavily on thermodynamic information, inaccurate soundings can result in MBPredict over– or under–predicting wind shear potential. A feedback mechanism was added to the Microburst Prediction Algorithm to mitigate potential sounding deficiencies.

The feedback mechanism sensitizes MBPredict based on real–time verification of the predictions against the detections from the ITWS Microburst Detection Algorithm (MBDetect). Data are compared over the previous 20 minutes. If there are more detections than predictions, MBPredict's sensitivity is increased slightly, thereby increasing the probability that more predictions will be made in the future. Conversely, if the Microburst Prediction Algorithm is over–warning, its sensitivity is decreased, thereby making it less probable that predictions will be made in the near term.

5.5. The False Prediction Bias of Feedback

The feedback cycle is primarily designed to reduce false predictions. Therefore, in situations where MBPredict has a significant number of false predictions, a large feedback correction is made to eliminate the chances of continued false predictions. Once an over–warning correction is made, it is extremely difficult for the Microburst Prediction Algorithm to make predictions in the near future (1–2 hour recovery time). While this correction may seem excessive, Air Traffic Control personnel expressed the need for MBPredict to have an extremely low probability of false prediction.

The feedback mechanism is also critical to the success of the overall algorithm. First, as mentioned, the quality of the sounding profile can be questionable. Second, there are some operational days where even the combination of precise water content and thermodynamic information does not accurately capture the microburst environment, causing MBPredict to over or under–predict outflow strengths (i.e. sections 5.6 and 5.7).

5.6. Temperature Inversions

A temperature "inversion" occurs when ambient temperatures are cooler at lower levels than they are at higher levels. Large scale surface–based inversions are commonly caused by nighttime radiational cooling, where the surface cools much faster than the air above. In addition, localized temperature inversions can be created by thunderstorm outflow activity. Thunderstorm outflows force cool mid–level air down to the surface. Whichever method causes the inversion, these cold pools of air form a barrier to new downdrafts, reducing the strength of future outflows. MBPredict captures the inhibiting effect of inversions via the sounding parameters.

As shown in Figure 6, inversions reduce both the overall full lapse rate and the low–level to full lapse rate ratio, thus requiring more water–loading to initiate any new outflows. The problem is that even weak inversions (that strong downdrafts can break through) will cause the algorithm to predict that no microburst outflow is possible. Unfortunately, the available temperature profile data is not of sufficient resolution to measure the relative strength of the inversion. The Microburst Prediction Algorithm will tend to under–predict on days with inversions that still produce microbursts. It is rare for downdrafts to be strong enough to break through an inversion and produce a microburst–strength outflow.

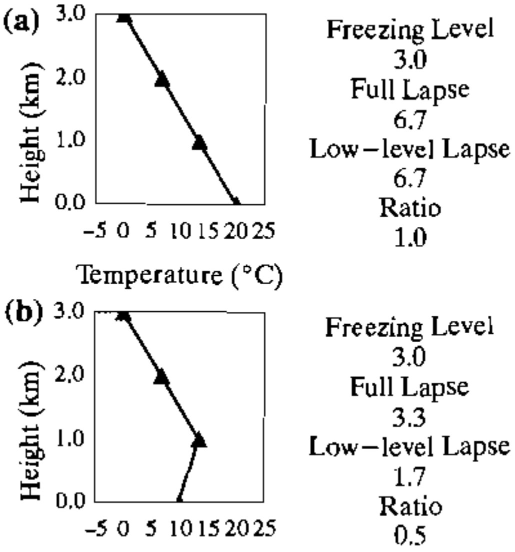


Figure 6. The temperature profile depicted in (a) illustrates the typical temperature decreasing with height. The profile in (b) illustrates a surface–based temperature inversion. The sounding parameters for each profile are shown on the right to illustrate the impact of inversions on MBPredict.

5.7. Vertical Wind Shear

Vertical wind shear is a rapid change of wind speed and/or direction with height. As shown in Figure 7, very strong vertical wind shear will cause thunderstorms and their downdrafts, to tilt with height. There are no considerations made for vertical wind shear in MBPredict. Even though strong vertical shear could result in an over prediction of the peak strength of an event, not all vertical wind shear situations adversely affect algorithm performance. Work should continue to determine ways to incorporate vertical wind shear into MBPredict.

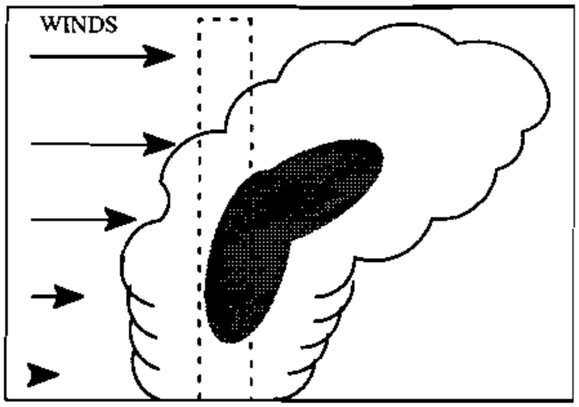


Figure 7. Illustration of the possible impact of vertical wind shear on downdraft. The downdraft forcing from vertical water loading is reduced due to the horizontal advection of upper–level moisture away from the downdraft core.

5.8. Coupling with Microburst Detection Algorithm

The Microburst Prediction Algorithm is coupled with the Microburst Detection Algorithm in two ways. First, weak surface wind shear is used to detect regions where the transition from downdraft to outflow has begun. Secondly, and more importantly, detections are used as truth in the feedback loop. This coupling means that the strengths and weaknesses of the ITWS Microburst Detection Algorithm affect the performance of the Microburst Prediction Algorithm. For example, if MBDetect missed a microburst event, but MBPredict makes an accurate prediction, feedback will desensitize MBPredict to correct the perceived false prediction problem. The reverse is true if MBDetect false alarms (resulting in an increased probability that the Microburst Prediction Algorithm will false predict in the future). The high POD and low PFA (probability of false alarm) of the Microburst Detection Algorithm, and the need for feedback makes the coupling extremely beneficial.

6. SUMMARY AND FUTURE WORK

The ITWS Microburst Prediction Algorithm has proven to be reliable and accurate in predicting microburst strength outflows in diverse thunderstorm environments. The key to this success is MBPredict's ability to both precisely measure the water content of the atmosphere via TDWR and accurately estimate the thermodynamic forcing of downdrafts via temperature and humidity profiles.

While the Microburst Prediction Algorithm has been successful, Lincoln Laboratory research into ways to improve the MBPredict should continue. Near term modifications should include plans to inhibit false predictions which occur during or after microburst–strength events and to investigate ways of incorporating vertical wind shear information into the MBPredict. The ITWS algorithm description incorporates many adaptable parameters and software features which will allow these modifications to be implemented. Long–term research needs to be done to determine how MBPredict can predict outflows in dry microburst environments while keeping false predictions to a minimum.

7. REFERENCES

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