OPERATIONAL FORECASTS OF MAXIMUM HAILSTONE DIAMETER IN MENDOZA, ARGENTINA

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Abstract. A coupled one-dimensional cloud and hail growth model was used to simulate the growth of hailstones in Mendoza, Argentina. The model-derived maximum hail size forecasts were based on 118 representative soundings released during the 1999-2000 hail season. Model ensemble, persistence and subjective hail forecasts were also verified against daily observations of the maximum hail size. The model control and ensemble showed promising skill when forecasting the occurrence of hail as measured by the Heidke's Skill Score (HSS=0.60). On days with severe hail (diameter of 2 cm or more), the model control forecasts showed the best skill (HSS=0.59). The model showed improved forecast skill when run using sounding and surface data from the Alberta Hail Project. This was likely attributable to the stringent criteria placed on the proximity soundings and the availability of real-time surface data in Alberta. Although certain cloud model parameters were useful for inferring the potential (and size) of hail in Mendoza, the best results were achieved using the coupled cloud and hail model. The data also suggest that the ensemble technique improves the accuracy and skill of the hail forecasts on some days.

1. INTRODUCTION

The province of Mendoza (32° S; 68° W; 800 m above sea level), Argentina is located less than 100 km east of the Andes (peaks higher than 6500 m). The region is prone to severe hailstorms during the austral summer, and annual losses to agriculture often amount to more than 10% of total production (Krauss et al. 2000). The climate is semi-arid with an annual rainfall of approximately 200 mm. Three irrigated oases have been established within the province to cultivate grapes and a variety of other fruits and vegetables.

In October 1999, the Government of Mendoza started a 5-year hail suppression program using aircraft dispensing silver-iodide pyrotechnics. The objective of the program is to reduce hail damage within the oases through an aggressive cloud seeding program that operates between 15 October and 31 March. Short-term forecasts (6 to 12 hours in advance) of the maximum expected hail size on the ground are essential for an effective hail suppression program. During the 1999-2000 season, a coupled one-dimensional cloud and hail model was employed daily to forecast the maximum expected hail size on the ground. The model was developed for the South African Weather Service by Poolman (1992) and was later improved upon and adapted for use in Alberta, Canada (Brimelow 1999, Brimelow et al. 2002).

In this paper, we assess the performance of the model (hereafter referred to as HAILCAST) during the 1999-2000 austral summer and compare the skill of the model hail forecasts against the subjective forecasts prepared by meteorologists of Weather Modification Inc. (WMI). We also test whether the HAILCAST model is transferable to geographic regions outside Alberta. To this end, the model's performance in Mendoza is compared with diagnostic model hail forecasts produced by Brimelow (1999) using Alberta Hail Project (AHP) data from 1983 to 1985. The AHP is considered one of the most comprehensive hail data sets in the world to date (Admirat et al. 1985), and is thus ideally suited for verifying HAILCAST's performance in forecasting hail size.

The feasibility of employing an ensemble approach to forecast the maximum hail size is also investigated. We propose that adopting an ensemble approach will negate the sensitivity of the modelled hail size to uncertainties in the input data (Brimelow 1999). This is particularly beneficial when the accuracy of the input data is uncertain, as is often the case in an operational setting. Our final objective is to investigate if certain parameters derived from the cloud model, such as the forecast cloud top, can be used independently of the hail growth model to

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*Corresponding author. E-mail: brimelow@ualberta.ca distinguish between thunderstorm days with no hail, non-severe hail and severe hail (diameter 2.0 cm or more).

In section 2, we describe the HAILCAST model. This is followed by a description of the Mendoza data set in section 3 and the ensemble technique in section 4. The hail forecasts in Mendoza are evaluated in section 5, and compared with the model's performance in Alberta in section 6. In section 7, we discuss the ability of selected model-derived parameters to indicate the potential for hail and severe hail. The summary and conclusions are presented in section 8.

2. THE HAILCAST MODEL

2.1 Cloud Model

The steady-state one-dimensional (1D) cloud model developed by Poolman (1992), is similar to the other 1D cloud models developed by Chisholm (1973) and Anthes (1977). The updraft velocity in the cloud model is governed by the amount of thermal buoyancy. The parcel's temperature and saturation mixing ratio (at each level) are adjusted by taking into account the mixing of environmental air with the parcel. Specifically, Poolman's cloud model parameterizes both cloud top and lateral entrainment using the saturation point analysis scheme of Betts (1982a,b). Allowance is also made for the impact of water mass loading on the updraft velocity. The impacts of the latent heat of freezing of cloud water and non-hydrostatic pressure gradients on the updraft velocity are not taken into account. The model can be run on a Pentium class PC, which is an advantage for operational field programs having limited computing resources.

2.2 Hail Growth Model

We employed the time-dependent hail growth model of Poolman (1992) to simulate the growth of individual hailstones. The model is based extensively on the work of Musil (1970), Dennis and Musil (1973), and Rasmussen and Heymsfield (1987a,b). The amount of accreted cloud water frozen by a growing hailstone is determined by the mass and heat budgets of the hailstone. These budgets are in turn a function of the hailstone's size and the environmental conditions. The steady-state one-dimensional cloud model of Poolman (1992) calculates the in-cloud profiles of pressure, temperature, saturation mixing ratio and vertical velocity that are required for modelling hail growth. The hail growth calculations assume that the modelled hailstones are spherical, that the accreted water and ice are assumed to form a high-density (0.9 g cm^{-3}) deposit and that the temperature is assumed to be uniform throughout the hailstone.

The growth of hail is initiated by introducing a 300 μm droplet at the base of the cloud. This droplet acts as a hail embryo, and is assumed to originate from the shedding of water from the surface of melting hail already present in the cloud (Rasmussen et al. 1984b). The droplet freezes as it passes through the –8 °C level. Above the –20 °C level, it grows by intercepting supercooled water droplets and cloud ice. After each time step, the hydrometeor is advected to a new height depending on the difference between its terminal fall speed and the updraft velocity. The surface temperature and change in mass (and new diameter) are then calculated at the new height. Also, depending on the heat transfer to and from the hailstone it grows in the wet or dry growth regime. In the wet growth regime, excess water is shed if the mass of water present on the hailstone's surface exceeds a critical limit. The critical shedding limit is determined by the empirically derived linear relationship of Rasmussen and Heymsfield (1987a). In the dry growth regime, all the accreted water freezes to the surface of the hailstone. The hailstone continues to grow until its fall speed exceeds that of the updraft, or the updraft collapses. The updraft duration ranges between 20 min and 60 min depending on the amount of Convective Available Potential Energy (CAPE) and vertical wind shear (Brimelow 1999). No more growth occurs below the freezing level due to the shedding of melt water from the hailstone's surface.

3. DATA SET

Subjective forecasts of the likelihood of deep convection and the maximum expected hail size were prepared daily by WMI meteorologists. An instrumented balloon was released from Cruz Negra (33.45° S; 68.97° W) at approximately 1300 Local Time (LT) each day, and data from the soundings provided forecasters with valuable information regarding the pre-storm environment. The Cruz Negra soundings, together with the forecast maximum surface temperature and dew-point for the location where the thunderstorms were expected to develop, where used as input for HAILCAST.

The need for representative soundings when modelling deep convection has been documented by Brooks et al. (1994) and Golden et al. (1986). Therefore, constraints were placed on the Cruz Negra soundings to identify only those soundings that were representative of the pre-storm environment. Soundings were excluded if: 1) sounding had missing data; 2) sounding was released in rain; 3) sounding was modified by frontal passage or a thunderstorm outflow boundary; 4) nocturnal hailstorms were observed (formed after 2100 LT).

Soundings were not available for 9 of the 169 days between 15 October 1999 and 31 March 2000. Of the 160 soundings screened, only 118 (74%) satisfied the above-mentioned criteria and were used to run HAILCAST. Of these, 80 (68%) were made on days with no hail, 15 (13%) on days with non-severe hail and 23 (19%) on severe hail days (maximum observed hail diameter 2.0 cm or more). Of the 42 soundings excluded from the data set, 28 (67%) had missing wind or dew-point data, 10 (24%) were made on days with nocturnal storms or were modified by outflow boundaries, and the remaining 4 (9%) were released in rain (i.e., were not representative of the pre-storm environment).

WMI employs the Convective Day Category (CDC) as described by Strong (1974) to classify the forecast and observed hailstones into the following categories: shot, < 0.4 cm; pea, 0.4-1.2 cm; grape, 1.3-2.0 cm; walnut, 2.1-3.2 cm; golfball, 3.3-5.2 cm; and larger than golfball, > 5.2 cm. Measurements of maximum hail diameter observed within the oases were obtained from farmers, the Ministry of Economy, and press reports. In this study, only reports of hail having a diameter of 5 mm or more are considered. We classified hail as being severe when the largest reported (or forecast) hail diameter was 2.0 cm or larger. In order to compare the model and WMI hail forecasts, the model-derived hail diameters (on the ground) were placed in the appropriate CDC.

4. ENSEMBLE HAIL FORECASTING TECHNIQUE

Mueller et al. (1993) and Crook (1996) employed three-dimensional cloud models to study the sensitivity of thunderstorm initiation and intensity to fluctuations of temperature and moisture in the boundary layer. Their experiments demonstrated that the modelled convection was very sensitive to small changes in the surface input data. In particular, Crook found that small variations in the surface temperature (1 °C) and moisture (1 g kg^{-1}) could differentiate between no convection and intense convection. Similarly, model sensitivity experiments conducted by Brimelow (1999) showed that model output from HAILCAST was sensitive to small changes in the surface temperature and dew-point. Given the sensitivity of numerical model simulations to small variations in surface temperature and moisture, Crook (1996) suggested that forecasting convection initiation using numerical models has limited potential. However, one possible method of improving our ability to predict the evolution of the atmosphere is to perform a number of model simulations (or ensemble members), each starting with slightly different initial conditions (Crook 1996). As long as the range of initial conditions span the domain of expected error in the initial fields, the ensemble mean should provide a more skilful forecast than the majority of the individual forecasts (Brooks et al. 1992).

Brooks et al. (1992) and Brooks et al. (1993) suggest adopting a quasi-Monte Carlo, or probabilistic approach when employing numerical cloud models to forecast convection. This approach requires the forecaster to vary the input data for the cloud model over a range of values expected in the area where convection is anticipated. For example, if the forecast value of the surface moisture is uncertain, the forecaster can conduct numerous cloud model runs for the range of moisture values expected on the day in question. By doing this, the forecaster can identify the most likely scenarios, as well as consider scenarios that may have at first been deemed unlikely.

HAILCAST is computationally efficient and consequently well suited for producing ensemble forecasts. The ensemble forecasts were prepared by varying both the surface temperature and dew-point between –1.0 °C, -0.5 °C, 0 °C, +0.5 °C and +1.0 °C from the forecast control value (see section 3). These ranges in temperature and dew-point were selected to span (a) surface temperature and moisture variations expected in the boundary layer on any given day and (b) expected forecast errors of the surface temperature and dew-point. HAILCAST was then run for each combination of the temperature and dew-point, resulting in a total of 25 individual hail diameter forecasts. The mean diameter from all 25 model runs was then used to determine the forecast ensemble diameter.

5. EVALUATION OF HAIL FORECASTING TECHNIQUES IN MENDOZA

To objectively assess the performance of the HAILCAST and WMI forecasts we computed the following skill scores from 2x2 contingency tables: Probability of Detection (POD), False Alarm Ratio (FAR) and Heidke's Skill Score (HSS). The POD and FAR vary between 0 and 1. The HSS is a popular skill score for the verification of rare event forecasts and is considered to measure the true skill of a forecast, because it takes all values in the contingency table into account (Doswell et al. 1990). The HSS varies between -1 for absolutely no forecast skill and 1 for a perfect forecast; a HSS greater than 0.40 is considered to be indicative of significant skill.

The hail forecasts were validated against surface observations of maximum hail size as described in section 3 and then classified as follows: a hit was noted when hail was forecast and hail was observed on the ground; a false alarm was noted when hail was forecast but none was observed; a miss was recorded when no hail was forecast but hail was observed and, finally, a null forecast was recorded when no hail was forecast and none was observed.

The above-mentioned skill scores were calculated for four techniques: the three already mentioned (WMI forecasts, control HAILCAST forecasts and ensemble HAILCAST forecasts) and the persistence forecasts (P). The persistence technique was used as a final comparison because in an analysis of Alberta Hail Project data from 1957-1985, Smith et al. (1998) found that the previous days' hail observations could be used as a persistence predictor to estimate the following day's hail size. In our study, we applied the persistence technique of Smith et al. as follows: if hail (severe or non-severe) was observed, we predicted hail the following day; otherwise no hail was forecast. We did not attempt to forecast the hail size when applying the persistence technique.

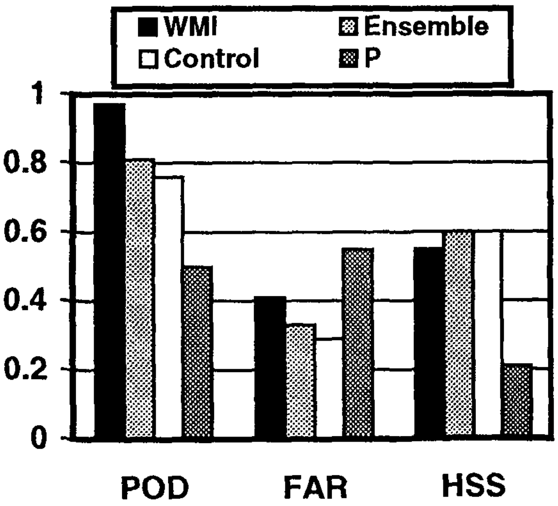

Figure 1: Skill scores for HAILCAST (ensemble and control), WMI and persistence (P) for 38 hail days observed between 15 October 1999 and 31 March 2000.

WMI displayed the greatest skill of all four techniques when forecasting the occurrence of hail and scored a POD of 0.97, compared to 0.81 for the model ensemble, 0.76 for the model control and 0.50 for the persistence forecasts (Fig. 1). This equates to correctly forecasting 37, 31, 29 and 19 of the 38 hail days respectively. The model control scored the lowest FAR of 0.29 (12 false alarms), compared to 0.33 (15 false alarms) for the model ensemble, 0.41 for WMI (26 false alarms) and 0.55 for P (23 false alarms). HAILCAST and WMI displayed much skill in distinguishing between hail and no-hail days, with Heidke's skill scores of 0.60 and 0.55, respectively. By contrast, the HSS for the persistence forecasts was only 0.21.

Table 1: HAILCAST and WMI forecast hail size category evaluation for 38 hail days observed between 15 October 1999 and 31 March 2000.

Size Category	HAILCAST Ensemble	HAILCAST Control	WMI
Correct	34%	34%	21%
Within one	60%	63%	76.5%
One too small	13%	16%	31.5%
Two or more too small	29%	26%	18.5%
One too large	13%	13%	24%
Two or more too large	11%	11%	5%

Regarding the hail size category forecasts, Table 1 shows that the model ensemble and control scored the greatest number of correct forecasts (34%), followed by WMI (21%). Almost 77% of the WMI forecasts were correct to within one size category. This was substantially higher than for the model control (63%) and ensemble (60%) forecasts. The model control and ensemble underestimated the hail size by one or more categories on 42% of hail days, compared to 50% for WMI. Almost 20% of the WMI forecasts were two or more categories too small, compared to 29% and 26% for the model ensemble and control respectively. Nearly 25% percent of the model control and ensemble forecasts were one or more categories too large, compared to 29% for WMI. Relative to the other techniques, the WMI forecasts were most unlikely to overestimate the hail size by two or more categories.

The performance of WMI and HAILCAST on severe hail days was less impressive (Fig. 2). WMI scored a POD of 0.48, compared to 0.65 and 0.61 for the model control and ensemble, respectively. The slightly higher POD of the control over the ensemble is due to one additional hit on 7 January 2000.

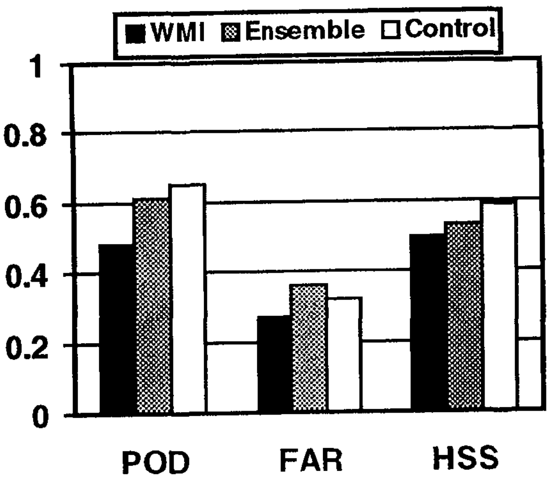

Figure 2: *Skill scores for HAILCAST (ensemble and control) and WMI for 23 severe hail days observed between 15 October 1999 and 31 March 2000.*

On this day, the model control forecast a maximum hail diameter of 2.0 cm (severe) versus 1.7 cm (non-severe) hail for the model ensemble. The model ensemble and control forecast hail on all but 3 of the missed severe hail days, while WMI forecast at least pea-sized hail on all of the missed severe hail days. The FAR on the severe hail days was higher than for all hail days. WMI scored the lowest FAR of all three techniques at 0.27 (4 false alarms), versus 0.36 for the model ensemble (8 false alarms) and 0.32 (7 false alarms) for the control. The high FAR values in turn resulted in lower HSS scores than for all hail days. Specifically, the model control scored a HSS of 0.59, followed by 0.53 for the ensemble, and 0.50 for WMI.

Performance of the hail size category forecasts on severe hail days is very similar to those for all hail days (Table 2). The model ensemble correctly forecast the hail size category on 39% of severe days compared to 30% for the control and 30% for WMI. Sixty-five percent of the WMI forecasts were within one size category versus 57% and 56% for the model control and ensemble respectively. Once again there was a tendency to underestimate the hail size, with 65% of the WMI forecasts one or more categories too small versus 48% for the model forecasts.

Table 2: *HAILCAST and WMI forecast hail size category evaluation for 23 severe hail days observed between 15 October 1999 and 31 March 2000.*

Size Category	HAILCAST Ensemble	HAILCAST Control	WMI
Correct	39%	30%	30%
Within one	57%	56%	65%
One too small	9%	13%	30%
Two or more too small	39%	35%	35%
One too large	9%	13%	5%
Two or more too large	4%	9%	0%

6. EVALUATION OF HAILCAST USING ALBERTA HAIL PROJECT DATA

The Alberta Hail Project (1957-1985) was established by the Alberta Research Council and several other groups to investigate hailstorms over central Alberta, and to reduce crop damage through an operational cloud seeding program (Deibert 1984). The project covered approximately 33,700 km^2 and was centered on the radar site located at Red Deer's Industrial Airport in Penhold (52.2° N, 113.9° W). Each spring, hail cards were mailed to approximately 20,000 farmers in the AHP area. On days with hail, between 10% and 20% of the farmers responded, yielding an average of 1 observer per 16-32 km^2 (Smith et al. 1998). Telephone surveys were also conducted on days with hailstorms, resulting in observation densities as high as 1 report per 3 km^2. Observers classified the maximum hail size using the Convective Day Category (CDC) scheme described in section 3.

Brimelow (1999) evaluated HAILCAST using 160 proximity soundings released from Penhold (at 1715 LT) during three summers between 1983 and 1985. The Penhold soundings were carefully screened using the same criteria outlined in section 3. However, the spatial and temporal constraints were more stringent than those applied to the Mendoza data set, and only soundings that were released within 3 hours and 100 km of a hail report were selected. Of the 160 soundings used in the Alberta study, 98 (61%) were made on days with no hail, 42 (26.5 %) on days with non-severe hail and 20 (12.5%) on severe hail days. The ensemble technique was not applied to the AHP data set, thus we only compare the performance of the control hail forecasts.

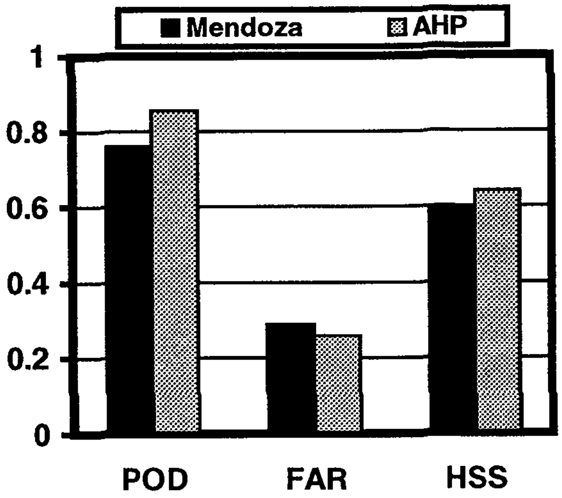

Figure 3: Comparison of HAILCAST's forecast skill for all hail days in Mendoza (38) and the AHP (62).

Figure 3 shows that HAILCAST displayed promising skill when forecasting the occurrence of hail using the AHP data (POD=0.85, FAR=0.26, HSS=0.64). However, while the model's performance when forecasting the occurrence of hail in Alberta was comparable with that in Mendoza, the model's skill when forecasting severe hail in Alberta was superior, scoring a POD of 0.90 and HSS of 0.67 (Fig. 4).

Table 3: Comparison between model-derived hail size category forecasts in Mendoza and Alberta.

Size Category	Mendoza	AHP
Correct	34%	39%
Within one	63%	81%
One too small	16%	27%
Two or more too small	26%	11%
One too large	13%	15%
Two or more too large	11%	8%

The hail size category forecasts in Alberta were more accurate than in those Mendoza (Table 3). Specifically, 39% of the AHP hail size category forecasts in the AHP were correct, compared to 34% in Mendoza. Moreover, 81% of the AHP forecasts were within one category, versus only 63% in Mendoza. The model forecasts in Alberta also showed a tendency to underestimate the hail size category, with 38% of the forecasts one or more categories too small, versus 23% being one or more categories too large.

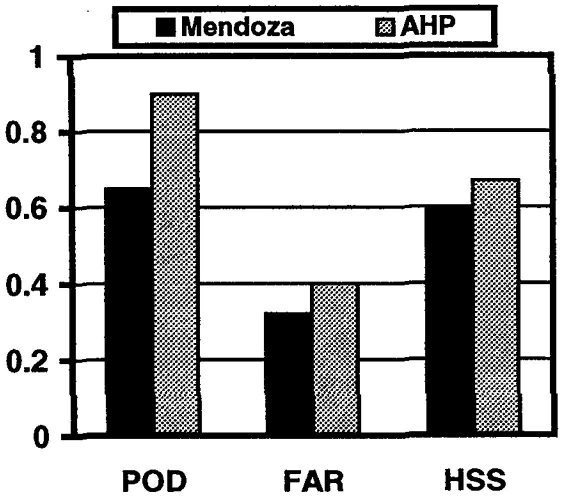

Figure 4: Comparison of HAILCAST's forecast skill for severe hail days in Mendoza (23) and the AHP (20).

The above statistics clearly illustrate that HAILCAST's performance was superior in Alberta. This was especially true on severe hail days. Possible explanations for this are:

1. In Mendoza, the surface temperature and dew-point at the time of convection were forecast subjectively; in Alberta, the surface temperature and dew-point recorded in the vicinity of the storm's inflow were used as input for HAILCAST.
2. On some days, evapotranspiration over the oases may have resulted in significantly higher surface dew-points than elsewhere in the project area. Forecasters did not have access to real-time surface observations over the oases and this placed a limitation on the accuracy of the forecast surface data used as input for the model in Mendoza. For example, on some hail days cloud base temperature measurements made by the WMI LearJet indicated that the dew-points used to run the model were 2 to 5 °C too low, and consequently no deep convection was simulated by HAILCAST when it otherwise would have been.
3. Most of the thunderstorms formed 3 to 9 hours after the Cruz Negra sounding was released, and portions of the southernmost oasis are 200 km from the sounding site. In Alberta, a sounding had to be released within 3 hours and 100 km of a hail event to be included in the dataset.
4. While the hail observation network over the AHP was fairly uniform, hail observations in Mendoza were only recorded within the oases.

Points 1 and 2 suggest a limitation of our ensemble approach, because the span of ensemble members would not include the actual surface temperature and/or dew-point if the forecast values were greater than 1 °C. Consequently, on days with forecast errors greater then 1 °C, the ensemble technique would do little to improve the skill of the model forecasts. Another possible limitation is that we assume changes in the modelled hail size result solely from variability in the surface data. In particular, we do not allow for the impact of changes in sounding data (T, Td and winds) above the boundary layer on the modelled hail.

7. MODEL-DERIVED STORM PARAMETERS

Several model-derived storm parameters were selected to determine if the cloud model could be used independently of the hail model to discriminate between thunderstorm days with no hail, non-severe hail and severe hail. Specifically, we selected the forecast cloud top height (defined as the first level where the forecast updraft velocity became negative), maximum updraft velocity and cloud base temperature. The aforementioned parameters were selected because they are useful for quantifying thunderstorm severity. The following data are based on the 1300 LT Cruz Negra soundings.

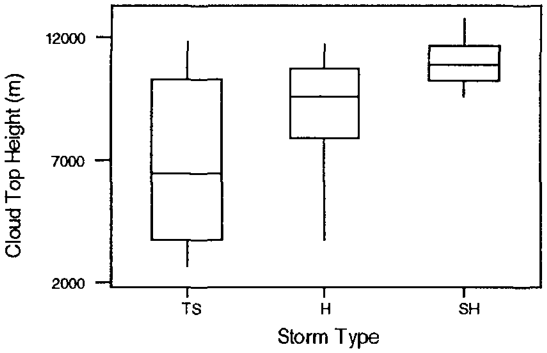

Figure 5: Model forecast cloud top for thunderstorm days with no hail (TS), non-severe hail (H) and severe hail (SH) in Mendoza. The bottom of the box is at the first quartile (Q1) and the top is at the third quartile (Q3). The whiskers represent the lowest and highest observations still inside the region defined by the lower limit Q1 - 1.5(Q3 - Q1) and the upper limit Q1 + 1.5(Q3 - Q1).

The box plots in Fig. 5 compare the forecast cloud top height statistics for thunderstorm days with no hail (TS), non-severe hail (H) and severe hail (SH). All heights are in meters above sea level. A clear increasing trend in the median forecast cloud top is apparent, with the median increasing from approximately 6.5 km for TS, to almost 11 km for SH. The inter-quartile distance (central 50% of the values) for H falls between 7.9 and 10.2 km, compared to 10.2 and 11.7 km for SH. There is a large range in the forecast cloud top heights for TS, with the cloud tops ranging from 3.5 to 12 km. The reason for this could possibly be attributed to HAILCAST not forecasting convection on some days and overestimating the intensity of the convection on others. This in turn, was most likely due to unrepresentative surface temperature and dew-point data being used to run the model (see section 6). Consequently, there is considerable overlap between the 25th and 75th percentile ranges for TS and H. Based on these data, the lower threshold for the model forecast cloud tops of non-severe hailstorms in Mendoza appears to be approximately 8.0 km and 10.0 km for severe hailstorms.

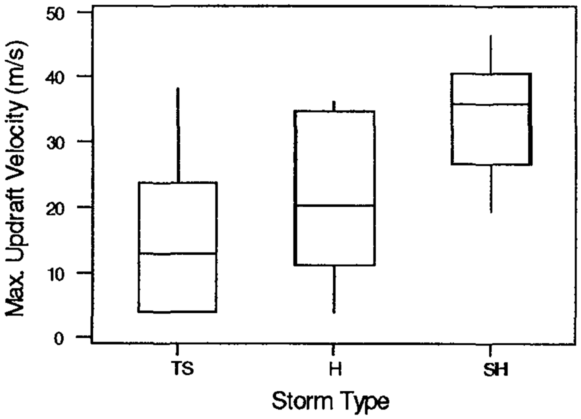

Figure 6: Same as Fig. 5, except for the forecast maximum updraft velocity.

The forecast maximum updraft velocities show a clear increasing trend with increasing storm intensity (Fig. 6). This trend is consistent with the increasing cloud top heights illustrated in Fig. 5. The median maximum updraft velocity increases from 12.7 m s^{-1} for TS, to 36.0 m s^{-1} for SH. By comparison, the median forecast maximum updraft velocity for H is 20.3 m s^{-1}. The inter-quartile distance for H ranges between 11 m s^{-1} and 34.7 m s^{-1}, compared to 26.7 m s^{-1} and 40.7 m s^{-1} for SH. The difference between the maximum forecast updraft velocity for H and SH is statistically significant at the 95% confidence level (p=0.0048). The relatively large overlap between the 25th and 75th percentile ranges in updraft velocities for TS and H, can once again likely be attributed to the model not forecasting convection on some days and overestimating the intensity of convection on others. Based on the 25th percentile statistics, a lower

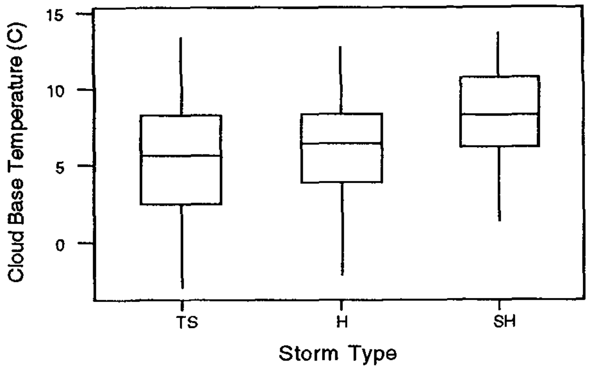

Figure 7: Same as Fig. 5, except for the forecast cloud base temperature.

threshold for the maximum updraft velocity in non-severe hailstorms is 11.0 m s^{-1} and 27 m s^{-1} for severe hailstorms.

The forecast cloud base temperatures do not clearly distinguish between TS and H, with considerable overlap evident between the categories (Fig. 7). Considerable overlap was also present when comparing the forecast cloud base temperatures for H and SH. Nevertheless, some trends are apparent. The median cloud base temperature is 2.6 °C warmer on SH than TS, implying higher in-cloud liquid water content and a favourable hail growth environment. The difference is more noticeable if one considers the 25th percentile for each category, which increases from about 2.5 °C for TS to 6.2 °C for SH. Also, on severe hail days, the forecast cloud base temperature was always greater than 0 °C.

It must be kept in mind that the cloud parameter statistics would be influenced by unrepresentative surface and sounding data used to run the model. Nevertheless, the above results indicate that the model is capable of realistically simulating the cloud structure on most days, even when applied operationally. When compared with the hail model forecasts, our findings suggest that one should exercise caution in using a single cloud model parameter to predict the likelihood and severity of hail, as there were many days in the data set which had similar forecast cloud top heights and/or updraft velocities, but vastly different hail sizes were forecast (and observed) on the ground. This also underscores the importance of including microphysics when forecasting hail size, because by doing so, one takes into account the impact of melting and other processes on the modelled hail growth.

8. SUMMARY AND CONCLUSIONS

This paper documents the performance of a coupled one-dimensional cloud and hail model employed by Weather Modification Inc. (WMI) to forecast the maximum hail size on the ground in Mendoza, Argentina. The model, known as HAILCAST, was run using selected pre-storm soundings released from Cruz Negra (33.45° S; 68.97° W) for 118 days between 15 October 1999 and 31 March 2000. We also investigated the feasibility of using an ensemble hail forecasting technique, to negate the impact of uncertainties in the input data on the modelled hail size.

Four hail forecasting techniques were evaluated using skill scores derived from 2x2 contingency tables for: subjective WMI forecasts, control HAILCAST forecasts, ensemble HAILCAST forecasts and the persistence forecasts. The hail size forecasts were validated against observations of maximum hail diameter obtained from farmers, the Ministry of Economy and press reports. The model control and model ensemble performed marginally better than WMI when forecasting the occurrence of hail, with a HSS of 0.60 and 0.55 respectively. The persistence forecasts displayed the least skill of all four techniques (HSS=0.21). The forecast skill of WMI and HAILCAST when forecasting severe hail (diameter 2.0 cm or more) was also promising. The model control showed the best overall skill when forecasting severe hail, with a HSS of 0.59, compared to 0.53 and 0.50 for the model ensemble and WMI forecasts respectively.

Regarding the accuracy of the hail size category forecasts, the model ensemble and control scored the greatest number of correct forecasts (34%), followed by WMI (21%). Nearly 80% of the WMI forecasts were correct to within one size category. This was substantially higher than for the model control (63%) and ensemble (60%) forecasts. The model ensemble and control were more likely to underestimate the hail size by two or more categories than was WMI. Results for the severe hail days were similar.

HAILCAST showed promising forecast skill when sounding and surface data from the Alberta Hail Project were used to run the model, this was especially true on severe hail days. It is proposed that the inferior performance of HAILCAST in Mendoza could possibly be attributed to the less stringent criteria placed on the proximity soundings and the absence of real-time surface temperature and dew-point observations. Also, the Mendoza observation network may have missed the largest hailstones if they fell outside the agricultural areas.

The cloud model was found to be a useful data stratification tool, with the forecast cloud top height and maximum updraft velocity distinguishing between thunderstorm days with no hail, non-severe hail and severe hail. Based on this data set, the lower thresholds for cloud top height and maximum updraft velocity of severe hailstorms in Mendoza are approximately 10.0 km and 27 m s^{-1} respectively. However, our results suggest that one should not use a single cloud model parameter to predict the likelihood and severity of hail, as there were many days which had similar forecast cloud top heights or updraft velocities, but vastly different hail sizes were forecast (and observed) on the ground.

In conclusion, this study has shown that HAILCAST provides useful guidance for forecasters wishing to predict the maximum expected hail size on the ground in different geographic regions. Preliminary indications are that the ensemble approach improves the skill and accuracy of the model hail forecasts on some days and warrants further investigation. The results shown herein, suggest that HAILCAST shows much promise for future applications as an operational forecasting tool. Future work will employ Numerical Weather Prediction (NWP) model soundings to run HAILCAST. In this way, hail size forecasts could be produced for many grid-points and for different times. Finally, this study has underscored the need for representative sounding and surface data, and the importance of directly modelling the hail growth in order to accurately forecast the maximum expected hail size.

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