18.3 TEMPORAL AND SPATIAL BEHAVIOR OF VISIBILITY OBTAINED FROM RUNWAY VISUAL RANGE (RVR) SENSORS DURING SNOWFALL EVENTS AT SEVERAL MAJOR AIRPORTS

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1. INTRODUCTION

The FAA's forward scatter-based Runway Visual Range (RVR) systems began service in 1994 at several key airports in the U.S and are now used throughout much of the National Airspace System (NAS). Since then, the USDOT Volpe Center has monitored data from a number of airports in order to test RVR system performance. This paper utilizes RVR data collected for this purpose at Minneapolis-St. Paul International Airport (MSP), Chicago/O'Hare International Airport (ORD) and Denver International Airport (DEN) to assess the inherent variability of RVR conditions during snowfall events. Previous studies (Seliga et al., 2001; Hazen et al., 2002) provided insights into RVR variability that occurred at three airports (PDX, SEA and ORD); the results showed evidence of strong spatial and temporal variability over the same airport. The criticality of the events (occurrences of Cat II and III conditions) at all three airports was found to often affect only a few of the runways or portions of a runway at a time. These results are consistent with the designated operational need for RVR sensors at touchdown, midway and liftoff regions of runways.

In this paper, a general statistical analysis of high accumulation snowfall cases is presented, followed by case studies of several select events. The latter focuses on visibility measurements from the entire array of sensors at a particular airport and employs extrapolated values across the entire runway service area. The results illustrate that such events are often highly variable and spatially inhomogeneous. One such event at DEN also provided an opportunity to compare RVR data from one of the RVR sensors with nearby snow gauge measurements made by the National Center for Atmospheric Research (NCAR), courtesy of Dr. Roy Rasmussen. The selection of high accumulation snowfall events was based on the official airport weather METAR reports, that is, periods of time with snow accumulations of 1" or more per hr.

The insights obtained from this and previous papers on this subject are expected to prove valuable for air traffic planning and lead to more effective operations in the future.

1.1 Terminology

Terms used in this report are defined as follows:

RVR is the distance of maximum visibility of runway objects as seen by a pilot approaching for a landing in visibility limiting conditions. In the US, RVR ranges from 100 - 6,500 ft. Reporting increments are: 100 ft for RVR between 100 -1,000 ft; 200 ft for RVR between 1,000 - 3,000 ft; and 500 ft from 3,000 - 6,500 ft. Internationally, RVR reports are in m: flexible steps of 25-60 m for RVR up to 800 m; and 100 m for RVR in the 800-1,500 m range (ICAO, 1995).

RVR Visibility Event is defined as any time when RVR is less than 6,500 ft (US) or 1,600 m (international). The most common causes are fog and snow. In the US, the 3 categories of RVR are: Cat I for 2,400 ≤ RVR ≤ 6,500 ft; Cat II for 1,200 ≤ RVR < 2,400 ft; and Cat III for RVR < 1,200 ft.

Although RVR products, reported to controllers, also depend on ambient light intensity and runway light illumination, the values used here are derived solely from extinction coefficient (σ) measurements using visibility sensors (VS) on active runways. That is, the RVR values are directly derived from σ through Koschmeider's Law for daytime conditions

$$V = 9842.5\ \sigma^{-1} \qquad (1)$$

where V is the visibility in ft and σ is in km^{-1}. This implies σ ranges from 1.5-4.1 km^{-1} for Cat I conditions, from 4.1-8.2 km^{-1} for Cat II and over 8.2 km^{-1} for Cat III.

METAR Data Format is the international standard for official reporting of surface weather conditions based on either human observations or automated observing systems. All weather conditions reported in this paper are derived from Automated Surface Observing System (ASOS) METAR data recorded at the three airports. METAR visibilities are reported in statute miles (SM). Precipitation and obstruction to visibility are also designated as: SN – snow; BLSN – blowing snow; FG – fog; FZFG – freezing fog; and/or BR – mist.

All times are given in Greenwich Mean Standard Time. Subtract six hrs for local time at MSP and ORD; seven hrs for DEN.

2. RVR MEASUREMENTS

Tables 1-3 identify the VS designations and their respective runway configurations. Corresponding maps of the runways at DEN, ORD and MSP are shown in Figs. 1-3, respectively. North is directed upwards in Figs. 1 and 3 and to the right in Fig. 2. The NCAR snow

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gauge system, including temperatures and winds, was located near VS 12 at DEN during the March 15, 2000 event discussed in Sect. 4. The ASOS used for generating the local METAR reports are located near VS04 at DEN, near VS04 at MSP and near the control tower at ORD.

Table 1. ORD Visibility Sensor Designations	
RUNWAY	**VS**
4R22L	VS01 and VS10
22R4L	VS03 and VS11
14R32L	VS04, VS05 and VS06
32R14L	VS07, VS08 and VS09
27R9L	VS03 and VS09
9R27L	VS02 and VS12
18-36	VS11

Table 2. DEN Visibility Sensor Designations	
RUNWAY	**VS**
17L35R	VS01, VS02 and VS03
17R35L	VS04, VS05 and VS06
16-34	VS10, VS11 and VS12
7-25	VS13 and VS14
8-26	VS15 and VS16
There are no VS07, VS08 or VS09 at DEN	

Table 3. MSP Visibility Sensor Designations	
RUNWAY	**VS**
30R12L	VS01 and VS05
12R30L	VS02, VS03 and VS04
14-22	VS06 and VS07

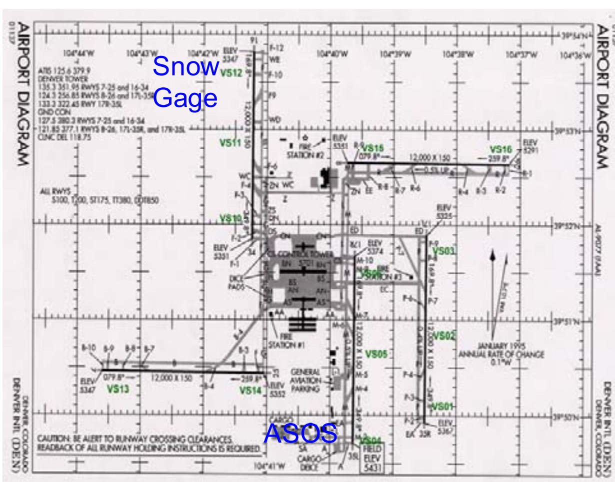

Fig. 1. Runway Map of DEN.

3. GENERAL PROPERTIES

Data for the following time periods were considered:

- DEN from 1998-2000;
- MSP from 1999-2001;
- ORD from 1998-2000.

DEN had: 12 hrs of high accumulation snow reports in 1998 during four days in March and April; 2 hrs in two days in March of 1999; and one hr in March 2000. MSP had: 7 hrs during six days in 1999; 24 hrs during seven days in 2000; and nine hrs during five days in 2001 (data collection stopped after Feb 2001). ORD had: two hrs during one day in 1998; 27 hrs during eight days in 1999; and 17 hrs during seven days in 2000. Thus, ORD had the most frequent high accumulation snow reports, and DEN the least frequent.

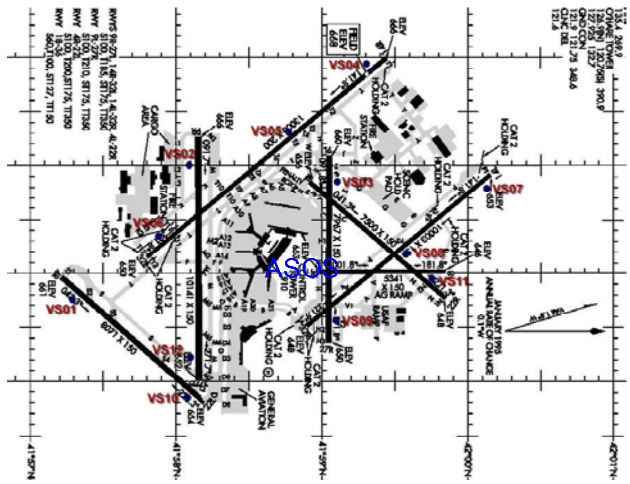

Fig. 2. Runway Map of ORD.

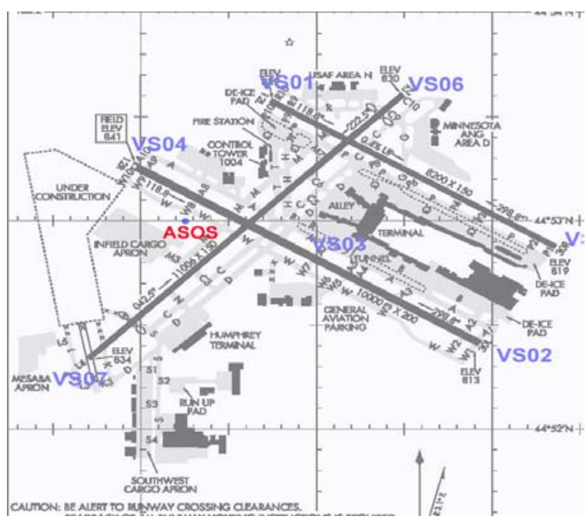

Fig. 3. Runway Map of MSP.

All the above events reported one-inch of snow, except for two inches on:

- DEN: 04/02/98 at 2053;
- MSP: 12/27/99 at 0053;
- ORD: 01/02/99 at 1256; 03/06/99 at 0056; 03/09/99 at 0256; 02/18/00 at 2256 and 2356.

High accumulation snow events occurred on consecutive days as follows:

- DEN: 04/02-03/98;
- MSP: 01/12-13/00; 02/07-08/01; and 02/24-25/01;
- ORD: 01/01-02/99; 03/05-07/99; 01/19-20/00; and 02/18-19/00.

High accumulation snow events occurred on consecutive hrs on the following days:

- DEN: 03/18/98 from 19:53-20:53; 04/02/98 from 19:53-20:52; and 04/02-03/98 from 22:53-02:53.
- MSP: 01/12/00 from 14:53-17:53; 01/13/00 from 00:53-01:53; 01/19/00 from 16:53-19:53; 02/12/00 from 17:53-18:53; 12/28/00 from 16:53-17:53 and 22:53-23:53; 02/07/01 from 17:53-19:53; and 02/25/01 from 08:53-09:53.
- ORD: 01/02/99 from 09:56-12:56 and 14:56-21:56; 01/06/99 from 16:56-17:56; 01/11/99 from 16:56-18:56; 03/05-06/99 from 23:56-01:56; 03/09/99 from 00:56-02:56; 01/20/00 from 00:56-01:56; 01/30/00 from 02:56-03:56; 02/18-19/00 from 20:56-01:56; and 12/11/00 from 13:56-15:56.

Note that ORD had the longest streak of consecutive high accumulation snow reports with eight hrs on Jan 2, 1999 with a four hr streak earlier that day. Another notable streak of six hrs occurred on Feb 18-19, 2000

Figs. 4-6 show the frequency distributions of average extinction coefficients (EXCO) from the VS' at DEN, MSP and ORD, respectively. The averages were taken over all the VS' at each airport and within the hr prior to the high accumulation METAR snow report, and then binned so that, for example, all EXCOs in the 4.0-4.9999 km^{-1} range were plotted in the 4 km^{-1} bin. The EXCOs peaked in the 4 km^{-1} and 6 km^{-1} bins at DEN and the 3 km^{-1} bin at MSP and ORD.

Using daytime as a reference, corresponding RVR values (see Eq. 1) were: mostly in the Cat II range at DEN; mostly Cat I with considerable Cat II at MSP; and mostly Cat II with considerable Cat I and Cat III at ORD.

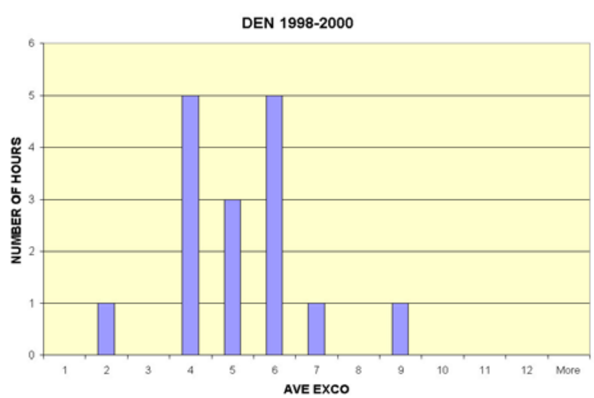

Fig. 4. Average EXCO Frequencies – DEN High Accumulation Cases.

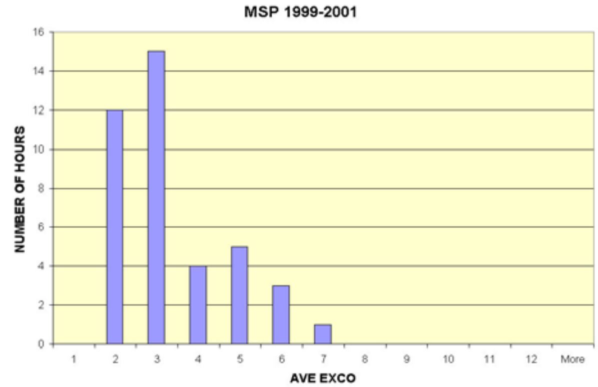

Fig. 5. Average EXCO Frequencies – MSP High Accumulation Cases.

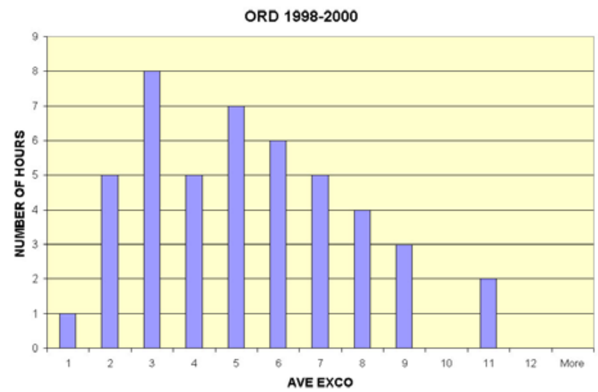

Fig. 6. Average EXCO Frequencies – ORD High Accumulation Cases.

Figs. 7-9 show the distribution of average EXCOs versus the maximum snow intensity reported (SN-, SN and SN+) within the hr prior to the high accumulation METAR snow report. Note that many of these high accumulation reports also included special (SPECIs) METAR reports issued within an hr prior to the high accumulation report. SPECIs typically result from significant changes in snow intensity, winds or present weather. Fig. 7 shows a strong increasing dependence of EXCO on snowfall intensity with some degree of overlap in EXCO distributions between adjacent snowfall intensities. Very different results occurred at MSP and ORD as seen in Figs. 8 and 9. The EXCO ranges were broader and overlapped much more at both MSP and ORD. In fact, the EXCOs increased only slightly from SN- and SN at both MSP and ORD. The mean of the distribution increased from SN to SN+ at ORD as expected, while the EXCOs decreased slightly downward at MSP.

Maximum and minimum average EXCOs for all events were also noted. DEN had a very wide spread between minimum and maximum average EXCOs (1.8-8.0 km^{-1}) for most of its high accumulation events. MSP showed the smallest range (1.0-6.2 km^{-1}). ORD exhibited the largest narrow range between minimum and maximum VS average EXCOs (0.9-10.3 km^{-1}) with several events exceeding 8 km^{-1}.

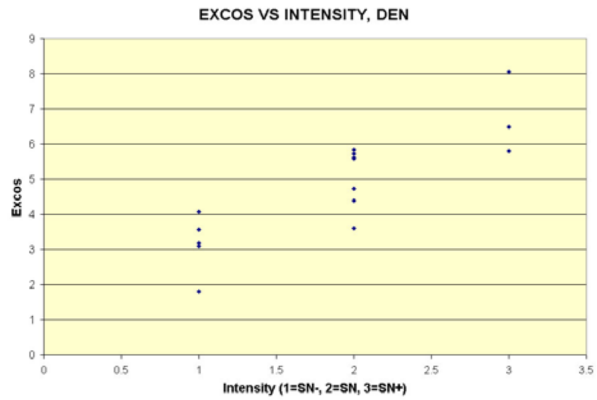

Fig. 7. Average EXCOs vs Snow Intensity at DEN.

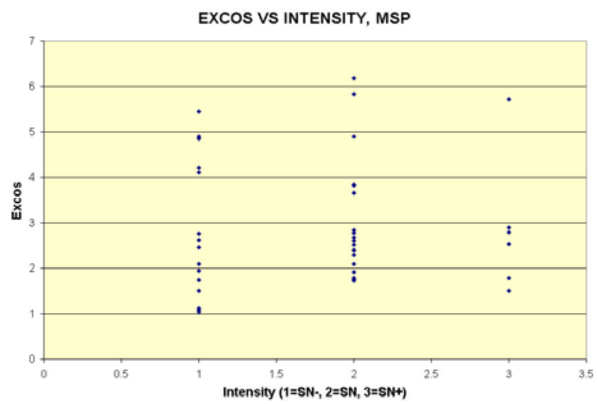

Fig. 8. Average EXCOs vs Snow Intensity at MSP.

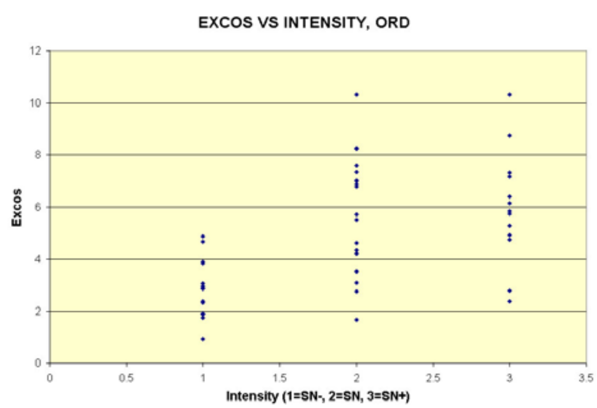

Fig. 9. Average EXCOs vs Snow Intensity at ORD.

4. SPECIFIC EVENTS

This section presents results from a few selected events, including the March 15, 2000 event at DEN that includes a comparison analysis of the nearest VS measurements of σ with NCAR snow gauge data. Five-minute running averages of the data were used for all animations in order to reduce variabilities that may have been associated with blowing snow effects. The animations cover only those periods of high snowfall accumulation and include the entire snow gauge DEN event of the March 15, 2000.

DEN Event of March 15, 2000: Snow gauge Comparison

Fig. 10 shows a comparison of 5-minute running averages of NCAR snow gauge and VS data during a snow event at DEN on March 15, 2000. The snow gauge was located nearest VS 12 at DEN at a distance of approximately 1,500 ft west of the VS. For this comparison, the snow gauge data were transformed to equivalent values of σ through normalization of the mean snowfall rates and σ's. The maximum correlation was found between the snow gauge sensor data and VS12 when a five-minute time lag was introduced between the two sensors. The results show a high degree of correlation between VS12 and the normalized snow gauge readings throughout most of the event. Beginning at around 160 min into the event, there is a period of around 20 min when the correlation breaks down (gage increases while VS decreases). Interestingly, during this time, the winds at the snow gauge site experienced a significant change, suggesting that the discrepancy between the gage and VS measurements are related to this change and, thus, can be reasonably attributed to spatial inhomogeneity in the snowfall occurring at the gage and VS sites. The key result gleaned from this comparison is the potential of using VS measurements of σ to infer snowfall rates in the airport environment.

DEN Event of March 15, 2000: Airport-Wide Results

The METAR reports indicated SN- from 16:46 through 19:14 that then intensified to SN from 19:53 through 23:53. A high accumulation (SNINCR) report of one inch per hr was issued at 23:53. The winds blew generally from the north during the event with speeds ranging from 9-14 kt. Visibilities decreased from 7 SM at 16:53 to 0.25 SM by 19:05 and remained at 0.25 SM the rest of the day. Temperatures were at 2^{o} C at 16:53 and decreased to 0^{o} C at 19:14 and further to -1^{o} C at 20:53, remaining at -1^{o} C the rest of the day. Dew points were at 0^{o} or -1^{o} C during the event until dropping to -2^{o} at 23:53. Mist was recorded from 17:30-19:14, then fog at 19:53 and freezing fog from 20:53 onwards.

An animation of this event was produced to show spatial and temporal variations over the entire airport. The normalized snow gauge data were used as an additional "VS" for this purpose. The snow gauge recorded data between 17:50-23:58. VS14 was not operating during that event and was thus excluded. The animation relies on interpolation of EXCOs obtained at the VS locations. A sample screen capture of the event is shown in Fig. 11. Data from the snow gauge and from the METAR reports are shown across the top of Fig. 11. Playback of the animation revealed considerable spatial and temporal variations within the runway area, with EXCOs occasionally peaking near the snow gauge location. The variations occurred in a time scale of minutes. Examples of such spatial inhomogeneities were at 20:20 when the EXCOs ranged from ~1 km^{-1} near VS05 to ~5 km^{-1} at VS12. Meanwhile, the snow gauge had an “EXCO” of ~3 km^{-1}. Another was at ~20:54 when the EXCOs ranged from a low of ~2 km^{-1} from VS02, VS04 and VS16 while the snow gauge registered an “EXCO” of ~7 km^{-1}. The highest EXCO from a regular VS was ~5 km^{-1} by VS10. The visibility was 0.25 SM with SN and FZFG at the 20:53 official observation time. The wind direction was 350° and the speed 9 kt. The temperature and dew point were both –1° C. The snow gauge had the highest “EXCOs” off and on between 19:50-20:02 and from 20:25-21:02.

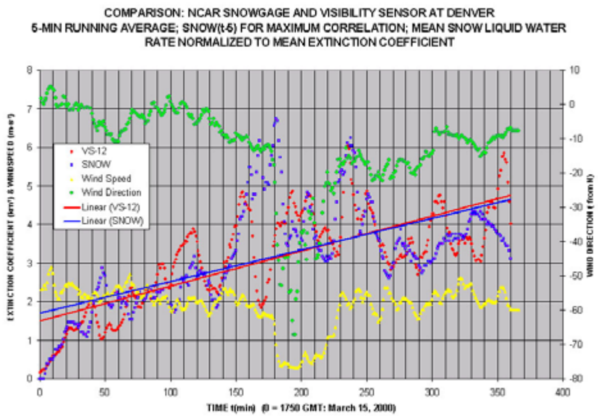

Fig. 10. Comparison of VS12 EXCO with NCAR Snow gauge at DEN on March 15, 2000.

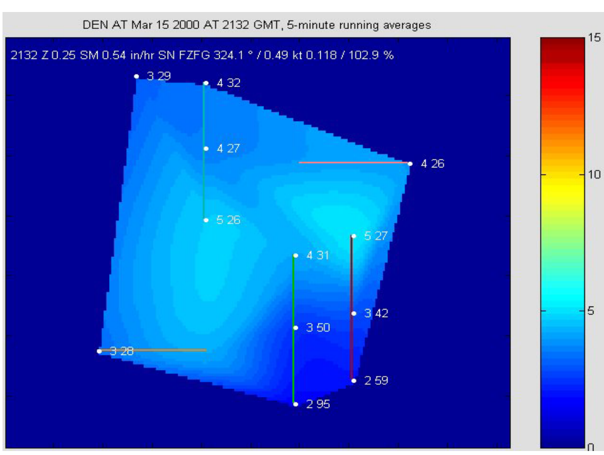

Fig. 11. Sample Screen Capture of EXCO Animation of DEN Event of March 15, 2000.

DEN Event of Apr. 2-3, 1998

This event was selected because several hrs of high accumulation METAR snow reports included two inches of snowfall between 19:54-20:53 and consecutive high snow accumulation reports between 22:53-02:53. Numerous SPECIs were issued within the hr prior to the 19:53 and 01:53 reports, indicating considerable variability in wind speeds, snow intensity and visibility occurring on a time scale of tens of minutes or less and spatial scales on the order of runway lengths.

SN- was reported at 16:35 with visibility decreasing from 3 SM at 16:39 to 1.5 SM at 17:31, improving to 3 SM at 17:39, and then decreasing after 18:43 to 1.75 SM then to 0.5 SM just three minutes later. Visibility deteriorated to less than 0.25 SM between 19:43-02:15 and improved to 0.25 SM at 02:53 until 09:30. Visibility fluctuated from 09:53-14:53 and improved steadily afterwards. Snow intensity went from SN- to SN at 18:46, and then to SN+ at 19:13. SN+ was reported until 20:53, then SN from 21:08-00:53. SN- was reported after 01:04 except SN at 01:17 and 02:53. SN- ended at 12:09.

The wind generally blew from NNE to ENE early on in the event with frequent gusts up to 26 kt from 17:31-19:01. The highest sustained wind was 22 kt at 17:39. The winds decreased to 7-14 kt after 19:13 during the heaviest snow accumulating part of the event and afterwards. The wind direction shifted to N and NW after 22:29 and shifted once more to the W at 10:53.

Temperatures started at 3° C and slowly declined to 0° or 1° C by the time of heaviest snow accumulation and afterwards (after 18:46). Dew point depressions were 2° or less during heaviest snow accumulations and afterwards and were up to 4° during the early part of the event.

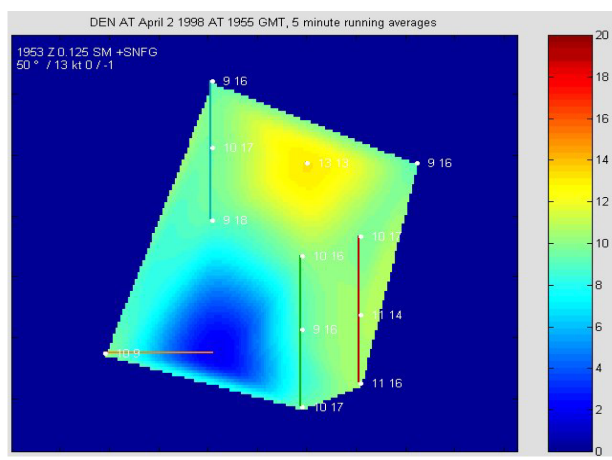

Fig. 12 – Sample Screen capture of animation of DEN Event of April 2-3, 1998.

Animations showed fairly rapid spatial changes in EXCOs over the airport runway area during the period of heaviest snow accumulations. A sample screen shot is shown in Fig. 12. The time scales of these spatial variations were on the order of several minutes, while the spatial scales were on the order of runway lengths. EXCO readings of ~20 km^{-1} were recorded at times from VS15 and vicinity with considerable variations of EXCOs recorded elsewhere in the runway area. One such time was at 20:04 when the EXCOs ranged from ~2 km^{-1} near

VS14, located SSE of the terminal, to ~19 km^{-1} near VS15, located NNE of the terminal. EXCOs were generally higher in the NW part of the runway area and lesser in the SW part of the runway area during much of this event. The METAR report issued at 20:04 indicated SN+ and FG with a visibility <0.25 SM. The temperature was 0° C and dew point –1° C. The wind direction was NE at 50° and blew at 13 kt. From about 22:28-23:58, the highest EXCOs (up to ~15 km^{-1}) were generally occurring in the NE part of the runway area while the lowest EXCOs (~2-4 km^{-1}) were occurring in the SE part of the runway area. The visibility remained <0.25 SM with SN and FG reported from 22:29 through the end of the day. The winds were from the NNW at 7-8 kt. The temperature was 0° C and dew point –1° C. The trend continued for a few hours on the 3rd except with high EXCOs (up to 21 km^{-1}) extending south from the NW part of the runway area from 00:47-01:25, with VS10, VS11 and VS12 (RW 16-34) all experiencing high EXCOs at times.

MSP Event of Feb. 7, 2001

This event is a case when rapid snow accumulations were reported even though no SN+ notations were evident on the METAR reports. One inch per hr was reported from 17:53-19:53 and at 21:53 with SN- and occasional SN reported.

SN- started at 14:03 and stayed SN- except for SN at 17:07, 17:53, 18:53-19:11, and 20:53. The visibility was 2.5 SM at 14:09 then decreased to 0.5 SM by 14:53. The visibility then fluctuated from 0.5 to 1.75 SM for the remainder of the day. The winds were from the NNE at the start of the event then shifted to E to SE after 15:53, then slowly shifted to ENE by the end of the day. The wind speeds ranged from 4-13 kt during the event. Temperatures started at –7° C, and then slowly decreased to –5° C by the end of the day. The dew points were generally a degree or two less than the temperatures.

An animation was produced covering the heaviest snow period of the event. A sample screen shot is shown in Fig. 13. The spatial variations were less pronounced as the previous cases, but still exhibited time scales on the order of several minutes at times. Probably the most pronounced spatial variation was at ~19:44 when the EXCOs ranged from ~2 km^{-1} over the central and southern parts of the runway area to ~4 km^{-1} near the NE edge of the runway area. The visibility was 0.75 SM at 19:36 with –SN and BR reported. The wind direction was 100° at a speed of 9 kt. The temperature was –5° C and dew point -7° C. The maximum EXCOs were less than the other events.

ORD Event of Feb 18-19, 2000

This event had six consecutive hrs of high snow accumulation reports from 20:56-01:56 with two inches per hr reported at 22:56 and 23:56. SN- started at 06:18 with visibility at 6 SM at 06:27. Visibility decreased to 2 SM at 08:23, increased to 4 SM at 09:03, decreased again to 0.75 SM at 10:03 and then varied from 0.25 to 3 SM until 19:56. Visibility remained at 0.25 SM or less the rest of Feb 18th and at 00:56 on the 19th. Visibility went to a SM from 01:33-02:32 and then improved to 2 SM by 03:23. After 05:56, visibility returned to normal.

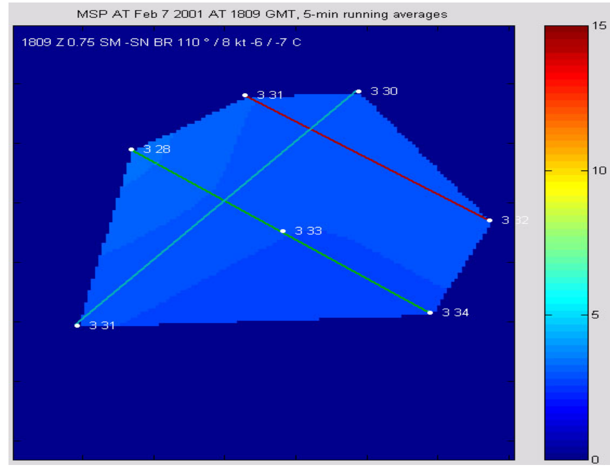

Fig. 13 – Sample Screen capture of animation of MSP Event of Feb. 7, 2001.

SN- fell from onset through 12:14, and then intensified briefly to SN+ by 13:56, then back to SN- from 15:17-16:56 and 17:56-19:34 after a brief SN at 17:09. There was a long period of SN+ from 19:56-22:56 except SN at 21:49; then SN from 23:56-00:56 and SN- from 01:33-05:44 when SN- ended. Winds started from the E then gradually shifted to NE during the heaviest snow and to the end of the 18th. Sustained wind speeds ranged from about 15-19 kt with gusts as high as 27 kt during the heaviest snow. The winds then shifted to N-NE on the 18th with speeds from about 9-13 kt.

Temperatures varied little during the event and were generally –2° or –1° C. Dew points were at most a degree or two less than the temperatures during almost the entire event.

An animation was generated for this event, covering the heavy snow accumulation period. A sample screen shot is shown in Fig. 14. Spatial variations occurred with time scales on the order of several minutes. The variations were generally moderate such as at 19:19 when the EXCOs ranged from ~10 to ~13 km^{-1} throughout the runway area.

5. CONCLUSIONS

This paper examined snow events at DEN, MSP and ORD, focusing on high accumulation cases derived from METAR reports. The results showed that care must be exercised in associating visibility conditions with snowfall intensity. Several low visibility events were used to illustrate details of spatial and temporal variability over the airports. One event at DEN incorporated a comparison of one RVR sensor EXCO measurements with snow gauge data provided by NCAR; the excellent correlation between EXCO and snowfall rate suggests that RVR sensors might prove useful for monitoring snowfall rates over the airport domain. The interpolated EXCO measurements provide important insights into behavior of RVR during SN events. The spatial and temporal variations were often significant over the airport with time scales of the order of minutes. Interpolations of sensor data were found useful for assessing visibility over the most critical parts of the airport. The results also suggest that a more complete picture of changing visibility would be possible if additional sensors were placed strategically along or outside the airport perimeter. Full understanding of the snowfall-visibility relationship, including their relationship to forcing meteorological conditions (not considered here), will require data gathered and analyzed over many years at many airports. Relating these findings to actual and projected airport operational scenarios should lead to enhanced safety and airport efficiency.

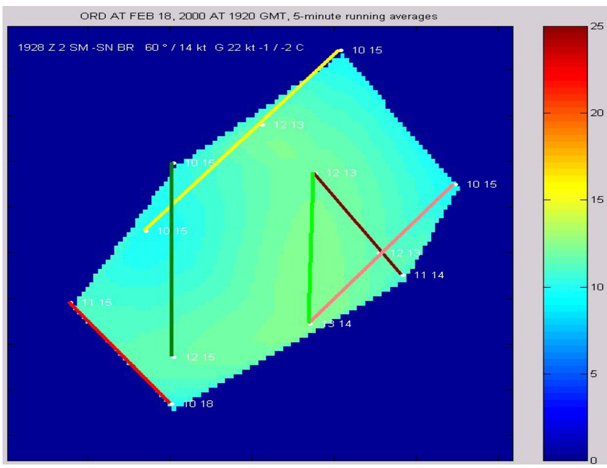

Fig. 14 – Sample Screen capture of animation of ORD Event of Feb. 18, 2000

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