Use of Enhanced IR/Visible Satellite Imagery to Determine Heavy Snow Areas

SAMUEL K. BECKMAN

Satellite Field Services Station, National Severe Storms Forecast Center, Kansas City, MO 64106

(Manuscript received 28 September 1985, in final form 23 February 1987)

ABSTRACT

Interpretation techniques are established which relate heavy snow (100 mm or more in a 12 h period) areas to real-time infrared and visible geostationary satellite imagery. An initial collection of cases totaled about 75 during the period from the fall of 1979 to the spring of 1984. The main area of concern extended from the Rockies to the Appalachians.

By using conventional surface and upper air data and numerical model output from the LFM-II, relationships were established between heavy snow occurrences and cloud patterns in the satellite imagery. The different cloud patterns and flow regimes suggest a classification of heavy snow events into four main types: High Plains cyclogenesis, northwest and southwest flow short-wave troughs, and orographic. Each type has preferred geographical locations, common snowfall durations, storm totals, and band widths and lengths. The snowfall maximum with each storm is influenced by the strength and movement of the system and the structure of the moist layer. Subtle mesoscale features on the satellite imagery are shown to relate to the local snowfall maximum.

Real-time analysis and forecasting techniques are discussed. The heavy snow threat is assessed by a three-step analysis method. An example demonstrates how future trends in heavy snow can be predicted.

1. Introduction

The advent of operational geostationary meteorological satellite imagery has added a new dimension to our understanding of the atmosphere. During the past 10 years, the availability of near real-time infrared (IR) imagery has provided 24 h viewing of the atmosphere at half-hour intervals.

The main purpose of this paper is to establish general interpretation techniques which relate heavy snow areas to IR and visible geostationary satellite imagery and demonstrate how the satellite imagery can be used to formulate rules to aid in predicting development and progression of the heavy snow.

Heavy snow is one of the most challenging forecast problems for meteorologists during the cold season because of the limited extent and abrupt decreases in storm totals near the snow band edges. Because of the disabling effect of a heavy snowfall on transportation and the public, it should be adequately informed by timely watches, warnings, and advisories relating to heavy snow.

Most early efforts relied on synoptic-climatological techniques for locating preliminary heavy snow threat areas (Faucett and Saylor, 1965; Goree and Younkin, 1966; Younkin, 1968; Browne and Younkin, 1970). Synoptic-scale features in the initial 1200 and 0000 UTC surface and upper air data, such as mid- and upper-level low centers and jets, as well as computed fields, i.e., 12 h pressure height fall centers, 500 mb absolute vorticity, and various pressure layer thicknesses, were incorporated in forecast techniques to locate heavy snow threat areas. The threat areas were positioned relative to the expected movement of the features during subsequent 12-h periods. A 6 year study by Weber (1978) listed subjective rules using operational National Weather Service (NWS) analyses, mainly height fall centers, to predict the path of heavy snow.

Many forecast offices have unpublished in-house heavy snow forecasting "rules of thumb." Specific cases have been documented in NWS interdepartmental notes (U.S. Weather Bureau, 1967) but distribution is generally limited to the regions where the events occur.

The use of objective guidance from numerical models in the form of precipitation probabilities to predict heavy snow has been addressed by Ostby (1974). Recently it has been shown how the Limited-area Fine Mesh (LFM) model output via Model Output Statistics (MOS) can be applied to expanding snow amount categories and extending the forecast periods (Bocchieri, 1983). Numerical guidance, though, which relies so heavily on the accuracy of the model, has its limitations (Gyakum, 1984; Schultz, 1980; Vinzani and Chagnon, 1981; Schechter, 1984). A goal of this study is to incorporate some of the National Meteorological Center (NMC) model guidance.

---

1 Heavy snow is defined as 4 or more inches in a 12 h period. Although there are allowable variations in certain regions of the United States, this criteria follows the general definition of the National Weather Service Operations Manual—Winter Weather Warnings (C-42). Observed snow amounts were recorded in inches but for the purpose of using the International System of Units (S.I.) in this paper, the following conversions were made: 4 inches = 100 mm, 6 inches = 150 mm, 1 foot = 300 mm, etc.
Parmenter (1976) was one of the first to publish a study of several cases which demonstrated the contribution of satellite data in detecting areas of cyclogenesis and heavy precipitation associated with eastern United States coastal storms. The satellite imagery were polar orbiting and limited to an early morning and an early afternoon pass each day.

Recent winter weather forecasting studies have utilized geostationary satellite imagery which are available every half hour, 24 hours a day, through the GOES Central Data Distribution System (CDDS). Scofield and Spayd (1983) developed a GOES satellite technique for estimating precipitation from extratropical cyclones during the winter season. The technique combines radar and satellite data with surface and upper air observations to develop a quantitative scheme which estimates hourly liquid and frozen precipitation. The technique is operationally used by the Synoptic Analysis Branch (SAB in NESDIS) meteorologists to provide winter storm precipitation estimates in very short range (0 to 3 h) forecasts called OUTLOOKS. Estimates and OUTLOOKS are given to National Weather Service Forecast Offices, River Forecast Centers and the Heavy Precipitation Branch (HPB) of NMC. Kadin (1982) and Scofield and Spayd (1984) describe how cloud signatures in enhanced IR GOES satellite imagery locate and time the occurrence of heavy snow.

The purpose of this paper is to expand on the initial work by Kadin by showing how heavy snow events can be recognized by cloud patterns in the visible and enhanced IR GOES satellite imagery. First, data collection and analysis will be described. Secondly, case studies relating the conventional weather observations at the surface and in the upper atmosphere to half-hour satellite imagery are presented and a heavy snow classification system is introduced. Next, it is demonstrated how subtle mesoscale features in the imagery are related to local snowfall maxima. Finally, real-time analysis and forecasting techniques are developed to assist the forecaster in selecting the best threat area for heavy snow.

2. Data collection and analysis

Meteorologists at the Kansas City Satellite Field Services Station (SFSS) have been accumulating data during heavy snow events since the spring of 1981. Whenever moderate or greater intensity snow was observed at official weather reporting sites over the SFSS area of responsibility (i.e., basically the area over the central United States from the Rockies to the Appalachians), data were collected. These consisted of primarily half-hour visible/IR satellite imagery, hourly and special surface weather observations, initial, 12 and 24 h forecast LFM-II thicknesses and standard pressure level charts, radar summary charts and special statements, storm bulletins and summaries from the Weather Service offices. Most of this information was relayed via the AFOS (Automation of Field Operations and Services) network or the FAA-WB-604 line through the Centralized Storm Information System (CSIS) (Anthony et al., 1982).

Satellite imagery are provided in two ways to the SFSS. One is through the GOES CDDS which sends an analog image by land telephone lines from Washington, D.C. to hard copy devices at Kansas City. The other method of receiving satellite imagery is directly by an antenna on the roof of the Federal Building in Kansas City via CSIS. Imagery are obtained every half-hour: the IR 24 hours a day, and, of course, the visible during the daylight hours. These data provide a unique collection of information which the meteorologist can use to observe the atmosphere from the large synoptic scale down to the mesoscale. Most importantly, satellite imagery can fill both the spatial and temporal gap between the surface standard and upper air reporting sites.

Most of the IR imagery received through the CDDS are enhanced by a standard curve adopted by the NWS called the “M5” (Clark, 1983). A description of the curve and an example are furnished in Fig. 1. This curve was designed with “all-around” features that would not be restricted seasonally. The steep slope in the first three temperature segments gives better definition to low and middle clouds. The remaining segments define convective cloud tops and estimate precipitation rates (Scofield and Spayd, 1983). The first level, or medium grey (−32° to −41°C), and second level, light grey (−42° to −52°C), enhancement segments will be shown to be important in heavy snow interpretation.

Surface reports were collected through the Service “A” communications network at the time the observations were made. This included all regular and special observations at the official weather service, military and flight service stations. These reports were included in the real-time assessment of heavy snow and were particularly helpful in determining the beginning or ending of the different snowfall intensities. No data were used from any of the special mesonetworks. Twenty-four hour snowfall totals from cooperative observers, which are collected at the state forecast centers and River Forecast Centers, were invaluable in determining the extent of the snow accumulations in post analysis.

Special weather statements, bulletins and state weather summaries issued by the NWS offices were also extremely helpful in evaluating the extent of the snow at the time of the event.

In most of the cases, at least some analysis was accomplished in real time. Snowfall rates were matched with the imagery as it occurred. It is difficult to determine from the hourly observations how much snow is falling when light intensity is reported since the condition “very light” is no longer used in official observation except occasionally as a remark. Visibilities have to be less than 1 km to meet the criteria for moderate intensity; any distance greater than 1 km is light in-
indicates just prolonged flurries. The remarks portion of the observations were very helpful, particularly regarding snow increase (SNOINCR 1, 3, 6) which state the accumulations during the past hour (if ≥ 25 mm), accumulations since the last six hourly observations (3 inches or 75 mm) and snowfall totals on the ground (6 inches or 150 mm).

Many cases were collected through the winters of 1981/82, 1982/83 and 1983/84. Basically, the final number of cases was selected using the criteria of amount (100 mm or more in a 12-h period) and areal coverage (at least 2 × 3 deg latitude grid, covering at least portions of two states and two or more official observation sites).

A summary of the nearly complete cases used in this study is presented in Table 1. There is almost an equal number of cases in November, December, January and February. The majority are in March with several cases extending into the first week of April. Although this study did not contain all of the heavy snow occurrences, it did include most of the significant record breaking rare or newsworthy events, e.g., the January 1982 Texas storm, January 1982 Minneapolis and St. Louis storms, the 1982 Denver Christmas storm and the March 1983 Nebraska/northwest Iowa storm.

The cases could have been divided by geographical area as commonly done in past studies of this type. Since we are relating the "weather" to satellite cloud signatures, it is natural to separate the events into four categories according to the main atmospheric feature causing the heavy snow: High Plains cyclogenesis, mesoscale shortwave troughs which are subdivided into northwest and southwest flow, and orographic. Geographical areas for the cases are listed in Table 1. The most common are Northern Plains/Upper Mississippi Valley, Middle Mississippi and Ohio Valleys, High Plains and Rockies, and the Gulf states. Figure 2 shows the areal coverage of the heavy snow for all the events in Table 1. The greatest concentration of cases was from the Central Plains to the Great Lakes.

During the postanalysis phase, each case was placed into one of the four categories. All hourly and special observations of moderate or greater intensity snow were recorded and matched with the satellite image closest to the time of the event. Particular attention was given to the image prior to the snowfall intensity changes, the beginning and ending of the precipitation and any other hydrometeors occurring with the snow such as ice pellets, fog, liquid precipitation or thunderstorms.

The image prior to intensity changes was important in assessing if it would have provided any clues for future trends.

---

Fig. 1. (a) Graphical display of Mb enhancement curve showing temperature segments in different shades of grey. (b) Satellite image annotated with Mb curve temperature segments.

---

2 According to the Federal Meteorological Handbook No. 1 (FMH No. 1), this is an acceptable standard reporting technique for civil and military agencies in the United States in agreement with the WMO and international and domestic aviation interests.
Table 1. List of cases used in study showing the date, area and items of significance.

<table>
<thead>
<tr>
<th>Date</th>
<th>Area</th>
<th>Note of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 Nov. 1981</td>
<td>Upper Mississippi Valley</td>
<td>NW flow: marginal data</td>
</tr>
<tr>
<td>16 Dec. 1981</td>
<td>Lower Missouri River Valley</td>
<td>NW flow: N of model track</td>
</tr>
<tr>
<td>12–14 Jan. 1982</td>
<td>Northern Gulf States</td>
<td>Record snow: 40 cm max</td>
</tr>
<tr>
<td>20 Jan. 1982</td>
<td>Upper Missouri Valley</td>
<td>24 h record MSP: 41 cm</td>
</tr>
<tr>
<td>30–31 Jan. 1982</td>
<td>Ozarks–Ohio Valley</td>
<td>Thunder 48 cm STL 60 cm max IL</td>
</tr>
<tr>
<td>3 Feb. 1982</td>
<td>Mid-Mississippi/Ohio Valley</td>
<td>30 cm new snow STL</td>
</tr>
<tr>
<td>4 Feb. 1982</td>
<td>Central Plains</td>
<td>Small vorticity max</td>
</tr>
<tr>
<td>8 Feb. 1982</td>
<td>Lower Missouri/Ohio River valleys</td>
<td>PVA &amp; warm air advection</td>
</tr>
<tr>
<td>4 Mar. 1982</td>
<td>Southeastern Nebraska/Northern Illinois</td>
<td>Good snow field next day</td>
</tr>
<tr>
<td>8 Mar. 1982</td>
<td>Upper Mississippi Valley</td>
<td>NW flow: marginal case</td>
</tr>
<tr>
<td>20 Mar. 1982</td>
<td>Upper Mississippi Valley</td>
<td>T to south E–W cloud band</td>
</tr>
<tr>
<td>5 Apr. 1982</td>
<td>Mid-Mississippi Valley/Lower Great Lakes</td>
<td>Near blizzard CHI/MKE</td>
</tr>
<tr>
<td>19–20 Oct. 1982</td>
<td>Upper Mississippi Valley</td>
<td>Thunder: 30 cm local</td>
</tr>
<tr>
<td>11–12 Nov. 1982</td>
<td>Nebraska Panhandle–Upper Mississippi</td>
<td>Thunder: 30 cm max</td>
</tr>
<tr>
<td>24–25 Dec. 1982</td>
<td>Valley</td>
<td>60 cm DEN record</td>
</tr>
<tr>
<td>27–28 Dec. 1982</td>
<td>High Plains</td>
<td>5 cm h7 MVP area</td>
</tr>
<tr>
<td>1 Jan. 1983</td>
<td>Southern Rockies/Plains</td>
<td>ELP season record</td>
</tr>
<tr>
<td>26–27 Mar. 1983</td>
<td>Northeastern Nebraska/NW Iowa</td>
<td>Deep low</td>
</tr>
<tr>
<td>6–7 Apr. 1983</td>
<td>Southern Rockies</td>
<td>ELP record (upslope)</td>
</tr>
<tr>
<td>8–9 Nov. 1983</td>
<td>Nebraska–Upper Mississippi Valley</td>
<td>Wet snow: marginal case</td>
</tr>
<tr>
<td>21–22 Nov. 1983</td>
<td>Central Rockies/Western Dakotas</td>
<td>Strong vorticity max</td>
</tr>
<tr>
<td>23 Nov. 1983</td>
<td>Upper Mississippi Valley</td>
<td>DLH 41 cm 24-hr record</td>
</tr>
<tr>
<td>26–28 Nov. 1983</td>
<td>High Plains–Southern Minnesota</td>
<td>400 mi I-70 closed</td>
</tr>
<tr>
<td>15–16 Dec. 1983</td>
<td>Southern Plains</td>
<td>N TX unusual snow</td>
</tr>
<tr>
<td>17–18 Jan. 1984</td>
<td>Tennessee/Ohio valleys</td>
<td>KY coal fields</td>
</tr>
<tr>
<td>29–30 Jan. 1984</td>
<td>East Dakotas–Lower Great Lakes</td>
<td>NW flow</td>
</tr>
<tr>
<td>18–19 Feb. 1984</td>
<td>High Plains–Upper Mississippi Valley</td>
<td>Record 38 cm GRI 50 cm OFK</td>
</tr>
<tr>
<td>26–27 Feb. 1984</td>
<td>Ozarks–Ohio Valley</td>
<td>Snow field next day</td>
</tr>
<tr>
<td>4–5 Mar. 1984</td>
<td>Upper Mississippi Valley</td>
<td>Well-defined vorticity comma</td>
</tr>
<tr>
<td>5 Mar. 1984</td>
<td>Southern Rockies</td>
<td>Upslope at ELP</td>
</tr>
<tr>
<td>7–8 Mar. 1984</td>
<td>Upper Mississippi Valley–Lower Great Lakes</td>
<td>NW flow</td>
</tr>
<tr>
<td>12 Mar. 1984</td>
<td>Kansas–Central Illinois</td>
<td>Marginal case</td>
</tr>
<tr>
<td>23 Mar. 1984</td>
<td>Texas Panhandle–SW Kansas</td>
<td>Vort max &amp; upslope case</td>
</tr>
<tr>
<td>2–3 Apr. 1984</td>
<td>Western Nebraska</td>
<td>60 cm snow total</td>
</tr>
</tbody>
</table>

Occasionally, when cloud cover was at a minimum, visible imagery a day or so after the event would reveal the extent of the snow field. Official 24 h snow totals, which were received around 1200 UTC from the regular synoptic reporting stations, were supplemented by reports from cooperative observers and plotted on the satellite image or plotting chart. This information was then matched with the corresponding imagery at the time of the event to refine the areas where the heaviest snow was most likely occurring at that time. This technique was extremely useful at many locations over the Central Plains and Dakotas because of the large spacing between official hourly reporting stations. Also, many of these stations close during part of the night, resulting in little information on the intensity or extent of the snow during the event. This is when satellite imagery becomes invaluable, once relationships are determined between the heavy snow and the imagery.

Since nearly all numerical guidance to the field forecaster was generated by the LFM-II (Schechter, 1984), selected initial and predicted output from the model were compared with the satellite cloud patterns and actual snowfall rates to determine if any relationships existed. This portion of the project will be discussed in section 5 when a forecast technique is developed.

Early cases suggested the best parameters which could be readily applied were the 1000–500 mb thickness and 850 mb temperature. These fields in the initial, 12 and, occasionally, 24 h forecast periods were then routinely incorporated in the remaining cases as they occurred to see how real-time application of the relationships worked out. It should be remembered that much of the development of satellite imagery snowfall rates and model parameter relationships were accomplished during the time of the events. The main purpose during this phase of the study was to get a better grasp of the heavy snow threat in a real-time operational sense, which is the primary function of the Satellite Field Services Stations.

3 The LFM-II forecast model remains part of the numerical forecast schemes; however, during the spring of 1985, NMC implemented the Nested Grid Model (NGM) which is a primitive equation model supplement to the forecast guidance provided by the LFM-II. The NGM is a forecast component of the Regional Analysis and Forecast System (RAFS). Although specific output from the LFM-II was studied in this paper, the same favorable parameters should be applicable from similar models.
3. Heavy snow classification

Classification of events into the four categories defined in section 2 evolved from experience and review of all the heavy snow cases. The orographic type contained the fewest number of complete cases because only the southern Rockies was included in this type. In the High Plains cyclogensis cases no distinction was made between the heavy snow produced by the dynamics of the developing system and orographic influences from the lee of the Rockies into the High Plains. The characteristics and common geographical areas for each of the four heavy snow types are presented in Table 2. Occasionally an event will be a combination of two types during its existence. Cloud-heavy snow relationships are still valid for each type but there is also a time or space transition zone between each type.

a. High Plains cyclogensis

Although cyclogensis is defined in the Glossary of Meteorology (1959) as “any development or strengthening of cyclonic circulation in the atmosphere” and “should not be used synonymously with deepening,” many operational meteorologists still equate the two. Cyclogensis can occur any place where the atmospheric conditions are favorable for development and strengthening of the cyclonic circulation in a baroclinic zone.

The two most frequent areas of cyclogensis over North America are in the lee of the Alberta and Colorado/New Mexico Rockies; hence the terms “Alberta Clipper” and “Panhandle Hook,” respectively (Harms, 1973). Many authors have expounded on storm developments over these areas during the past few decades. Galway and Pearson (1981) have related severe thunderstorm, tornadoes and heavy snow/ice areas to the mean track of surface lows which develop in the Oklahoma/Texas Panhandle area. Faucett and Saylor (1965) studied storms which formed in the lee of the Colorado Rockies and looked at the relationships between the probability and form of precipitation and surface/500 mb circulation patterns during the
period 12 h before to 48 h after cyclogenesis. The northwest flow, short-wave trough, heavy snow type will usually be Alberta Clippers. At present, the focus will be on storms which are born in the lee of the Colorado Rockies.

Storms which develop in the lee of the Colorado Rockies into the adjacent High Plains are, depending on availability of abundant Gulf of Mexico moisture, prolific snow producers. A large area of 250–300 mm (10–12 inch) snowfall accumulation is common on the north side of the system over Nebraska and northeast Colorado with typical snow maximum accumulations from this type of storm near 600 mm (2 feet) (see Table 2). In this study, the main characteristic of this type storm is a surface low (at least two closed isobars at the standard 4 mb interval) and a closed low (at least one standard 60 m interval height contour) at the 700 and 500 mb isobaric surfaces.

Boatman and Reinking (1984) utilized aircraft soundings and surface data from the PROFS mesonetwork in Colorado to examine the kinematic and microphysical processes that generate winter precipitation over this area. They found that the dynamic support aloft in the deep upslope storms is aided by the topography, and latent heat released as moisture is drawn into the system from the Gulf of California (midlevels at first) and Gulf of Mexico (low levels later). In the early phases of these storms, the upslope effect on vertical motion and precipitation is large but it becomes relatively less significant as the storms move east.

A classic example of High Plains cyclogenesis occurred 26–28 November 1983. Storms of this size develop for 12–18 h, allowing for a deep moisture layer originating from the Gulf of Mexico to wrap around the system, producing snowfall rates of 20–30 mm per hour. Strong gusty winds on the west side of these systems create blizzard conditions and dangerous wind chill temperatures. Travel becomes impossible and many cities are isolated. This was the case over northeast Colorado the night of the twenty sixth and morning of the twenty seventh. Snow drifts of 1–2 m were common.

The sequence of satellite imagery in Fig. 3 vividly portrays the relationship between the enhanced IR satellite imagery and heavy snow. Surface and upper air composite charts during this time are shown in Fig. 4. Observing sites, reporting moderate or greater intensity snow during most of the period between 1200 and 2000 UTC, are indicated by dots on the imagery. Many observations in the remarks section indicated a snowfall rate of 25 mm h\(^{-1}\). Fortunately, this event occurred during the day when hourly observations are the most numerous so it was relatively simple matching the snowfall intensities to the enhanced IR satellite imagery.

At 1100 UTC on the twenty seventh (Fig. 3a), light to moderate intensity rain was falling from the cloud band extending from northcentral Texas across Oklahoma into the eastern half of Kansas. The precipitation turned to snow over Nebraska. Moderate or greater intensity snow, accumulating at the rate of 20–30 mm h\(^{-1}\), was reported from the Nebraska Panhandle into southeast Wyoming, northeast and northcentral Colorado (medium and light grey enhancement). Very light snow or none at all was reported a few kilometers south of the IR enhancement temperature gradient (B).

Clouds in the satellite image seldom match instantaneous vertical motion. We see the net vertical motion which air parcels have experienced for several hours. Often dry air at midlevels is entrained into the south and then east part of systems as the storm develops (Fig. 4). A schematic composite of airflow through midlatitude cyclones is vividly displayed and described by Carlson (1980). Carr and Millard (1985) used composite sectionals and soundings to describe, quantitatively, the kinematic and thermodynamic environment in each part of the satellite comma cloud system. It appears that the best combination of deep layered moisture and vertical motion is usually near the southern edge of enhanced clouds which wraps around the northeast quadrant of a developing system. Many fac-
FIG. 3. Sequence of 2 km equivalent IR satellite imagery on 27 November 1983. (a) 1100 UTC, (b) 1600 UTC, (c) 1800 UTC, and (d) 0700 UTC 28 November 1983.
tors govern the northern extent of the heaviest snow. In general, a fiberous or fragmented poleward cloud edge such as over the Dakotas indicates a decrease in the depth of the moisture layer. Visible imagery, when available, is also very helpful because terrain features can often be seen through thin cirrus or middle level clouds. In this case, the heavy snow extended northward across most of Nebraska, a distance of nearly 400 km. Experience has shown that the heavy snow band is the largest with developing cyclogenesis storms over the plains such as in this case.

A chronological listing of Concordia, Kansas (A) observations is presented in Table 3. A combination of very light ice pellets, freezing rain and drizzle occurred prior to 1600 UTC (Fig. 3b). This was well within the cold cloud tops (light grey enhancement). At 1637 UTC, snow started to fall and it became heavy around 1800 UTC (Fig. 3c). A rate of 25 mm per hour continued during the afternoon as the cloud band rotated northward across northern Kansas. Just west of Concordia was a pivot point. As the upper system progressed eastward across the Oklahoma Panhandle (Fig.
Table 3. Record and special observations at Concordia, Kansas between 1300 and 0200 UTC on 27 November 1983.

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>CIG/VSB/WX/Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1350</td>
<td>8B52R-IP-F</td>
</tr>
<tr>
<td>1450</td>
<td>4B22R-F</td>
</tr>
<tr>
<td>1550</td>
<td>4B15ZL-F</td>
</tr>
<tr>
<td>1637</td>
<td>4B15IP-SF SB36</td>
</tr>
<tr>
<td>1650</td>
<td>W1×6S+6-F</td>
</tr>
<tr>
<td>1740</td>
<td>W1×6S+S/F SNOINCR 1/1/1</td>
</tr>
<tr>
<td>1850</td>
<td>W1×6S+S/F SNOINCR 1/1/2</td>
</tr>
<tr>
<td>1950</td>
<td>W1×6S+S/F SNOINCR 1/2/3</td>
</tr>
<tr>
<td>2050</td>
<td>W1×6SBS SNOINCR 1/3/4</td>
</tr>
<tr>
<td>2150</td>
<td>W1×6S+BS SNOINCR 1/4/5</td>
</tr>
<tr>
<td>2250</td>
<td>W1×6S+BS SNOINCR 1/5/6</td>
</tr>
<tr>
<td>2350</td>
<td>MISG</td>
</tr>
<tr>
<td>0050</td>
<td>4B25-BS SNO VRY LGT</td>
</tr>
<tr>
<td>0110</td>
<td>8B07</td>
</tr>
</tbody>
</table>

4a, b), the enhanced cloud band rapidly cleared eastern Kansas while the western part dropped southward into eastern Colorado and western Kansas.

The dark grey enhancement (C), which turned westward across western Nebraska between 1400 and 1800 UTC, related to the heaviest snow. Mullen, Nebraska (D) was receiving 50 mm per hour at 1600 UTC with 150 mm accumulating in a 4-h period between 1200 and 1600 UTC.

The cloud band dipping southward over Colorado added 100–150 mm of new snow during the afternoon, bringing the Fort Morgan (E) area 600 mm of snow with 1.5 m drifts and Denver’s total to 500 mm. Interstate Highway 70, a major east–west artery across the central United States, was closed from Denver to Salina, in central Kansas, a distance of over 600 km. Snow also increased later in the afternoon at Goodland, in northwest Kansas, with the approach of the thicker clouds from the north and east. Snowfall totals at 0000 UTC on the twenty-eighth are presented in Fig. 5.

A typical characteristic of this type of system is strong midlevel drying (700 mb dewpoint temperatures < −30°C) to push northward and eastward on the east side of the storm during the later stages of development (Fig. 4b, c). The precipitation tapers off to very light amounts as higher clouds decrease and wrap into the north and west part of the storm. As the system moves eastward, moderate to heavy intensity snow continues in the southern part of the enhanced cloud band (A–B in Fig. 3d). The cloud band holds nearly stationary as the system slips by to the south (Fig. 4b, c). The prime area for the heaviest snow is from the northeast through north to northwest portion of the system. In this case, snow fell at the rate of 20–30 mm per hour and accumulated to around 200 mm across southcentral Minnesota and northern Wisconsin.

b. Southwest flow shortwave trough

The majority of the heavy snow events which are of the southwest-flow, short-wave–trough type occur in about an 8 week period during the middle of the winter, from the last week in December through January, and into the middle of February. The prime areas affected are from Kansas and west Oklahoma northeastward into the Great Lakes and from east Oklahoma and Arkansas to the Ohio Valley. An example, presented later in this section, occurred over the latter area. There may, on occasion, be surface cyclogenesis, but often in this type of heavy snow there is little or no surface development. The system slips along the southern edge of the baroclinic zone on the south side of a large anticyclone near the southern edge of the existing snow field.

In the late fall and early spring, short-wave trough, heavy snow episodes occur from east Colorado and Wyoming to the northern Great Lakes. These systems move faster and are not as developed as the High Plains cyclogenesis heavy snow types and therefore do not have the quantity of snow. See Table 2 for a general summary.

Satellite cloud patterns with this type of system are in several forms. One pattern is the compact positive vorticity advection (PVA) comma cloud as described by Anderson (1974), Reed (1979), Burtt and Junker (1976) and Millard and Carr (1982). The cloud pattern is similar to the large synoptic-scale low heavy snow type as described in subsection 3a, but the size is limited to only a couple of states (horizontal dimensions are generally less than 600 km).

In most cases, however, the cloud pattern is more complex because there is a combination of PVA and warm air advection providing the vertical motion to

![Image of map showing storm snowfall totals (millimeters) at 0000 UTC 28 November 1983.](image-url)
produce widespread precipitation. These concepts have been addressed by Maddox and Doswell (1982) when examining widespread and persistent convective events during the warm season. The effect of warm air advection and resulting errors in the NMC models have been addressed by Gyakum (1984) for a winter precipitation event in the Ohio Valley.

The effects of positive vorticity and warm air advection are seen in the satellite imagery as an elongated multiple layered cloud pattern. The influence of the vorticity advection, depending on the strength of the system, generates clouds out to about 600 km from the 500 mb vorticity center. The cloudiness generated by the low and middle tropospheric (850–500 mb) warm air advection continues, on the average, some 600–1300 km downstream (ahead or east) of the vorticity center. There may occasionally be a subtle break in clouds and/or precipitation between these two areas, but generally there is a transition zone where both warm air and vorticity advection clouds occur simultaneously.

The satellite imagery during the late afternoon and evening of 8 February 1982 supported a double vorticity structure with a center moving into northwest...

---

4 During the past several years, with the aid of GOES imagery, empirical relationships have been established between the 500 mb vorticity centers and cloud patterns such as the comma. The center of maximum vorticity may not necessarily be at the 500 mb level in the atmosphere but the only vorticity guidance available to the operational forecaster is the 500 mb analyses from the NMC models. Therefore, in an operational sense, satellite, aviation and public service meteorologists generally communicate in terms of the vorticity at 500 mb irrespective of the actual level of maximum vorticity.
Oklahoma and another into east-central Arizona (Fig. 6a–c). The break in clouds from east Oklahoma into southwest Missouri suggested the "weather" (thicker clouds and precipitation) was caused by two different forcing mechanisms; warm air advection across the thick clouds and thunderstorms from Louisiana to the Lower Ohio Valley, and vorticity advection over the deeper cold air in Kansas and northern Oklahoma. Composite analyses, indicating selected fields at mandatory pressure levels from the surface to 250 mb, for the 0000 UTC RAOB period are shown in Fig. 7.

Low-pass filter objective quantitative analyses (Barnes, 1964) of temperature advection by the geostrophic wind at 850 and 700 mb for 0000 UTC are presented in Fig. 8. Strong warm air advection (>4°C h⁻¹ × 10⁶) was present at both levels from eastern Arkansas and southeast Missouri, northeast across the Ohio Valley. The 850 mb temperature was below 0°C north of a line from the Ohio River to extreme northern Arkansas (Fig. 7a) so the precipitation was quickly changing to moderate intensity snow near the southern edge of an enhanced (dark grey) cloud patch over east-central Missouri and the southern half of Illinois into the southwest corner of Indiana. Snowfall rates of 20–30 mm per hour were common. This case was very similar to the snow and thunder event described by Blakley et al. (1986). They compared quasi-geostrophic (Q-G) omega diagnostics and isentropic omega fields which showed increasing vertical motion upward through the mid troposphere.

Rather high visibilities at the surface indicated very light intensity snow in the cloud breaks at Springfield, Missouri (A, Fig. 6a) at 2300 UTC. Occasional moderate intensity snow, however, continued in the zone where warm air advection and increasing positive vorticity advection overlapped in west central Missouri (B). The snowfall intensity increased beneath the colder topped clouds in the comma cloud head, representing the area of maximum PVA, over eastern Kansas. Rates of 20–30 mm per hour were occasionally reported.

The snow continued across central Missouri into Illinois during the evening (Fig. 6b), ending from the west with the passage of the enhanced clouds. Clouds thickened over southwest Oklahoma and north Texas as a second short-wave trough moved out of New Mexico (Fig. 7b). Moderate snow was observed at several stations in southwest Oklahoma at 0500 UTC (Fig. 6c) as this secondary area of snow developed eastward across Oklahoma during the night.

c. Northwest flow shortwave trough

During the initial review of all the cases, a number of events had characteristics similar to a warm season counterpart: northwest flow severe weather outbreaks (Johns 1982). The heavy snow producing systems moved with a south-of-west component with the heavy snow axes almost identical to the major high-frequency severe weather outbreaks (Johns, Fig. 4 and discussion) from southern Minnesota to the Lower Great Lakes.
Since the systems were moving rapidly (speeds greater than 15 m s⁻¹) and the accompanying baroclinic zone was often quite cold with a low capacity to hold moisture, the heavy snow tracks were generally long (greater than 1000 km) and narrow (around 200 km) with snowfall totals ranging between 80 and 150 mm (Table 2). This type of heavy snow system can often lead to complacency on the part of forecasters, but attendant high winds and very cold temperatures can cause near blizzard conditions. A recent example has been documented by Vinnizni and Changnon (1981).

A 6 h sequence of enhanced IR satellite imagery showing the progression of a system during an 18 h period in March 1984 is presented in Fig. 9. The imagery depicts a well-defined comma-shaped enhanced cloud band associated with a short-wave trough and vorticity center (x in Fig. 9b) dropping from the eastern Dakotas to the Lower Great Lakes. Selected surface and upper air parameters at the three RAOB times during this event are presented in Fig. 10.

Snowfall totals were generally in the 70–120 mm range. As is most often the case in northwest flow situations, the system was moving quickly and only had moisture available in the baroclinic zone during most of its lifetime. Surface temperatures were in the mid-teens to mid-twenties, indicating a shallow dome of cold air. This was also reflected by 850 mb temperatures in the -10° to -15°C range (see dash lines in Fig. 10) and 1000–500 mb thicknesses between 510 and 522 dm.

Low- and midlevel clouds were observed beneath the colder (medium and light grey) cloud tops. Surface precipitation was close to the west and south edge of the colder cloud tops with the heaviest snow near the edge of the medium grey enhancement upstream toward the vorticity center. The different cloud layers are more readily apparent in visible imagery.

The dots on the images represent official hourly observation sites which reported moderate or greater snow at least once during this period. The heaviest snow at Waterloo, Iowa (B, Fig. 9b–c), occurred between 0000 and 0600 UTC when a little over 80 mm fell. This area was in the northeast quadrant of the vorticity center, near the west edge of the IR cloud top temperature gradient.

The area of stratocumulus over the Ozarks in southern Missouri pulled northeast across southern Illinois into western Indiana during the late afternoon and evening (C, Fig. 9c–d). This additional input of low-level moisture ahead of the system probably accounted for the highest snowfall totals of around 150 mm over parts of west central Indiana and the only remarks of 20–30 mm per hour snowfall rates in east central Illinois.

d. Orographic

Although this type of heavy snow occurs with short-wave troughs and generally an identifiable vorticity maximum, the location and overall conditions for development necessitate a separate classification. Orographic effects also exist most of the time in the early development of the High Plains cyclogenesis type heavy snow, but in these cases the low-level moisture wrap-
ping around the system from the Gulf of Mexico is greater. It will be shown that the synoptic situation and cloud patterns in the satellite imagery dictate a unique classification for some of the heavy snow events in the area from the New Mexico and southern Colorado Rockies into the adjacent High Plains to near 100°W longitude.

The usual sequence of events for this type of heavy snow is a long-wave trough over the southwest United States and northwest Mexico with high pressure near the surface over the Central Plains funneling in cold air behind a baroclinic zone from Texas to the Great Lakes. If surface temperatures are near freezing, adiabatic cooling of air pushed by easterly low-level winds up the eastern slopes of the Rockies creates a deep pocket of below freezing temperatures so any resulting precipitation is in the form of snow. Snow band characteristics and typical rates, storm totals and durations are similar to those of the southwest flow short-wave trough type (Table 2). A short-wave trough or series of short-wave troughs ejected out of the main upper trough pull middle-level moisture into the area from the lower latitudes of the east Pacific across northwest Mexico. This moisture from the southeast Pacific moistens the air column in the upper levels. The resultant thick moist layer and additional dynamic lift from the short-wave trough can produce widespread precipitation. Brown and Brintzenhofe (1956) documented a case when a slow-moving, closed, upper low provided upslope winds and a constant moisture supply for a prolonged period of light snow over New Mexico.

Satellite imagery during a 2-day period in April 1983 illustrates a record breaking snow in the El Paso, Texas area (Fig. 11). Three hundred and fifty millimeters of

---

**Fig. 9.** Sequence of 2 km equivalent IR satellite imagery with mb enhancement curve on 7–8 March 1984. (a) 1800 UTC, (b) 0000 UTC, (c) 0630 UTC, (d) 1000 UTC. The “x” is the initial LFM 500 mb vorticity (10^{-3} sec^{-1}).
snow fell during the 2 days, the most for any April. The largest amount on the ground was 250 mm on the morning of the seventh. Also during this time, 210 mm accumulated in a 24 h period, the greatest amount ever recorded.

An abbreviated chronological listing of surface observations at El Paso about every 3 h is presented in Table 4. Satellite imagery around 0600 and 1200 UTC on the sixth and seventh show the occurrence of the heaviest snow with two short-wave troughs which are depicted at 700/500 mb levels in the composite charts at RAOB times in Fig. 12. The first (A, Fig. 11a and Fig. 12a) deposited 170 mm of snow in the El Paso area. The snow quickly decreased as the trough moved away from the higher amounts of low-level moisture; in southeast New Mexico and northwest Texas, totals

Fig. 10. Composite analyses for (a) 1200 UTC 7 March 1984, (b) 0000 UTC 8 March, (c) 1200 UTC 8 March. Dash lines are 850 mb isotherms. Solid lines are 500 mb heights ($\times 10^3$ m). Dotted lines are 700 mb isodrosotherms. LOW indicates upper lows (closed height contour). Heavy solid arrows are 250 mb jetstreams with isotach maxima annotated by jet and speed.
Fig. 11. The 4 km equivalent IR satellite imagery with Mt. enhancement curves on 6-7 April 1983. The 0°C and -5°C isotherms from RAOB are dashed on the 1200 UTC image (a) 0630 UTC 6 April 1983; (b) 0600 UTC 7 April 1983; and (c) 1145 UTC 7 April 1983.
were only around 50 mm. Clouds thickened with the approach of the second trough (B, Fig. 11c and Fig. 12b, c) as it drew in moisture (C) from the Gulf of California early in the morning of the seventh. Occasional moderate snow fell until midday. The cold air rebuilt southwestward over southwest Texas behind the first trough, allowing the snow with the second shortwave to occur farther south into the Big Bend National Park area.

The heaviest snow extended east and south across the higher terrain of southwest Texas and southwest-central New Mexico west of the Pecos River where amounts of 150–250 mm were common. A visible image two days later (Fig. 13) shows the local influence of higher terrain with the heaviest snow remaining over the mountains. Note that most of this area is between the regular reporting sites (dots). This fact and forecast problems relating to local events over New Mexico have been addressed in a case study by Grice (1977).

4. Factors controlling snowfall amounts

Several factors govern the amount of snow which occurs with a system. Scofield and Spayd (1983, 1984) have shown in IR schematics the evolution of different types of satellite cloud signatures. Subtle short-term (2–6 h) changes in these signatures are matched with conventional data to estimate hourly liquid precipitation rates from extratropical cyclones during the winter season. These rates can be converted into snowfall equivalents if the precipitation is in the form of snow. Figures and diagrams in these papers extensively describe the specific techniques. Cases in this study have suggested that in addition to the overall dynamical strength of the system, the storm speed of movement, the availability of moisture, and mesoscale features are important factors which influence the storm snow totals and are quickly determined operationally in near–real time in satellite imagery.

a. System movement

Most of the High Plains cyclogenetic type storms take several hours to develop. The longer duration and initial slow movement account for prolonged snow, generally from the Colorado foothills into western Nebraska and Kansas. On many occasions very heavy snow (250–350 mm) will fall over central Kansas and Nebraska, but, as the storm accelerates eastward into the Ohio Valley and Great Lakes regions, snowfall amounts generally decrease to the 100–200 mm range. Moisture availability is also a mutual factor in these cases. These factors are discussed in a well-documented case by Schlatter et al. (1983) over the PROFS mesonetwork.

Figure 14a is an example of a cyclogenetic type storm. A blocking pattern was over the Canadian/northern United States Rockies with the upper low slowly reforming east across Wyoming into South Dakota during the period of interest. A baroclinic zone was firmly established in the northeast quadrant of the circulation with an elongated stationary band of clouds from the Dakotas eastward across central Minnesota and northern Wisconsin. Surface temperatures were around −15°C beneath the clouds and in the 15°–25°C range over the clear area from southern Nebraska into Kansas. An important factor in the production of 400–500 mm of snow along the Dakotas border was the continuous regeneration of thundershowers and convective type clouds upstream (south) of the baroclinic zone. This is best seen in the visible imagery (Fig. 14b).

Early morning thundershowers moving northward over Iowa and Nebraska were stabilized by cooling from below. The precipitation quickly turned to snow in the deeper cold air. Strong (>6°C h⁻¹ × 10⁴) low and middle level warm air advection into the south side of the cloud band supplied plenty of lift for the continues regeneration of upstream clouds (to the south) which fed into the baroclinic zone. The 2200 UTC visible image (Fig. 14b) clearly depicts the convective type clouds building northward into the south side of the east–west enhanced cloud band. The real-time animated satellite imagery at the Kansas City SSFS showed the clouds wrapping back to the west across the Dakotas through the baroclinic zone. The axis of maximum snow aligned with the southern edge of colder topped, enhanced clouds. This is where the convective type clouds in the visible imagery continued to feed west-northwestward into the area.

b. Moisture availability

An example of a poorly defined system (southwest flow–short-wave trough type) in the satellite imagery, primarily because of limited low-level moisture, is provided by a case in January 1984. Figure 15a shows clear skies over the northwest Gulf of Mexico off the
Texas coast and northwest/southeast stratocumulus cloud streets (A) over the northcentral gulf, indicating a continuation of cold air advection. During the next 11 hours, a shallow layer of stratocumulus formed over Louisiana and adjacent waters but the deeper moisture only got as far north as the Galveston Bay area by 1600 UTC (B in Fig. 15b). Brownsville, Texas was saturated at 850 mb with a 6°C dewpoint temperature at 1200 UTC (Fig. 16). Other RAOB sites over the Southern Plains had dewpoint temperatures < -6°C at 850 mb. Even though the dewpoint temperature had increased by 10°C since the 0000 UTC RAOB, the moisture did not recover quickly enough to be a factor in the storm to the north.

Snowfall amounts with this system were generally around 20–50 mm except for an area in central Kansas.
changing to light, occasional moderate, intensity snow at Abilene (A). Scattered showers developed to the south of Abilene during the morning (Fig. 17b). The precipitation turned to heavy snow as cloud elements from these showers moved northward into parts of north-central Texas and southwest Oklahoma.

Since surface temperatures were a little above freezing, quite a bit of the falling snow melted. This is a factor which needs to be considered when determining the snowfall accumulation during an event. Wichita Falls (B, Fig. 17b) recorded a liquid precipitation total of about 12 mm but only 50 mm of snow was reported on the ground between 1800 and 0000 UTC, indicating the snow was very wet and melting. The largest snowfall total on the ground was 200 mm to the southeast of Childress (C, Fig. 17c) and southwest of Wichita Falls. During the day, the convective type clouds with cold tops fed into this area. The heaviest snow occurred at Wichita Falls between 1800 and 0000 UTC as the southern portion of the cold cloud band rotated through (Fig. 17c–d).

As seen in the 1530 UTC (Fig. 17b) visible image, the low-level moisture decreased rapidly across central Oklahoma. Fort Sill (D) in southwest Oklahoma recorded 50 mm of snow, but Oklahoma City to the northeast received ice pellets and light snow with little accumulation. Cloud tops continued to warm after 0000 UTC and the system weakened as it moved northeastward away from the low-level moisture.

c. Mesoscale effects

The significance of convective clouds with thunder in producing local areas of heavy snow is well documented in a southwest flow–short-wave trough case on 19–20 October 1982 near the South Dakota–Iowa border.

The morning RAOB/surface composite chart is drawn in Fig. 18a. Visible and IR satellite imagery in Fig. 18b–d show thundershowers (A) developing over eastern Nebraska ahead of a 500 mb short-wave trough (B–C in Fig. 18b) moving eastward across the Central Plains. The visible image (Fig. 18c) better defines the convective cloud clusters which moved northeastward into the southeast corner of South Dakota/northwest Iowa and produced heavy snow bursts. At 1500 UTC (Fig. 18b), Sioux City, Iowa (D), was reporting a heavy intensity thunderstorm while to the north, Sioux Falls, South Dakota (E), was receiving a mixture of ice pellets and light rain before changing to moderate intensity snow 1 h later.

A plot of snowfall totals (Fig. 18e) on a visible satellite image 2 days later shows three distinct areas of up to 300 mm of snow. Since the visible image was a couple of days after the event, some melting probably occurred because of the warm ground. Low clouds were obscuring part of the snow field in Wisconsin.

The occurrence of the heaviest snow between the

---

**FIG. 13.** The 1 km visible satellite image at 1830 UTC 9 April 1983.
regular reporting stations (Sioux City and Sioux Falls) is of particular interest. The area of heaviest snow correlated very well with the cold thundershower cloud tops in the IR (Fig. 18b, d) in the southern portion of enhanced clouds. A combination of additional moisture feeding into the area from Illinois, Iowa and Missouri during the evening (F, Fig. 18d) and lake effects in the northerly flow after storm passage, accounted for 200–300 mm accumulations over upper Michigan and northern Wisconsin.

Convective type clouds with thunder are most often seen in heavy snow situations during the early and late parts of the cold season over the Northern Plains and Upper Mississippi Valley. These months are October,
November, March and April. During this time, there is ample low-level warm air advection and generally strong dynamics in the cold air aloft to generate sufficient vertical motion and instability for thunderstorms. In the middle of the cold season (late December through January into early February), thunderstorms accompanying heavy snow are infrequent, but, in unusually strong deepening systems, adequate moisture and instability are present to form thunderstorms and heavy snow. The prime area for this to happen is from Arkansas northeastward into the Middle Mississippi and Lower Ohio valleys. Some of the record breaking heavy snows with storm totals 400–600 mm have occurred during the past few years in these cases. It is not uncommon for thunderstorms to produce snowfall rates of 30–50 mm h⁻¹.

5. Real-time analysis and forecasting techniques

a. Three-step analysis method

This subject is very important to the operational forecaster who has to assess the state of the atmosphere, continuously, 24 h a day. Although the main topic is heavy snow, some of the techniques described could apply to other forecasting problems. Table 5 summarizes the approach which has been found by the author's more than 10 years at the SFSS to be most useful in assessing the threat of heavy snow. This approach is called the three-step analysis method. Although the first two steps may appear superfluous to the veteran forecaster, they are included for completeness in the heavy snow assessment routine for all levels of forecasting experience.

The first step is primarily concerned with checking the current surface and radar observations to see where precipitation is occurring. Of particular interest is the area of heaviest precipitation (rain or snow). At this time, the dividing zone between rain, freezing rain and sleet versus snow can be determined. Since we are concerned with heavy snow, an evaluation needs to be
made on the various intensities over the area of interest. The remarks part of the surface observation may contain information on snowfall rates if significant accumulations are occurring. Low ceilings and visibilities generally convey heavier snowfall intensities, but these may be misleading when there is fog or strong gusty winds. Radar echoes, especially precipitation aloft, give the first indication of precipitation formation. Radar is also helpful in determining the intensity and extent of the precipitation. As noted previously in section 4, nearby convective clouds with thunder are prolific snow producers and should be monitored closely.

The NMC guidance is in many different forms, ranging from manually prepared forecasts to numerical prediction models and innumerable initial and forecast fields produced by them. All cases in this study have consistently shown the significance of the 850 mb thermal field, especially the 0°C isotherm in locating the southern extent of heavy snow (Figs. 11b, d and 17a, d). The 1000–500 mb thickness field has also been very useful. Wagner (1957) derived a map of 1000–500 mb thickness values for the equal probability of occurrence of frozen and nonfrozen precipitation. Local forecast studies or rules of thumb at the various forecast offices

Fig. 17. The IR and visible satellite imagery for 1–2 January 1983. (a) 1200 UTC, (b) 1530 UTC (VSB), (c) 1800 UTC, and (d) 0000 UTC. Dashed lines on 1200 and 0000 UTC images are 850 mb isotherms.
probably have a favorite value for each of these parameters. Although variations have been noted according to early, mid- or late season and the latitude of the storm, most heavy snow in this study has been near the $0^\circ$ and $-5^\circ$C 850 mb isotherms and the 534–540 dm 1000–500 mb thickness ribbons. Over the past several years, it has been observed that the LFM-II does a reasonable job, in most cases, predicting these fields in the first 24 h after initialization. Much has been written about the success of the different numerical
TABLE 5. Three-step analysis method.

I. Check recent observations (surface, radar)
   A. Look for areas of heaviest precipitation
   B. Note remarks on snowfall rates
   C. Watch for nearby thunder
II. Review latest NMC guidance
   A. Check Model Parameters
      • 1000–500 mb thickness
      • 540–534 decameters
      • 850 mb temperature
      • 0° to −5°C
      • POP Chart
      • rain/snow line
   B. Adjust for biases
   C. Review manually prepared charts
III. Satellite image interpretation
   A. Recognize the heavy snow type/combination
   B. Relate clouds to heaviest precipitation
      1. Changes in IR cloud top temperature
      2. Changes in IR cloud size
      3. Changes in shape of IR cloud edge (sharp/ragged)
      4. Texture in visible imagery
      5. Key on unusually heavy convective clouds (thunder)
         near or south of snow area in southern portion of
         enhanced clouds as system develops
   C. Fill in gap between observations (most important at night)

models. Silberberg and Bosart (1982) have recently addressed the systematic errors in the LFM-II forecasts of winter storms at the 24 and 48 h periods.

The last analysis step, satellite image interpretation, is the main one that has been developed in this paper. A particular weather situation should be investigated to see if it fits any or part of the heavy snow types described in this paper. A problem in classifying events such as heavy snow into types is that not all cases can be placed in a specific category. Occasionally, an adjustment may be needed where an event is placed into one type for a while, then phased into another type. After a specific type is determined, Table 2 can be consulted to make a rough estimate of the heavy snow band size in addition to typical rates, durations and storm totals/maxima.

Next, the clouds in the satellite imagery are related to the precipitation intensities with particular attention to the clouds which are producing known or recent heavy snow. Techniques such as those described by Scofield and Spayd (1983, 1984) are most valuable in assigning specific hourly liquid and frozen precipitation amounts. It is important to monitor continuously any changes in IR cloud top temperatures (warming/cooling), size of the colder clouds (increasing/decreasing) and shape of the enhanced cloud edges (sharp/ragged, more anticyclonic). The reader is encouraged to refer to the above referenced documents for the exact hourly precipitation estimating procedures.

As previously detailed, convective type clouds are a major producer of heavy snow, especially near the southern edge of colder, enhanced clouds. This zone, where dry air at middle levels often intersects low-level moisture, creates unstable type clouds in a zone of strong upward vertical motion. These circumstances result in the heaviest snowfall rates.

The most important aspect of the continuous, half-hour GOES satellite imagery is the spatial qualities which allow the forecaster to fill in the data void areas, especially at night. There are many places in the Plains where the distance between surface observations is greater than 200 km. It is virtually impossible for the forecaster to put very high confidence on the location of heavy snow boundaries if he or she only has information at resolutions greater than 200 km.

The application of the three-step analysis method is best shown by an example which simulates the real-time application. A sequence of GOES IR and visible satellite imagery on 11 November 1982 in Fig. 19 traces the movement of a High Plains cyclogenesis type system from the Central Rockies to the Upper Mississippi Valley. The morning and evening surface and upper air features during this time are depicted by the composite charts in Fig. 20.

Employing the method presented in Table 5 at an initial time of say 1130 UTC (satellite image in Fig. 19a and the corresponding composite analysis in Fig. 20a), the forecaster would determine the following: In the first step, conventional data indicated snow at Cheyenne, Wyoming (A) and light rain changing to occasional light snow at Scottsbluff, Nebraska (B). Light rain or drizzle extended east-northeast across Nebraska and Iowa. Convective type precipitation was occurring near the Iowa/Nebraska border and thunder was being heard at Omaha (C).

In the second step, the NMC numerical models were indicating cyclogenesis with the very cold upper trough moving into the Central Plains and to the Great Lakes during the next 24 h. The LFM 12 h forecast (valid at 0000 UTC) 0° and −5°C 850 mb isotherms from the 1200 UTC forecast run are drawn by dash lines on the satellite image in Fig. 19a. The cloud band from east Wyoming to south Minnesota was represented by the surface to 500 mb, >70% RH isohume (not shown) which the LFM rotated north across Minnesota the next 12 h as midlevel dry air entrained into the east side of the developing system. This is common in cyclogenesis type events. The conventional upper air data (Fig. 20a) showed plenty of low-level moisture advecting into the system from the south (850 mb dewpoint temperatures > 6°C).

In the third and final step, the precipitation at the surface is related to the clouds in the satellite imagery. The initial snow at Cheyenne (A in Fig. 19a) was occurring where the cold air in the mid troposphere (centered around 500 mb) over the Central Rockies was starting to advect across the lower tropospheric (700 mb and below) moisture band (colder, enhanced tops), feeding westward across South Dakota and Nebraska on the north side of the developing system.
Fig. 19. The 2 km equivalent IR and 2 km visible satellite imagery during a 12 h period from 1130 UTC (IR) 11 November 1982 to 0000 UTC (IR) 12 November 1982. (a) 1130 UTC (IR), (b) 1531 UTC (visible), (c) 1900 UTC and (d) 0000 UTC. Initial LFM 500 mb upper low (L) and vorticity center (x).
b. Future trends

Once a particular weather situation is analyzed and a threat of heavy snow is determined, the forecaster is challenged to specify where the heavy snow will occur, how much will fall and during what time interval. According to information collected in this study, the forecaster can follow suggested guidelines presented in Table 6 when predicting heavy snow trends. The expected heavy snow area can be projected to whatever time interval is required to complete the forecast period(s) of concern. Techniques work best for the first period (0–12 h) of a forecast. The case of 11 November 1982, initially analyzed in subsection 5a, will be used to demonstrate how a forecaster can predict heavy snow trends during the remainder of the day.

Since this paper shows that (given favorable low-level temperatures) heavy snow is likely to occur in the southern part of the cold topped (enhanced) clouds in the IR satellite imagery, it is important that future movement of the cloud band can be determined. This is the first part of predicting future trends described in Table 6.

The area of maximum surface to 500 mb RH (a measure of the degree of air mass saturation through a deep layer of lower troposphere) in the NMC numerical models relates well to the cold enhanced clouds in the satellite imagery. Six or 12 h changes (maximum values or size of area) in the RH patterns can help the forecaster assess future trends in movement and drying/moistening of the cloud band. These changes are generally related to the movement of the synoptic-scale low (surface and aloft), vorticity center(s) or short-wave trough(s). In most cases there may be little change. The most drastic changes occur with rapid developing cyclogenetic cases when the warm sector midlevel dry slot wraps around the system. The moist band generally aligns with the low and middle tropospheric thickness isopleths which are also related to the isotherms. If NMC guidance is not readily available, the forecaster could extrapolate the thick, cold topped enhanced cloud band downstream along the initially analyzed thickness isopleths or isotherms.

<table>
<thead>
<tr>
<th>Table 6. Predicting heavy snow trends (0–12 h).</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Orientate cloud band associated with main precipitation</td>
</tr>
<tr>
<td>A. NMC numerical guidance as initial guess</td>
</tr>
<tr>
<td>1. Relate sfc-500 mb max RH to projected track of low or vorticity center</td>
</tr>
<tr>
<td>2. Select favorite 12 h parameters/values</td>
</tr>
<tr>
<td>850 mb temperature/1000–500 mb thickness</td>
</tr>
<tr>
<td>B. Satellite trends during evolution</td>
</tr>
<tr>
<td>1. Identify more persistent enhanced clouds with snow</td>
</tr>
<tr>
<td>2. Monitor precipitation band movement</td>
</tr>
<tr>
<td>II. Estimate heavy snow rates/storm totals</td>
</tr>
<tr>
<td>A. Initial (general) estimates from system type (Table 2)</td>
</tr>
<tr>
<td>B. Formal hourly estimates from Scofield/Spayd scheme</td>
</tr>
<tr>
<td>1. Monitor changes in cloud top temperatures (warmer/colder)</td>
</tr>
<tr>
<td>2. Monitor changes in cloud size (growth/decay)</td>
</tr>
<tr>
<td>3. Watch for nearby convective clouds (thunder)</td>
</tr>
</tbody>
</table>
As mentioned in subsection 5a, the NMC numerical models were indicating cyclogensis over Nebraska during the day with the moisture band rotating counterclockwise north and west of the developing system. The forecast 0° and −5°C 850 mb isotherms (dash lines with a more northeast/southwest orientation in Fig. 19a) suggest the zone with the highest potential for heavy snow extends from the Nebraska panhandle northeast into central Minnesota.

At this time, the second part of Table 6 recommends initial estimates of heavy snow rates can be made following the guidance in Table 2. Since the system is expected to develop rapidly eastward, the storm totals should be in the low range or about 250 mm over the Nebraska panhandle with rates of 20–30 mm per hour near the south edge of the enhanced cloud band. These amounts should continue northeast along the south part of the band as the storm develops across southeast South Dakota into central Minnesota. The area north of the convective clouds with thunder (eastern South Dakota and south central Minnesota) would have to be closely monitored for possible heavy snow rates of 30–50 mm per hour which would result in higher storm snowfall totals of close to 300 mm.

The next phase of predicting heavy snow trends is concerned with monitoring cloud movements in satellite imagery and very short-term (hour or half-hour) variations in area or temperature of coldest cloud tops which relate to changes in snowfall rates.

During the morning into early afternoon the enhanced cloud band pivoted northward across southeast South Dakota and southern Minnesota. The cold air aloft spread northeastward into northcentral Nebraska and changed the rain to snow. Moderate intensity snow developed across the northeast corner of Colorado into the east Nebraska panhandle. At 1900 UTC, Kimball, Nebraska (C in Fig. 19c) reported moderate intensity snow with 130 mm on the ground since early morning. This was at the south edge of the colder cloud tops which extended northeast across southeast South Dakota, pointing to the best area for heavy snow to develop.

Low- and mid-level warm air advection across the warm front was maintaining the increasing convective clouds with thunder in Iowa and eastern Nebraska where many stations were reporting moderate rain. The convective clouds, which were best seen in the visible satellite imagery (Fig. 19b), moved north and merged into the south portion of the enhanced cloud band in southcentral Minnesota and extreme east South Dakota, indicating that this area needed to be closely watched during the afternoon for possible moderate to heavy snow with rates of 30–50 mm h⁻¹. An area of thundershowers was forming near the intersection of the dry line with the warm front over southwest Iowa. Early trends indicated that the showers were moving north on the east side of the developing system and would enter south-central Minnesota during the evening.

At 0000 UTC (Fig. 19d), moderate intensity snow was occurring across north-central Nebraska into southeast South Dakota as the upper trough moved into western Kansas and central Nebraska. The initial LFM 500 mb upper low (L) and vorticity center (x) are annotated on this image. Selected surface and upper air features at this time are shown in Fig. 20b. Moderate intensity snow with rates of 50 mm h⁻¹ were occurring over extreme eastern South Dakota into central Minnesota (D–E). This was the area where the earlier convective activity merged with the south part of the cold topped cloud band. The area of thundershowers continued to move north over northwest Iowa (F), keeping a continued supply of deep moisture feeding into the southern edge of enhanced clouds over central Minnesota.

A decrease in colder cloud tops across central Nebraska behind the developing system related to a lessening in snow intensities to a few (<10) millimeters per hour for a couple of hours before diminishing to flurries with no additional accumulations. Once the movement of the west edge of colder cloud tops is determined, the edge can be projected northeast in 2 or 3 h increments for an estimated ending of the more significant snow. Also the calculated edge movement can be extrapolated through the downstream heavy snow area (i.e., South Dakota/Minnesota border) to get an approximate ending time. The difference between the ending and current time multiplied by the snowfall rate would also give an estimate of the total snowfall:

\[ (T_{\text{end}} - T_{\text{now}}) \text{ Snow rate} = \text{Storm Total} \]

A midday visible satellite image the next day (Fig. 21) captured the extent of the snow field from Nebraska to southwest Minnesota. Clouds obscured the eastern part of the snow band. A sampling of the official snowfall from the storm is superimposed on the image. The heaviest amount of around 300 mm occurred near the central South Dakota/Minnesota border which was affected most by the convective clouds which moved into the south portion of the cloud band (Fig. 19b) and deepened the moist layer.

Northerly flow behind the system off Lake Superior accounted for a maximum over north Wisconsin. Another maximum over west Nebraska appeared to be related to a longer period of moderate intensity snow during the initial stages of storm development (previous morning) when east, low-level flow provided terrain induced lift.

6. Summary and conclusions

Geostationary meteorological satellite imagery has provided 24 h, near real-time half-hour viewing of the atmosphere, filling the temporal and spatial void in the conventional surface and upper air observations. Satellite imagery are most important over the Plains at
night when many observing sites are closed and are especially important in detecting local effects.

Recognizing heavy snowfall patterns in the IR and visible imagery, and using techniques described in this paper, the timing and projected path of heavy snow can be produced (works best up to 12 h). The characteristics and common geographical areas for each of the four heavy snow types developed in this paper are summarized in Table 2. The values presented may vary according to each specific event, but, on the average, the numbers are a reasonable initial estimate.

Occasionally, an event is a combination of two types or may begin as one type and change to another type during its life cycle. The relationships developed are still valid for each type. There also needs to be a time and/or space adjustment in the transition zone between the different types.

Several factors such as the dynamic strength of the system, speed of movement, and structure of the moist layer control the total amount of snow which occurs with each type. Convective type clouds, especially with thunder (best seen in the visible imagery), are significant when moving into the snow threat area. This is especially noticeable during the early and late part of the cold season over the Northern Plains and Upper Mississippi Valley when dynamics and warm air advection are strong and most often during rapid deepening storms over the Lower Mississippi, Ohio, and Tennessee valleys in the middle of the cold season.

Experience has shown that the three-step analysis method presented in Table 5 is a useful approach to assess the threat of heavy snow. This melds together the latest observations, the current numerical guidance and latest satellite imagery to obtain the best estimate of the heavy snow threat. Once the initial threat is assessed, the forecaster, knowing the relationships between the heavy snow and the satellite imagery, can apply the information in Table 6 to predict future trends in heavy snow for the forecast interval or period of interest.

This study was not meant to be an objective statistical exercise with hard and fast theories or proofs. The very nature of operational forecasting dictates an empirical, subjective approach which lays the foundation for future knowledge. This paper does not profess to be the complete solution to the heavy snow forecasting problem but hopefully is a starting point considering the relatively new observation medium of satellite imagery.

Acknowledgments. This work has been a culmination of effort by everyone, present and past, of the Kansas City SFSS staff. Much of the pioneering efforts in data collection and initial analyses were accomplished by Bill Hirt (currently with the SELS staff at NSSFC) and Ned Johnston (WSFO Milwaukee). I am forever grateful for their contributions at the beginning of this project. Comments by Rod Scofield and an anonymous reviewer were very helpful and appreciated. The original manuscript was prepared by Beverly Lambert.

REFERENCES


