Examination of USAF Nephanalysis Performance in the Marginal Cryosphere Region

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ABSTRACT

Cloud retrieval from satellite data in the regions of snow and ice cover is generally acknowledged to be difficult with the present generation of meteorological satellites. Despite potential advances to be made in this field (e.g., 1.6 μm sensor to be operated on NOAA satellites) large-scale cloud analysis techniques are likely to require information on the location of the margin of seasonal snow cover. In this paper we investigate the accuracy of one snow-cover dataset currently utilized by a global nephanalysis model, the United States Air Force (USAF) RT Nephanalysis, and investigate the effect of inaccuracies in the snow cover information on the derived cloud field. There are found to be situations where the snow model is inaccurate because of the advanced state of the spring melt with respect to climatology which causes errors in the derived cloud amount. The USAF policy of including surface cloud observations in the RT Nephanalysis leads to correction of the erroneous cloud amount in regions where surface observations are available.

1. Introduction

The margin of hemispheric snow and ice fields (snow and ice transition zone or SITZ) is of key climatological as well as practical importance. It is the zone where fresh snow cover, compact ice, melting snow, patchy snow, broken ice, snow-free ground and open water coexist. Intricate feedback mechanisms operate there, involving radiation, clouds, water vapor, atmospheric contaminants, and snow and ice. It is the zone where rapid changes occur in the mechanical properties of soils, affecting air and ground transportation and engineering operations. It is the zone where climate models lead us to expect high sensitivity to a carbon dioxide induced warming (e.g., Washington and Meehl 1983). Climate modelers still require information on the nature of interactions in this area.

Variability of the climate system is strongly influenced by changes in cloudiness and the extent of snow and ice fields. Clouds reflect, absorb and transmit incoming solar radiation and absorb infrared radiation emitted from the surface of the Earth. They reradiate to space at lower temperatures, reducing the amount of outgoing infrared radiation from the system. The exact interaction between the clouds and atmospheric radiative fluxes is a function of cloud type and height and the surface properties. The latter are critically affected by the presence of snow and ice, which display unique reflective, insulating, and radiative properties (e.g., Kukla 1981).

The interaction between clouds and the cryosphere in the middle and high latitudes is not well known at present (Barry et al. 1984), partly a result of (i) a lack of empirical data, (ii) large discrepancies in the available information on the extent of cloudiness, particularly in high latitudes (Crane and Barry 1984) and (iii) the complex interactions between the atmosphere and the surface. For instance, the timing of the formation and dissipation of seasonal snow and ice fields in high latitudes appears to be influenced by the presence and type of cloud cover (Vowinckel and Orvig 1970; Herman and Goody 1976; Jayaweera 1977). The dissipation of snow fields is a complicated process, starting in subfreezing temperatures. It has been noted that clouds may reduce the longwave radiation loss from the surface and enhance the melt of a deep snow pack, but in other circumstances the melt of a shallow snow layer will start under clear skies while being inhibited by clouds (Crane et al. 1982). It is suspected that in the high Arctic, the multiple reflection between the cloud base and the surface is a key process maintaining the melted surface during summer. The realistic modeling of the role of clouds in snow melt would considerably improve the accuracy of predictions of the future carbon dioxide impact currently being modeled by general circulation climate modelers.

Namias (1962) noted a deflection of storm tracks south of the snow line and correlations between the ice

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front and hemispheric patterns of extratropical cyclonic activity were noted by Carleton (1984). Fluctuations in snow and ice cover are associated with departures from normal temperatures in response to variations in short- and longwave radiation fluxes, sensible and latent heat fluxes, and variations in atmospheric circulation patterns. Hemispheric running means of air temperature and snow and ice cover correlate well (Walsh et al. 1982) and fluctuations of United States surface temperature have been found to be most highly correlated with snow cover in a broad east–west band straddling the normal winter snow line (Walsh et al. 1985). Temperatures do not rise much above freezing until snow cover disappears. Correlations of snow cover with 700 hPa heights, atmospheric persistence, including blocking, and monsoonal circulation have also been noted (Hahn and Shukla 1976; Walsh et al. 1982; Heim and Dewey 1984) and the influence of snow cover has been studied by Walsh (1987) using the NCAR community forecast model.

Study of these cryosphere–climate relationships is needed, incorporating accurate cloud data in order that a better understanding might be achieved of the associated regional and continental radiative dynamics. In addition, empirical information on clouds and the cryosphere is also necessary for the adequate modeling of the climatic impact of tropospheric aerosols on snow and ice fields. Do aerosols warm the surface air and enhance melt or does the reduced direct shortwave radiation penetrating the snow surface delay the melt?

Considerable effort has been devoted in recent years to understanding the role played by clouds in the SITZ. In this paper we evaluate the performance of the RT Nephanalysis on a regional basis. Data from RT Nephanalysis box 36 (Alaska/northern Canada, Fig. 1) have been examined to provide such an assessment. As a first stage analysis, the snow cover data provided in the RT Nephanalysis snow flag were compared with results of a snow analysis derived from DMSP imagery in the same region. The second stage considered the cloud analysis provided by the RT Nephanalysis and compared it with a cloud analysis performed from DMSP imagery.

2. Data sources and analysis procedure

A major reason why few reliable data exist on the spatial and temporal variability of clouds over snow and ice fields is the lack of a sufficiently dense ground database (Cogley and Henderson-Sellers 1984) and the difficulty in differentiating clouds from the earth's surface in operational shortwave and thermal infrared satellite imagery (McGuffe and Henderson-Sellers 1986). Time-consuming interactive visual and machine methods (e.g., Ebert 1987) need to be applied to operational shortwave data in order to differentiate clouds from snow reliably in the SITZ.

The keys to identifying snow in the shortwave are pattern continuity, landmark identification and texture,

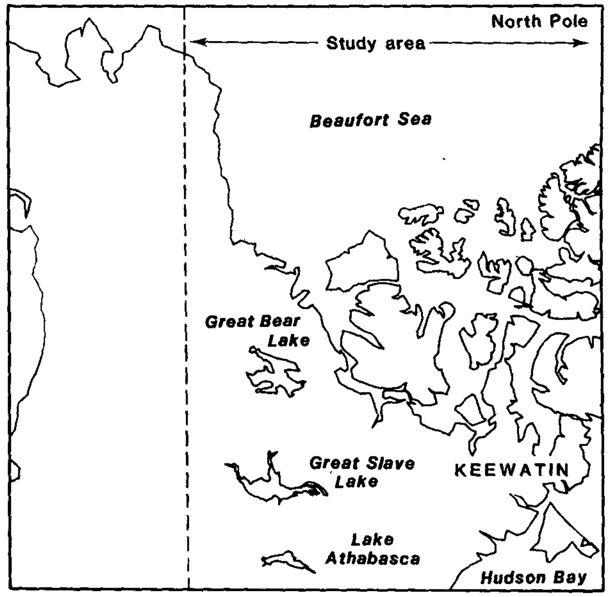

FIG. 1. Base map of northern Canada and Alaska showing study area used for this work. Major land features are indicated.

revealed by variations in surface brightness. They are a function of the type and density of vegetation and the depth and age of the snow. A persistent high brightness in shortwave imagery for a given area is associated with fresh snow and a frozen subsurface. The commencement of melt is recognized by a decrease in brightness, an increased visible/near-infrared ratio and by changes in the standard deviation, skewness and kurtosis of brightness histograms of the region, indicating the occurrence of patchy snow fields and muddy thawed soil (Robinson and Kukla 1982). The maximum albedo dataset for snow-covered lands of Robinson and Kukla (1985) provides an upper threshold for brightness and associated histogram statistics.

Investigations using microwave remotely sensed data have shown the utility of these wavelengths to "see" through clouds and recognize snow-covered ground. Microwaves can also be used to detect the onset of snow melt and the snow depth, and clouds have been distinguished from snow using an experimental sensor, with a spectral range centered close to 1.6 μm, flown on board a defense meteorological satellite (Bunting and d'Entremont 1982; Crane 1982). Major limitations of both the microwave and 1.6 μm sensors, particularly over the SITZ, are their relatively low spatial resolution and their inability to document albedo. Both sensors remain experimental at this time. Operational use is anticipated within the next decade, via the SSM/I now being flown on DMSP (Weaver et al. 1987) and the 1.6 μm channel to be flown on NOAA satellites. Extensive testing of their utility (in conjunction with shortwave imagery) in the improvement of Air Force cloud and snow products is therefore needed (e.g., Robinson et al. 1984).

Regional snow depth can be estimated from station data, shortwave imagery [depths < 15 cm if snow age is known (Robinson and Kukla 1982)] and microwave data. The snow age can be estimated from its persistence and stability in shortwave and microwave imagery and locally from ground stations.

One of the most positive aspects of the USAF Nephanalysis algorithm (RT Nephanalysis) is the incorporation of traditional ground and aircraft observations of cloudiness into a satellite-based nephanalysis. Only by such a methodology can reliable large scale cloud height information be obtained. Unfortunately, the merging of surface observations with satellite data is not as yet fully successful. The problems are most serious in the SITZ, where the infrared cloud retrieval algorithm often fails, due to the similar temperature signatures of clouds and snow, inversions and/or subpixel cloud and surface features. This often results in surface stations standing out as "bulls eyes" in the USAF RT Nephanalysis. The problem is particularly noticeable with the DEW-line stations in the Arctic basin (Fig. 2). The reason is twofold: (i) an inability to discriminate between clouds and the cryosphere in the infrared retrieval, and (ii) a mismatch of spatial scales, making merging of conventional and satellite data very difficult.

The relative optical thickness of clouds can be estimated by identifying visually the clarity of surface features visible under a cloud mass, a technique used successfully by Robinson et al. (1985) and Kukla and Robinson (1988). The height of clouds above a snow-covered surface can be estimated from shortwave imagery at low solar elevations from the width of the cloud shadow cast on the surface.

The only existing operational global cloud dataset suited to a high-resolution analysis such as this is the USAF RT Nephanalysis (and previously the 3D Nephanalysis). It has a horizontal resolution of 25 n mi (~46 km). A data array of 64 × 64 of these elements is produced every 3 h for each of 120 boxes covering the globe (Fye 1978). The vertical resolution is such that the positions (top and bottom) of up to four cloud layers are archived between the surface and approximately 55 000 ft (17 000 m). In addition, a variety of cloud and meteorological parameters are archived on a global scale. The primary sources of cloud data to produce the nephanalysis are satellite surveillance and conventional surface observations. Surface estimates of cloud amount include errors of varying magnitude depending on the experience of the observer, the location of the observing station, and the method of observation. Conventional observations are reputed to overestimate cloud amount, as gaps between individual clouds are not recognized when viewed at low-elevation angles (Sherr et al. 1968; Malberg 1973), a situation which is exaggerated in the highly multiple-scattering atmosphere of the cryospheric region. Henderson-Sellers et al. (1987) describe a detailed comparison of surface and satellite-derived cloud amounts and find the relationship will also depend strongly on satellite viewing angle (e.g., Snow et al. 1985). McGuffie et al. (1988) discussed the problem of surface–satellite comparison with particular reference to the high latitudes and suggested that the different "background" for surface observers and satellite image interpreters might lead to additional disagreements unique to high latitudes.

Satellite observations are primarily from visible and infrared sensors of the Defense Meteorological Satellite Program (DMSP). Weaknesses in satellite cloud assessment stem from their low spatial resolution relative to some cloud features, limitations to cloud height estimates, due for instance to inversions, limited passes per day and the previously discussed difficulties in differentiating between snow and clouds. Secondary problems stem from the reliance on the infrared channel in these regions and the difficulty of merging traditional observations into the satellite retrievals. The "bulls eyes" around high-latitude surface stations in RT Nephanalysis are apparent all year round.

The USAF RT Nephanalysis product, as well as containing cloud and weather information, contains a series of "diagnostic and source flags". This is an additional feature which was incorporated at the time of upgrade from 3D Nephanalysis. These "flags" are mainly single bit indications of the nature of the processing undertaken and data sources used at the particular grid point in question. The availability of diagnostic information (provided it does not comprise too great a data volume) is of considerable value to users of any global cloud analysis.

The USAF snow charts are constructed using the SNODEP model, an automated snow cover analysis model (Woronicz 1981; Hall 1986). Global charts of snow depth and age are produced once a day with a grid point spacing of 25 n mi (~46 km) at 60°N and S. Model input includes WMO surface weather observations, climatic values, weekly Navy/NOAA ice cover data, and satellite data. Satellite data are only used to control the quality of the final analysis. Major weaknesses of the model are (i) the unrepresentative situation of a number of WMO stations; (ii) sparse surface observations, especially in northern high latitudes; (iii) the need to use climatological values, due to (i) and (ii); and (iv) the extensive use of a data spreading technique to cover areas with poor information. Comparisons of the SNODEP output with the NOAA/NESDIS *Weekly Snow and Ice chart,* which is presently the primary source used in Northern Hemisphere snow studies, show that the two products frequently differ (Scaldione and Robock 1987). The Air Force product is consistently more accurate when persistent clouds prohibit the satellite-based manual charting used to construct the NOAA charts. However the NOAA product is currently better over remote regions where ground stations are sparse and the SNODEP model relies on climatology (Robinson and Kukla 1988).

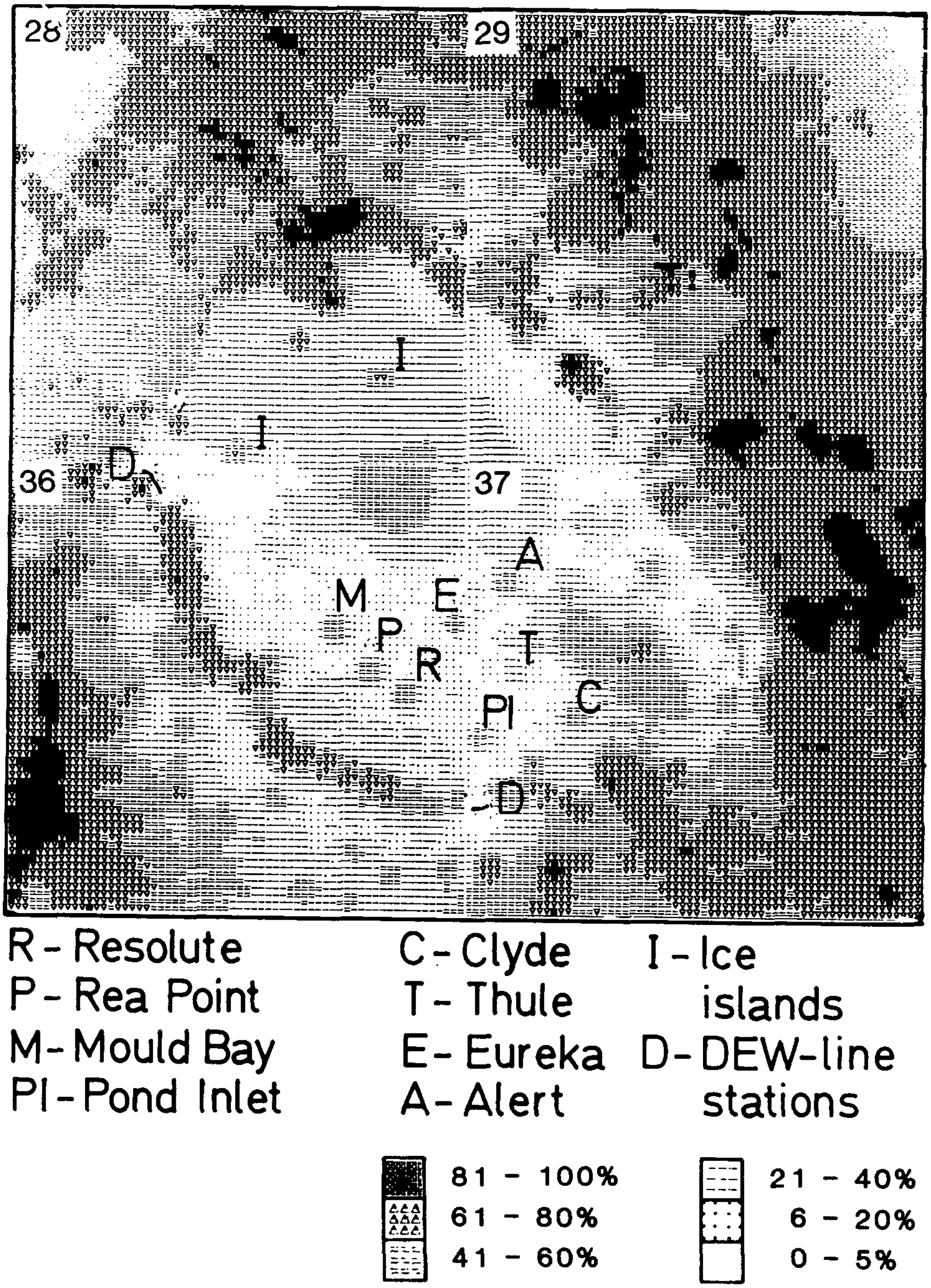

FIG. 2. Mean total cloud amount for the Arctic for May 1979 derived from 3D Nephanalysis, illustrating features caused by surface station data input. Data are for Nephanalysis boxes 28, 29, 36, and 37. The North Pole is at the center of the figure. Bottom center of the figure is 80°W.

Analyses of snow and cloud data in box 36 were performed for 3-day periods between 13 April and 24 May 1984. Snow-cover charts are presented both from the Air Force SNODEP model and from manually produced charts. The latter only cover the eastern two-thirds of box 36, as do the manual cloud charts produced for the study, due to difficulties in image analysis over the mountainous terrain in the western third of the box. The RT Nephanalysis data for this period are also used in this study. This high-latitude box was selected for study as it contains a widely spaced yet relatively extensive, network of surface stations and high-resolution (2.8 and some 0.6 km) DMSP imagery, and Air Force cloud and snow data were available on a daily basis during the study interval. Areas of particular concern with regard to the accuracy of RT Nephanalysis would be those where a disagreement exists between the SNODEP-derived snow-cover flag, and the snow cover information manually derived from DMSP imagery.

Prior to undertaking the comparison, an important step was to evaluate where data were being input from conventional stations. As discussed above, in addition to information on snow cover, the RT Nephanalysis archive also contains information on the input of conventional cloud observations into the archive. The appropriate data flag was analyzed and Fig. 3 shows the result of this exercise. The positions of the RT Nephanalysis grid points where conventional data were input for 2 sample days during April and early May are shown. These are also likely positions for snow observation input to SNODEP.

The manual cloud charts were produced using the technique of Kukla (1984) and Kukla and Robinson (1988) where classification was on the basis of visibility of surface features (e.g., leads in sea-ice, coastlines, lakes and forest stands) through the cloud. Sky conditions were categorized as 1) opaque clouds, through which no surface features were visible; 2) semitransparent clouds, through which surface features were just visible; 3) thin—quite transparent clouds (surface features clearly visible but with reduced contrast); and 4) clear (surface features visible with high contrast).

The manual snow charts were constructed by examining DMSP hard copy imagery visually for all available clear-sky scenes in the eastern two-thirds of RT Nephanalysis box 36. This was done on each of 3 days of the chosen study periods. Land surfaces were classified according to their relative brightness. Brightness class 6 (darkest) indicates snow-free conditions and a brightness of 1–5 means that some snow cover is present; the lower the number the brighter the area. The southwest (bottom left) portion of box 36 only attains a brightness of about 2 or 3 when fully snow covered, due to vegetation masking of the snow (Robinson and Kukla 1985), while the remainder of the box is class 1 or 2 when fully covered. This was taken into account when evaluating the degree of snow melt across the box, as a forested region ranked as class 4 during a particular interval may still be over 50% snow covered while a class 4 region over tundra has only 10%–50% cover. Only those 3 day study intervals where sky conditions permitted the vast majority of the study zone to be charted have been presented here. The lack of visible satellite data during the polar night means that the study cannot be extended to the wintertime Arctic.

In order to compare the manual and Air Force snow charts, the manual chart was divided into grid cells using the standard U.S. National Meteorological Center (NMC) grid. Grid orientation is identical to the Air Force grid, with each cell containing 16 Air Force grid points. The dominant brightness class in each NMC cell was assigned to the entire cell. Similarly, the NMC grid was placed over the Air Force charts and if eight

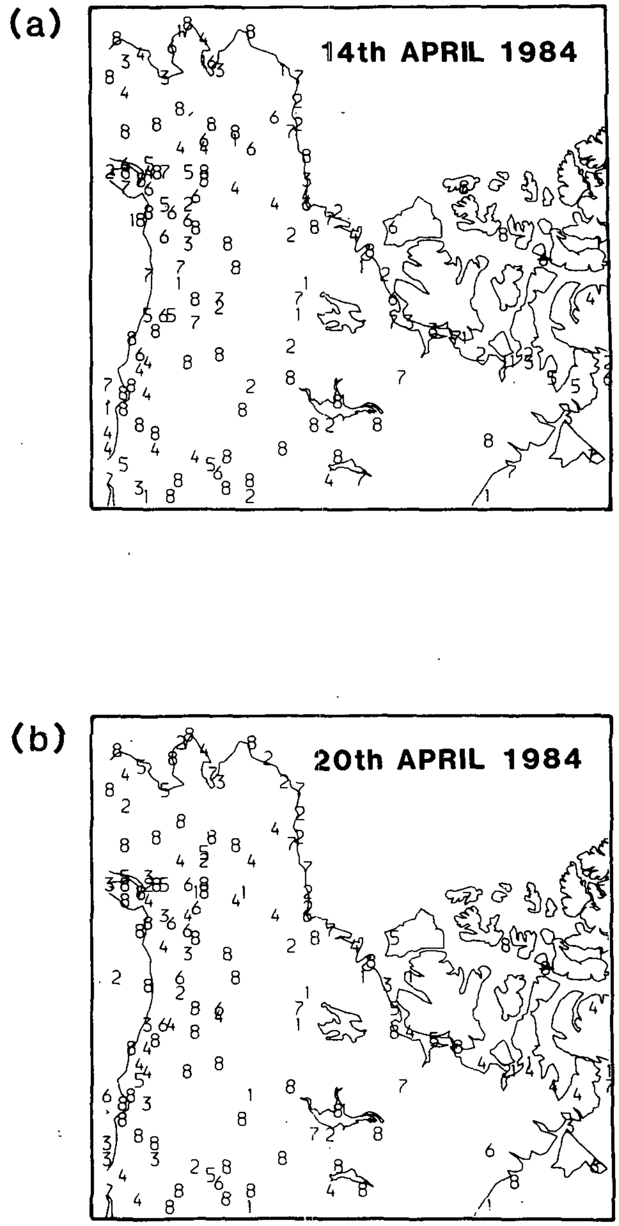

FIG. 3. Grid point locations where conventional data were input into the cloud analysis for box 36 for 2 sample days in spring 1984. The numbers represent the number of times a conventional observation was input at each grid point. Grid points with no conventional data input are not shown. The maximum value is eight. Conventional data from these points are spread to a maximum radius of four grid points.

or more Air Force grid points in an NMC cell report snow cover on at least 1 day of the 3 day interval, the NMC cell was classified as snow-covered.

The manual brightness class for each land cell was charted but in the course of the manual charting, classes 1 and 2 were combined as class 1. Grid cells reported to have a brightness of 1–4 on the manual charts and reported as snow-covered on Air Force charts are classified as being in agreement. Similarly, grid cells charted as 5 or 6 on the manual charts and snow-free on Air Force charts are left blank.

Differences have been noted where the manual charts reported snow-cover and the Air Force charts reported more than 50% cover in areas which appear dark (snow free) in the DMSP imagery.

3. Results

The Air Force snow charts display evidence of the considerable conventional data input which contributes to this analysis. Woronicz (1981) reported that the Air Force model (SNODEP) is basically a snow-cover climatology, updated by surface observations of snow cover. Observation/climatology disagreements are evident (Fig. 4) in the appearance of regularly shaped features in the snow field, indicating station reports of snow in an area which is snow free in the climatology (or vice versa). Derivation of snow-cover extent on a real time basis is difficult for many of the same reasons that cloud-cover information is hard to obtain. More specifically problematic about snow is the potential areal unrepresentativeness of station snow observations. The station may be at an elevation unrepresentative of the surounding area and the presence of human habitation inevitably contaminates the snow, leading to an advance in the state of the melt with respect to the surrounding terrain. The SNODEP model is used to indicate RT Nephanalysis grid points which are to be excluded in the analysis of visible satellite data. Consequently, any error in the snow field would likely have an influence on the derived cloud field.

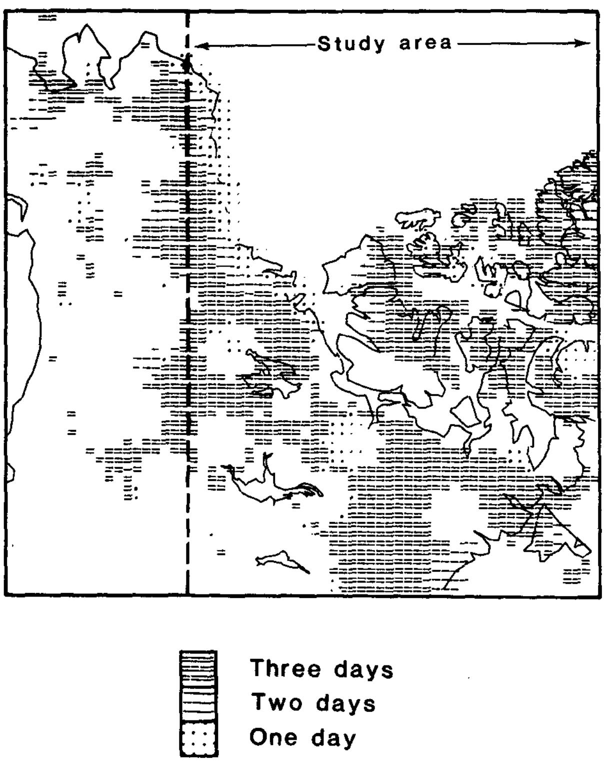

FIG. 4. Sample snow chart derived from the USAF RT Nephanalysis model. The figure shows the number of days in a sample 3 day period when snow was reported at a particular grid point. The map shows the features caused by the input of surface observations of snow-cover state. The station reports often reflect premature melting around inhabited regions, but they improve the quality of the archive when cloud cover prevents manual charting.

a. 13–15 April (Fig. 5)

In the Air Force snow chart, stations in the southwest corner of the study area report snow-free conditions. Where no stations are present, the Air Force climatology comes into use and indicates that snow is likely to be present. The Lamont snow chart indicates that little or no snow remains in this region, in agreement with the surface reports. Also shown in Fig. 5 are the corresponding cloud analyses for the middle day of the 3 day period. There is clearly some disagreement between the RT Nephanalysis cloudiness and the Lamont cloudiness. Over the Arctic basin there is an indication of negative correlation between RT Nephanalysis and Lamont-derived cloudiness. In general, on this day there does not appear to be a strong relationship between cloud thickness, as derived by the manual cloud classification, and RT Nephanalysis cloud amount.

b. 19–21 April (Fig. 6)

The previous disagreement in the southwest portion of the study area has diminished by this time; however, a few cells are now evident where a station is reporting snow-free conditions while snow is still quite prevalent according to the manual analysis. The lower of the three grid cells indicating LDGO *snow*/USAF *no snow* in Fig. 6 is, in part, a result of the ice-covered Great Slave Lake remaining bright. The cloud charts show improved agreement for the twentieth. The area of cloud to the north and west of Great Bear Lake appears on both analyses. Similarly well represented, are areas of clear sky over the Keewatin area and just off the Arctic coast to the north. The minor misidentification of snow-covered regions has not obviously affected the cloud retrieval.

c. 22–24 April (Fig. 7)

The distribution is broadly similar to the previous period. In the southwest, melt appears to be proceeding in advance of the Air Force climatology as indicated by the three cells, where the manual analysis indicates the area to be snow free although the Air Force charts report snow. Cloud areas agree well between the two analyses, although a region indicated as clear in the

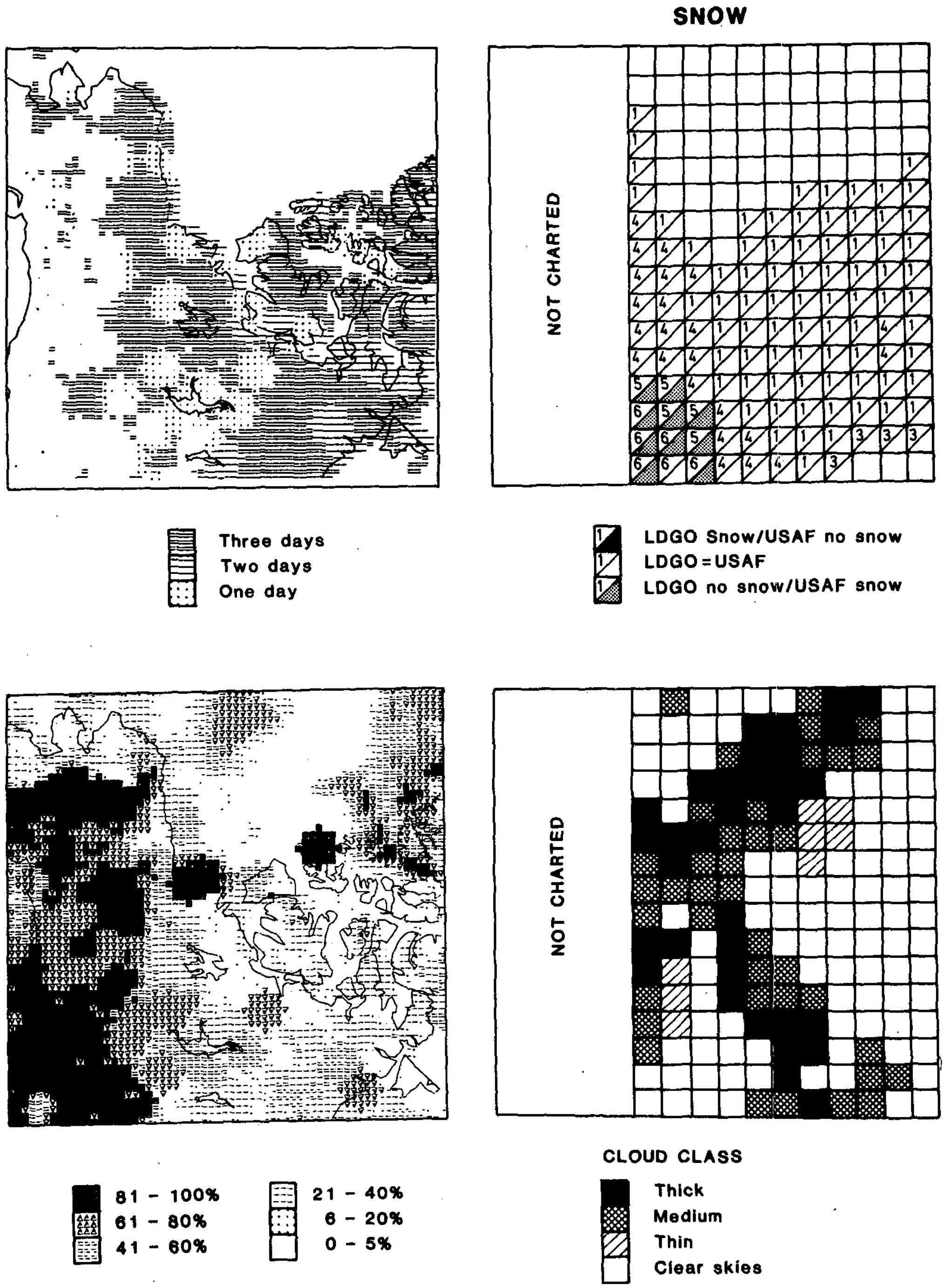

FIG. 5. Snow and cloud analysis for box 36. The RT nephanalysis charts are illustrated on the left (snow, top left; cloud, bottom left) with the corresponding manual analysis on the right. The top right frame shows the Lamont brightness classes (1 is brightest) and the lower right frame shows the Lamont cloud classification. Snow analyses are for the three days 13–15 April 1984 and the cloud analyses are for 14 April.

manual analysis appears as cloudy in the RT Nephanalysis. Again, there is no evidence of errors in RT nephanalysis due to the wrong information on snow cover being presented.

d. 28–30 April (Fig. 8)

The progression of the melt, as indicated by the Air Force snow chart, is lagging behind that indicated by

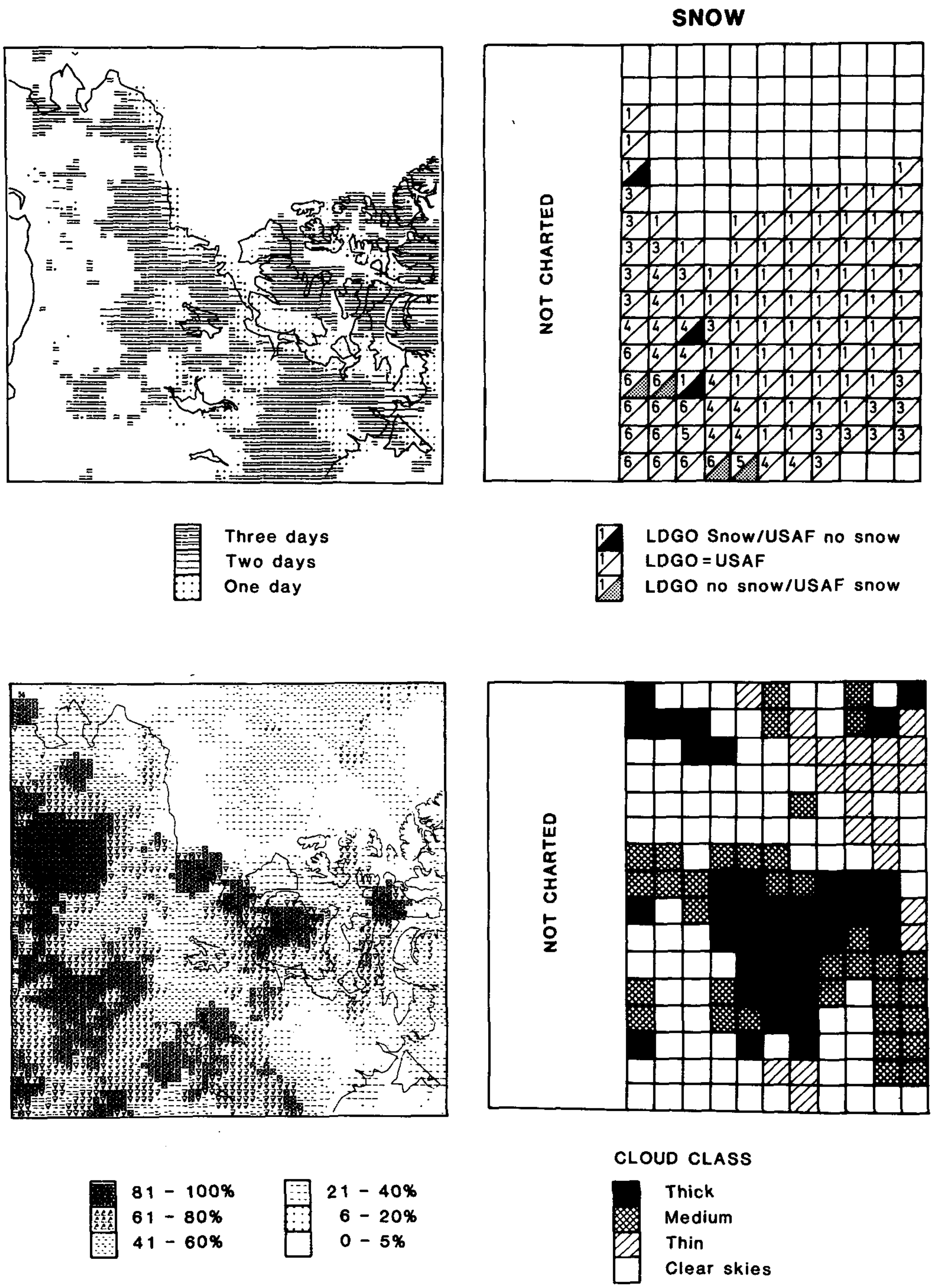

FIG. 6. As in Fig. 5, except snow analyses are for the 3 days 19–21 April 1984 and the cloud analyses are for 20 April.

the manual analysis. Such a disagreement is not one likely to induce errors in the RT Nephanalysis cloud field, since it leads only to unnecessary exclusion of visible data. Areas of cloud match well between the two analyses. The area in the center of the study area which is persistently cloudy is present on both analyses, as is the clear area to the south.

e. 16–18 May (Fig. 9)

At this point, the climatology, along with the scattered station reports, appears to be leading the actual melt. This leads to extensive areas where the presence of snow is not reported to the RT Nephanalysis algorithm. Agreement between the cloud analyses is good

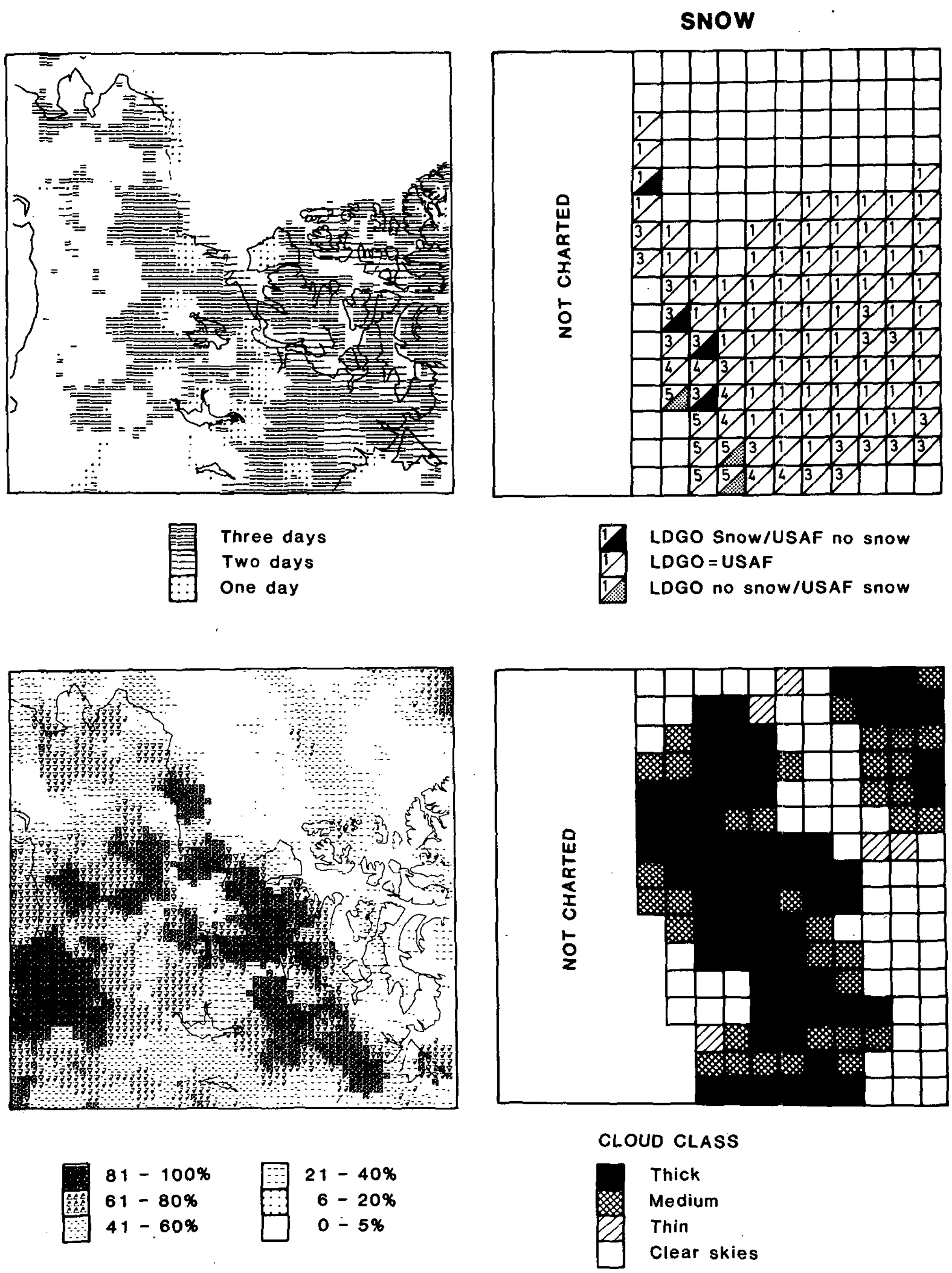

FIG. 7. As in Fig. 5, except snow analyses are for the 3 days 22–24 April 1984 and the cloud analyses are for 23 April.

except for a region of cloud over the Arctic Ocean reported by RT Nephanalysis, which is reported as clear in the manual charts.

f. 19–21 May (Fig. 10)

The Air Force snow assessment still leads the manual snow assessment but over a lesser area than the previous chart. Cloud-cover charts agree fairly well.

g. 22–24 May (Fig. 11)

In this period, there is a substantial area along the snow margin where the Air Force chart is likely to lead to errors in RT Nephanalysis cloud identification. From the Arctic coast south, past the Great Bear and Great Slave lakes, there is a region of cloud in RT Nephanalysis which coincides with the snow-cover disagreement reported. The southernmost area of ap-

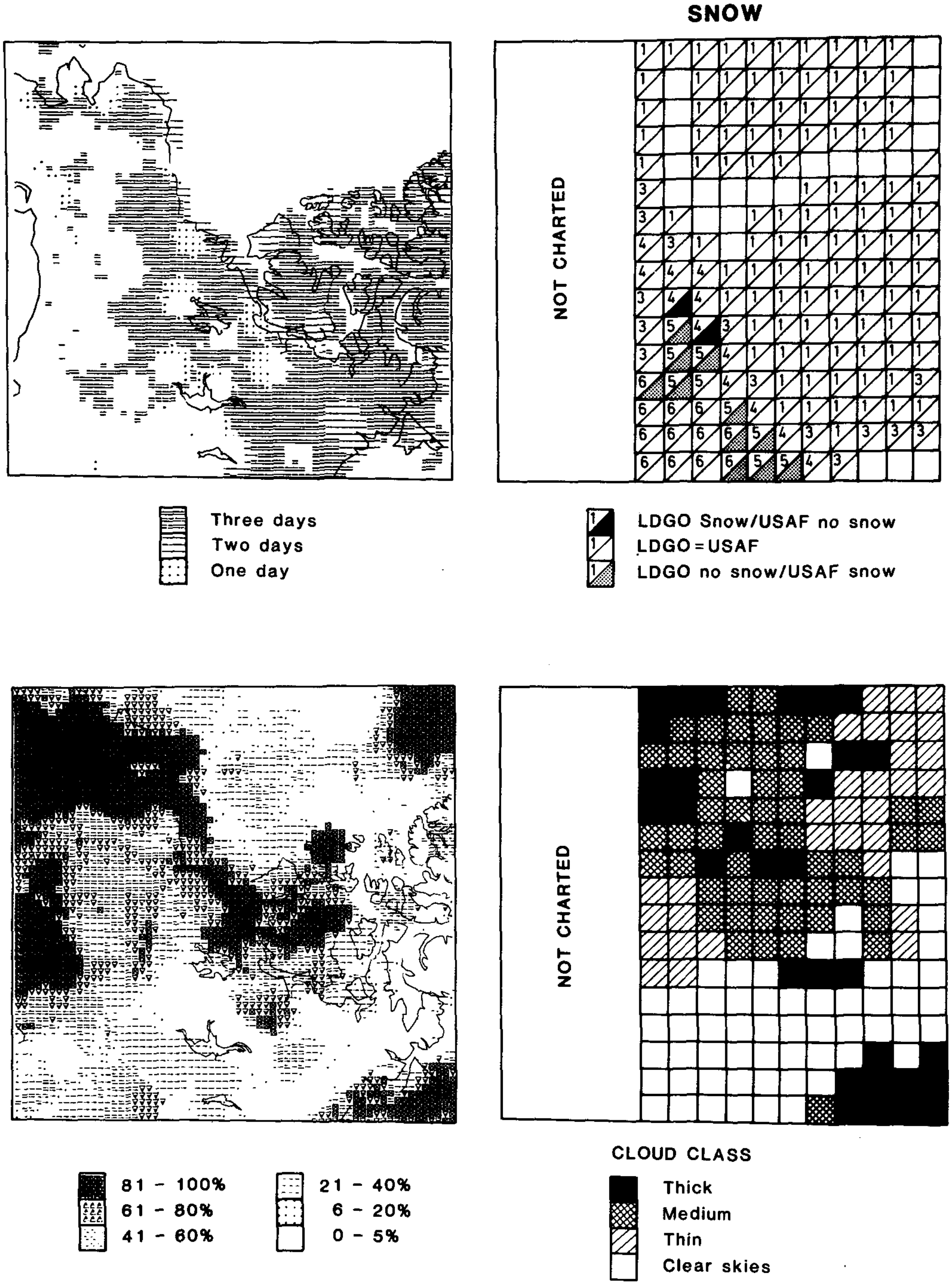

FIG. 8. As in Fig. 5, except snow analyses are for the 3 days 28–30 April 1984 and the cloud analyses are for 29 April.

parent cloud cover is reported by the manual analysis but not the area to the north.

4. Conclusions

From a sample of days during the spring of 1984 in northern Canada, an assessment has been made as to the quality of the RT nephanalysis snow flag. In general, it was found that the quality was good. On occasions, however, the difference between Air Force snow cover and manual-derived snow cover was such that errors might be introduced into the RT Nephanalysis. In the cases where the area which was misidentified as snow free was very large, this was found to have an influence

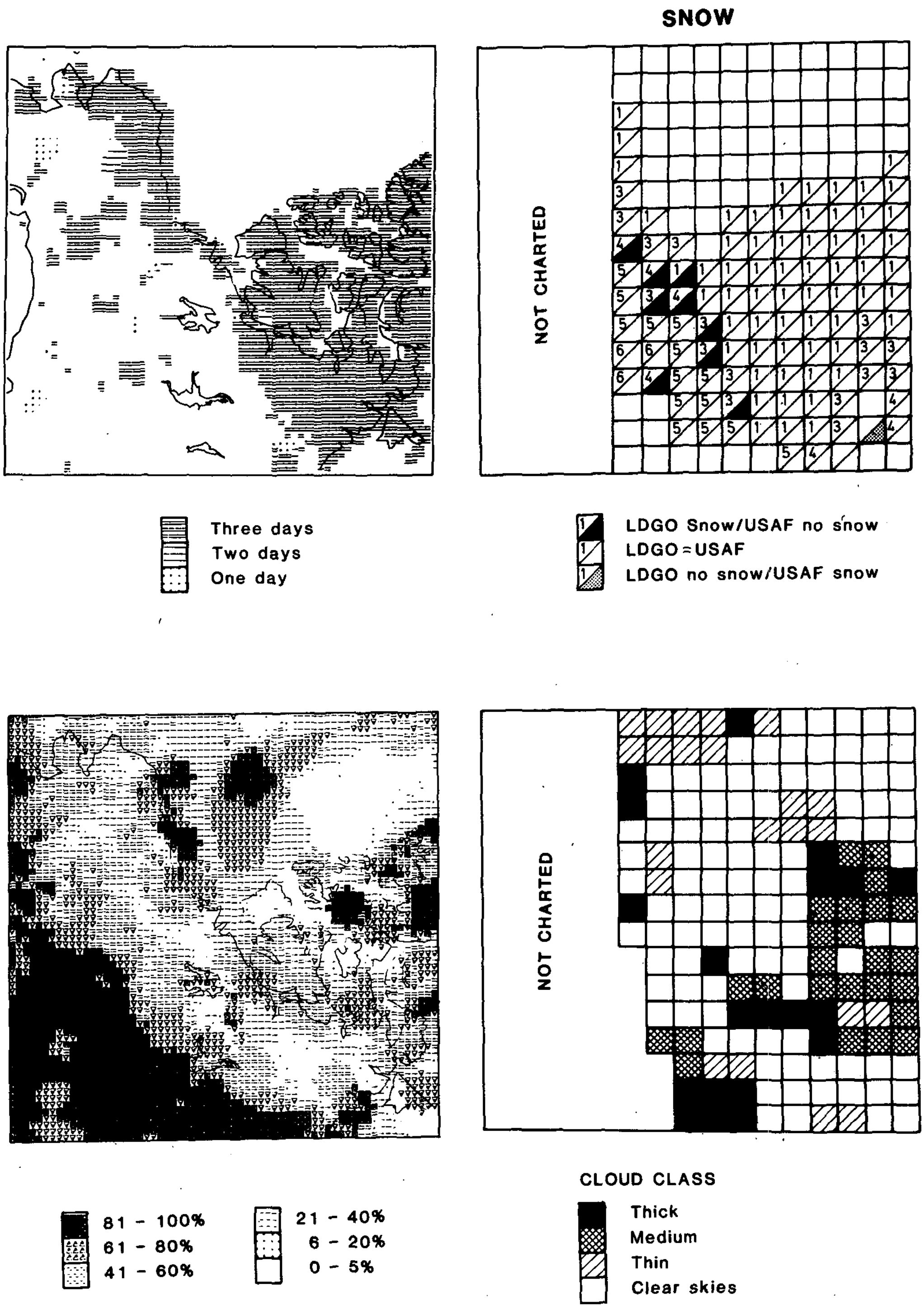

FIG. 9. As in Fig. 5, except snow analyses are for the 3 days 16–18 May 1984 and the cloud analyses are for 17 May.

on the cloud analysis produced. On many of these occasions, the presence of surface cloud observations somewhat corrected the error in cloud amount. The lack of a definitive cloud amount analysis means that the errors can only be qualitatively described. Although this examination is specific to RT Nephanalysis, the problems encountered by this algorithm in the polar regions will be characteristic of those encountered by

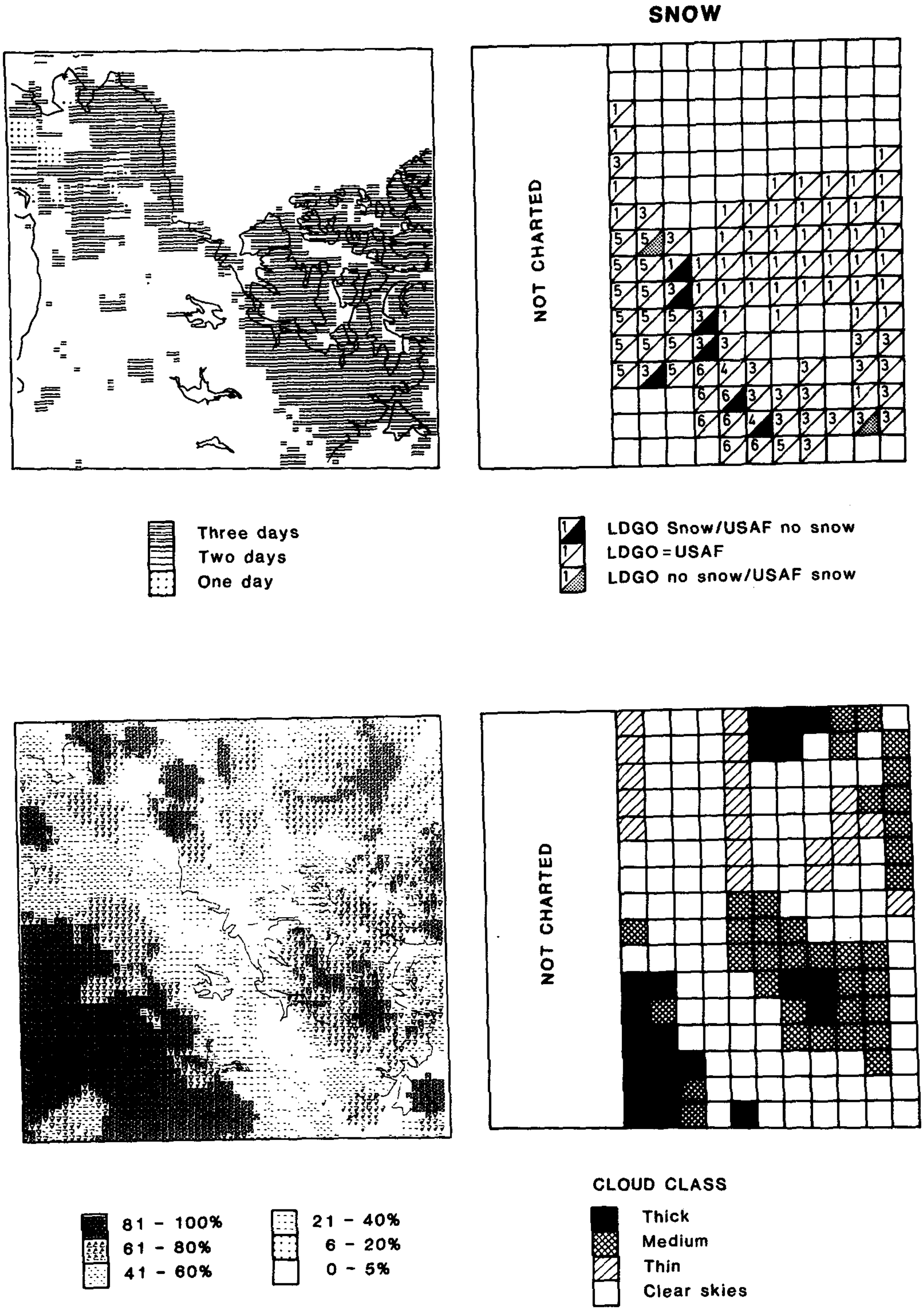

FIG. 10. As in Fig. 5, except snow analyses are for the 3 days 19–21 May 1984 and the cloud analyses are for 20 May.

any cloud detection algorithm utilizing currently available satellite imagery. The work is currently being extended over wider space and time scales but these results show clearly the benefits of utilizing surface cloud observations in the construction of a global cloud model.

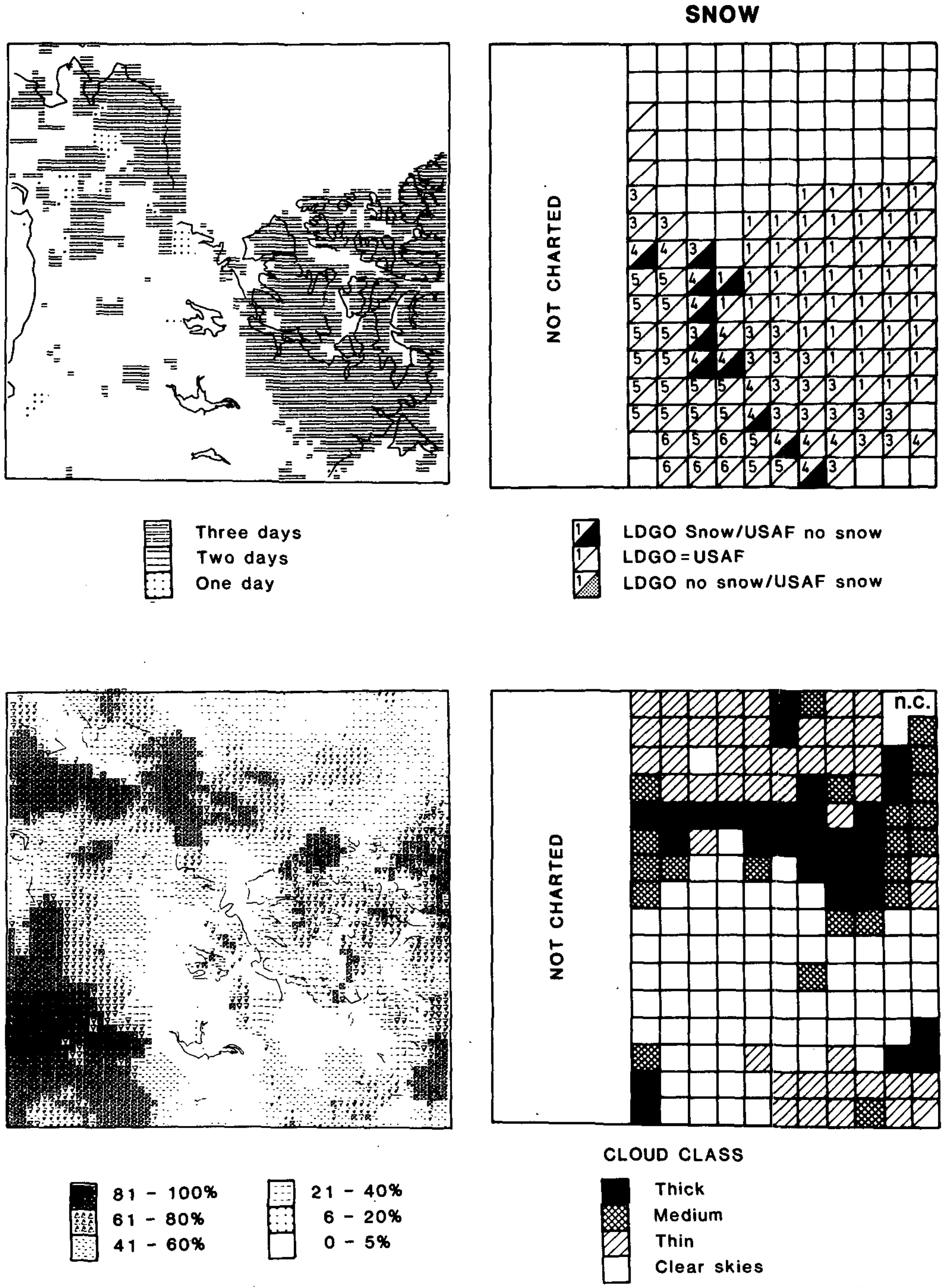

FIG. 11. As in Fig. 5, except snow analyses are for the 3 days 22–24 May 1984 and the cloud analyses are for 23 May.

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