AFOSR-TR- 89-0590

(2)



# COMPLETED PROJECT SUMMARY

**TITLE:** Cloud/Cryosphere Interactions

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**JUNIOR RESEARCH PERSONNEL:**

Ted Baker
Mike Sheinkman
Susan Walker

**PUBLICATIONS:**

"Initiation of spring snowmelt over arctic lands", D.A. Robinson, In: *Cold Regions Hydrology Symposium Proceedings*. Fairbanks, AK, American Water Resources Association, 547-554 (1986).

"Remotely sensed albedo of snow-covered lands", D.A. Robinson, In: *Proceedings of the Second Conference on Satellite Meteorology/Remote Sensing and Applications*. Williamsburg, VA, American Meteorological Society, 173-176 (1986).

"Snow melt and surface albedo in the Arctic Basin", D.A. Robinson, G. Scharfen, M.C. Serreze, G. Kukla and R.G. Barry, *Geophysical Research Letters* 13, 945-948 (1986).

"Analysis of interannual variations of snow melt on arctic sea ice mapped from meteorological satellite imagery", D.A. Robinson, G. Scharfen, R.G. Barry and G. Kukla, In: *Large-Scale Effects of Seasonal Snow Cover*. International Association of Hydrological Sciences Publication 166, 315-327 (1987).

"Large-scale patterns of snow melt on Arctic sea ice mapped from meteorological satellite imagery", G. Scharfen, R.G. Barry, D.A. Robinson, G. Kukla and M.C. Serreze, *Annals of Glaciology* 9, 1-6 (1987).

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Major ~~project~~ objectives included investigating cryospheric dynamics, ~~in~~ particular relationships and feedbacks between clouds and the cryosphere when snow cover is forming or dissipating, and assessing ~~and suggesting improvements in~~ algorithms and climatologies used in ~~the Air Force~~ A.F. operational snow and cloud cover products. ~~These objectives have been met, resulting in~~ improvements in snow and cloud climatologies as well as increased understanding of: 1) seasonal and interannual variations in snow and cloud cover, 2) the dynamics of the onset of melt season in arctic regions, 3) the performance of ~~Air Force~~ nephanalyses in marginal cryosphere regions, and 4) the performance of the A.F. ~~Air Force~~ SNODEP model. Study results have been reported in twelve publications, presented at eight conferences and discussed in detail with personnel at several Air Force installations. ~~Specific~~ project results may be summarized as follows: include:

1 ) Cloud cover in the Arctic Basin has a late May-early June maximum in extent and thickness, followed by a period of less extensive and thinner cover extending into early August. Cloud conditions are associated with the distribution of surface pressure and the flow of air into the Basin at the surface and aloft.


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block number 19 (abstract) continued:

2 ) Over arctic lands and sea ice, the timing and duration of the snow melt season, which strongly influences the surface mobility of personnel and machinery, has been observed to vary geographically within a year and across the region from year to year.

3 ) Increased Spring cloudiness and the onset of the melt season over sea ice are coincident, suggesting that both are related to the northward transport of moist air into the Basin by synoptic disturbances, rather than one solely driving the other. Results over arctic lands are less conclusive. Varying conditions of the snow pack, the surface albedo, the seasonal and latitudinal distribution of solar insolation reaching the top of the atmosphere are among the other factors influencing melt.

4 ) A southward shift in the mid-winter snow line was found over the central United States in the past 50 years. This has been accompanied by trends towards colder surface air temperatures and lower precipitation during winter. Considerable year-to-year, month-to-month and week-to-week variability in snow cover exists in this region.

5) Short-term variability of snow extent was observed over the Tibetan Plateau. Despite the cold winter temperatures in this region, the presence of snow cover is strongly precipitation dependent, perhaps more so than in any other part of the world.

6 ) A comparative study of manually-produced cloud and snow charts and USAF nephanalyses in the high northern latitudes found errors in the latter caused by the incorrect positioning of snow cover in the USAF SNODEP model.

7 ) The SNODEP output was found to be considerably more accurate than the NOAA satellite-derived snow data set in periods of persistent cloudiness. In remote regions with few ground stations the NOAA product performed better. Inclusion of satellite-derived information in the SNODEP model, particularly in the latter regions, would considerably increase the quality of the product.

Aside from the contributions of the project to basic climatologic research and to improved understanding of cryosphere and cloud dynamics, information with more direct or practical benefits to the Air Force has resulted from this project. This output falls into several categories, including the recognition of clouds and snow in marginal cryospheric regions. The characteristics of these elements have important military ramifications in terms of directive energy, space surveillance and identification of the transit of a threat across the area. Knowledge of the dynamics of snow melt in the marginal cryosphere are useful in understanding or assessing ground stability in these regions. Improved climatologies of snow cover and arctic cloud cover are useful for planning and modeling purposes. Finally, critical evaluations of Air Force snow and cloud models and recommendations for their improvement should make these operational products more useful for planning purposes.

"Snow cover as an indicator of climate change", D.A. Robinson, In: *Large-Scale Effects of Seasonal Snow Cover.* International Association of Hydrological Sciences Publication 166, 15-25 (1987).

"Analysis of clouds over arctic sea ice" D.A. Robinson and G. Kukla, In: *Presentations at the Fifth Tri-Service Clouds Modeling Workshop.* U.S. Naval Academy, Annapolis MD, 115-128 (1987).

"Comments on "Comparison of Northern Hemisphere Snow Cover Data Sets"", D.A. Robinson and G. Kukla, *Journal of Climate* 1, 435-440 (1988).

"Summer cryospheric and atmospheric variability in the Arctic Basin", D.A. Robinson and G. Scharfen, In: *Proceedings of the Second Conference on Polar Meteorology and Oceanography,* American Meteorological Society, 44-47 (1988).

"Variability of summer cloudiness in the Arctic Basin", G.J. Kukla and D.A. Robinson, *Meteorology and Atmospheric Physics* 39, 42-50 (1988).

"Intercomparison of satellite-derived cloud analyses for the Arctic Ocean in spring and summer", K. McGuffie, R.G. Barry, J. Newell, A. Schweiger and D.A. Robinson, *International Journal of Remote Sensing* 9, 447-467 (1988).

"Examination of USAF Nephanalysis performance in the marginal cryosphere region" K. McGuffie and D.A. Robinson, *Journal of Climate* 1, 1124-1137 (1988).

## ABSTRACT OF OBJECTIVES AND ACCOMPLISHMENTS:

***Project Objectives:***

Major research objectives included investigating cryospheric dynamics, in particular, relationships and feedbacks between clouds and the cryosphere when snow cover is forming or dissipating, and assessing and suggesting improvements in algorithms and climatologies used in Air Force operational snow and cloud cover products.

***Project accomplishments are summarized as follows:***

1 ) Cloud cover in the Arctic Basin has a late May-early June maximum in extent and thickness, followed by a period of less extensive and thinner cover extending into early August. Cloud conditions are associated with the distribution of surface pressure and the flow of air into the Basin at the surface and aloft.

2 ) Over arctic lands and sea ice, the timing and duration of the snow melt season, which strongly influences the surface mobility of personnel and machinery, has been observed to vary geographically within a year and across the region from year to year.

3 ) Increased Spring cloudiness and the onset of the melt season over sea ice are coincident, suggesting that both are related to the northward transport of moist air into the Basin by synoptic disturbances, rather than one solely driving the other. Results over arctic lands are less conclusive. Varying conditions of the snow pack, the surface albedo, the seasonal and latitudinal distribution of solar insolation reaching the top of the atmosphere are among the other factors influencing melt.

4 ) A southward shift in the mid-winter snow line was found over the central United States in the past 50 years. This has been accompanied by trends towards colder surface air temperatures and lower precipitation during winter. Considerable year-to-year, month-to-month and week-to-week variability in snow cover exists in this region.

5) Short-term variability of snow extent was observed over the Tibetan Plateau. Despite the cold winter temperatures in this region, the presence of snow cover is strongly precipitation dependent, perhaps more so than in any other part of the world.

6 ) A comparative study of manually-produced cloud and snow charts and USAF nephanalyses in the high northern latitudes found errors in the latter caused by the incorrect positioning of snow cover in the USAF SNODEP model.

7 ) The SNODEP output was found to be considerably more accurate than the NOAA satellite-derived snow data set in periods of persistent cloudiness. In remote regions with few ground stations the NOAA product performed better. Inclusion of satellite-derived information in the SNODEP model, particularly in the latter regions, would considerably increase the quality of the product.

**CLOUD/CRYOSPHERE INTERACTIONS**
**Final Report: AFOSR 86-0053**

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COMPREHENSIVE FINAL REPORT

# CLOUD/CRYOSPHERE INTERACTIONS
# AFOSR 86-0053

Co-investigators:

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New Brunswick, NJ 08903

April 1989

## *SUMMARY*

Project objectives have been met, resulting in improvements in snow and cloud climatologies as well as increased understanding of: 1) seasonal and interannual variations in snow and cloud cover, 2) the dynamics of the onset of the melt season in Arctic regions, 3) the performance of nephanalyses in marginal cryosphere regions, and 4) the performance of the Air Force SNODEP model. Study results have been reported in twelve publications, presented at 8 conferences and discussed in detail with personnel at several Air Force installations.

## *PROJECT OBJECTIVES*

Major project objectives included investigating cryospheric dynamics, in particular, relationships and feedbacks between clouds and the cryosphere when snow cover is forming or dissipating, and assessing and suggesting improvements in algorithms and climatologies used in the Air Force operational snow and cloud cover products.

## *RESEARCH SYNOPSIS*

### 1) Arctic Basin

*a) Summer clouds and snow cover*

Spring and summer snow and cloud cover dynamics in the Arctic Basin were investigated using satellite and ground station data from the mid 1970's to mid 1980's. Satellite data included output from polar orbiting Defense Meteorological Satellite Program (DMSP) and NOAA satellites. Cloud cover appears to have a late May-early June maximum in extent and thickness over the Basin, followed by a period of less-extensive and thinner cover extending into early August. Autumn cloud cover is more extensive, while winter is the least cloudy period of the year. Figure 1 shows two examples of spring and summer conditions in a major portion of the Basin. At this time of the year cloud conditions are associated with the distribution of surface pressure and the flow of air into the Basin at the surface and aloft (fig. 2). (Robinson and Kukla, 1987; Kukla and Robinson, 1988)

The progression of snow melt over the arctic pack ice exhibits variations of as much as three weeks. As a result, basin-wide surface albedo varies by upwards of 0.08 in June, ranging from approximately 0.58 to 0.66. May and July showed interannual variations in albedo of up to 0.05. Figure 3 shows the progression of melt in four of the ten study years which fell between 1975 and 1988. The 1977 melt season was the earliest of the ten. The coincident nature of increased cloudiness and the onset of surface melt suggests that both are related to the northward transport of warm moist air into the Basin by synoptic disturbances, rather than one solely driving the other (fig. 4). The central Arctic (north of approximately $80^{o}$) becomes essentially snow free by mid-July in some years but retains a partial cover throughout the summer in others. Each year by mid August a fresh snow pack begins to appear. (Robinson et al., 1986; Scharfen et al., 1987; Robinson et al., 1987)

Potential relationships between snow melt and arctic surface air temperatures in spring, spring cloudiness and the extent of late summer ice were noted. For instance, an association between positive anomalies of surface air temperature and negative anomalies of Basin-wide surface albedo was apparent in May and three of the four Junes in a study which included data from 1977, 1979, 1984 and 1985 (fig. 5). Such a relationship was not evident in July. This suggests that the temperature data are not representative of the inner Basin, but are related to melt in the coastal seas located near the reporting stations. More data and more detailed assessments are needed before any strong confidence can be ascribed to any of these potential associations. (Robinson and Scharfen, 1988)

*b) Surface and atmospheric spectral characteristics*

The earth/atmosphere system in the high Arctic exhibits complex spectral characteristics throughout the year, as recorded by visible (solar) and infrared (thermal) sensors on board polar orbiting satellites (fig. 6). The spectral responses of the ice, snow, cloud, water and land vary with season and location. The reflection and emission of the solar and thermal radiation by different surfaces and atmospheric layers depends on solar elevation, atmospheric transparency and the condition of the surface. Comparisons between responses in the infrared and visible over a given surface show variations in the spatial homogeneity of signals. Also, subpixel and multilayer cloud and surface features influence to the spectral signature or its pattern over a given area.

*c) Air Force nephanalysis performance*

Comparisons of the Lamont cloud charts from June 1979 with coincident Air Force 3D Nephanalysis and cloud charts produced by the University of Colorado show broad agreement between the three products. However, errors affected several geographical areas and cloud types. The Lamont and Colorado manual analyses show more clouds over the Arctic than the automated 3D Neph (fig. 7). The automated infrared-threshold technique employed in the nephanalysis has problems picking up clouds in the Arctic because of the near-isothermal structure of the lower atmosphere and persistent stratiform clouds in summer. The manual analysis was found to be affected by the skill of the analyst, with decisions as to the nature of the cloud cover in complex situations differing between analysts. (McGuffie et al., 1988)

## 2) Continental Arctic and Sub-arctic

*a) Alaska snow melt*

Snow melt was studied in several regions of Alaska using satellite and ground station data. Two areas exhibiting major differences in the timing of melt are the Tanana Basin and North Slope. Results from an eight year (1978-1985) study of these two regions include:

1) The period of most rapid regional snow dissipation begins approximately 7 weeks later on the North Slope than over the Tanana Basin. The onset of this interval in each region was found to correlate with daily regionally averaged values of parameterized absorbed shortwave radiation at the ground (Q) of between 6 and 8 $MJ/m^{2}/day$. Q was calculated from a simple model whose input includes surface albedo, fractional cloud cover, relative cloud optical thickness and insolation at the top of the atmosphere. Since interannual and interregional mean cloudiness varied little during the study years, and since the top of the atmosphere insolation is similar in both regions, the primary controlling variable in the initiation of the melt season appears to be the difference in regional albedo of the bright snow-covered tundra on the Slope and the dark moderately forested Tanana Basin.

2) Interannual variations in the duration of melt within individual regions appear to be influenced by the character, timing, frequency and duration of air masses advected into a region. These systems may accelerate or retard the progression of the snow melt.

3) The duration of melt and the unstable surface conditions accompanying it appears to be more sensitive to the initial water content of the snow pack in the Basin than they

do on the Slope. In the latter region, the timing of melt initiation (not necessarily the period of most rapid melt) appears to be more important (early initiation = long duration) (tables 1 and 2). (Robinson, 1986a)

*b) Air Force nephanalysis and snow model performances*

The performances of the USAF Real Time Nephanalysis (RT Neph) and USAF snow depth and age (SNODEP) models in identifying clouds and snow on a regional basis were tested using spring 1984 data from RT Neph box 36 (Alaska/Northern Canada). As a first-stage analysis, the snow cover data provided in the RT Neph snow flag (from the SNODEP model) were compared with results of an analysis of DMSP imagery in the same region. The second stage considered the cloud analysis provided by the RT Neph and compared it with a cloud analysis performed from DMSP imagery.

In general, the quality of the SNODEP model was acceptable. Occasionally, however, the difference between Air Force snow cover and manually-derived snow cover was large and errors in the model are likely to degrade the RT Nephanalysis. Where available, surface observations reduced the error in the nephanalysis cloud amount.

Two examples from the study are shown in figures 8 and 9. In the first, covering the 13-15 April period, the stations reporting in the southwest corner of the study area show snow-free conditions on the Air Force chart. 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 figure 8 are the corresponding cloud analyses for the middle day of the three day period. Disagreement exists between the RT Nephanalysis cloudiness and the Lamont cloudiness. Over the Arctic Basin there is an indication of a negative correlation between RT Neph and Lamont derived cloudiness. On this day, the cloud thickness derived by the manual cloud classification and the RT Neph cloud amount differ considerably.

In the second example from 22-24 May, there is a substantial area along the snow margin where the Air Force snow product likely led to errors in RT Neph cloud identification. From the Arctic coast south, past Great Bear and Great Slave Lakes, there is a region shown as cloud in the RT Nephanalysis which coincides with the snow cover disagreement reported. The southern-most area of apparent cloud cover is reported by the manual analysis but not the area to the north.

Although this examination was specific to RT Neph, the problems encountered by this algorithm in the Sub-arctic and Arctic regions are likely to persist in any other cloud detection algorithm utilizing currently available satellite imagery. (McGuffie and Robinson, 1988)

### 3) Central United States

The utility of using long-term snow data sets as potential indicators of climate change and as a means of improving snow cover climatology was proven using a 143 station network in the central U.S. (fig. 10). Station records were virtually complete from 1900 to 1978.

The year-by-year January snow cover durations for three $1^{\circ}$ latitude by $4^{\circ}$ longitude cells in the region (fig. 11) indicate a significant increase in the number of days with snow cover in portions of Nebraska and Kansas in the past few decades compared with the earlier portion of this century. In North Dakota, trends in snow duration and depth are not seen. In the Central Plains, the trend is not recognized earlier in the snow season but continues into Spring (fig. 12). It should be noted that the methodology of reporting snow on the ground has not changed during this century.

Looking at the entire study zone, the decades in this century with the least and the greatest January snow cover were 1900-09 and 1970-79, respectively (fig. 13). A general upward trend in January cover in the central U.S. throughout this century is noted (fig. 14). In January, there appears to be a positive relationship between cold temperature anomalies and above normal snow cover and warm anomalies and below normal cover on annual and long-term scales in this zone. There is also some suggestion of a relationship between long-term trends of decreasing precipitation and increasing snow cover.

No connection is apparent between the timing of the dates of the first and last snow cover in a winter, nor with the beginning or ending dates of continuous snow cover in the northern portions of the zone. Figure 15 exemplifies the latter for the town of Napoleon in southeastern North Dakota. There does appear to be a positive relationship between maximum winter snow depth and the duration of continuous snow cover at Napoleon (fig. 16). (Robinson, 1987)

#### 4) South-central Asia

Snow cover and cloud cover were charted over a period of 45 days (Dec. 18, 1977-Jan. 31, 1978) in south central Asia using DMSP imagery (fig. 17). Within $1^{o}x1^{o}$ study cells, when greater than 50% of the cell was cloud free, the surface was classified as being snow free or falling into one of five snow covered brightness classes. Variations in brightness when snow is present are primarily a result of the thickness and areal coverage of the snow pack in this lightly-vegetated zone (Robinson, 1986b). In mountainous portions of the region, shadowing results in some decrease in brightness. Cells covered with greater than 50% cloud cover were classified as optically thin, moderately thick or thick. Only in the latter class is the underlying surface totally obscured.

Figures 18-21 show time series for four cells (cf. fig. 17) during the study period. The two Tibetan cells, while having some snow present throughout the period, show significant fluctuations in the areal coverage of snow. The central plateau cell is less frequently cloud covered than the southwestern cell, however in the latter the clouds are not optically thick. The Takla Makan cell is frequently cloudy and on the nine days when the surface is visible it is seen as snow covered. Based on information provided by Chinese climatologists, the presence of the snow cover in this usually dry zone is surprising. Whether this interval was anomalous or not will require a more extensive study. The northwestern China cell is predominantly clear and fully snow covered during the interval, although the surface brightness suggests that the snow may be less than 10cm deep. (Robinson et al., in preparation a)

**5) Comparison of USAF SNODEP Product With NOAA Snow Charts**

A paper by Scialdone and Robock (1987) provided the impetus to expand upon earlier Lamont studies (Kukla and Robinson, 1981a & b) regarding the accuracy of operational snow cover products. The crux of the issue was that Scialdone and Robock took the NOAA/NESDIS Weekly Snow and Ice Charts as their standard, and concluded that any other product, including the USAF SNODEP product, was inaccurate if it failed to agree with the NOAA chart. However, they provided no independent analysis to support this assumption. Such analyses done at Lamont have found that neither the NOAA/NESDIS charts nor the USAF SNODEP model-derived charts are superior. The Air Force product is consistently more accurate when persistent clouds prohibit the satellite-based manual charting used to construct the NOAA charts. On the other hand, the NOAA product is currently better over remote regions where ground stations are sparse and the SNODEP model relies on climatology.

The two operational products were compared with Lamont charts, which were independently constructed from satellite imagery and surface data. Figure 22 shows such a comparison over central Canada in April 1984. Here, a reasonably good agreement was found between the charts when the areas classified as patchy snow by NOAA and Lamont and having less than 2 inches of snow by the Air Force were eliminated. The largest differences between the three charts occurred at mid month (22A), where the NOAA chart showed a large area of patchy cover in an area reported to have deep snow by the Air Force and having nearly complete snow cover on the Lamont chart. Much of this area was classified as full cover on the subsequent NOAA chart (22B). However, during the same mid-month interval (22A), the SNODEP model reported snow over 2 inches deep in the southeast portion of the study zone where Lamont and NOAA agreed on the presence of patchy cover. In the south central area, Lamont and NOAA showed patchy cover where Air Force reported snow-free conditions. (Robinson and Kukla, 1988)

**6) Strategy for Sampling Snow Cover Using Shortwave Satellite Imagery**

Throughout the project, shortwave satellite imagery was frequently relied upon to accurately chart continental snow cover. Whether done subjectively by trained observers or interactively using an image processing system such charting is extremely tedious and time consuming. In the course of these efforts the question therefore naturally arose as to what might be the optimum temporal sampling strategy to accurately monitor snow yet reduce the charting load as much as possible. As a first approach to addressing this question, a study region in the midwestern U.S. was selected and daily charts of snow and cloud conditions were produced from DMSP imagery for March 1979. Monthly mean snow cover for each of the 70 $1^{o}x1^{o}$ cells in the zone was estimated from all days on which the cell was cloud free using imagery from every day, every other day and so on up to every seventh day. Weekly cover was estimated by assuming that the last cloud free day of the week (or the previous week if all seven days were cloudy) represented weekly conditions. Weekly cover was similarly estimated using sampling strategies of every other day and every third day. Monthly and weekly results were compared to snow cover charts derived from a dense network of 236 ground stations within or adjacent to the region. For the purpose of this exercise these charts were considered to be accurate.

Preliminary results show that the satellite-based estimates of monthly snow cover under report cover by several degrees of latitude. Accuracy decreases with less frequent sampling. Weekly satellite snow estimates were least accurate in marginal snow areas where daily sampling is a necessity. More detailed results will appear in a forthcoming paper (Robinson et al., in preparation b).

## *PRACTICAL BENEFITS OF PROJECT TO THE AIR FORCE*

Aside from the contributions of the project to basic climatologic research and to improved understanding of cryosphere and cloud dynamics, this project has produced information with more direct or practical benefits to the Air Force. This output falls into several categories, including: 1) Keys to the recognition of clouds and snow in marginal cryospheric regions. The characteristics of these elements have important military ramifications in terms of directive energy, space surveillance and identification of the transit of a threat across the area. 2) Knowledge of the dynamics of snow melt in the marginal cryosphere are useful in understanding or assessing ground stability in these regions. 3) Improved climatologies of snow cover and arctic cloud cover are useful for planning and modelling purposes. 4) Critical evaluations of Air Force snow and cloud models and recommendations for their improvement should make these operational products more useful for planning purposes.

## *INTERACTIONS WITH AIR FORCE GROUPS*

### Air Force Global Weather Central (AFGWC), Offutt AFB

Contact was maintained with personnel at AFGWC throughout the project. In March of 1987, both principal investigators traveled to Nebraska for discussions with GWC staff regarding the production of the DMSP hard copy imagery, the workings of the RT Nephanalysis algorithm and, in particular, the intricacies of the SNODEP model. Major Tim Crum and Mr. Sam Hall of the Software Development Branch acquainted us with the snow algorithm and together we discussed where efforts could be made to test the output and to improve portions of the algorithm. Lt. Col. Michael Kelly, AFGWC DOX, coordinated arrangements for this visit.

**Headquarters Air Weather Service(AWS), Scott AFB**

Captain Michael Remeika of the AWS coordinated our acquisition of global station data from files at the Environmental Technical Applications Center (ETAC).

**ETAC, Scott AFB**

Mr. Mark Surmeier, Chief, Special Projects Section and Mr. William Bainter generated a tape of daily station data for the central regions of North America and Eurasia. Delays in the arrival of the ten-year data set at Lamont (summer 1988) limited its utility to the project, but it will be of great use in any future endeavors between our team and the Air Force. In the process of compiling this set, one of us (DAR) met with the ETAC group at Scott in November 1987. Some glitches our team discovered in the algorithms used to flag the data were discussed.

**ETAC/Operating Location A (OLA), Asheville, N.C.**

Robert Davy and John Walsh of OLA provided us with a tape containing daily SNODEP charts of both snow depth and age for October and November 1985 which were employed in SNODEP model assessment. We also cooperated with OLA in the improvement of the Air Force snow cover climatology which serves as a key input in the SNODEP model. This included conducting a literature search and providing OLA with various U.S. and foreign publications concerning regional and hemispheric snow cover. They were also advised of the major variations in central U.S. snow cover we discovered during the course of this century and the effects such changes might have on the Air Force snow climatology (Robinson, 1987). Finally, one of us (DAR) spent several days with OLA personnel critiquing the penultimate version of the revised monthly Air Force Global Snow Depth Climatology (Foster and Davy, 1988).

### *PROFESSIONAL PERSONNEL*

The following individuals were associated with this research effort and are affiliated with a university:

Dr. George Kukla, Lamont-Doherty Geological Observatory of Columbia University.

Dr. David A. Robinson, Department of Geography, Rutgers University

Mr. Ted Baker, Lamont-Doherty Geological Observatory of Columbia University

Mr. Mike Sheinkman, Lamont-Doherty Geological Observatory of Columbia University

Ms. Susan Walker, Lamont-Doherty Geological Observatory of Columbia University

Dr. Ann Henderson-Sellers, School of Earth Sciences, Macquarie University, Sydney, Australia

Dr. Kendal McGuffie, University of Technology, Sydney, Australia

Dr. Roger G. Barry, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder

Mr. Greg Scharfen, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder

### *PROJECT PUBLICATIONS*

**1986**

Robinson, D.A.: Remotely sensed albedo of snow-covered lands. In: *Proceedings of the Second Conference on Satellite Meteorology/Remote Sensing and Applications.* Williamsburg, VA, American Meteorological Society, 173-176.

Robinson, D.A.: Initiation of spring snowmelt over Arctic lands. In: *Cold Regions Hydrology Symposium Proceedings.* Fairbanks, AK, American Water Resources Association, 547-554.

Robinson, D.A., G. Scharfen, M.C. Serreze, G. Kukla and R.G. Barry: Snow melt and surface albedo in the Arctic Basin. *Geophysical Research Letters* 13, 945-948.

**1987**

Robinson, D.A.: Snow cover as an indicator of climate change. In: *Large-Scale Effects of Seasonal Snow Cover.* International Association of Hydrological Sciences Publication 166, 15-25.

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Robinson, D. A. and G. Scharfen: Summer cryospheric and atmospheric variability in the Arctic Basin. In: *Proceedings of the Second Conference on Polar Meteorology and Oceanography,* American Meteorological Society, 44-47.

**In preparation**

Robinson, D.A., P. Li and G. Kukla: Variability of winter snow cover and cloudiness over the Tibetan Plateau. *Nature.*

Robinson, D.A., G. Kukla and S. Walker: Strategy for sampling snow cover using shortwave satellite imagery. Photogrammetric Engineering and Remote Sensing.

## *PRESENTATIONS AT MEETINGS*

1 ) Summer Cloud Cover in the Arctic Basin

Fall Meeting of the American Geophysical Union, San Francisco, Dec. 1985

Presented by: David A. Robinson

2 ) Utility of Microwave and Shortwave Satellite Data for Determining Snow Melt in the Arctic

Fall Meeting of the American Geophysical Union, San Francisco, Dec. 1985

Presented by: David A. Robinson

3 ) Satellite-derived Albedo of Seasonally Snow-covered Lands

Spring Meeting of the American Geophysical Union, Baltimore, May 1986

Presented by: David A. Robinson

4 ) Initiation of Spring Snow Melt Over Arctic Lands

Cold Regions Hydrology Conference, Fairbanks, AK, July 1986

Presented by: David A. Robinson

5 ) Variability of Central United States Snow Cover: 1900 to Present

Association of American Geographers Annual Meeting, Portland, OR, April 1987

Presented by: David A. Robinson

6 ) The Snow Melt Regime on the Arctic Sea Ice: Characteristics, Interannual Variations and Significance

Association of American Geographers Annual Meeting, Portland, OR, April 1987

Presented by: Roger G. Barry

7 ) Satellite Analysis of Clouds Over Arctic Sea Ice

Tri-Service Clouds Modeling Conference, U.S. Naval Academy, June 1987

Presented by: David A. Robinson

8 ) Snow Cover as an Indicator of Climate Change

International Union of Geodesy and Geophysics General Assembly/International Association of Hydrological Sciences, Vancouver, Canada, August 1987

Presented by: David A. Robinson

9 ) Analysis of Interannual Variations of Snow Melt on Arctic Sea Ice Mapped From Meteorological Satellite Imagery

International Union of Geodesy and Geophysics General Assembly/International Association of Hydrological Sciences, Vancouver, Canada, August 1987

Presented by: Roger G. Barry

10 ) Summer Cryospheric and Atmospheric Variability in the Arctic Basin

Second Conference on Polar Meteorology and Oceanography, Madison, WI, March 1988

Presented by: Greg Scharfen

11 ) Generating Optimum Snow Cover Information

Tri-Service Climatology Conference, Asheville, NC, October 1988

Presented by: David A. Robinson

### *ADDITIONAL MEETINGS ATTENDED*

1 ) Tri-Service Climatology Conference, Scott Air Force Base, Illinois, November 1987

2 ) DMSP-SPO Special Sensor Microwave Imager Workshop, National Snow and Ice Data Center, Boulder, Colorado, October 1986 (DAR: session chairman)

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*Climate Monitor.* 1985b. Update table for graphs appearing in *Climate Monitor,* 14, 82.

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TABLE 1. Dates on which the major period of snowmelt started (albedo fell below 0.75) and ended (albedo reached 0.25) on the North Slope. The duration (Dura.) of melt and the daily parameterized absorbed shortwave radiation at the ground (Q) ($MJm^{-2} day^{-1}$) in the region on the date melt commenced and at the start of the most rapid 10 day period of albedo decrease are also given.

| Year | Start Date | Start Q | End | Dura. (days) | Rapid start: Date | Rapid start: Q |
|---|---|---|---|---|---|---|
| 1978 | 5/24 | 4.4 | 6/13 | 20 | 6/5 | 7.2 |
| 1979 | 4/19 | 2.8 | 6/4 | 46 | 5/28 | 10.9 |
| 1980 | 5/21 | 4.2 | 6/15 | 25 | 6/6 | 7.3 |
| 1981 | 5/6 | 3.6 | 6/13 | 38 | 5/28 | 8.1 |
| 1982 | 5/29 | 4.5 | 6/18 | 20 | 5/31 | 6.1 |
| 1983 | 4/13 | 2.5 | 6/7 | 55 | 5/29 | 7.8 |
| 1984 | 5/28 | 4.5 | 6/14 | 17 | 6/6 | 6.9 |
| 1985 | 5/16 | 4.2 | 6/3 | 18 | 5/24 | 6.7 |

TABLE 2. Dates on which the major period of snowmelt started (albedo fell and stayed below the spring maximum) and ended (albedo reached 0.20) in the Tanana Basin. The duration (Dura.) of melt and the daily parameterized absorbed shortwave radiation at the ground (Q) ($MJm^{-2} day^{-1}$) in the region on the date melt commenced are also given.

| Year | Start Date | Start Q | End | Dura. (days) |
|---|---|---|---|---|
| 1978 | 4/9 | 7.2 | 4/28 | 19 |
| 1979 | 4/14 | 7.9 | 5/2 | 18 |
| 1980 | 3/27 | 5.9 | 4/29 | 33 |
| 1981 | 4/14 | 8.1 | 4/28 | 14 |
| 1982 | 4/6 | 6.6 | 5/13 | 37 |
| 1983 | 4/9 | 7.2 | 4/30 | 21 |
| 1984 | 4/10 | 7.5 | 5/8 | 28 |
| 1985 | 4/23 | 8.5 | 5/20 | 27 |

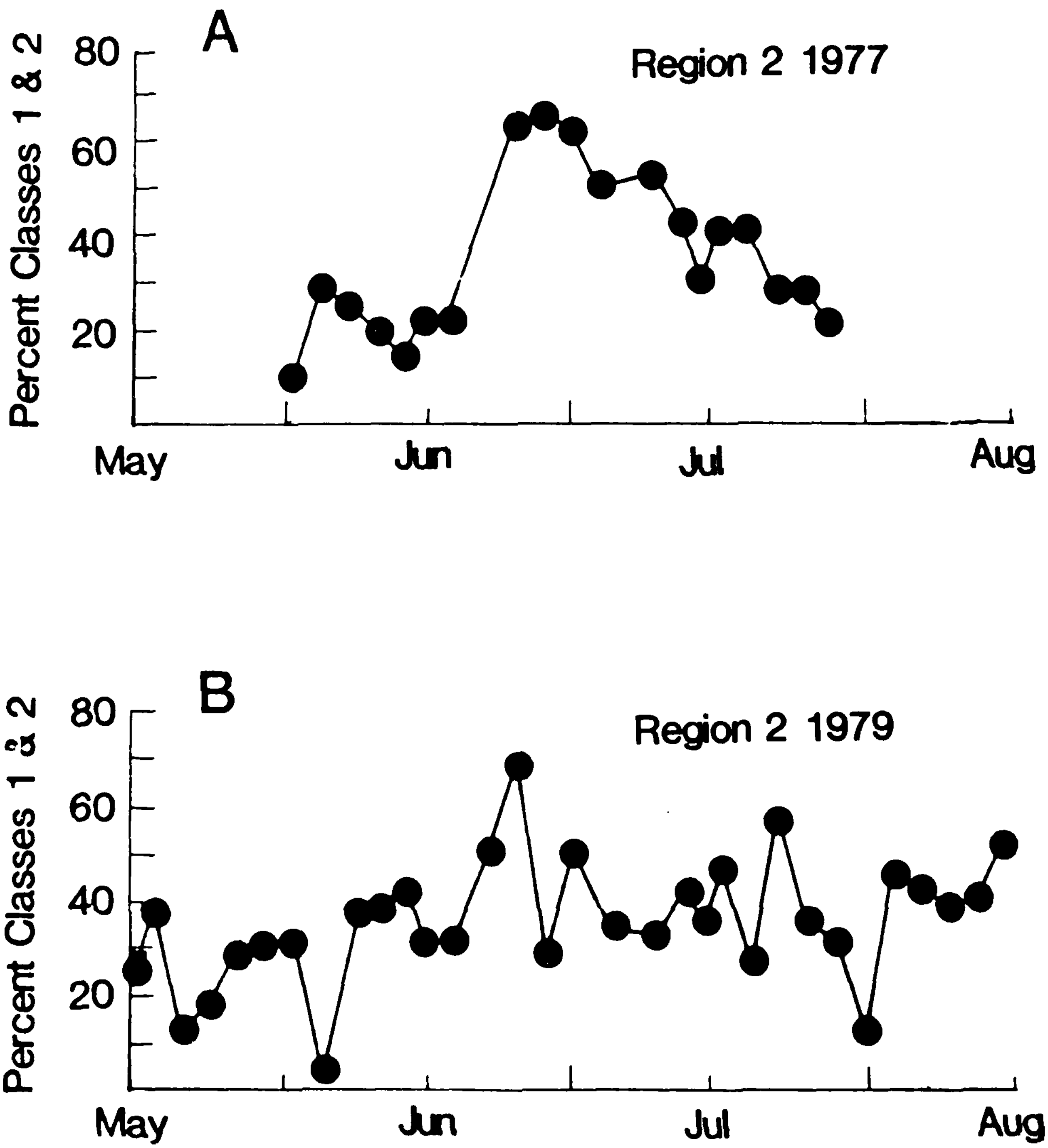



Fig. 1) a) Coverage of cloud-free skies plus optically thin clouds over a region which covers the Arctic Ocean south of 85°N (except within about 200 km of the coast) for approximately every three days in June and July 1977.

b) Same as a, except for May 15 to August 15, 1979.

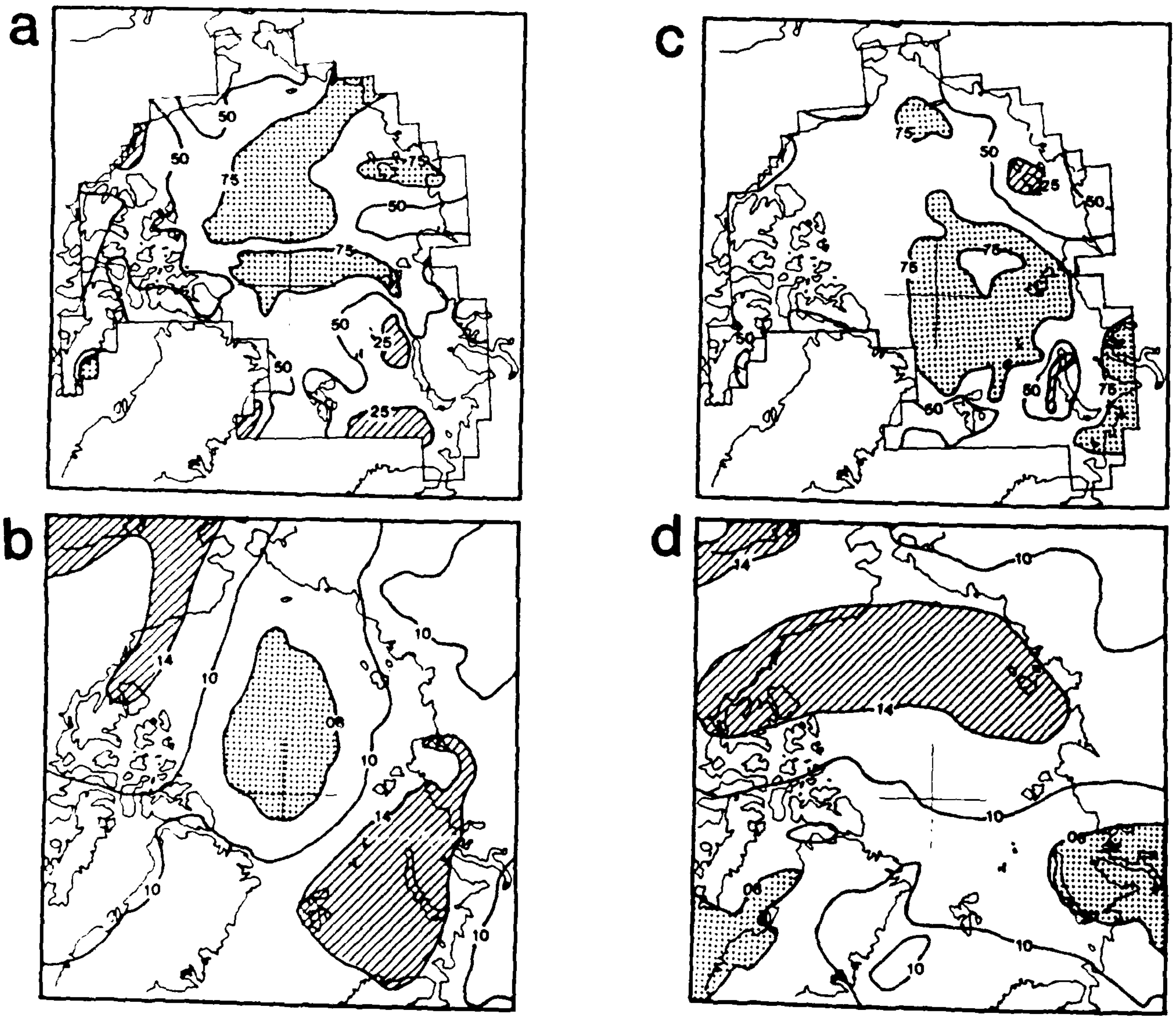



Fig. 2 ) a) Percent frequency of moderate and thick cloud cover for June 1979 within the Arctic Basin. Areas with >75% cover shown with stippling, >25% cover with hatching.

b) Mean-monthly surface-pressure field for June 1979. Derived from NMC charts on dates when clouds were charted. Add 1000mb to all values.

c) Same as a, except for July 1979.

d) Same as c, except for July 1979.

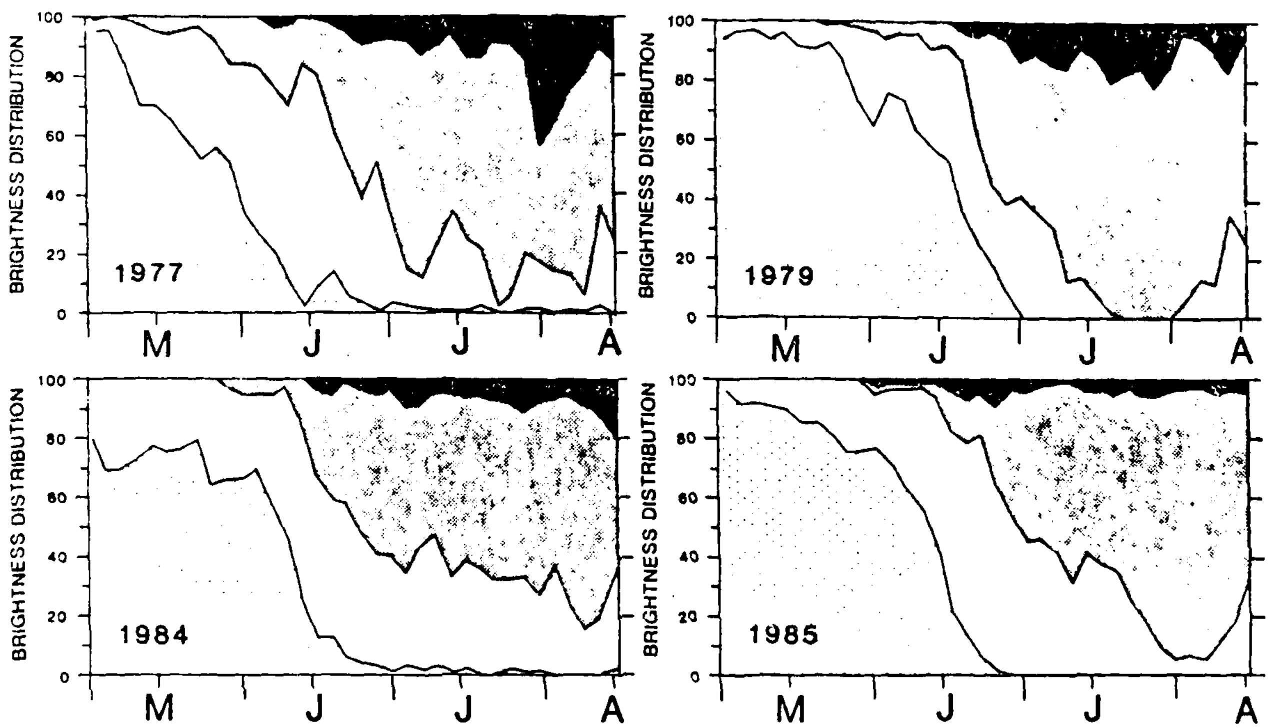



FIG. 3 Progression of snow melt and subsequent ponding and drainage on Arctic sea ice from May to mid-August of the four study years, as shown by the changing distribution of brightness classes

Classes shaded from light grey (class 1) to dark grey (class 4). Areas with less than approximately 10% ice concentration or with open water are omitted.

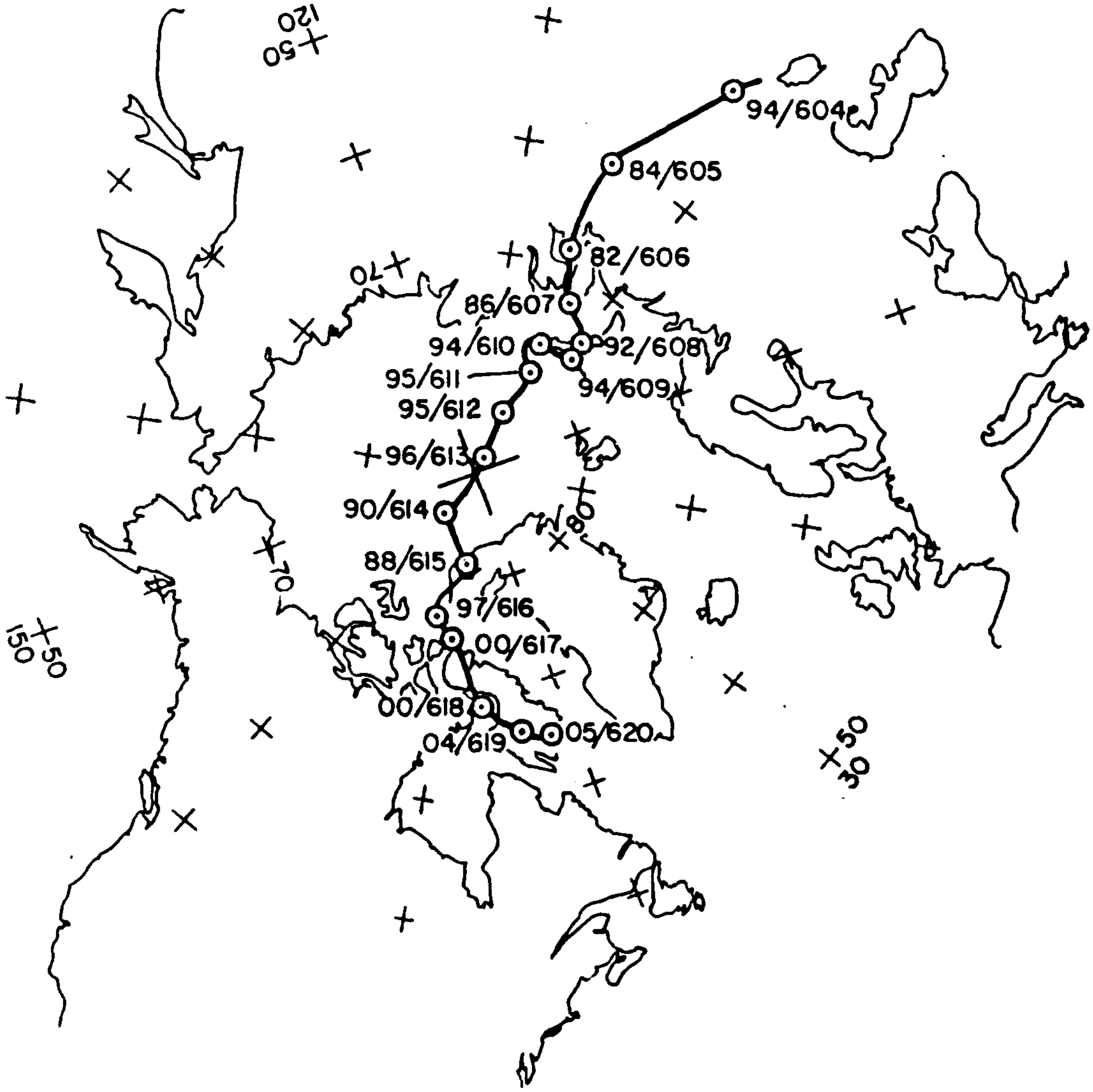



Fig. 4) Progression of a surface low pressure system across the Arctic Basin from June 4 to June 20, 1979, as taken from NMC 00Z Northern Hemisphere charts (June 4-6 and 17-20) and 1200Z buoy and station data (June 7-16) from Thorndike and Colony (1980). Pressure in millibars (add 900mb to values >50 and add 1000mb to values <50). Month and day given in the denominator.

Fig. 5) Comparison of monthly anomalies of surface albedo over the Arctic Basin and surface air temperature from 65-85$^{o}$N, for May (triangles), June (circles) and July (squares) of the four study years. Albedo anomalies are based on an average of the years 1977, 1979, 1984 and 1985. Temperature anomalies are based on 1951-1970 means (Jones, 1985; Climate Monitor, 1985a and 1985b)

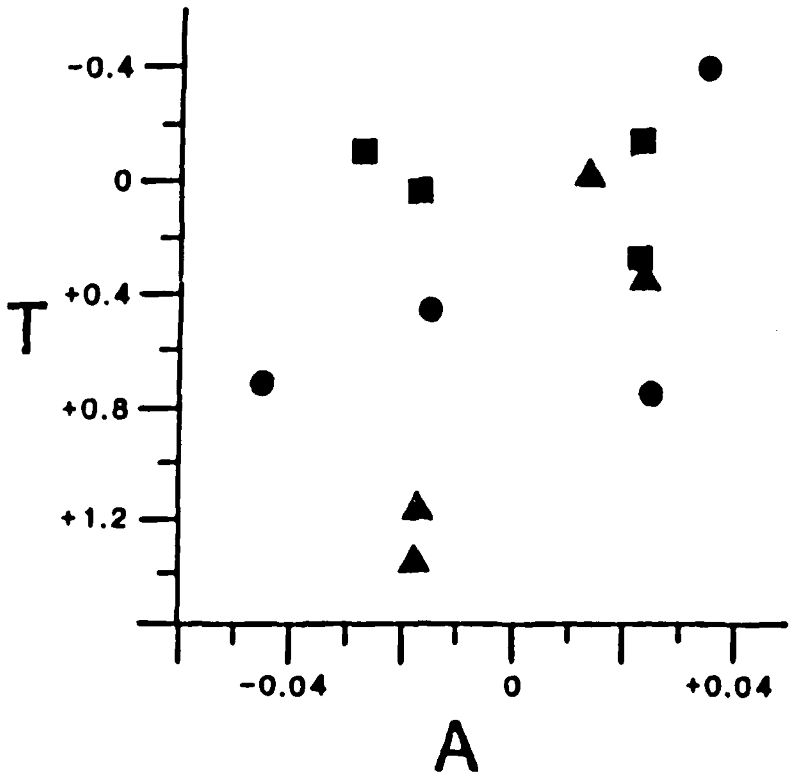
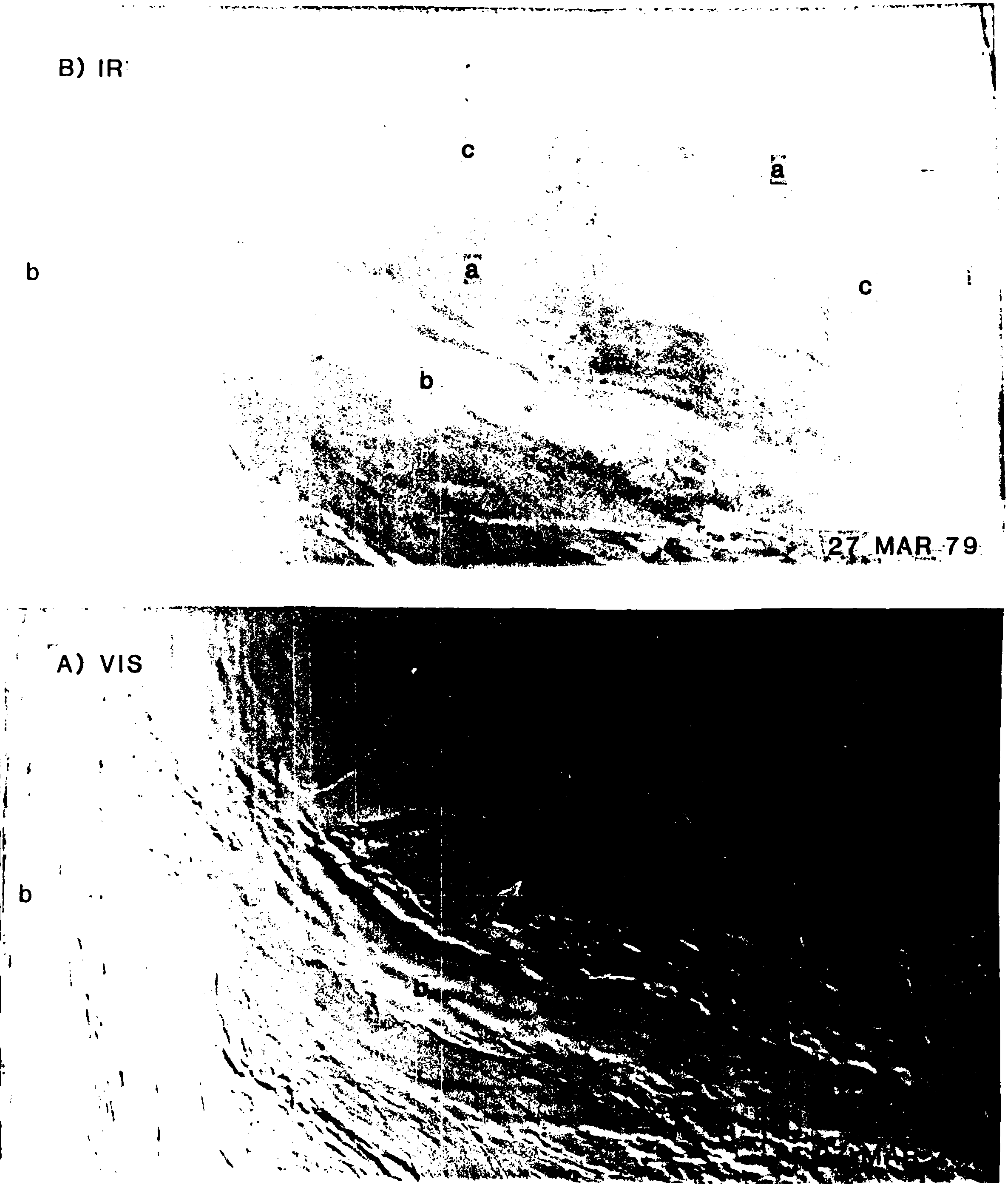


Fig. 6) NOAA Advanced Very High Resolution Radiometer A) visible (0.55-0.90μ) and B) infrared (10.5-11.5μ) images of the eastern central Arctic on 27 May 1979 showing the complex nature of satellite spectral signatures over the polar regions. The north pole is towards the top right of the images, the sun's rays are reaching this area from the lower left. The images show low (a) and high (b) clouds and regions where skies are clear (c). Solar enhancement and shadowing and variations in illumination across the scene are noted in the visible image. Cold (whiter on the image) high clouds and a cold surface contrast with the warmer tops of the low clouds in the infrared. Inversions like this are quite common in the basin in all seasons. Leads in the ice pack are seen as dark in the visible (low reflectivity) and infrared (warm).


B) IR
c
a
b
a
c
b
27 MAR 79
A) VIS
b

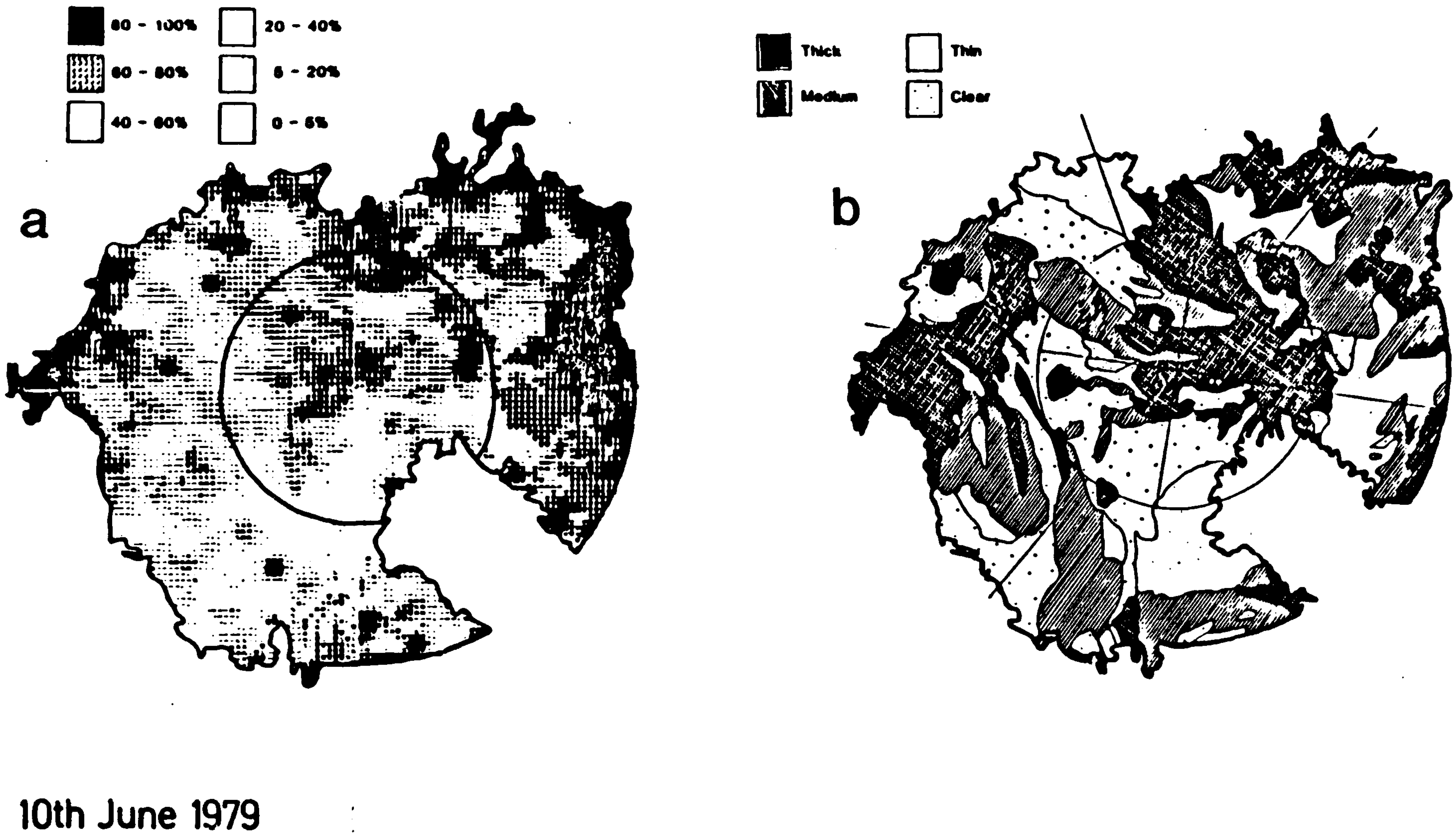



Fig. 7) Total cloud amount for June 10, 1979:
a) from 3-D Nephanalysis, percent (from McGuffie, 1985)
b) from DMSP imagery analysis (from Robinson et al., 1985)
c) average for synoptic type 4 (Kara Sea low, Beaufort Sea high) (log scale with 5 classes divided at 4.7, 6.9, 8.5 and 9.5 tenths) (from Barry et al., 1986).

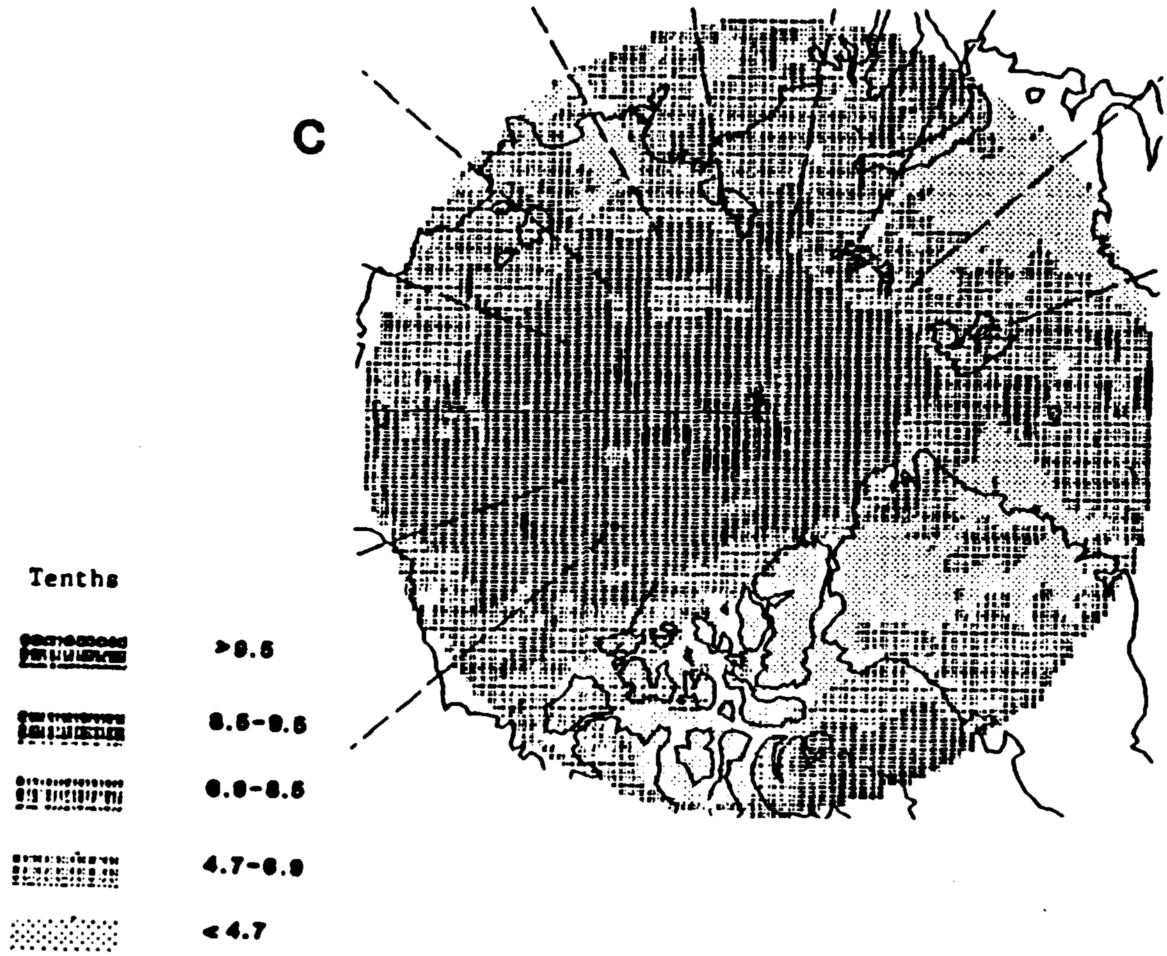

C
Tenths
>9.5
8.5-9.5
6.9-8.5
4.7-6.9
<4.7

Fig. 8) Snow and cloud conditions over nephanalysis box 36 between 13-15 April 1984. Snow cover as charted by the Air Force SNODEP model is seen in A. In B, areas of agreement and disagreement between the Air Force and Lamont snow products are shown. Numbers indicate surface brightness classes from bright (fully snow covered and lightly vegetated) (1) to dark (snow free) (6). The percent cloud cover on 14 April, as charted by the Air Force Real Time Nephanalysis model, is shown in C and D shows the cloud extent and relative optical thickness on the 14th as plotted by Lamont.

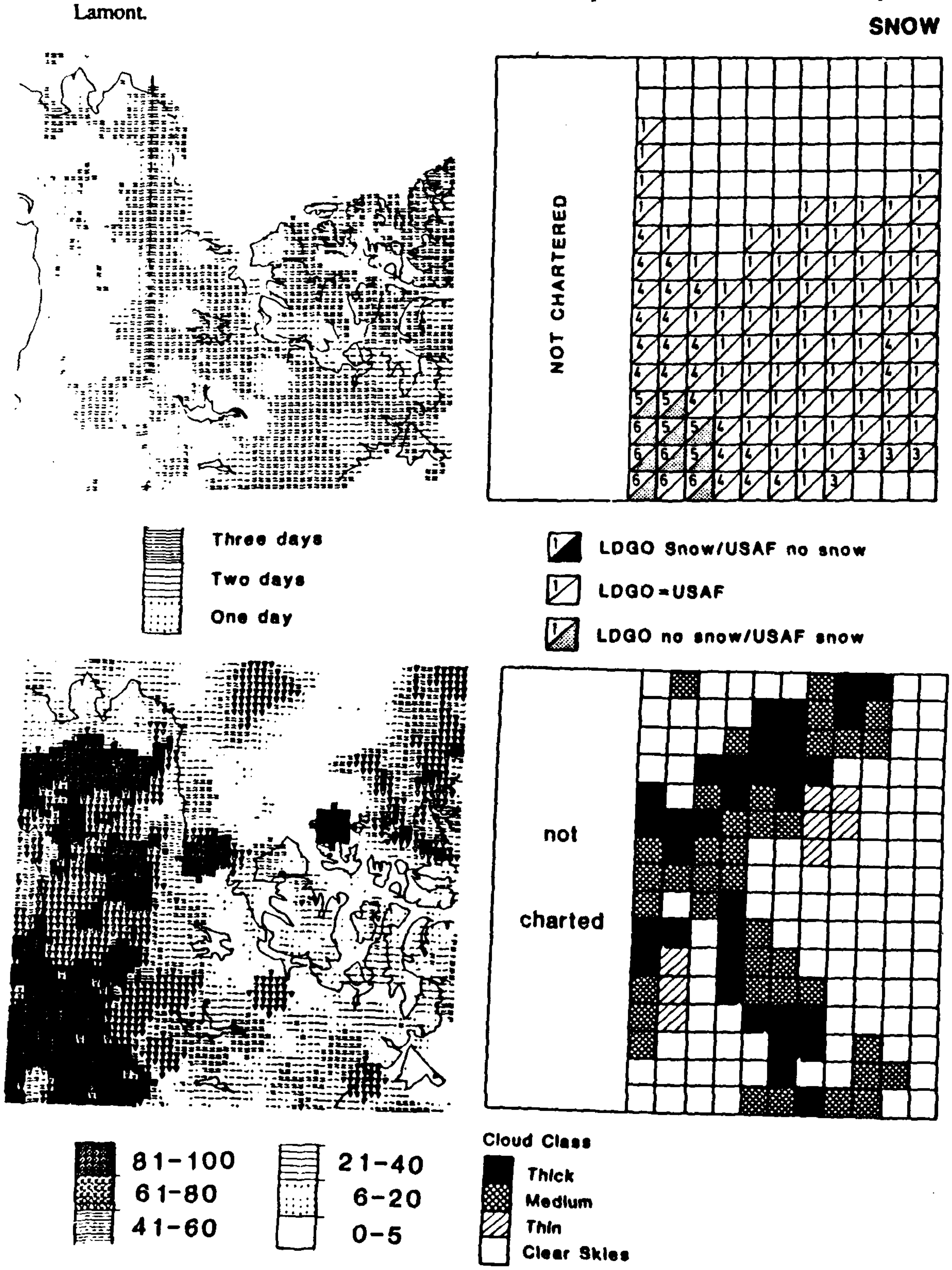
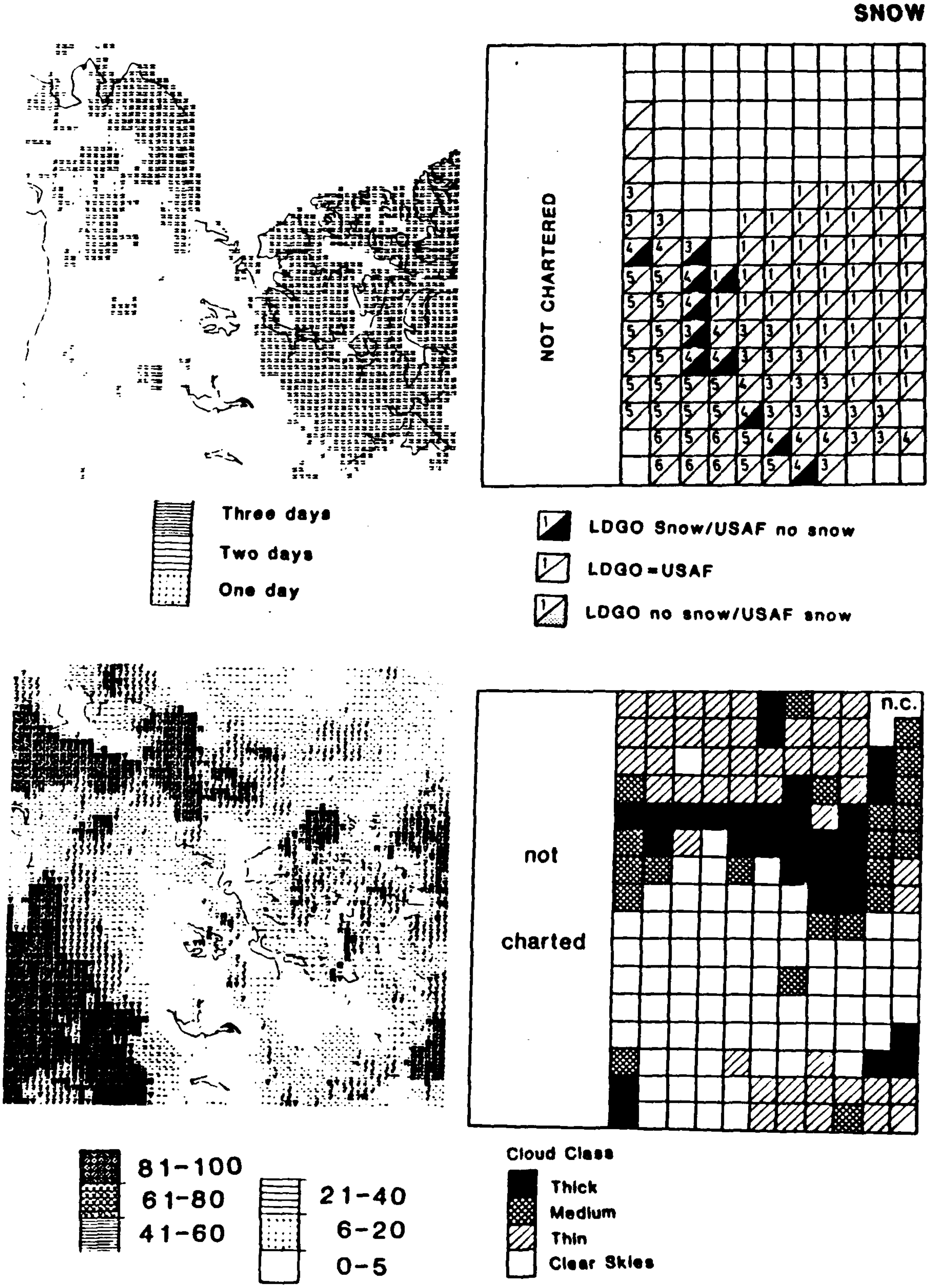


Fig. 9) Same as fig. 8, except for 22-24 May 1984.



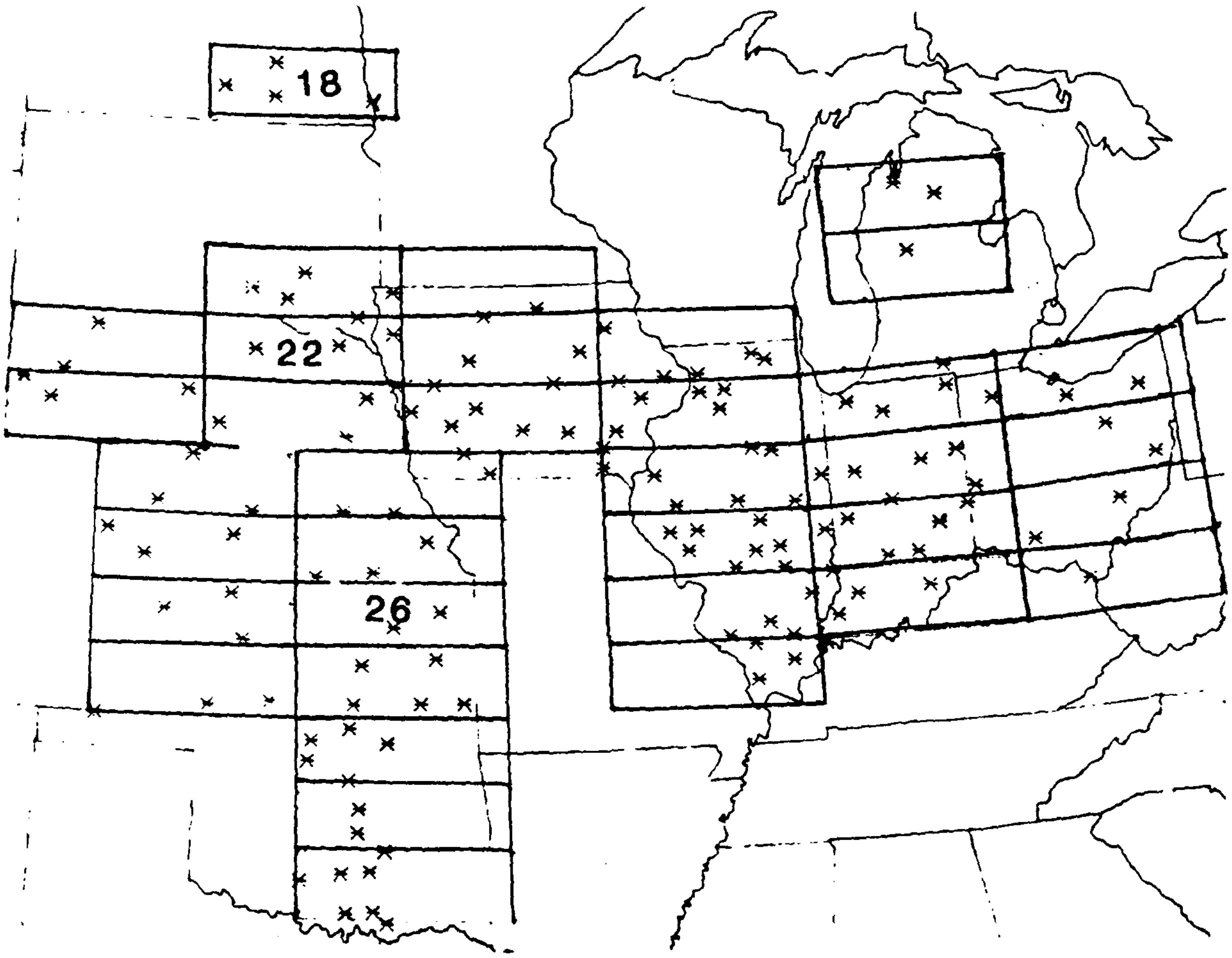



Fig. 10) Distribution of data network and study divisions in the central U.S. snow study.

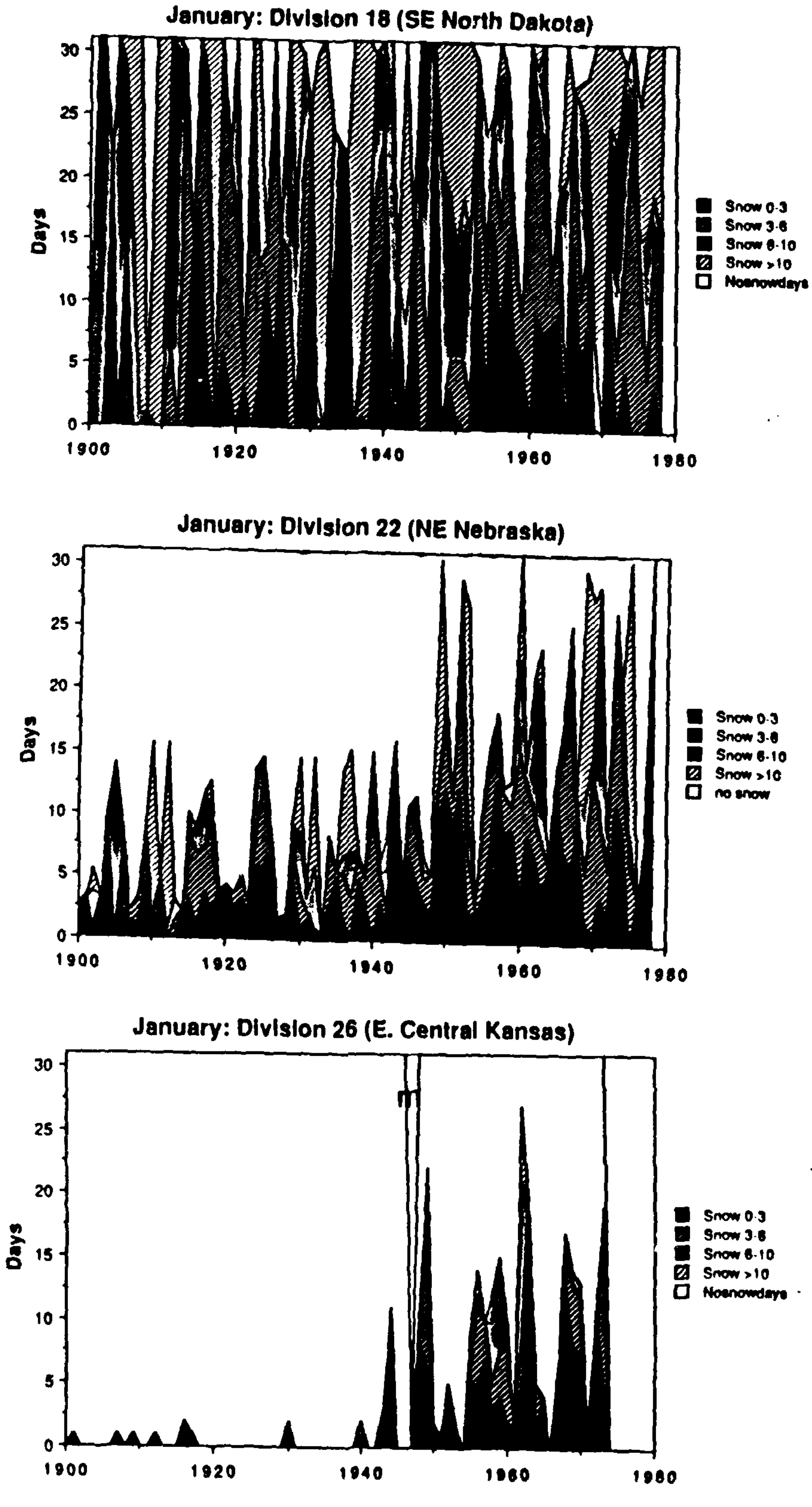



Fig. 11) Duration of snow cover of different depths over divisions 18, 22 and 26 (cf. fig. 10) during Januaries from 1900 to 1978. (m=missing year)

March: Division 22 (NE Nebraska)

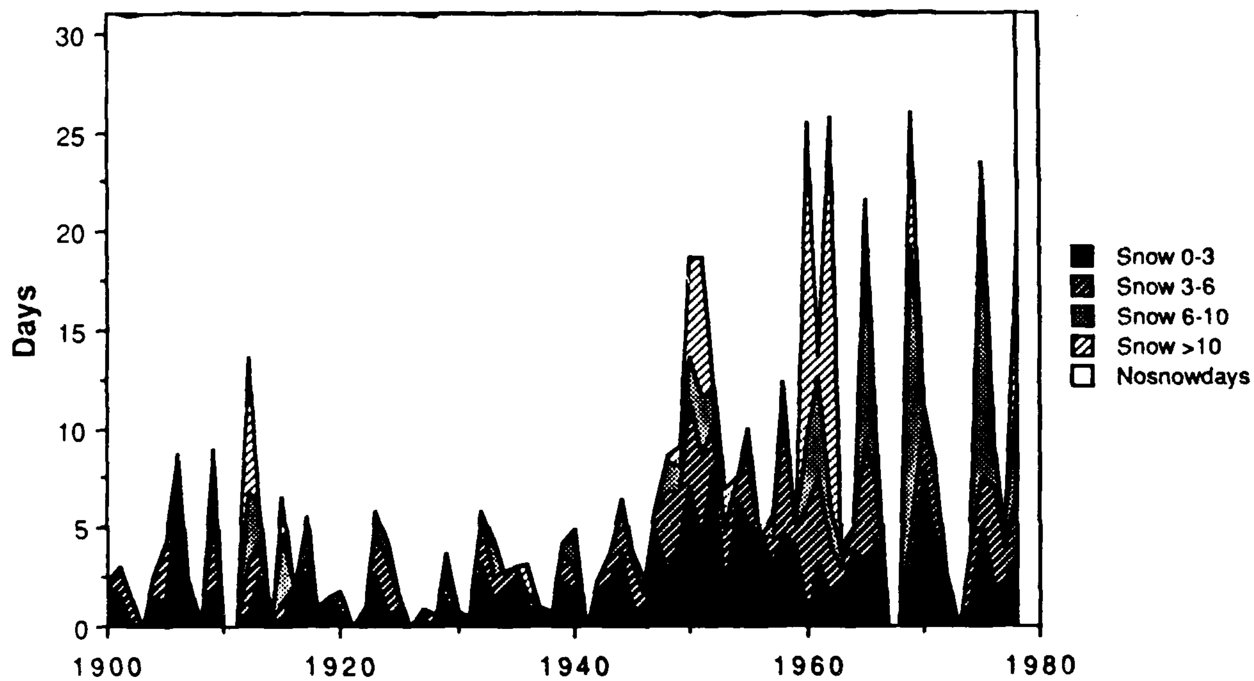
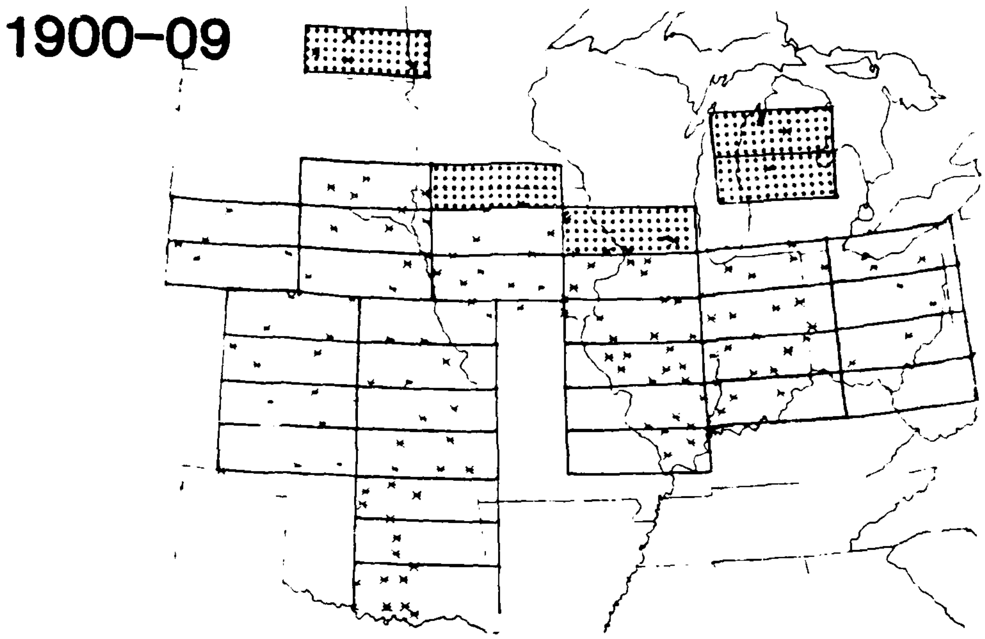



Fig. 12) Duration of snow cover of different depths over division 22 during Marches from 1900 to 1978.



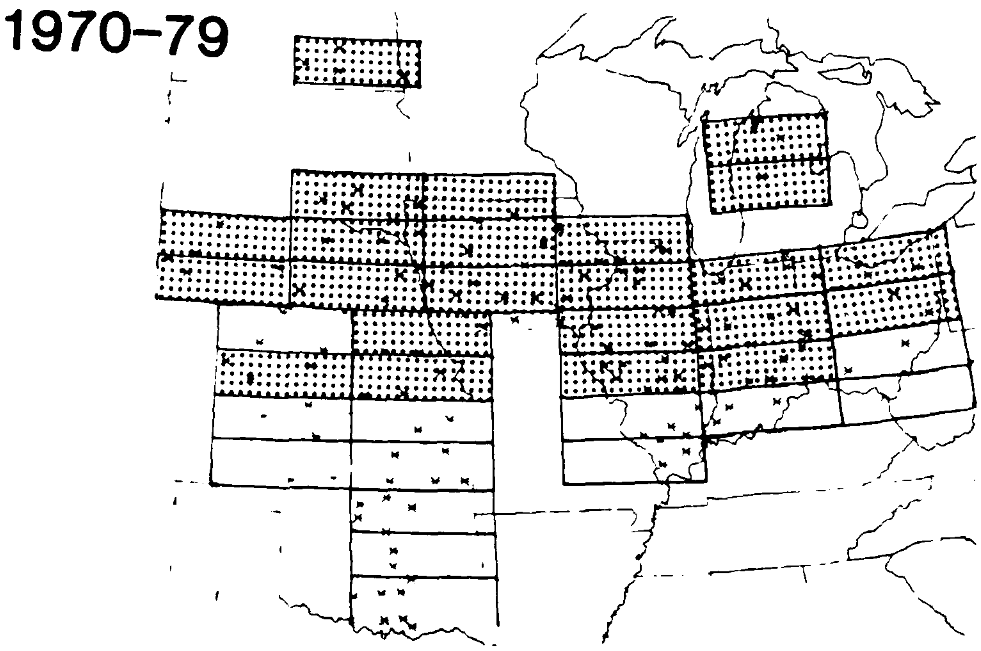




Fig. 13) Divisions with 16 or more days of snow cover (≥1") in January in 5 or more of the years between a) 1900-1909 and b) 1970-1979 are stippled.

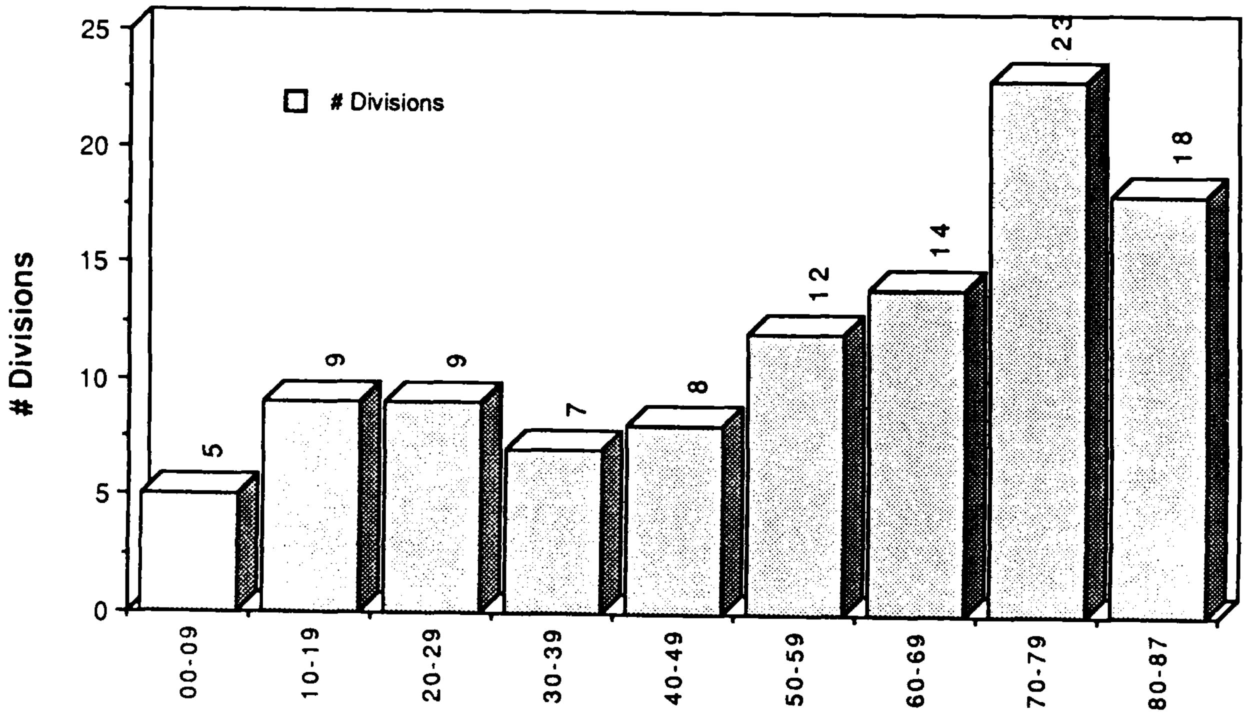



Fig. 14) Number of divisions in the central U.S. study region (cf. fig. 10) with ≥16 days of snow cover (≥1 inch) in five or more Januaries by decade. 1979-1987 data from NOAA weekly snow charts.

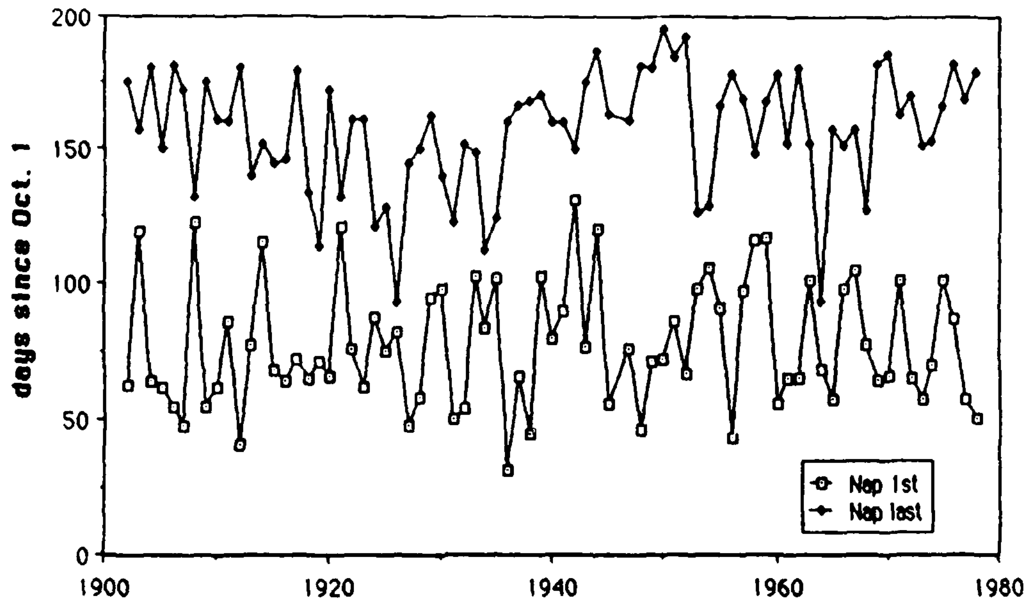



Fig. 15) Starting and ending dates of continuous snow cover (≥1 inch) in Napoleon, North Dakota from 1902 to 1978.

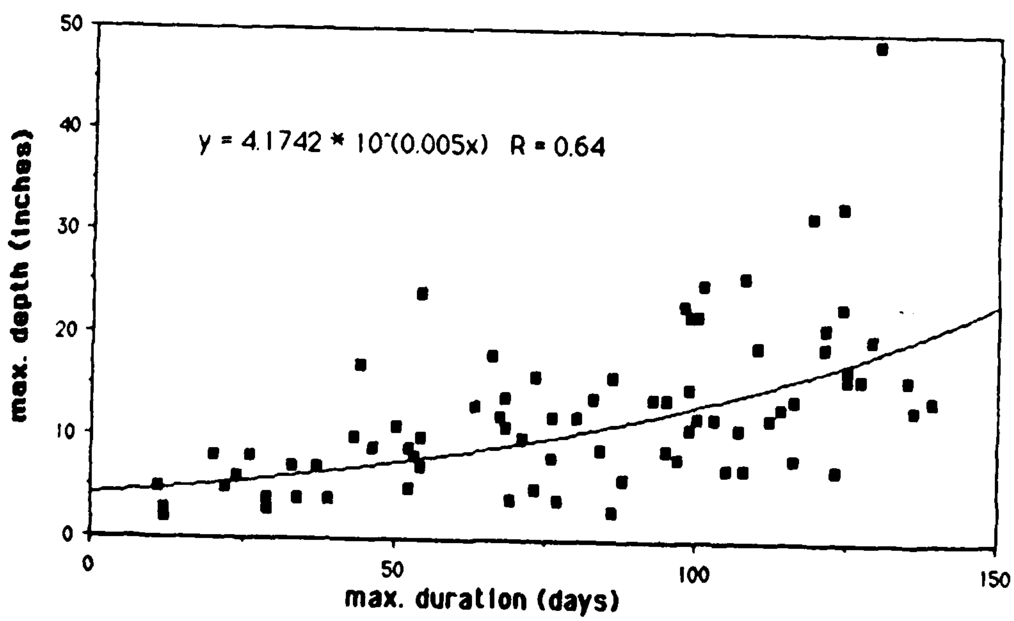



Fig. 16) Maximum duration of continuous snow cover (≥1 inch) in a given year versus the maximum depth of snow during that interval in Napoleon, North Dakota during the 1902-1978 period.

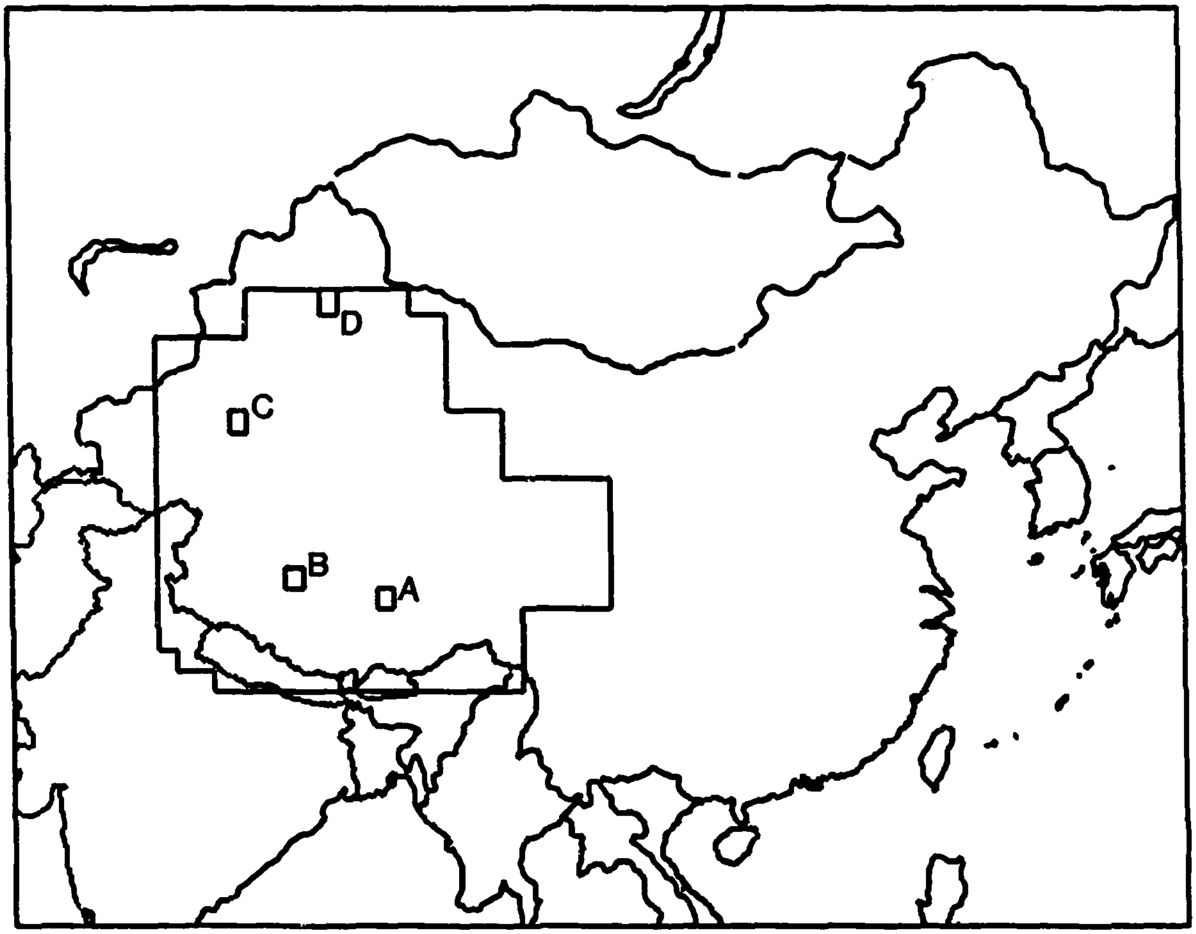



Fig. 17) Western China study zone (straight lines) and the four $1^{o} \times 1^{o}$ cells shown in figures 18-21.

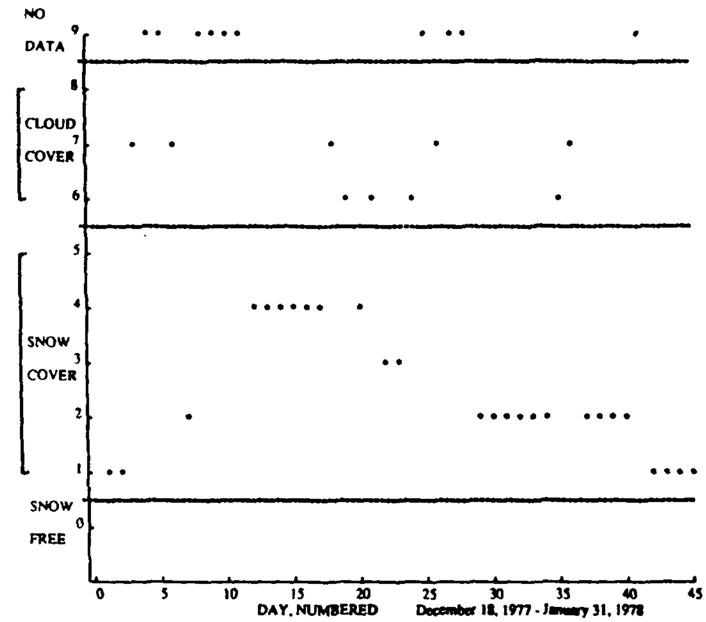



Fig. 18) Surface and cloud conditions in Tibetan cell A (cf. fig. 17) between 18 December 1977 and 31 January 1978 as charted from DMSP imagery. When snow cover is present it may range from very patchy (class 1) to deep and full (class 5). Clouds are either optically thin (class 6), moderately thick (7) or thick (8). Only in the latter class is the underlying surface totally obscured.

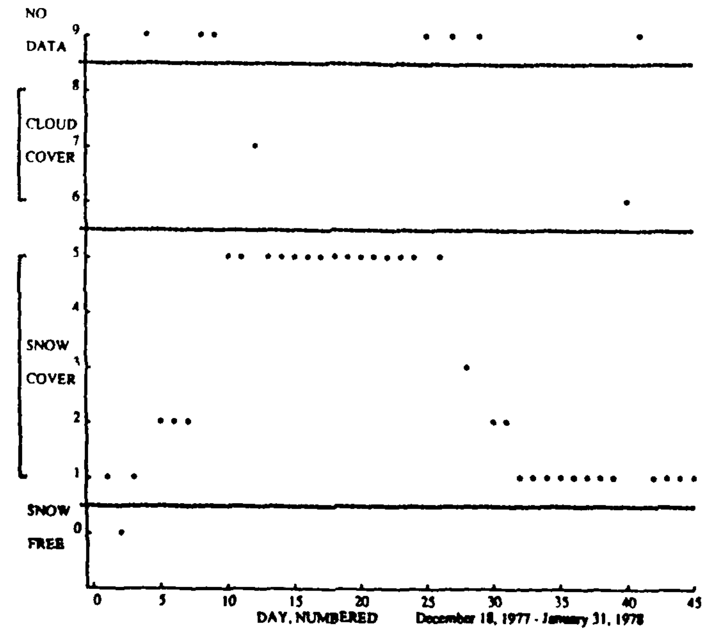



Fig. 19 ) Same as fig. 18, except for central Tibetan cell B.

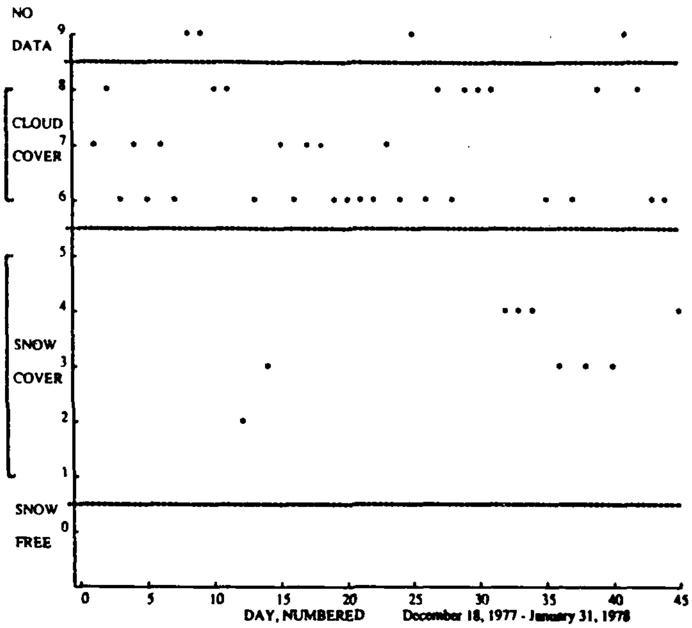



Fig. 20 Same as fig. 18, except for Takla Makan cell C.

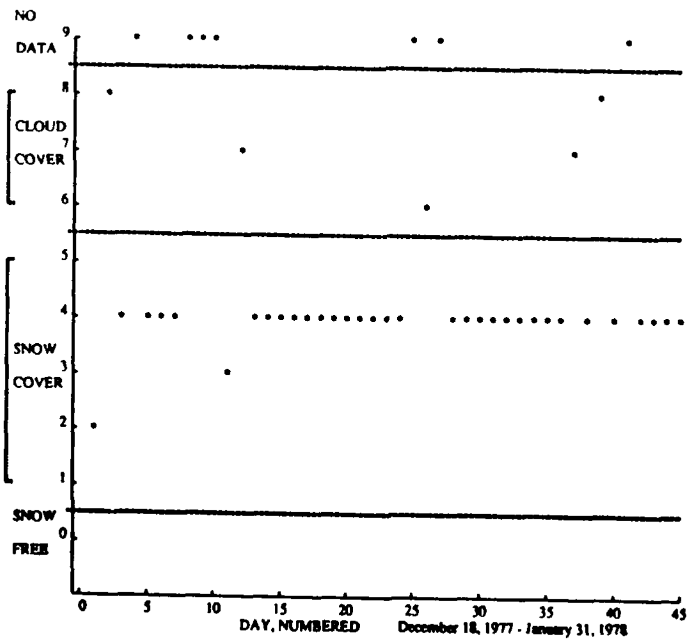



Fig. 21) Same as fig.18 , except for northwestern China cell D.

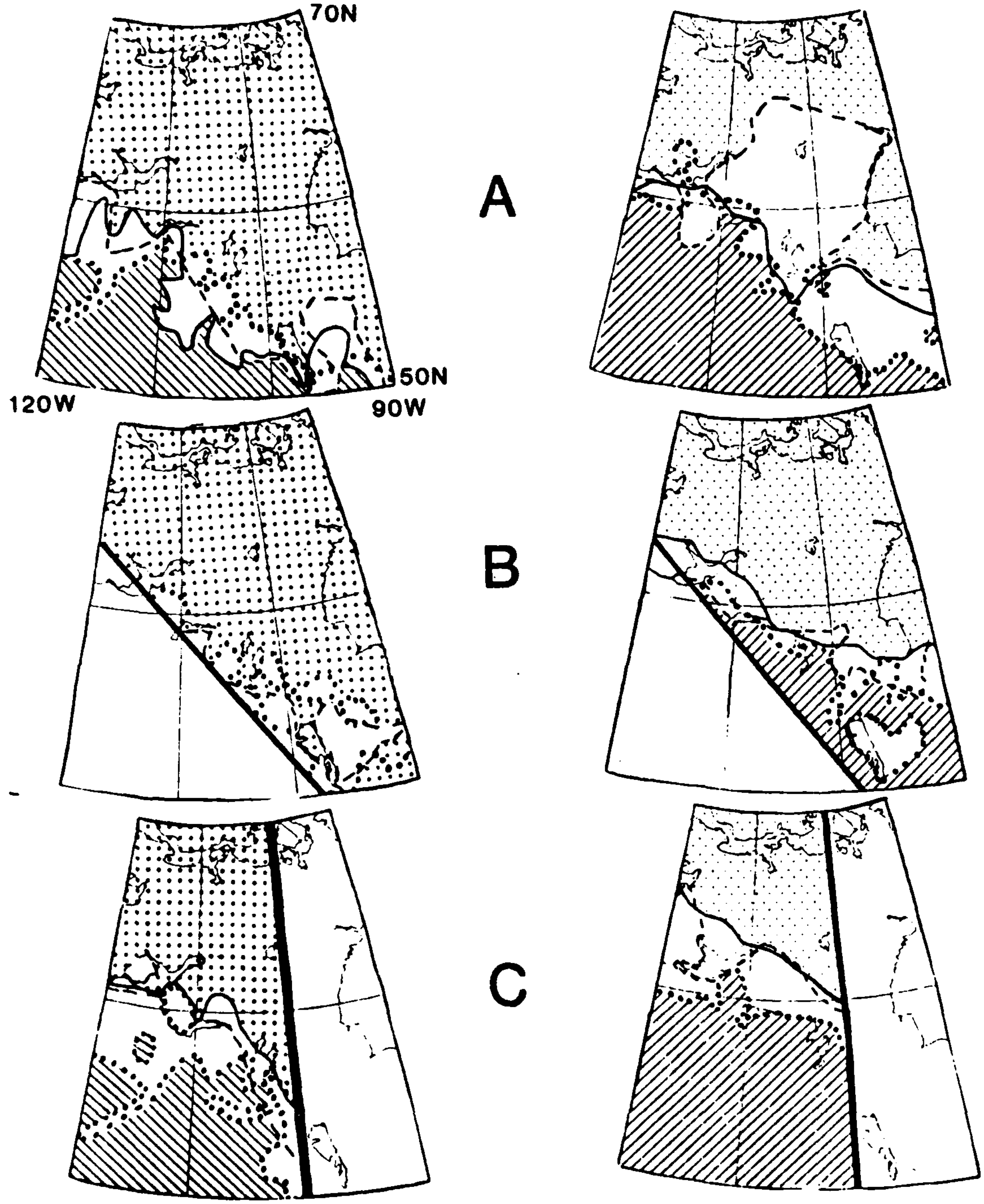



Fig. 22 ) Snow boundaries over central Canada in April 1984 according to Lamont (solid line), NOAA weekly snow charts (dashed line) and Air Force charts (dotted line). Charts on the left show the boundaries between full or patchy snow cover and snow-free ground according to NOAA and Lamont and between areas with a trace or more cover and snow-free ground according to the Air Force. Charts on the right show the boundaries between full snow cover and patchy or no snow cover according to NOAA and Lamont and between areas with 2 inches or more snow cover and those with less than 2 inches or no snow cover according to Air Force. Stippled areas on the charts to the left snow where all products agree that snow cover is present, whether it be full or patchy, and hatched areas show where all agree the surface is snow free. Stippled areas on the charts to the right show where all products agree that full snow cover is present and hatched areas show where all agree snow cover is not present. Charts at the top (A) are for 14-16 April (Lamont), 9-15 (NOAA), 16 (AF); (B) for 22-24 (Lam), 16-22 (NOAA), 23 (AF); (C) for 28-30 (Lam), 23-29 (NOAA), 30 (AF).