*Large Scale Effects of Seasonal Snow Cover* (Proceedings of the Vancouver Symposium, August 1987). IAHS Publ. no. 166

# Analysis of interannual variations of snow melt on Arctic sea ice mapped from meteorological satellite imagery

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**ABSTRACT** The seasonal progression of snow melt on the Arctic ice pack was mapped from shortwave satellite imagery for 1977, 1979, 1984 and 1985. The four years showed substantial differences in the timing of the melt interval. The progression of melt in May and June of the earliest melt year (1977) was about three weeks ahead of the latest year (1979). As a result, basin-wide surface albedo varied by upwards of 0.08 in June, ranging from 0.58 in 1977 to 0.66 in 1979. May and July showed interannual variations in albedo of up to 0.05. The extent of snow melt varied from year to year in the central Arctic. The region was essentially snow-free by mid-July in 1977 and 1979, but retained some snow throughout the summer in 1984 and for all but two weeks in 1985. Although limited in extent, our data base suggests relationships between snow melt and Arctic surface air temperatures in spring, spring cloudiness, and the extent of late summer ice.

## *Analyse de la variation interannuelle de la fonte de la neige sur la banquise arctique tracée d'après les images de satellite météorologique*

**RÉSUMÉ** La progression saisonnière de la fonte de la neige sur la banquise arctique est tracée d'après les images par ondes courtes de satellites pour 1977, 1979, 1984 et 1985. Ces quatre années présentent des différences importantes quant à l'époque de la fonte. La progression de la fonte en mai et juin de l'année où celle-ci a été la plus précoce (1977) était environ trois semaines en avance sur l'année ou la fonte était la plus tardive (1979). En conséquence, l'albédo à la surface de l'ensemble du bassin a varié de plus de 0.08 en juin, variant de 0.58 en 1977 à 0.66 en 1979. Mai et juillet ont présenté des variations interannuelles de l'albédo atteignant 0.05. L'étendue de la fonte a varié d'année en année dans le centre de l'Arctique. La région était essentiellement dépourvue de neige à la mi-juillet en 1977 et 1979, mais a conservé de la neige pendant tout l'été 1984, et pendant tout l'été moins deux semaines en 1985. Malgré ses limites, notre base de données suggère des relations entre la fonte de la neige et la température de l'air à la surface au printemps, la nébulosité au printemps et l'étendue de la banquise à la fin de l'été.

## INTRODUCTION

The extent and timing of snow melt on the Arctic pack ice have long been recognized as a potentially critical forcing for the summer climatic regime, with implications for the long-term mass balance and stability of the ice (Fletcher, 1966; Barry, 1985). Before the present study, information on snow melt and the resultant changes in surface albedo was limited to drifting station measurements and a few aircraft programmes (e.g. Laktionov, 1953; Untersteiner, 1961; Hanson, 1961; Nazinstev, 1964; Buzuev *et al.*, 1965; Langleben, 1971; Kuznetsov & Timerev, 1973; Hanson, 1980; Grenfell & Perovich, 1984; Holt & Digby, 1985), including a basin-wide assessment using single-frequency passive microwave data for summer 1974 by Carsey (1985). Using operational daily meteorological satellite imagery, we have mapped the degree and progression of melt on the ice during four spring-summer seasons.

## DATA AND METHODS

The study makes use of shortwave (0.4-1.1 $\mu$m) images from the Defense Meteorological Satellite Program (DMSP) satellite, with resolutions of 0.6 km for direct read-out products and 2.7 km for orbital swath format images, as well as some NOAA Advanced Very High Resolution Radiometer (AVHRR) 1.1 km resolution images. The mapping was done by careful manual analysis of tonal contrasts and textural patterns; separate studies show that there are many days with sufficiently cloud-free conditions to permit such analysis (Robinson *et al.*, 1986a; Barry *et al.*, 1986). Parameterized albedos have been assigned to different brightness classes by analyzing satellite data on an image processor.

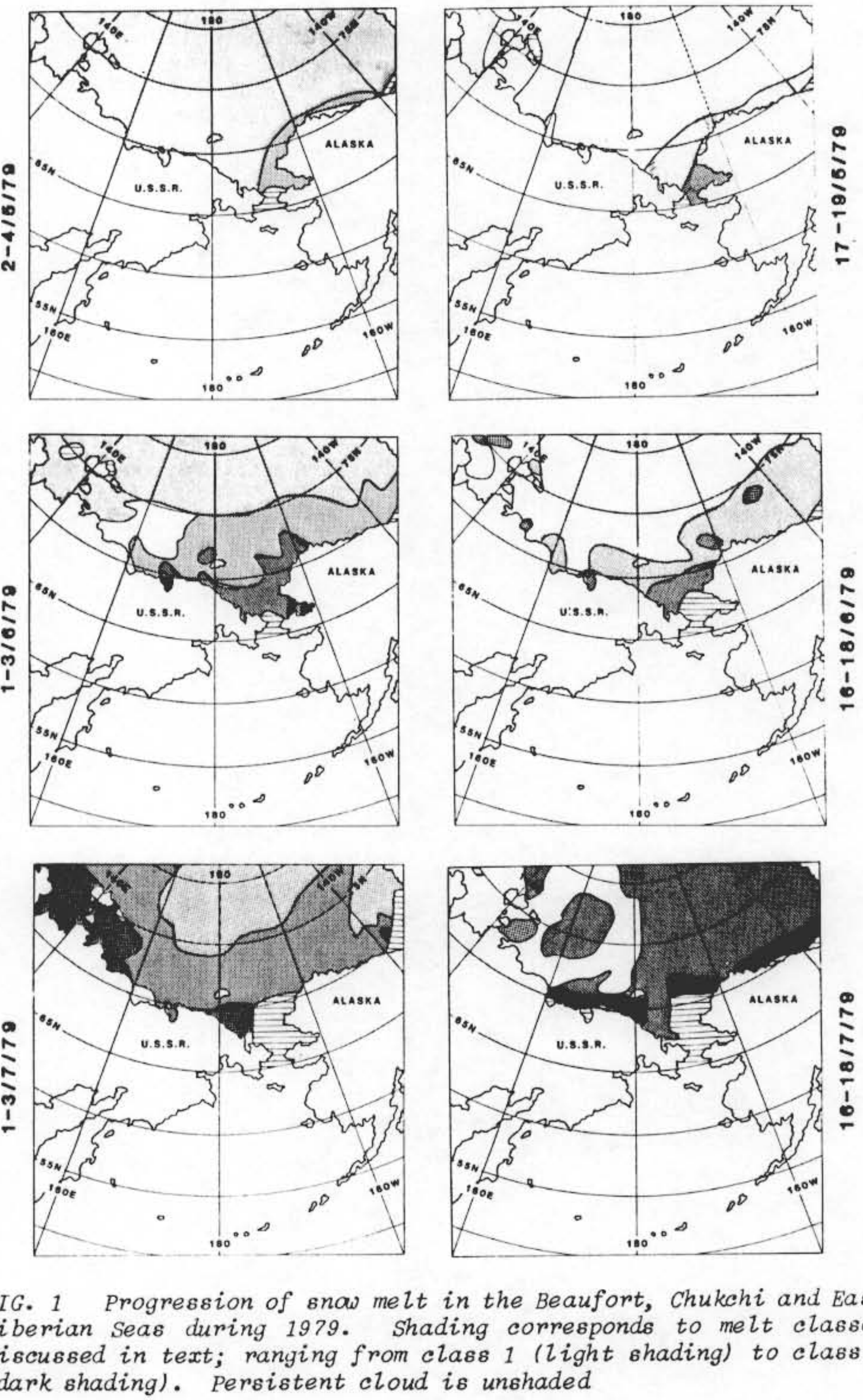


*FIG. 1 Progression of snow melt in the Beaufort, Chukchi and East Siberian Seas during 1979. Shading corresponds to melt classes discussed in text; ranging from class 1 (light shading) to class 4 (dark shading). Persistent cloud is unshaded*

Basin-wide maps of surface brightness were constructed in three-day increments from May through mid-August 1977, 1979, 1984 and 1985. Four categories of melt were charted and calibrated in terms of surface albedo, based on published information and image analysis tests. Class 1 represents fresh snow cover over 95% of the ice (albedo 0.80). For class 2, snow covers between 50-95% of the surface, with the remainder being bare or ponded ice; in spring this is considered the initial stage of active snow melt, (albedo 0.64). Class 3 represents the final stage of active snow melt, with between 10-50% of the ice surface snow-covered and with numerous melt ponds, or, following pond drainage, predominantly bare ice, with snow patches and scattered ponds (albedo 0.49). Class 4 represents heavily-ponded or flooded ice with less than 10% snow cover or exposed bare ice (albedo 0.29). Standard deviations of the estimated albedos range from 0.05 (class 4) to 0.08 (class 3). Minor adjustments are made to class albedos for average summer cloudiness and to account for the presence of open water within the pack.

For more detailed information on charting procedures and albedo derivation see Robinson *et al.* (1986b) and Scharfen *et al.* (1987).

## RESULTS

A typical sequence of melt in the Beaufort, Chukchi and East Siberian Seas is shown in Fig. 1 for 1979. Melt began in the southern Chukchi by mid-May, then progressed along the Arctic coasts of Alaska and Siberia during the last half of May and first half of June, and eventually extended towards the Pole from mid-June onwards. The timing of this sequence differed in the other three years, although the same general pattern was maintained. The earliest melt in these seas occurred in 1977, with conditions about two weeks ahead of 1979, and the latest melt occurred in 1985, with conditions between one and two weeks behind 1979.

The progression of melt over five regions in the basin (Fig. 2), in terms of albedo trends and monthly means, is shown in Fig. 3 and Table 1, respectively. In the four years analyzed, melt tended to begin first in the Kara and Barents and Beaufort and Chukchi sectors. The year-to-year timing of melt varied most in the Kara and Barents, and East Siberian and Laptev regions and the least in the Northwest North Atlantic, and Beaufort and Chukchi sectors. The early onset of extensive snow melt in 1977, compared with the other three years, was most pronounced in the East Siberian and Laptev Seas, and in the Central Arctic. Later in the summer, the albedo differences between years in the coastal seas were a result of differences in ice extent. This is particularly evident in the East Siberian and Laptev Seas, where the early August albedo ranged between 0.25 (1977) and 0.47 (1984).

In the Central Arctic, there was no appreciable snow cover by the middle of July in 1977 and 1979, whereas in 1984 some snow remained throughout the summer and in 1985 until early August. This resulted in July albedos of 0.52 in 1977, 0.53 in 1979, 0.58

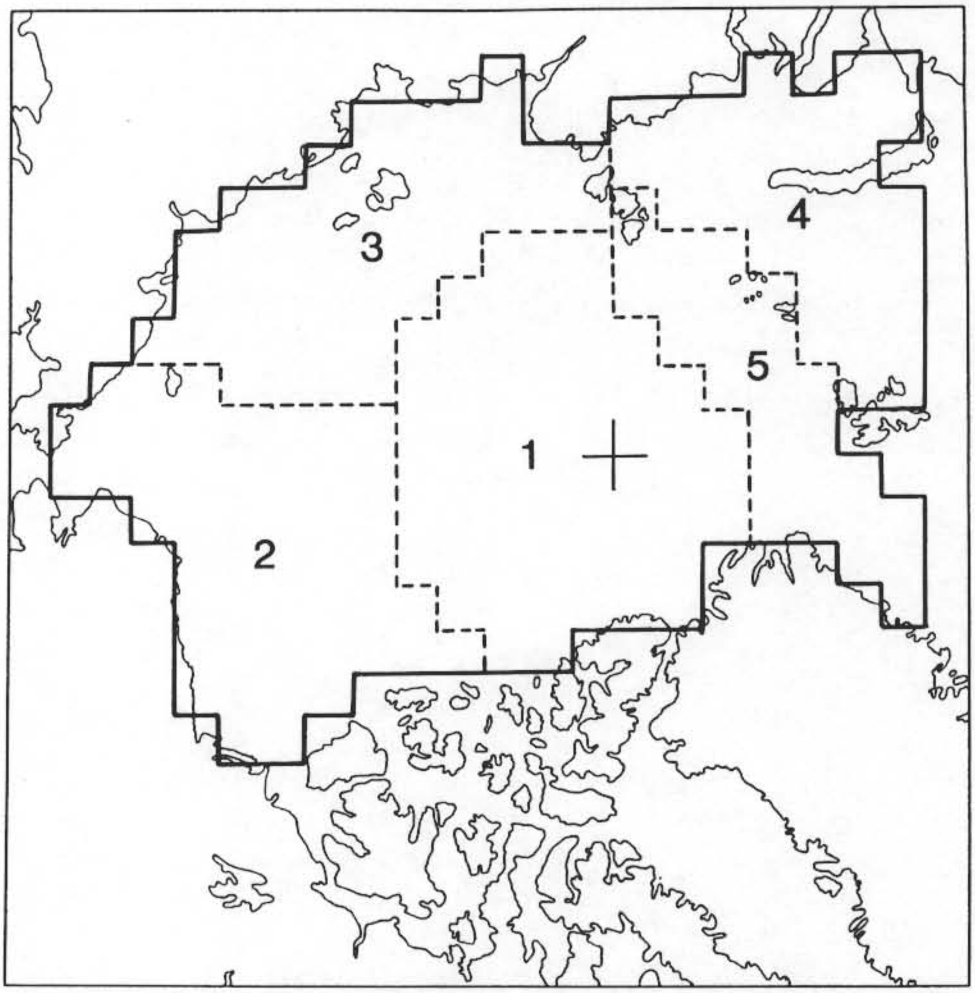


*FIG. 2 Arctic Basin study zone (heavy line) divided into five regions (dashed lines): 1) Central Arctic, 2) Beaufort/Chukchi Seas, 3) East Siberian/Laptev Seas, 4) Kara/Barents Seas and 5) Northwest North Atlantic*

in 1984 and 0.59 in 1985. Towards the middle of August, when the extent of fresh snow cover in the Central Arctic began to increase, albedo rose by 0.05 to 0.10 in all years.

Interannual variations in the timing of snow melt are also quite evident in the basin as a whole (Fig. 4). Note that only areas with greater than 12% ice cover are charted in Fig. 4. This results in a relatively steady decline in the surface area analyzed as summer progresses, from approximately 95% of the basin in late June to about 80% in mid-August (70% in 1977). The timing of the Arctic-wide melt sequence differed by two to four weeks during the four study years. In 1977, active melt (classes 2 and 3) covered 50% of the basin by the end of May, while over half of the basin was categorized as class 3 or 4 by the end of June. Melt began almost three week later in 1979, yet, as in 1977, more than half of the

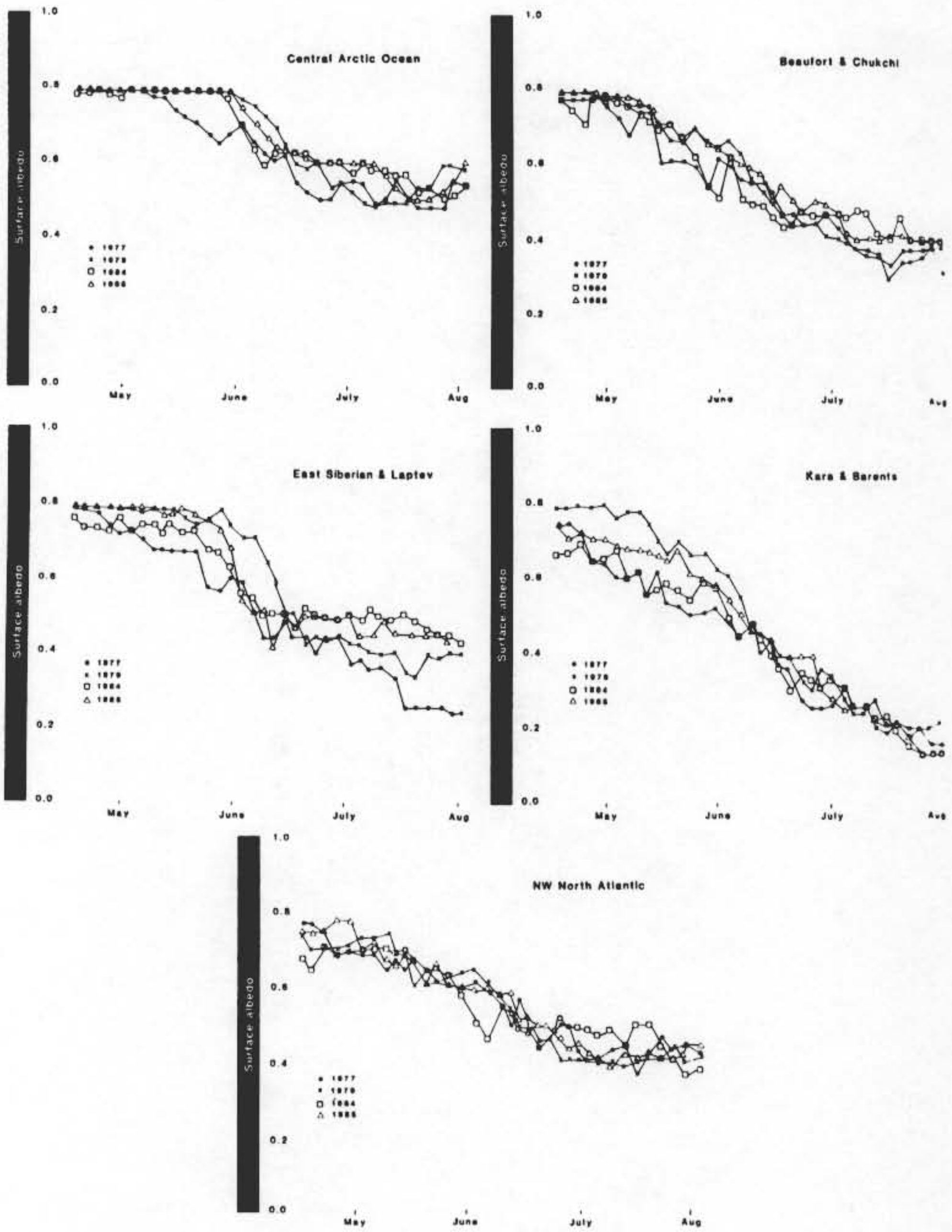


*FIG. 3 Changes in surface albedo in the five Arctic Basin study regions during the four summers studied. Three day values are calculated for the entire region, ice and open water*

basin was classified as class 3 or 4 by the end of June. In 1984, melt began prior to May 1 in the southern Beaufort and Chukchi Seas, however it was not as extensive in May as it was in 1977. In

*TABLE 1 Average surface albedo over regions of the Arctic Basin for each month in the four study years*

| | | Central Arctic | Beaufort/ Chukchi | E.Siberian/ Laptev | Kara/ Barents | NW North Atlantic |
|---|---|---|---|---|---|---|
| | 1977 | 0.78 | 0.74 | 0.73 | 0.66 | 0.72 |
| May | 1979 | 0.79 | 0.76 | 0.79 | 0.77 | 0.73 |
| | 1984 | 0.79 | 0.75 | 0.74 | 0.63 | 0.70 |
| | 1985 | 0.79 | 0.77 | 0.79 | 0.69 | 0.74 |
| | 1977 | 0.66 | 0.58 | 0.55 | 0.48 | 0.60 |
| June | 1979 | 0.76 | 0.62 | 0.67 | 0.58 | 0.62 |
| | 1984 | 0.69 | 0.59 | 0.63 | 0.51 | 0.59 |
| | 1985 | 0.73 | 0.65 | 0.62 | 0.54 | 0.62 |
| | 1977 | 0.52 | 0.42 | 0.40 | 0.27 | 0.46 |
| July | 1979 | 0.53 | 0.41 | 0.42 | 0.32 | 0.45 |
| | 1984 | 0.58 | 0.45 | 0.49 | 0.30 | 0.50 |
| | 1985 | 0.59 | 0.47 | 0.48 | 0.31 | 0.47 |
| | 1977 | 0.50 | 0.33 | 0.25 | 0.19 | 0.44 |
| Aug.* | 1979 | 0.53 | 0.37 | 0.39 | 0.22 | 0.43 |
| | 1984 | 0.54 | 0.42 | 0.47 | 0.15 | 0.43 |
| | 1985 | 0.54 | 0.41 | 0.45 | 0.17 | 0.44 |

* *for the period August 1-17*

1984, areas with concentrated narrow leads in seas bordering the Asian continent resulted in a large-scale surface brightness equivalent to unbroken ice undergoing partial melt (class 2). However, active melt did not begin over more than 10-15% of the basin until late May. Over half of the basin was classified as classes 3 and 4 by the end of June 1984. Melt began at about the same time in 1985 as in 1979, with about 25% of the basin categorized as class 2 at the end of May. Approximately 50% of the basin was classified as classes 3 and 4 by the end of June. Variations throughout the remainder of the summer were primarily due to snow conditions in the Central Arctic and variations in the area of flooded ice (class 4) in surrounding seas in the basin.

Due to the earlier melt in 1977 and the combination of melt and lower ice concentration in 1984, basin albedo averaged 0.73 in May 1977 and 1984, compared with 0.77 in 1979 and 0.76 in 1985 (Table 2). Basin albedo was highest in June 1979 (0.66) and lowest in 1977 (0.58). By July, basin albedo dropped to 0.43 in 1977, 0.44 in 1979 and 0.48 in 1984 and 1985. The first half of August averaged 0.36 in 1977, and between 0.40 and 0.42 in the other years, the major difference in 1977 being the relatively large amount of open water in the basin. The late July and early August albedo of the ice surface (sea water excluded), in those parts of the basin where ice concentration exceeded 75%, was approximately 0.45 in 1977 and 1979 and 0.50 in 1984 and 1985.

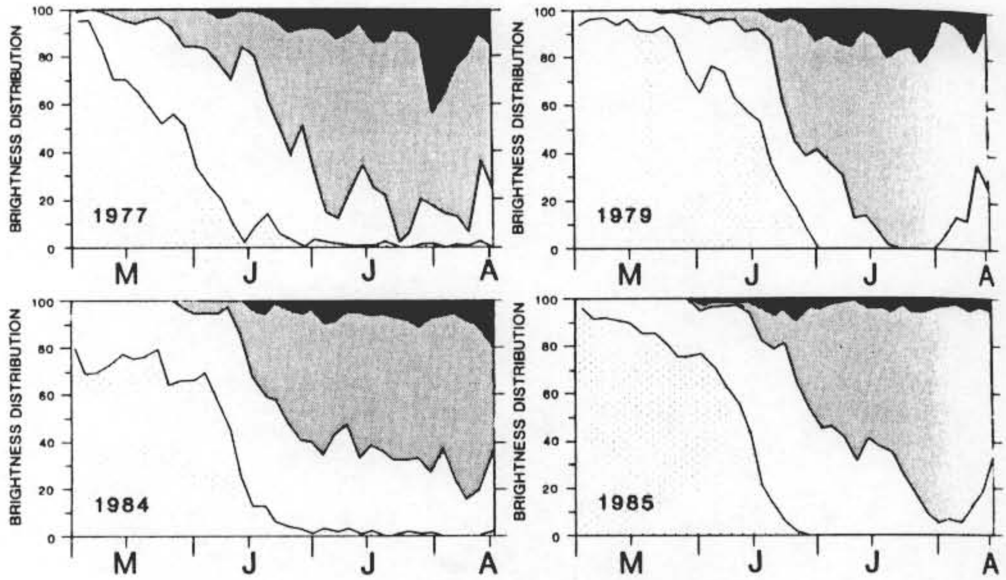


*FIG. 4 Progression of snow melt and subsequent ponding and drainage on Arctic sea ice from May to mid-August of the four study years, as shown by the changing distribution of brightness classes (cf. text for class descriptions). Classes shaded from light grey (class 1) to dark grey (class 4). Areas with less than approximately 10% ice concentration or with open water are omitted*

*TABLE 2 Average surface albedo over the Arctic Basin for each month in the four study years*

| *Month/Year* | *1977* | *1979* | *1984* | *1985* |
|---|---|---|---|---|
| *May* | *0.73* | *0.77* | *0.73* | *0.76* |
| *June* | *0.58* | *0.66* | *0.61* | *0.65* |
| *July* | *0.43* | *0.44* | *0.48* | *0.48* |
| *August** | *0.36* | *0.40* | *0.42* | *0.42* |

**for the period August 1-17*

The four-year mean monthly albedos estimated for the Central Arctic sector are compared with published values of surface albedo at 85°N in Fig. 5. Our data fall within the range of values estimated by Hummel & Reck (1979), Kukla & Robinson (1980) and Robock (1980) for the four months studied. Robock's values for June-August appear to be far too low, while the other two estimates are too high in August.

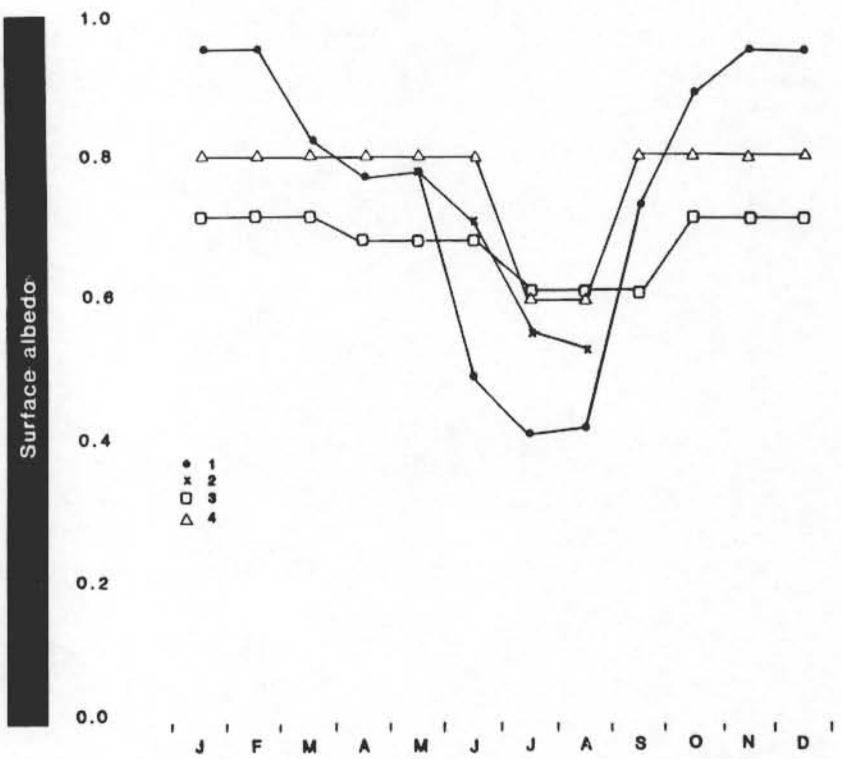


*FIG. 5 Variation of surface albedo with month at 85°N from the surface albedo compilations of (1) Robock (1980; (3) Hummel and Reck (1979); and (4) Kukla and Robinson (1980) (after Shine & Henderson-Sellers, 1985); and (2) mean monthly albedo estimates for the Central Arctic from the four-year set discussed in this paper*

## DISCUSSION

Climate models suggest that an early loss of snow cover may have an impact on sea ice extent later in the summer (Maykut & Untersteiner, 1971; Semtner, 1976). In 1977, when the snow melt and ponding came early, the subsequent late summer ice extent was considerably reduced compared to ice cover in the other years. This relationship was most evident in the Beaufort and Chukchi Seas and the East Siberian and Laptev seas. Whether such a dependence was coincidental or not must remain speculative until more years are examined.

Cloud cover, mapped at approximately three-day intervals in the summers of 1977 and 1979, showed a late May-early June maximum in thickness and extent (averaging approximately 90%) over the basin, followed by a period of somewhat thinner and less extensive (approximately 75%) cover extending into early August (Robinson *et al.* 1986a). This suggests that early stages of surfaces melt may be related to the early season cloudiness, which appears to be associated with the poleward retreat of the Arctic front and

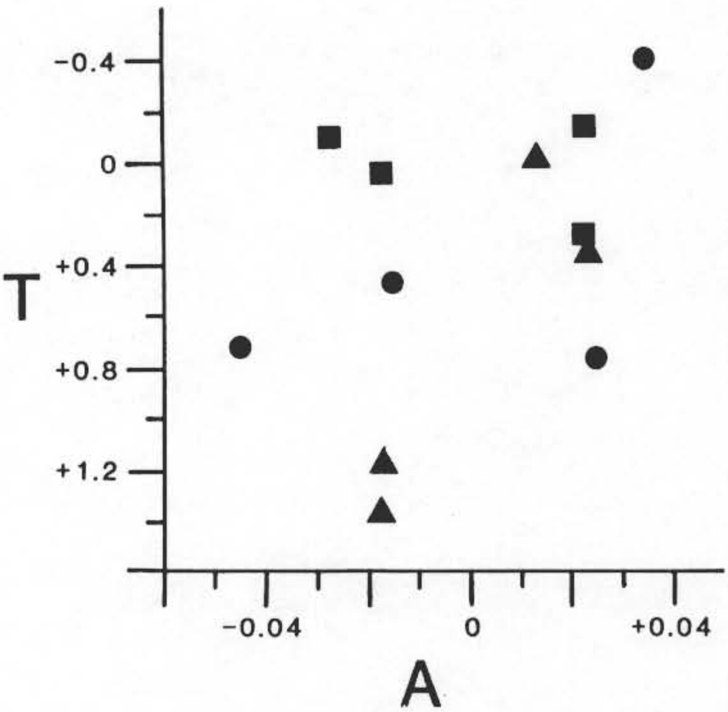


*FIG. 6 Comparison of monthly anomalies of surface albedo over the Arctic Basin and surface air temperature from 65-85°N, for May (triangles), June (circles) and July (squares) of the four study years. Albedo anomalies are based on an average of the four years. Temperature anomalies are based on 1951-1970 means (Jones, 1985; Climate Monitor, 1985a & 1985b)*

advection of air from lower latitudes by synoptic disturbances (Barry *et al.* 1986). Early melt may also be enhanced by the increase in infrared radiation at the surface due to the cloud cover. This results in an increase in surface net radiation over high-albedo Arctic surfaces (e.g. Ambach, 1974).

The relationship between snow melt and large-scale Arctic surface air temperatures was studied using monthly temperature and albedo anomalies (Fig. 6). Temperature anomalies are based on 1951-1970 means for 65-85°N (Jones, 1985; Climate Monitor, 1985a & 1985b). Albedo anomalies are calculated from the average values of the four study years (cf. Table 2). A positive relationship between increasingly positive anomalies of temperature and negative anomalies of basin-wide surface albedo is suggested in May and three of the four Junes studied, but is not evident in July. This may imply that the temperature data are not representative of the inner Arctic basin, but are affected by open water in the coastal seas close to the reporting stations.

## CONCLUSIONS

This work provides the first direct evidence of the fluctuations of snow cover and surface albedo across the entire Arctic Basin in spring and summer. While the pattern of snow melt on the Arctic ice does not appear to vary significantly from year to year, the timing of melt onset does, by at least several weeks. The extent of snow melt in the Central Arctic also appears to vary from year to year. These variations will have a significant impact on the heat and mass balance of the Arctic, since the surface albedo and the thermodynamics of the ice are strongly related to the presence of snow. Improved knowledge of the spring and summer surface albedo in the Arctic is important in climate models and may also help in recognizing the initial signs of any climatic changes induced by $CO_2$ and other trace gases.

**ACKNOWLEDGEMENTS** We thank M. Serreze, D. Van Metre and S. Innes for assistance in the analysis. DMSP data are archived for NOAA/NESDIS at the University of Colorado, CIRES/National Snow and Ice Data Center, Campus Box 449, Boulder, CO 80309. This work was supported by NSF grant ATM 83-18676, the Air Force Office of Scientific Research, Air Force Systems Command, USAF, under grant AFOSR86-0053 and the Office of Naval Research N00014-86-K-0695 to Dartmouth College, subcontract 5-36378. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon.

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