INITIATION OF SPRING SNOWMELT OVER ARCTIC LANDS

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ABSTRACT: The springtime initiation of snowmelt in the Tanana River Basin and over the North Slope of Alaska was found to correlate with daily regionally averaged values of parameterized absorbed shortwave radiation at the ground (Q) of from 6-8 MJm^{-2} and 2.5-4.5 MJm^{-2}, respectively. These values are a function of solar insolation, surface albedo and atmospheric screening factors. Results are based on analyses of satellite imagery and ground station data from 1978-1985. During these springs, the date melt started ranged from 3/27 to 4/23 (ave. 4/10) in the Basin and from 4/13 to 5/28 (ave. 5/10) on the Slope. An early or late melt in the Basin was not paralleled on the Slope. Regional albedo at the start of melt was approximately 0.35 in the Basin and 0.75 on the Slope. As the two regions differ by only several degrees of latitude, this difference in albedo appears to be the primary explanation for the considerably later date at which melt commenced on the Slope. In both regions, an early start of melt appeared to be caused by abnormally warm air advected into a region. On the Slope, regardless of the starting date, the most rapid interval of decreasing albedo occurred once a secondary threshold of 6-8 $MJm^{-2}day^{-1}$ was reached. Correlations between Q and local and regional temperatures appeared strongest on the Slope.
(KEY TERMS: snowmelt, absorbed shortwave radiation, albedo, temperature, runoff.)

INTRODUCTION

The impact of spring snowmelt on hydrologic regimes in the arctic and subarctic depends on the water content of the snowpack and on the timing and duration of the melt period. An early, rapid, melt might result in spring flooding, followed by drought in summer.

While considerable effort has gone into improving estimates of the potential runoff from a snowpack (eg. Rango _et al._, 1975; Ostrem _et al._, 1979; Shafer _et al._, 1979), less attention has been paid to the prediction of the start and duration of snowmelt, with some notable exceptions (eg. Carlson _et al._, 1974; Rasmussen and Ffolliott, 1979). Here, using shortwave satellite and ground data, we report on variations of spring snowmelt in the Tanana River Basin and on the North Slope of Alaska from 1978 to 1985.

We found that during the study period the initiation of melt in these regions was related to the amount of shortwave energy available for surface heating, which in spring was primarily controlled by insolation and surface albedo. The latter, in turn, is a function of relief, the height and density of the vegetation canopy and of the extent, depth and physical characteristics of the snowpack (Kung _et al._, 1964; Robinson and Kukla, 1984). The latter properties depend on the age of the upper layers of the pack. The timing and duration of snowmelt was monitored by observing regional changes in surface brightness using satellite data.

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DATA

Imagery from NOAA TIROS and Defense Meteorological Satellite Program (DMSP) near-polar orbiting satellites was examined. The Advanced Very High Resolution Radiometer onboard the NOAA satellites provided imagery with a resolution of 1 km in both visible (0.55-0.68um) and infrared (10.5-11.5um) channels. Daily data covering Alaska were available throughout the study period. Direct readout DMSP imagery was used for scattered intervals during the period. Spectral ranges are 0.4-1.1um and 10.5-12.5um. Resolution is 0.6 km.

Daily data of surface air temperature and snow depth were taken from Climatological Data for Alaska (NOAA, 1978-85).

METHOD

Daily sets of surface albedo, temperature, snow depth, cloudiness and absorbed shortwave radiation at the surface were assembled for the Tanana Basin and North Slope regions (Figure 1) from March 15 to May 15 and April 15 to June 15 of each study year, respectively, as follows:

1. Surface albedo: Clear-sky shortwave AVHRR scenes close to the satellite subtract and showing different stages of progressing snowmelt were selected from the eight year data base to create a "master melt progression set" for each region. The average surface brightness of each scene of the sequential set was measured on an image processor. Specular reflectance is minimal over the surfaces measured at spring solar zenith angles in Alaska and at the satellite viewing angle (Taylor and Stowe, 1984). Surface albedo was computed from brightness data by linear interpolation between homogeneous bright and dark snow-covered or snow-free targets in each scene, whose surface albedos were estimated from data gathered in Alaska and elsewhere (eg. Larsson and Orvig, 1962; McFadden and Ragotzkie, 1967; Weller et al., 1972; Maykut and Church, 1973; Robinson and Kukla, 1984). This method effectively eliminates differences in brightness between images resulting from variations in image production. Shine and Henderson-Sellers (1983), using a radiative transfer scheme, showed that this approach works well with satellite imagery, regardless of channel width. Albedos so calculated on an independent image may be up to 0.10 too low or 0.05 too high (Robinson and Kukla, 1985). However, monitoring the time progression of brightness histogram statistics throughout the melt period, such as standard deviation, skewness and kurtosis, narrowed the error range.

The albedo of a study region on a specific day during the eight year period was obtained by visual comparison of a clear-sky image for that day with the measured "master melt progression set". Where clouds prevented analysis, albedo was estimated by linear interpolation from the closest clear-sky dates.

2. Temperature and snow depth: Daily regional averages of high and low temperature and snow depth were calculated by averaging reports from stations evenly distributed within the study regions (Figure 1). The Tanana Basin stations included Big Delta, Fairbanks, McKinley Park and Tanana. Barrow, Barter Island and Umiat comprised the North Slope network.

3. Absorbed radiation: Daily parameterized shortwave radiation available for surface heating or evaporation was computed

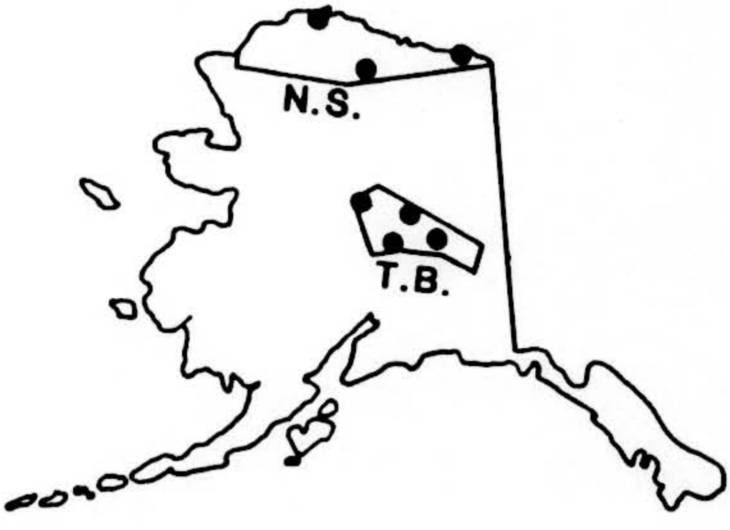

Figure 1. State of Alaska, showing the locations of the North Slope (NS) and Tanana Basin (TB) study regions. The locations of climate stations used in the study are marked with dots.

from a simple model, whose inputs were regional surface albedo (a), insolation at the top of the atmosphere (I) and a parameterized regional atmospheric screening factor (S) (equation 1).

$$Q = (1-a)\ I\ S \qquad (1)$$

Since an analysis of cloud cover from the polar orbiter imagery showed no seasonal trends in either region, the average observed cloud coverage during the eight melt seasons was used to derive a mean atmospheric screening factor of 0.47 in the Basin and 0.44 on the Slope. The preceding values were obtained from once-a-day visual estimates of areal cloud cover in each study region, following a method previously employed over arctic sea ice (Robinson et al., 1985). This involved a visual inspection and charting of clouds in shortwave and infrared imagery, determining a fraction of cloud-covered area in the study region and estimating relative cloud thickness from the degree to which the clouds obscured the underlying surface contrast. Clouds were classified as thin, moderately thick or thick. Features under thin clouds were clearly recognizable but with reduced contrast. Features were marginally recognizable through moderately thick clouds and fully obscured under thick clouds. Cloud-class screening factors used in calculating regional screening factors were 0.6 (thin clouds), 0.4 (moderate) and 0.2 (thick) and clear skies 0.7. These highly approximate values were based on measurements in other regions at solar zenith angles of between 40° and 70° (Robinson, unpublished), the range of spring midday angles in the study regions. As only one morning or midday image per day was available for analysis, the cloudiness statistics do not take into account any potential diurnal cycle of cloud cover.

RESULTS

North Slope

In the early spring each year, regional surface brightness was homogeneous, with surface albedo close to 0.80. Subsequently, rivers began to appear as dark ribbons through the snow-covered region, as snowmelt runoff from the foothills of the Brooks Range reached the area (cf. Holmgren et al. (1975) for a detailed description of breakup on the North Slope). As a result, regional albedo decreased to about 0.75. Once the paths of streams originating in the tundra began to appear, albedo fell below 0.75. At this time we considered regional melt to be underway. When albedo reached approximately 0.25, only a few patches of snow and numerous frozen ponds were recognized on the imagery as being brighter than the surrounding snow-free tundra. At this point the major period of melt was considered over.

The timing and duration of the North Slope melt varied by up to 45 and 38 days, respectively, during the 1978-1985 period (Table 1). When melt began in late April to mid-May (Figure 2) it tended to last longer than when it commenced later in May (Figure 3).

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

Early melt was associated with abnormally warm temperatures. On the average, highs were near $0^{\circ}C$ during the period of initial slow albedo decreases of from about 0.75 to 0.55. Following this, an interval of stable albedo and colder temperatures was common. In the last week of May, the albedo again dropped at an increased rate. The major melt

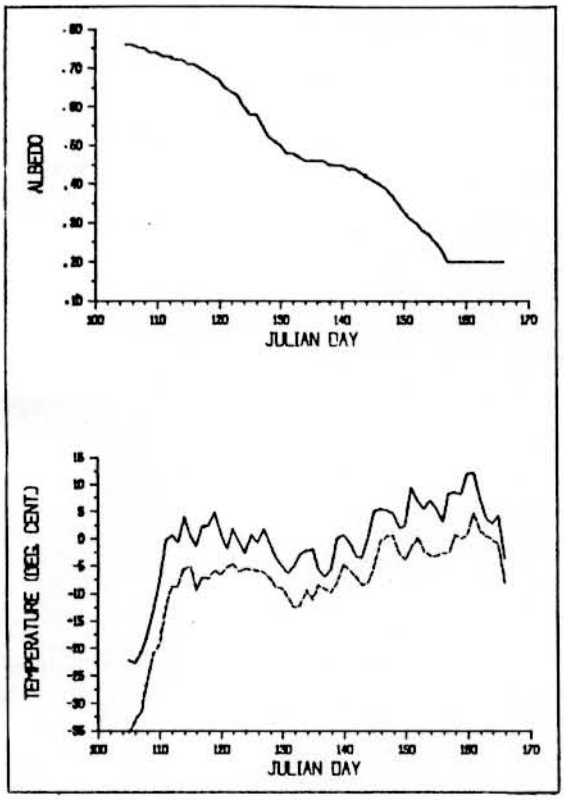

Figure 2. Daily regional surface albedo (top) and regionally averaged high and low temperatures (bottom) from April 15 (Julian day 105) to June 15 (Julian day 166), 1979 on the North Slope.

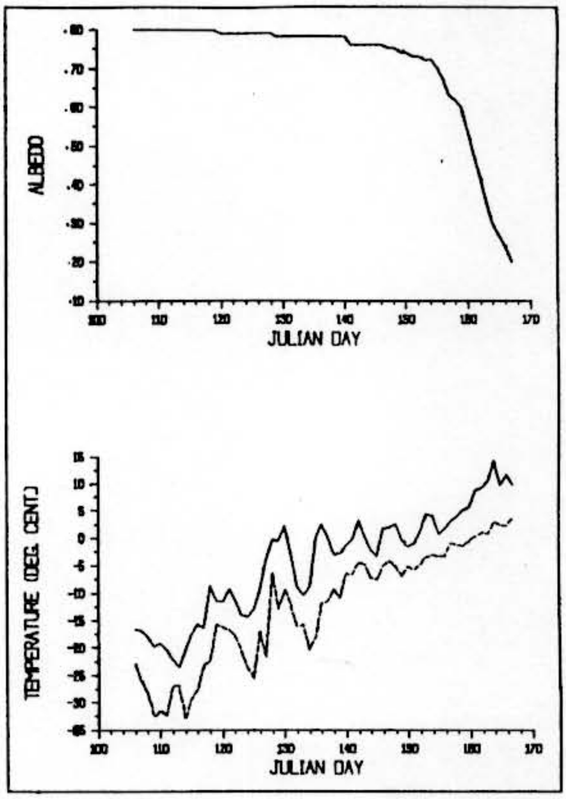

Figure 3. Same as Figure 2, but for 1984 (Julian days 106 to 167).

ended between June 3 and 13. High temperatures were close to +5°C during the last active phase of melt and frequently rose above 5°C following the melt. Low temperatures generally remained below 0°C until melt was complete. In years with a later start of melt, temperatures prior to, during and following the melt were similar to those for the early start years. However, in late years melt was most active in early June and ended between June 13 and 18.

There was no relationship between snow depth measured at the start of melt at the three Slope stations and the satellite-derived timing and duration of the regional melt. It is uncertain, however, to what degree these stations represent regional conditions.

Daily parameterized absorbed shortwave radiation at the ground at the commencement of regional melt ranged from 2.5-4.2 MJm^{-2} (1J=0.239cal) in early melt years and 4.2-4.5 MJm^{-2} in late melt years (Table 1). At the beginning of the most rapid 10 day decline in surface albedo, albedo values ranged from 0.53 to 0.65 and daily Q values were between 6.1 and 8.1 MJm^{-2}. The only exception was the 10.9 MJm^{-2} value in 1979, when albedo was 0.37.

There was a large range between the daily values of Q over the North Slope in the earliest and latest melt cases (Figure 4). On average, over twice as much radiation was absorbed on a given date in late May or early June in 1979 than in 1984. Correspondingly, in May 1979, Slope temperatures were 4°C higher than in 1984. Within the region, high temperatures in May 1979 differed by 10°C between Umiat, where the high averaged +5°C, and Barrow, where the high averaged -5°C. Albedo during this month was considerably lower in the vicinity of Umiat than at Barrow. In 1984 the Slope remained snow

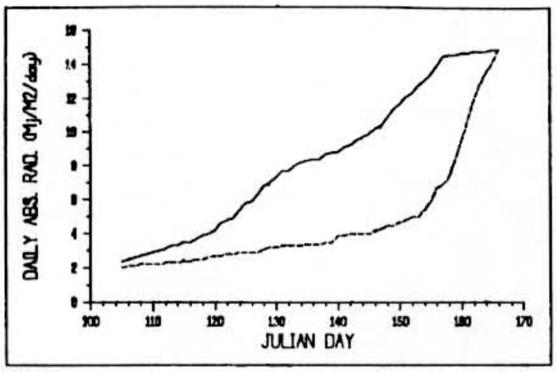

Figure 4. Daily parameterized absorbed shortwave radiation at the ground in the North Slope test region from April 15 to June 15 in 1979 (top curve) and during the same period in 1984 (bottom curve). Results based on a model which incorporates realistic surface albedo, top of atmosphere insolation and parameterized mean eight year surface radiation income. Bottom axis shows Julian days in 1979. Add one day to get Julian days in 1984.

covered throughout May and the mean Umiat high ($-1^{\circ}C$) was only $4^{\circ}C$ higher than Barrow's ($-5^{\circ}C$).

Tanana Basin

In late March and early April of the eight studied years, surface albedo in the Tanana Basin ranged between 0.32 and 0.38. The higher value appeared to come close to the Basin's potential maximum, while the lower value was the result of meager snow cover in upstream valley regions. Once the surface brightness began to continuously decrease, the melt was considered to be underway. The rate at which albedo decreased remained relatively constant until the regional surface albedo was close to 0.20. This was considered the active period of melt. When albedo reached 0.20, snow cover was only visible on the higher ground and occassionally in downstream portions of the Basin and the major melt period was considered over.

The timing and duration of Basin melt varied by up to 27 and 19 days, respectively, between 1978-1985 (Table 2). Melt commenced between April 6 and 14 in six of the eight years, with 1980 (March 27) (Figure 5) and 1985 (April 23) (Figure 6) being the only exceptions. There was some indication that the melt took longer when it began earlier, but snow depth, which on a regional scale was poorly known, may also have affected the duration. In 1981, when the depth of the snowpack at the four Basin stations averaged the lowest (17cm), the melt duration was the shortest (14 days). Conversely, in 1985, when the pack was deepest (64cm), the duration was relatively long (24 days), despite having the latest starting date.

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		End	Dura.
	Date	Q		(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

High temperatures during the early stages of melt were generally within several degrees of freezing. Only in 1980, when there was a persistent period of abnormal highs of about $+5^{\circ}C$ in late March and early April, were temperatures noticeably higher at the beginning of melt. In all years, highs were usually between $+5^{\circ}C$ and $10^{\circ}C$ during the middle and later stages of melt and regularly above 10° following melt. Low temperatures generally remained below $0^{\circ}C$ until melt was complete.

Daily parameterized values of Q were between 6.6 and 8.1 MJm^{-2} at the commencement of melt in six of the eight years (Table 2). Only in 1980 ($5.9 MJm^{-2}$) and in 1985 ($8.5 MJm^{-2}$) did they fall outside of this range. These two years exhibited the largest

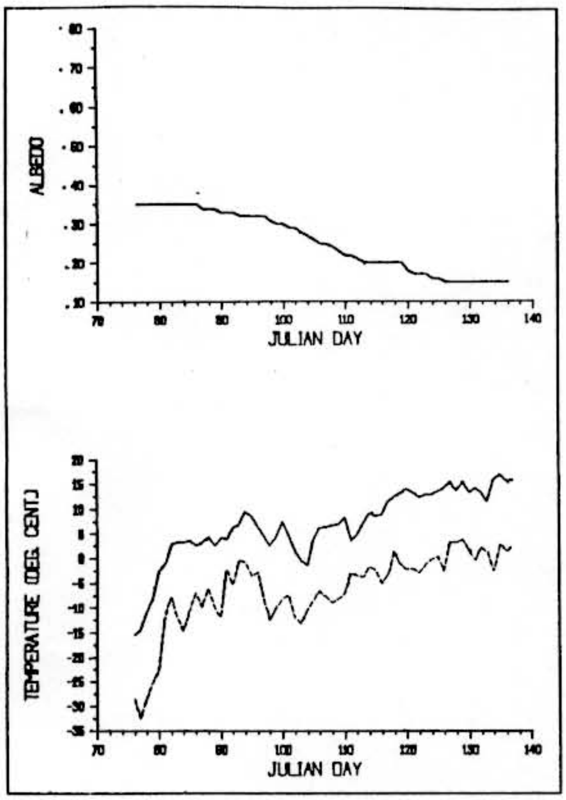

Figure 5. Daily regional surface albedo (top) and regionally averaged high and low temperatures (bottom) from March 15 (Julian day 75) to May 15 (Julian day 136), 1980 in the Tanana Basin.

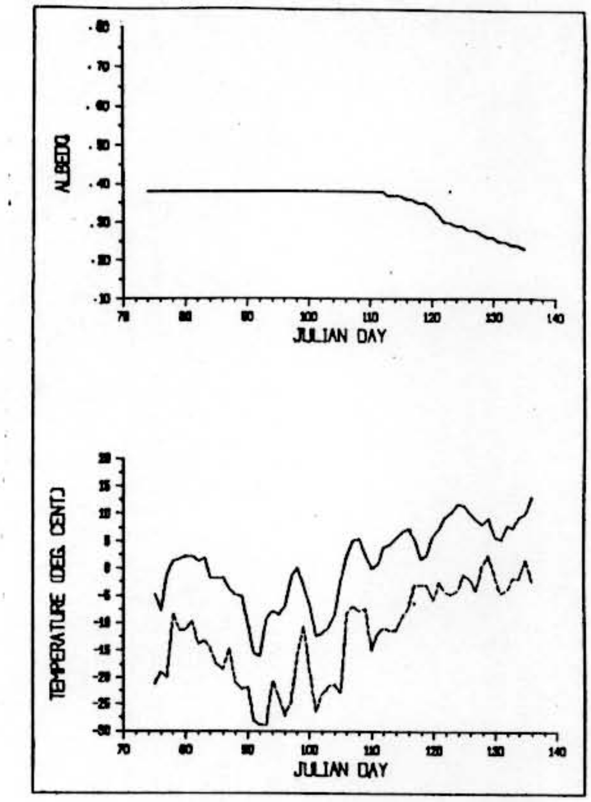

Figure 6. Same as Figure 5, but for 1985 (Julian days 74 to 135).

differences in daily Q amongst the years studied (Figure 7). In the latter half of April, daily values differed by close to 2.5 MJm^{-2}, with 1985 values lagging about 2 weeks behind those in 1980 (Figure 7). In April 1980, the mean temperature in the region was $+1^{o}C$, while in April 1985 it was $-8^{o}C$.

DISCUSSION

The approximately six degree difference in latitude of the Tanana Basin ($64^{o}N$) and North Slope ($70^{o}N$) study regions results in the Slope receiving 16% less daily insolation at the top of the atmosphere than over the Basin on April 1 and 6% less on May 1. Thus, there would be a difference of only several days in melt initiation between the two

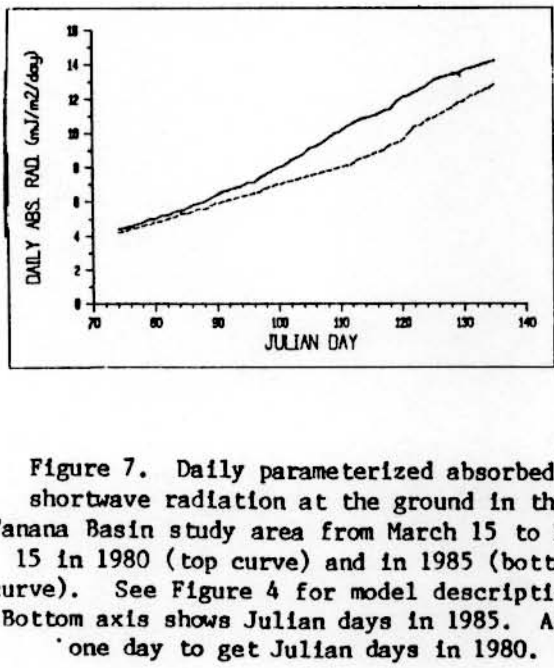

Figure 7. Daily parameterized absorbed shortwave radiation at the ground in the Tanana Basin study area from March 15 to May 15 in 1980 (top curve) and in 1985 (bottom curve). See Figure 4 for model description. Bottom axis shows Julian days in 1985. Add one day to get Julian days in 1980.

regions in April if regional snow-covered albedos were the same. By late May, the Slope receives more insolation at the top of the atmosphere than the Basin. Therefore, the difference in the regional albedos of the two regions when snow covered appears to be the primary reason why the most active period of melt in the open country of the Slope began an average of 51 days later than the start of the active period of melt in the forested Basin. In each region, there was a threshold range of daily Q of approximately 6-8 MJm^{-2} reached before the most active period of decreasing albedo began. This threshold range was reached in mid-April in the Basin but in the last week of May or first week of June on the Slope.

An early or late start of melt in the Basin did not necessarily correlate with the relative timing of initial melt on the Slope. The starting date of initial melt in the two regions differed by as few as 4 days and as many as 55 days. This range was generally a reflection of the widely ranging starting dates on the North Slope. There was also no relationship between the two regions regarding the time at which melt ended. This differed from 14-57 days.

An early commencement of melt on the North Slope in April or early May did not trigger the rapid demise of snow cover over the entire Slope, apparently because of the low values of absorbed radiation which exist at that time of spring. Insolation is considerably below its late spring values and the albedo, despite a partial decrease from its maximum, remains relatively high.

Correlations between absorbed radiation and the most active period of melt and between absorbed radiation and local and regional temperatures appear strongest on the North Slope. This is likely due to the greater simplicity of the boundary layer dynamics on the Slope compared to the Basin. In the latter, the water content of the snowpack is more variable in an absolute sense in a given year as well as between years. The forests in the Basin add to the complexity of the radiation budget, as does its more variable topography and frequent inversions. The radiation budget of the Slope is more singularly and directly affected by the snowpack.

Several of the study results stand out as being of importance to the hydrologic community. 1) There is not a parallel relationship between an early or late melt in the Basin and on the Slope. 2) The major period of snowmelt runoff can not be expected to occur in either region until the initial shortwave radiation threshold is reached. 3) When the secondary threshold of 6-8 $MJm^{-2}day^{-1}$ is reached on the Slope, the subsequent runoff should be reduced in years when the melt starts early. 4) The duration of melt in the Basin appears to be more sensitive to the initial water content of the snowpack than on the Slope.

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