Kukla, G; Barry, R.G.; Hecht, A.; Wiesnet, D. eds. (1986) SNOW WATCH '85. Proceedings of the Workshop held 28-30 October 1985 at the University of Maryland, College Park, MD. Boulder, Colorado, World Data Center A for Glaciology (Snow and Ice), Glaciological Data, Report GD-18, p.63-72.

Progression of Regional Snow Melt

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Abstract:

Snow melt may be accurately monitored by observing time-related variations of surface albedo. When snow is present, regional surface albedo is primarily a function of 1) the physical properties of snow, 2) the fraction of the snow covered surface which is unobstructed and 3) the amount of exposed snowfree ground. The second is a function of the height and density of vegetation or other objects protruding through the pack. The most accurate means of obtaining data on regional to continental scales is through the analysis of shortwave satellite imagery in an interactive manner on an image processor by an observer familiar with the studied area.

Introduction:

As snow dissipates its strong insulating and atmospheric drying capacities diminish. Its capacity to cool the atmosphere, which stems from its high emissivity and high albedo, also decreases. This is primarily a result of changes in the physical properties of snow, including snow depth, increases in snow grain size, wetness and contaminants, and changes in the amount of exposed snowfree ground.

Presently, the most accurate means of monitoring the state of a regional snow cover is by observing its surface albedo in shortwave satellite imagery. The utility of ground station data in monitoring melt is limited because of drifting, topography, local variations in initial snow depth and heat island effects.

Shortwave image analysis is not without its problems. Clouds may obscure the surface, particularly in the transitional zone between fully snow-covered and snowfree terrain. Albedo can not be directly measured from satellites when skies are clear, due to atmospheric attenuation of solar radiation reaching the surface and reflected from it, and due to the narrow-band bi-directional nature of the sensors. For these reasons, it is necessary to have ground-truth knowledge of different regions under a variety of snow-cover conditions. Here we present albedo data gathered on the ground and from aerial and satellite platforms to exemplify their utility in monitoring the progression of melt and, also, to show how the albedo of different surfaces varies with changing snow conditions.

Ground truth:

Measurements of broadband hemispheric albedo (0.28-2.80 microns) were made following a snowstorm in order to document melt conditions over surfaces representative of broad regions of the middle latitudes. The study was undertaken in southeastern New York and northern New Jersey following the major East Coast storm of February 11-12, 1983. Albedo was monitored on the ground and from a low-flying aircraft as a 50 cm deep snowpack dissipated. Data were collected during a three week period where daily high temperatures were above freezing and no significant rain or snow fell until March 2.

Ground measurements of the snowpack were made at midday over a short grassy field. Albedo of the pack fell by 0.29, from 0.83 to 0.54, between the 13th and 25th (fig. 1). While the snow was slushy on the 25th, and some portion of the reflected signal was from the underlying grass, no grass blades had yet protruded through the pack. Thus, significant changes in regional albedo occurred when snow continued to cover 100% of the surface. However, it was observed that over all but extremely level and smooth surfaces some bare ground began to be exposed prior to the albedo of most of the snowpack falling below 0.70 (Feb. 21).

Time series of albedo were constructed over key middle latitude surfaces as the snow dissipated (fig. 2). Data were gathered from wingtip-mounted pyranometers flown at an altitude of approximately 200m.

Forests (lines B & C) masked much of the snow, thus initial albedo values were low. They diminished in a quasi-linear fashion as the snow dissipated. Shrubland (F) albedo initially dropped rapidly, in response to snowpack settling and snow falling off of branches, and later slowed. The opposite pattern was observed over open fields and meadows (A,D,E) where albedos initially were as much as eight times their snowfree values. Initial decreases in albedo paralleled the snowpack values. Later, as bare ground became exposed, the melt accelerated and albedo decreased more rapidly. Over residential sites (H) and particularly over industrial locations (G), albedo decreased and snow disappeared more rapidly than over natural terrain.

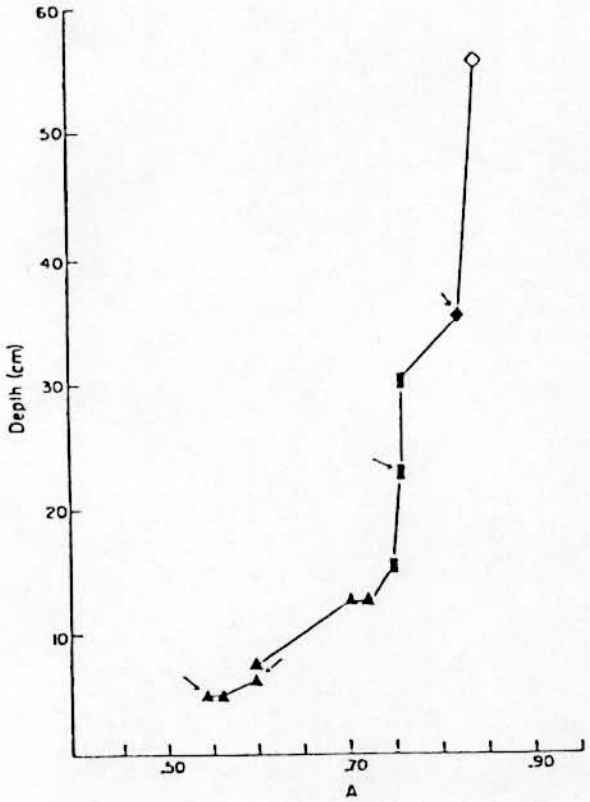


Figure 1. Midday albedo of a complete snowpack over a short grassy field at the Lamont Observatory ($41^{\circ}N$) from Feb. 13-25, 1983. Albedo is shown with a diamond for 1-3 day old snow (open diamond: dry, Feb. 13 and 14), squares 4-6 days old, triangles 7 days or more old. Solid symbols indicate a wet snowpack. Datum for Feb. 20 is missing. Arrows point to cases where global atmospheric transmissivity was below 40%. (after Robinson, 1984)

The ground truth study also exemplified the difficulties in using station snow depth data alone, even a dense network, when monitoring regional snow dissipation. Albedos from 26 sites along the flight path on a day with 13 cm deep 3 day old snow (Feb. 10, 1983) were approximately 20% greater than the identical sites on a day with 13 cm deep 9 day old snow (Feb. 22, 1983) (fig. 3). Snow depth was averaged from a network of stations with a density of approximately 1 per $100km^2$. Skies were clear on both dates. The albedo of the snowpack was 0.78 on the 10th and 0.60 on the 22nd. Only the industrial site (cf. Figure 2 G), where snow of any depth remained for only a short time, does not fit the relationship.

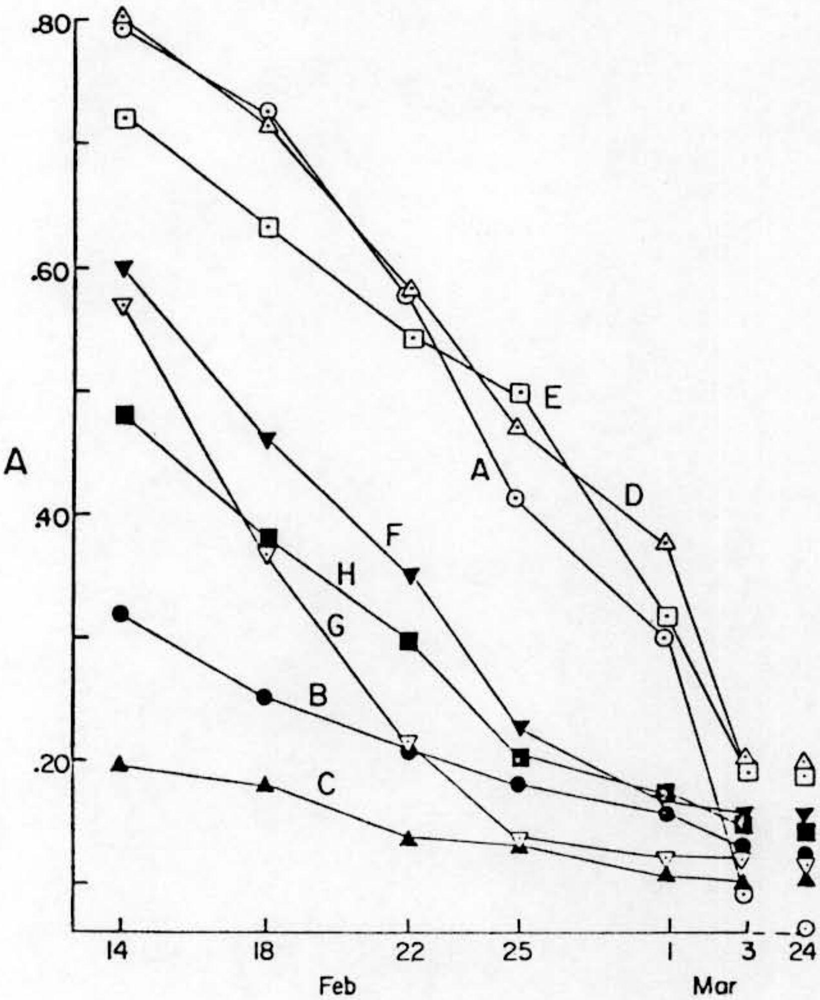


Figure 2. Albedo (A) of major surface elements in southeastern New York and northern New Jersey under winterlike snowfree (March 24, 1983) and a variety of snow-cover (Feb. 14-March 3, 1983) conditions. The lettered curves indicate locations which include: (A) dark soiled farmland, (B) deciduous forest, (C) mixed coniferous forest, (D) cultivated field, (E) grassy meadow, (F) shrubby grassland, (G) industrial and (H) residential. (from Robinson and Kukla, 1984)

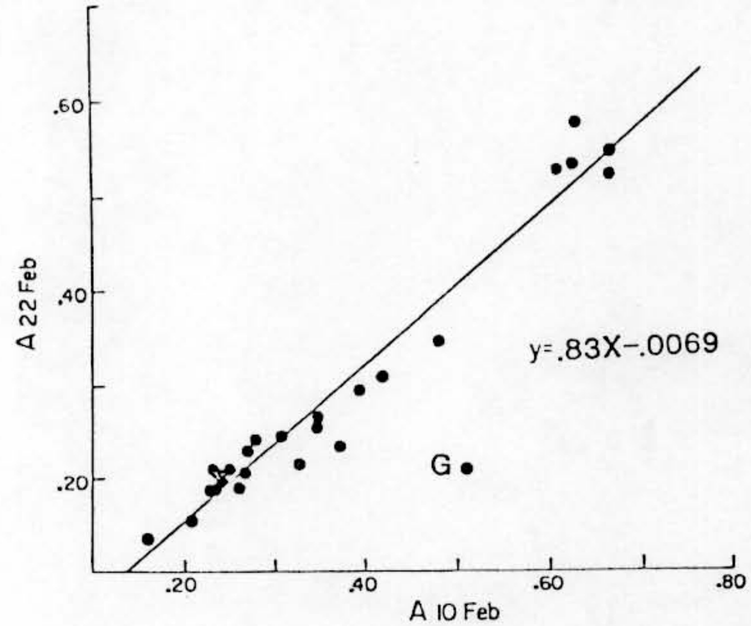


Figure 3. Snow depth-age-albedo relationships. The albedo of a site on Feb. 10, 1983 is plotted against the albedo of the identical site on Feb. 22, 1983. Both days had clear skies and identical snow depths at forest and field test sites. Snow on the 10th was 3 days old and dry with an albedo of 0.78. Snow on the 22nd was 10 days old and wet with an albedo of 0.60. The regression equation has a correlation of 0.96. It does not include point G which is an industrial site (cf. fig. 2, location G). (from Robinson and Kukla, 1984)

Satellite observations:

To permit an assessment of regional snow melt from satellite imagery it is first necessary to know the maximum regional albedo that may be expected under deep fresh snow-cover conditions. This has been done in $1^{o} \times 1^{o}$ latitude/longitude cells over Northern Hemisphere seasonally snow covered lands (fig. 4) (Robinson and Kukla, 1985). Data were obtained by image processor analyses of clear-sky Defense Meteorological Satellite Program (DMSP) imagery. Scene brightness was converted to surface albedo by linear interpolation between bright and dark snow-covered surfaces with known albedo.

A broad zonal distribution of forests masks the underlying snowpack in Eurasia and North America. For instance, in Eurasia the areally averaged albedo is 0.36 over the boreal forest zone between 60^{o} and 65^{o}N. It rises to 0.76 over the short grassy tundra further north.

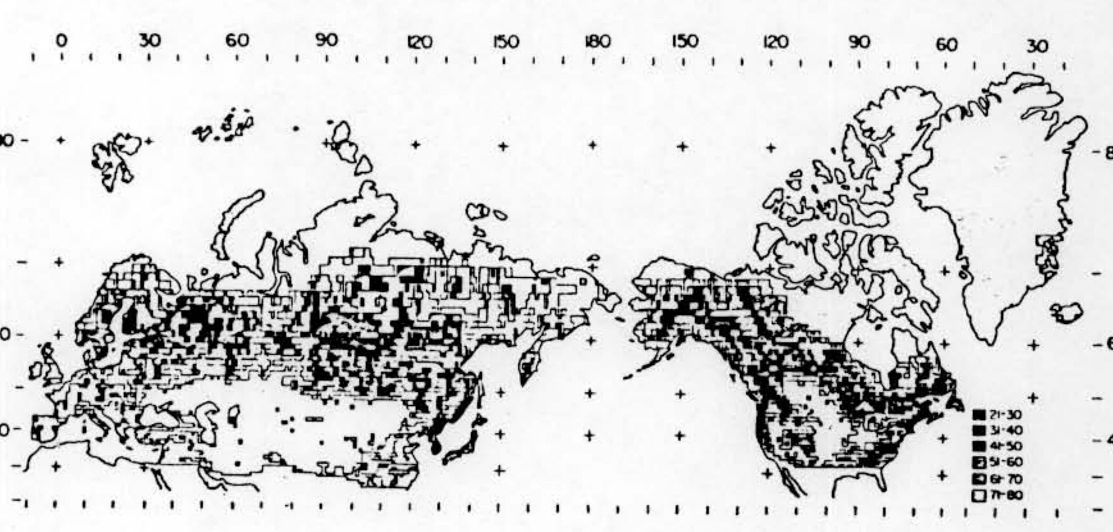
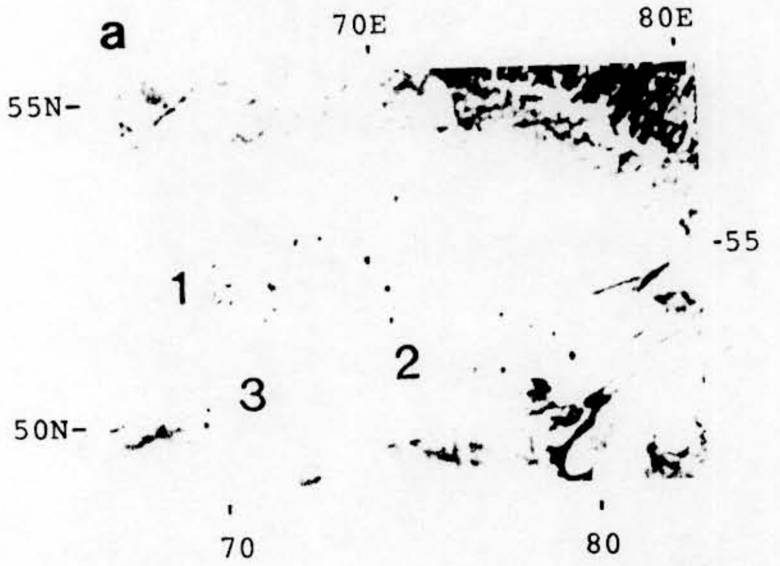


Figure 4. Maximum surface albedo of Northern Hemisphere land with the potential of developing seasonal snow cover. Cells, measuring $1^{o} \times 1^{o}$, are marked in 0.10 increments. Comparisons with Figure 5a may be made in south central Asia. (from Robinson and Kukla, 1985)

The ground truth study exemplified the fact that regional albedo with snow present is frequently below its potential maximum. This is particularly so where the climate is dry and snow cover shallow (eg. south central Asia) or in the snow transition zone. In figure 5a the fully snow-covered steppe (points 1-3) is considerably brighter than the forested hills to the northwest (point 4), where the snow cover is masked by the forest canopy. In Figure 5b the snow cover has melted over portions of the steppe and bare ground is exposed (points 1 and 2). The dark pattern of roads and rails radiating from cities (point 3) is more pronounced in b.

Thus, many of the same characteristics of snow-covered and partly snow-covered lands observed on and near the ground are recognized on clear-sky shortwave satellite images. Analysis of this imagery in an interactive manner on an image processor by an observer familiar with the studied area is quite useful in identifying and quantifying this information. Figure 6 shows brightness histograms measured from NOAA Very High Resolution Radiometer (VHRR) images over an approximately 100,000 km^2 portion of central U.S. farmland. Histogram 1 shows the area a year earlier, when it was covered with over 15cm of fresh snow. There is a single peak at a high brightness value.

The February 1, 1977 histogram (2) quantifies the distribution of snow over the region when an originally complete snow cover was 7 days old. Some bare ground had begun to appear, giving the histogram a slightly bimodal character. Compared to histogram 1, the bright peak is shifted towards the



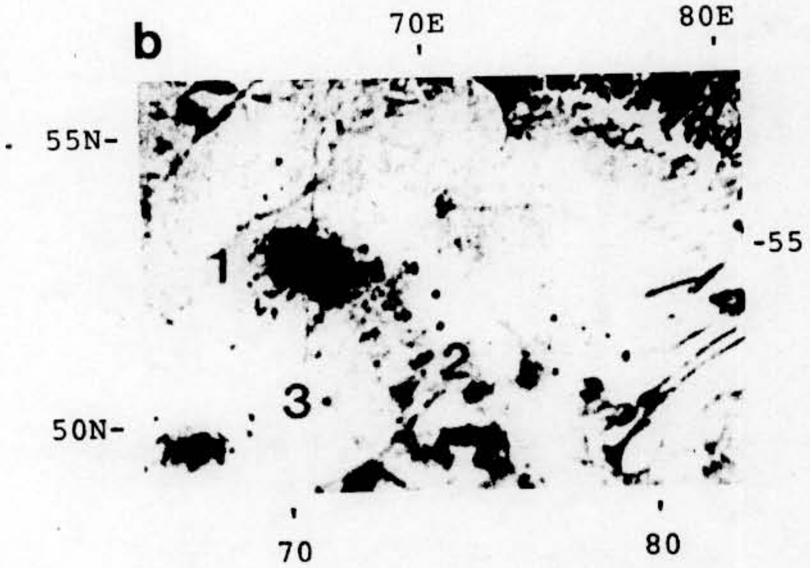


Figure 5. A portion of a DMSP image covering south-central Asia on (a) Feb. 19, 1979 and (b) March 23, 1979, showing a decrease of surface albedo due to progressing snow melt. (after Robinson and Kukla, 1985)

dark end, probably due to a combination of decreasing snow albedo and subresolution patches of bare ground. Some 80% of the stations in the region reported snow cover on the 1st. At these stations the average depth was 10 cm. In subsequent days (histograms 3-5), the amount of snowfree ground began to exceed that of snow-covered ground. By the 10th the single dark peak on the histogram (5) indicates that most surfaces were snowfree, however, some subresolution snow patches were present, which broadens the peak and skews it towards the right. On this date, 50% of the stations reported snow cover, with the depth averaging 4 cm.

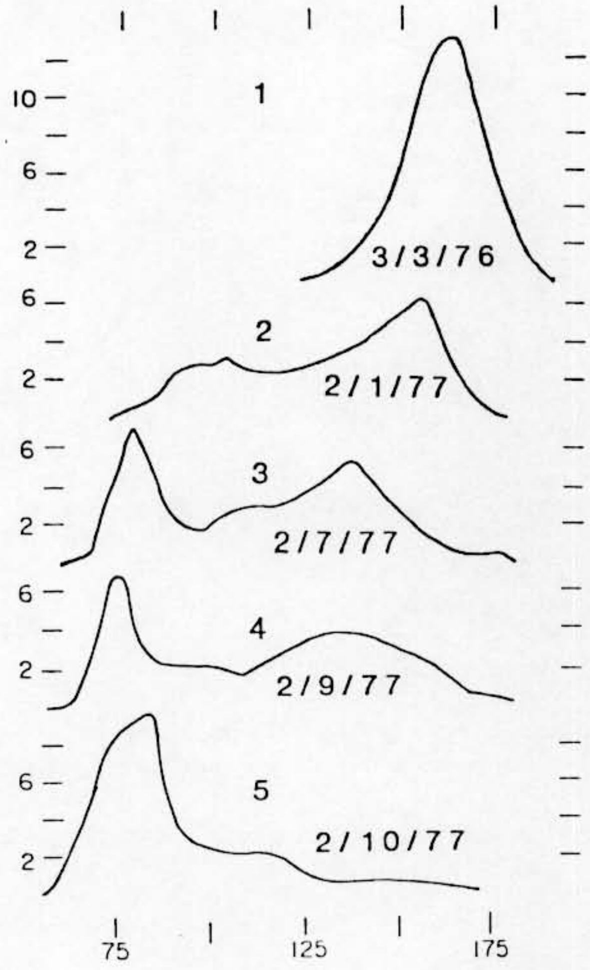


Figure 6. Brightness histograms with different snow-cover conditions over central U.S. farmland. Vertical axis shows the number of processor pixels ($x\ 10^3$) with a particular brightness (horizontal axis). (after Robinson and Kukla, 1982)

Further evidence of the utility of satellite-derived time series in monitoring regional snow melt is shown in figure 7. Brightness histogram statistics from clear-sky Advanced VHRR imagery over tundra and forest in Alaska are plotted for the springs of 1981 and 1980, respectively. Mean brightness is expressed as surface albedo. Each region is approximately 50,000 km^2.

In both regions, decreases in brightness as snow melted were found to be accompanied by simultaneous shifts in other histogram statistics. For instance, standard deviation decreased and kurtosis and skewness rose as snow disappeared in forested areas. These shifts indicate that the open fields, lakes, rivers, etc. in this region were no longer brightly snow covered. Once both the woodlands and the openings were snowfree, skewness fell to zero. In the tundra, standard deviation rose, kurtosis fell and skewness became negative once snowfree areas began to appear. Once dark snowfree areas predominated, skewness became positive, standard deviation decreased and kurtosis increased. When snowfree conditions were reached (around June 15), relatively bright ice-covered water bodies resulted in skewness remaining positive and the standard deviation staying high.

Snow dissipation can be successfully monitored by only observing changes in skewness, kurtosis and standard deviation. This is useful in cases where image quality or thin homogeneous clouds permit the surface to be seen but prohibit accurate albedo estimates.

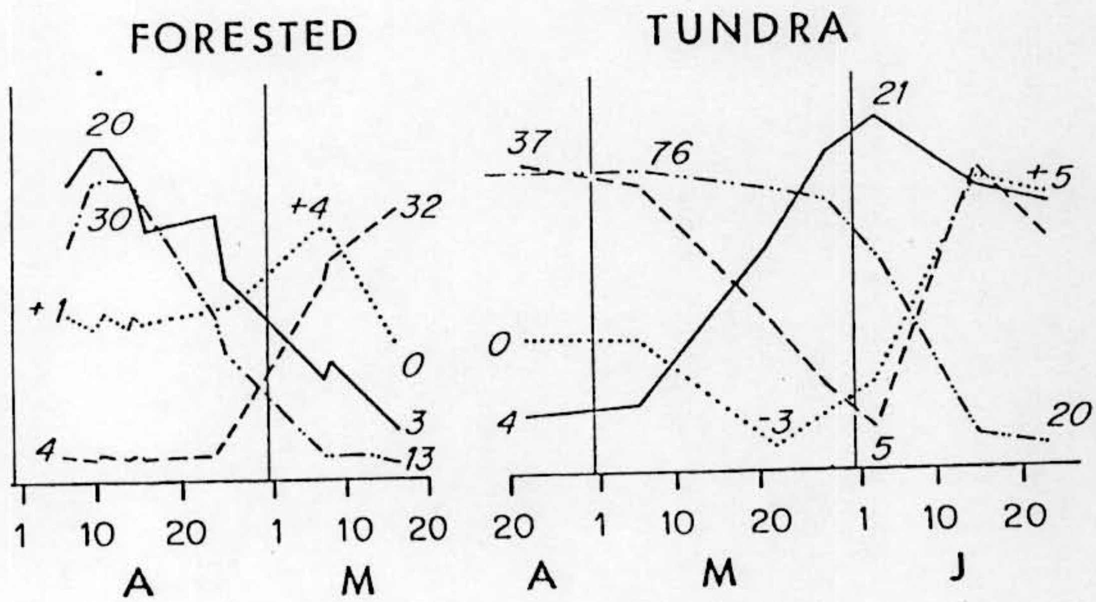


Figure 7. Response of brightness histogram standard deviation (———), skewness (.......), kurtosis (- - - -) and surface albedo (-..-..) to snow melt in forest and tundra areas of Alaska in the springs of 1981 and 1980, respectively. Horizontal scale shows dates between April 1 and June 23. (from Robinson and Kukla, 1982)

Conclusions:

Accurate representation of snow cover and its impact on surface albedo is important for the realistic performance of climate models used to project climate perturbations due to increasing levels of CO_2. Continued monitoring of snow melt is needed, as model results to date indicate that the initial signs of a CO_2 climate impact may be recognized in the marginal cryosphere. Shortwave satellite imagery is the most accurate means of obtaining this data on regional to continental scales, particularly if it is analysed in an interactive manner on an image processor by an observer familiar with the studied area.

References:

Robinson, D.A. (1984) Anthropogenic Impact On Winter Surface Albedo. Doctoral thesis, Columbia Universtiy, 384pp.

Robinson, D.A.; Kukla, G. (1982) Remotely sensed characteristics of snow covered lands. in: (Keydel, W., ed.) 1982 IEEE International Geoscience and Remote Sensing Symposium Digest, WA-1, 2.1-2.9.

Robinson, D.A.; Kukla, G. (1984) Albedo of a dissipating snow cover. Journal of Climate and Applied Meteorology, 23, 1626-1634.

Robinson, D.A.; Kukla, G. (1985) Maximum surface albedo of seasonally snow-covered lands in the Northern Hemisphere. Journal of Climate and Applied Meteorology, 24, 402-411.