retreated into the glacier valley the melt-water from the Kluane Glacier would have taken the easier route across the ablation drift at the confluence of the two valleys. The complexity of the network of river channels indicates a number of periods of formation which may have been due to fluctuations of the Donjek Glacier terminus. Drainage changes have occurred over the last 35 years with periods of surge and ablation of the Donjek Glacier and it is thought that similar late Hypsithermal fluctuations may have been responsible for the formation of the gorges.

It is considered that there is evidence for a stable phase of the Donjek and Kluane Glaciers late in the Hypsithermal period. This position is down valley of the Neoglacial maximum position which contrasts with the documented situation in the Kaskawulsh Valley. Late in the Hypsithermal the glaciers retreated from this stable position, the Kluane Glacier retreating to a Neoglacial position 15 miles up valley and the Donjek Glacier apparently retreating only a short distance before readvancing to its Neoglacial maximum position.

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REFERENCES

[1]Denton, G. H. and M. Stuiver. 1966. Neoglacial chronology, northeastern St. Elias Mountains, Canada. *American Journal of Science,* 264(3): 577-99.

[2]Sharp, R. P. 1951. Glacial history of Wolf Creek, St. Elias Range, Canada. *Journal of Geology,* 59: 97-115.

[3]Krinsley, D. B. 1965. Pleistocene geology of S.W. Yukon Territory, Canada. *Journal of Glaciology,* 5: 385-97.

[4]Borns, H. W. and R. F. Goldthwait. 1966. Late Pleistocene fluctuations of Kaskawulsh Glacier, south-west Yukon Territory. *American Journal of Science,* 8: 600-19.

[5]Denton, G. H. and M. Stuiver. 1967. Late Pleistocene glacial stratigraphy and chronology, north-eastern St. Elias Mountains, Yukon Territory, Canada. *Bulletin of the Geological Society of America,* 78(4): 485-570.

[6]Muller, J. E. 1967. Kluane Lake map-area, Yukon Territory. *Geological Survey of Canada, Memoir* 340, pp. 137.

[7]Rampton, V. N. 1969. Pleistocene geology of the Snag-Klutlan area south-western Yukon, Canada. Ph.D. Thesis. Faculty of Graduate School, University of Minnesota. 237 pp.

[8]———. 1970. Neoglacial fluctuations of the Natazhat and Klutlan Glaciers, Yukon Territory, Canada. *Canadian Journal of Earth Science,* 7(5): 1236-63.

[9]Bostock, H. S. 1952. Geology of northwest Shakwak Valley, Yukon Territory, Canada. *Geological Survey of Canada, Memoir* 267, pp. 54.

[10]Fahnestock, R. K. 1969. *Morphology of the Slims River. Icefield Ranges Research Project. Scientific Results,* 1: 161-72.

[11]Lerbekmo, J. F. and F. A. Campbell. 1969. Distribution composition and source of the White River ash, Yukon Territory. *Canadian Journal of Earth Science,* 6(1): 109-16.

The Simulation of Subsurface Effects on the Diurnal Surface Thermal Regime in Cold Regions

BACKGROUND

Layered substrate materials are common in nature; these include naturally stratified soils, ice and snow. In addition solar radiation penetrates the surface and produces subsurface heating in snow and ice terrain. The stratification problem has been treated by numerous authors as variation of the periodic heat flow problem using surface temperature as the forcing function[1,2]. Maykut and Untersteiner[3] have also treated the problem of radiation penetration in their thermodynamic model of arctic sea ice.

In recent years there has been a considerable interest in the possibility of acquiring surface environmental information using the spatial variance in the phase and amplitude of the diurnal surface thermal regime as an indicator. The most promising data acquisition system for such an undertaking is the thermal mapping of terrain from stiff-winged aircraft at several intervals during the diurnal cycle. This type of information and its analysis have been selected as a priority area for the application of remote sensing technology[4].

THE PROBLEM

Surface travel velocity in cold regions is largely dictated by phase transitions in near surface water and the depth to which these transitions have extended during the warm season of the year. A major site factor in the location of arctic buildings, pipelines, roadways and airfields is the substrate environment and the distribution of large masses of ground ice which are relatively free of mineral soil. Under certain conditions several tens of metres of relatively pure ice may underlie surface materials which in no way appear radically different from the surrounding terrain or similar features. Two extreme examples are the massive segregation ice beds of the western Canadian Arctic coast[5] and ice-cored rock glaciers[6].

THE LAYERED-SUBSTRATE SURFACE CLIMATE SIMULATOR

As an extension of earlier research on the simulation of needle ice growth and ablation at Vancouver, British Columbia, a surface climate simulator based on equilibrium temperature theory has been improved to handle the variation of substrate thermal properties with depth and the penetration of solar radiation in the case of ice and snow cover. The layered model employs an iterative solution of the Fickian diffusion equation over equally spaced grid points. The spacing of the grid points is determined by the layer having the largest value of thermal diffusivity using the numerical stability criteria discussed by Kreith[7]. The penetration of solar radiation, in the snow and ice case, and the estimation of resultant subsurface heating effects follows the treatment by Maykut and Untersteiner[3]. Each grid point in the one-dimensional model is assigned thermal properties determined by the substrate stratigraphy. A description of the development of the general simulator and its application is already in the literature[8,9]. This treatment provides numerical stability when the computation depth is terminated at an isothermal layer or level due to phase change (active layer, lake-sea ice) at depths less than the diurnal damping depth of the substrate composite. Two examples of possible applications follow.

THE ACTIVE LAYER SIMULATION

The effect of increasing active layer depth on the surface thermal regime was simulated for a western Canadian coastal location at 69° 30′ N., under clear summer solstice conditions. The area was assumed to be homogeneously covered with a 10 cm. deep layer of wet peat above sandy gravel. The depth of the active layer was varied from 10 to 20 cm., 30 cm., and 40 cm. beneath wet peat surface by setting the temperature at 0°C. at all grid points below this level for all iterations. The results of that simulation are presented in Fig. 1. Note that the maximum contrast occurs during the period of low sun and that the contrast rapidly decreases with active layer depth. The same pattern was noted earlier in an investigation of the thermal influence of a rock glacier ice core[10].

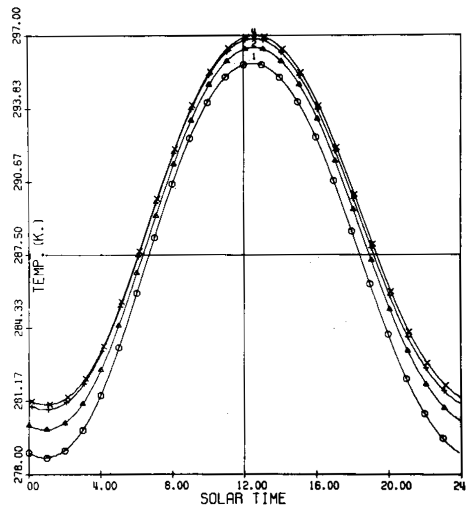

FIG. 1. Surface thermal response; stratigraphy: 10 cm. wet peat above sandy gravel; 1) Active layer depth 10 cm.; 2) Active layer depth 20 cm.; 3) Active layer depth 30 cm.; 4) Active layer depth 40 cm.

LAKE ICE DEPTH SIMULATION

The effect of increasing lake ice depth was also simulated with surface radiation penetration for a Great Lakes location at 50° N. under clear winter solstice conditions. Thirty per cent of the absorbed solar radiation was assumed to penetrate the surface and the pure ice depth was varied from 140 to 70 cm. and 35 cm. by setting all temperatures in the substrate grid at the ice point as above. In addition one run was made with the following stratigraphy to explore the effects of stratified snow cover: 0 to 5 cm. fresh snow, 5 to 15 cm. packed drift and 15 to 160 cm. lake ice. The surface thermal responses are presented in Fig. 2.

Note the wide variance in mean diurnal temperature produced by the decreasing depth of pure lake ice and the influence of snow cover and its large distortion of both the mean surface temperature and the phase and amplitude relationships in comparison with the deep pure ice case.

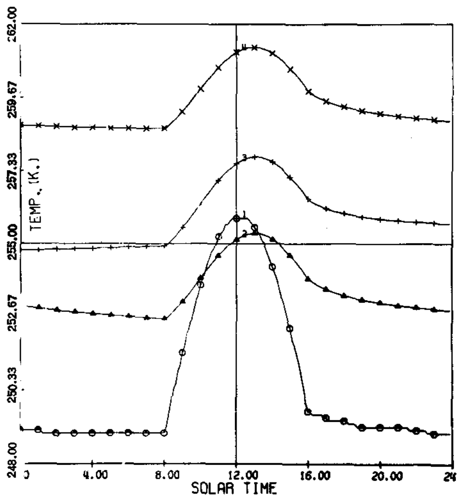

FIG. 2. Surface thermal response to lake ice depth; 1) Stratigraphy: 0-5 cm. fresh snow, 5-15 cm. packed drift, 15-160 cm. lake ice; 2) Pure lake ice depth 140 cm.; 3) Pure lake ice depth 70 cm.; 4) Pure lake ice depth 35 cm.

SUMMARY AND CONCLUSION

It would appear that melting rock glacier ice cores, massive ground ice and active layer depth variations contribute significantly to the surface thermal regime variance when these features are relatively close to the surface. It would however appear that lake and sea ice depth variations with either spatially homogeneous light snow cover or none should be detectable particularly where there are large depth variations.

Whereas surface climate simulation presents an explicit method of estimating the influence of a wide range of surface environmental factors, specifically albedo, emissivity, substrate radiation extinction (ice and snow), roughness, wetness, stratified thermal properties, slope and exposure, the method would appear to be extremely valuable in the experimental design and hypothesis formation phases of thermal mapping investigations in cold regions. Furthermore as the strategy can be employed to estimate the sensitivity of the surface thermal response to individual environmental factors the method dictates the ground truth requirements for exploratory investigations. Lastly as process and environmental information becomes available the strategy can be used to construct explicit deterministic physical models of the spatial and temporal variance of surface thermal response which can be employed as an analytical portion of a remote sensing reconnaissance system specific to trafficability and site studies in arctic and alpine environments. In short, the capacity for modelling the surface thermal response as a function of the surface and substrate environment vastly increases the accessible information content of thermal infrared maps particularly where these are acquired at several times during the diurnal cycle.

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REFERENCES

[1]Van Wijk, W. R. and W. J. Derksen. 1966. Sinusoidal temperature variation in a layeral soil. In: *The physics of plant environment*. Amsterdam: North-Holland Publishing Co. 382 pp.

[2]Lachenbruch, A. H. 1959. Periodic heat flow in a stratified medium with application to permafrost problems. *U.S. Geological Survey Bulletin* 1083-A, 36 pp.

[3]Maykut, G. A. and N. Untersteiner. 1971. Some results from a time dependent thermodynamic model of sea ice. *Journal of Geophysical Research,* 76(6): 1550-75.

[4]Holter, M. R. *et al.* 1970. Research needs: The influence of discrimination, data processing, and system design. In: *Remote Sensing.* Committee on Remote Sensing for Agricultural Purposes. Agricultural Board. Washington, D.C.: National Research Council, National Academy of Sciences, pp. 354-421.

[5]Mackay, J. R. 1971. The origin of massive icy beds in permafrost, western arctic coast, Canada. *Canadian Journal of Earth Sciences,* 8(4): 387-422.

[6]Outcalt, S. I. and J. B. Benedict. 1965. Photo-interpretation of two types of rock glaciers in the Colorado Front Range, U.S.A. *Journal of Glaciology,* 5(42): 849-36.

[7]Kreith, F. 1967. *Principles of heat transfer.* Scranton, Pa.: International Textbook Co., pp. 175-88.

[8]Outcalt, S. I. 1971. A numerical surface climate simulator. *Geographical Analysis,* 3(4): 379-92.

[9]Outcalt, S. I. 1971. The climatonomy of a needle ice event. *Archiv für Meteorologie Geophysik und Bioklimatologie,* Series B, 19: 325-30.

[10]Outcalt, S. I. 1972. The development and application of a simple digital surface climate simulator. *Journal of Applied Meteorology.* 11(4): 629-36.