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The Simulation of Diurnal Surface Thermal Contrast in Sea Ice and Tundra Terrain

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With 3 Figures

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Summary

A simple surface climate simulator has the capacity to model the thermal contrast produced by stratification, variable sea ice or active layer thickness and albedo in the environment of the Alaskan North Slope. These simulations form the background for modeling the probable effects of terrain modifications produced by Arctic construction. This strategy should allow investigators to estimate the most appropriate times for the discrimination of specific targets using thermal imagery as a prospecting medium and facilitate the interpretation of existing imagery. Lastly, the scheme allows investigators of surface modification effects to select probable subsets of processes for field evaluation by examining the sensitivity of the thermal response to variations of the input properties over their anticipated ranges in conjunction with estimates of the local meteorological environment. This sequence can also be used to test the physical validity of process arguments used in the interpretation of thermal contrast in reconnaissance imagery.

Zusammenfassung

Simulation des täglichen thermischen Oberflächenkontrastes im Meereis und im Tundragelände

Ein einfaches Modell des Bodenklimas besitzt die Fähigkeit, den thermischen Kontrast, der durch Stratifikation, variable Eisbedeckung oder aktive Schichtdecke und Albedo in der Umgebung des Nordhanges Alaskas hervorgerufen wird, abzubilden. Die Modellrechnungen bilden die Basis für eine Abschätzung des Effektes von Veränderungen des Geländes im Zusammenhang mit Bauarbeiten in der Arktis. Mit diesem Modell sollte es auch möglich sein, die günstigsten Zeiten für die unterschiedliche Behandlung spezifischer Zielgebiete unter Anwendung von Temperaturabbildungen als Aufschließungsmittel ausfindig zu machen und die Interpretation der bestehenden Temperaturabbildungen zu erleichtern. Letzten Endes erlaubt das Modell, auf Grund einer Untersuchung der Empfindlichkeit der thermischen Reaktion auf Änderungen der Anfangsbedingungen in ihrem möglichen Variationsbereich im Zusammenhang mit den örtlichen meteorologischen Bedingungen die Auswahl von Teilprozessen bei der Untersuchung von Auswirkungen der Veränderungen der Oberflächenschicht des Bodens. Mittels dieses Modells kann auch die physikalische Richtigkeit verschiedener Argumente geprüft werden, die in der Interpretation von Temperaturunterschieden, welche bei Gebietsuntersuchungen auftreten, angewendet werden.

1. Introduction

Horvath and Lowe [3] and Horvath and Brown [2] have analyzed multispectral imagery of sea ice and snow covered tundra acquired near Point Barrow, Alaska. Their work includes an analysis of thermal plumes downwind from unheated buildings and documents apparent temperature contrasts between targets with highly variable substrate conditions (e. g. snow covered tundra, lake ice and varied ages of sea ice) under autumn conditions (October 16, 1967).

This author and his students have developed a simple digital computer model to simulate diurnal surface and substrate thermal regime contrasts between sites with varied thermal and optical properties [6, 7, 8]. The multispectral survey materials provided an interesting data bank for simulation although the site stratigraphic data was extremely generalized and some material properties had to be estimated from the published literature. It is the purpose of this paper to review these simulation tests and discuss some of the implications of that task.

2. The Simulator

The numerical model used in these simulations is described in detail in the current literature [8]. Essentially the scheme is to specify the thermal structure of stratified materials down to the diurnal damping depth and to simulate the turbulent fluxes into the atmosphere by means of a simple exchange coefficient based on the surface roughness length and wind speed. This coefficient is later corrected for atmospheric stability. The model is forced by a subroutine which generates "clear weather" solar radiation information based on absorption and scattering coefficients calculated from empirical formulas. The atmospheric properties are assumed to be representative of a "free air condition" at a level above the surface which best satisfies the requirements of the bulk atmospheric diffusivity used to calculate turbulent flux and the depth of penetration of a diurnal thermal disturbance with that diffusivity.

When all the atmospheric and substrate thermal information is specified a search is made for the surface temperature which will satisfy the energy conservation equation. An interval-halving algorithm is employed in this search. When the absolute error in the energy conservation equation is less than 1 mly/min the surface-soil and energy transfer component matrix for that iteration is retained and the soil thermal structure is specified for the next iterative step by means of a finite difference solution to the soil thermal diffusion equation using a one dimensional vector of nodes. The spacing of nodes depends upon the time step magnitude due to the requirements imposed by the stability modulus (e. g. with a 15 minute time step the internode spacing is 5 cm). The model permits the specification of stratigraphic thermal properties, the penetration and absorption of solar radiation in the substrate as well as the influence of isothermal levels or layers in the substrate (e. g. the base of the active layer or sea ice).

3. Target Analysis

The environmental data employed by the simulator consists of a common set of meteorological data and site specific materials information. The common set is listed in Tab. 1.

Table 1. *Meteorological Common Data**

Latitude = 71.3° N	Air Temp. = −14° C
Date = October 16	Air Relative Humidity = 95%
Station Pressure = 1013 mb	Wind Velocity = 3 m/sec
Precipitable Water = 6 mm	Sky Radiant Temp. = −30° C
Atm. Dust Content = 0.2 Particles/cc	

* Approximations aided by Horvath's field notes.

Further, it was necessary to make the following uniform assumptions concerning thermal and radiation properties of the target materials.

In the cases of lake ice and refreezing tundra soil the fusion temperature at the base of the freezing layer was assumed to be 0° C whereas a fusion temperature of —2° C was assumed at the base of sea ice. The aerodynamic roughness length was assumed to be 1 cm for all targets as there was no substantive data available for ranging these values. The target solar albedo was derived from the multispectral data and the site stratigraphy estimated from the observers notes and sea ice age classification criteria. Thus, the simulated target thermal contrasts are constrained as functions of multispectral sampled albedo and stratigraphy. These values are listed in Tab. 3.

Table 2. *Assumed Thermal-Optical Property Values**

Material	Thermal Diffusivity (c. g. s.)	Vol. Heat Cap. (c. g. s.)	Extinction Coeff. (c. g. s.)
Packed Drifted Snow	0.038	0.16	0.1
Sea Ice	0.012	0.44	0.015
Lake Ice	0.012	0.44	0.015
Frozen Soil	0.012	0.50	—

* Ref. [1, 4, 5] and others

Table 3. *Target Data*

Target	Stratigraphy (cm)	Albedo
Tundra	0—10 Packed Drift 10—60 Frozen Soil 60 Freezing Plane (0° C)	0.60
Lake	0—10 Packed Drift 10—15 Lake Ice 15 Fresh Water (0° C)	0.62
Sea Ice-Age 3	0—5 Packed Drift 5—15 Sea Ice 15 Sea Water (−2° C)	0.42
Sea Ice-Age 4	0—10 Packed Drift 10—30 Sea Ice 30 Sea Water (−2° C)	0.50
Sea Ice-Age 5	0—10 Packed Drift 10—70 Sea Ice 70 Sea Water (−2° C)	0.72
Sea Ice-Polar Flow	0—10 Packed Drift 10—210 Sea Ice 210 Sea Water (−2° C)	0.78

Recall that the target surface thermal response contrast in the simulation is only a function of variation in the stratigraphy and solar albedo's listed in Tab. 3. The simulated surface thermal contrast between the Snow Covered Tundra Surface and a Fresh Water Thaw Lake is presented as Fig. 1 and the regimes of the four classes of sea ice are presented in Fig. 2. The results of the simulation are compared to data abstracted from Horvath and Brown ([2], Fig. 16) in Tab. 4.

Table 4. *Apparent Target Temperature-Simulation Comparison (1300—1400 AST., October 16, 1967)*

Target	Mean app. temp. (^{0} C)	Number of samples	Range	Simulation temp. (^{0} C)	Diff. (^{0} C)
Tundra	−15.5 (4.5)	8	−16.8 to −14.5	−15.2 (4)	−0.3
Lake Ice	−14.0 (3)	5	−13.5 to −14.5	−14.5 (3)	+0.5
Sea Ice 3	−12.5 (1)	5	−13.0 to −11.5	−13.7 (1)*	+1.2
Sea Ice 4	−13.5 (2)	10	−15.0 to −11.5	−14.3 (2)	+0.8
Sea Ice 5	−15.5 (4.5)	1	—	−15.5 (5)	0.0
Polar Flow	−17.0 (6)	1	—	−15.8 (6)	−1.2

( ) Thermal rank   * outside range

The largest absolute discrepancy is 1.2^{0}C when compared to the imagery of 27 % or the total apparent temperature range in the targets. However, the thermal ranks of *all* simulated targets match

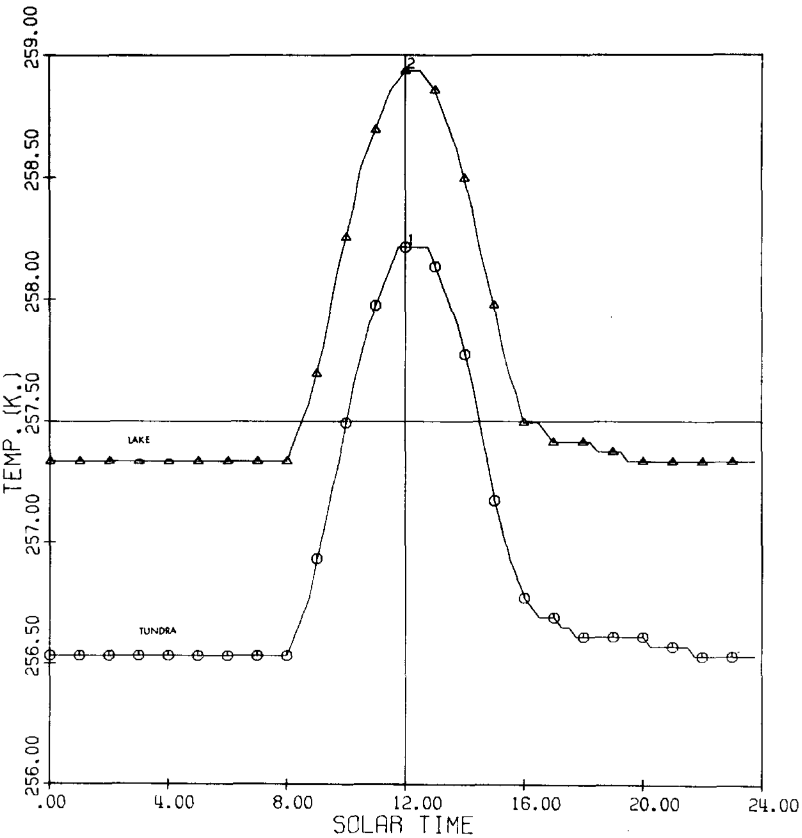

Fig. 1. The simulated thermal regimes of snowcovered Tundra and Thaw Lakes

the imagery and in $^3/_4$ of the cases of multiple samples the simulations are not outside the range of the set. If these results suggest that the simulator is "reasonably mimicking nature" then the simulator with reasonable input data may be employed as a tool for estimating specific types of environmental impact due to surface modification in cold regions.

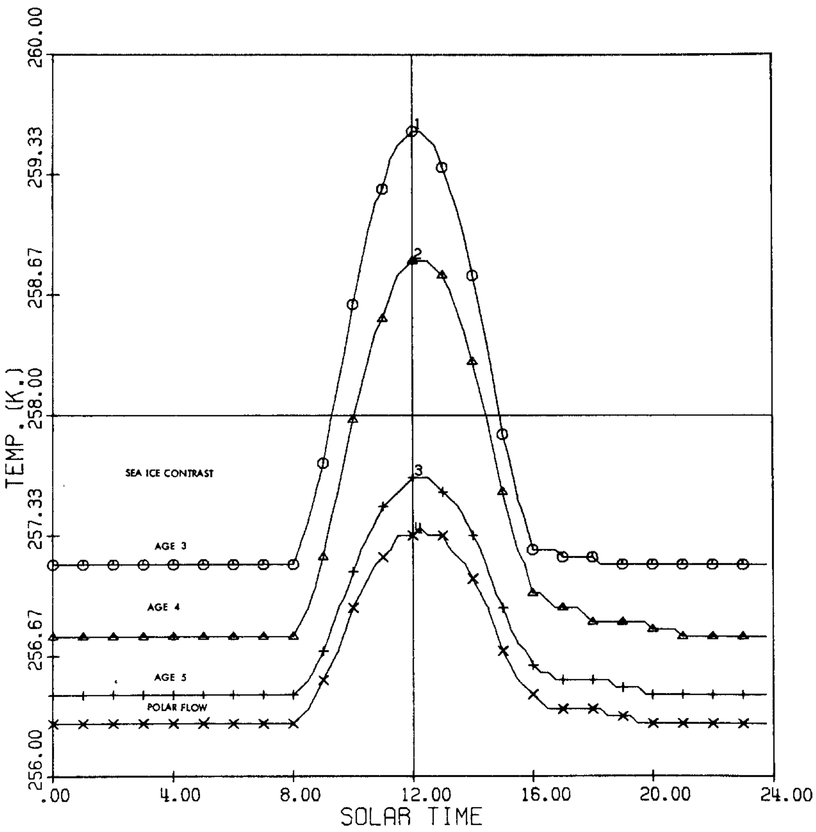

Fig. 2. The simulated thermal regimes of four classes of sea ice

4. Thermal Modification in Lee of Construction Sites

In an earlier article this author indicated that the winter environment of the north slope was ideal for producing surface contrast due to above ground construction [9]. The imagery analyzed by Horvath and Lowe [3] exhibited a warmed area of the snow surface extending 250 meters downwind from unheated buildings and oil drum dumps. This effect was simulated and this author finds Horvath and Lowe's [3] analysis which suggests an "increase in the con-

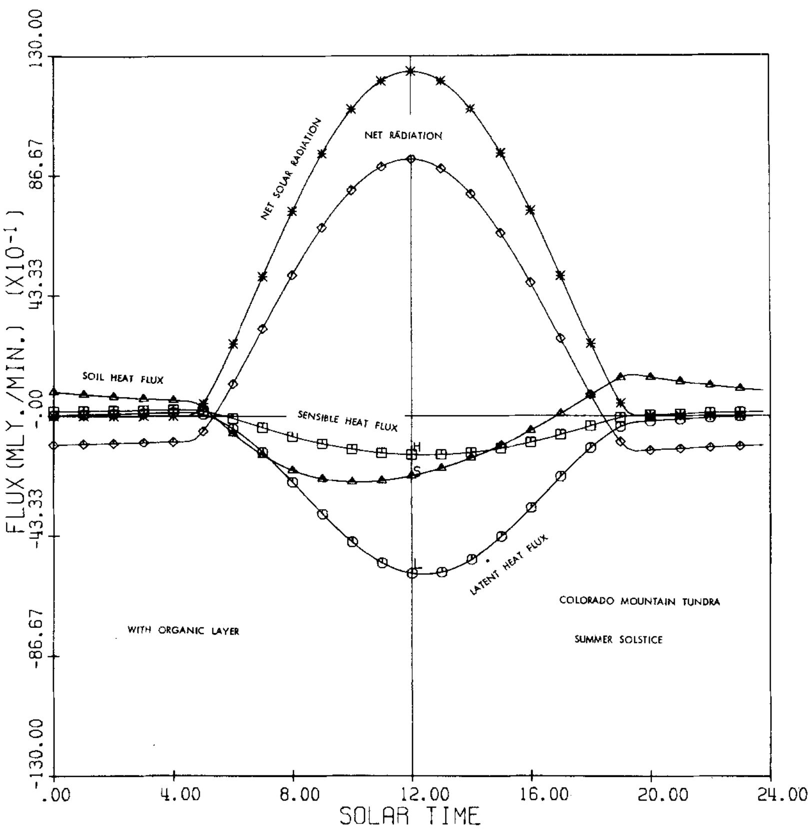

Fig. 3a

Fig. 3. The energy-budget and thermal regime dislocations produced by the removal of a 10 cm organic layer from the surface of Mountain Tundra.

a) With organic layer, b) removed organic layer, c) comparison between the thermal regime with organic layer and removed organic layer

vective heat transfer coefficient which thermally couples the air to the tundra surface" due to increased surface roughness physically reasonable in terms of the environmental conditions observed and heat transfer theory as the effect is duplicated by simulation. Preliminary trail calculations using an annual surface climate simulator developed by Mr. Cecil Goodwin indicates that the active layer depth would be reduced approximately 50 % if a plume effect existed throughout an annual cycle.

5. Estimating the Probable Impact of Organic Layer Removal

Fig. 3 examines the probable impact on the energy regime of mountain tundra due to the removal of an organic surface layer *only*. Note, the dramatic effects on the phase and amplitude of the energy budget components and the surface thermal regime. It is also of value to note that with the removal of the organic layer more heat is transfered into and retained in the soil at depth. An examination of the thermal contrast graph demonstrates that shortly before sunset the presence of an organic layer would not be detectable.

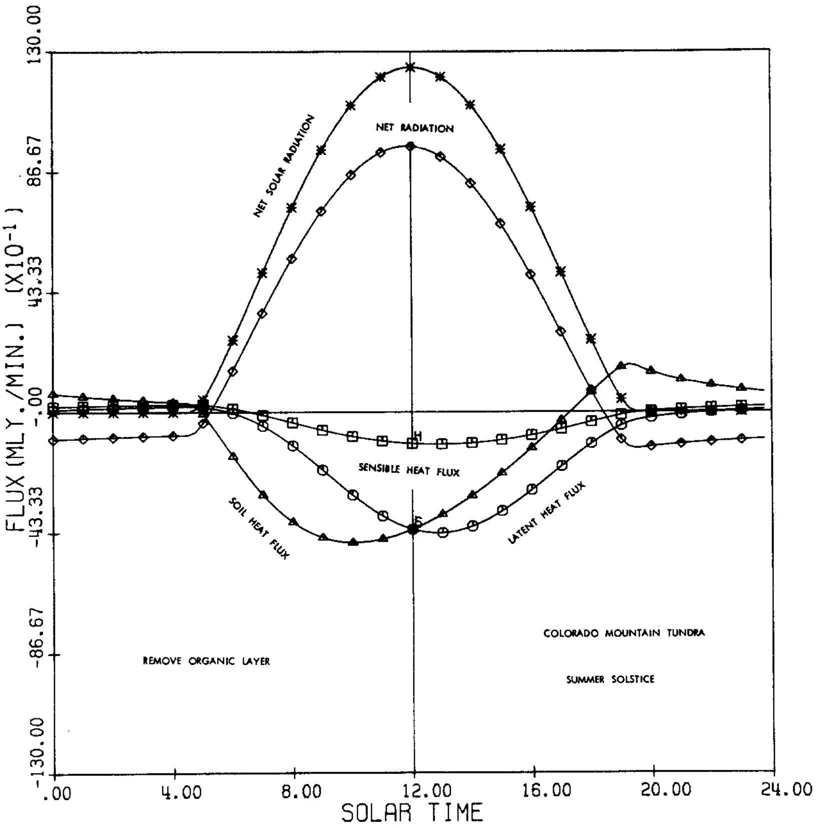

Fig. 3b

6. Conclusions

This work demonstrates that surface thermal contrast can be simulated and suggests that simulation may be a viable strategy in planning and analysis thermal mapping projects with specific goals as well as a method for focusing impact investigations on a probable set of physically reasonable mechanisms.

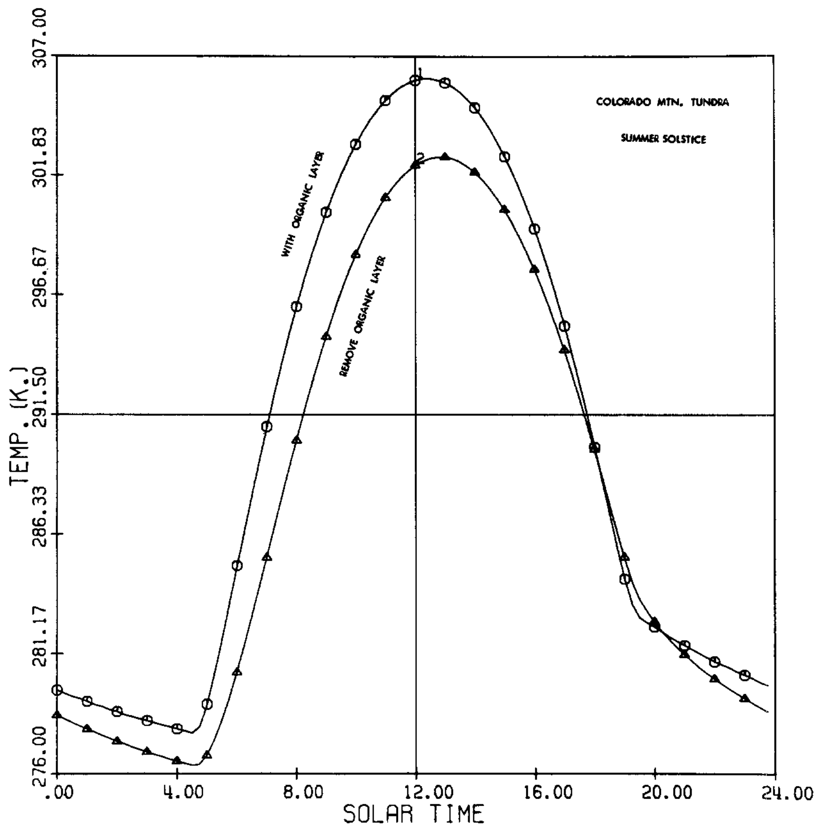

Fig. 3c

Lastly, the work strongly implies that thermal plume effects may be significant in some smooth arctic tundra terrain and that the effect should be investigated in considerable detail as a possible impact of arctic construction.

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