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***One-Dimensional Temperature
Modeling Techniques
Review and Recommendations***

Lee K. Balick, John R. Hummel,
James A. Smith and Daniel S. Kimes

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SWOE Report 90-1
August 1990

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PREFACE

This report was prepared by Dr. Lee K. Balick of EG&G Energy Measurements, Inc., Las Vegas, Nevada; Dr. John R. Hummel of SPARTA, Inc., Lexington, Massachusetts; and Dr. James A. Smith and Dr. Daniel S. Kimes of the NASA Goddard Space Flight Center, Greenbelt, Maryland.

EG&G Energy Measurements, Inc., performed a portion of this work for the United States Department of Defense through an EAO transfer of funds to contract DE-AC08-88NV10617 with the United States Department of Energy. SPARTA, Inc., was funded through contract F19628-88-C-0038.

This report was commissioned by the Balanced Technology Initiative (BTI) Smart Weapons Operability Enhancement (SWOE) Program Management Office to provide an independent review of computer models suitable for estimating surface temperatures of thermal infrared background components for image simulation. Recommendations of specific models for use in SWOE, an assessment of current capabilities and identification of deficiencies are derived from the review.

The BTI/SWOE Program Director is Dr. L.E. Link, Technical Director of the U.S. Army Cold Region Research and Engineering Laboratory (CRREL) and the Program Manager is Dr. J.P. Welsh, also at CRREL. The Technical Area Manager for the Modeling task area of BTI/SWOE is LTC George G. Koenig of the USAF Geophysics Laboratory (GL), Air Force Systems Command. Dr. Lee K. Balick is the review panel leader. Other participants are Dr. John R. Hummel, Dr. James A. Smith and Dr. Daniel S. Kimes.

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One-Dimensional Temperature Modeling Techniques

Review and Recommendations

LEE K. BALICK, JOHN R. HUMMEL, JAMES A. SMITH AND DANIEL S. KIMES

I. INTRODUCTION

Background

One of the primary objectives of the Balanced Technology Initiative (BTI) Smart Weapons Operability Enhancement (SWOE) program is the simulation of complex thermal infrared background images to support designers and users of smart weapons systems. Emphasis is placed on physically realistic simulation of environmental effects on these images using "first-principles" models whenever possible. In first-principles models, the individual physical processes that influence the radiance are explicitly treated with a minimal reliance on empirical or parametric formulations or analogs. This results in the greatest generality of the models so that a wide array of conditions and effects can be realistically simulated. Since image simulations are expected at a spatial resolution on the order of a meter, a capability to simulate the temperatures for a wide variety of materials and geometries is desired. A complete treatment of the temperature prediction problem requires a full three-dimensional description of energy and mass transfers—a capability not yet available for complex backgrounds. On the other hand, point models of terrain temperatures, which assume horizontal homogeneity, have been used to predict thermal background temperatures by a number of organizations for over 15 years. This base of experience is intended to serve as a starting point for temperature modeling in the SWOE program.

An independent review of existing one-dimensional temperature models was commissioned by the SWOE Program Office at the beginning of the program. The purpose was to provide early guidance for the establishment of an integrated capability to model background surface temperatures. The domain of consideration is limited to one-dimensional surface temperature models (horizontally homogeneous with time variability included) that are currently available and appropriate for operational use. The SWOE program assumes evolu-

tion. Inclusion of new capabilities and changes in one-dimensional modeling are expected and, ultimately, a full three-dimensional capability will be developed. The task here is envisioned as providing recommendations for the construction of a firm foundation with existing, proven capabilities of models.

Objectives and scope

The broad objective of this work is to recommend one-dimensional background surface temperature modeling techniques for implementation in SWOE. Specific objectives are the following:

1. Identify and review existing models useful for SWOE and determine current capabilities in 1-D temperature modeling.
2. Recommend modeling techniques for use in the early phases of SWOE.
3. Identify deficiencies and recommend research and development priorities.

This review is focused on one-dimensional models judged appropriate for thermal infrared background image modeling. The range of models considered was determined by discussions and meetings with the Program Manager, Technical Area Managers (TAMs) and their staff. Recommendations are based on these interactions, tempered by what techniques are currently available and our expectations for future developments.

An overview of one-dimensional background surface temperature modeling is presented in Part II. It describes the physical processes involved and the modeling techniques commonly used to simulate them. Specific evaluation criteria are presented in Part III. These consist of an outline to direct attention to model technical features as well as practical aspects of integration and use in the SWOE program. Technical capabilities of groups of models are presented along with a description of major assumptions and limitations. Recommendations for priorities on model development outside SWOE are given based on estimates of their importance and scientific tractability. Part IV contains

specific recommendations for initial 1-D temperature model implementation in SWOE. Reasonable alternatives and rationale for selection are discussed. Recommendations are given for each of several background types where treatments of energy fluxes through the materials are sufficiently different to require separate modeling. Part V is a summary of this report, and Appendix A is an annotated list of the final set of models considered. Appendix B contains a list of models initially examined but not given further examination and a statement about why that decision was made.

II. OVERVIEW OF SURFACE TEMPERATURE MODELING

First-principles surface temperature models evaluate energy fluxes at the interface between the atmosphere and the background material and also within the materials when heat storage is important. (The term *surface temperature* in this report means the physical temperature of a surface or an ensemble of surfaces of the background material at its interface with the atmosphere.) Energy can be exchanged between the surface and the atmosphere or between the surface and the interior of the material. The overall process is evaluated as an energy budget that is the sum of individual energy flux densities (energy per unit area) that sum to zero as follows:

$$S + R_{\text{down}} + R_{\text{up}} + H + L + G = 0$$

where S = the solar irradiance absorbed
 $R_{\text{down}}, R_{\text{up}}$ = the downward and upward thermal infrared flux densities absorbed and emitted
 H = sensible heat flux density
 L = latent heat flux density
 G = energy conducted to or from the surface.

The material's surface temperature is found by a numerical scheme that satisfies the above equality. Terms are discussed individually below. Individual components are either measured and input as data or simulated with a submodel of the appropriate process. A diagram of the energy budget and its individual components is given in Figure 1 for a simple case—a flat, smooth solid material with two layers of materials. (This might be a parking lot with asphalt on soil, for example.)

One of the most dynamic components of the energy budget is solar irradiance or insolation S . A portion of insolation is absorbed at the surface and a portion is

reflected: it is only the absorbed energy that affects surface temperature. Insolation has both a direct beam S_{dir} and a diffuse component S_{diff} . These quantities should be separated to account for changes of insolation with surface slope and insolation in shadows. The proportion of energy absorbed changes with directional characteristics of irradiance, mostly with sun elevation. This effect is often neglected because the biggest changes for horizontal surfaces occur when the magnitude is small for most surface types. Insolation is also affected by absorption and scattering along its path through the atmosphere. Clouds reduce the spatially averaged insolation at the surface but can increase energy locally by reflection from/between clouds and the surface. Solar energy reflected from nearby objects can be significant. Although not explicitly included in strictly one-dimensional models, multidimensional effects of solar insolation can be treated (Weiss and Scoggins 1989).

Downwelling infrared radiation R_{down} is received from the atmosphere and consists of contributions from the atmospheric gases, particulates and clouds. In cloud-free conditions, most of the energy comes from the lowest few hundred meters and is dependent mostly on atmospheric temperature and humidity. The atmosphere is often assumed to be an isotropic source under these conditions. As with insolation, only the energy absorbed at the surface affects temperature, but the reflected energy can affect the total radiance leaving the surface toward the sensor. Objects occluding the sky, such as clouds, trees and buildings, generally radiate more energy than the sky. As with insolation, these multidimensional effects are not explicitly treated in one-dimensional models but they can be included in the energy budget (Weiss and Scoggins 1989).

The surface emits thermal infrared energy R_{up} in proportion to its temperature and gray body emissivity. This is the energy detected by passive infrared systems originating at the surface. For most natural backgrounds, emissivity has no strong directional properties. However, if the surface is not smooth, directional differences in emitted energy will exist. Most backgrounds have no sharp spectral features (significant exceptions exist for certain minerals) but significant differences in magnitude exist between commonly used remote sensing bands.

Convective, or mass, transport of sensible heat H and latent heat L occur through the net flux of air with different temperature and water vapor content along gradients between the surface and the atmosphere. The actual fluid dynamic processes are quite complex, but satisfactory computational procedures have been developed for simple horizontal surfaces. Convective fluxes are proportional to wind speed gradients in the atmospheric boundary layer as well as the temperature

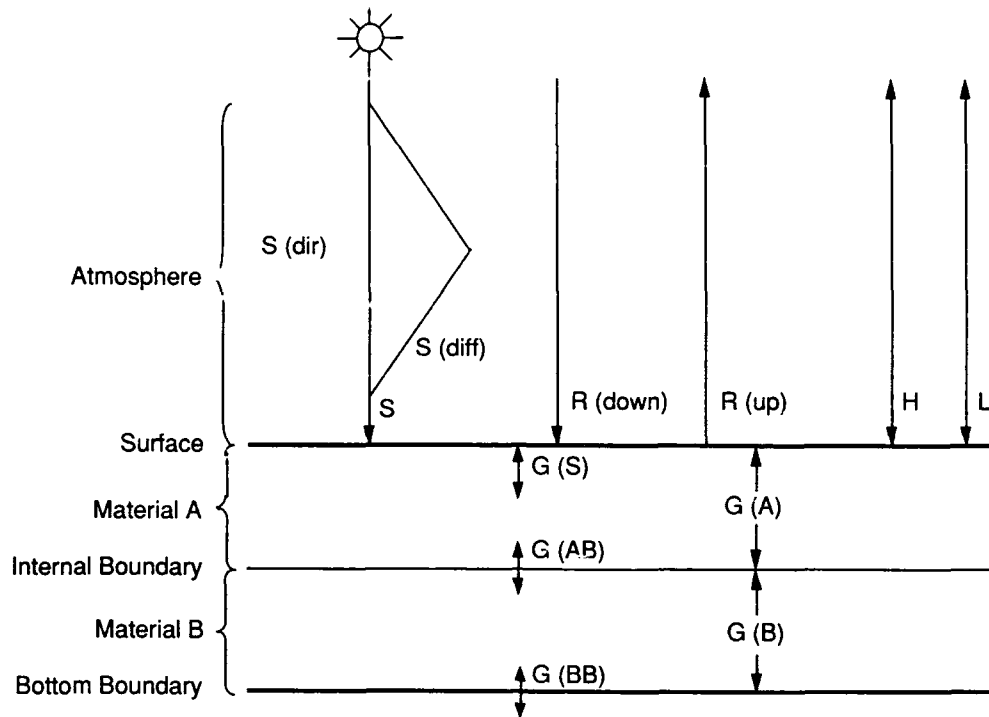


Figure 1. Diagram of energy budget for flat, smooth solid area with two layers of materials.

or humidity gradient. In one-dimensional models, all gradients are vertical. Normally, atmospheric values are measured at standard instrument heights above the ground.

Energy flux density in solids is by conduction and is proportional to the heat conductance of the solid and the temperature gradient between the surface and the interior of the solid, $G(S)$. Heat flux within the material is calculated with a numerical procedure, usually a finite-difference technique. In Figure 1, heat transfer by conduction occurs within material A, $G(A)$, within material B, $G(B)$, across an internal boundary between them, $G(AB)$ and at the bottom boundary $G(BB)$. The temperature gradient in a layer near the surface most strongly affects the short-term fluctuations of surface temperature. Energy that is conducted deeper into the solid is effectively stored and affects longer time fluctuations of the surface temperature. This is where the system's memory (dependence on antecedent conditions) is incorporated in the model.

Most of the energy budget components are computed separately but several of them interact strongly in the models through their dependence on surface temperature. The exceptions are insolation and downwelling thermal infrared, which are driven by atmospheric conditions. Strong feedbacks exist between the energy budget components that are functions of the surface temperature: conduction, sensible and latent heat and the infrared energy emitted at the surface. For example, everything

else remaining constant, increasing the heat conductivity of a soil (at noon) has the result of not only increasing the conduction of heat away from the surface but also of reducing sensible and latent heat fluxes as well as the energy emitted by the surface. More heat is lost from the surface by conduction but less heat is lost to the atmosphere, thus reducing the net effect on surface temperature.

One-dimensional models assume horizontal homogeneity of materials and the environment. There is no horizontal heat flux in the background materials at boundaries between material types, or advective changes as air moves from one surface to another (it is not modified by interactions with the surface), and incoming radiant energy is assumed to be spatially uniform. This has been a workable assumption for mostly flat backgrounds when the field of view of the sky is unobstructed and it is clear or overcast. Simplistic modifications to the radiant energy components have been proposed to account for some effects of nearby objects.

Most background materials are not flat, smooth or solid. This creates complications in processes that need to be modeled as well as the inputs needed to operate a model. Within porous solids, such as sand or gravel, heat transport can also occur through mass diffusion, particularly if the porous materials are moist. Snow is a material that often contains air as well as the solid, liquid and gaseous states of water that change phase. As a result, energy flux processes within snow are very

complex. Water bodies can transfer heat through mixing. There are rapid changes of reflectance with sun angle, and solar energy is absorbed through a depth of water near the surface rather than at the surface. Vegetation presents a fuzzy interface between the air and the ground, and the idealized surface is a useful concept for only a limited range of conditions. Vegetation canopies consist of a volume of plant constituents with different thermal properties and orientations, in addition to those of the ground, and can be viewed as an ensemble of many different temperatures. Norman (1989) has shown that the effective emissivity of canopies can also change with view angle and that both the magnitude and direction of change depend on sun and canopy geometry. Other complications arise because of the wide array of vegetation types in thermal images: trees are not like grass, individual plants are not like canopies and biological processes can affect temperatures.

No model is general enough to simulate all material types. In fact, most models describe a fairly limited range of materials and rapidly become complicated with increasing generalization. Therefore, a battery of models that can be integrated under a common driver will be needed.

III. EVALUATION CRITERIA

Rationale

A major component of the review was the establishment of objective evaluation criteria. The only guidance given was that the models should be based on first principles, that the models be in the public domain, government owned or available under inexpensive license and that source code be available. These requirements, considered as more or less absolute, served as a filter for the models to be examined. With minor exceptions, all models considered for detailed review met these criteria. Time to obtain the model codes and compare them with test data was not available. Detailed process models exist that demand high levels of specialized expertise or input requirements that cannot be supported by SWOE. These models are not given detailed consideration.

Models were separated into categories of the type of background materials simulated. The divisions were arbitrary and subdividable, but were determined by major differences in the physical processes of heat flux within the materials. Most existing models simulate temperatures for only one of these categories: 1) solids, 2) water, 3) vegetation and 4) snow.

Additional attention was given to fresh and saltwater ice. Wide ranges of conditions exist within these categories, perhaps requiring more than one model in each

category. It should also be realized that these categories do not cover materials and conditions in the real world and that hybrid conditions exist.

Scientific evaluation

General and detailed criteria were established. General criteria were in the form of the following questions:

1. For what material(s) does the model simulate surface temperatures?
2. What is the degree of reliance on fundamental, rather than empirical or parametric, representation of processes?
3. Are the physical (and biological) processes and environmental factors correct for the background material?
4. Is the validation and sensitivity of the model established?
5. Are the input requirements and expertise required consistent with the SWOE operating environment?
6. Does the model have any extensions to account for the effects of nearby or imbedded objects?

Detailed evaluation addressed the appropriateness, completeness, advantages and unique features (if any) of the techniques used in the models. Techniques examined included those used to evaluate the individual energy budget terms, the numerical methods employed, and requirements for initializing the model. Although the comparison was performed model by model, we sought the best techniques available for each task. (Indeed, our recommendations extend beyond those techniques found in the models reviewed.) Recommendations will be presented for the topics in the following list (rather than model by model): 1) insolation, 2) downwelling longwave (thermal IR) energy, 3) upwelling longwave (thermal IR) energy, 4) convective atmospheric fluxes (sensible and latent heat), 5) heat conduction within the material, and 6) numerical methods.

Implementation and integration criteria

Appropriate scientific content of a model does not establish a model's utility for SWOE. The model must also be readily available for use in SWOE and for distribution within SWOE users. It must be adaptable to the anticipated SWOE software structure and understood by scientists and programmers. It is preferred that knowledgeable support be available if needed. These issues and others are presented more formally in the following outline:

- A. Availability of the model
 1. Acquisition or distribution constraints
 2. Source code
 3. Science documentation
- B. Code
 1. Language

2. Code documentation (internal, manuals, etc.)
3. Program structure (modularity)
- C. Availability of support
 1. Originator still active/available?
 2. Expert support available?

IV. MODEL RECOMMENDATIONS

Much is known about the environmental influences on thermal infrared backgrounds, but only a portion of that knowledge is sufficiently quantitative to be included in operational first-principles models. The development of one-dimensional models of surface temperatures of solid materials has been underway for over 25 years, and capabilities in this area are relatively strong. Several models have been developed for solids that are based on heat conduction (temperature diffusion) within materials and an evaluation of the surface energy budget. Freshwater temperature modeling seems to be nearly as mature. Capabilities to simulate the surface temperatures of some porous solids, snow and ice have recently been developed and are being tested. Very simplistic models for vegetation complexes seem appropriate for leaves and simple canopies with no wood; however, important vegetation types cannot be simulated with process models at this time.

Some very sophisticated models exist in the scientific community that represent capabilities beyond those considered for SWOE at this time. Some of them are individual scientist's research tools and thus require specialized expertise or inputs that are not routinely available. Often they are insufficiently documented for implementation and are unsupported. Active work directed toward developing operational background temperature models is very limited within the scientific community.

In this section, recommendations are given for each of the main calculations needed to simulate the surface temperatures of a variety of background materials. All of the models reviewed have common requirements to simulate energy fluxes between the surface and the atmosphere. Models given the most intense scrutiny are in Appendix A and other models reviewed are in Appendix B. For an integrated system, shared calculations should be as consistent as possible. Modeling of different material types differs mostly in the way heat fluxes within the materials are treated (both the physical processes and numerical methods). Therefore, recommendations for computing individual fluxes between the surface and the atmosphere are given as one group and recommendations for computing fluxes within the materials are given in a second group.

By choosing the best techniques for each component

it is expected that the best composite model will be obtained. A particular model is recommended to provide the framework for the implementation of the recommended techniques. Since extensive departures from this model are recommended, its identity will be essentially transformed into an integrated SWOE model. The recommendations of first-principles modeling techniques do not cover all background materials and, for those not covered, recommendations are given for interim treatments and/or research and development activity.

Generally, we recommended that actual measurements of the energy fluxes be used, when available, in lieu of calculated values and that the integrated model drivers allow for this option.

Surface-atmosphere energy fluxes

Solar irradiance

The solar energy absorbed at the surface is the product of 1) the energy incident at the surface and 2) an absorption coefficient (one minus reflectance). The first is a product of environmental factors largely independent of the material but the second is a surface material property. Solar irradiance can be a large and highly dynamic term in the energy budget, and this component must be computed accurately because surface temperatures are very sensitive to it. Spectral variations are not important, but separation of the diffuse and direct components is required to account for different slopes and, eventually, for full three-dimensional modeling. Aerosols and clouds play an important role in the magnitude of irradiance as well as the proportion of direct and diffuse energy. The most appropriate model for performing these calculations is LOWTRAN7 (Kneizys et al. 1988). Not all of this model's capabilities are required and only a small number of the inputs are needed. Therefore, we recommend that a simplified version of LOWTRAN7 be developed under supervision by the U.S. Air Force Geophysics Laboratory to perform calculations of direct and diffuse energy incident at the ground.

Absorption of the solar energy at the surface is often modeled to be a constant portion of the incident flux. This is rarely true for backgrounds where absorption is dependent on the directional distribution over the sky hemisphere. In general, absorption should be allowed to vary with sun elevation angle and the ratio of direct and diffuse irradiance. However, this information is often unavailable and the assumption of a constant becomes necessary. This assumption may be acceptable for many conditions because the effects are largest when the sun is low. Absorption does vary in some of the models reviewed but techniques are limited to particular material types.

Downwelling thermal infrared energy

Typically, more energy enters the system from downwelling thermal infrared energy over the course of an entire day than from any of the other energy budget components. However, it is not strongly dynamic under most weather conditions. It is mostly dependent on the temperature and humidity of the lower atmosphere, the amount of cloud cover and the effective temperatures of the cloud bases. Because downwelling thermal infrared energy originates in the atmosphere (given an unobstructed sky) we recommend that a simplified version of LOWTRAN7 be developed to compute this term. This is consistent with the recommendations for insolation and atmospheric propagation calculations, and maximizes the use of first principles.

This recommendation extends beyond the techniques currently used in background temperature models. Empirical techniques, such as those presented by Oke (1978), are currently used in most energy budget models. Empirical adjustments for cloud effects have proven useful for many modeling tasks but the range of conditions they simulate is limited. If the recommendation for the use of LOWTRAN7 proves unfeasible, these techniques can be used as a temporary measure, but they should not be considered as a permanent solution for SWOE.

Like the solar irradiance, the downwelling energy absorbed by the material is the product of the irradiance and an absorption coefficient (gray body emittance), and the coefficient is generally assumed to be a constant depending on material type. Additionally, irradiance is assumed to be isotropic. Little information is available on the directional properties of the emittance of background materials but the importance of the assumptions needs to be tested as three-dimensional modeling capabilities are developed. Since the radiant emittance is crucial in predicting the power radiated from background surfaces, it should be known as well as possible.

Emitted thermal infrared energy

For situations that are reasonably well approximated by one-dimensional descriptions, the emitted thermal infrared energy is described by the Stefan-Boltzmann equation, which is a function of the surface temperature and the gray body emittance. The surface temperature is produced by the model, and the emittance is the same as that used to evaluate downwelling thermal infrared energy absorbed.

Convective fluxes—sensible and latent heat

Convective fluxes in the atmospheric boundary layer are important topics that have received much attention in atmospheric research. The processes are very complex and much effort has been devoted to develop-

ing simplified formulations suitable for modeling one-dimensional surface fluxes (for a particularly succinct discussion, see Oke 1978). The surface temperature models reviewed use various forms of the aerodynamic approach because it can be driven with standard meteorological data. The aerodynamic approach requires knowledge of the vertical gradients of wind speed, temperature (for sensible heat) and water vapor (for latent heat). With standard meteorological data, these variables are known at only one height so that some techniques or assumptions are required to approximate the wind speed, temperature and humidity at the surface.

Implementation of the aerodynamic techniques seems to take one of two approaches. One is to assume a logarithmic profile of the wind scaled by an aerodynamic roughness of the surface. A second assumes that the wind speed goes to zero at the molecular boundary due to friction. The use of aerodynamic roughness has the advantage of being dependent on site properties; however, the selection of actual aerodynamic roughness can be a problem because it can vary widely within any given surface type. Without site-specific measurements, there is uncertainty over what value to use. Additionally, in the SWOE context, two values of aerodynamic roughness are needed to take advantage of site specificity: one at the measurement site and one at the site that is being modeled. The assumption of zero wind speed at the molecular boundary is independent of aerodynamic roughness but approaches the form of the basic equations given by Oke (1978). The validity of this assumption has been examined in the field and has been found to be satisfactory for some difficult situations. Given the uncertainty in spatial variations of the wind speed in a scene and the uncertainty in the values of aerodynamic roughness of surfaces, it is recommended that the simpler, second treatment of wind speed gradients be used. In particular, the implementation taken from Oke (1978) and used in the Terrain Surface Temperature Model (TSTM; Balick et al. 1981a) should be used initially. It is also recommended that attention be given to the performance of this approach and that this recommendation be reevaluated in the future.

Estimation of the water vapor at the surface, expressed either in terms of absolute humidity or vapor pressure, presents somewhat of a different problem. If the surface is dry, then there is no net evaporation or condensation. If the surface is wet, then the value at saturation at the surface temperature can be used. In between, the situation is more complex and specific treatments may depend on surface material type. Several of the surface temperature models use a dimensionless parameter, ranging from 0 to 1.0, which is multi-

plied by the potential water vapor pressure gradient (the gradient computed as if the surface were saturated). These models use this parameter as a constant and its meaning becomes unclear if condensation begins or a wet surface dries. Over water the problem is moot; over snow the problem may be severe. This approach used in the surface temperature models is recommended initially because of its simplicity but the issue of parameterization of evaporation and condensation with moist, unsaturated surfaces must be given more consideration.

Energy fluxes within materials

There are two principal aspects in the treatment of energy fluxes within materials: the physical processes included and the numerical methods used. It is in these areas that the processes in the models for different material types are the most distinct. It is also in these areas that calculations and computer codes are the most intricate. Thorough integration at this level should not be expected for the initial phases of SWOE model development. Specific recommendations are presented by major material type.

Solids

Heat fluxes in solids occur through conduction only and are proportional to the heat conductivity and the local temperature gradient. Heat fluxes can be tracked through the material using a numerical finite-difference scheme. Numerical techniques can be found that are unconditionally stable but need additional effort to merge with boundary flux calculations. Simpler techniques can become unstable, but these rarely lose stability for natural backgrounds. Also, unstable conditions are predictable and potential problems can be avoided.

A solid material can be described as a layer with continually changing properties or as a stack of layers. The advantage of describing solids as layers is that systems such as pavement/roadbed/soil can be treated explicitly. An advantage of describing a material as continuously varying with depth is that more complex processes (i.e., mass diffusion) can be incorporated more easily. As far as we know, models that have been implemented in a 3-D sense have all been single layered. The procedure recommended for modeling heat flux through solids is the layered approach as implemented in TSTM, with a method to adjust grid spacing to assure numerical stability.

Snow

Heat fluxes in snow are considerably more complex than in solids. In addition to conduction, heat flux within snow is accomplished through mass diffusion and phase changes. Also, sunlight penetrates the surface to internal components of the material and the snow has

a solid substrate. The model, SNTHERM.89, developed by Jordan (1990), is recommended for implementation in SWOE. It is readily available and has several desirable features and extensions unavailable elsewhere. Integration of SNTHERM.89 surface-atmosphere energy flux techniques with this model will require additional effort.

Water

Fresh water. Heat transfer through water can take place by turbulent mixing of the water as well as conduction and diffusion. Like snow, sunlight penetrates the surface and is absorbed deep within the materials. No existing model is known that is appropriate for implementation in SWOE in its current form. However, there are several water quality models that simulate temperatures within water bodies and energy exchanges at the surface. These are available at several levels of detail. We recommend that the techniques used within the model CE-QUAL-R1, developed at the U.S. Army Engineer Waterways Experiment Station (USA EWES Environmental Laboratory 1986), be adapted for use within SWOE. We recommend that the expertise at the WES be tapped, if possible, to perform this simplification of their model and to interact with SWOE personnel to identify the trade-offs on some of the specific options for details and input requirements. An alternative is the WES model, CE-QUAL-W2 (USA EWES Environmental and Hydraulics Laboratories 1986). This model has a more detailed evaluation of the water-atmosphere convective energy fluxes, which may be more accurate than those developed for land, and has algorithms for simulating freezing and surface temperatures of ice. However, the very complex main program has insufficient documentation to enable simplification for SWOE implementation. At this time, it seems preferable to use the simpler algorithm in CE-QUAL-R1, but this should be reevaluated.

Seawater and ice. No models of sea surface temperature have been located and no recommendations are made. The lack of models seems largely due to the small response of sea surface temperatures in the open ocean (less than 1°C) to short-term environmental fluctuations. Changes of currents, tidal effects and coastal processes do change water temperatures at a location, but the process is more usually associated with changes in the source than environmental effects. Sea ice surface temperatures can be simulated with models used for solids with some adjustments (Maykut 1985). During the arctic winter, thick sea ice remains slightly (less than 1°C) below air temperature. While melting it remains at about 0°C. Thin ice, less than a meter or so thick, can be modeled as a solid with a constant bottom boundary temperature. Adjustments to the thermal conductivity

to account for brine pockets, temperature and salinity can be made but consideration of the directional dependence of the absorption of solar energy is needed. The use of the solid material model is recommended for sea ice, when a model is necessary, and specific adaptations for sea ice should be incorporated as needed.

Vegetation

Thermal models for vegetation are the least developed of all those for which specific recommendations are made. This is due to the diverse array of vegetation types, the complex geometry of plant components in three-dimensional space and within the atmosphere (no distinct separation or surface) and the fact that plant canopies are composed of a number of components of differing thermal properties. The variability and distribution of canopy elements within a volume means that remote sensors actually view an ensemble of temperatures even in simple canopies. There are at least two models, PRISM/CANOPY (Howard et al. 1987) and Foley (1982), which compute the energy budget of leaves and are more or less linked with the energy budget of the ground beneath them. Another model, TSTM/VEGIE (Balick et al. 1981b) has an integrated simple canopy model with more complete linkage with the ground. Two other models applicable to forests have been developed that treat the geometric structure of the foliage. These models, which need to be linked with a ground temperature model, predict changes in radiant emittance as a function of view depression angle from horizontal. All the models deal exclusively with the foliage of the vegetation. There are no models for leafless deciduous forests or trees, especially those seen at forest edges or woody parts of single or groups of trees. Nor are there any models for open or discontinuous canopies, such as savannah or desert shrub communities. The geometric characteristics of agricultural fields should also be modeled.

We recommend that the VEGIE (Balick et al. 1981b) module of TSTM be implemented for the prediction of temperatures of simple short canopies such as lawns and pastures. The Thermal Vegetation Canopy Model (TVCM; Smith et al. 1981a, 1981b) is recommended for simulating forest canopies, although only generic grass, conifer (two types) and hardwood canopies can be simulated easily. It has been used by SWOE participants and linked with TSTM to predict ground temperatures. We recommend, however, that this linkage be improved. The use of the leaf model as implemented by Foley (1982) may be useful under some circumstances. The equations for direct sunlight penetration and the probability of viewing leaf or ground as a function of view depression angle can be made more physically based. These calculations can be incorporated in VEGIE to make temperature determination dependent on view angle.

Initial model framework

Rather than implementing the above recommendations from scratch, it is suggested that an existing model be used as a framework with the recommendations invoked as modifications. This model should contain some of the recommendations and handle time, inputs and outputs in a manner close to that required by SWOE. For this purpose, the C language version of TSTM, which uses some of the suggested techniques, is recommended. Temporal data are handled as continuing discrete inputs of variable time intervals, rather than the 24-hour values used in the original version. Its software architecture is highly modular and it has a shell designed to allow for inclusion of alternative modules. Some debugging features have been designed to facilitate the process.

Other models

Other models are of continuing interest to the SWOE program. Some seem appropriate and useful to SWOE but adequate documentation to review their technical attributes is unavailable. Others do not fit the criteria of first principles but have the potential to augment current capabilities in models. These are briefly discussed below.

Insufficiently documented models

The Georgia Tech Research Institute (GTRI) has been the most active organization found in developing background temperature models. This is a result of continuing work in developing research grade tactical decision aids that has brought about an understanding of environmental influences on thermal backgrounds. Because of this work, the SWOE review panel visited the GTRI facility and had follow-up telephone conversations. GTRI has completed, or has nearly completed, models for vegetation, water, porous soils and a preliminary model for beach sand. Any of these models seem to be contenders for implementation in SWOE, but sufficient technical information is not available in spite of our specific requests. A technical report from GTRI was due in October 1989, too late for consideration in this review. We recommend that GTRI's efforts be evaluated when sufficient information becomes available.

Given some general written descriptions of several models that could not be given a technical review, there is no evidence that capabilities exist in those models that do not exist in the reviewed models. No recommendations on them seem appropriate.

Supplemental models

One-dimensional models are not available for all background material types, and one-dimensional assumptions are poor for many three-dimensional ob-

jects. Of particular concern are parts of structures, some types of vegetation, rocks, wetlands and many coastal features. Other materials can be modeled under some conditions but the inputs in transitional states are not well known. These include solids after a rain, thawing ground and a forest in the fall. Since the overall SWOE objectives require temperature estimates for these backgrounds and conditions, it seems necessary to implement some way of estimating temperatures. There are a number of choices including the use of actual data, expert judgment, and Fourier or thermal inertia models. These are empirical approaches. There is also a hybrid model developed for the Infrared Measurement and Analysis (IRMA) system (Botkin et al. 1981). The hybrid approach is recommended because it has the potential to capture some of the basic physics involved and is driven by the same environmental data as the first-principles models.

Research and development

One-dimensional models

High priority should be given to model development for structurally complex vegetation. Complexities arise because of the three-dimensional geometry and the variety of materials in a vegetated scene. Several categories of these exist:

1. Agriculture (dynamic canopies with row effects)
2. Discontinuous shrub and tree stands
3. Forest edges
4. Fully leafed forests with woody components
5. Leafless deciduous forests
6. Single trees and groups of trees.

Each of these categories presents unique modeling problems. Because of apparent needs in the SWOE program, early emphasis should be given to single and groups of trees and to forest edges.

Another area that requires development is in the conversion of surface temperatures to directional radiant emittance. Some directional variations exist as an inherent material property. For natural backgrounds, changes are generally due to geometric characteristics of the surface. Most natural surfaces have facets oriented in many directions and some in shadow so that a variety of temperatures exist within a given pixel. During the day, the proportion of warm and cool facets observed varies systematically with sun and view angles. The largest amount of variation can be attributed to the portions of sunlit and shaded areas in the pixel.

The broad area of mass transport through porous media deserves additional consideration in models. This includes the following:

1. Thermally driven mass transport (dry air and water vapor) within materials such as sands, gravels and porous soils.

2. Net heat flux due to water phase changes.
3. Evaporation from moist, unsaturated surfaces.

The recommended model for heat flux within snow (Jordan 1990) captures many of these processes. This model should be further examined to determine the extent to which these formulations can be adapted to other materials. Otherwise, the GTRI porous soil model or the JPL model (see App. A), possibly with enhancements, may be implemented.

Somewhat related to these issues are problems related to beaches, where materials have been sorted by wave action, and there is a constantly varying supply of subsurface water. The depth from the surface to water changes continuously with distance inland and with both time and space due to tidal effects. Changes of sea level create changes of the recent thermal history, and therefore temperature, of a point. Seawater enters the system laterally with tidal changes, creating continuous influx or drainage of subsurface water. This is a thermally complicated system that should be examined and modeled in more detail than is currently available.

Temporal transitions of material characteristics are generally not smoothly handled in the models. Transitions occur at a variety of rates and include seasonal changes of vegetation, freezing of the ground, changes of sea ice brine pockets and the onset or cessation of rain. While there are notable exceptions, model parameters are most often constant for the course of the model run. Sometimes these can be treated by giving parameters a functional dependence where known (for example, changing the heat conductivity of sea ice as a function of temperature). Modeling others can require values for variables that are not measured (for instance, the Foley model requires rain temperature to predict rain effects). While no specific technical recommendations are given here, identification of transitional conditions of importance to SWOE should be made so that their effects can be included in future development of SWOE models.

Quantitative model parameter estimation techniques need to be developed to provide model inputs when measurement is not feasible. Specific model implementation needs to be done in the context of the accuracy and representativeness of the parameter values. For instance, where site visits are not feasible, techniques need to be developed to take soil maps and estimate numerical values from the soil thermophysical properties, the probable range of values and vertical structure. Does a value for the thermal conductivity pertain to the top centimeter, top 10 cm or top meter? How does thermal conductivity change with differences of soil moisture? At what level of detail does vertical structure make a difference in a given soil type and climate? When site visits are possible, can heat conductivity be measured directly or what measurements are needed to estimate

it? These kinds of questions arise for all material types and properties. Scientists can make reasonable estimates in their area of expertise if given adequate contextual information but this skill may not be available to a SWOE model operator. Systematic, repeatable and justifiable procedures should be developed for estimating parameter values as well as estimates of ranges and errors.

Toward 3-D models

In the process of performing the review and with the knowledge that a three-dimensional modeling capability would follow the one-dimensional model, we developed several ideas related to creating three-dimensional models. The ideas, somewhat speculative in the details, are presented below.

Complete 3-D modeling of backgrounds must take into account many factors not included in one-dimensional models, including horizontal fluxes within and between materials, the directional distribution of insolation, local radiant interactions between surfaces, radiant interaction at the scale of topography, local wind effects (circulation around objects), thermally driven winds at the scale of topography, three-dimensional structure of air temperature, the effects of the surface on the atmosphere, the modeling of complex material ensembles (i.e., forest edges) and the merging of widely different geometries. These need to be examined in some detail to establish implementation priorities in SWOE.

Horizontal heat fluxes have been treated using a finite-element network (Johnson and Owens 1987, Bernstein et al. 1989). These models are extensions of target models where high-temperature contrast in highly conductive materials exist. In natural backgrounds, horizontal temperature gradients are often relatively small, mechanisms for horizontal transfers are relatively weak and the areas (facets) modeled are often very large. Given sensor resolution limits and atmospheric modulation, horizontal conduction heat fluxes between materials may not be a major problem in SWOE. If so, this would simplify the modeling effort considerably by allowing the use of one-dimensional models for the within-material heat fluxes with adjustments for three-dimensional effects on the atmosphere-material energy fluxes.

Local radiant interactions around objects can create temperature differences of several degrees. Examples are shadows and corner reflections. Boundaries can be sharp and changes are on the spatial scale of the objects and targets. Therefore these effects are important to local contrast and spatial properties of background images and are not neglectable. Since these interactions are inversely proportional to distance, establishing a

sphere of influence around objects may reduce calculations. However, this might be inefficient in scenes with many objects.

Radiant interaction at the scale of the topography is important to the overall temperature of the backgrounds and to regional energy fluxes. However, it probably does not contribute much to local contrast because adjacent scene components are similarly affected unless reflectances are largely different.

The effect of modification of local air circulation around objects is potentially a significant effect. Fluid dynamics or air flow at these scales is very complex and close examination may show that it is not feasible to include it at this time.

Atmospheric circulation at the scale of the topography is important to spatial structure of air temperature and convective heat fluxes and can affect local temperature magnitudes and contrasts in major ways. Examples of these phenomena include nocturnal drainage winds and sea breezes. The Genessis model (Acquista et al. 1987) permits input of spatially varying air temperature and temperature lapse rates requiring a priori knowledge of these variations. While the processes are complex, mesoscale meteorological models developed to simulate them probably can be integrated into the SWOE model package. The simulation of environmental effects on backgrounds over 4- x 5-km areas begs inclusion of these processes in SWOE simulations.

Directional reflectance and emittance are of more importance in the three-dimensional context than in one-dimensional modeling, and more information and techniques need to be developed to incorporate these effects. Related to this is the inclusion of directional and environmental effects on image component (polygon, facet) texture.

Most images contain large flat areas (fields, lawns) and highly three-dimensional objects (trees, houses). Methods optimum for one type of geometry are not necessarily efficient for the other. Methods to integrate the two, geometrically as well as energetically, will require continuing attention and ingenuity.

V. SUMMARY

Available models were reviewed and evaluated for implementation in SWOE. As a result, current capabilities in one-dimensional modeling were determined and specific recommendations for implementation were made. Robust capabilities exist for solid materials, snow, fresh water and simple vegetation layers. Modeling freshwater ice and sea ice are tractable at this time. Serious deficiencies exist in complex vegetation because of the mix of materials comprising the canopy and their three-dimensional distribution. Simulation of most

porous solid materials seems inadequate.

The use of the C language version of TSTM is recommended to serve as an initial model framework in which to implement the technical recommendations.

Recommendations for specific implementation were made in three groups: atmosphere-material energy fluxes, within-material energy fluxes (for several material types), and the initial model framework. For atmosphere-material energy fluxes, the following recommendations were made:

1. Solar irradiance. A simplified version of LOWTRAN7 should be developed to compute total direct and diffuse solar irradiance.

2. Downwelling thermal infrared energy. A simplified version of LOWTRAN7 should be developed to compute downwelling thermal infrared energy.

3. Convective fluxes (sensible and latent heat). The formulation in TSTM should be implemented initially. Modifications for parameterizing evaporation from moist surfaces should be sought.

4. Emitted thermal infrared energy. The Stefan-Boltzmann equation is adequate for temperature modeling (not so for radiance modeling).

For modeling fluxes within materials the following recommendations are made:

1. Solid materials. The layered material heat conduction scheme implemented in TSTM should be used.

2. Snow. SNTHERM.89, the model developed by Jordan (1990) at CRREL is recommended.

3. Vegetation. The VEGIE module of TSTM should be used for short grass canopies. TVCM should be used for fully leafed generic canopies. No recommendations were made for complex canopies.

4. Water. A simplified version of the CE-QUAL-R1 model developed at WES should be used initially for fresh water. CE-QUAL-W2 model can be used if a more detailed treatment is required or for freshwater ice. TSTM with slight modification can be used for sea ice when a model is necessary.

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APPENDIX A: ANNOTATED LIST OF MODELS OF SPECIAL INTEREST

Models with features that were being considered toward the end of the review are listed with brief annotations in this appendix. These models contained techniques or attributes that were unique or seemed useful as a whole model. Models are grouped by major material types.

SOLID MATERIALS

Terrain Surface Temperature Model (TSTM)

Originator: U.S. Army Engineer Waterways Experiment Station

Reference: Balick et al. (1981a)

Technique: Numerical solution of 1-D temperature diffusion equation with explicit evaluation of surface energy budget components when measurements are not available. The model represents terrain as one to six layers, thus allowing for distinct changes of materials or properties beneath the surface.

Comments: This model has been in use for about 10 years with significant validation effort at WES and other agencies. Its main principles are rather generic and similar to several other models. Differences exist in the way energy budget components are evaluated when not available as measurements. The model has been integrated in scene model software, extended to treat the effects of nearby objects on the radiant energy budget components (Weiss and Scoggins 1989) and an extension to petroleum tanks has been published (Hodge 1989). There are no strong model development activities at this time. The model would be easy to obtain and implement.

Infrared Modeling and Analysis (IRMA)

Originator: U.S. Air Force Armament Laboratory, Eglin AFB

Reference: Botkin et al. (1981)

Technique: Numerical evaluation of 1-D temperature diffusion equation with highly parameterized evaluation of surface energy budget.

Comments: Old versions require empirical derivation of parameters but work is underway to define these coefficients in physical terms. Empirical coefficients have been derived for materials to which the physical principles of the model do not apply very well. The model has been under development and in use for several years and is integrated in scene modeling software. Model

development and use is supported by the USAF and the model would be easy to obtain and implement.

Foley Model

Originator: U.S. Air Force Avionics Laboratory, Wright-Patterson AFB

Reference: Foley (1982)

Technique: Very similar in essence to the TSTM with different treatment of individual surface energy budget components.

Comments: Although very much like TSTM in concept, different submodels are used to evaluate the energy budget. Certain extensions allow calculations for leaf temperatures, shading of ground by foliage and rainfall. These extensions are coarse approximations and, while of interest, need careful scrutiny before they can be implemented in SWOE. Active support may not be available.

Genesis

Originator: Photon Research Associates, under contract to DoD

Reference: Acquista et al. (1987)

Technique: Numerical solution to the one-dimensional temperature diffusion equation with explicit evaluation of surface energy budget components. This is a single material model.

Comments: The most important difference between this model and others is its unconditionally stable numerical methods. However, this advantage may be nullified by additional steps in the analysis. The model is part of a scene modeling package with user interfaces to build input files for generic or specific material types. Model distribution is not unlimited, but source code and manuals are available at nominal cost.

GTSIG/TCM2

Originator: Georgia Tech Research Institute under contract to USAF

Technique: Numerical solution to temperature diffusion solved in three dimensions.

Reference: Johnson and Owens (1987)

Comments: The model was developed as a three-dimensional target and background model. It can be reduced to one-dimensional operation, although the best reason for doing so would be for compatibility with 3-D implementation. Technical documentation of temperature models is incomplete at this time. Documentation

seems to be a limiting factor in evaluating GTRI software. The models are integrated into a scene modeling system as a "research grade" TDA and it should be noted that they use IRMA in practice for most background simulations.

JPL Model

Originator: Jet Propulsion Laboratory, California Institute of Technology

References: Schieldge et al. (1982); Njoku et al. (1980)

Technique: The model uses simultaneous numerical solution of differential equations for temperature diffusion and for mass diffusion with separate tracking of dry air and water in soil. Explicit evaluation of energy budget components is provided.

Comments: This is a rigorous simulation of heat and mass fluxes in soils that allows for dynamic adjustment of soil parameters for changes of internal conditions. The model is documented but not supported. It is primarily a research model.

SNOW

SNTHERM.89

Originator: U.S. Army Eng. Cold Regions Res. & Eng. Lab. (CRREL)

Reference: Jordan (1990)

Technique: The model provides numerical solution of heat flux in snow, incorporating the effects of mass movement and phase changes as well as explicit treatment of the surface energy budget.

Comments: The model contains all the major features of heat fluxes within snow. It is state of the art and readily available to SWOE.

FRESH WATER

CE-QUAL-R1

Originator: U.S. Army Engineer Waterways Experiment Station

Reference: USAEWES Environmental Laboratory (1986)

Technique: Numerical solution of mass and energy transport in liquids with explicit treatment of most surface energy budget components.

Comments: These calculations are part of a water quality model that performs more calculations than SWOE probably needs. Simplification of the model to calculation of energy fluxes is possible, although the question of how much simplification needs to be done is unanswered.

CE-QUAL-W2

Originator: U.S. Army Engineer Waterways Experiment Station

Reference: USAEWES Environmental and Hydraulics Laboratories (1986)

Technique: Numerical solution of mass and energy transport in liquids with a detailed explicit treatment of surface energy budget components. Algorithms for freezing and heat flux through ice are included.

Comments: Like CE-QUAL-R1, the temperature prediction algorithms are part of a water quality model but CE-QUAL-W2 is considerably more complicated. The manual does not contain the same level of detail and the level of difficulty to simplify the model is unclear.

VEGETATION

PRISM (Subroutine CANOPY) PRISM/CANOPY

Originator: Keweenaw Research Center (KRC), Michigan Technological University

Reference: Howard et al. (1987)

Technique: Computes the energy budget for a leaf layer with no energy storage only radiant interaction with the ground.

Comments: Very simplified treatment that may be sufficient given close coupling of leaf and air temperatures. Convective energy fluxes are with free air are unmodified by the canopy. The model is readily available.

Foley Model

Originator: U.S. Air Force Avionics Lab., Wright-Patterson AFB

Reference: Foley (1982)

Technique: Single leaf energy model linked to ground model.

Comments: Similar to KRC/CANOPY in concept differing in detail. Treatment of ground shading more sophisticated than KRC/CANOPY. Calculations are a subroutine in a more general model.

VEGIE

Originator: U.S. Army Engineer Waterways Experiment Station

Reference: Balick et al. (1981b)

Technique: Linked to a soil model, VEGIE evaluates the energy budget of a porous canopy layer including effects on the radiant and convective energy budget on the combined system producing a composite temperature estimate. Not applicable to forest canopies.

Thermal Vegetation Canopy Model (TVCM)

Originator: Colorado State University for Army Research Office & USAEWES

References: Smith et al. (1981), Smith et al. (1981b), Kimes et al. (1981)

Technique: Evaluates the energy budget of three layers of canopy and the probability of seeing each layer and the ground. A composite temperature as a function of

depression (elevation) angle is produced.

Comments: The model uses fairly detailed specification of canopy architecture to compute energy fluxes and line of sight. Solar energy absorption calculations require the computation of coefficients using another model that is not user oriented. Coefficients have been determined for some typical canopies. The model assumes a horizontally homogeneous canopy. No heat storage in woody material is treated and no azimuthal variation are included, but this is the first model to treat view angle variations. Tests show it is more accurate for forests than VEGIE.

Rough Surface TVCM

Originator: Colorado State University for USAE WES

Reference: McGuire et al. (1989)

Technique: This is an extension of TVCM allowing for spatial variation of leaf area projected toward the sun and toward the sensor along a transect.

Comments: The spatial variation of temperature due to variations of canopy architecture can be estimated allowing for modeling of texture as well as mean temperatures. This model does not include azimuthal effects from the sun or heat storage in wood and therefore is effective only for nighttime or overcast conditions.

APPENDIX B: MODELS NOT EVALUATED IN DETAIL

This appendix lists models that were considered early in the review process and did not satisfy evaluation criteria or offered no capabilities beyond those offered by other models. Elimination at this point does not mean that the model is deficient. Models are grouped by major category.

SOLIDS

Pratt and Ellyet Model

Reference: Pratt and Ellyet (1979)

Comments: This is a Fourier series model that does not allow for rapid responses to changes of the environment. The model is designed to aid image interpretation of thermal infrared/thermal inertia imagery for geologic applications.

Watson Model

Reference: Watson (1973)

Comments: This is a pioneering model of ground temperatures for geologic applications. It is based on Fourier series and does not allow for simulating rapid changes of the environment. Developments subsequent to the original model focused on spatial environmental effects, elevation, slope, etc., but these are handled more easily in numerical models. Code and technical documentation are unavailable.

Kahle Model

Reference: Kahle (1977)

Comments: An early model of the surface energy budget using numerical methods. Simple and straightforward but offers nothing exceptional. Code and technical documentation are unavailable.

SPACE

Reference: D'Agastino (1987)

Comments: Apparently a typical model of the surface energy budget with numerical procedures for heat flux within solids. Only a user manual was made available. User interface and graphical support for SPACE appear well developed, but the source code seems to be in BASIC. No scientific documentation was supplied and the originating scientist has left the company. The model is not actively supported or used.

HFLUX

Reference: Dodd (1980)

Comments: Another numerical model of the surface energy budget and heat flux in solids. This model uses somewhat different thermophysical properties than others of its type but is essentially the same. The model has undergone development since the above reference but it does not offer unique capabilities.

PRISM

Reference: Howard et al. (1987)

Comments: This is a simple model of the surface energy budget and heat flux within solids. The model uses a matrix structure to compute within-material heat fluxed but the evaluation of the surface energy budget is relatively simplistic.

Technology Service Corporation Model

Reference: Bernstein et al. (1989)

Comments: Adequate scientific documentation for evaluation was not supplied. The model describes heat fluxes for solids and is of interest because it is part of a three-dimensional image modeling package. Products indicate that the package simulates complex targets on simple backgrounds.

WATER

WES/Martin Model

Reference: Martin (1986)

Comments: A very highly parameterized steady-state model of water temperatures. It may serve as an easy alternative to other models but, due to its parametric nature, is not recommended for SWOE application.

VEGETATION

TERGA

Reference: Soer (1980)

Comments: This is a detailed model of soil-plant-air interactions developed in Europe. The model has seen extensive use, particularly for the estimation of regional evapotranspiration but requires detailed specification of the system. Code, documentation and support are not easily available.

CUPID

Reference: Norman (1979)

Comments: This is a highly detailed model of soil-plant-air interactions that has been under continuous development for nearly 15 years. The model can produce estimates of directional radiant emittance from uniform foliage cover. It is a research model. Code is available but documentation and support are limited.

Goudriaan Model

Reference: Goudriaan (1977)

Comments: This is another research model of plant-soil-air interactions that can simulate vegetation canopy temperatures and the processes that determine them. Extensive scientific documentation exists but computer code and support are probably unavailable. Its current status is unknown.

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