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Prescription of Land-Surface Boundary Conditions in GISS GCM II: A Simple Method Based On High-Resolution Vegetation Data Bases

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Prescription of land-surface boundary conditions in GISS GCM II:

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Abstract

A simple method was developed for improved prescription of seasonal surface characteristics and parameterization of land-surface processes in climate models. This method, developed for the Goddard Institute for Space Studies General Circulation Model II (GISS GCM II), maintains the spatial variability of fine-resolution land-cover data while restricting to 8 the number of vegetation types handled in the model. This was achieved by: redefining the large number of vegetation classes in the 1° x 1° resolution Matthews (1983) vegetation data base as percentages of 8 simple types; deriving roughness length, field capacity, masking depth and seasonal, spectral refelectivity for the 8 types; and aggregating these surface features from the 1° x 1° resolution to coarser model resolutions, e.g., 8° latitude x 10° longitude or 4° latitude x 5° longitude. Abridged results of the method were presented by Hansen et al. (1983). In this report we present the complete method.

1. Introduction

Climate-model prescriptions of land-surface boundary conditions (e.g., albedo, roughness length, masking depth and field capacity) and associated parameterizations of surface processes have been until recent years, relatively crude. This has been due, among other things, to the unavailability of digital, land-cover data appropriately classified for climate-model applications, and the difficulty (both computational and theoretical) in parameterizing atmosphere-biosphere interactions. During the past few years, there has been increasing interest in the role of surface processes in climate models (Eagleson, 1982; ISLSCP, 1983). In 1978, we began a long-range project of compiling global land-cover data bases, at fine resolution, from published sources. This project was designed to improve the prescription of land-surface boundary conditions and parameterizations, mentioned above, in the GISS GCM. Several methods were evaluated for incorporating the detailed and fine-resolution land-cover data into the model in manageable form. Abbreviated results of the final method, based on the vegetation data only, were published by Hansen et al., (1983); we present the entire method here. The method and the data as outlined in this paper represent the first stage in the incorporation of fine-resolution land-cover data into the model; surface albedo was the primary focus, with a more modest effort spent on the other areas. Additional fine-resolution data bases of land use (Matthews, 1983) and soils (Zobler and Cary, 1984) are now completed. This method will be used, in conjunction with these new data sets, to continue development of land-surface prescriptions and parameterizations for GISS Model III, with particular emphasis on soil-vegetation hydrologic interactions.

2. Data

Documentation of the vegetation data used in this work, including research design, classification methods and data sources, is presented in Matthews (1983). In the following, we briefly outline several aspects of the design as they relate to the incorporation method presented here.

Prior to data compilation, we reviewed several vegetation-classification systems to evaluate their suitability in climate-oriented data bases. Specifically, we looked for a system that classifies vegetation on the basis of climatically-important vegetation characteristics such as structure (including height, and plant and/or canopy architecture), seasonality, and density. The UNESCO (1973) system satisfied our classification requirements. The primary classification criteria of this hierarchical system are dominant lifeform, the seasonality, height and density of dominant lifeform, secondary lifeform components, and the seasonality, height and density of secondary components. Vegetation is classified, in order of increasing detail, into formation class, formation subclass, formation group, formation, and subformation according to lifeform characteristics mentioned above in addition to plant architecture (e.g., broadleaf, needleleaf), seasonality (e.g., drought-deciduous, cold-deciduous, evergreen), climate (e.g., tropical, temperate), altitude (e.g., lowland, montane), and environmental setting (e.g., seasonally flooded). Legends from all compilation sources were translated into the UNESCO system and recorded in UNESCO code. The result of the vegetation compilation is a raw data base, at 1° resolution, including 178 types identified by a maximum of 5 hierarchical code elements, in addition to three types (desert, cultivation, and ice) that are not included in the UNESCO (1973) system. We first grouped these vegetation types to produce a 1° resolution data base of 22 vegetation types. These types, along with brief descriptions and UNESCO (1973) codes of the major groups included in them, are listed in Table 1.

3. Strategy

Our aim was to derive improved prescriptions of land-surface features based on new, high-resolution data bases of land cover, for the GISS GCM II. We wanted to define land-cover with relatively few vegetation types while taking advantage of the detail available in the original data bases. At the same time, we required a method whereby these nominal data could be aggregated to several coarser resolutions of the model. A simple grouping of the 22 vegetation types in Table 1 would result in the loss of spatial detail at 1° resolution, without the benefit of allowing simple aggregation to coarser resolutions.

The sections that follow outline, separately, several aspects of our work, but it should be noted that the efforts were concurrent and often interrelated.

A. Vegetation

The 22 vegetation types (Table 1) were redefined into percentages of the 9 simple types listed in Table 2A, as shown in Table 2B. The first order redefinitions were based on reasonable estimates of the height, seasonality, density and architecture of primary and secondary components *of the vegetation as described in UNESCO (1973) and assume* that ecosystems can be reasonably described as the sum of

Table 1. Detailed vegetation types included in the raw data base of Matthews (1983) were grouped into 22 types. The main components of these 22 types are listed below, with brief descriptions and associated UNESCO (1973) codes.

#	UNESCO	DESCRIPTION
1	1.A.1	tropical evergreen rainforest
	1.A.2	tropical/subtropical evergreen seasonal forest
	1.A.3	tropical/subtropical semi-deciduous forest
	1.A.4	subtropical evergreen rainforest
	1.A.5	mangrove
	1.A.6	temperate/subpolar evergreen rainforest
2	1.A.7	temperate evergreen broadleaved seasonal forest
3	1.A.8	evergreen broadleaved sclerophyllous forest, winter rain
4	1.A.9	tropical/subtropical evergreen needleleaved forest
	1.A.10	temperate/subpolar evergreen needleleaved forest
5	1.B.1	tropical/subtropical drought-deciduous forest
6	1.B.2	cold-deciduous forest, with evergreens
	1.B.3A	temperate lowland/submontane cold-deciduous forest without evergreens
	1.B.3C	subalpine/subpolar cold-deciduous forest, without evergreens
	1.B.3B(1)	montane/boreal broadleaved cold-deciduous forest, without evergreens
	1.B.3B(3)	montane/boreal broadleaved and needleleaved cold-deciduous forest, without evergreens
7	1.B.3B(2)	montane/boreal needleleaved cold-deciduous forest, without evergreens (larch)
8	1C,2C, 3C,4C	extremely xeromorphic forest, woodland, shrubland, dwarf shrubland
9	2.A.1	evergreen broadleaved woodland
10	2.A.2	evergreen needleaved woodland
11	2.B.1	drought-deciduous woodland
12	2.B.2	cold-deciduous woodland, with evergreens
	2.B.3A	cold-deciduous broadleaved woodland, without evergreens
	2.B.3C	cold-deciduous broadleaved and needleleaved woodland without evergreens

13	2.B.3B	cold-deciduous needleleaved woodland, without evergreens (larch)
14	3.A,4.A	evergreen shrubland/dwarf shrubland
15	3.B,4.B	deciduous shrubland/dwarf shrubland
16	4.D	tundra (shrub, moss, lichen)
	4.E	mossy bog
	5.C.8	graminoid tundra (alpine)
17	5.A.1	tall grassland, 10-40% tree cover
	5.A.2	tall grassland, <10% tree cover
	5.A.4	tall grassland, tuft plant cover
	5.B.1	medium grassland, 10-40% tree cover
	5.B.2	medium grassland, <10% tree cover
	5.B.4	medium grassland, tuft plant cover
	5.C.1	short grassland, 10-40% tree cover
	5.C.2	short grassland, <10% tree cover
	5.C.4	short grassland, tuft plant cover
18	5.A.3	tall grassland, shrub cover
	5.B.3	medium grassland, shrub cover
	5.C.3	short grassland, shrub cover
19	5.A.5	tall grassland, no woody cover
	5.B.5	medium grassland, no woody cover
	5.C.5	short grassland, no woody cover
	5.C.6	
	5.C.7	meadow
	5.D	forb formations
	9	cultivation
20	6	desert
21	7	ice
22	1.A.10	temperate/subpolar evergreen needleleaved forest, east of 50 E., north of 50 N.

Table 2A. Major vegetation types of Model II (Hansen et al., 1983).

#	VEGETATION
1	desert
2	tundra
3	grassland
4	grassland with shrub cover
5	grassland with tree cover
6	deciduous forest
7	evergreen forest
8	rainforest
9	ice

Table 2B. The 22 land-cover types listed in Table 1 are redefined as proportions of 8 simple vegetation types or ice (see Table 2A) as shown below.

#	% 1	% 2	% 3	% 4	% 5	% 6	% 7	% 8	% 9
1	0	0	0	0	0	0	0	100	0
2	0	0	25	0	0	0	75	0	0
3	40	0	0	0	0	0	60	0	0
4	0	0	0	0	0	0	100	0	0
5	0	0	25	0	0	75	0	0	0
6	0	0	0	0	0	100	0	0	0
7	15	0	0	0	0	85	0	0	0
8	85	0	0	0	0	15	0	0	0
9	35	0	0	0	0	0	65	0	0
10	25	0	25	0	0	0	50	0	0
11	35	0	0	0	0	65	0	0	0
12	30	0	0	0	0	70	0	0	0
13	0	0	50	0	0	50	0	0	0
14	10	0	80	0	0	0	10	0	0
15	10	0	80	0	0	10	0	0	0
16	0	100	0	0	0	0	0	0	0
17	0	0	0	0	100	0	0	0	0
18	0	0	0	100	0	0	0	0	0
19	0	0	100	0	0	0	0	0	0
20	100	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	100
22	30	0	0	0	0	0	70	0	0

their individual components. For example, evergreen needleleaved forests (#4) are defined as 100% evergreen forest, while less dense evergreen needleleaved woodlands (#10) are defined as 50% evergreen forest, 25% grassland, 25% desert (bare soil), and evergreen shrublands (#14) are defined as 10% evergreen forest, 80% grassland, and 10% desert (bare soil). Using this redefinition method, in conjunction with the digital vegetation data base, we are able to create a data set at any resolution, with each cell described as a combination of percentages of each of 9 types (8 vegetation types and ice) as shown by:

$$1 = \sum_{j=1}^{9} Pj \qquad (1)$$

where j = cover type and Pj = proportion of the grid cell occupied by type j.

Surface boundary-condition data sets can then be produced, at any resolution, by weighting vegetation-related surface features by the areal proportion of the vegetation types in the cell, as shown by:

$$q = \sum_{j=1}^{9} (Pj\ qj) \qquad (2)$$

where q = boundary-condition surface feature, j = cover type, Pj = proportion of cell occupied by type j, and qj = boundary-condition surface feature for type j.

4. Land-Surface Characteristics

A. Albedo

We reviewed a comprehensive body of albedo literature to determine the completeness of spectral and seasonal measurements of vegetation types, and to identify types exhibiting similarities in spectral and seasonal reflectance behavior. The complete bibliography of albedo references used in this study is included as an Appendix. We found, not surprisingly, that agricultural crops, particularly during the growing season, are best represented in terms of spectral measurements, although many are published as radiance values which are not always translatable into percent reflectance and therefore not always comparable between spectral regions. Boreal and temperate forests, woodlands and tundras are reasonably well represented seasonally but less well covered in terms of spectral precision. Only 2 measurements were found for tropical rainforest.

We constructed curves of seasonal snow-free integrated albedo for major vegetation types well represented in the literature. At the same time, we compiled for vegetation types, from the more extensive but temporally restricted, spectral reflectance measurements, two series of complementary data: 1) spectrally discrete reflectance measurements, and 2) ratios of near-IR/visible reflectances, (either as radiance ratios or % reflectance ratios). We found it more common, in the remote sensing literature, to provide various forms of near-IR/visible ratios than to publish reflectances (either in % or in energy units) in individual spectral regions. These ratios, providing both seasonal and spectral information about the reflectance behavior of vegetation types, are useful complements to broad-band measurements; the ratios allowed us to integrate and in effect, to "extend" the seasonal, spectral and vegetation-type coverage of published measurements. However, there are still significant gaps in the seasonal and spectral measurement profiles of vegetation types.

Table 3 lists seasonal integrated snow-free albedo, near-IR/visible ratio, and visible and near-IR reflectance, for the 8 vegetation types; ice was not included here because the prescription and parameterization of snow and ice surfaces are unique to individual models. The spectral reflectances in Table 3 uniformly assume that 60% of the radiation incident at the surface is in the visible wavelengths (<.7 micrometers) and 40% is in the infrared (>.7 micrometers).

Several general patterns in the annual reflectivity behavior of vegetation are prominant. The increase in the integrated albedo from the early part of the growing season, i.e. spring, to the height of the summer growing season is followed by an autumn decline. The spring-summer trend is governed by stable or decreasing reflectance in the visible and increasing reflectance in the infrared. Seasonal variations in the visible wavelengths are modest, on the order of a few percent for snow-free conditions, while infrared variations are considerably larger, on the order of tens of percent. As a result, the ratio of IR/visible reflectivity (expressed as % reflectance in the two regions) generally increases during the course of the growing season, and declines in the fall.

Table 3. Land-surface boundary conditions were specified in GISS GCM II using the vegetation-related surface features shown below, weighted by the proportional grid-cell area occupied by each vegetation type (refer to Tables 2A and 2B, and discussion in text) (unabridged version of Table 6 in Hansen et al., 1983)

	1	2	3	4	5	6	7	8
Integrated Albedo (%)								
winter	35	12	16	16	14	18	12	11
spring	35	12	20	18	14	12	12	11
summer	35	17	20	25	17	15	15	11
fall	35	15	18	20	12	12	11	11
Ratio near-IR/visible								
winter	1.0	3.0	3.0	3.0	2.8	3.0	2.8	3.0
summer	1.0	3.8	4.0	3.0	3.8	5.0	3.0	3.0
Visible reflectance (%)								
winter	35	7	9	9	8	10	7	6
spring	35	6	10	10	7	5	7	6
summer	35	8	9	14	8	6	8	6
fall	35	8	9	11	6	5	6	6
Near-IR reflectance (%)								
winter	35	20	27	27	23	30	20	18
spring	35	21	35	30	24	22	20	18
summer	35	30	36	42	30	29	25	18
fall	35	25	31	33	20	22	18	18
Masking depth (m)	0.1	0.2	0.2	0.5	2.0	5.0	10.0	25.0
Roughness length (cm)	0.5	0.5	1.0	1.0	1.8	32.0	100.0	200.0
Field capacity (mm)								
layer 1	10	30	30	30	30	30	30	200
layer 2	10	200	200	300	300	450	450	450

B. Masking Depth

The variable increase in surface albedo produced by a given depth of snowfall over different vegetation types is roughly related to vegetation height and density. In the model, masking depth controls the increase in albedo associated with snowfall, and equals the snow depth at which the albedo of pure snow replaces the snow-free ground albedo (Hansen et al., 1983). The albedo of snow-covered ground, in Model II, is dependent upon the snow-free ground albedo, height and density of the vegetation cover, and age and depth of snow, as shown by:

$$A = Ag + (As - Ag)[(1-\exp(-ds/d_s^*)] \qquad (3)$$

where Ag = snow-free ground albedo, As = snow albedo, and ds and d_s^* = snow depth and masking depth, in equivalent thickness of liquid water (Hansen et al., 1983). In Model II, masking depths were subjectively defined for the 8 major cover types (Table 3) and range from .1 M for deserts to 25 M for rainforests, reflecting the increasing height and density characteristics of the vegetative cover.

C. Surface Roughness

Surface roughness, at 8° by 10° resolution of Model II, is determined primarily by large-scale topography. The roughness length related to vegetation is the lower limit of surface roughness and is effective in lowland regions covered by forests of significant height, such as the Amazon Basin. Roughness lengths for the 8 vegetation types were compiled from the work of Tanner and Pelton (1960), Kung (1961), Lettau (1969), Stanhill (1969), and Garratt (1977a,b). Low sparse cover types such as desert, tundra and various grasslands are associated with roughness lengths of < 2cm, while roughness lengths for forests range from 32 to 200 cm (Table 3).

D. Field Capacity

The amount of water available for evaporation at the ground or plant-canopy surface is a function of the amount of water in the soil and the efficiency of delivery of that water to an evaporative surface. This efficiency varies as a function of soil characteristics (e.g., conductivity, porosity), rooting depth and morphology, density, physiology and rainfall-interception characteristics of the vegetation cover, and the amount of water in the soil (see, for example, Slatyer, 1967; Hillel, 1971; Epstein, 1973; Rutter, 1975; Jarvis et al., 1976; Rauner, 1976; Ripley and Redmann, 1976; Miller, 1977; Williams et al., 1978; Johns et al., 1981; Larsson, 1981; Parton et al., 1981; Wallace et al., 1981; Yasada and Toya, 1981; Lockwood and Sellers, 1982; Sansigolo and Ferraz, 1982). In general, field capacity and hydraulic conductivity are inversely related; fine-textured soils (e.g., clay) have high water-holding capacity and low hydraulic conductivity, while coarse-textured soils (e.g., sand) have lower water-holding potential and higher hydraulic conductivity. In addition, hydraulic conductivity decreases exponentially with decreasing soil moisture. When the evaporative demand rate of the of the atmosphere is higher than the the water-delivery rate of the soil-vegetation complex, the reduced soil moisture in combination with declining conductivity can result in water stress, stomatal closure and abrupt decline in evapotranspiration. Dense vegetation, with high leaf area index, modulates potential evaporation primarily by exposing larger evaporative surfaces to direct contact with the atmospheric demand, and by directly intercepting and re-evaporating rainfall. Dense and/or deep roots increase the potential for water extraction and evaporation by increasing the proportion of the soil water in direct contact with an absorbing and conducting surface; very fine dense roots allow extraction of water from small pore spaces in low conductivity soils, effectively increasing the extractable water pool.

In Model II, evaporation from the surface is a function of potential evapotranspiration modified by an efficiency factor linearly proportional to the amount water in the upper ground layer (Hansen et al., 1983). Interactive modulation of evaporation by the plant-soil complex, as discussed above, was simulated but not explicitly parameterized; diffusion of water from the lower to the upper ground layer was allowed in vegetated regions during a growing season defined by date and the general enhancement effect of vegetation on evaporation at the surface was subjectively approximated by defining high field capacities in both ground layers for the dense vegetation types, with lower field capacities for sparser and more arid types (Table 3). Increasing field capacities, in both ground layers (f_1 and f_2), from f_1 = 10 mm, f_2 = 10 mm for deserts to f_1 = 200 mm, f_2 = 450 mm in tropical rainforests accommodate the general trend of greater efficiency of water extraction and delivery to the surface with increased rooting depth, and higher vegetation- and root-density.

E. Summary

The prescribed land-surface characteristics discussed above were used in conjunction with the digital vegetation data

(Tables 1, 2A and 2B) to define surface-boundary conditions for Model II, according to eqs. 1 and 2. Snow-free albedo was defined for 4 seasons with linear interpolation between seasons; masking depth, surface roughness and field capacity remain constant throughout the year. Geographic distributions of surface boundary conditions resulting from the method described here, along with the results of sensitivity studies related to these prescriptions, are presented in Hansen et al. (1983).

5. Final Remarks

We have presented an efficient method whereby detailed, fine-resolution vegetation data were used to refine the specification of land-surface boundary conditions and the parameterization of land-surface processes in the GISS GCM II (Hansen et al, 1983). The main focus of the effort was on surface albedo prescriptions, including masking depth. Hydrology-related surface features and parameterizations, such as field capacity and evaporation, were crudely simulated in the absence of detailed soil information. A recently-compiled soil data base (Zobler and Cary, 1984) will form the basis, in conjunction with vegetation and land-use data bases of Matthews (1983) for explicit and more realistic parameterization of land-surface processes in Model III, with emphasis on the hydrologic cycle.

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Albedo Appendix

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16. Abstract

A simple method was developed for improved prescription of seasonal surface characteristics and parameterization of land-surface processes in climate models. This method, developed for the Goddard Institute for Space Studies General Circulation Model II (GISS GCM II), maintains the spatial variability of fine-resolution land-cover data while restricting to 8 the number of vegetation types handled in the model. This was achieved by: redefining the large number of vegetation classes in the 1° resolution Matthews (1983) vegetation data base as percentages of 8 simple types; deriving roughness length, field capacity, masking depth, and seasonal spectral reflectivity for the 8 types; and aggregating these surface features from the 1° resolution to coarser model resolution, e.g. 8° latitude x 10° longitude or 4° latitude x 5° longitude. Abridged results of the method were presented in Hansen et al. (1983). In this report, we present the complete methodology.

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