GLOBAL DATA SETS FOR LAND SURFACE SCHEMES AND EXPERIENCE IN THE INCORPORATION OF VEGETATION INTO ATMOSPHERIC GENERAL CIRCULATION MODELS.

A.J.Pitman
Liverpool University
Liverpool, England.

A.Henderson-Sellers
Macquarie University
North Ryde, Australia.

J.G.Cogley
Trent University,
Peterborough, Canada

1. ABSTRACT

The availability of global data sets for use in General Circulation Models (GCMs) is reviewed. Global data sets exist to support the most complete land surface parameterization schemes, provided that algorithms to average the data to an appropriate resolution are used carefully.

A new land surface scheme (Bare EsSenTials, BEST) which incorporates vegetation and that has been used as the surface physics package in a GCM is briefly discussed. The effects of incorporating BEST in the Canadian Climate Centre (CCC) GCM are described, followed by a discussion on the effects of removing the canopy element of this parameterization on the simulated climate.

It is pointed out that global data sets now available are good enough to support models of vegetation in GCMs, and that it has become necessary to include some representation of the canopy in climate change or climate prediction experiments. The major differences simulated by the CCC GCM with and without the inclusion of a canopy suggests that simulations by GCMs which fail to incorporate vegetation will not be reliable.

2.1 INTRODUCTION

Since Mintz (1984) wrote his review on the sensitivity of numerically simulated climates, a number of more sensitive perturbation experiments have been conducted. Rather than testing the sensitivity of the atmosphere to massive perturbations at the land surface (cf Shukla and Mintz, 1982), attempts have been made to assess how land surface schemes need to be improved, and which elements in any parameterization are most important, in the simulation of the Earth's climate.

Wilson et al. (1987) examined the sensitivity of the National Centre for Atmospheric Research (NCAR) Community Climate Model (CCM) (in regions of tundra vegetation) to a number of comparatively small changes in the formulation of the land surface model described by Dickinson et al. (1986). They found that the simulation of the atmosphere was sensitive to the state of the surface, and in particular, to the surface moisture regime. Pitman et al. (a, in prep) used the Canadian Climate Centre (CCC) GCM to examine the influence of soil texture on climate simulations. It was found that at high northern latitudes, large changes in the soil thermal and hydrological regime could be induced by running the CCC GCM with a globally average soil texture instead of the soil texture usually prescribed for a grid box.

Both these studies used the global data set of Wilson and Henderson-Sellers (1985) to provide the canopy and soils information required by the land surface parameterizations. In both studies, this data set was modified in some way, in order to investigate the response to some change. Pitman et al. (a, in prep) commented that, with reference to soil texture, the actual value used in the GCM at high latitudes needs to be rather close to the "actual" or "real" value. If the soil texture is poorly prescribed then the regional climate simulated by the GCM will be unreliable.

Here we briefly review the main types of global data that are available to the climate modelling community. It will be shown that although there are relatively few choices at present, enough data sets exist to provide climate modellers with those data they require.

Two experiments with the CCC GCM will then be discussed. The effects of incorporating BEST in the CCC GCM and the effects of removing the canopy element on the simulated climate will be described.

2.2 Global data sets

This review is taken largely from a recent NCAR technical note (Henderson-Sellers et al., 1986) who described seven global archives. These are the main global data sets available to the global climate modelling community.

Matthews (1983,1984a,1984b,1985) produced a global archive of land cover and natural vegetation for incorporation into the Goddard Institute for Space Studies (GISS) GCM. This data set provided natural vegetation data and a cultivation intensity index (Figure 1) which could be integrated to provide an estimate of the present day land cover type. Matthews (1983) condensed her archive specifically for the use of climate modellers.

Wilson and Henderson-Sellers (1985) describe a second global land cover archive. It was developed for use in the UK Meteorological Office (UKMO) 11 layer GCM, but has also been used in the CCC GCM and the NCAR CCM. This data set provides the "current" land cover type, rather than the natural vegetation type. Wilson and Henderson-Sellers (1985) also provided a global soils data base containing soil colour, texture and drainage characteristics (Figure 2) which can be linked to the vegetation data base to provide a coherent archive of soils and vegetation data. A more complete soils data set was provided by Gildea and Moore (1986). Although both data sets are derived from the FAO/UNESCO (1974) soils map of the world, the Gildea and Moore (1986) archive is at a higher resolution and contains more of the original data than Wilson

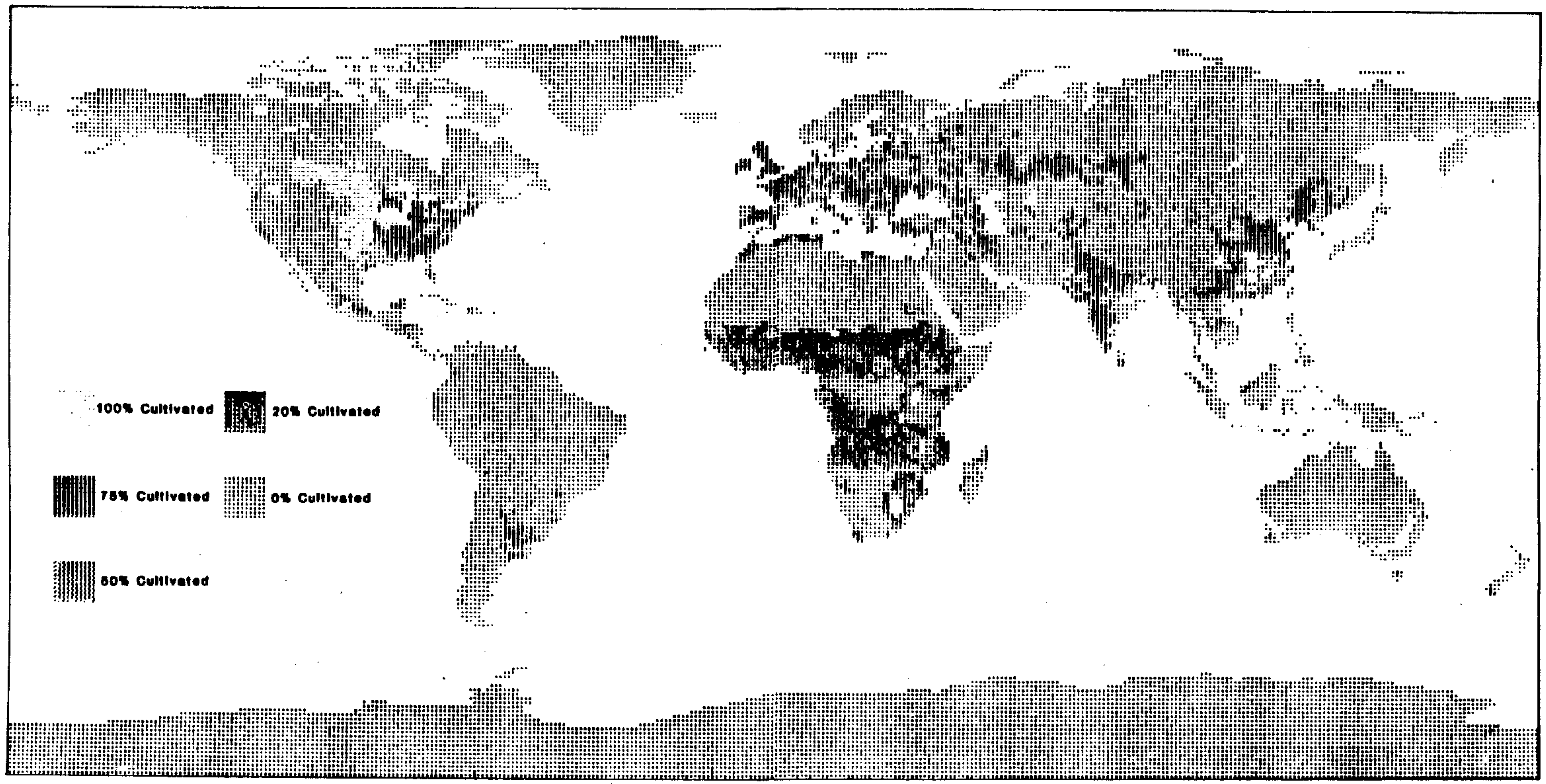


Figure 1. Cultivation intensity (after Matthews, 1983)

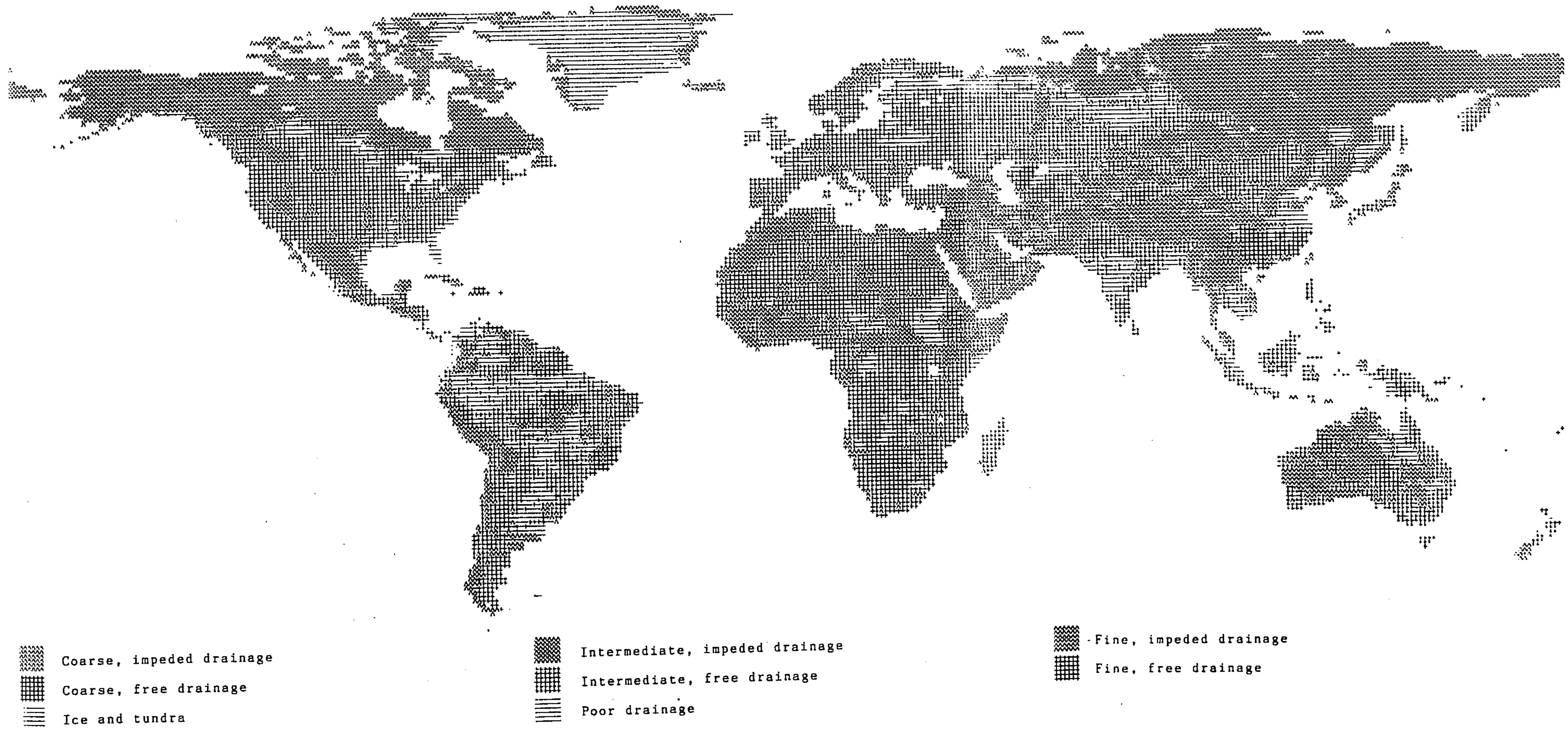
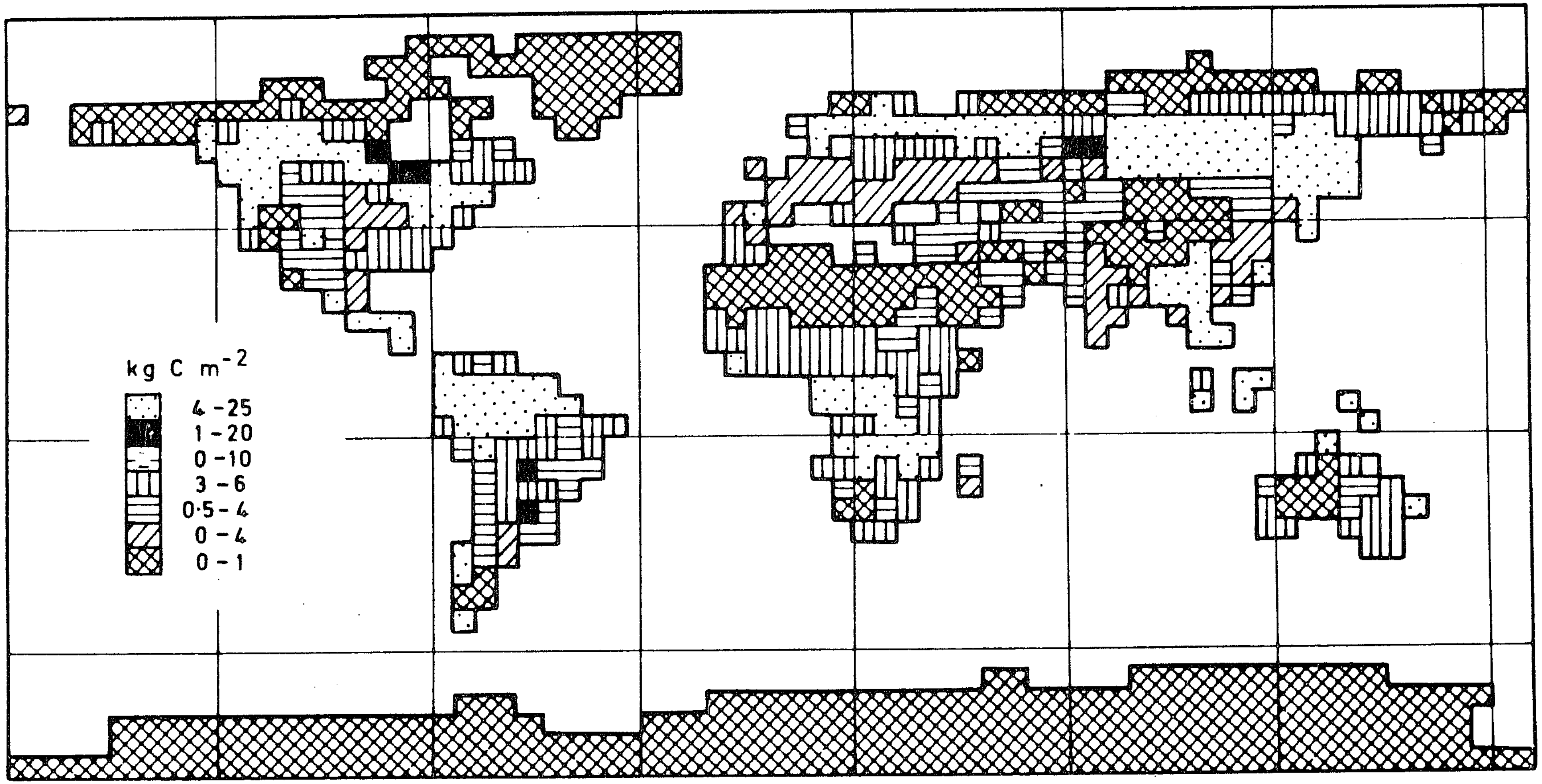


Figure 2. Global distribution of soil texture and drainage (after Wilson and Henderson-Sellers, 1985)

and Henderson-Sellers (1985) archive. However, the 1° by 1° resolution of the Wilson and Henderson-Sellers (1985) archive make it ideal for climate modelling purposes.

Olson et al. (1983) provided a global ecotype classification based on and expanded from the Hummel and Reck (1979) data archive. This data set classifies vegetation types on the basis of carbon density or biomass (Figure 3). It is not yet relevent to the modelling of the land surface in GCMs, but as models become more sophisticated, and as accurate CO_2 climate change predictions become more urgent, it may become more valuable.

A satellite derived global vegetation data base has been under development at the National Oceanic and Atmospheric Administration (NOAA) using the NOAA-7 Advanced Very High Resolution Radiometer (AVHRR). Known as the Global Vegetation Index (GVI) it is intended to provide a data set at a resolution of 15-30km and at a temporal resolution distinct from the "one off" approach of the atlas derived data sets. The spatial and temporal resolution can be averaged to the resolution appropriate to any specific GCM, thus the GVI provides an attractive qualitative description of land cover characteristics and land cover changes (Figure 4). However, Thomas and Henderson-Sellers (1987) showed that the GVI can not yet provide a consistent data set. They evaluated the suitability of the GVI as a source of land cover characteristics for GCMs, focussing on two aspects of the data set in particular; the necessary maximization time period for removal of atmospheric contamination and the regional compatability of the recovered values. Previous studies had indicated that a 3 or 4 week compositing of the basic weekly GVI product reduces the level of contamination by cloud, snow and scan angle effects (Users' Guide, 1983; Justice et al., 1985) although it was not entirely clear what percentage of pixels remain contaminated at the end of 3 or 4 weeks. In addition, extended time period compositing may lead to confusion between vegetation activity and removal of contamination such as clouds. The GVI has been shown to exhibit



<u>Figure 3.</u> Standing biomass (kg of carbon) at 5° x 5° generated from the Olsen <u>et al.</u> (1983) data archive.

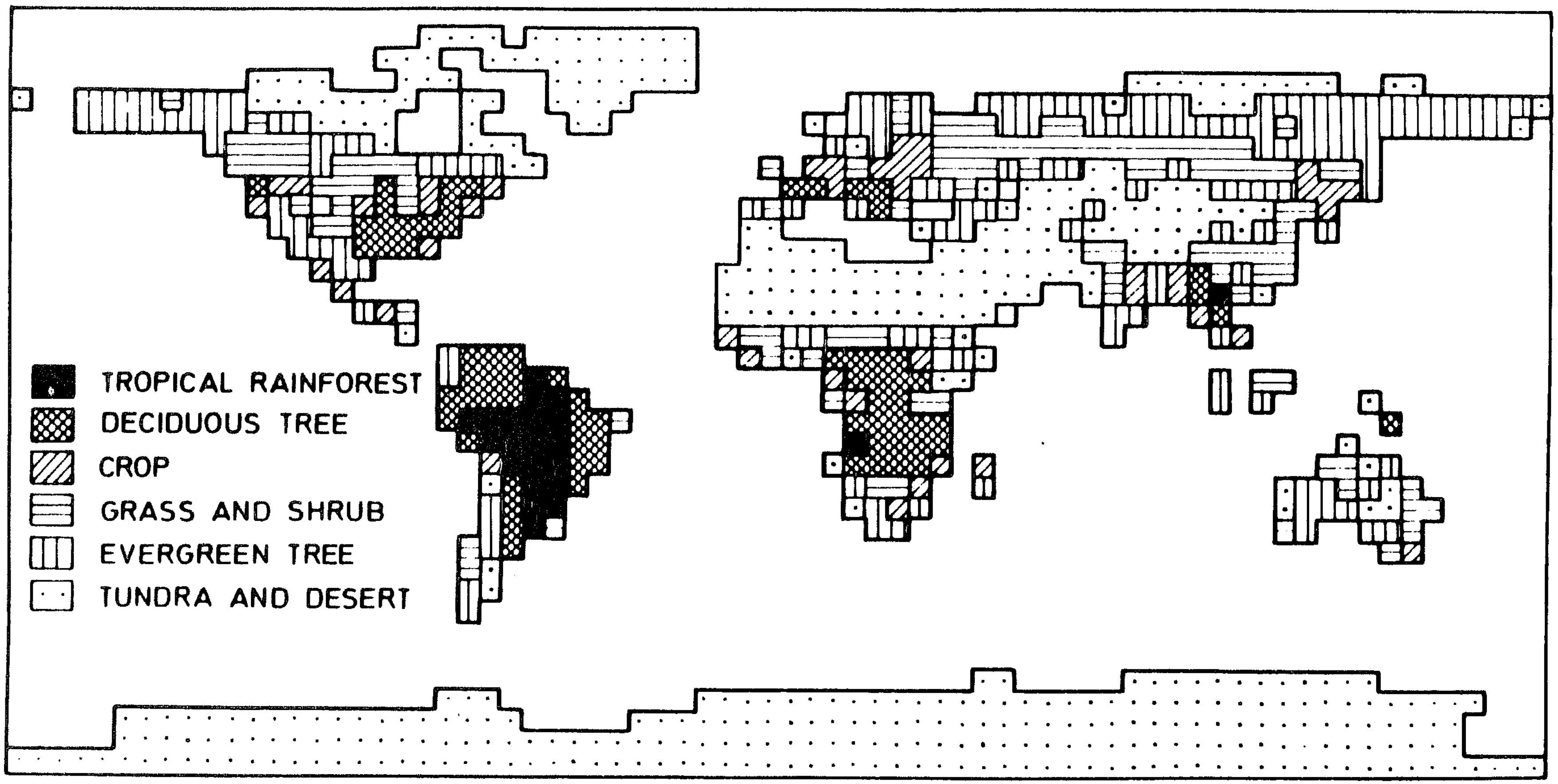


Figure 4. NOAA normalized vegetation index derived distribution of major ecotypes (5° x 5°) established from one year's data (May 1982 to April 1983, and taking one 7-day composite from each month represented).

considerable seasonal variations for particular vegetation formations (Tucker et al., 1983; Justice et al., 1985) and consequently vegetation induced changes in the GVI may become obscured when compositing (to remove atmospheric effects) is carried out over an extended time period. Thomas and Henderson-Sellers (1987) considered three study regions over three different time periods (17 weeks in all). Considering the general acceptance of a 3 or 4 week compositing period, they found that a suprisingly high percentage of pixels were still being maximised after these periods. After 3 weeks in May/June 1982, three 20° x 20° regions in North America , South America and Africa had 92%, 14% and 29% of their pixels altered while for a four and five week period in July/August 1982 the same three regions had 1%, 25% and 33% (4th week) and 39%, 5% and 54% (5th week) respecively altered by sequential maximization.

Interpretation of this continuing alteration in pixel values of the GVI is difficult. As photosynthetic activity in a particular region increases (decreases), so the percentage of pixels exhibiting a change in clear-sky GVI value should increase (decrease). The continued increase in the number of pixels being maximized after the standard compositing period could therefore be taken as an indication of increasing biophysical activity (although this can only be confirmed by ground truth data). All methods of classification are likely to be less successful in marginal areas where vegetation is stressed or dying and/or bare soil composes part of the pixel area. Where the vegetation cover is green but discontinuous, the relationship between the GVI and the land-cover is weakened, leading to problems in interpretation (Harris, 1986). These difficulties were underlined by Sellers (1985, pp 1365 and 1366): "the presence of even a small proportion of bare ground (as opposed to an even distribution of vegetation) may seriously complicate the interpretation of multispectral data" and "the presence of even a small fraction of dead leaves in the canopy would apprear to reduce (the) vegetation index...drastically."

Recently Choudhury and Tucker (1987a,b) have suggested using microwave radiance data to supplement information about vegetation characteristics in areas of incomplete ground cover. Microwave surface brightness depends upon a number of factors including soil moisture, surface roughness and vegetation water content. As the latter increases the sensed surface brightness decreases in the 6-37 GHz frequency range. Moreover vegetation induces a strong depolarization at 37 GHz so that the difference between the vertically and horizontally polarized brightness temperatures is about 25K for dry bare soils but is 5K or less over short crops such as alfalfa. Choudhury and Tucker (1987a) showed that the temporal variation in this difference follows the phenology of the vegetation and, in some areas, is inversely related to the GVI. This inverse relationship has been extended to a number of other areas by Choudhury and Tucker (1987b), who show that the 37 GHz polarization differenced brightness temperatures have the potential to extend the sensitivity of remotely retrieved data to vegetation characteristics in areas where the GVI is a relatively poor indicator. This suggests that mounting 37 GHz systems with spatial resolutions of 5 and 10 km will offer an invaluable data source for the study of arid and semi-arid vegetation.

The classification and aggregation methods employed with these satellite data require urgent review since, at present, there seems to be poor understanding of spatial concepts among many of those generating and using these data. For example, the GVI data were originally supplied in the form of two hemispheric (1024 x 1024 pixels) polar stereographic arrays but, more recently, the archive has begun to be re-mapped and distributed on Mercator and plate carree projections (NOAA, 1988). A vitally important failing common to all these projections is that they are not <u>equal area</u>. In the arrays of these three projections used by NOAA the area on the ground represented by individual array elements varies considerably (see below).

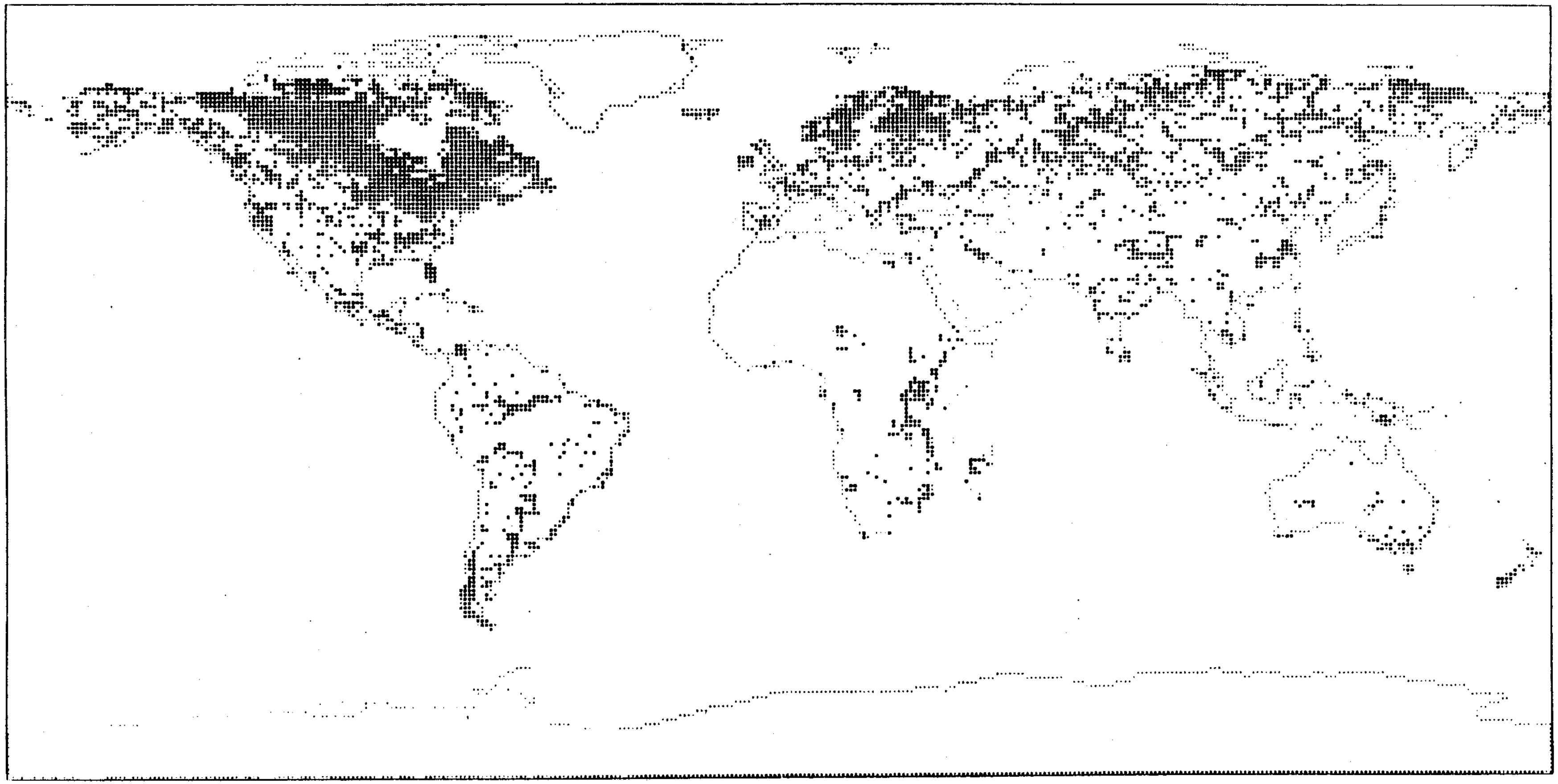
Projection	Equator	60° N & S
polar stereographic	162 km^2	567 km^2
plate carree	256 km^2	128 km^2
Mercator	380 km^2	95 km^2

(from Lloyd and D'Souza, 1987).

Since the raw satellite radiances are retrieved for normally uniform spatial resolution, such remapping onto non equal area projections inevitably shows some parts of the Earth's surface in greater detail than others. Both data duplication and redundancy distort the archived data in any such area. The use of equal-area radial projections (e.g. Peters, 1983) should be encouraged especially when it is recognised that such projections contain more information for a similarly sized array than any of those currently used and permit straightforward projection changes. The advantage of radial projections for archival and display of satellite data extend to other digital data displays such as output from GCMs and have the additional benifit of providing an egalitarian representation of the Earth's surface. The data input to the GVI have pixel resolution of 1 x 3 km and even the "coarse" resolution microwave data have resolutions of about 5 to 10 km which are very different from the spatial resolution of grid elements in GCMs. Great care will therefore be required if this relatively high resolution satellite data is to be used to construct land surface characteristic fields of resolution of about 5° (i.e 500 km x 500 km).

The final global data set has been provided by Cogley (1986) (e.g Figure 5). This hydrographic data set provides a description of the areal coverage of different types of water body on the land surface. In each 1° by 1° grid cell, the percentage coverage of lake, river, marsh, ice etc and stream frequency (in counts per grid cell) are provided. This data set is the only one from which information concerning surface water can be ascertained.

Although this archive is not used in any GCM, the



<u>Figure 5.</u> Global distribution (1° x 1°) of perennial freshwater lakes derived from the THYDRO data set of Cogley (1985). The map shows those 1° x 1° element which contains any percentage of perennial freshwater.

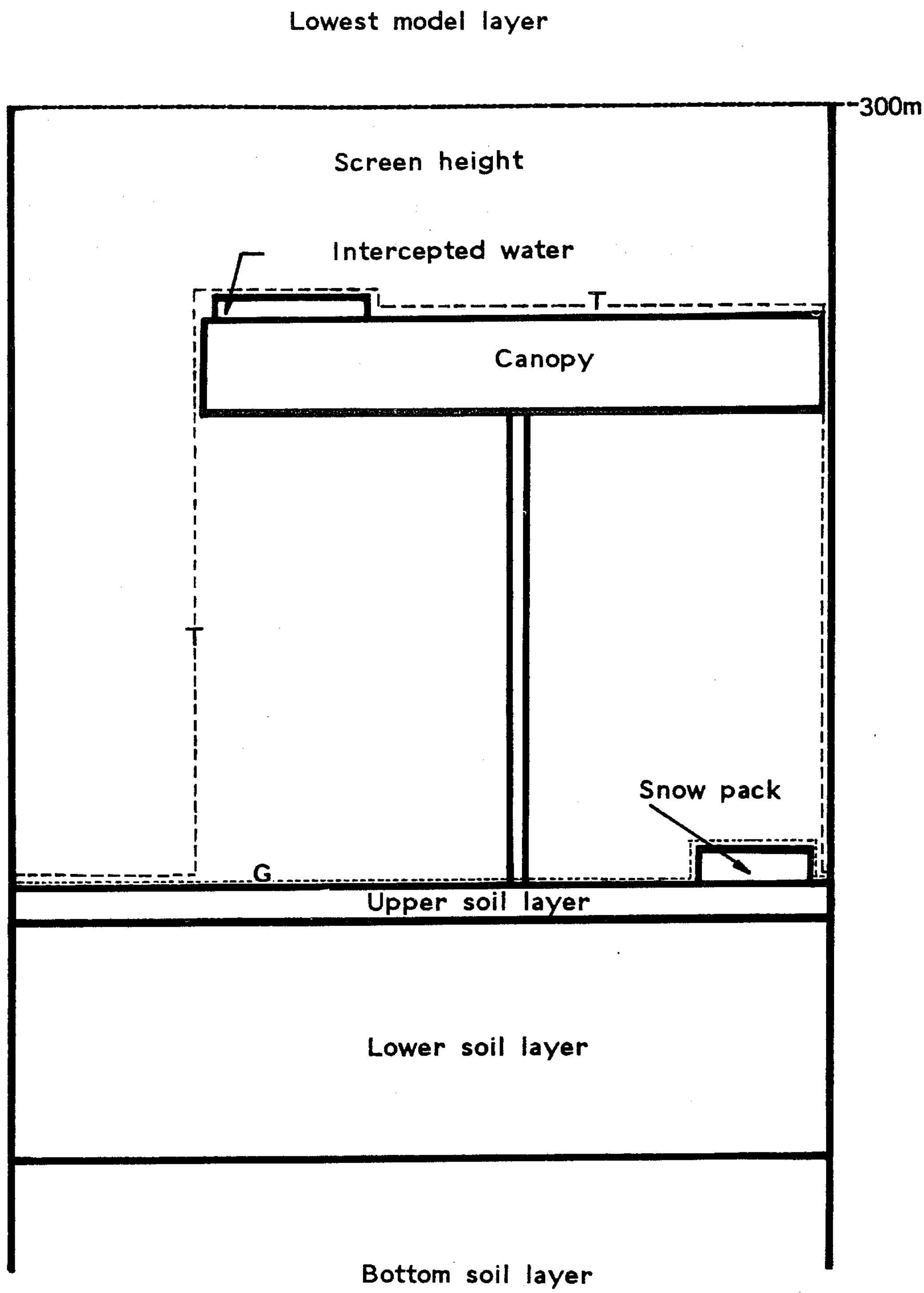
distribution of open water at the land surface is important. At present, unless the open water is assumed to cover the entire grid square, (as a background field), it will not be accounted for in the calculation of surface fluxes. Present land-surface schemes could be modified to accommodate this part of Cogley's (1986) data set relatively easily.

Henderson-Sellers et al. (1986) suggested that it would be useful to attempt to provide an "agreed" global vegetation data set from the archives of Matthews, Wilson and Henderson-Sellers and the GVI. This suggestion does not seen to have been taken on board. There is clearly a need to do this since simulations by the GISS GCM using Matthews data and simulations by the UKMO(11), NCAR and CCC GCMs using Wilson and Henderson-Sellers (1985) data are not easily comparable. If all GCMs used a common soil and vegetation data set we could examine and compare different land-surface parameterizations rather than different background fields rather more easily.

2.3 Experience with canopies in GCMs.

Until recently, the CCC GCM incorporated a "bucket" type surface hydrology package (Boer et al., 1984). Pitman (1988) developed a new parameterization of the land surface for the CCC GCM. The new model, "Bare EsSenTials" (BEST) was developed to provide the minimum, or bare essentials, of a land surface scheme (Figure 6) (full details will be available in Pitman et al., b, in prep.). BEST has been designed to consider each element of the land surface system at an appropriate and similar level of sophistication - i.e the canopy is represented as a single layer and the soil as two layers. BEST calculates three moisture stores and three temperatures (two soil and one canopy).

This balance of a single canopy layer with two soil layers was found to be adequate to account for the canopy hydrological characteristics and the seasonal and diurnal stores of soil heat and moisture. Without the second soil layer, seasonal



---- T denotes the "terrestrial surface" , a weighted average of canopy and unvegetated surfaces.

········ G denotes the "ground surface" , a weighted average of bare and snow covered soil

Figure 6. The basic structure of BEST, showing the main stores represented by the model.

effects (in particular freeze-thaw cycles at high latitudes), could not be simulated. The incorporation of the canopy was essential in order to parameterize the space and time variability, and partitioning between, fluxes of sensible and latent heat from the surface to the lowest model layer, in particular during and after precipitation events.

BEST accounts for all fluxes of water and energy, including surface and sub-surface runoff, soil sensible, latent and longwave fluxes, canopy transpiration, sensible, latent (re-evaporation of intercepted water) and longwave fluxes. BEST uses the background soil and vegetation data from Wilson and Henderson-Sellers (1985). A seasonal variation is imposed onto the fraction of the GCM's grid box that is vegetated, and onto the physiological characteristics of the vegetation.

Pitman (1988) showed that BEST was able to simulate a variety of ecotypes realistically in a stand-alone mode for an annual cycle. When BEST was incorporated into the CCC GCM the simulated climate was generally improved. In particular, areas of maximum precipitation over India and Central Africa were shifted to much more realistic positions (Figure 7) over regions of dense vegetation.

By incorporating BEST the overall temperature of the land surface was cooled quite markedly. The problem appeared to be an excessive availability of water. In the CCC GCM without BEST evaporation from the ground surface takes place from a bare surface according to the potential evaporation rate and the soil wetness. In the CCC GCM with BEST, the wetness of the upper soil layer becomes less important if the grid square is vegetated. Transpiration from the canopy leds to higher latent heat fluxes because the lower soil layer was often wet enough to provide water (for transpiration) even if the upper soil layer became dry.

The latest version of BEST is to be tested in the CCC GCM next month. Stand-alone tests suggest that the main problem in the earlier experiment (surface temperature too cool) has been solved by a reformulation of the canopy temperature and

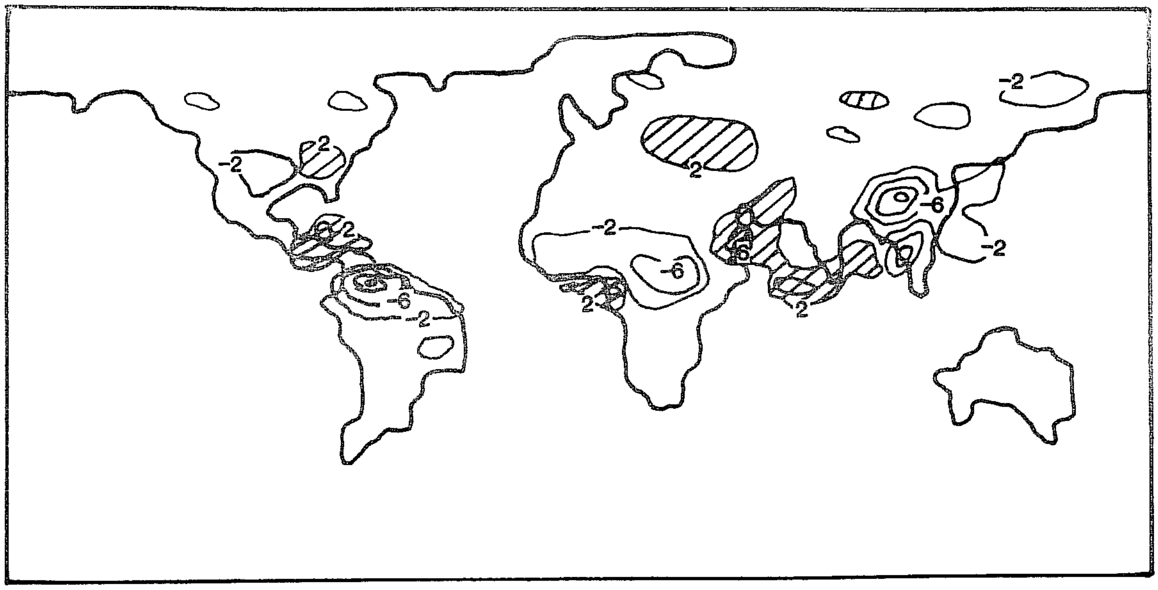


Figure 7. Difference between the J,J,A precipitation rate simulated by the CCC GCM incorporating BEST (experiment) minus the CCC GCM without BEST (control). Contour interval 2 mm d^{-1}.

Figure 8. Difference between the J,J,A terrestrial temperature simulated by the CCC GCM without a canopy (experiment) minus the CCC GCM with a canopy (control). Contour interval 2K. Shaded regions < -1K.

transpiration rate.

In the past the lower soil layer in a GCM would not warrant much attention. However Rind (1988) pointed out that results from climate change simulations with the Goddard Institute for Space Sciences (GISS) GCM were sensitive to the hydrological regime in the previous season. The lower soil layer in GCMs stores heat and moisture on a seasonal time-scale. It is clear, at least with the CCC GCM, that unless the removal of water from this layer, and the redistribution of heat from it, could be simulated reasonably, then the partitioning of available energy at the land surface between latent and sensible heat would not be modelled well. It is clearly pointless to incorporate a canopy if it simply leads to a worse simulation due to an inability to calculate and re-distribute soil moisture properly. However, it is also probably impossible to simulate surface fluxes and the surface temperature properly without the canopy (e.g. Deardorff, 1978; Taconet et al., 1986).

The climate simulated by the CCC GCM with and without the canopy element of BEST is quite different. Figure 8 shows the terrestrial surface temperature difference for the CCC GCM with and without BEST. The terrestrial temperature is the grid box mean surface temperature taking into account the fraction of the grid box that is vegetated, bare ground or snow covered (see Figure 6). Over regions where there has been the most drastic change (e.g tropical forest areas) the terrestrial temperature is up to 7K warmer. Elsewhere temperature changes of 3-5K are commonplace. A major change in the partitioning between latent and sensible heat takes place with reductions in the latent flux (including transpiration) of up to 100 W m^{-2} in central west Africa and falls of more than 60 W m^{-2} over large areas (Figure 9). The sensible heat flux is larger in these areas by a similar amount (Figure 10). The most dramatic change, however, takes place in the soil water store. Figure 11 shows the upper soil layer moisture store. Excluding high northern latitudes and desert regions where there are only a

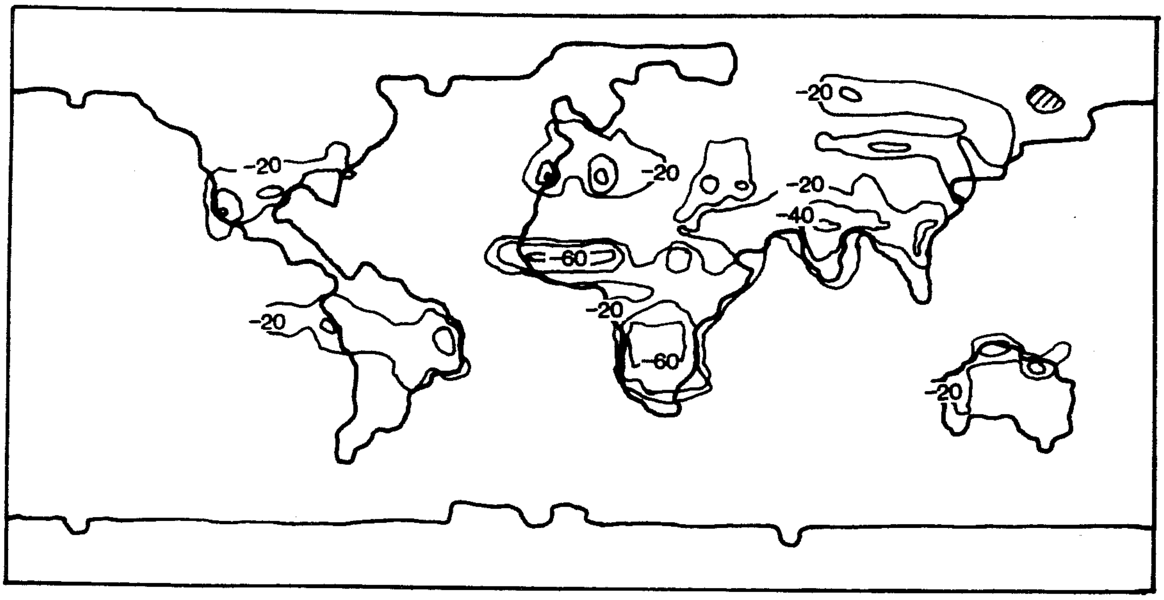


Figure 9. As Figure 8 but for the latent heat flux. Contour interval 40 W m^{-2}. Shaded regions > 20 W m^{-2}.

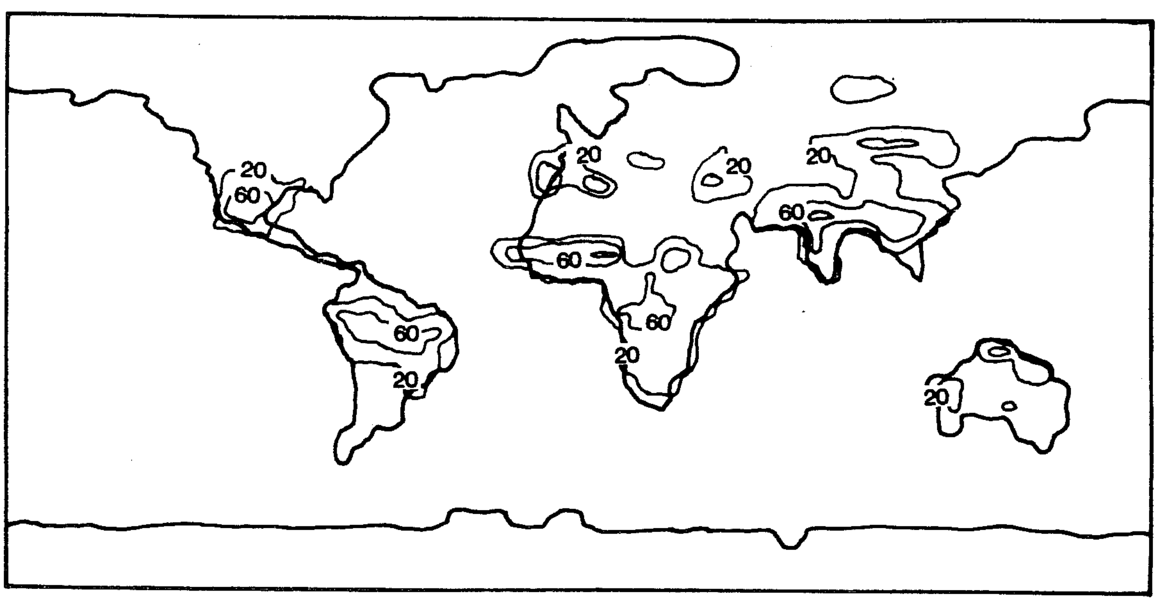


Figure 10. As Figure 8 but for the sensible heat flux. Contour interval 40 W m^{-2}.

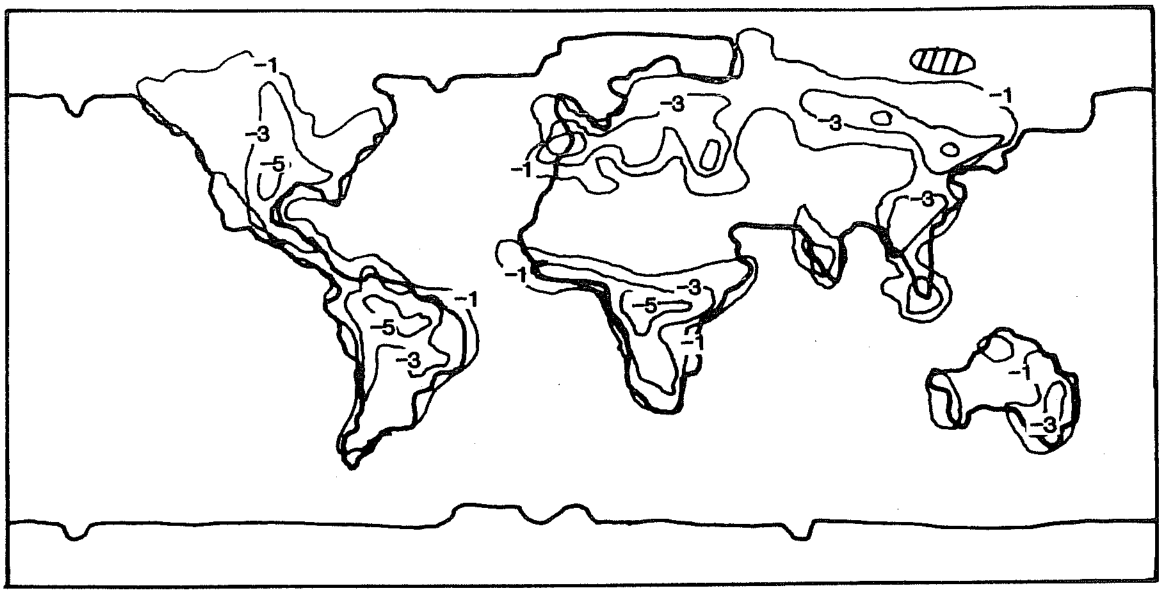


Figure 11. As Figure 8 but for the wetness of the upper soil layer. (Contour interval 2, expressed as a fraction of field capacity). Note that the units should be interpreted as percentage change / 10 - i.e 3 = 30% change etc. Shaded regions > 2.

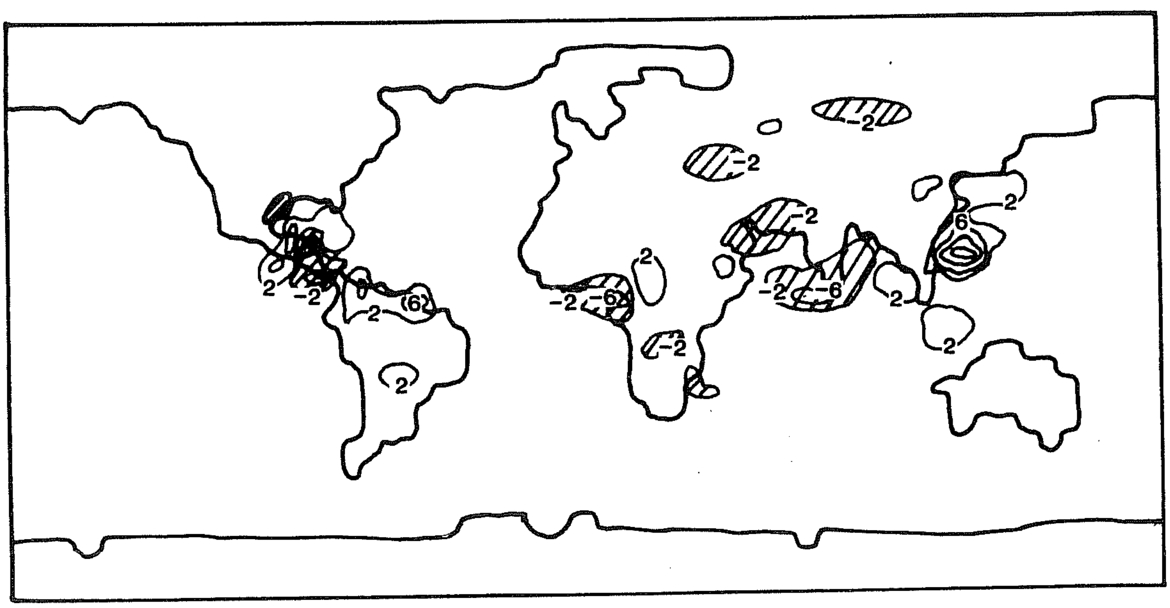


Figure 12. As Figure 8 but for the precipitation rate. Contour interval 2 mm d^{-1}. Shaded regions > 2 mm d^{-2}.

few minor changes, most of the world undergoes a drastic modification. Note, for instance, South America where in one region the soil wetness has been reduced by 50% due to the removal of the forest. South Africa, and parts of North America undergo similarly large falls in the soil moisture store. Some of these changes are due to the change in the precipitation pattern (Figure 12). The removal of tropical forest over South America and Central Africa leads to large falls in the precipitation rate, and therefore a fall in the soil moisture level in these regions. Finally, Figure 13 shows the lowest model level temperature. South America is very much warmer (9-11K), southern Africa and India are 5-7K warmer while most of the land surface between 10°N and 40°N is 1-5K warmer.

Although the general climate of the atmosphere can be simulated without a canopy, precipitation patterns seem to be offset in the CCC GCM when the canopy is not included, whereas with BEST, the precipitation maxima occur over areas of vegetation and are thus simulated rather better. Without the canopy the CCC GCM simulated a much warmer, drier surface climate, and a warmer lowest model layer. For climate change experiments, where regional climates are to be analysed (e.g Rind, 1988) it may be essential to incorporate a canopy. It is clear from the preceeding maps that the control climatology in any climate change experiment with the CCC GCM will be very different if a canopy is included, and there is a strong likelihood that the "vegetated" GCM would respond differently to a climate perturbation compared to the more common "bare ground" GCM.

3. Discussion and conclusions

The global archives of soils and vegetation are essential prerequisites, if the parameterization of the land surface in GCMs is to continue to advance. Models which incorporate soils and vegetation data and could be modified to include the hydrologic data set of Cogley (1986). From these basic global

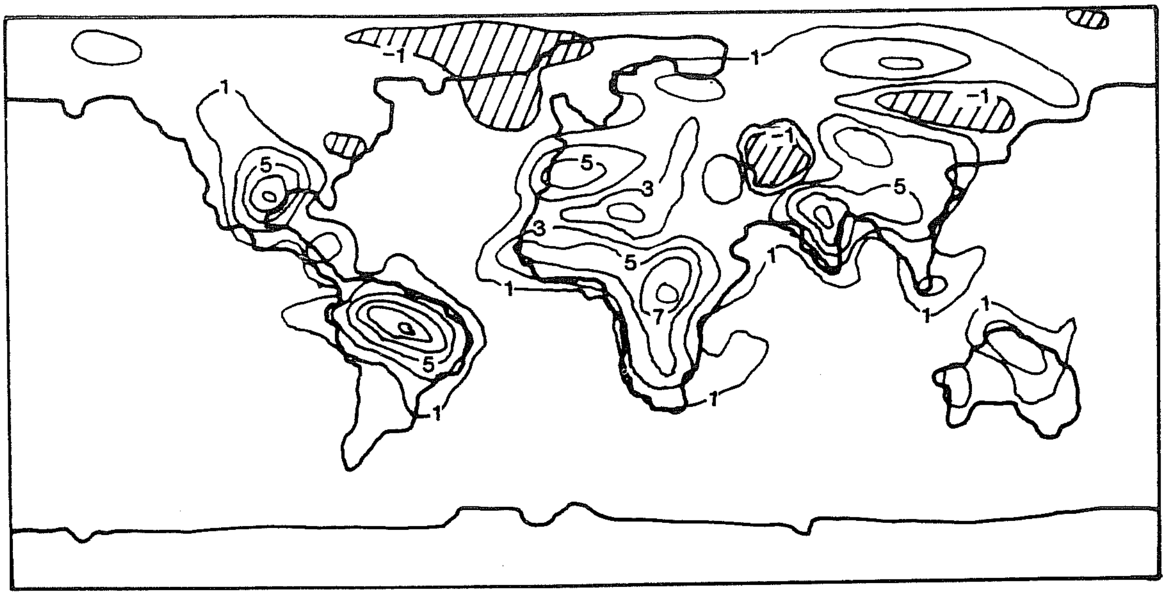


Figure 13. As Figure 8 but for the lowest model layer temperature. Contour interval 2K, shaded regions < -1K.

data sets a variety of other valuable data could be derived including, for instance, the effective surface roughness length, surface albedo, minimum stomatal resistance, a measure of slope for soil drainage efficiency, soil thermal and soil hydrological characteristics. Many of these are shown in Henderson-Sellers et al. (1986), but there is still an arguement on how to derive the effective roughness length, and what the result physically means (see Shuttleworth, 1988).

It has been shown that incorporating BEST into the CCC GCM improves the climate simulated by the model. Further, removing the canopy element has a dramatic effect on the modelled climate. In particular, the surface moisture, energy balance and temperature undergo major changes.

The importance and value of vegetation in GCMs is therefore in the process of being proved. Its inclusion certainly changes the simulated climate, and in most all cases the new climatology is a distinct improvement. This is a suprise since most GCMs will have become tuned to produce a reasonable climatology despite the inaccuracies in their surface parameterization. Since the computational expense is comparatively small, GCMs should incorporate a canopy parameterization. For regional scale climatic perturbation experiments, and for climatic predictions which seek to describe the state of the surface or the changes at the surface, an advanced parameterization of the land surface has become a necessity.

References.

Boer, G.J., McFarlane, N.A., Laprise, R., Henderson, J.D. and Blanchet, J-P., 1984, The Canadian Climate Center spectral atmospheric general circulation model, Atmosphere - Ocean, 22, 397-429.

Choudhury, B.J. and Tucker, C.J., 1987a, Satellite observed seasonal and interannual variation of vegetation over the Kalahari, The Great Victoria Desert and the Great Sandy Desert: 1979-1984, Rem. Sens. Env., 23, 233-241.

Choudhury, B.J. and Tucker, C.J., 1987b, Monitoring global vegetation using Nimbus-7 37 GHz data: some empirical relations, Int. J. Rem. Sens., 8, 1085-1090.

Cogley, J.G., 1986, THYDRO: A terrestrial hydrographic data set.

Deardorff, J.W. 1978, Efficient prediction of ground surface temperature and moisture with inclusion of a layer of vegetation, J.Geophys.Res., 83, 1889-1903.

Dickinson, R.E., Henderson-Sellers,A., Kennedy, P.J. and Wilson, M.F., 1986, Biosphere Atmosphere Transfer Scheme (BATS) for the NCAR Community Climate Model, NCAR Technical Note, NCAR, TN275+STR, 69pp.

FAO/UNESCO, 1974, Soil map of the world, 1:5,000,000, FAO,Paris.

Gildea, M.P. and Moore, B., 1986, FAOSOL - A global soils archive (in prep.).

Harris, R., 1986, Vegetation index models for the assessment of vegetation in marginal areas, in Proceedings of the ISLSCP Conference on Parameterization of Land-Surface Characteristics; Use of Satellite Data in Climate Models, and First Results of ISLSCP, Rome, 2-6 December, 1985, ESA SP-248, 584pp.

Henderson-Sellers, A., Wilson, M.F., Thomas, G. and Dickinson, R.E., 1986, Current global land surface data sets for use in climate related studies, NCAR tech. note, TN-272+STR,110pp.

Hummel, J. and Reck, R., 1979, A global surface albedo model, J.Appl. Meteor., 18, 239-253.

Justice, C.O., Townshend, J.R.G, Holben, B.N. and Tucker, C.J., 1985, Analysis of the phenology of global vegetation using meteorological satellite data, Int. J. Rem. Sens., 6, 1271-1318.

Lloyd, D. and D'Souza, G., 1987, Mapping NOAA-AVHRR imagery using equal-area radial projections, Int. J. Rem. Sens., 8, 1869-1878.

Matthews, E., 1983, Global vegetation and land use: new high-resolution data bases for climate studies, J.Clim.Appl. Meteor.,22, 474-487.

Matthews, E., 1984a, Prescription of land-surface boundary conditions in GISS GCM (II) and Vegetation, land-use and seasonal albedo data sets: Documentation of archived data tape, NASA, Goddard Institute for Space Science, New York, N.Y., 20pp. and 9pp.

Matthews, E., 1984b, Vegetation, land-use and seasonal albedo data sets: Documentation of archived data tape. NASA tech. memo. 86107, 12pp.

Matthews, E., 1985, Atlas of archived vegetation, land-use and seasonal albedo data sets, NASA tech. memo. 86199, Febuary 1985.

Mintz, Y., 1984, The sensitivity of numerically simulated climates to land-surface boundary conditions, The Global Climate, Houghton, J.T., (ed.), Cambridge University Press, 79-105.

NOAA, 1988, Global Vegetation Index Users' Guide, Data Services Division, NCDC, Washington DC.

Olson, J.S., Watts, J.A. and Allison, L.J., 1983, Carbon in live vegetation of major world ecosystems, DOC/NBB Report No. TR004, Oak Ridge National Laboratory, Oak Ridge, TN 7830, 152pp.

Peters, A., 1983, The New Cartography, Friendship Press, New York, 163pp.

Pitman, A.J., 1988, The development and implementation of a new land-surface scheme for use in GCMs, unpublished Ph.D thesis, Liverpool University, 481pp.

Pitman, A.J., Henderson-Sellers, A. and Cogley, J.G., 1988 a, The Effects of changing soil texture on the surface climatology simulated by the Canadian Climate Center General circulation model (in preparation).

Pitman, A.J., Cogley, J.G. and Henderson-Sellers, A., 1988 b, The development of "Bare Essentials" - a new land-surface parameterization for the Canadian Climate Centre General Circulation Model, Canadian Climate Centre Technical Note, in preparation.

Rind, D.,1988, The doubled CO_2 climate and the sensitivity of the modeled hydrological cycle, J.Geophys.Res., 93, 5385-5412.

Sellers, P.J., 1985, Canopy reflectance, photosynthesis and transpiration, Int. J. Rem. Sens., 6, 1335-1372.

Shukla, J. and Mintz, Y., 1982, Influence of land surface evapotranspiration on Earth's climate, Science, 215, 1498-1501.

Shuttleworth, W.J., 1988, Evaporation from Amazonian rain forest, Proc.Roy.Soc.Lond.B, 223, 321-346.

Taconet, O., Bernard, R. and Vidal-Madjar, D., 1986, Evaluation of a surface/vegetation parameterization using satellite measurements of surface temperature, J.Clim.Appl.Meteor., 25, 1752-1767.

Thomas, G. and Henderson-Sellers, A., 1987, Evaluation of satellite derived land cover characteristics for global climate modelling, Climate Change, 11, 313-347.

Tucker, C.J., Townshend, J.R.G. and Goff, T.E., 1983, Continental land-cover classification using meteorological satellite data, NASA Technical Memorandum, 86060, 20pp.

Users' Guide to Global Vegetation Index, 1983, Satellite Data Services Division (SDSD), National Climate Data Center, National Environmental Satellite Data and Information Service, World Weather Building, Washington, D.C., 6pp.

Wilson, M.F. and Henderson-Sellers, A., 1985, A global archive of land cover and soil data sets for use in general circulation climate models, J.Climatol., 5, 119-143.

Wilson, M.F., Henderson-Sellers, A., Dickinson, R.E. and Kennedy, P.J., 1987, Investigation of the sensitivity of the land-surface parameterization of the NCAR Community Climate Model in regions of tundra vegetation, J.Climatol., 7, 319-343.