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Use of satellite-based sensing in land surface climatology

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Abstract: Common types of satellite-derived measurements are reviewed with respect to how they are used to provide information on variables important to land surface climatology. The variables considered include solar radiation, surface albedo, surface temperature, outgoing longwave radiation, cloud cover, net radiation, soil moisture, latent and sensible heat flux, surface cover and leaf area index. A selection of land surface climate modelling schemes is identified and considered with a view to their practicality for use with satellite-derived data. Issues arising from the foregoing considerations include the absence from satellite data of some variables required by land surface climate models, the importance of extreme pixel values in model parameterization, the importance of matching spatial resolution in satellite data and climate model, and the need to have concurrent, independently observed, meteorological data in order to make full use of the satellite data.

Key words: remote sensing, climatology, satellite, climate models.

I Introduction

Although information from satellites has been available for three decades, the use of such information in land surface climatology has been most prevalent only since the 1980s. This parallels the growing realization by atmospheric scientists, over this recent period, that the land surface, and the part of the biosphere thereon, plays a very important role in the operation of the atmosphere from the smallest to the largest scales. This important role was recognized by the establishment of the International Satellite Land Surface Climatology Project (ISLSCP) and its related field programmes. Within the atmospheric remote-sensing community this has made land surface climatology of virtually equal importance to such studies as those of the Earth radiation budget (Earth Radiation Budget Experiment – ERBE) and cloud climatology (International Satellite Cloud Climatology Project – ISCCP).

The purpose of this article is to:

1) summarize what satellite measurements have been used for land surface climatology and the way in which they have been employed;
2) identify the kind of surface climatology models which potentially could, or do, use satellite-derived data; and
3) note some of the critical issues arising in attempting to use satellite data in land surface climate modelling.

The article concentrates on climate of micro- to meso-scale areas at the Earth's surface principally under snow-free, cloud-free skies. It also concentrates on factors of importance to the biosphere.

II Use of satellite-derived data for land surface climatology

Important issues relate to the geographic scale at which the data can be obtained. The scale is usually a function of the type of satellite being considered and its sensors. In recent years the most frequently used satellites for land surface climatology have been the USA GOES (Geostationary Operational Environmental Satellite) and Landsat, and the European METEOSAT. Several others have been used but either in earlier times or for variables other than those directly relating to land surface climatology. GOES has a spatial resolution providing a pixel size of about 8 km while its advanced very high resolution radiometer (AVHRR) has a 1 km spatial resolution. The pixels of Landsat and METEOSAT sensed data are about 30–120 m and 2.5–5.0 km respectively. Occasionally aircraft platforms carrying additional observing systems such as the NASA thermal infrared multispectral scanner (TIMS) have been used to support satellite-derived data for meteorological programmes. TIMS has a surface resolution of between 5–30 m. Most of these resolutions vary according to the application for which the data are being used and which of the wavebands of information are being considered.

The most important variables in land surface climatology are the surface heat budget components and those variables which relate to them. The surface heat budget components are net radiation, sensible and latent heat fluxes, substrate heat flux, and sometimes canopy heat storage or change. Variables which relate to these include direct and diffuse shortwave solar radiation, surface albedo, surface temperature and emissivity, longwave radiant fluxes to and from the atmosphere, cloud cover, soil moisture, air water vapour pressure and vapour pressure deficits, surface and aerodynamic resistances to latent heat flux, leaf area index (LAI), atmospheric stability, and substrate thermal properties such as conductivity. Many, but not all, of these variables can now be measured fully, or in part, by satellite.

The land surface climatology variables which so far elude direct or straightforward indirect measurement by satellite include substrate heat flux, canopy heat storage or change, longwave radiant fluxes from the atmosphere, air water vapour pressure and vapour deficits, atmospheric stability, and substrate thermal properties and heat flux. Obviously research effort should be directed towards the satellite estimation of these variables. Those variables in some way amenable to satellite measurement are discussed below.

1 Solar radiation

Carleton (1991) suggests that methods used to retrieve surface irradiance from satellite data may be classified as statistically (regression) based (Tarpley, 1979) – satellite-derived brightness is regressed against surface pyranometer observations – physically based (Gautier *et al.*, 1980), or those having attributes of both (Powell *et al.*, 1984). In none of these methods is direct and diffuse radiation explicitly resolved but the physical methods and refinements of them (Pinker and Ewing, 1985) do begin to make such a resolution in the sense that they consider atmospheric absorption and scattering of radiation and clear and cloudy skies. One of the most recent and powerful estimations of incoming solar radiation from satellite data is that of Pinker and Laszlo (1992) who used GOES AVHRR data to examine the interannual variability of incoming shortwave radiation for the Amazon Basin.

Irrespective of satellite data, solar radiation received at the surface may be computed from the theoretical amount arriving at the top of the atmosphere, information on the amount absorbed and reflected by atmospheric gases, and clouds. Many of the problems in obtaining solar irradiance from satellite data are the same ones found in attempting to estimate surface albedo values and are discussed in the following section.

2 Surface albedo

Three issues have to be addressed regarding surface albedo. First the effect of the atmosphere on radiant flow, both up and down, must be treated. Secondly, satellite sensor measurements which are usually in limited wavebands must be adjusted so that they are equivalent to all wavelength estimates. Thirdly, bidirectional albedo measurements (i.e. those sensed at one point in time as the sun makes its daily path through the sky) strictly need to be adjusted to become the equivalent of hemispheric albedos (which take into account the complete daily path of the sun). Numerous ways have been suggested to approach these difficulties (Carleton, 1991). Some examples are given here.

In the absence of direct independent measurements of atmospheric parameters, the effect of the atmosphere is commonly estimated using previously developed models of atmospheric transmission, scattering and absorption (Otterman and Fraser, 1976; Kim, 1992). Both these sets of investigators used Landsat data but their methods potentially can be used with data from other sensors. A critical part of the technique is the dark-pixel method. It is assumed that from a dark pixel in the imagery, upwelling radiance from the low reflectance target is primarily of atmospheric origin. Deviation from Lambertian-assumed radiance values is taken as a measure of the atmospheric effects such as aerosol densities. Moran *et al.* (1992) have tested the dark-pixel method (dark object subtraction – DOS) and the use of radiative transfer codes (RTCs) for model atmospheres at a test site in Arizona and concluded that simple atmospheric correction methods can be feasible. In their field area the use of DOS alone did not improve accuracy.

A common method for adjusting noncontinuous waveband data is to use weighting factors representing the contribution to radiation in each waveband to the continuous solar radiation spectrum. For example, Otterman and Fraser (1976) created a narrow band to broad band conversion by using the weights 2/6, 1/6, 1/8, 3/8 for the Landsat MSS 4,5,6,7 bands respectively. Kim (1992) actually algebraically created another band. Jackson (1984) developed an ingenious approach to deal with narrow band to broad band conversion and atmospheric effects in his development of partial spectrum to total spectrum ratios (P/T ratios). Combining atmospheric models and field measurements he found that the P/T ratios were independent of atmospheric scattering and solar zenith angles but were affected by atmospheric water vapour for which allowances can be made. The ratios can be adjusted for vegetation cover by adequate weighting of visible and infrared (IR) components. Jackson comments that the scheme may not be appropriate for high-level satellite data due to extra scattering and absorption effects but since most of these occur in the lower, denser atmosphere, the ratios may yet be of use.

The most difficult problem has been to obtain hemispheric values from bidirectional values. For relatively large (subcontinental) areas the zenith angle dependence of albedo found from geostationary platforms during the day can be used to provide corrections for bidirectional albedo values from fixed local-time-sampling polar-orbiting platforms (Carleton, 1991). Using NIMBUS-7 ERB data Taylor and Stowe (1984) constructed graphs of bidirectional albedo with zenith angle for a number of different surfaces. Data from these graphs have been used to adjust AVHRR reflectance data (Gutman *et al.*, 1989a). Gutman *et al.* (1989b) have also used the nine-day repeat cycle of NOAA-9 AVHRR data to correct bidirectional reflectances. Kimes *et al.* (1987) show how to use strings of bidirectional data, if available, to obtain hemispheric values. Pinker and Laszlo (1990) employ a technique which matches theoretically estimated planetary albedos and downward shortwave flux with GOES data of the same variables thereby permitting a fairly accurate calibration and temporal extrapolation of the satellite-derived incoming shortwave radiation and albedo values. They base their approach on GOES data with an approximate 8 km spatial resolution. Logically, for smaller spatial resolution data such a Landsat, a theory-based method would be appropriate. Dickinson *et al.* (1990) have provided such a method. They set up an analytical solution (model) for reflection from a homogeneous leaf canopy which essentially has four parameters. They numerically find the values of the four parameters by minimizing an error expression and they substitute the values back into the original model which can be integrated for all zenith angles. A simpler approach was suggested by Otterman and Tucker (1985) based on a model giving the reduction of zenith bidirectional reflectivity when viewed in nonzenith directions. Pinty and Verstraete (1992) (the coauthors in the Dickinson *et al.*, 1990, paper above) have reviewed the state of the art in modelling the bidirectional reflectance of natural surfaces.

When surface hemispheric albedo can be calculated from Landsat data some very interesting results are often found. Otterman and Fraser (1976) reported albedos of 0.34–0.52 for arid surfaces which are higher values than previously noted. Otterman (1977) found that exclosure to grazing in the Sinai desert markedly lowered the surface reflectivity. Courel *et al.* (1984), assuming Landsat data represent hemispherical measurements, show a decline in Sahel albedo 1973–79. These results contradict Charney's albedo feedback mechanism hypothesis which suggested that albedo increased due to overgrazing in the Sahel exacerbated drought conditions in that area.

3 Surface temperature

The estimation of surface temperature (*Ts*) from satellite data is very important for many reasons not least because the temperatures can then be fed into estimates of sensible and latent heat fluxes. Carleton (1991) suggests that, since the emissivity of the Earth's surface is close to one in the thermal infrared window (e.g., Landsat band 6, 10.4–12.5 microns), theoretically, satellite measured radiance can be entered into Planck's law and *Ts* can be solved as an inversion problem. In practice, allowances have to be made for several variables. Atmospheric effects (e.g., water vapour) can be reduced by narrow band sensing in bands which minimize such effects, or by subtracting temperature-dependent spectra from broad band observations, or by using spectrally weighted irradiance values. As in the case of the albedo, surface temperature, of course, has a marked diurnal variation. There is also a temporal lag between the maximum observed surface temperature and maximum observed screen temperatures. Different surface types also give rise to variations in the size of diurnal temperature change. The use of a model which relates surface type, or diurnal variations at nearby surface observation stations, to diurnal temperature change (e.g., respectively, Myrup, 1969; Running *et al.*, 1987) can estimate adjustments which should be made to directly derived local-time satellite surface temperatures. Variation in actual surface emissivity values is sometimes ignored using an assumed unity value for all surfaces (Carleton, 1991), or assumed actual emissivity values for different surfaces may be employed (Otterman and Tucker, 1985; Campbell, 1987). If imagery from two separate times of the day is available then the 'thermal inertia' of the various surfaces may be computed along with diurnal temperature curves (Campbell, 1987). Kim (1992) derives the amplitude of the thermal diurnal cycle using a function of the Landsat TM brightness temperature recorded at 9.33 a.m. local time and the predawn NWS observed temperature along with an assumed unity value of surface emissivity. Kahle and Alley (1992) have described methods which obtain *Ts* from either using curve-fitting techniques or assumed values of emitance and recycling them back into radiative flow equations to obtain atmospheric parameters and then using these to obtain a more accurate emissivity value. Another useful method is to obtain emissivities by spectral ratios (Watson, 1992).

Recently, a very useful summary of reflectance of terrestrial materials in the 8–14 micron window has been presented by Salisbury and D'Aria (1992). According to these investigators emissivity values can be obtained from these reflectance values by using Kirchoff's law. These data will be helpful when assumptions about emissivity values have to be made for surface climate models.

4 Outgoing longwave radiation

A knowledge of outgoing longwave radiation (OLR) is required to complete a surface energy budget computation and is, of course, related to the surface temperatures discussed above. While considerable attention has been given to outgoing longwave radiation on a global scale (Carleton, 1991) rather less has been given to its estimation in smaller geographic areas. That which has concentrates, for obvious reasons, on surface temperature estimation. Even less attention has been given to satellite-produced estimates of incoming longwave radiation to the surface. Consequently this value is more often modelled than obtained from satellite data. Incoming longwave radiation is not generally measured by satellite.

5 Cloud cover

Cloud cover is one of the most frequently measured of all atmospheric variables obtained by satellites. It plays a crucial role in affecting the value of the Earth's radiation and energy budgets on all geographic scales. The development of the ISCCP is testimony to the importance. Carleton (1991) covers the topic in great detail. An important role of clouds is to affect the values of radiant fluxes to and from the Earth's surface. With the exception of cirrus clouds and cloud over high albedo value surfaces, cloud cover is fairly easily detected by satellite sensors. Often some threshold value for a cloud/no-cloud decision is used for each pixel of the imagery. The effect of clouds on the radiation fluxes, however, is much more complex and its treatment is implicit in the discussion of incoming shortwave radiation and albedo estimation in the sections above.

6 Net radiation

Similarly, net radiation is a value treated by satellite measurements on the largest geographic areas as in the ERB. For small areas it is more likely that net radiation values are either modelled independently of satellite data or that different components of satellite data are used to estimate the individual parts of net radiation.

7 Soil moisture

Soil moisture has been estimated from GOES satellite data by Wetzel *et al.* (1984) who used the morning/afternoon difference in surface temperature together with records of observed ground-surface precipitation. A more sophisticated scheme employs several other surface climate variables to estimate soil moisture (Wetzel and Woodward, 1987). Schmugge (1978) used polarization in *Ts* records from Nimbus-7 data to obtain soil moisture estimates.

8 Latent and sensible heat flux

Kim (1992) describes the use of the Penman-Montieth model (P-M) and a general aerodynamic turbulent heat-transfer equation for partitioning the turblent latent (*LE*) and sensible (*H*) heat fluxes. He uses an analogy of the dark-pixel method; in this case it might be called the 'dry' pixel method. He assumes that over dry soil and concrete surfaces, 95% of available radiant heat is used in sensible heat. The *H* value is then used in the general aerodynamic turbulent heat-flux equation to obtain aerodynamic resistance (*Ra*) which, in turn, can then be used in the P-M equation from which *LE* is estimated. In the latter process, assumed values of canopy resistance are utilized based on the type of vegetation under consideration. Moran *et al.* (1989) also advocate the use of a general turbulent heat-transfer equation incorporating surface and air temperature difference and an aerodynamic resistance term. In addition, these workers refer to procedures for estimating daily total values of latent heat flow from instantaneous values assuming constant wind speed. Simple empirical methods of obtaining LE values from the difference between surface and air temperatures have been developed by Carlson and Buffum (1989) for use with GOES and AVHRR data.

9 Surface cover and leaf area index

An often-used variable which incorporates information on biospheric surface cover and leaf area index (LAI) is the normalized difference vegetation index, NDVI. The index is derived from the difference ratioing of AVHRR channel 1 and 2 data. Landsat MSS bands 4 or 5 and 7 could also be used. Carleton (1991) reports that the NDVI is an integrated function of photosynthesis, leaf area and evapotranspiration. Its value ranges from −1.0 to +1.0. Clouds, water and snow display negative values. Soils and rocks have values close to zero. Active vegetation has positive values usually ranging from 0.1 to 0.6 where the higher values indicate increased photosynthesis and canopy density. Goward (1989) has provided a comprehensive and instructive review of the use of visible/near infrared indicies and the information they give for vegetation investigations. On a continental to global scale the values of the indicies have been related to the geography and seasonality of vegetation cover, the global carbon cycle, biome-level net primary productivity and seasonal cycles of temperature and precipitation.

An important relationship, from the point of view of surface energy budget climatology, is one between NDVI and the ratio of net radiation/ground heat flow given by Moran *et al.* (1989). The existence of this relation circumvents the need for either neglecting or making assumptions about the ground-heat flow term. The value of the term is usually small but its inclusion can add extra accuracy to heat-budget computations.

III Land-surface climate models for use with satellite-derived data

It is instructive now to describe some commonly used models for estimating land surface energy and moisture fluxes with a view to considering their practicality for use with satellite-derived data. The models considered do not provide an all-inclusive list but the selection is broad enough to help identify practical issues which arise.

1 Surface temperature equilibrium and similar models

This model, first introduced by Myrup (1969) and subsequently much modified, operates on the basis that, given specified boundary conditions, there is only one value of the surface temperature that satisfies the surface heat-budget equation. The model finds that temperature by an iterative error halving procedure. In the present context the model is useful for estimating diurnal variation of many surface climate variables. Assuming surface albedo is known, a problem is obtaining reliable input information for wind velocity, roughness length and zero plane displacement, atmospheric moisture and optical properties, and soil-heat capacity and thermal conductivity, surface resistance, and temperature boundary conditions. Satellite observations generally cannot give these values. The surface temperature equilibrium model has been used to gain insights concerning the interaction of different alpine tundra vegetation surfaces and atmospheric flows of energy and moisture (Greenland, 1992). Typical input variables for the surface temperature equilibrium model are given in Table 1. Another model which has similarities and which has been used in atmosphere–biosphere interaction studies is the climate part of the CENTURY model (Parton *et al.*, 1987).

2 MT-CLIM

MT-CLIM (Running *et al.*, 1987) extrapolates surface-climate variable values from those measured at a base station to sites of interest in complex terrain. It corrects for base station/site differences in elevation, slope and aspect. It seeks to apply the concept 'operational environment' which defines environmental variables from the perspective of the plant. Four subroutines calculate air temperature, incoming shortwave radiation, humidity and precipitation. Within the generally broad limits of accuracy that might be expected in complex terrain, MT-CLIM has been successfully coupled with tree water balance and photosynthesis models. It has also successfully been applied using AVHRR data as input

Table 1 Typical input variables required for the surface temperature equilibrium model (Greenland, 1992)

Latitude
Date
Number of model days simulated
Time step
Lower boundary depth
Temperature at lower boundary
Number of substrate layers
Substrate heat capacity
Substrate thermal conductivity
Upper boundary height
Temperature at upper boundary
Number of air layers
Windspeed at upper boundary
Surface roughness length
Zero plane displacement
Barometric pressure
Dew point at upper boundary
Surface resistance
Albedo
Cloud summary

(Running *et al.*, 1989). The authors indicate that the approximately 1.0 km resoultion of AVHRR data is probably the smallest resolution on which the model should be run in order to achieve usable accuracy.

3 Composite surface layer–mixed layer model

Diak and Stewart (1989) have suggested that in the context of merging boundary layer modelling with satellite data input it would be helpful to consider not only the surface layer but also the higher mixed layer which in some ways is more simple. Consequently they have devised a composite surface layer–mixed layer model which treats energy, moisture and momentum fluxes through the layers. Despite the sophistication of the model, in practice it still depends on assumed or parameterized values of such factors as soil moisture, surface emissivity, albedo, roughness length and even, in some applications, Bowen ratio. The model does not include advective processes. It was developed to be applied on a scale consistent with the resolution of GOES data.

4 Regional atmospheric modelling scheme (RAMS)

Possibly the state-of-the-art boundary layer modelling is that based on the meso-scale numerical modelling system originally developed by Pielke (1974) and further refined by him and others over the last two decades (Avissar and Maher, 1988; Segal *et al.*, 1989). The system has been very powerful in demonstrating the importance of including the biosphere into meso- and larger-scale atmospheric modelling (Pielke *et al.*, 1991). The basic model is a three-dimensional numerical model requiring considerable computer power and experience to use. Somewhat comparable meso-scale models have also been developed at the National Center for Atmospheric Research and Scripps Institute for

Oceanography. Initial input information for these models are more usually obtained from standard surface observations than from satellite-derived sources.

5 Land surface parameterization schemes for general circulation models (SiB, BATS)

Two land surface parameterization schemes were developed for use with general circulation models but represent important and sophisticated models for incorporating the biosphere into land surface climate. The schemes are the simple biosphere model and the biosphere–atmosphere transfer scheme model. The simple biosphere model (SiB) was described by Sellers *et al.* (1986). As outlined by Dorman and Sellers (1989), SiB consists of three submodels which describe the processes of radiative transfer, turbulent transfer and the biophysical control of evapotranspiration. Each of the models operates on a set of parameters for a given vegetation type and generates values of albedo, roughness length and surface resistance (to evaporative heat flow) as well as surface energy budget values. The full model contains a canopy layer. Table 2 identifies the input parameters and variables required to operationalize this model. Sellers and Dorman (1987) have demonstrated how SiB may be operationalized and tested using a mixture of actual observations and estimated parameters. The model has been applied, partly using remote sensing data, to the tropical rainforest vegetation surface of Amazonia by Sellers *et al.* (1989).

The biosphere–atmosphere transfer scheme (BATS) has been described in detail by Dickinson *et al.* (1981) and the evapotranspiration treatment is discussed by Dickinson (1984). It has a two-layer soil model and computes infiltration and soil moisture. Air temperature, wind speed and precipitation are specified. Specific and relative humidity, net surface longwave radiation are computed. Soil thermal, radiative, hydraulic and vegetative properties for a given soil texture and colour have been prescribed for different surfaces. Actual evaporation is computed as the minimum of the potential evaporation and the maximum moisture flux that the soil can sustain. Gravitational drainage is allowed between two layers, and surface runoff is computed as a function of soil moisture. Transpiration, interception and re-evaporation of precipitation are computed explicitly (Verstraete, 1989). Sensitivity studies by Wilson *et al.* (1987) found the scheme to be particularly sensitive to soil textures and their related hydraulic conductivity and diffusivity and to snow-cover changes operating through albedo values. Input values for the BATS are also listed in Table 3.

6 Results from FIFE

The first ISLCP field experiment (FIFE) was the first comprehensive attempt to relate satellite data with surface climate models and observations. A review of the results has been given by Hall *et al.* (1989) and Hall *et al.* (1990). Investigators showed that GOES data could be used to estimate surface insolation to within 5% of its mean value. It was found that unstressed canopy conductance is linearly related to the simple ratio of near infrared to red reflectance. Remote sensing estimation of sensible heat appeared to be more difficult than the estimation of latent heat flux. The reviews give the impression that while some extremely important results were gained, the overall goal of complete integration of satellite data to surface energy budget estimation at a relatively high degree of accuracy was not entirely met. This situation may be changed when FIFE II results are reported in January 1993 (see note at end of article). Additional important findings will no

Table 2 Typical input variables required for the simple biosphere model (SiB) (Sellers and Dorman, 1987)

Soil data
Soil moisture potential at saturation
Soil moisture potential parameter
Soil saturation conductance
Soil moisture storage depths
Soil reflectance (VIS, NIR)
Plant data
Height of canopy top
Height of canopy base
Ground roughness length
Leaf area index
Leaf angle distribution
Leaf drag coefficient
Leaf shelter factor
Upper storey cover fraction
Root density
Root depth
Root cross-section
Root resistance
Stem resistance
Leaf reflectance
Leaf transmission
Light parameters
Leaf-water potential parameters
Soil temperature
Atmospheric data
Air temperature at 2 m
Wet bulb temperature at 2 m
Wind speed at 2 m
Downward solar radiation
Downward longwave radiation
Net radiation
Ground heat flux
Latent heat flux
Sensible heat flux
Surface temperature
Rainfall rates above canopy
Rainfall rates below canopy
Soil moisture
Leaf stomatal resistance
Leaf water potential

doubt be forthcoming from the Wisconsin first ISCCP regional experiment (FIRE) (Whitlock *et al.*, 1990).

IV Issues in the use of satellite data in land surface climate modelling

The above discussion suggests that there are certain recurrent themes when we try to relate satellite-derived data with surface climate models. These include the following:

Table 3 Typical input variables required for the biosphere–atmosphere transfer scheme (Wilson *et al.*, 1987)

Soil data
Porosity (volume of voids to volume of soil)
Soil suction
Saturated hydraulic conductivity
Ratio of saturated thermal conductivity to that of saturated loam
Exponent *b* defined in Clapp and Hornberger (1978)
Moisture content relative to saturation at which transpiration ceases (calculated to fit equation in Clapp and Hornberger, 1978)
Dry soil albedo (<0.7 microns)
Dry soil albedo (> = 0.7 microns)
Saturated soil albedo (<0.7 microns)
Saturated soil albedo (> = 0.7 microns)
Vegetation data
Maximum fractional vegetation
Difference between max fractional vegetation cover at and cover temperature of 269°K
Roughness length
Depth of total soil layer
Depth of upper soil layer
Rooting ratio (upper to lower soil layers)
Vegetation albedo (<0.7 microns)
Vegetation albedo (> = 0.7 microns)
Minimum stomatal resistance
Maximum LAI
Minimum LAI
Stem and dead-matter area index
Inverse square root of leaf dimension
Light sensitivity factor

1) There are some surface properties which boundary layer models commonly require but which are not currently retrievable from satellite data, at least on an operational (i.e., daily or monthly application) basis. Properties such as soil thermal characteristics, canopy resistance and surface roughness are examples. In some cases it might be possible to develop methods to retrieve such information from satellite data. For example, geologists have made good progress in mineral identification from satellite data. This kind of information might be able to be assembled in a manner from which soil thermal properties could be deduced. Usable values of surface roughness should be able to be obtained from land cover types which can be, in turn, deduced from spatially high resolution surface reflectances.
2) The use of extreme-value pixels seems to have great utility in providing limiting conditions and other information required to parameterize surface climate models. The dark-pixel or dark-object subtraction (DOS) procedure (Moran *et al.*, 1992) and 'dry' pixel have been used so far but there will probably be many other applications of this technique in the future.
3) Care must be exercised in matching the spatial resolution of the satellite data with the appropriate spatial resolution of the climate model employed. Although some land

surface climate models have been developed for use for large geographic areas (e.g., Sellers *et al.*, 1986), there are few examples of meso- or micro-scale land surface models which have been designed specifically for the use with remotely sensed data. A corollary to this, which seems to emerge from the literature, is the difference in geographic scales at which investigators from different backgrounds feel comfortable. Microclimatologists usually concentrate on measurements and models at one point and identify difficulties in even working in this framework. Scientists from other backgrounds feel less awed by considerations of spatial extrapolation of land surface climate variable values. Of interest also is that even timescale differences can be important. According to Hall *et al.* (1990), part of the analysis error in FIFE studies arose from the comparison of spectral data acquired at timescales of seconds to flux data averaged over an hour.

4) Currenty it appears almost essential to have some observed meteorological data in order to operate most satellite-based estimation methods of surface climatology. Consequently research oriented to the development of satellite-based surface-climate estimation methods which do not call for concurrent meteorological data should receive urgent attention.

V Conclusion

The field of obtaining land surface climatology values and linking satellite-derived data to surface climatology models is a very important area of knowledge and a fast developing one. We will never have sufficient ground observation for driving surface climate models and so it is extremely important that we develop methods to employ existing and future satellite-gained information. The speed of development of satellite technology has important implications. The first implication is that there are few 'standard' methods for applying satellite data to surface climate models. Continually, new improvements, parameterization methods and satellite-data retrieval algorithms are being produced. As a result most satellite data-based studies have a one-time only quality about them. Any replication of the study often uses one or more different techniques. A second implication is that satellite technology is changing faster than is the theoretical development of surface climate models. Consequently we should be on constant alert to review our surface climate models to make the best use of new satellite-derived data as they become available. In the late 1990s launching of the new Earth observing system (EOS) platforms are scheduled in the USA. EOS will provide an enormous amount of new satellite data. Many investigators are currently working hard to ensure that these data can be efficiently used for providing information about land surface climatology and a host of other topics. Such advances make it a very exciting and potentially productive time for physical geography and geographers.

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Note

This article was written before the comprehensive results of the FIFE experiment were published. Readers interested in FIFE results should refer to the special issue of the *Journal of Geophysical Research* 97 D17, 1992.

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