IMPROVED PREDICTION OF MOMENTUM AND SCALAR FLUXES USING MODIS IMAGERY

Project Summary / Final Report for grant NAG5-8699
8/15/1999 – 8/14/2003

Awarded to Bucknell University
Bucknell Principal Investigator: Richard D. Crago
rcrago@bucknell.edu
Department of Civil and Environmental Engineering
Lewisburg, PA 17837
570-577-1094

Principal Investigator (funded under separate NASA grant):
Michael F. Jasinski, NASA/GSFC Hydrological Sciences Branch, mjasinsk@hsb.gsfc.nasa.gov

Date
November 8, 2003

Note:
This grant is part of a collaborative proposal from investigators at NASA/GSFC and at Bucknell University. Due to asynchronous schedules between the two institutions, this final report from Bucknell is being written prior to the conclusion of the project at NASA/GSFC, where the gridded dataset is being developed. Therefore, this report will deal with the work at Bucknell and with accomplishments to date on the ongoing work at NASA/GSFC. The role of Bucknell researchers in the management plan of the proposal was to "focus on the interaction of the land surface with atmospheric turbulence."

Introduction
Virtually all numerical atmospheric simulation models used today, including operational weather forecast models and global climate models, employ aerodynamic roughness lengths for momentum, heat, and other scalar fluxes. The roughness lengths must be prescribed prior to running the model for each grid box in the simulation domain. The current practice in almost all instances is simply to assign roughness lengths using a rather crude look-up table procedure based on association with major vegetation classes such as rangeland, agricultural land, coniferous/deciduous forest, urban area, etc. Unfortunately, this coarse association does not allow important further sub-class discrimination on the basis of such factors as plant height, leaf density, and plant shape, including seasonal variability. The current practice may lead to significant errors in simulating the land-air exchanges and their impact on horizontal convergence and the formation of clouds and precipitation. Improved methods for prescribing roughness using the recently launched MODIS sensor should lead to improved prediction of large-scale momentum and scalar fluxes in atmospheric and hydrologic simulation models.

Objectives
There are remote sensing and science objectives. The <u>remote sensing objectives</u> are:

1. To develop and test a theoretical method for estimating local momentum aerodynamic roughness length, z_{0m}, using satellite multispectral imagery.

2. To adapt the method to the MODIS imagery.

3. To develop a high-resolution (~1km) gridded dataset of local momentum roughness for the continental United States and southern Canada, using MODIS imagery and other MODIS derived products.

The <u>science objective</u> is:

4. To determine the sensitivity of improved satellite-derived (MODIS-) estimates of surface roughness on the momentum and scalar fluxes, within the context of 3-D atmospheric modeling.

Approach
The basic framework for this work comes from Jasinski and Crago (1999), who adapted the theoretical roughness length formulation of Raupach (1992, 1994) for use with remotely sensed data. Raupach applied simple scaling arguments and empirical drag coefficients and wake-speading coefficients to develop an analytical expression for the momentum roughness length of a vegetation canopy. Jasinski and Crago (1999) assumed Poisson-distributed plants, and used a 3-D, geometrical representation of plant shape to develop a parameterization of the canopy area index (an input

variable to Raupach's formulation) for individual pixels, in terms of either the fractional vegetation cover or the leaf area index. Estimates of both variables from satellite imagery are available.

Results

1. Maps of roughness length from maps of LAI at the Southern Great Plains (SGP-97) experiment, and larger scale maps of roughness length from MODIS data covering most of Oklahoma and neighboring areas have been produced. Maps of roughness length for a 10,000 sq. km portion of the 1994 Boreal Ecosystem-Atmosphere Study Southern Study Area (BOREAS-SSA) have also been developed through this project. Application of the Raupach algorithm to produce maps of roughness length at these large scales has thus been shown to be feasible. Based on this successful work, the south central United States region, in which the SGP experiment was embedded, will be the first to be analyzed with the revised algorithm (see result 2 below). This work was largely done at NASA/GSFC.

2. Preliminary work showed that the Raupach (1992, 1994) formulation for roughness can be sensitive to the values of some of its parameters (especially the foliage element drag coefficient and a wake spreading coefficient). These parameters have solid physical meanings. On physical grounds, it is expected that these parameters ought to have different values within canopies having different structures. A careful investigation of field data and roughness element shape for the dominant natural land classifications in the south-central United States (grasslands and deciduous, coniferous, and mixed forests) has resulted in revisions of the values of the drag and wake-spreading coefficients for these land classifications. Once coefficient values have been determined for the land classes in a region, the Raupach formula can be quickly applied to develop maps of roughness length and displacement height using MODIS products. This work was done at NASA/GSFC with frequent (approximately twice monthly) teleconferences with Bucknell.

3. Field data from SGP-97 have been analyzed to estimate roughness length at the El Reno tower sites for all the days available. An example of these results is given in Figure 1. The roughness length maps can be partially validated by comparing the mapped roughness lengths (for the pixels within the flux footprint of the towers) with the field estimates. This work was done at Bucknell.

4. In preparation for studies of the sensitivity of a 3-D meteorological model to the value of momentum and scalar roughness lengths (see Objective 4 above), work has been done at Bucknell to parameterize the scalar roughness lengths and the ratio kB^{-1}, defined as $\ln(z_0/z_{0h})$ where z_0 is the momentum roughness length and z_{0h} is the scalar roughness length for sensible heat or water vapor. There have been two strands to this work:

   a. Work with ALARM. The Analytical Land Atmosphere Radiometer Model (ALARM), developed by Crago (1998), has been developed and tested for grasslands [Suleiman and Crago, 2002; Zibognon et al., 2002; Suleiman and Crago, 2002; Crago and Suleiman, 2002]. The model converts from a radiometric surface temperature measured at any zenith view angle, and converts it to a temperature called the equivalent isothermal surface temperature (Brutsaert and Sugita, 1996), which is the surface temperature "felt" by the turbulence. This temperature is then used with air temperatures aloft to generate sensible heat fluxes. Results are demonstrated in Figure 2 from Crago and Suleiman (2003).

   b. A new method was developed to estimate kB^{-1} from field data collected by R. Qualls at the CASES 97 experiment. The method uses the complementary evaporation equations (specifically, the advection aridity method) to give an alternative expression of kB^{-1} or z_{0v} independent of the measurement of surface variables (Crago and Crowley, 2003b). Key results were that as a canopy becomes taller and denser,

kB^{-1} decreases, meaning that as z_0 increases z_{0v} increases more rapidly (see Figure 4). In other words, as canopy height and density increase (at least in the ranges observed: $1.13<LAI<1.79$) the transport efficiency of water vapor increases more rapidly than the transport efficiency of momentum (Crago and Crowley, 2003b). This basic result is supported by the theoretical canopy transport model results of Brutsaert (1979) as presented in Brutsaert (1982), in which less dense canopies such as grass had larger kB^{-1} values than those for an aspen forest.

Conclusions
The several strands of research reported here indicate that maps of momentum and scalar roughness lengths for the continental United States and southern Canada are feasible, and that the methods of Jasinski and Crago (1999) and Raupach (1992; 1994) can be adapted to work with MODIS imagery. The completed work at Bucknell, in particular the research into scalar roughness parameterization and the interactions between atmospheric turbulence and canopies, provides a firm foundation for the ongoing work at NASA/GSFC of actually producing maps of momentum and scalar roughness lengths.

Impacts
The project uses MODIS imagery to address a deficiency in most atmospheric models today. The completed maps will provide a unique dataset for global and mesoscale atmospheric and hydrologic modelers. The proper description of the land surface is essential in these models, since this description serves as the lower boundary condition of the models. Incorporation of this dataset into models is therefore expected to increase the accuracy of the models themselves and of their predictions.
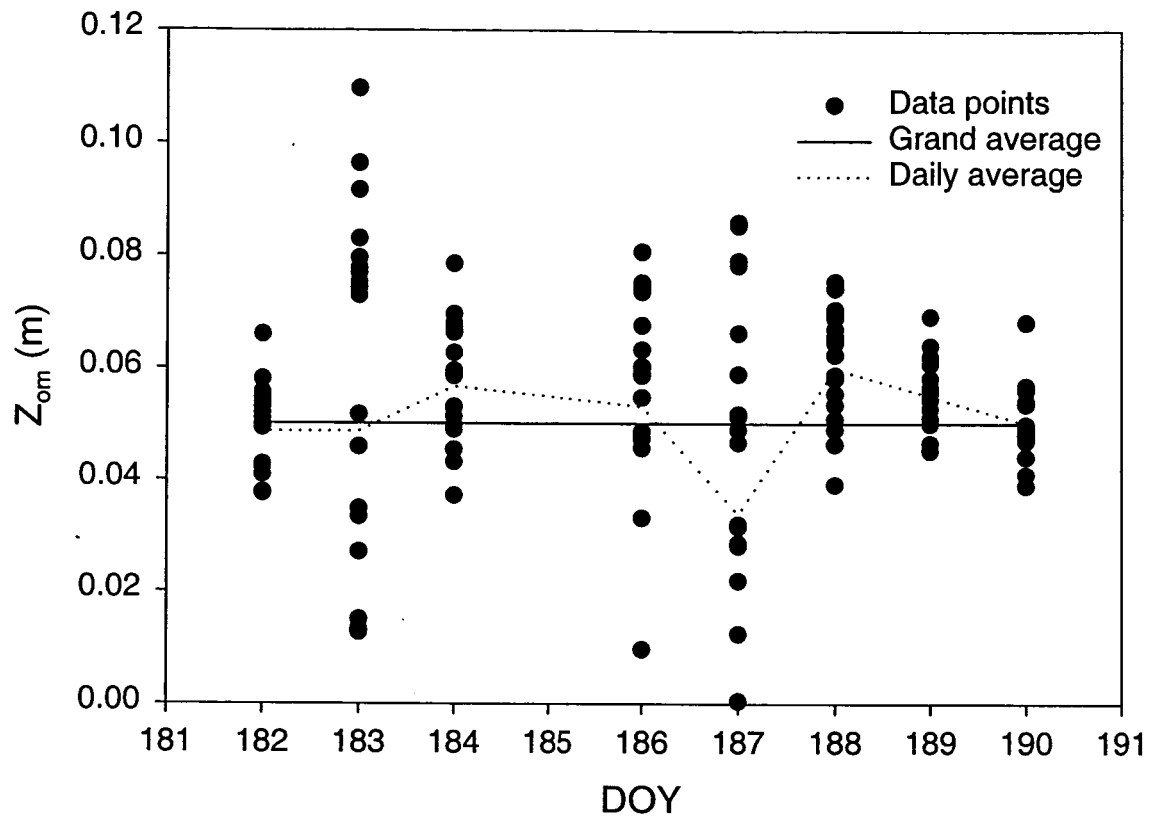
Figure 1. Momentum roughness length for nine days of SGP-97 at site ER01.
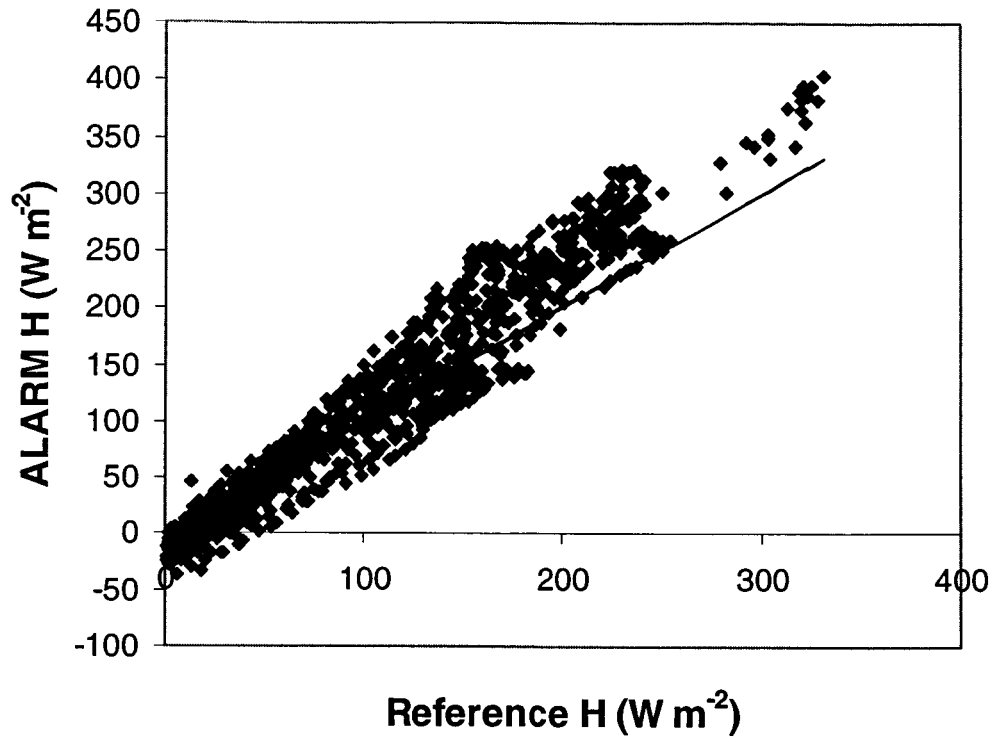
Fig 2. Results of the ALARM parameterization from the CASES dataset (from Crago and Suleiman, 2003).

References

Bouchet, R.J., 1963. Evapotranspiration reelle et potentielle, signification climatiqe. *Int. Assoc. Sci. Hydrol., Proc.* Berkeley, Calif. Symp., Publ. 62: 134-142.

Brutsaert, W.: 1982, *Evaporation into the Atmosphere*, D. Reidel, Boston, 299 pp.

Brustaert, W. and Stricker, H., 1979. An advection-aridity approach to estimate actual regional evapotranspiration. *Water Resour. Res.*, 15: 443-449.

Brutsaert, W., and Sugita, M.: 1996, 'Sensible heat transfer parameterization for surface with anisothermal dense vegetation', J. Atmos. Sci. 53(2), 209-216.

Crago, RD, Radiometric and equivalent isothermal surface temperatures, Water Resour. Res. 34(11), 3017-3023, 1998.

Friedl, MA, Modeling land surface fluxes using a sparse canopy model and radiometric surface temperature, J. Geophys. Res., 100(D12), 25,435-25,446, 1995.

Friedl, M.A., 2002. Forward and inverse modeling of land surface energy balance using surface temperature measurements. Remote Sens. Environ., 79: 344-354.

Granger, R.J., 1989a. A complementary relationship approach for evaporation from nonsaturated surfaces, J. Hydrol., 111: 31-38.

Jasinski, M.F. and Crago, R.D. Estimation of vegetation aerodynamic roughness of natural regions using frontal area density determined from satellite imagery. Agricultural and Forest Meteorology, 94, 65-99, 1999

Kustas, WP and JM Norman, A two-source approach for estimating turbulent fluxes using multiple angle thermal infrared observations, *Water Resour. Res.*, 33, 1495-1508, 1997.

Kustas, W. P., and Norman, J. M.: 1999, 'Evaluation of soil and vegetation heat flux predictions using a simple two-source model with radiometric temperatures for partial canopy cover', *Agric. Forest Meteorol.* 94, 13-29.

Morton, F.I., 1976. Climatological estimates of evapotranspiration. *J. Hydraul. Div. Proc. Am. Soc. Civ. Eng.*, 102(HY3): 275-291.

Price, JC, Estimating leaf area index from satellite data, *IEEE Trans. Geosci. and Rem. Sens.*, 31(3), 727-734, 1993.

Qualls, R. J., and Hopson, T.: 1998, 'Combined use of vegetation density, friction velocity, and solar elevation to parameterize the scalar roughness for sensible heat', *J. Atmos. Sci.* 55, 1198-2008.

Raupach, M. R., Drag and drag partition on rough surfaces, *Boundary Layer Meteorology*, 60, 375-395, 1992.

Raupach, M.R. Simplified expressions for vegetation roughness length and zero-plane displacement as functions of canopy height and area index, *Boundary Layer Meteorology*, 71, 211-216, 1994.

Project Publications

Crago, R. and R. Crowley, Complementary relationships for near-instantaneous evpotranspiration, *J. Hydrology*, in review, 2003 (a).

Crago, R. and R. Crowley, Scalar Roughness Lengths Through A Complementary Evaporation Approach, manuscript in preparation, 2003 (b).

Crago, R. and A. Suleiman, Heat flux parameterization for sparse and dense grasslands with the Analytical Land Atmosphere Radiometer Model (ALARM), *Boundary Layer Meteorology*, in review, 2003.

Jasinski, M.F. and Crago, R.D. Estimation of vegetation aerodynamic roughness of natural regions using frontal area density determined from satellite imagery. Agricultural and Forest Meteorology, 94, 65-99, 1999

Suleiman, A. and R. Crago, Hourly and daytime total evapotranspiration using radiometric surface temperatures, *Agronomy Journal*, accepted for publication, 2003.

Suleiman, A. and R. Crago, Analytical land atmosphere radiometer model (ALARM) applied to a dense canopy, *Agricultural and Forest Meteorology*, 112 (3-4), 151-159, 2002a.

Suleiman, A. and R. Crago, Analytical land-atmosphere radiometer model, *Journal of Applied Meteorology*, 41, 177-187, 2002b.

Zibognon, M., R. Crago, and A. Suleiman, Conversion of radiometric to aerodynamic surface temperature with an anisothermal canopy model, *Water Resources Research*, 38 (6), 3-1 to 3-6, 2002.

Some of the above results were presented at the American Geophysical Union Fall Meeting, San Francisco, December, 1999.