STRUCTURE OF TURBULENCE AT VEGETATED SURFACES: OBSERVATION AND SIMULATION

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INTRODUCTION

Plant and animal life responds to or employs microclimates established by vegetation, while humans have adapted and manipulated vegetative cover to advantage in everyday living and in commercial endeavors such as agriculture. Trees provide shade from the sun and shelter from the wind, hence the interest in agroforestry in tropical regimes, in which a sparse overstory moderates the near-surface microclimate for animal husbandry or cash crops, and the extensive use of shelterbelts to protect sensitive crop plants and to reduce soil erosion. To evaluate the effectiveness of shelter under the existing wide variety of vegetation regimes, it is necessary to examine and to understand atmospheric processes at this interface between biology and meteorology.

The turbulent nature of the wind through vegetation is responsible for the removal of water vapor evaporated from the soil or transpired by green tissue. It is responsible for the removal of dust particles or fungal spores from plant surfaces, for the diffusion of pathogens or pheromones emitted by insects, and for the physical forces that can cause damage to leaves, stems, branches or complete trees. Over most land surfaces, vegetation forms the lower boundary to the atmosphere and an accurate treatment of that surface is essential to any consideration of the exchange of heat, mass or momentum with the lower atmosphere. For example, flux/profile relationships (with diabatic corrections) fail above tall vegetation because sources and sinks are vertically distributed within the canopy layer, and cannot be represented adequately by a single "zero plane displacement". This paper examines some of the physical processes taking place at the plant/atmosphere interface and considers approaches to observation and model formulation designed to promote our understanding of this aspect of biometeorology.

FEATURES OF CANOPY FLOW

Meteorologically, the most interesting aspect of surface layers with canopies is the result of the presence of a semi-permanent inflection in the wind profile, which is thought to make the flow more characteristic of a mixing layer than of a wall layer (Raupach et al., 1989). Consequences of this feature include (i) unique profiles of streamwise and vertical velocity skewnesses (each of which changes sign from above to within the canopy), (ii) a significant increase in the magnitude of the horizontal and vertical velocity correlation coefficient at the canopy top, and (iii) the dominance of coherent motions in scalar and momentum transport. It has been recognized for a long time that scales of motion equal to or greater than the depth of the canopy are of utmost importance in exchanges between the canopy and the "free" atmosphere above but only recently have such coherent structures been isolated as, for example, by Gao et al. (1989) and Bergström and Högström (1989). Both studies were set in forests and both showed that repeatable patterns in the velocity and temperature signals were associated with the major part of the vertical fluxes of heat and momentum. More recent studies have shown that coherent motions occur in shorter crop canopies also (Paw U et al., 1992).

INVESTIGATIVE APPROACHES

Approaches to investigating atmospheric surface layer and canopy layer physics have included direct field observation using arrays of triaxial sonic anemometers (Shaw et al., 1988; Baldocchi and Meyers, 1988), wind tunnel studies (Brunet et al., 1994), and numerical models (Wilson and Shaw, 1977; Wilson, 1988). All have contributed to the understanding of canopy aerodynamics but all have limitations. The major constraint regarding field studies is the limited number of fast response sensors that can be exposed. While a relatively small number of instruments might be sufficient to obtain profiles of integral statistics, attempts to examine the three-dimensional character of organized atmospheric motions are very limited, as are attempts to study heterogeneous canopies.

Wind tunnel simulation of an atmospheric surface layer with an underlying plant canopy has been successful, and has had the advantage over field studies of control of external conditions. Yet, fetches are usually limited, reproduction of the details of thermal stratification in a canopy is very difficult and, again, only a small number of probes is employed.

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Computer simulations of surface layers with canopies have progressed from simple K-theory models (Cionco, 1965), to second- and higher-order closure models (Wilson and Shaw, 1977; Meyers and Paw U, 1986; Wilson, 1988), and recently to large-eddy simulation (Shaw and Schumann, 1992; Kanda and Hino, 1994). While economical computationally, ensemble average models yield only statistical descriptions of flow fields. They can be made to include aspects of prescribed flow structures but cannot be used as a tool to examine the formation and structure of organized motions. For example, Li et al. (1985) describe a first-order closure scheme to which is added a term to represent the ejection/sweep process. While the added term reproduces some of the transport properties of coherent structures, such as counter-gradient diffusion, it does not advance understanding of the mechanism itself.

In terms of computational modeling, large-eddy simulation (LES) alone is capable of making a contribution to a basic understanding of the formation and structure of the relatively large scale, coherent motions that are so important at the interface between the atmosphere and a layer of vegetation. Large-eddy simulation explicitly simulates the dominant energetic turbulent scales resolved by a three-dimensional grid array within the computational domain (Deardorff, 1972). Closure approximations are thus limited to sub-grid-scale (SGS) motions. This paper presents the results of a large-eddy simulation and compares such computation with field observations.

LARGE-EDDY SIMULATION

Large-eddy simulation provides a time-dependent solution to the Navier-Stokes equations and to scalar equations, such as that for sensible heat, while parameterizing sub-grid-scale processes (Shaw and Schumann, 1992). We chose to use the numerical procedures described by Moeng (1984) and Moeng and Wyngaard (1988) that involve pseudospectral differencing to estimate horizontal derivatives, and second-order centered-in-space finite differencing to approximate vertical derivatives. Boundary conditions unique to our simulation include the upper boundary at which we impose a frictionless rigid lid, and the soil surface beneath the canopy where we specify a roughness length. Since the upper boundary condition does not allow the surface layer to be driven by a flux of momentum from higher levels in the planetary boundary layer, a streamwise pressure gradient maintains the flow. The code adjusts this pressure gradient each time step to maintain a predetermined integrated flow through the domain. At the soil surface, we assign a roughness length and use similarity theory to compute surface fluxes. We consider this a sufficiently accurate approximation since fluxes at the soil surface are quite small compared with those at the top of the canopy.

The 96x96x30 array used to date, with the lowest one third of the domain reserved for the canopy, is sufficient to resolve major variations in area density within the vegetation and scales of motion down to a fraction of the full height of the canopy. At present, the vertical extent of the domain is limited to a few times the canopy height (three times the canopy height in work reported so far). Because of the difficulty in specifying a turbulent upper boundary, we have imposed a rigid but frictionless upper lid to the domain, unrealistically forcing the Reynolds stress to decrease to zero at this boundary. In defense, evidence from field and wind tunnel studies demonstrates that coherent structures at the vegetation/atmosphere interface are the product of the inflection point instability in that region. This suggests that the events of primary interest might be rather insensitive to details of the upper boundary conditions.

COMPARISON OF OBSERVED AND SIMULATED FLOWS

Vertical profiles of integral statistics computed from large-eddy simulations illustrate the degree to which computations can match field observations. Generally, the higher the order of the statistical moment, the greater is the departure from reality. For example, while computed flow fields show the correct positive streamwise velocity skewness and negative vertical velocity skewness within the canopy, the magnitudes of the skewnesses are smaller than expected. This likely results from the smallness of the computational domain and consequent limitation of the scales of motion.

Evaluation of the turbulent kinetic energy budget from the LES output (Dwyer et al., 1997) shows all of the expected patterns that reveal the production, transport, and dissipation of wind energy. Production from velocity shear peaks near the top of the canopy, while turbulent energy loss is mostly a consequence of the drag of canopy elements (suppressing the turbulent motions as well as the mean flow). Turbulent diffusion transfers energy from the primary production region to the lower portion of the stand. Of particular interest is the role of pressure perturbations in the kinetic energy and stress budgets, because pressure is notoriously difficult to measure in a field or wind tunnel experiment, whereas it is an integral part of the LES solution. It had been thought that pressure perturbations play an important role in maintaining turbulent flow in the lower reaches of plant canopies, especially forests (Shaw and Zhang, 1992; Conklin and Knoerr, 1994). We show that, indeed, pressure diffusion is a dominant influence on sub-canopy flow.

Coherent structures are most easily identified by the characteristic ramp patterns they create in scalar signals. Examples are shown from field observations of temperature and humidity (Gao et al., 1989). Ramps are also found extensively in the output from large-eddy simulations we have performed. Examination of ramp patterns in the LES shows that the scalar field is tilted in the downwind direction and that a scalar microfront separates a zone of updraft (an ejection) from a downdraft (a sweep), as in the real situation. The power of numerical simulation is revealed when one realizes that detailed analysis of such structures is not possible using tower observations because individual structures cannot be followed, and inferences must be made from time traces as structures (of unknown stage of maturity) pass a vertical array of instruments.

Large-eddy simulation has also been applied to situations with strong inhomogeneity of canopy area density but, since the code imposes periodic boundary conditions, any pattern of heterogeneity is necessarily repeated each domain length. A prime example of inhomogeneity is the windbreak or shelterbelt. Incorporation of inhomogeneity into the code is straightforward and restricted only by the resolution of the grid network. However, since we have control over the density of the drag elements and their drag coefficient, a fence of any porosity can be imposed, and porosity can vary with height. An example is shown of a comparison between a computer simulation and a wind tunnel model of multiple windbreaks (Judd et al., 1996).

SUMMARY

Integral statistics provide hints that exchange processes at the interface between vegetation and the atmosphere are characterized by repeated and coherent structures, but make little contribution towards any revelation of these special characteristics of this portion of the atmosphere. Conditional sampling of field data makes it clear that large fractions of the fluxes of heat, mass and momentum occur in relatively short time periods but the expense of installation of reasonably large numbers of sophisticated field instruments makes numerical simulation an attractive alternative. This paper has emphasized a computationally expensive approach to modeling the atmosphere/canopy interaction. It has been demonstrated that large-eddy simulation creates flow fields that are correct not only in terms of integral statistics but correct also in terms of the organized patterns seen in field data. Large-eddy simulation proves to be a useful instrument for examination of the structure of turbulence at the plant/atmosphere interface.

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