UTILIZING A BIOPHYSICAL MODEL OF ECOSYSTEM-ATMOSPHERE EXCHANGE TO IMPROVE FIRE DANGER ASSESSMENT AND MESOSCALE METEOROLOGICAL FORECASTS

Ned Nikolov *, Karl F. Zeller
USDA FS Rocky Mountain Research Station, Fort Collins, Colorado

1. INTRODUCTION

Forecasting of the regional (mesoscale) weather including stability and wind flow pattern is an important aspect of the fire operations and fire management efforts during the active season. Accurate prediction of meteorological conditions from 24 to 60 hours into the future is critical for fighting wildland fires, and making go/no-go decisions about prescribed burns. Predictions of atmospheric parameters such as temperature, humidity, wind speed, and wind direction as well as fuel moisture need be considered to properly assess immediate fire danger, and allocate fire-fighting resources. Knowing with a high degree of certainty how future wind fields and atmospheric stability might change over a region is also indispensable for evaluation of smoke dispersion from prescribed burns. The latter is critical for air quality management and mitigation of the smoke impact on public health. The safety of fire fighters is another vital management issue, which calls for reliable and accurate local weather forecast. Corrected

Regional weather forecasts are currently produced by 3-D numeric simulation models of mesoscale atmospheric circulation running at 4 to 12 km horizontal grid spacing. These models (e.g. MM5, RAMS, WRF) describe atmospheric physics in great details. Due to a high non-linearity of atmospheric processes, weather models are quite sensitive to initial and boundary conditions. Initial conditions are the fields of temperature, humidity and cloud cover provided as input at the beginning of a simulation. Boundary conditions are the fluxes of mass and energy at the borders of the spatial domain of the model. High model sensitivity means that small changes in boundary conditions, for example, can lead to large shifts in the predicted weather pattern over a short period of time.

Over the past 10 years, a significant body of research involving weather models has demonstrated the critical importance of lower boundary conditions (i.e. terrestrial vegetation and land surface properties) in predicting mesoscale atmospheric circulation, especially for simulations utilizing spatial resolutions of 10 km or less (e.g. Chase et al. 1996; Fennessy & Xue 1997; Pielke *et al*. 1997, 1998; Pielke 2001). In mesoscale models, the lower boundary is defined by the fluxes of latent and sensible heat emitted from vegetation and soils. Short-wave and thermal radiation received from the sun and the upper atmosphere is partitioned at the land surface into energy that evaporates water (latent heat flux) and heat that warms the ambient air (sensible heat flux). This partitioning of the total incoming solar energy, often expressed as a ratio of sensible to latent heat flux (i.e. the Bowen ratio), is a crucial factor controlling the development of the planetary boundary layer (PBL), which governs most mesoscale weather phenomena including near-surface air flow, temperature and humidity fields as well as fuel and soil moisture. The amount of latent heat flux (also known as evapo-transpiration) emitted from the land surface depends on the type of vegetation present, its canopy density (defined as leaf area index, LAI), soil texture, soil moisture, and current meteorological conditions (i.e. temperature, humidity, incident radiation, and wind speed). Vegetation exercises a major control over the latent heat flux (hence, the energy partitioning) through its spatial coverage, foliage density, and physiology via leaf stomatal conductance. Thus, vegetation plays an essential role in atmospheric dynamics and weather formation at the mesoscale level (Pielke *et al*. 1997, 1998; Lynn et al. 2001).

2. CURRENT STATUS OF MESOSCALE LAND SURFACE MODELS

Present atmospheric models implement land surface models (LSM) that only provide a crude simulation of the complex vegetation-atmosphere interactions. For instance, most LSMs employ simple semi-empirical relationships to predict energy fluxes that do not account for feedbacks between transpiration and carbon assimilation. Some schemes do not even include a vegetation layer assuming that the entire land surface is bare soil. None of the current schemes uses *actual* leaf area index (LAI) as an independent data layer to scale energy fluxes from a leaf to the canopy level. LAI is a measure of vegetation density and is defined as the one-sided area of green foliage projected over a unit area of ground surface. LAI is a critical structural parameter of vegetation controlling the latent heat flux and, hence, the surface energy partitioning. Spatial variation of LAI greatly influences regional evapo-transpiration. Current LSMs assume that canopy density is correlated with vegetation types. Thus, most LSMs use a land cover dataset as input where each land cover category is assigned a fixed maximum LAI value that varies seasonally but not spatially within a vegetation type. However, since most vegetation types support a wide range of LAI values and the spatial pattern of

---

* *Corresponding author address*: Ned Nikolov, USFS RMRS, Fort Collins, CO 80521; e-mail: nnikolov@fs.fed.us

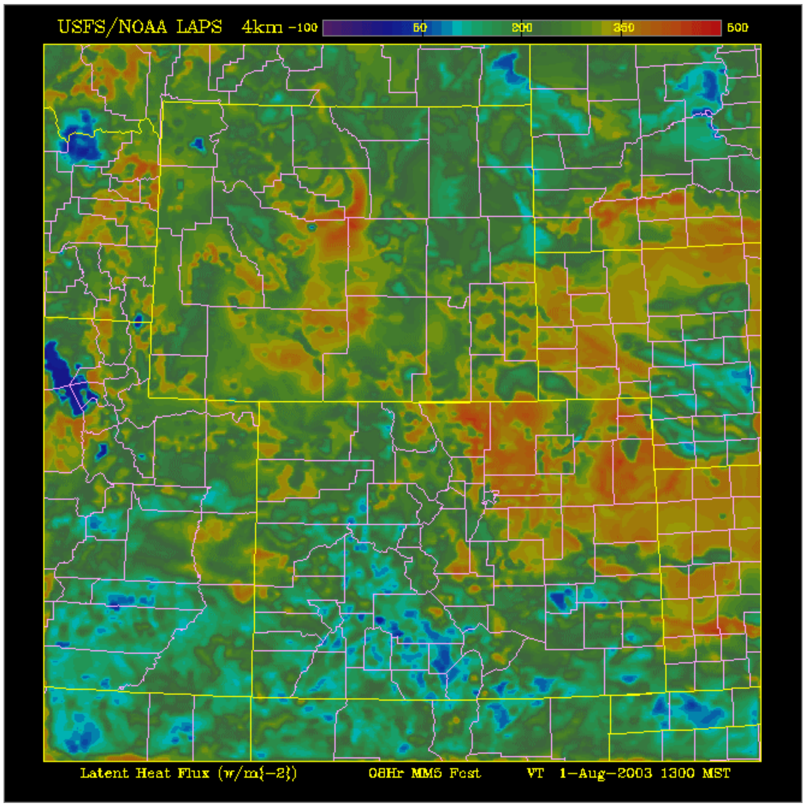

Figure 1. Spatial pattern of surface latent heat flux predicted by the OSU Land Surface Scheme for CO-WY at 13:00 MST on Aug. 01, 2003.

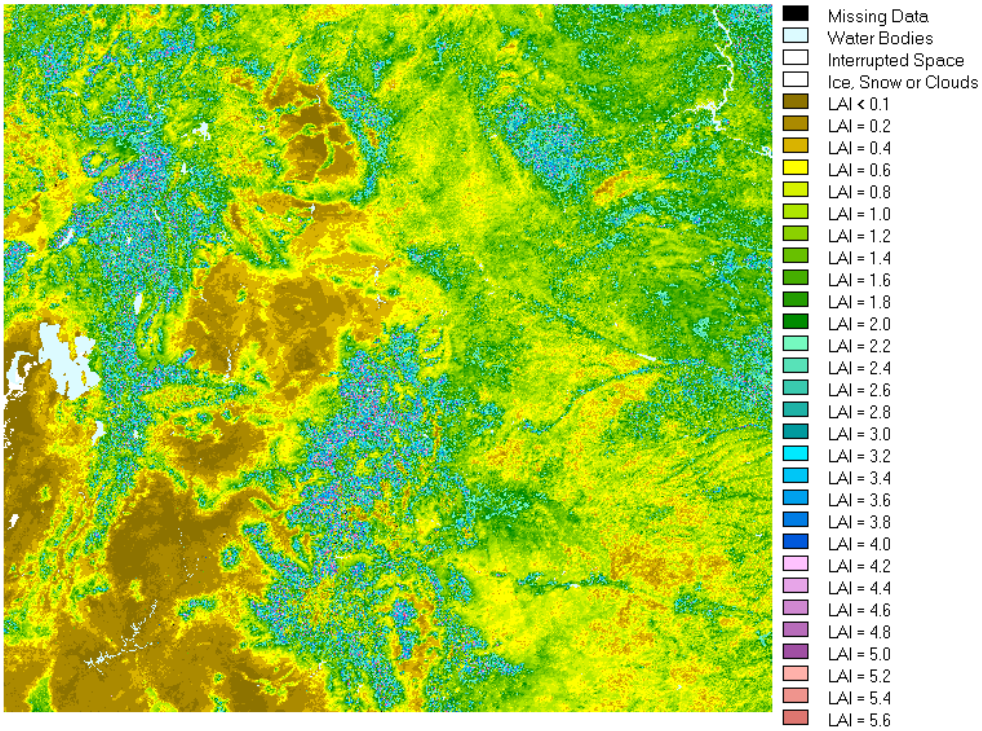

Figure 2. Spatial pattern of canopy leaf area index (LAI) (m^2 m^{-2}) over CO-WY estimated from 1-km resolution AVHRR data (Nikolov 1999).

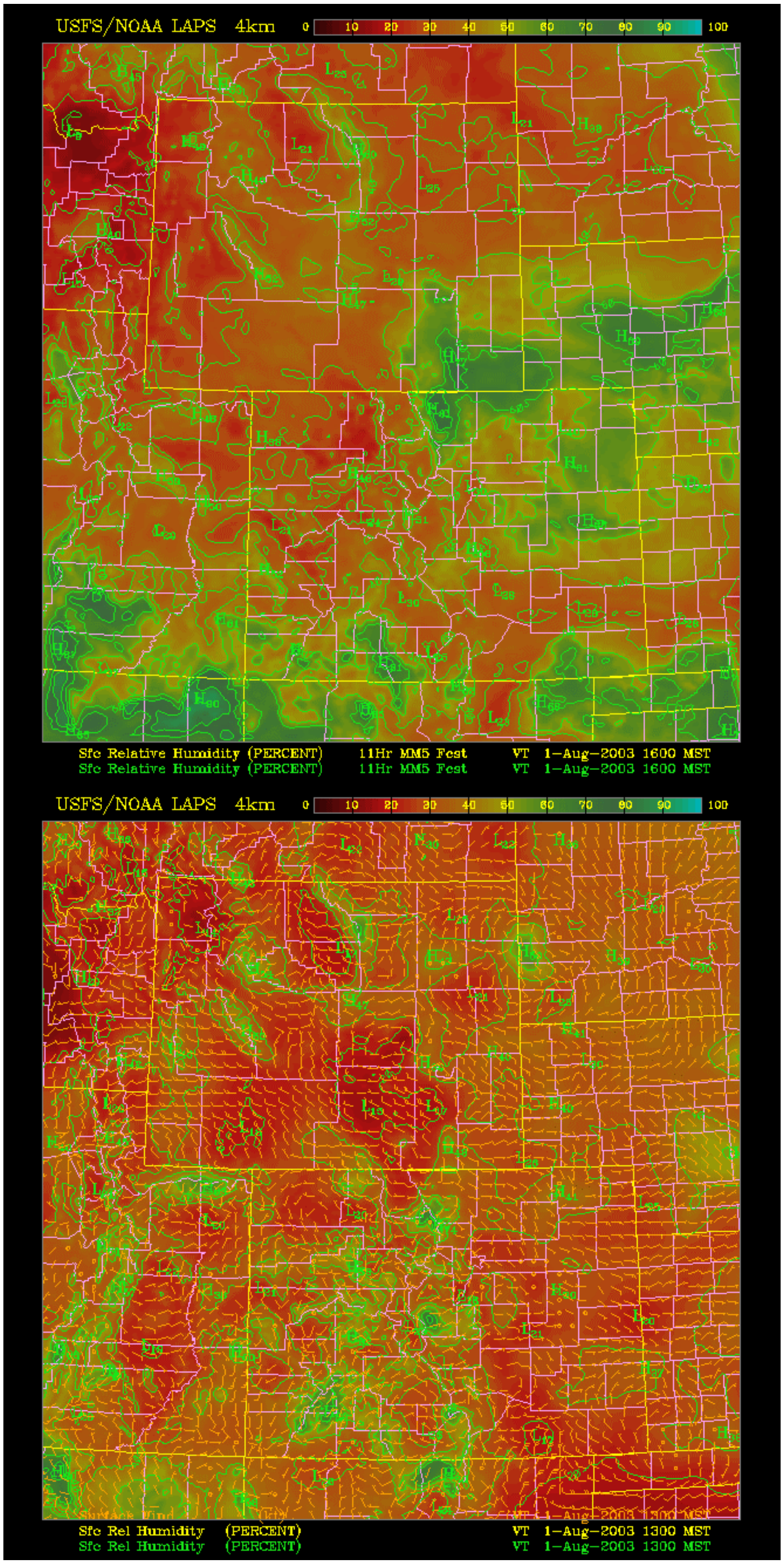

Figure 3. Fields of surface relative humidity predicted by MM5 (upper panel) and calculated from ground observations by LAPS analysis (lower panel) at 13:00h MST on Aug. 01, 2003.

LAI is rather poorly correlated with that of vegetation types, this simplification causes significant scaling errors in flux estimates.

As a result of using land surface schemes based on overly simplified assumptions, current weather models oftentimes fail to simulate realistic lower boundary conditions, which negatively impacts regional weather predictions by rapidly increasing forecast uncertainty beyond 9 hours. This is particularly true for the mountainous terrain of the Western U.S.A., where topography and vegetation patchiness create a complex pattern of surface energy exchange that impacts regional airflow and wind fields (Pielke 2001). For instance, the MM5 Community Model currently employed by the USFS Rocky Mountain Center (a member of FCAMMS) to predict mesoscale fire weather over the Interior Western USA (see http://www.fs.fed.us/rmc/), uses the Oregon State University (OSU) land-surface model (Chen and Dudhia 2001a,b). The OSU LSM is one of the most advanced schemes available with MM5. It utilizes the 30-sec USGS land-cover data set and assumes a fixed mean LAI value for each ecosystem type. Figure 1 shows the spatial pattern of predicted latent heat flux by the OSU scheme for the CO-WY domain at 13:00h MST on August 01, 2003. This is output from the 8th hour of a regular operational MM5 forecast. Figure 2 depicts a 1-km resolution map of summer LAI for approximately the same region. The LAI data were estimated from 1-km resolution multispectral satellite images using inversion of a bi-directional reflectance model (Nikolov 1999). Notably, over most semiarid and grassland areas, the OSU LSM predicted fluxes in excess of 350 W m^{-2}. Measurements based on the eddy-covariance method suggest a maximum magnitude of midday latent heat flux of about 100 W m^{-2} for these ecosystems and time of year (Massman et al. 1990; Zeller et al. 2001). Hence, OSU-predicted fluxes appear to be considerably exaggerated. In addition, the spatial pattern of estimated evapo-transpiration seems unrealistic since dry grasslands and semiarid regions are predicted to produce a significantly higher flux than forested mountain areas (Figures 1 and 2).

Figure 3 compares fields of surface relative humidity (RH) predicted by MM5 and calculated from observations at 13:00h MST on August 01, 2003 for the same domain. The model overestimated RH by up to 41% over regions of western Nebraska, eastern Colorado and central Wyoming. These regions approximately coincide with areas of over-predicted evapo-transpiration (see Fig. 1). As a result of overestimating RH, MM5 underestimated surface air temperature by 5 to 13 °F over the same regions (plot not shown). This suggests that inaccuracies in the predicted latent heat flux may be an important contributing factor to the well-documented temperature-humidity bias in MM5. Since temperature and humidity fields are critical to fire danger assessments, accurate forecast of dry summer weather is essential.

The evidence discussed above suggests that improving the land-surface scheme of mesoscale models may be a promising approach towards a better forecast of regional fire weather and airflow. An improved weather forecast would increase fire fighter safety and advance the operational management of prescribed burns, wildfires, and related air quality issues.

3. DEVELOPMENT OF A NEW LAND-SURFACE SCHEME FOR MM5

A research project was recently launched at the USFS Rocky Mountain Research Station to develop a new land-surface scheme for MM5 based on a state-of-the-art biophysical model named FORFLUX. This is a multi-layered process model that simulates the simultaneous exchange of water vapor (i.e. latent heat), carbon dioxide, and ozone between terrestrial ecosystems and the atmosphere (Zeller & Nikolov 2000; Nikolov & Zeller 2003). It mechanistically couples all major processes controlling ecosystem flows of water, carbon, and ozone by implementing recent concepts from plant eco-physiology, micrometeorology, and soil hydrology. The model consists of four interconnected modules - a leaf photosynthesis model (LEAFC3, Nikolov et al. 1995), a canopy flux model, a soil heat-, water- and CO_2-transport model, and a snow pack model. FORFLUX runs at hourly time steps and predicts latent heat fluxes from all surfaces of an ecosystem (i.e. canopy, soil/litter, and snow pack). The model requires for input hourly data on ambient temperature, relative humidity, incident short-wave radiation, precipitation, above-canopy wind speed, and ambient ozone concentration (optional). The meteorological input can be provided by actual observations or model simulation. Species eco-physiology is described through 20 parameters. An ecosystem is defined by latitude, longitude, elevation, slope and aspect, vegetation type (i.e. dominant plant species), leaf area index, duff layer thickness, and soil physical characteristics (such as texture, depth, and bulk density). The model provides a detailed description of the biophysical processes governing plant stomatal conductance, which is critical for predicting vegetation transpiration.

Unlike other land-surface schemes, FORFLUX mechanistically couples evapo-transpiration with CO_2 assimilation on a leaf level, and uses vegetation LAI to scale mass and energy fluxes from a leaf to canopy level. The model accounts for feedbacks between soil moisture, plant water uptake, and stomatal conductance. FORFLUX has been verified against tower flux measurements over several different ecosystems (see Nikolov 1997; Zeller & Nikolov 2000; Amthor et al. 2001). Despite its comprehensive approach towards simulation of the energy exchange processes between ecosystems and the atmosphere, FORFLUX is computationally very efficient, and can be modified for use as a land-surface model in MM5.

To be coupled with MM5, FORFLUX needs be converted from a one-dimensional point model to two-dimensional geo-referenced model. This requires that I/O parts of the code be extensively modified. Currently, the model reads input information about vegetation, soils and site topography only once in the beginning of a simulation, and saves the output variables at the end. MM5 requires that FORFLUX runs for thousands of locations (grid points), reading input data for each point and providing output fluxes to the atmospheric model at every time step. Although the flux prediction kernel of FORFLUX will not change, the model must be restructured into a subroutine that can be called from within the FORTRAN code of MM5. In addition, spatial data sets need be developed to meet FORFLUX input requirements. These data sets include LAI, vegetation type-specific eco-physiological parameters, and soil characteristics.

A spatial dataset of seasonal LAI will be derived from multispectral images provided by the MODIS sensor on board of the Terra satellite. LAI retrieval will employ the algorithm of Nikolov (1999, 2003). This method is based on inversion of a canopy bi-directional reflectance model. The radiative transfer model uses an analytical solution to the multiple scattering equation proposed by Camillo (1987). The algorithm explicitly accounts for effects of sensor view angle, solar elevation, sun-satellite relative azimuth, foliage clumping, and anisotropic soil reflectance on the relationship between LAI and Greenness Index (a ratio of near-infrared to red reflectance). The algorithm is unique in that it considers the impact of spatial variations in viewing and illumination geometry on canopy reflectance characteristics.

A digital map of vegetation types will be needed as input to the FORFLUX model to define plant eco-physiological parameters at every grid point. We will implement the 1-km resolution land-cover dataset developed jointly by the USGS and the University of Nebraska (http://edcdaac.usgs.gov/glcc/glcc.html). We will use a version currently employed by MM5, which contains 24 vegetation categories. For each vegetation type (category), we will estimate the plant eco-physiological parameters required by FORFLUX using published data and meta-analysis studies (e.g. Wullschleger 1993).

The soil data required by FORFLUX include depth, texture, and bulk density. These characteristics can be obtained from various spatial data sets. We plan to utilize a database of soil properties recently developed by the Global Soil Data Task, an IGPB-funded international project led by Dr. Bob Scholes (Council for Scientific and Industrial Research, South Africa). This database compiles the best soil information currently available. It combines the FAO UNESCO Soil map with a 3D pedon database of 1125 profiles and provides a software, which produces data sets of 8 to 10-km resolution for any region of the world with information on soil type, depth, texture, organic content, bulk density, hydraulic and chemical properties.

The coupled MM5-FORFLUX mesoscale model will be tested for accuracy of the predicted meteorological fields of temperature, humidity, wind speed, and wind direction using statistical procedures developed by the NOAA Forecast Systems Laboratory in Boulder CO. These procedures evaluate model forecast capabilities with respect to gridded real observations (provided by ground stations, air-borne balloons, airplanes etc.). Comparisons with previous versions of MM5 will also be conducted to assess the relative improvement of weather forecast due to inclusion of the new land-surface scheme.

4. REFERENCES

Amthor, J.S., Chen, J.M., Clein, J.S., Frolking, S.E., Goulden, M.L., Grant, R.F., Kimball, J.S., King, A.W., McGuire, A.D., Nikolov, N.T., Potter, C.S., Wang, S., Wofsy, S.C., 2001: Boreal forest CO_2 exchange and evapo-transpiration predicted by nine ecosystem process models: intermodel comparisons and relationships to field measurements. *J. Geophys. Res.* **106**, 33,623–33,648

Camillo, P. 1987: A canopy reflectance model based on an analytical solution to the multiple scattering equation. *Remote Sensing of Environ.*, **23**, 453-477.

Chen, F. and J. Dudhia 2001a: Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Mon. Wea. Rev.*, **129**, 569-585.

Chen, F. and J. Dudhia 2001b: Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part II: Preliminary model validation. *Mon. Wea. Rev.*, **129**, 587-604

Chase, T.N., R.A. Pielke, T.G.F. Kittel, R. Nemani, and S.W. Running, 1996: The sensitivity of a general circulation model to global changes in leaf area index. J. Geophys. Res., **101,** 7393-7408.

Fennessy & Xue. 1997: Impact of USGS vegetation map on GCM simulations over the United States. *Ecol. Applications* **7**(1), 22-33.

Lynn BH, Stauffer DR, Wetzel PJ, Tao WK, Alpert P, Perlin N, Baker RD, Munoz R, Boone A, Jia YQ. 2001: Improved simulation of Florida summer convection using the PLACE land model and a 1.5-order turbulence parameterization coupled to the Penn State-NCAR mesoscale model. *Monthly Weather Review*, **129** (6), 1441-1461.

Massman, W.J.; Fox, D.G.; Zeller, K.F.; Lukens, D. 1990: Verifying eddy correlation measurements: a study of the energy balance components of the Pawnee grasslands. USDA Forest Service Rocky Mountain Forest and Range Experiment Station. Research Paper RM-288 14p.

Nikolov, N. 2003: Retrieval of global vegetation leaf area index from 8-km resolution multispectral satellite data. *Remote Sens. Environ*. (in review).

Nikolov, N.T. 1999: *A 1-km Resolution Database of Monthly Vegetation Leaf Area Index and Canopy Clumping Factor for the Western USA*. Technical Report submitted the UDSA FS/Pacific Southwest Research Station, Agreement No PSW-99-001-RJVA, N & T Services, Oak Ridge TN 37830.

Nikolov, N.T. 1997: Mathematical Modeling of Seasonal Biogeophysical Interactions in Forest Ecosystems. Ph.D. Dissertation, Colorado State University, Fort Collins CO, 149 pp.

Nikolov, N.T., Massman, W.J., and Shoettle, A.W. 1995: Coupling biochemical and biophysical processes at the leaf level: An equilibrium photosynthesis model for leaves of C_3 plants. *Ecological Modelling*, **80**, 205-235.

Nikolov, N. & Zeller, K.F. 2003: Modeling coupled interactions of carbon, water and ozone exchange between terrestrial ecosystems and the atmosphere: I Model description. *Environ. Pollution*, **124**, 231-246.

Pielke Sr., R.A., 2001: Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. Rev. Geophys., **39**, 151-177.

Pielke, R.A. et al. 1997: Use of USGS-provided data to improve weather and climate simulations. *Ecol. Applications* **7**(1), 3-21

Pielke, R.A., Avissar, R, Raupach, M., Dolman, A.J., Zeng, X. & Denning, A.S. 1998: Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. *Global Change Biology* **4**, 461-475.

Zeller, K. & Nikolov, N. 2000: Quantifying simultaneous fluxes of ozone, carbon dioxide and water vapor above a subalpine forest ecosystem. *Environ. Pollution* **107**, 1-20.

Zeller, K., G. Zimmerman, T. Hehn, E. Donev, D. Denny, J. Welker, 2001: Analysis of Inadvertent Microprocessor Lag Time on Eddy Covariance Results, *J. Appl. Meteor*. **40**, 1640-1646.

Wullschleger, S.D. 1993: Biochemical limitations to carbon assimilation in C_3 plants – a retrospective analysis of the A/C_i curves from 109 species. *J. Exp. Botany* **44**(262), 907-920.