Introduction

Canopy-scale flux measurements and inferential models are useful for developing estimates of net emission or deposition of trace gases and aerosols above forests. However, more detailed measurements and models are needed to relate net fluxes to biological, physical, and chemical processes occurring within the air-canopy-soil system, which occur over multiple time scales. The objective of this work is to develop modeling tools that can be used to link atmosphere-biosphere fluxes of reactive compounds to specific ecosystem compartments (e.g., canopy, understory, ground).

Direct measurements of vertical source-sink profiles (fluxes) of most reactive nitrogen, carbon, and sulfur compounds are not possible, either due to limitation or absence of analytical methods capable of direct flux measurements, inability to measure fluxes at appropriate locations within the canopy, or both. However, measured concentration profiles can be used to infer the effective source-sink distribution if the flow field is known. In this study, a combination of inverse source-sink modeling approaches are used to estimate vertical flux and source sink profiles in a forest using measurements of air concentrations and the flow field within and above the canopy.

Study Site

- Coweeta Hydrologic Laboratory, North Carolina
- Mature southern Appalachian forest (~95 years since harvesting)
- Deciduous overstory (tulip poplar, sweet birch, red maple, oak), mean canopy height 30 m
- Evergreen understory (rhododendron, mountain laurel)
- Complex topography (base elevation 700 m)
- Mean annual temperature: 12.7 °C

Measurements

- Above canopy (43.5 m) and sub canopy (2 m) eddy covariance heat, CO₂, H₂O, CO₂, H₂O concentration profile (7 heights)
- Air temperature profile (6 heights)
- Air concentrations of NH₃, HNO₃, SO₂, NO₂, NO₃⁻, and SO₄²⁻ (10 heights)
- Daytime chemistry profiles URG annular denuder 3-hour sampling time
- Five seasonal intensives during 2015-16 Southern Appalachian Nitrogen Deposition Study (SANDS)

Modeling

1. Eulerian frame of reference

The effective source or sink (S) is estimated from the steady state mean scalar conservation equation:

$$\frac{d}{dz} \left( \frac{dC}{dz} \right) + S = 0$$

where the flux \( \frac{dC}{dz} \) is estimated from the corresponding flux budget equation:

$$\frac{d}{dz} \left( \frac{dC}{dz} \right) = -w' \frac{dC}{dz} - \frac{dC}{dz} + \frac{dC}{dz}$$

with the following closures:

$$w' \frac{dC}{dz} = \frac{1}{2} \left( -w' w' \frac{dC}{dz} - w' C' \frac{dC'}{dz} - 2w' w' \frac{dC}{dz} \right)$$

This method requires the velocity variance (\( w' w' \)), skewness (\( w' w' w' \)), an Eulerian time scale (\( t_e \)), and the two constants (\( C_4, C_8 \)).

2. Lagrangian localized near-field theory - LNF

A dispersion kernel is generated by dividing the canopy into \( n \) layers. Concentration profiles are calculated for a uniformly distributed unit source from each of these layers resulting in a transformation matrix (\( D \)) that relates \( S \) to the mean concentration (\( C \)):

$$C = C_0 = D \cdot S$$

where \( C_0 \) is a reference concentration

\( D \) is calculated by superimposing near- (\( C_n \)) and far- (\( C_f \)) field contributions, assuming vertical dispersion only, locally homogenous turbulence, and constant time scale. This method requires the velocity variance (\( w' w' \)) and Lagrangian time scale (\( t_L \)).

Results

(1) Chemistry profiles

- NH₃ and SO₄²⁻ concentrations decrease by ~ 95% and 80%, respectively, from the upper canopy to the forest floor.
- Aerosol profiles reflect much slower deposition than gases.
- NH₃ profiles indicate deposition to vegetation and emission from the forest floor.

(2) Flow field

- Wind speed decreased from above the canopy to the middle canopy and then increased slightly above the trunk area above the forest floor.
- Reynolds stress and velocity variances followed typical patterns.

(3) Source/Sink profiles

- Models predict positive NH₃ fluxes near the forest floor, indicating emissions from litter or soil.
- The forest was a net sink of NH₄⁺.
- Most uptake of HNO₃ and SO₂ occurred in the upper canopy.
- Significant differences in the estimated source/sink can be found between different models and for different time scales.

Next Steps

- Analysis of full data sets from five seasonal intensives.
- Evaluation and comparison of source-sink modeling approaches.
- Evaluation of source-sink models against measured fluxes of heat, CO₂, H₂O, and reactive nitrogen and sulfur compounds.
- Comparison of source-sink models to multilayer resistance based and big-leaf canopy scale models.

Fig. 1 Study area

Fig. 2 Tower schematic

Fig. 3 Median vertical concentration profiles for summer 2016 campaign. Concentration at height \( z_C \) is normalized by the reference concentration (\( C_{ref} \)) measured at \( z_C = 1.4 \), where \( h_c \) is canopy height. Observations represent the median of \( n = 19 \) profiles.

Fig. 4 Flow statistics used for source/sink estimation for an example profile on July 21, 2016. Statistics averaged over 4 hour (11:00-15:00) duration of chemical measurements. Three Lagrangian time scales (right hand panel) were considered, estimated from the auto-correlation of \( w' \) (T11, blue line), a far-field diffusion time scale (tau 1, red line), and a constant based on the canopy height and \( w_c \) (tau 3, black line).

Fig. 5 Example measured (circles) and modeled (lines) concentration profiles (\( \mu g/m^3 \)) (left panel) along with modeled flux profiles (\( \mu g/m^2/s \)) (middle panel) and source/sink distribution (\( \mu g/m^3/s \)) for NH₃, N₂O, HNO₃, N, and SO₂-S, respectively. Flow statistics in Fig. 4.