Modeling carbon dioxide assimilation processes by riverine mangroves

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Introduction

Traditionally, assimilation of carbon dioxide (CO_2) by mangroves has focused on the translocation of atmospheric CO_2 into biomass (e.g., Chen and Twilley 1999) in the form of leaf litter production, growth of tree boles, and the production of roots. This type of research has been very important to the ecological community, but an atmospheric-based approach is necessary to determine the amount carbon assimilation by mangroves from the atmosphere over half-hourly to yearly time scales so that improved estimates of the biospheric CO_2 sink can be reliably estimated.

The emerging knowledge from the world wide network of eddy covariance flux towers (FLUXNET) indicates that forests throughout the world constitute major sinks for atmospheric carbon dioxide (Baldocchi et al. 2001). The knowledge gained from these forests provides a valuable starting point for understanding carbon assimilation by mangroves. Mangrove forests, like most ecosystems located along the marine-terrestrial interface, have not been systematically investigated for their carbon uptake capabilities (Wofsy and Harris 2002).

Here, we highlight a newly developed atmospheric-biospheric modeling system, which predicts mangrove carbon dioxide assimilation from the atmosphere under some typical local climate forcings. Modeled fluxes of sensible heat, water vapor, and carbon dioxide were verified diurnally and seasonally over the period January to August 2004 using fluxes determined from the eddy covariance method (**Figure 1**). Thus, the model has to capture the physical processes of carbon assimilation in near real time under a variety of local climate forcings. Photosynthetic production and ecosystem respiration processes change dramatically under the influence of cool (~10 °C) air masses and clear-skies during January compared to the hot air masses, periods of cloudiness, and afternoon thunderstorms during the summer (June to September).

Our coupled atmospheric-biospheric modeling system is used to compute trace gas exchange between the mangrove forest (**Figure 2**) and overlying atmosphere (**Figure 1**). While the model borrows many important components developed for terrestrial ecosystems, several key elements are specific to mangroves along Shark River near the FCE-LTER SRS-6 site.

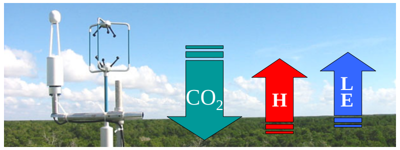


Figure 1. Eddy covariance system at the SRS-6 site showing daytime flux components

Figure 2. Forest floor (above) and flux tower (right) at the SRS-6 site

Model Structure

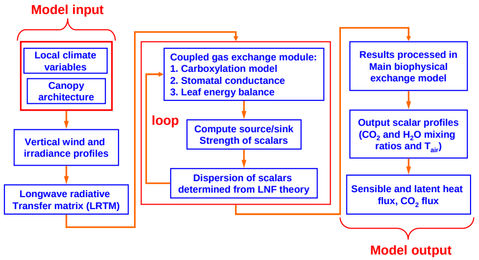
The general structure of the mangrove biophysical exchange model (**Figure 3**) has several features specific to mangrove forests. These include:

1. A plant biochemistry module incorporating foliage physiological characteristics determined from red *(Rhizophora mangle)* and black (*Avicennia germinans*) mangrove leaves inside the forest canopy. Multiple measurements were made with a LiCor 6400 gas exchange system while harnessed to our 27-m flux tower.

2. A new stomatal conductance algorithm to understand water usage at the leaf level.

3. Ecosystem respiration rates as a function of air and soil temperature determined from eddy covariance and ancillary measurements.

4. A realistic canopy architecture module to understand the disposition of solar irradiance through the canopy.



Model input

Local climate variables

Canopy architecture

Vertical wind and irradiance profiles

Longwave radiative Transfer matrix (LRTM)

Coupled gas exchange module:
1. Carboxylation model
2. Stomatal conductance
3. Leaf energy balance

loop

Compute source/sink Strength of scalars

Dispersion of scalars determined from LNF theory

Results processed in Main biophysical exchange model

Output scalar profiles (CO_2 and H_2O mixing ratios and T_{air})

Sensible and latent heat flux, CO_2 flux

Model output

Figure 3. Basic structure of mangrove biophysical exchange model

Results

The model reproduced diurnal trends of carbon dioxide fluxes during winter (**Figure 4**), spring (**Figure 5**), and summer (**Figure 6**) periods. Carbon assimilation was limited by day length during the winter (**Figure 4**), but nighttime respiration was suppressed as a result of cool air masses and cool waters from the estuary. During the spring, higher irradiance levels and longer days compared to the winter resulted in the greatest seasonal daytime carbon fluxes (**Figure 5**). Also, nighttime air masses remained cool (< 15 °C), and forest carbon assimilation benefited from continued suppression of ecosystem respiration (< 5 μmol m^{-2} s^{-1}). During the summer, daily carbon assimilation (**Figure 6**) was limited by high ecosystem respiration rates (5-10 μmol m^{-2} s^{-1}) at night and the combination of photo-respiration and photosynthesis deactivation processes during the daytime. Also, carbon assimilation is limited during overcast periods in the wet season (data not shown).

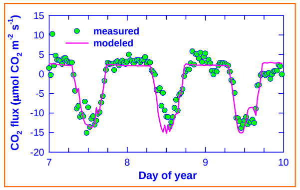


Figure 4. Diurnal carbon dioxide fluxes during winter

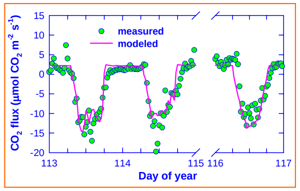


Figure 5. Diurnal carbon dioxide fluxes during spring

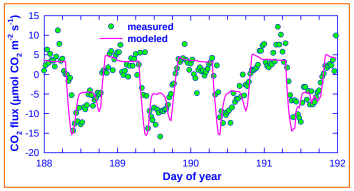


Figure 6. Diurnal carbon dioxide fluxes during summer

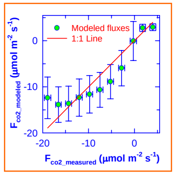


Figure 7. Verification of half-hourly modeled carbon dioxide fluxes during 2004.

Results - model verification

The model reproduced not only fluxes of carbon dioxide (**Figure 7**), but also sensible (**Figure 8**) and latent (**Figure 9**) heat fluxes. The model captured the general trends of carbon dioxide fluxes and latent heat fluxes without explicitly including seasonal changes in salinity and changes in nutrient allocation to foliage. The model systematically overestimated sensible heat fluxes (Figure 8). However, overestimation of either H or LE was expected since the model forces energy closure. In reality, eddy covariance measurements close the energy budget by ~70-90 %.

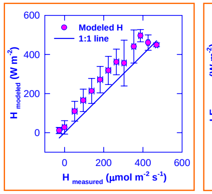


Figure 8. Verification of half-hourly modeled sensible heat fluxes during 2004.

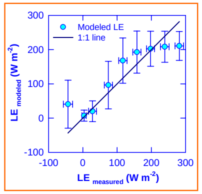


Figure 9. Verification of half-hourly modeled latent heat fluxes during 2004.

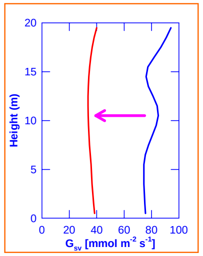


Figure 10. Modeled stomatal conductance (Gsv) profiles during 09 July 2004.

Summer heat stress:

Temperature and irradiance stress resulted in suppressed stomatal conductance to water vapor during the midday on clear sky summer days (**Figure 10**).

Afternoon photosynthesis deactivation and stomatal closure was not observed during the winter and spring (**Figure 11**).

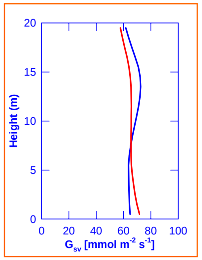


Figure 11. Modeled stomatal conductance (Gsv) profiles during 25 March 2004.

Climate change scenarios

Changes in the global and regional climate may be particularly important to mangrove health. In particular, rising levels of atmospheric carbon dioxide represent a forcing on carbon assimilation at the foliage level. At the regional scale, seasonal changes in water flow will result in different salinity patterns in Shark River near SRS-6. This, in turn, could alter water use by mangroves as manifest in 'tuning' of foliage stomatal conductance algorithms. Model runs were performed with varying atmospheric CO_2 mixing ratios during DOY 116 (**Figure 12**), which is during the best part of the growing season. A 20% and 50% increase in carbon dioxide mixing ratio resulted in marked increases in midday fluxes (**Figure 12**). Fresh water is a precious commodity in a mangrove forest, and mangroves display high water use efficiencies compared to their terrestrial counterparts. Water use is controlled through the amount of stomatal pore opening represented by stomatal conductance algorithms. We considered changes in water usage under climate change scenarios by adjusting the slope and intercept of the stomatal conductance algorithm at the foliage dimension. A ratio greater than 1 indicates a more liberal use of water than mangroves currently have, and a ratio less than 1 indicates a more conservative use of water (**Figure 13**). A 40% reduction in stomatal conductance (**Figure 13**) and a 35% reduction if atmospheric carbon dioxide mixing ratio (**Figure 13**) resulted in the same reduction in diurnal carbon assimilation. Perhaps the most interesting result was that an increase in stomatal conductance did not result in greater midday carbon dioxide fluxes (**Figure 13)**. This result provides evidence that mangroves are optimizing carbon assimilation while sacrificing as little water as possible.

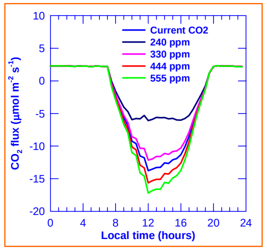


Figure 12. Modeled carbon dioxide fluxes during 25 March 2004 considering various atmospheric CO_2 mixing ratios.

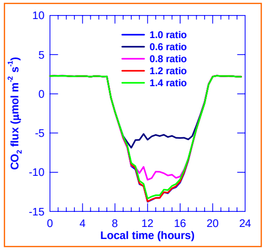


Figure 13. Modeled carbon dioxide fluxes during 25 March 2004 considering changes in the slope and intercept of the stomatal conductance algorithm.

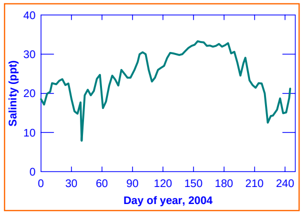


Figure 14. Seasonal salinity levels in Shark River beside the SRS-6 boardwalk during 2004.

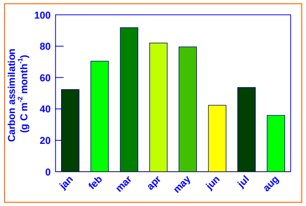


Figure 15. Monthly carbon assimilation from the atmosphere by the SRS-6 mangrove forest determined from eddy covariance flux measurements during 2004.

Summary and Conclusions

Our mangrove biophysical exchange model reproduces carbon dioxide, latent heat, and sensible heat fluxes in near real time. Because it incorporates the physical processes of gas exchange across the forest-atmosphere interface, the model can easily be adapted to consider regional and global climate change. Specifically, we can change the forcings of air temperature, irradiance levels, and water use, as manifest in the stomatal conductance algorithms, to understand future changes in the health and functioning of the mangrove biome. Currently, the model does not explicitly include seasonal changes in salinity **(Figure 14)**, yet the model still captures diurnal flux trends of carbon dioxide. During the winter when salinity is low (~20 ppt), the evaporative demand is low. During the late spring and early summer when salinity is higher (~30 ppt), the influence of salinity may be hidden by midday temperature-induced photosynthesis deactivation and high photo-respiration rates (**Figure 6**) on clear sky days. Reduced photosynthesis resulted in lower stomatal conductance values and greater water conservation during hot summer days. Thus, the conservation of water could mostly be explained by the local climate rather than by edaphic conditions. In summary, our mangrove model provided an understanding of the physical processes that resulted in unique diurnal and seasonal (Figure 15) carbon assimilation trends. Also, our model may be adapted to understand future carbon assimilation rates resulting from regional climate change in the Florida Everglades.

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