Title

Understanding the Stable Isotope Composition of Biosphere-Atmosphere CO_2 Exchange

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Future Directions

SRTM data are provided in near-global coverage from 56°S to 60°N. While Antarctica will not be covered by HydroSHEDS, the region north of 60°N will be completed in the 30-arc-second resolution by inserting existing global data (GTOPO30 and HYDRO1k). Higher-resolution elevation data will be utilized in future updates where available (United States, Canada, Europe).

To date, the focus in data processing has been to provide the following core layers: void-filled and hydrologically conditioned elevation and drainage directions at all resolutions; and flow accumulation, river network, and first-order basin outlines at 15- and 30-arc-second resolutions. Future developments will add new layers of information and enhanced attributes. The following updates are planned: slope; full-resolution flow accumulations; flow distances; stream network and subbasin delineations according to various river-ordering schemes, including Pfafstetter coding [*Verdin and Verdin*, 1999]; and modeled flow quantities. As the upscaling algorithm of HydroSHEDS is flexible, all data sets may be provided at additional resolutions in the future.

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Understanding the Stable Isotope Composition of Biosphere-Atmosphere CO_2 Exchange

PAGES 94–95

Stable isotopes of atmospheric carbon dioxide (CO_2) contain a wealth of information regarding biosphere-atmosphere interactions. The carbon isotope ratio of CO_2 ($\delta^{13}C$) reflects the terrestrial carbon cycle including processes of photosynthesis, respiration, and decomposition. The oxygen isotope ratio ($\delta^{18}O$) reflects terrestrial carbon and water coupling due to CO_2-H_2O oxygen exchange. Isotopic CO_2 measurements, in combination with ecosystem-isotopic exchange models, allow for the quantification of patterns and mechanisms regulating terrestrial carbon and water cycles, as well as for hypothesis development, data interpretation, and forecasting. Isotopic measurements and models have evolved significantly over the past two decades, resulting in organizations that promote model-measurement networks, e.g., the U.S. National Science Foundation's Biosphere-Atmosphere Stable Isotope Network, the European Stable Isotopes in Biosphere-Atmosphere Exchange Network, and the U.S. National Environmental Observatory Network.

Unfortunately, technical limitations associated with atmospheric flask sampling and subsequent analyses via mass spectrometry have constrained high-frequency data useful for in-depth quantification of patterns and controls. As a consequence, state-of-the-art models of ecosystem stable isotope exchange have evolved beyond their counterpart measurement systems, leaving model assumptions vulnerable due to a lack of validation data sets.

The recent development of laser-based systems for high-frequency, continuous sampling of CO_2 isotopologues (at least one atom with a different number of neutrons), i.e., $^{12}CO_2$, $^{13}CO_2$, and $^{12}C^{16}O^{18}O$, allows, for the first time, rigorous model testing at compatible timescales. Numerous laser systems are in development and all have advantages and disadvantages; however, all of them share the potential of having precision and accuracy on par with traditional flask/mass spectrometry techniques while providing continuous, high-frequency data (i.e., <1–15 minutes). Model-measurement comparisons can now be used to interpret observations and identify knowledge gaps via sensitivity analyses, thereby creating a closed loop of hypotheses-observation-interpretation-hypotheses.

Biosphere-Atmosphere Isotopic Exchange

We compared 2 years of near-continuous measurements of nocturnal ecosystem-respired CO_2 ($\delta^{13}C_R$ and $\delta^{18}O_R$) from a semiarid juniper woodland—located at the Los Alamos National Laboratory in northern New Mexico—with outputs from three models of ecosystem stable isotope exchange. Our objective was to determine if new insight into the strengths and weaknesses of models could be revealed using continuous, high-frequency observations.

Measurements collected via tunable diode laser spectroscopy (Campbell Scientific's TGA100) were used to test the models: CanIsotope (canopy-isotope) for $\delta^{13}C_R$ (a simple steady state model), SIM (simple isotope model) for $\delta^{18}O_R$, and ISOLSM (isotope land surface model) for both $\delta^{13}C_R$ and $\delta^{18}O_R$. Though not an exhaustive comparison of all models, these three models represent end points in the spectrum from detailed to simple process representations. All three models received similar input data: meteorology, leaf area, photosynthetic capacity, and $\delta^{18}O$ of precipitation, soil, and stem water.

All three models provided some encouraging successes when simulations were compared with observations. The models reproduced the observations of ecosystem CO_2, latent and sensible heat fluxes, and the ratio of CO_2 partial pressure within canopy foliage relative to the partial pressure of CO_2 in the surrounding atmosphere. Also, the timing and direction of $\delta^{18}O_R$ variation was well captured (Figure 1). Thus, a range of model complexity and assumptions captured photosynthesis and $\delta^{18}O$ dynamics associated with the large daily and seasonal variation in humidity and precipitation that occurs at this woodland.

Models captured $\delta^{18}O_R$ better than $\delta^{13}C_R$. This demonstrates our limited understanding of carbon cycling compared with oxygen isotope exchanges between soil and leaf H_2O and CO_2. The discrepancy partially occurred because these models lack carbon pools, and thus they simulated $\delta^{13}C$ of photosynthate rather than $\delta^{13}C_R$, assumed that carbon translocation to respiration was immediate, and assumed that no respiratory fractionation occurred (we note that some models exist that do represent these processes). In addition, the models assumed isohydric (constant) regulation of leaf water potential, which leads to strong feedbacks between water availability and stomatal conductance. However, juniper has anisohydric (nonconstant) leaf water potential regulation, as do many semiarid species, leading to less sensitive water-stomatal conductance dependency. The failure to include anisohydric stomatal conductance led models to predict a stronger relationship between $\delta^{13}C_R$ and moisture than was observed. The inclusion of carbon residence time and disequilibrium, decomposition, respiratory fractionation, and anisohydric water potential regulation should reduce the model-measurement gap by enriching $\delta^{13}C_R$ predictions and reducing variability.

Knowledge gaps were also revealed for $\delta^{18}O_R$. Measured $\delta^{18}O_R$ was frequently underestimated by 8–10‰. Nocturnal isotopic equilibration of CO_2 with leaf water $\delta^{18}O$ and subsequent atmospheric retro-flux may affect observed $\delta^{18}O_R$ more than predicted. The depth distribution of isotopic exchange between soil CO_2 and water $\delta^{18}O$ and subsequent surface flux may also induce discrepancies. Finally, both $\delta^{13}C$ and $\delta^{18}O$ simulations were sensitive to parameterization of CO_2 conductance from stomata to chloroplast; however, this process is poorly characterized. All of the weaknesses listed above can be empirically examined through laser-based experiments.

There are advantages to combining high-frequency sampling with models for understanding terrestrial carbon and water cycling. Isotope measurements allow additional constraints for model tests and validation. Isotopic models must simulate chloroplast CO_2 to predict $\delta^{18}O$ or $\delta^{13}C$, thus requiring the prediction of photosynthetic capacity as well as mesophyll CO_2 conductance. The simulation of soil-respired $\delta^{13}C$ tests our understanding of carbon turnover. Other novel applications of combining models with high-frequency sampling include flux partitioning, fast detection of climate impacts on CO_2 and H_2O cycling and coupling, and fast-response physiology.

However, isotope exchange models require additional parameterization data than do traditional biophysical models. Modeling $\delta^{13}C$ requires knowledge of $\delta^{13}C$ of atmospheric CO_2 and $\delta^{13}C$ of CO_2 evolved from organic matter decomposition, the latter of which is poorly understood. For $\delta^{18}O$, knowledge of ecosystem and atmospheric water pool $\delta^{18}O$ and the $\delta^{18}O$ of background CO_2 are required to verify that models predict $\delta^{18}O_R$ correctly and for the right reason. Last, because most process models are currently validated using eddy covariance, it remains critical to colocate laser-based isotope systems and eddy covariance towers.

Over the past two decades, models and measurements of biosphere-atmosphere CO_2 exchange have advanced significantly. With the development of fast-response laser systems for quantifying $\delta^{13}C$ and $\delta^{18}O$ of CO_2, we can now test models continuously, at high frequency, and with new constraints, enhancing our ability to characterize ecosystem carbon and water cycling.

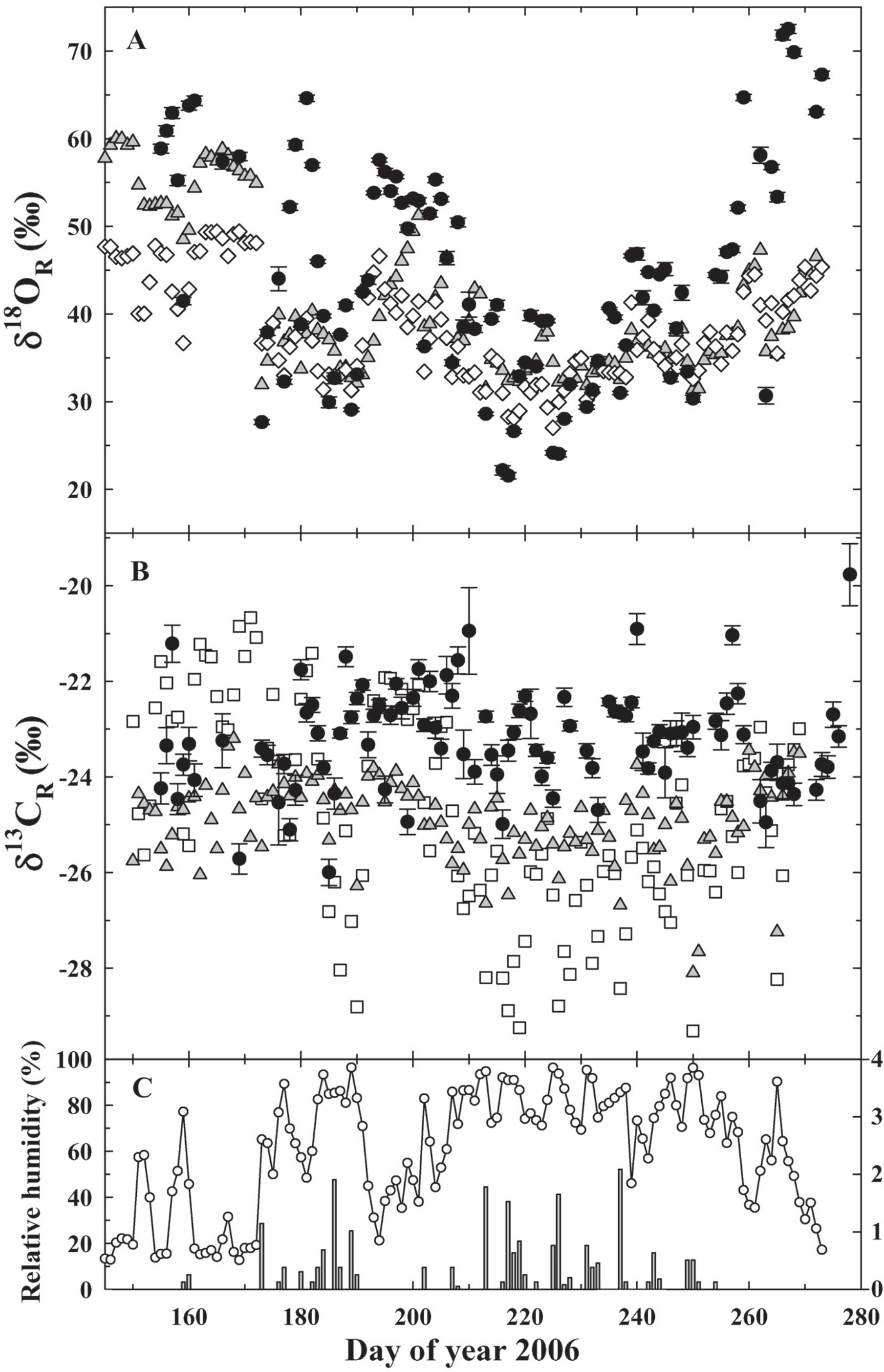

Fig. 1. Observations and model predictions of (a) $\delta^{18}O_R$ and (b) $\delta^{13}C_R$ versus day of year 2006. Solid circles are observations with standard error bars, and predictions are gray triangles (isotope land surface model), open diamonds (simple isotope model), and open squares (canopy-isotope, or CanIsotope). (c) Daily average relative humidity (circles) and precipitation (in millimeters; gray bars).

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