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GEOCARBON

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Abstract: In this work package we have specifically investigated the atmospheric record of the $\delta^{13}C$ of CO_2. This isotopic signature is known to be an indicator of terrestrial vs oceanic carbon exchange on large scales, and of vegetation drought stress on small scales. We show in our study that: (a) the atmospheric budget of $\delta^{13}C$ is not closed given our current best estimates of carbon exchange world wide, (b) its interannual variability suggests that more processes are at play in the carbon/isotope budget than considered in previous studies, (c) it is possible to improve carbon dynamics of terrestrial vegetation models based on $\delta^{13}C$ observations, and (d) the atmospheric $\delta^{13}C$ record contains interpretable signals of changing water-use efficiency during large droughts of the past decade.

The large amount of observations, more detailed biogeochemical modeling, and availability of more powerful data assimilation methods all contribute to these results. Maintaining and expanding the atmospheric $\delta^{13}C$ observing network should therefore have very high priority, especially considering the new spectroscopic continuous analyzers built by several companies (such as Picarro, and Aerodyne).

1. Introduction

Traditionally, measurements of Carbon-13 (^{13}C) in CO_2 have been used in plant breeding programs to improve the drought resilience of crops. If the demand for water for evaporation (and conversely photosynthesis) exceeds the moisture available to the plant,

it can regulate water loss and carbon uptake by closing its stomata. Plants are thus believed to control their stomates to optimize the amount of water loss and the amount of carbon assimilated (Cowan and Farquhar, 1977). This trade-off is quantified as the water use efficiency (WUE). But when stomatal conductance decreases, the concentration ratio of CO_2 between intercellular cavities and ambient atmosphere (Ci/Ca) also decreases. And since photosynthetic isotope discrimination strongly correlates with the Ci/Ca ratio, ^{13}C is regarded as a useful diagnostic for the WUE of plants (Brugnoli and Farquhar, 2000).

Besides the biological applications there is also a continuing effort of using measured atmospheric isotope ratios of CO_2 to improve our understanding of the global carbon budget and carbon exchange estimates (e.g. Tans et al., 1993; Ciais et al., 1995; Rayner et al., 2008), which are traditionally based on atmospheric CO_2 mixing ratios alone. The Carbon-14 isotope in CO_2 can help for instance to identify fossil fuel combustion (Bozhinova et al., 2013), while the ^{13}C isotope in CO_2 can help distinguish carbon exchange between the terrestrial biosphere and the ocean, given that each flux discriminates slightly differently against the heavier ^{13}C isotope. This process gives terrestrial and ocean carbon exchange its own distinct influence on the isotopic composition of the atmosphere. But besides direct influences during carbon uptake we also need detailed understanding of other processes in the ^{13}C budget. Special attention should be given to the isotopic disequilibrium flux (Tans, 1980; Tans et al., 1993), which is associated with CO_2 release towards the atmosphere and stems from differences in isotopic composition between 'old' carbon released from oceanic and terrestrial reservoirs and 'new' carbon being taken up from the atmosphere. This is a consequence of the continuing depletion of atmospheric isotopic composition by the emissions of ^{13}C-depleted fossil CO_2 (also known as the Suess effect; Suess, 1955) causing the atmosphere to be become isotopically lighter over time.

For this deliverable of GEOCARBON (14.4) we combined these two different research angles of ^{13}C (the biological and the atmospheric) to study whether measurements of ^{13}C in the atmosphere can constrain the large-scale changes in WUE. This work builds on terrestrial biosphere modeling of ^{13}C exchange, and data assimilation with atmospheric transport modeling. Additional optimization of the isotope discrimination parameter in the terrestrial biosphere is one of the several novel developments in this project. The core of this study is published or is in the process of being published in peer-reviewed journals. This report summarizes main the findings so far.

2. Atmospheric ^{13}C budget

In Van der Velde et al. (2013), we studied the global ^{13}C budget and interannual variability (IAV) using different inventories for fossil fuel combustion, net ocean exchange and ocean isotopic disequilibrium. The terrestrial estimates for biomass burning, discrimination and isotopic disequilibrium came from the SiBCASA model (Schaefer et al., 2008), which we co-developed, and enhanced with the full spectrum of ^{13}C exchange. This includes a well-known discrimination model for C3 and C4 plant types (Suits et al., 2005), and the allocation and turnover of ^{13}C biomass in different plant and soil pools.

One of the major findings is that these bottom-up estimates are not consistent with the measured global mean isotopic composition in CO_2. We found a gap in the global mean budget as well as in the IAV. This is further illustrated in Fig. 1. We first closed the CO_2 budget given the rate of change of CO_2, the rate of fossil fuel combustion, the rate of

biomass burning, as well as the ocean exchange to be well-known, and thus assigning the remainder of budget to terrestrial net exchange. The solution of this budgeting is shown in Fig. 1a. Increases in CO_2 from fossil fuel combustion and biomass burning are partly countered by uptake in the terrestrial biosphere and oceans. The remainder of the emitted CO_2 accumulates on average with 3.6 PgC yr^{-1} in the atmosphere (black line). These four flux terms of the CO_2 budget are used to estimate ^{13}C isofluxes (in units of PgC‰ yr^{-1}) to close ^{13}C budget. This requires additional information on the ocean (fixed value) and terrestrial discrimination (variable value from SiBCASA) and isotopic disequilibrium fluxes from both reservoirs. By adding up all the terms we found a substantial underestimation of the total mean ^{13}C isoflux and a large missing fraction in the IAV budget (gray line, Fig.1b). Closer inspection points to a few processes that dominate the budget, and thus could be held responsible for this gap.
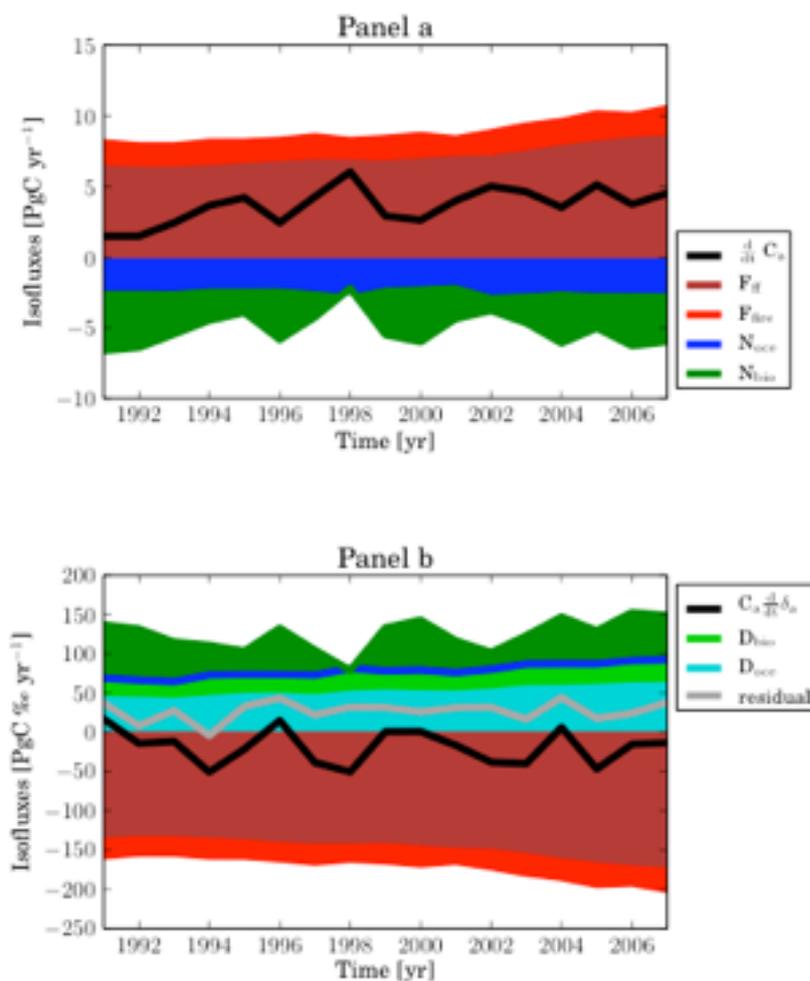

Figure 1. *Timeseries of each term of the CO_2 budget (panel a) and ^{13}C budget (panel b). The global annual isofluxes are plotted as stacked area timeseries. Global annual observed rate of change of CO_2 and ^{13}C are plotted as a black line, and the global annual residual isoflux in ^{13}C is plotted as a gray line (From Van der Velde et al. 2013).*

One of the suspects is the lack of additional variability in isotopic discrimination. Since its parameterization is strongly coupled to stomatal conductance, it could mean we miss

sensitivity to water stress (see Section 3). More IAV in either C3/C4 plant distributions or their relative responses to climate anomalies could also invoke more IAV in global discrimination and thus also in atmospheric ^{13}C. Besides uncertainty in the bottom-up estimates we also found that the constraint on the IAV of the global atmospheric ^{13}C growth rate might not be as robust as previously thought. Out of the 100 realistic realizations of different global measurement networks we found a large spread in the global mean IAV. Nevertheless, this study hinted that there is untapped information in the available $^{13}CO_2$ records that can help to further constrain the land/ocean carbon uptake partitioning through discrimination signals, and perhaps even the gross carbon release by vegetation and oceans through the disequilibrium. The variability budget of $^{13}CO_2$ was so far unstudied, and provides a new piece of information from this tracer.

3. Humidity response to isotope exchange and water use efficiency

In Van der Velde et al. (2014, under review), we studied in more detail the internal mechanisms of simulated isotopic discrimination, and its response to environmental conditions, as well as the terrestrial disequilibrium, and biomass burning, which were all included in the SiBCASA model.

With SiBCASA we are able to predict daily values for isotopic discrimination (in units of ‰) globally on 1 by 1 degree resolution. As seen in Fig. 2a, large spatial differences in the global annual plant discrimination (gpp-weighted) are determined by the C3/C4 plant distribution. Regions with lower values of discrimination correspond to the dominant presence of C4 plants, such as the South American grasslands, African subtropical savannas, Northern Australia, and North American crop fields. The largest IAV is on the Northern Hemisphere within C3 dominant areas due to changes in climate conditions, water availability and relative humidity (Fig. 2b). These parameters affect the stomatal conductance, and subsequently control discrimination through changes in the ratios of C_i/C_a. As shown in Van der Velde et al. (2013), discrimination is one of the key parameters that could hold much more variability than currently simulated.
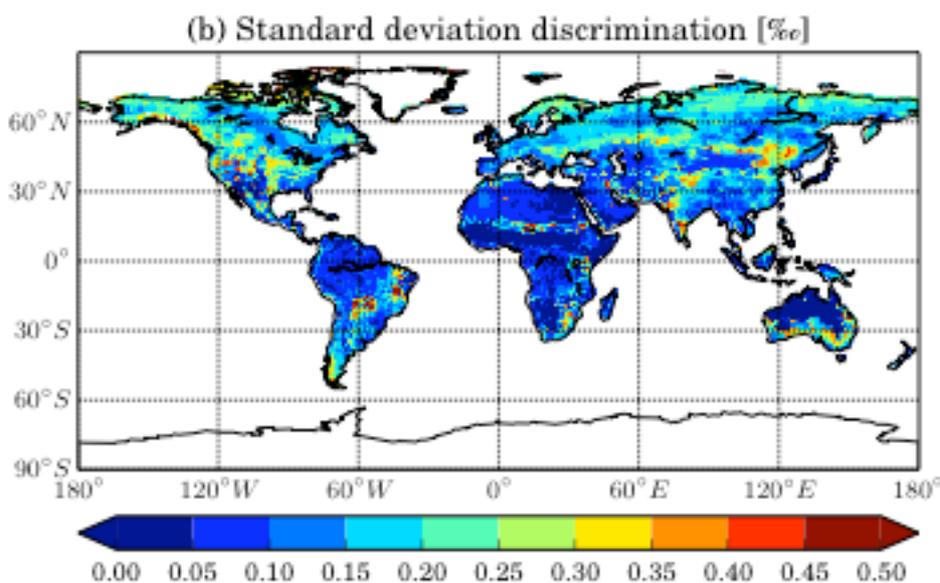

Figure 2. *SiBCASA assimilation-weighted annual plant discrimination (panel a), from a 13-*

year period (1997-2009), and the year-to-year variability of the annual discrimination values determined from the same 13 year period (panel b). Differences in C3 and C4 metabolic pathways give the clear spatial contrast in the annual mean discrimination. Relative humidity, precipitation and soil moisture conditions largely drive the interannual variability in discrimination. Large variations are also found in parts of South America and Africa in mixed C3/C4 grid cells, where independent changes in C3 or C4 GPP can change grid cell mean discrimination value significantly. Note that the color scale in panel (a) is non-linear. (From Van der Velde et al. 2014, under review).

An important contributor to the stomatal induced variations in isotopic discrimination is humidity as shown in several studies (e.g. Ekblad and Hogberg, 2001; Bowling et al. 2002). The humidity in the atmosphere affects stomatal conductance, which is reflected in discrimination, and ultimately alters the isotopic composition the plant tissue and the CO_2 that is respired back to the atmosphere after only several days.

In the model though we observe (1) a small response in discrimination to changes in vapor pressure deficit (VPD), (2) a large latency in recently assimilated carbon to become available for respiration, (3) possibly, the absence of additional processes that contribute to additional stomatal stress, and (4) the absence of additional isotope effects that could contribute to the variability in respired CO_2 isotopic composition. The comparison of simulated respiration signature with observed values is shown in Fig. 3. Increasing humidity stress under greater VPD regimes, which decreases the Ci/Ca ratio, improves the slope substantially between isotopic composition of plant respiration and VPD.
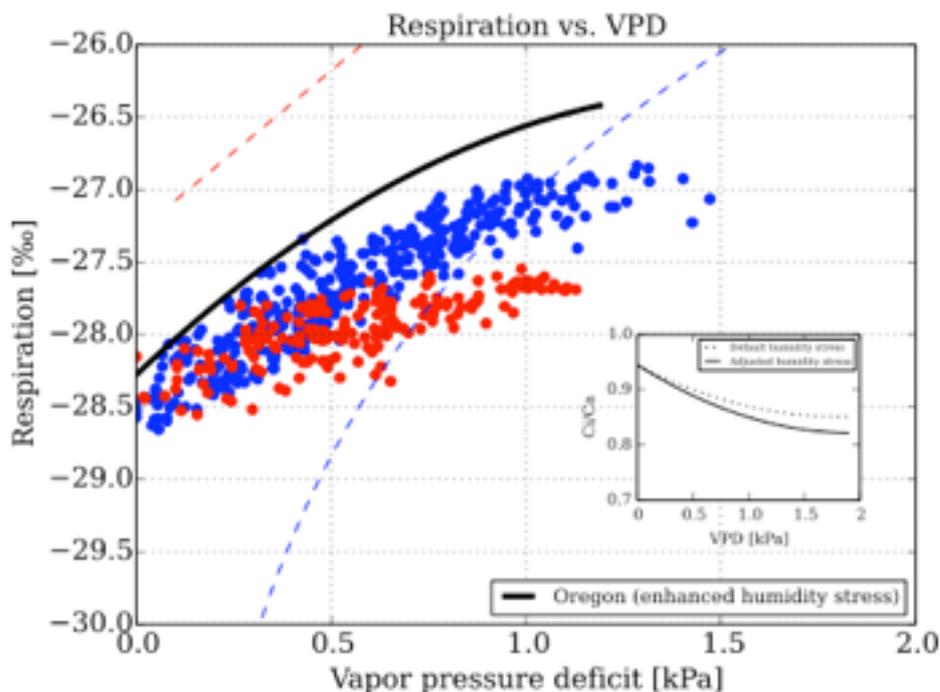

Figure 3. *Isotopic composition in respiration [‰] as a function of the vapor pressure deficit (VPD, kPa) for two locations: Oregon (blue) and Sweden (red). The daily mean values are from the SiBCASA simulation at Oregon (blue dots) and Sweden (red dots) taken during the months in 2000, 2001 and 2002 when carbon uptake peaked. The daily mean VPD is*

derived from daylight hours. The blue dashed line represents a logarithmic fit to measured ^{13}C taken from sites in Oregon (Bowling et al. 2002). The red dashed line represents a linear fit to measured ^{13}C in a mixed coniferous boreal forest in northern Sweden (Ekblad and Hogberg, 2001). The black line is represents a fit through simulated values at Oregon in case of enhanced humidity stress to improve the fit with measured respiration-VPD relationship. Inserted panel shows the change in Ci/Ca ratio as a consequence of the additional stress (From Van der Velde et al. 2014, under review).

4. Large-scale signals of changing WUE during droughts

What is interesting to consider is that under extreme circumstances, during extended periods of drought, strong reductions in discrimination are expected. These are associated with changes in WUE. Whether such dynamics can be detected using measured isotope ratios in CO_2 is studied. We developed a prototype of a multi-tracer carbon cycle data-assimilation framework that uses not only observations and bottom-up estimates of CO2, but also observations of ^{13}C in CO_2 and the exchange of ^{13}C at the earth surface, including SiBCASA. We would traditionally only scale the net carbon exchange fluxes of the terrestrial biosphere and oceans to obtain mixing ratios of CO2, which are consistent with observations. However, now we are also able to scale the discrimination parameter to get simultaneously consistent isotope ratios of [13]C. Over land variations in ^{13}C reflect differences in the strength of plant discrimination but can also vary as a function of moisture conditions and can inform thus on drought stress.
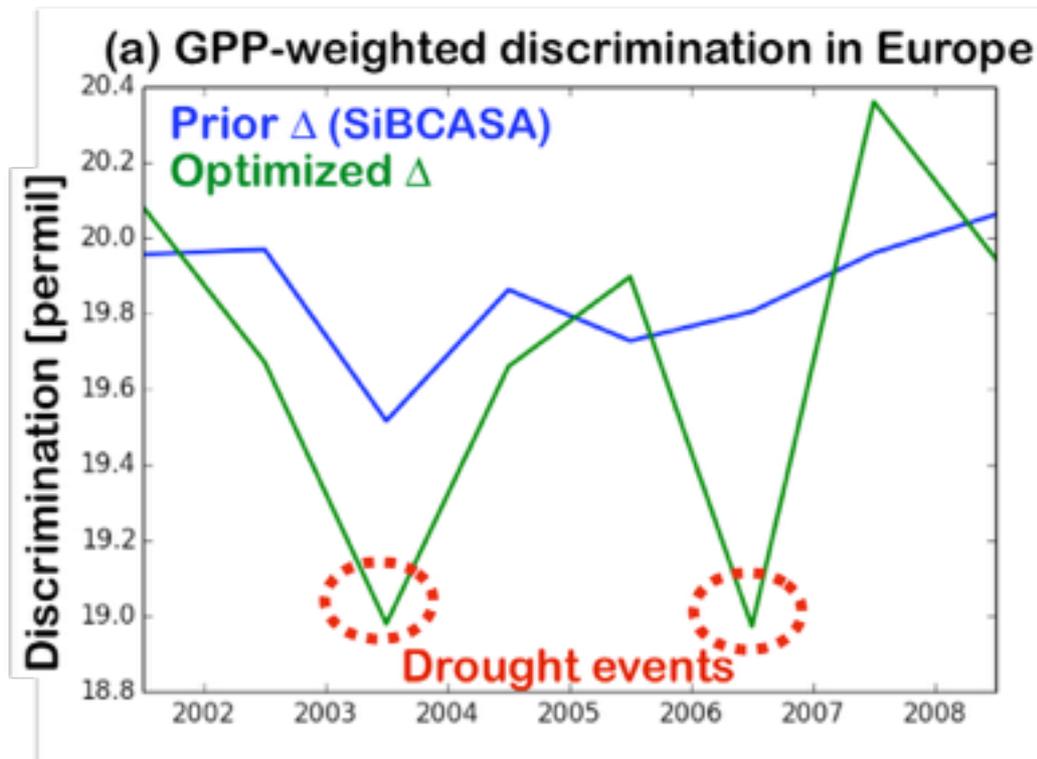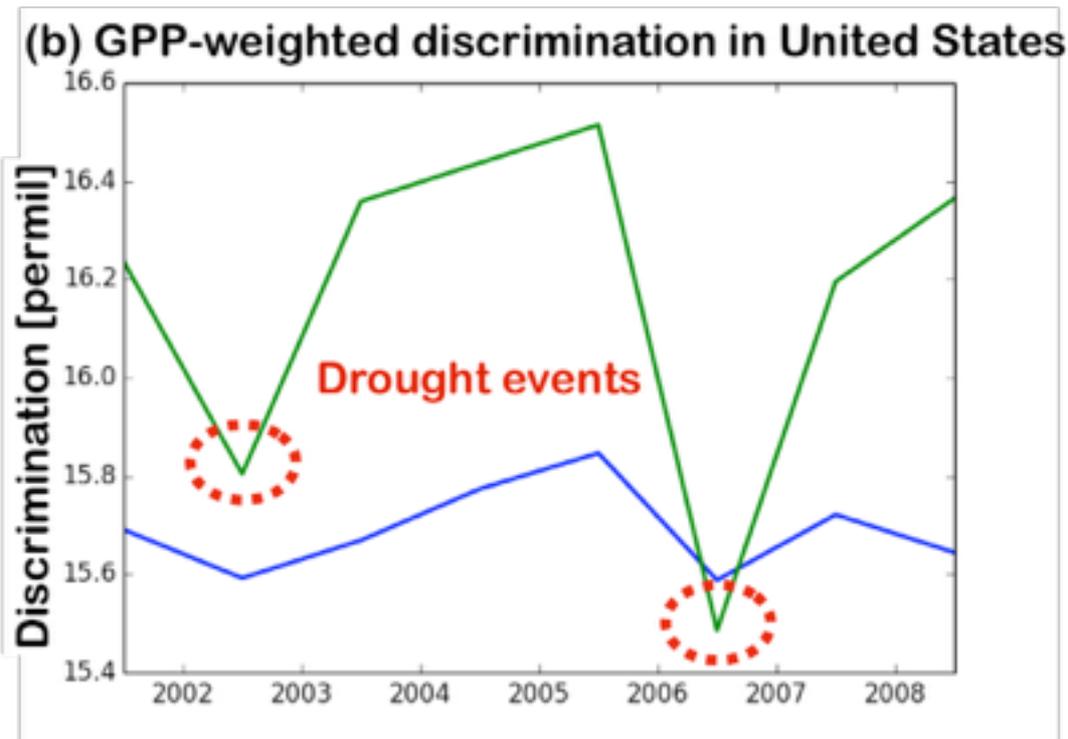
Figure 4. *Annual area averaged discrimination (gpp-weighted) for Europe (a) and United States (b). Prior discrimination parameters are shown in blue and optimized parameters are shown in green.*

Although this is still work in progress the first inversion results look very promising. During the European drought anomaly of 2003 not only the carbon sink was greatly reduced, we also observed a clear reduction in the European averaged discrimination parameter, which is clear sign of increased WUE integrated over a large area (Fig. 4a). Strong reduction is also detected for 2006, when the summer was also above average warm. Similar drought responses are also detected in the United States in 2002 and 2006 (Fig. 4b), and in Russia (2010, not shown). Here we also see that the IAV of discrimination is more amplified compared to SiBCASA, which seems to be in line with actual isotope measurements taken in plants and tree rings. Another interesting feature is the offset between prior discrimination parameter and the larger optimized parameter. This is an indication that there is in reality less C4 photosynthesis (less discriminating) than prescribed in the model.

5. Conclusions

We conclude from our study that there is a lot of untapped potential in the interpretation of $\delta^{13}C$ of CO_2 from the atmosphere. The large amount of observations, more detailed biogeochemical modeling, and availability of more powerful data assimilation methods all contribute to this. Where previous studies have mostly focused on the possibility to learn about the global NEE distribution from $\delta^{13}C$, we show that it additionally holds interpretable signals on water-use efficiency in plants, and carbon cycling through the vegetation on scales of hours to weeks. Maintaining and expanding the atmospheric $\delta^{13}C$ observing network should therefore have very high priority, especially considering the new spectroscopic continuous analyzers built by several companies (such as Picarro, and Aerodyne).

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