A High-Altitude Balloon Platform for Determining Regional Uptake of Carbon Dioxide over Agricultural Landscapes with Relation to Normalized Difference Vegetation Index

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Abstract

In the global carbon cycle, a mixture of human perturbed and natural processes take in and release carbon at various rates. The process of photosynthesis and respiration occur naturally, however humans converting land to agriculture and burning fossil fuels affects the balance of carbon as well, so quantifying the net amount of carbon dioxide taken in through agriculture is important in understanding this cycle today. To do this, High Altitude Balloons (HABs) equipped with carbon dioxide sensors can be launched and tracked using GPS. This is an inexpensive alternative to other methods used to collect atmospheric data cited in literature. The carbon dioxide concentrations measured during the ascents of two HAB launches conducted on the same day were converted to a molar difference using the observed temperature and pressure of the atmosphere, and a flux was calculated by summing the molar differences at altitudes under 6,000 meters and dividing by the time difference between flights. This value is the Net Ecosystem Exchange (NEE), which has seasonal variations. Another way that seasonal trends over agricultural landscapes can be observed is through NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) program to produce a Normalized Difference Vegetation Index (NDVI). NDVI values quantify an average value of how much vegetation is present on a given plot of land. It was found that trends in NEE and NDVI over 2014 and 2015 do align with one another, however NEE declined from its peak more rapidly than NDVI did throughout the summer. This correlation strengthens the legitimacy of HABs as a viable method of collecting atmospheric carbon data.

Introduction

In the global carbon cycle, carbon is exchanged in various forms throughout the four spheres present in Earth systems, which are the lithosphere, hydrosphere, atmosphere, and biosphere. Carbon dioxide is a greenhouse gas, meaning it remains in the atmosphere to trap infrared radiation, warming the Earth. Interactions between the biosphere and atmosphere take place in this cycle through the processes of photosynthesis and respiration. Through photosynthesis, plants take in carbon dioxide from the atmosphere and use it to grow, while through respiration, ecosystems release carbon dioxide into the atmosphere. Humans perturb this cycle by releasing carbon dioxide through burning fossil fuels. Annually, there is a release of 14.8 gigatons of carbon dioxide into the atmosphere, 7.8 gigatons of which are attributed to the combustion of fossil fuels (Ciais and Sabine, 2014). Analysis of the carbon cycle has found that approximately half of the carbon dioxide released through the combustion of fossil fuels remains in the atmosphere, while the rest can dissolve in ocean water or be incorporated into plant biomass through photosynthesis (Schneising et al., 2013). Another human perturbation in the carbon cycle is appropriation of photosynthesis through agriculture, which is estimated to have taken in 11.9 gigatons of carbon in 2005 (Kausmann et al., 2013). Agricultural landscapes make up a large portion of the biosphere, so the interactions between crops and atmospheric carbon dioxide levels are key in understanding the carbon cycle. Certain studies have shown that there is an annual balance between atmosphere-biosphere fluxes of carbon dioxide, but this balance varies depending on the location of the study and the length of the growing season there (Churkina et al., 2005).

The rate at which carbon dioxide moves between the biosphere and atmosphere can be quantified through a value known as Net Ecosystem Exchange (NEE). A negative NEE signifies that the biosphere is taking in carbon dioxide from the atmosphere and a positive NEE means that carbon dioxide is being released by the biosphere to the atmosphere. Because agricultural landscapes are so prevalent on a global scale, this makes their contribution to the carbon cycle so significant to study. Calculating NEE can show whether agriculture is an effective way to offset some of the carbon dioxide that was released into the atmosphere through anthropogenic causes. Agricultural practices that increase soil organic carbon (SOC) remove carbon dioxide from the atmosphere. While there is debate about the effectiveness of no-tillage farming (Luo et al., 2010), cover crops are another method being considered for increasing SOC (Poeplau and Don, 2015). The effectiveness of these practices can be determined by measuring the exchange of carbon dioxide between the agricultural systems and the atmosphere. A variety of different strategies have been employed to measure carbon dioxide fluxes in an effort to understand the impact that the anthropogenic combustion of fossil fuels has on the carbon cycle.

The value of NEE is related to the Gross Primary Productivity (GPP), Net Primary Productivity (NPP) and Net Ecosystem Productivity (NEP) of an ecosystem. GPP is the total amount of carbon fixed by the biosphere through photosynthesis, NPP is the amount of carbon fixed after plant respiration has been subtracted and has been observed to be highest in the humid tropics and lowest in cold, arid climates (Cramer et al., 1999). NEP takes the NPP of an ecosystem and subtracts the respiration of microbes, animals, and anthropogenic sources of carbon dioxide to determine the net loss or gain of carbon from the ecosystem. NEE can be assumed to equal the negative of NEP, but the two measurements differ in one key way. NEP measures the balance of carbon dioxide in an ecosystem as a whole, while NEE is concerned with the flux of carbon dioxide between the biosphere and atmosphere without regard to the ecosystem. By definition when NEE is negative, carbon dioxide is being removed from the atmosphere and photosynthesis is greater than total respiration.

Measuring NEE can be accomplished by comparing two sets of carbon dioxide concentration measurements taken from two different times of day at a range of altitudes. The difference in these values can be summed over the specified altitude range to calculate NEE. When carbon dioxide concentration is higher throughout the first set of measurements than the second, carbon dioxide is being removed from the atmosphere. While if it is lower throughout the first set of measurements, carbon dioxide is being released into the atmosphere (Figure 1).

During the daytime in the summer, the atmosphere is homogenous in its carbon dioxide concentration at ground level since it is mixed by convection cells, but at an altitude of around 1,000 meters there is a large increase in carbon dioxide concentration over a relatively short change in altitude because convection cells are no longer present (Monson and Baldocchi, 2012). This distinct change occurs at what is known as the boundary layer. The boundary layer should increase in altitude for the second set of measurements. When the concentration of carbon dioxide is larger at altitudes above this boundary than below, that signifies that there was a removal of carbon dioxide from the atmosphere (Figure 1).

Towers, satellites, airplanes and high-altitude balloons have all been used to quantify fluxes of carbon dioxide. Instruments attached to towers can collect data over areas of approximately 1 kilometer squared from which fluxes can be calculated using an eddy-covariance approach (Monson and Baldocchi, 2012). However, there is not a large amount of data available that measures carbon dioxide concentrations in agricultural areas using this technique (Barzca et al., 2009). Collecting data via satellites and performing inverse models is one way to measure carbon dioxide fluxes over areas of land on the order of $1.0x10^{13}$ meters squared, but again there is not a large body of data available and errors in measurements are common (Reuter et al., 2014). A less costly alternative to using towers or satellites involves attaching carbon dioxide sensors to high-altitude balloons (HABs). Since HABs are relatively inexpensive to use, a larger body of data can be collected. They also are able to collect data at an intermediate scale between the small-scale measurements collected by towers and large-scale measurements collected using satellites.

The vegetation present in a landscape has been captured in satellite images from NASA through their Moderate Resolution Imaging Spectroradiometer (MODIS) program to produce a Normalized Difference Vegetation Index (NDVI). These NDVI values have been used to create carbon cycle models in other studies, showing seasonal variations in the amount of carbon dioxide plants take in through photosynthesis (Sims et al., 2008). The data from MODIS satellites provide NDVI values, which are related to the chlorophyll content of vegetation. By quantifying vegetation in this manner, it is easier to compare differences over land and time. However, NDVI is not always an accurate predictor of crop yields, in some cases predictions based on NDVI measurements predict lower crop yields than what was actually grown (Mkhabela et al., 2005). For example, NDVI values point to carbon sinks in irrigated croplands and temperate forests across the United States (Potter et al., 2007). This conflicts with other studies that used data from satellite-based MODIS instruments and show variations in uptake in agricultural land depending on land management, which serves as a major factor of uncertainty in the accuracy of NEE measurements (Sus et al., 2012). Differences in sowing dates through fields make it difficult to measure NEE over expanses of land with certainty (Sus et al., 2012). But even with these limitations there is often a correlation between NDVI and NEE.

Agricultural landscapes change in their level of chlorophyll based on how far into the growing season it is, so there are seasonal trends in NDVI. During the spring and early summer when crops are growing, NDVI increases as crops leaf out and leaf chlorophyll content increases. In the summer, crops are fully expanded and NDVI reaches a maximum value. In autumn, crops are left in the field to dry, and NDVI decreases throughout this process as leaf chlorophyll content decreases during senescence. In the winter after harvest, NDVI is lowest since bare ground is exposed and has NDVI values close to zero.

Seasonal trends in NEE are also present. Moving from spring to summer, NEE becomes negative because crops are growing and photosynthesis exceeds total respiration. NEE is most negative in the middle of summer when plants are conducting photosynthesis rapidly. As the summer continues, NEE becomes positive because crops are not actively growing but continue to respire along with the soil, releasing carbon dioxide into the atmosphere. When crops are left in the field to dry or are harvested, the expectation is that NEE would be positive because crops are not conducting photosynthesis or growing, while the soil is still respiring.

Both NDVI values found through MODIS satellite images and NEE values collected through HAB launches have been shown in literature to follow seasonal trends. In this paper, the trends observed in NDVI and NEE values are compared to see whether they correlate with each other in an agricultural landscape. There is uncertainty in the literature involving various methods of collecting atmospheric carbon dioxide fluxes, but comparing NEE and NDVI gives more confidence in HAB methodology if the two values follow similar trends.

Materials and Methods

Throughout the summers of 2014 and 2015, a total of ten launch dates occurred and calculations were performed to produce a single value of NEE per launch date. Four of these launches took place from July to September 2014, and six took place from June to September 2015. During launches, a HAB was filled with helium, attached to a parachute, tracking devices, and a sensor that measured carbon dioxide. As the balloon ascended, burst, and descended it was followed by a chase vehicle using information received from the tracking devices. Once the balloon was retrieved, the process was repeated approximately three hours later. The values of NEE calculated for each launch date were then compared to NDVI values calculated from the NASA Terra MODIS satellite.

The launches took place at an athletic field at Pontiac Township High School in Pontiac, IL (40.887714, -88.616127) with the exception of the flight on July 17, 2014, which took place at Koerner Aviation in Kankakee, IL (41.096307, -87.913497). Both of these locations were small towns surrounded by agricultural fields of soy and corn crops. Two balloon launches per date were conducted approximately three hours apart from one another and calculations were performed to compare readings of carbon dioxide over the first 6,000 meters of each flight. The calculations used a mass-balance approach to find the rate at which carbon dioxide is exchanged between the atmosphere and biosphere, referred to as NEE. This procedure is a modification on a previous method (Pocs, 2014) where one balloon launch was conducted per day and NEE was calculated on the difference in carbon dioxide values recorded during the ascent and descent of the flight. The methodology was modified in the summer of 2014 to consist of two launches per date. This way, data from approximately the same land was observed on each flight because the launch location was the same. In previous methodology, the balloon would compare carbon dioxide concentrations between the launch site and retrieval site, which could potentially have dissimilar vegetation. The additional time between flights, when compared to the time between ascent and descent of a single flight, allowed for a clearer change in flux to be seen because a larger gap of time between flights allows the boundary layer to increase in height more dramaticallty. By waiting for the boundary layer to change, more distinct differences in carbon dioxide concentrations between flights would be observed.

The equipment launched during each flight consisted of a balloon, parachute, two GPS devices, a carbon dioxide sensor and an ozone sensor (2015 flights only, Figure 2). The ozone data were collected for a project to measure ozone exchange (Cody Sabo, manuscript in preparation).

The parachute was attached to the balloon via two 18 foot lines made of masonry cord. The parachute was attached to a Stratostar GPS command module (Noblesville, IN) via 6 foot lines. The command module was the primary source for tracking the location of the balloon. It also collected data on pressure, which would be used as a proxy for height in later calculations. These data were relayed in real time to the chase vehicle via a 900 MHz radio signal. The Stratostar GPS was connected to a package containing instruments to measure atmospheric carbon dioxide via 8 foot lines.

The primary piece of equipment used to collect this data was an LICOR LI-620 (Lincoln, NE), which measured carbon dioxide concentration by pumping air through first an air filter and then the device. The package was powered by ten Lithium AA disposable batteries. This device was also used to measure atmospheric pressure and temperature inside the measurement cell of the instrument, which was controlled to 50 degrees Celsius. On the June 19, 2015; July 2, 2015; and July 15, 2015 flights a LICOR LI-640 was used. This is an updated sensor that was also able to collect data on water vapor concentrations. The data were collected from the LICOR instrument using an Arduino (http://www.arduino.cc/) microcontroller system. A backup analog data logger (HOBO U12, Onset, Bourne, MA) was also in the flight package.

This package was connected to a ham radio (APRS) GPS tracker via 8 foot lines which was used as a secondary tracking device that sent location data via a network of amateur ham radio operators (Automatic Packet Reporting System, http://aprs.fi/) to the internet.

Prior to each launch date, the flight paths were predicted using the Cambridge University Spaceflight Landing Predictor (http://predict.habhub.org/), which uses winds generated by the NOAA GFS (National Oceanic and Atmospheric Administration Global Forecast System) Model (Figure 3). Initially, on 2014 launches a 200 gram latex balloon was filled with industrial grade helium until it obtained around 5 kilograms of lift, which produced an initial ascent rate of approximately 3.5 meters per second for our payload weight of 5.45 kilograms. In 2015, the balloon was filled until it obtained 7 to 8 kilograms of lift to produce an ascent rate of around 4 meters per second. It was necessary to obtain more lift on 2015 launches because an extra ozone sensor was attached to the flight package, making it 3.65 kilograms. Obtaining more lift was used to offset the extra 1.8 kilograms of the ozone sensor. On the August 13, 2015 and September 12, 2015 flights a 150 gram balloon was used. Typically the balloons reached an altitude of around 14,500 meters before bursting, but by using smaller 150 gram balloon on the August 13, 2015 and September 12, 2015 flights, the burst altitude was reduced to approximately 9,000 meters (Table 1).

Once the launch data were collected, it was analyzed using the program R Studio Version 0.99.484 using R version 3.0.2 (9/25/13) to produce one NEE value per launch date. A mass-balance approach was taken to perform calculations. First, data were averaged into bins by altitude at 100 meter intervals in which the first bin began with data at 300 meters (the launch sites were about 230 meters above sea level) and the last bin ended with data collected at 6,000 meters above sea level. The ambient temperature was calculated by applying the hydrostatic equation to the change in pressure over altitudes provided by the Stratostar GPS and assuming that temperature did not change with altitude. Once temperature was calculated, average density of air was found using the ideal gas law. The density of air (n_a/V), where n_a is the moles of air and V is a unit volume of air in cubic meters, was multiplied by the difference in the concentration of carbon dioxide ($C_2 - C_1$) in micromoles of carbon dioxide per moles of air measured between the two flights. This value is the molar difference of carbon dioxide between flights. This was divided by the time that passed between the two launches (Δt, s) to turn the measurement into a rate. This rate is the NEE. A positive value indicated that carbon dioxide was being released from the biosphere into the atmosphere, and a negative value indicated that carbon dioxide was being taken up by the biosphere.

$$NEE = \sum_{i=3}^{60} \frac{\frac{n_a}{V}(C_2 - C_1)}{\Delta t} \times 100$$

Each value for NEE was then compared to Normalized Difference Vegetation Index (NDVI) values obtained from MODIS Satellites that were retrieved from an online database. NDVI is an index that corresponds with the amount of vegetation in a landscape. The landscape measured was broken into 1 mile square plots of agricultural land consisting of corn and soybean crops (Figure 4). Measurements were taken by the satellites over 16 day time periods and averaged together to create a single image for that time period. MODIS includes scenes taken by several different satellites but for this research, the values relayed by the Terra POD Vegetation were recorded. The sampled area spanned from 40.770˚ to 41.084° N latitude and -88.121̊ to -88.977° W longitude. All the values within the sampled area were averaged to obtain one NDVI value per date with R. So this provided one NDVI value for each 16 day period from April 2014 to September 2015. These values were compared with NEE values so that seasonal trends in both measurements could be observed and compared to one another.

Results and Discussion

Based on the data gathered, seasonal trends in NDVI and NEE were observed, and they were consistent with values reported in literature. The two time series did have similar shapes, but NEE dropped off from its peak earlier in the summer and at a faster rate than NDVI values.

An ideal flight is shown in Figure 1, and while observed flights have a general pattern of lower carbon dioxide concentration at ground level, and a sharp increase around 1,200 meters, there is more variation than in the conceptual model. For example, on August 14, 2014 the second flight had lower carbon dioxide concentrations than the first and a negative spike in NEE at approximately 1,500 meters, but around 2,000 meters, carbon dioxide concentrations between the two flights matched (Figure 5, top-left panel). This could be explained by an increase in the boundary layer height. One flight on July 23, 2015 did not follow this pattern (Figure 5, top-right panel). On this launch, NEE fluctuated at ground level, producing positive spikes in NEE and the carbon dioxide concentrations did not match up completely above the boundary layer. This could be due to mechanical errors in readings.

There was an issue with a new carbon dioxide sensor used on three flights: June 19, July 2 and July 15, 2015. Carbon dioxide concentrations above the boundary layer height systematically differed, unlike during all the other flights where they were almost identical. Concentrations of carbon dioxide in the second flight were consistently 4 parts per million higher than the first flight, which is a factor of approximately 1% of the total concentration. The concentration was adjusted by reducing the measured pressure values by 1% for the second flight. Because pressure is used by the instrument to calculate the molar ratio of carbon dioxide concentration, the carbon dioxide values for the second flight were also decreased by 1% (Figure 5, bottom two panels). After the adjustment, the data matched the conceptual model which demonstrated an increase in the boundary layer height, with an indication that the first flight observed a residual boundary layer.

Our calculations of NEE found seasonal trends in those values. NEE were most negative in mid July and became more positive as the summer went on (Table 1). There was a minimum on June 19, 2015 at -31.8 µmol m^{-2} s^{-1} and a maximum on September 19, 2015 of 5.97 µmol m^{-2} s^{-1}. This pattern of variation is consistent with trends observed in data collected using the first-generation approach from 2012 to 2013 (Pocs, 2014).

Based on NEE vales recorded in literature, it appears that the values calculated using the methodology in this paper are reasonable. Temperate regions, which are where agriculture primarily occurs, have been measured to take in 500 to 700 grams of carbon per square meter annually, after plant respiration has been accounted for (Cramer et al., 1999). If one assumes a 100 day growing season (Figure 6) and 12 hours of carbon dioxide uptake occurring per day, the following calculation can be used to calculate the total carbon dioxide uptake per year.

$$25\,\frac{\mu mol}{m^2 * s} \times 12\,\frac{\mu gC}{\mu mol} \times \frac{1\ g}{10^6 \mu g} \times \frac{3600\ s}{1\ hr} \times \frac{12\ hr}{1\ day} \times \frac{100\ day}{year}$$

When the values of NEE collected using this methodology are converted to grams, the amount of carbon taken in annually per square meter is 1,300 grams, but this value is likely too high because it does not account for cloudy days or other less than ideal conditions that would limit photosynthesis. However, this is on the same order of magnitude as the values cited in literature, which bolsters the confidence of these measurements. Also, the values recorded during 2014 and 2015 are quite similar to those reported by Pocs in 2014, which range from -50.8 to 37.5 µmol m^{-2} s^{-1}.

NDVI values followed a similar pattern in 2014 and 2015, and the values collected at most dates in one year are very close to values collected in the other year on those same dates. Two values from January 2015 were not used because they did not match the seasonal trend. These readings were most likely inaccurate due to snow melting and exposing dark soil, which would read as a high value. NDVI values peaked in mid July at 0.879 and reached a minimum in January at 0.224.

NDVI values are expected to fluctuate between 0 and 1 depending on the season, with values closer to 1 when crops are in the fields. Compared to NDVI values taken throughout the year in agricultural areas of Nebraska, the range of values in Table 1 from 0.879 in mid-July to 0.224 in mid-January are slightly higher than measurements recorded in literature and decline at a faster pace in the fall (Eastman et al., 2013). This could be due to different instrumentation and different satellites being used to take measurements for the two studies.

In 2014, the seasonal trends observed in NEE and NDVI values correlate clearly (Figure 6). The peak in 2014 for both measurements occurs in mid July and follows a negative slope from there. In 2015 NDVI values are slightly lower than those recorded in 2014, but follow the same pattern. NEE values in

2015 peaked in mid-June, but did not drop off dramatically until August. However different launch dates were used during the summers so direct comparisons of NEE values are not possible.

When graphed together, seasonal trends in NDVI and NEE mirror each other, however NEE declines sooner after its peak, while NDVI declines later (Figure 6). This could be due to the time that crops spend in the field waiting to be harvested. In late summer and autumn, crops are no longer growing, but they remain in the field for a period of time before senescing. This change is due to heat and water stress. There is a lag between NDVI and NEE measurements because NDVI satellites would sense vegetation when crops are present in the field even if they are not undergoing photosynthesis. Since the crops stopped conducting photosynthesis, NEE would become positive quickly. In general, when NDVI was at a maximum, NEE values were most negative, and when NDVI values were at a minimum, NEE was positive. This means that the more vegetation detected by MODIS satellites, the more carbon dioxide was taken in by the biosphere. When NEE and NDVI are compared to each other, there is a slight negative correlation between the variables. This linear correlation is rather weak because NDVI values lagged while NEE changed rapidly from July to September (Figure 6).

The slight correlation seen here strengthens the legitimacy for using HABs as a tool to measure atmospheric carbon dioxide fluxes. By comparing NEE values found through launching HABs with NDVI values from satellites and finding a correlation between the two, it shows that these NEE values are sensible for their respective launch dates. There are some downsides to using HABs. First, the horizontal area that contributes to data recorded is unknown, meaning that it is uncertain where exactly the carbon dioxide that is being measured is coming from. Also, to ensure that NEE values are accurate, there needs to be a large homogenous landscape for hundreds or thousands of kilometers. In central Illinois where agriculture encompasses most of the land, this is not a problem. Over other parcels of land that are more diverse, this could lead to inaccurate data. Agricultural fields are also flat and do not have tall vegetation which makes it easy to retrieve flight packages once they land. In a forest or urban area, the retrieval process would be more difficult due to trees or buildings obstructing the landing.

Further research on carbon dioxide fluxes could be done to show the validity of this method. Multiple launches could be conducted on the same day in different locations, which would help model the spatial scale. This could provide more information on where the carbon dioxide that the sensor is measuring originated. Or, multiple launches preformed on one day at the same location would reinforce data already collected by allowing daily cycles in NEE to be observed. When the sun is shining most strongly, it would be expected that NEE would be most negative because crops have the necessary sunlight to power photosynthesis. When the sun is rising or setting, sunlight is not as readily available so uptake of carbon dioxide should not occur as rapidly. At night, NEE should be positive because plants are not conducting any photosynthesis to take in carbon dioxide.

NEE and NDVI are both helpful in relaying more information about biotic and atmospheric interactions in relation to the carbon cycle. In the past, processes of respiration among heterotrophs and photosynthesis by autotrophs were the key processes in moving carbon dioxide between the two sites. Now, humans interfere with the carbon cycle in these two areas by burning fossil fuels, which releases carbon dioxide into the atmosphere, and through agriculture, which moves atmospheric carbon dioxide into the biosphere. By measuring NEE and NDVI and relating them to one another, this serves to quantify carbon dioxide being taken out of the atmosphere through the practice of agriculture throughout the year. Agriculture occupies a vast amount of land, so understanding its ability to take up or release carbon dioxide is crucial for understanding the carbon cycle as a whole.

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Table

Date	Burst Height 1	Ascent Rate 1	Burst Height 2	Ascent Rate 2	NEE	NDVI
7/17/2014	14769.82	464.9	13268.83865	690.1	-25.62	0.885
8/14/2014	14997.82	552.8	14813.81986	627.2	-9.74	0.880
8/21/2014	14764.82	698.9	15230.81479	686.6	-9.23	0.930
9/19/2014	13287.84	765.3	13852.83155	704.3	5.97	0.510
6/19/2015	14196.83	495.1	12938.84266	560.0	-31.8	0.700
7/2/2015	13028.84	652.2	13729.83304	560.4	-17.1	0.785
7/15/2015	12343.85	742.5	13445.8365	706.4	-21.2	0.840
7/23/2015	12933.84	729.4	12492.84809	779.7	-2.35	0.850
8/13/2015	13807.83	764.9	13195.83954	796.6	-25.27	0.840
9/12/2015	9034.89	785.5	9255.887447	684.5	5.62	0.620

Table 1: This includes flight data from all flights conducted during the summers of 2014 and 2015. Burst Height is listed in meters, ascent rate is listed in feet per minute and NEE is listed in µmol m^{-2} s^{-1}.

Figures

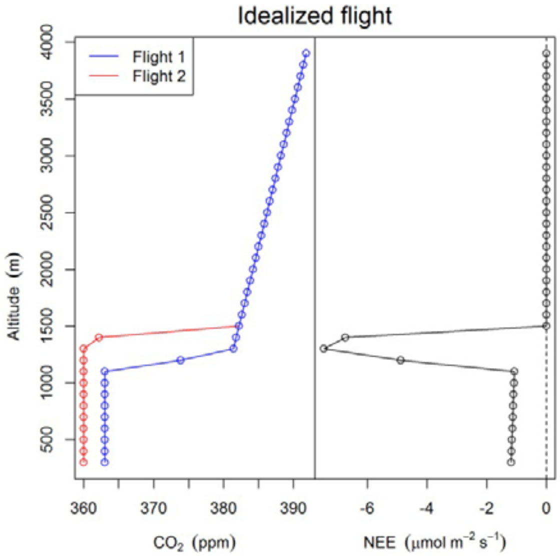


Figure 1: This graph shows an idealized flight that includes a well-mixed, homogenous concentration of carbon dioxide near ground level, then a decrease in carbon dioxide concentration from the first launch (blue) to second launch (red) between 1,000 and 1,500 meters. Above a certain altitude concentrations between the flights would match again, because ground-level photosynthetic activity does not affect carbon dioxide concentrations above this altitude (left panel). This corresponds with a negative spike in NEE at the boundary layer (right panel).

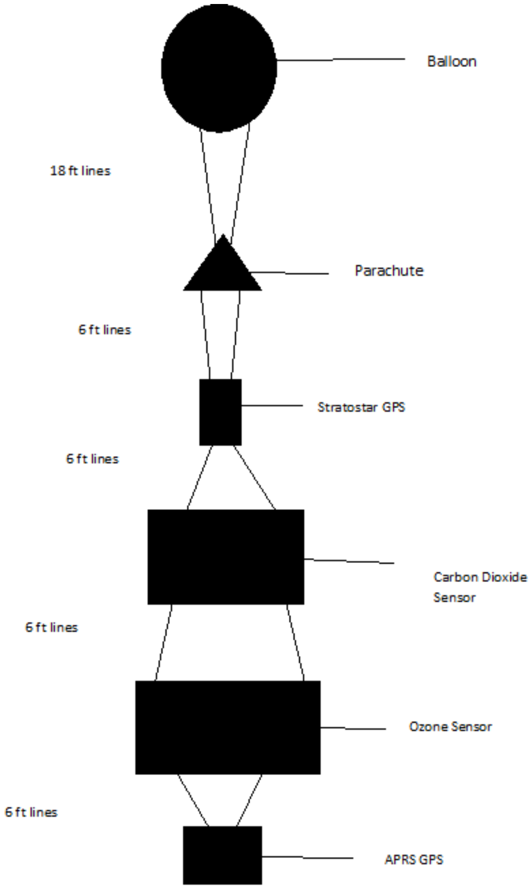
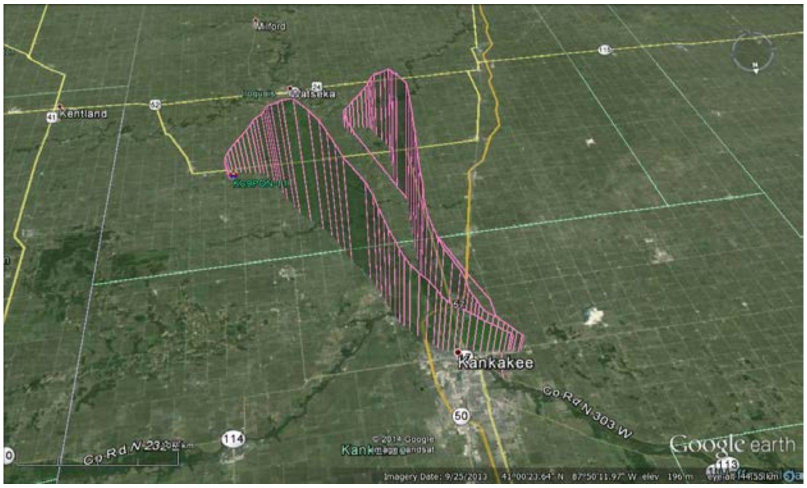
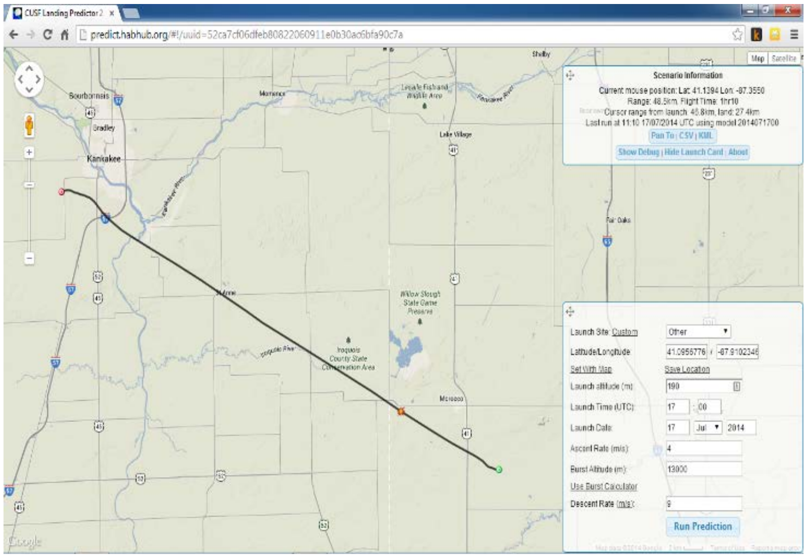


Figure 2**:** Diagram of flight package launched. The total package weight of 5.45 kilograms was lifted by a 200 gram balloon that was filled with industrial-grade helium. The package had an average ascent rate of 670 feet per minute and burst at an average height of 13,000 meters.





predict.habhub.org/#!/uuid=52ca7cf06dfeb80822060911e0b30ac6bfa90c7a

Scenario Information

Current mouse position: Lat 41.1394 Lon: -87.3550
Range: 48.5km, Flight Time: 1hr10
Cursor range from launch: 45.8km, land: 27.4km
Last run at 11:10 17/07/2014 UTC using model 2014071700

Pan To | CSV | KML
Show Debug | Hide Launch Card | About

Launch Site: Custom — Other
Latitude/Longitude: 41.0956776 / -87.9102346
Set With Map — Save Location
Launch altitude (m): 190
Launch Time (UTC): 17 : 00
Launch Date: 17 Jul 2014
Ascent Rate (m/s): 4
Burst Altitude (m): 13000
Use Burst Calculator
Descent Rate (m/s): 9
Run Prediction

Figure 3: Comparison of actual (top) and predicted (bottom) flight on July 17, 2014. Flights were predicted prior to launch using NOAA GFS (National Oceanic and Atmospheric Administration Global Forecast System) Models. The actual flight path was tracked using a Stratostar Command Module.

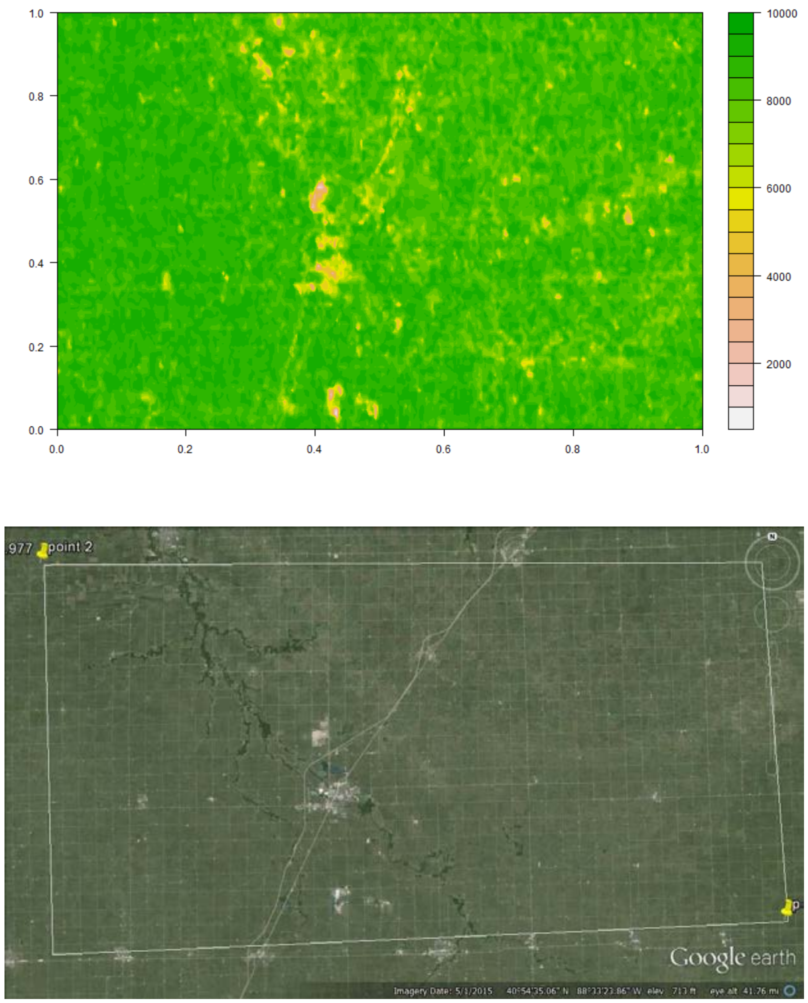


Figure 4: Comparison of NDVI generated image of the launch area ranging from 41.084˚ west to 40.770˚ west and -88.121˚ north to -88.977˚ north to a Google Earth image of that same area outlined in white. The bright green color in the NDVI image corresponds with land covered by vegetation, and the orange colored areas represent land that is not vegetated due to cities, gravel pits, or roads.

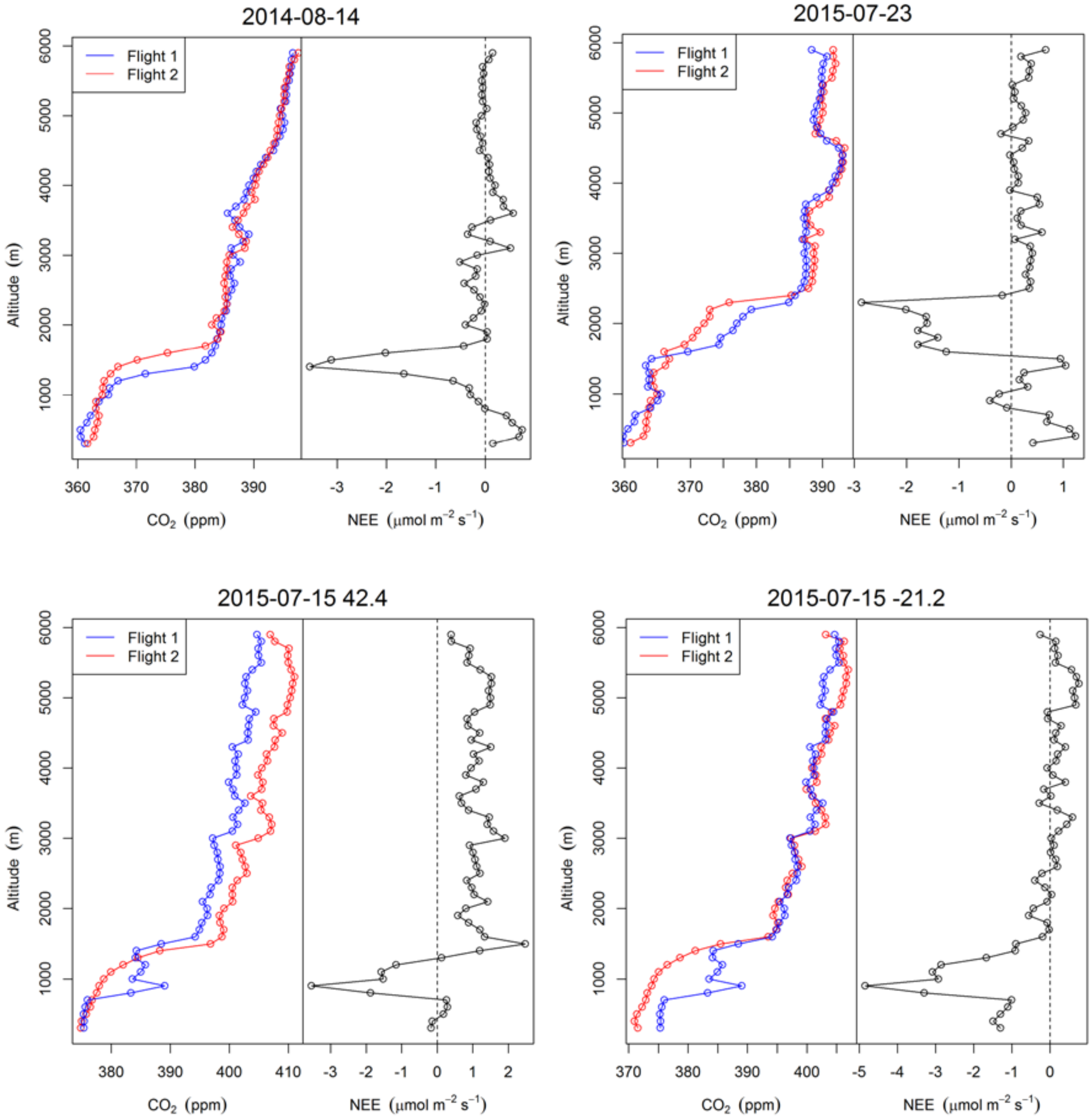


Figure 5: The left portion of each graph shows the concentration of carbon dioxide in parts per million over the first 6,000 meters of the two flights. The first flight of the day, shown in blue, tends to have a higher concentration of carbon dioxide at low altitudes during the growing season. This difference in concentration is shown as NEE in the right portion of each graph. The top-left panel, from August 14, 2014 shows a flight that is close to what an ideal graph would look like based on the conceptual model. The top-right panel, from July 23, 2015 shows a flight that does not match expected trends in carbon dioxide concentration over the given altitudes. The bottom panels from July 15, 2015 show a flight that was mathematically corrected. The original data (bottom-left) measured carbon dioxide concentrations during flight two that were larger than expected. This was a systematic difference that was corrected mathematically to produce a graph that looks more like what was expected (bottom-right).

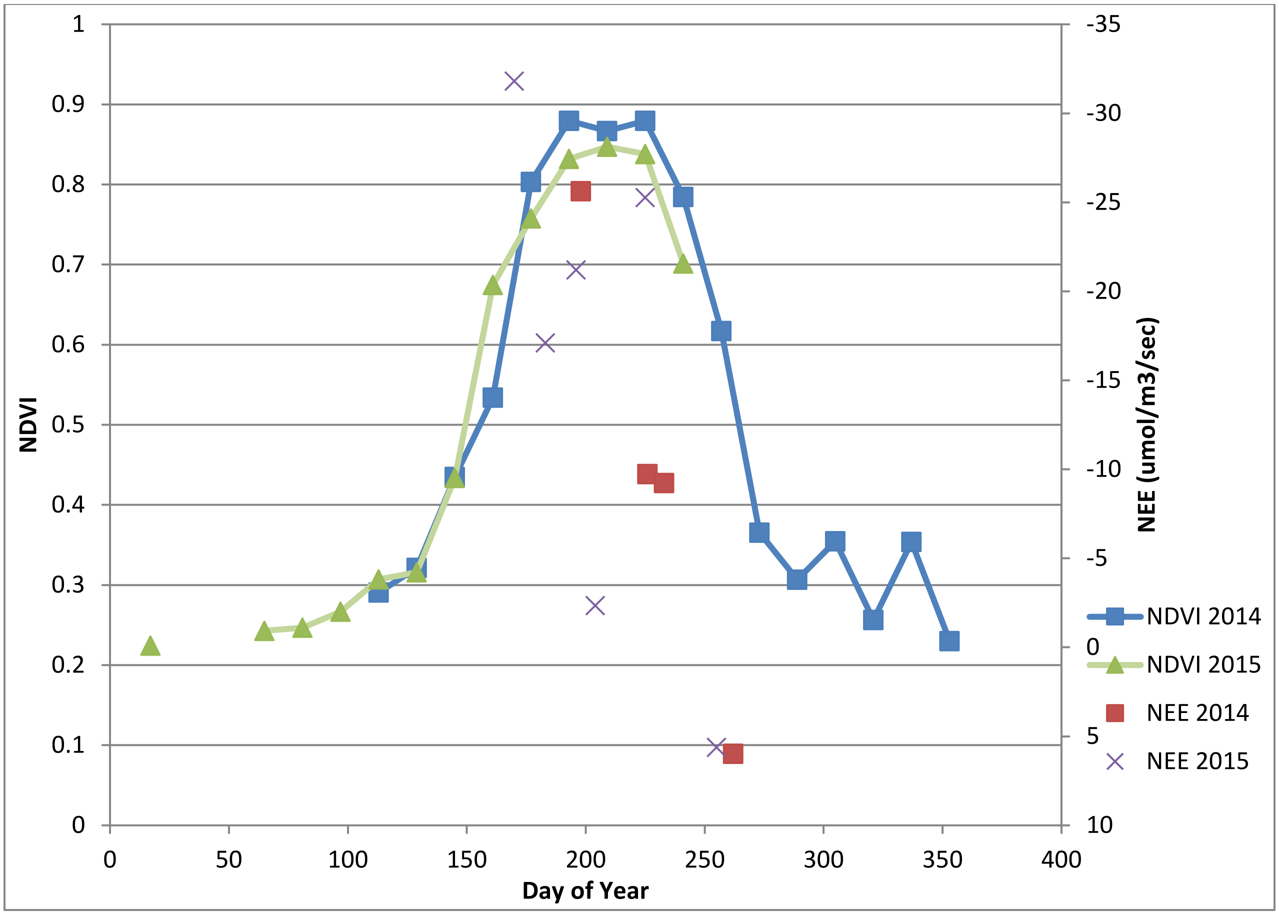


Figure 6: Seasonal patterns in NDVI and NEE over 2014 and 2015. In 2014 and 2015 NDVI peaks in July, meaning that vegetation was most noticeable that time of year from the satellite. Launches performed in June and July had the most negative NEE, meaning that the biosphere took in the most carbon dioxide during that time of year.

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