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DePaul Discoveries

Volume 3 | Issue 1 Article 2

2014

A High-altitude Balloon Platform for Exploring the Terrestrial Carbon Cycle

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ABSTRACT Carbon dioxide uptake by plants is a major component of the global carbon cycle that can be affected by climate change. This experiment quantifies the rate of landscape exchange of CO_2 in the time between a high altitude balloon's ascent and descent. It was hypothesized that measured seasonal trends would match a predicted trend of spring and fall release and summer uptake showing that the high altitude balloon method was a valid method. This was supported by the collected data where three flights showed landscape uptake, seven flights showed release and four showed no net exchange.

INTRODUCTION

In recent years there has been an increase in greenhouse gas output from anthropogenic sources. Greenhouse gases, mainly carbon dioxide, methane, nitrous oxide and ozone, increase the re-radiation of thermal energy from the sun and in turn they change the surface temperature of the globe. Industrialization has increased the consumption of fossil fuels in developed and developing countries which in turn has increased greenhouse gas emission. When modern atmospheric greenhouse gas measurements are compared to data from ice core samplings there is a large increase in greenhouse gases due to anthropogenic sources (IPCC 2007). Studies have shown that there has been a 0.2°C increase in temperature per decade that has occurred simultaneously with the increased greenhouse gas concentrations (Hansen et al. 2006). A rise in global temperature can affect ocean, atmospheric, and terrestrial systems and their interactions with one another. One of these important interactions is the exchanges of the greenhouse gas carbon dioxide between the atmosphere and landscape.

Carbon dioxide contributes about 60% of all anthropogenic greenhouse gas effects and its concentration is increasing at a rate of more than 0.5% per year (Rodhe 1990). Carbon dioxide's effect on global temperature may in turn affect carbon dioxide exchange with the biosphere. Plants take up carbon dioxide and produce oxygen (photosynthesis) and output carbon dioxide through respiration and these processes are affected by temperature. An increase in temperature can increase the stress on plants and reduce photosynthesis rates and increase respiration rates (Hobson 1979). Currently plants do take up a large amount of carbon dioxide from anthropogenic sources, but this may change in the future (IPCC 2007). As shown in Figure 1, with an increase in temperature plants may not take up as much carbon dioxide meaning that more carbon dioxide will stay in the atmosphere further accelerating global climate change.

There are often differences in urban and rural carbon dioxide. Urban areas are expected to be net sources of carbon dioxide since there is

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a dense population of people consuming fossil fuels and producing greenhouse gases. Rural areas are expected to be sinks for carbon dioxide since their plant-dominated landscapes absorb carbon dioxide while the plants grow, but seasonal cycles affect the uptake and output. These seasonal cycles associated with plant growth involve more landscape uptake when plants are growing and less once they are harvested or before they begin to grow. Urban areas may also have seasonal cycle, but it is unlikely that these cycles would be closely associated with plant growth.

Agricultural and rural sites provide a valuable opportunity to see the effects of plant life on the concentrations of carbon dioxide, a sort of baseline to compare to highly populated areas. Rural experiments can also remove variability from human sources in order to look at the influences of vegetation more carefully. These sites can show the large landscape-scale effects of drought, temperature and day length on the exchange rate of carbon dioxide between atmosphere and landscape. At these sites photosynthesis and respiration of plant life are the predominant processes that affect the carbon fluxes. One such study looked extensively at the trends and variations of carbon dioxide concentrations at a rural site in Europe (Haszpra et al. 2008). This study attempted to compare local tendencies with global trends to draw out regional, seasonal and diurnal variations. They found that vegetation over the agricultural site only begins to be a carbon dioxide sink in spring when the crops are starting to grow. There is significant seasonal variation in carbon dioxide concentrations showing evidence that "the nighttime release [is] comparable with daytime uptake" (Haszpra et al. 2008, pg. 8710). This would indicate that plant cycling of carbon dioxide is balanced daily as well as seasonally for a rural area in which the same crops are grown. If there is a drought or a rise in temperature this balance may tilt toward releasing more than taking up carbon dioxide. These data indicate that vegetation does have a large effect on carbon dioxide concentration in the troposphere. Unmanaged landscapes, like deciduous forests, take up slightly more carbon dioxide than they release, taking carbon dioxide out of the troposphere. In Figure 2 the deciduous forest annual cycles show this large uptake between Day 100 and Day 300 (Baldocchi 2008). The deciduous forest and crop annual cycle shows little release or uptake in the winter months. The deciduous forest releases carbon dioxide as it begins to leaf out and respires more around March. For the crops, they begin to grow later in May and release carbon dioxide. When crops are releasing and growing in May the deciduous forest is taking up carbon dioxide for growth. Crops begin rapid uptake in June and then dry out in August before being harvested in October. As crops dry before harvest they release carbon dioxide and after harvest they do not release or uptake any carbon dioxide. This dry out release peak is absent from the deciduous forest annual cycle (Baldocchi 2008). The crop cycle is the expected cycle used for this experiment.

Another study conducted at a rural site specifically looked at the diurnal cycling of carbon dioxide in the lower atmosphere to examine its patterns in the vertical atmospheric profile over a rural landscape (Pérez et al. 2012). Higher concentrations were reached during the night when plants are not photosynthesizing and lower concentrations were reached during the day when they are photosynthesizing. This study confirms that diurnal cycling does occur in an agricultural environment and that it can be measured in the lower atmosphere. High concentrations were also associated with low wind speeds that usually occur late in the night. Lower wind speeds reduce the mechanical mixing of the lower atmosphere vertically causing carbon dioxide to build up (Pérez et al. 2012). The conditions just above the landscape are important factors that can affect the carbon dioxide concentration readings. Knowledge of this diurnal cycle is necessary for the interpretation of the high-altitude balloon data and the calculation of the landscape carbon dioxide exchange.

Periodic monitoring of how time of year affects the absorption of carbon dioxide by plants is necessary especially as the climate changes. Rural studies have been performed at stationary monitoring sites that only measure fluxes over relatively small spatial scales (about 1 km). These studies are costly and take a large amount of time and maintenance. In contrast, a mobile platform, like a high altitude balloon, can ascend and descend within a day with modest cost and can be a viable option for measuring carbon dioxide fluxes over homogenous landscapes. High altitude balloons are large latex balloons filled with helium that are able to carry equipment up into the atmosphere to take readings throughout a flight. They are able to measure greater altitudes than stationary towers and thus overcome any rectifier effects. Rectifier effects occur when night winds die down and cause carbon dioxide to build up more making it appear unbalanced with the daytime uptake as seen in the study noted previously (Pérez et al. 2012). These effects appear in measurements from stationary towers that can only measure to a certain altitude. The balloon can measure to high altitudes and can account for the changing altitude of the boundary layer. The boundary layer is the atmospheric layer closest to the earth which is directly influenced by the landscape. The height of the top of this layer varies depending on the mixing within the boundary layer which is dependent on how much solar radiation is input into the system.

This experiment compares rates of carbon dioxide exchange between the landscape and atmosphere at different points of the year over a rural landscape using high altitude balloons. Working under the assumptions that the landscape is homogenous and that there is no gain or loss of carbon dioxide in the horizontal direction, it is hypothesized that measurements taken from the high-altitude balloon platform will show that during peak growing seasons there will be uptake of carbon dioxide while in the spring and fall there will release. These trends have been observed from stationary monitoring towers as seen in Figure 2. As mentioned previously, in crop systems there is a yearly cycle in which there is little uptake or release in the winter and uptake in the summer during prime growing seasons. The crop trend was used as a baseline expectation for this experiment.

METHODS

Two GPS sensors, a main payload that contained recording devices and the carbon dioxide sensor, and a parachute were tied to a high altitude balloon filled with helium (See Figure 3 for layout). The LI-820 CO_2 sensor measured molar density of CO_2 every second based on light absorption of a specific wavelength in the infrared. This sensor then used the ideal gas law, with the measurement of pressure and temperature, to compute the molar density of air and from that the relative concentration of carbon dioxide in parts per million (ppm). The cell temperature is controlled to be constant at 50°C. In the same package with the carbon dioxide sensor were two redundant data collection systems. One was a HOBO analog data logger that recorded CO_2 concentration and pressure in the cell and the second was an Arduino digital recorder that recorded cell temperature, pressure and CO_2 concentration. The Stratostar GPS measured outside pressure, temperature (slow response because of large sensor size), relative humidity and location/altitude while using line of sight radio to transmit this information to the chase vehicle. The APRS GPS used amateur radio communication and served as a backup in case the primary GPS fell below the horizon or otherwise failed. Each flight lasted approximately one hour before the low pressure expanded the balloon and popped it between about 9 and 30 km. Flights considered to be "good data points" and useful for analysis were flights where the balloon took off and landed in similar landscapes (agricultural field to nearby agricultural field) without traveling through air plumes largely affected by anthropogenic carbon sources. The calibration of the carbon dioxide sensor also needed to be correct, the full data set needed to be saved (from launch to land) and one of the sensors used needed to be clean with pumps free of water or dirt.

$$P_{average} = P_o\left(\frac{H}{Z_2 - Z_1}\right)\left(\exp\left(-\frac{Z_1}{H}\right) - \exp\left(-\frac{Z_2}{H}\right)\right)$$

The average pressure ($P_{average}$) was found by integration over the Z_1 to the Z_2 interval where Z_2 is the boundary layer height, H is the scale height (the relationship between pressure and height that assumes constant temperature), Z_1 is the launch height and P_o is the calculated sea-level pressure from the ln(Pressure) vs. Altitude Graph (Figure 4 is an example of this type of graph).

$$\frac{n}{V} = \frac{P_{average}}{RT}$$

Next the average density of air (n/V) was found using the ideal gas law. Where R is the gas constant (R=8.314 J/Kmol) and T is the calculated temperature in Kelvin from the corresponding ln(Pressure) vs. Altitude Graph.

$$NEE = \left(\frac{n}{V}\right)(CO_{2descent} - CO_{2ascent})\left(\frac{Z_2 - Z_1}{\Delta t}\right)$$

Finally the net ecosystem exchange (NEE), the exchange rate of the carbon dioxide between the landscape and atmosphere, was calculated using n/V, Z_1, and Z_2, where $CO_{2ascent}$ is the concentration of carbon dioxide for the ascent, $CO_{2descent}$ is the concentration of carbon dioxide of the descent and Δt is the change in time between ascent and descent. An example of an idealized change between descent and ascent is shown by the gray shaded space between the ascent and descent lines in the lower atmosphere in Figure 5. In this figure the upper atmosphere is well mixed so the carbon dioxide measurements on the ascent and descent would be the same while the measurements taken along the descent in the lower atmosphere would be lower since the plants were taking up carbon dioxide while the balloon was in flight. The difference or the gray area is the amount that the landscape was able to uptake in the period of time that the balloon was in the air.

RESULTS

Overall fourteen flights were performed. Table 1 shows all the flights that have been performed. Each flight has the calculated Net Ecosystem Exchange value and the conditions of the flight. Some flights were excluded due to calibration issues, equipment problems that resulted in inaccurate descent data, large anthropogenic source crossings or too great of difference between the launch site and landing site. The 10/10/2010, 01/21/2011, 08/29/2012, 05/18/2013, 07/10/2013, 07/16/2013b and 08/16/2013 flights showed the landscape was releasing carbon dioxide. The 05/12/2012, 07/16/2013a and 07/24/2013 flights showed the landscape was taking up carbon dioxide. The 05/21/2012, 02/09/2013, 07/02/2013 and 09/13/2013 flights showed no significant uptake or release from the landscape.

Over the course of each flight carbon dioxide concentration readings were taken. Figure 6 shows examples of the relationship between carbon dioxide concentration and height for the three types of flights that were observed. Uptake flights (left panel) showed that the lower atmosphere's carbon dioxide concentrations decreased between the ascent and descent of the sensor. Release flights (middle panel) showed that the lower atmosphere's carbon dioxide concentrations increased between the ascent and descent. Zero flights (right panel) shows that the lower atmosphere's carbon dioxide concentrations did not change much between the ascent and descent of the sensor. Not much change was observed during these zero flights because the crops were not leafed out during winter, after harvest or early in the growing season.

All the flights were plotted in Figure 7 which shows their NEE value compared to the month of year. The red data points are bad data as summarized by Table 1. The blue good data begin to show the expected seasonal variability with near zero NEE values in the winter, low uptake in the spring, maximum uptake in the summer and some release in late summer and early fall. The good data flights are the 05/21/2011, 05/12/2012, 08/29/2012, 02/09/2013, 07/16/2013a, 07/24/2013, 8/16/2013. 01/21/2011 was flagged as a bad data point because the instrument cell was dirty. The 05/18/2013, 07/02/2013, 07/16/2013a had highly variable descents, meaning the readings were very different from second to second, that caused the descent carbon dioxide concentrations to be unreliable. The 07/10/2013 flight was considered a bad data point because the balloon traveled over 80 mi in distance and the homogenous landscape assumption was not valid. Likewise the 09/13/2013b flight began in a woody park and landed in a field which also disrupted the homogenous landscape assumption. Finally the 10/10/2010 flight was considered to be bad data because on the descent the balloon passed through two anthropogenic factory plumes which caused the carbon dioxide concentrations to spike.

DISCUSSION

The trends outlined were seen in the successful good data from the balloon flights throughout the year with near zero exchange in the winter months, small release in the early growing season and large uptake in the primary growing season. In two of the August flights there was release from the landscape, but there was severe drought during these flights which may explain why the landscape was releasing carbon dioxide instead of taking it up despite being in the primary growing season. The 08/29/2012 flight had higher release since the drought was more severe than the 08/16/2013 flight where the drought was less severe. Data retrieved from the high altitude balloon flights under ideal situations fit the expected seasonal trends of carbon dioxide exchange between the atmosphere and the landscape which supports the hypothesis. This in turn means that high altitude balloons can potentially serve as inexpensive instruments to measure carbon dioxide fluxes and to support studies at towers, satellites, planes and global models to constrain these other methods while avoiding the drawbacks of stationary towers and their limited altitude for measurement.

Besides supporting the viability of the high altitude balloon as a research tool, the data have important implications for future interactions between the landscape and atmosphere. The late summer temperatures show a release of carbon dioxide from the landscape which reflects the expected increase in temperature of the future. As temperature increases and/or water availability decreases plants are less able to uptake carbon dioxide which in turn means that the atmosphere retains more carbon dioxide. As the globe becomes warmer a positive feedback loop may be established in which increased temperatures increase landscape carbon release which adds carbon dioxide to the atmosphere and further increases temperatures.

Future experiments should be performed to ensure than all data fits the expected seasonal trends. Different crops or other homogenous landscapes should be measured using this high altitude balloon system, especially in areas where there are towers to directly measure the carbon dioxide exchange. Different biomes should have different seasonal trends that should be quantified and examined to better understand carbon dioxide exchanges across the globe. Another potential experiment could involve investigating the exchanges in urban environments to see if anthropogenic sources could be measured using carbon dioxide sensors attached to free-flying or tethered high altitude balloons.

Figure 1 Carbon cycle and the effect of Global Warming on the carbon cycle

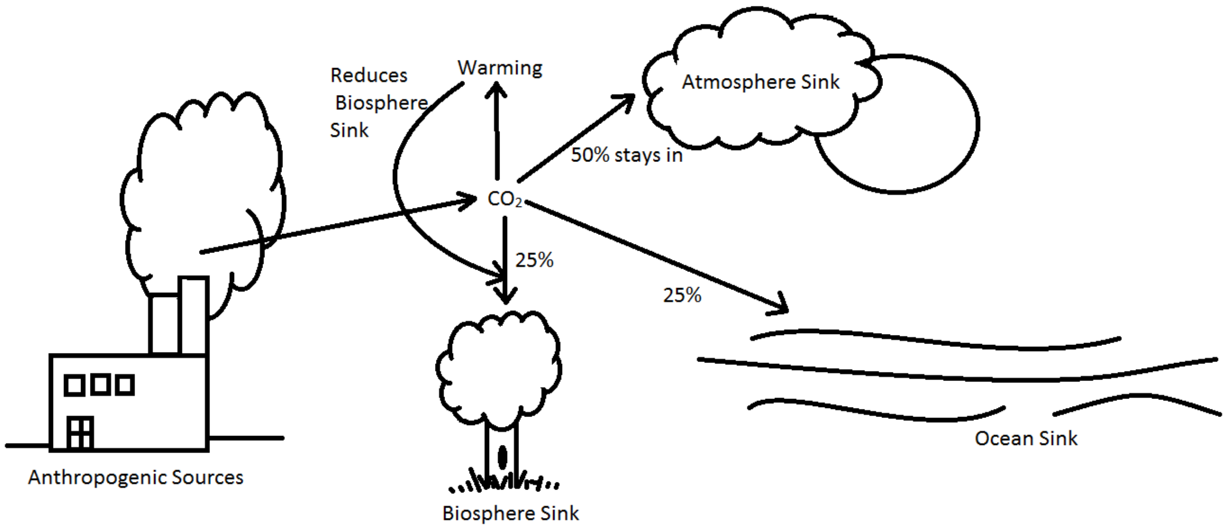


Figure 2 Reference for annual trends

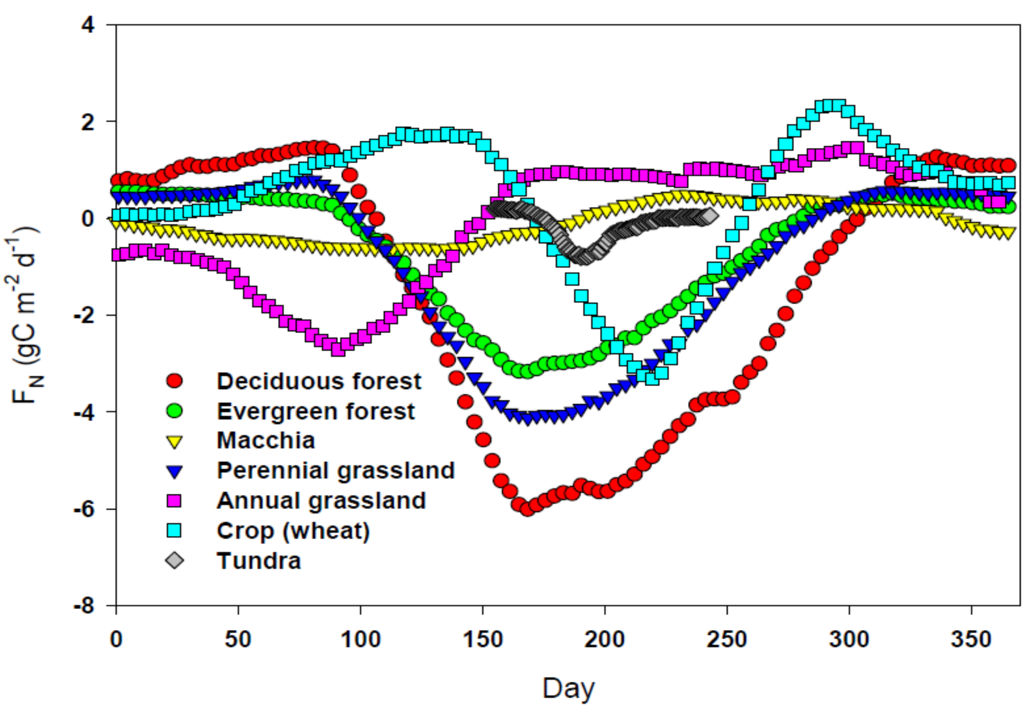


Figure 3 Balloon setup diagram

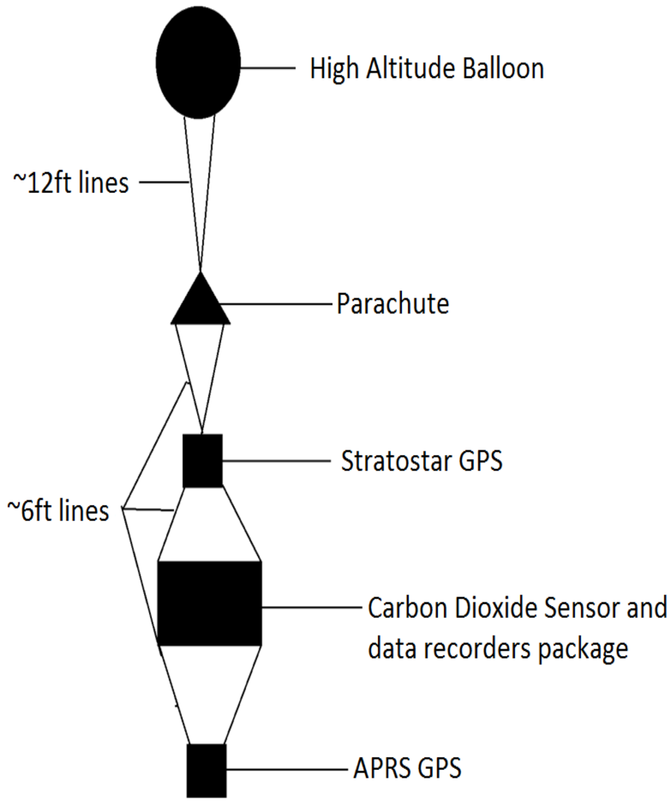


Figure 4 ln(Pressure) vs. Altitude Graph Example from 02/09/2012

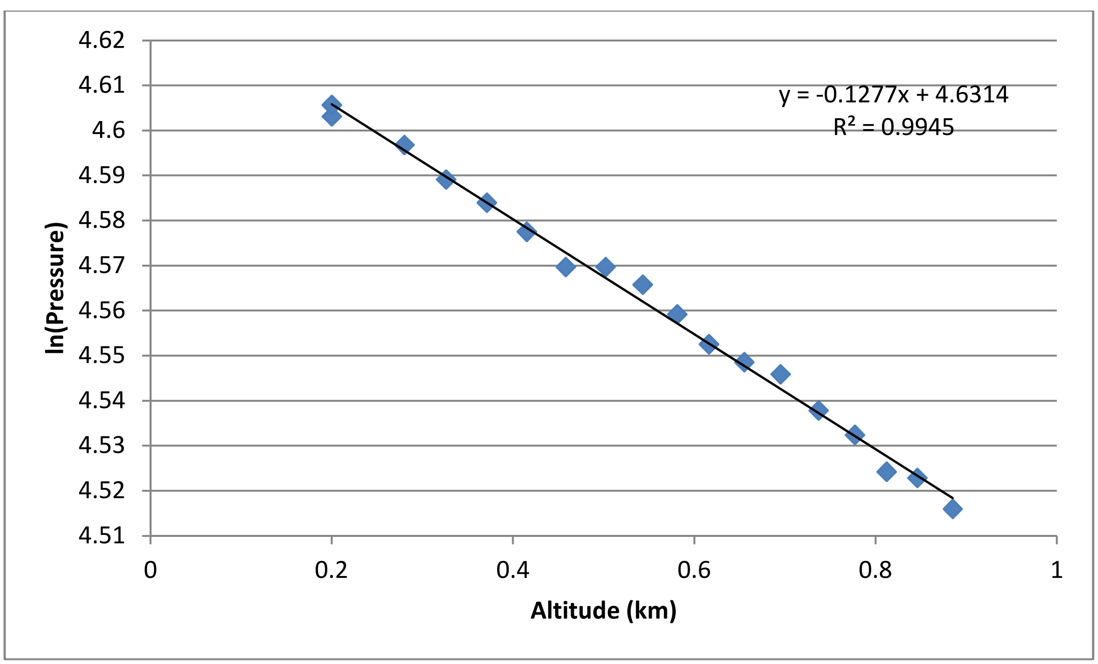


Figure 5 The ideal graph of a balloon flight

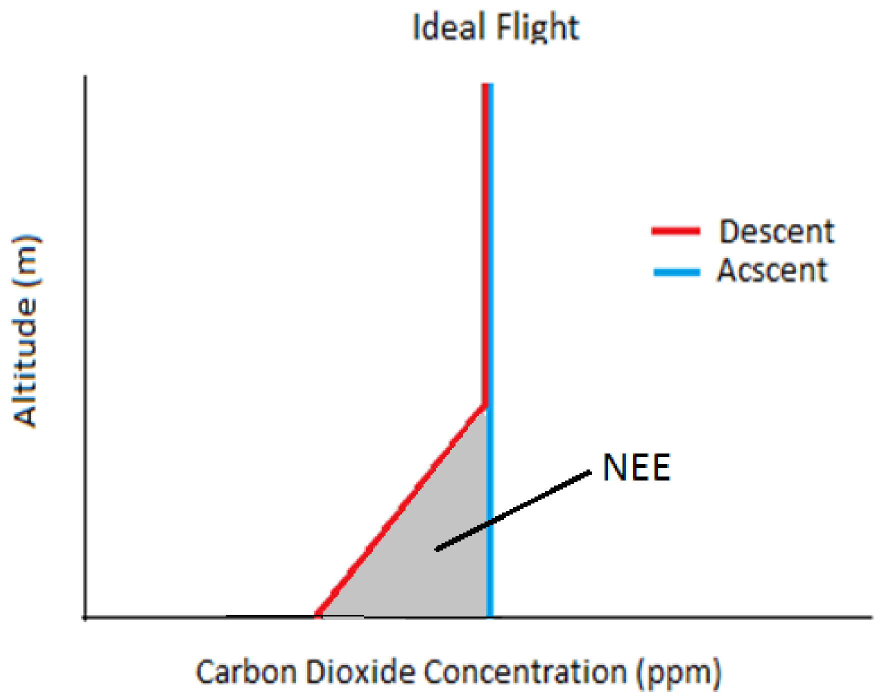


Table 1 Dates of the flights and their corresponding Net Ecosystem Exchange values and conditions

Date	NEE (μmolm^2/s)	Conditions	Good or Bad Data
10/10/2010	93.2	Factory plumes	Bad
01/21/2011	61.9	Dirty cell	Bad
05/21/2011	1.13	Bad calibration	Good
05/12/2012	-19.9	Lake landing	Good
08/29/2012	37.5	Drought	Good
02/09/2013	-0.36	Winter	Good
05/18/2013	11.2	Crops just started to grow	Bad
07/02/2013	5.14	Variable Descent	Bad
07/10/2013	112.8	Over 80mi flight	Bad
07/16/2013a	-39.9	Good	Good
07/16/2013b	11.8	Variable Descent	Bad
07/24/2013	-50.8	Good	Good
08/16/2013	19.2	Good	Good
09/13/2013	4.63	Park launch and field land	Bad

Figure 6 Examples of positive, negative and zero NEE graphs

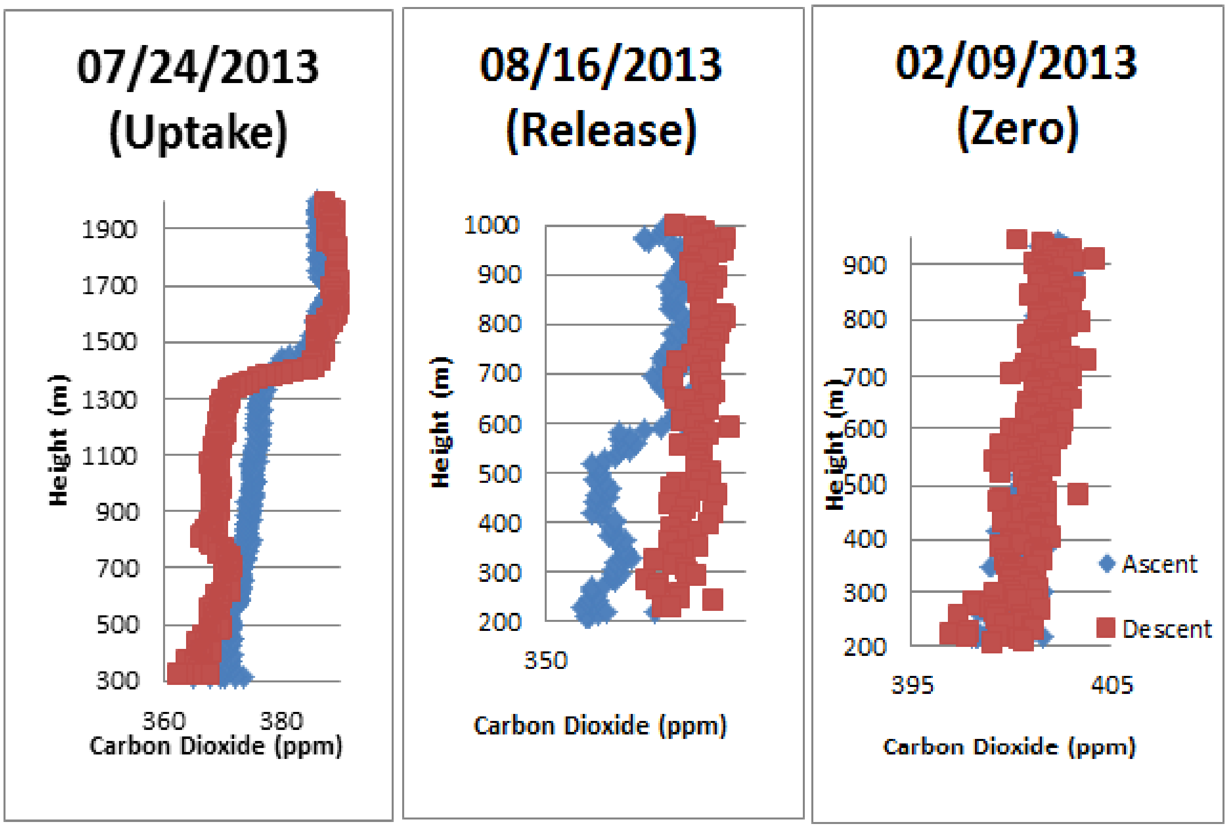
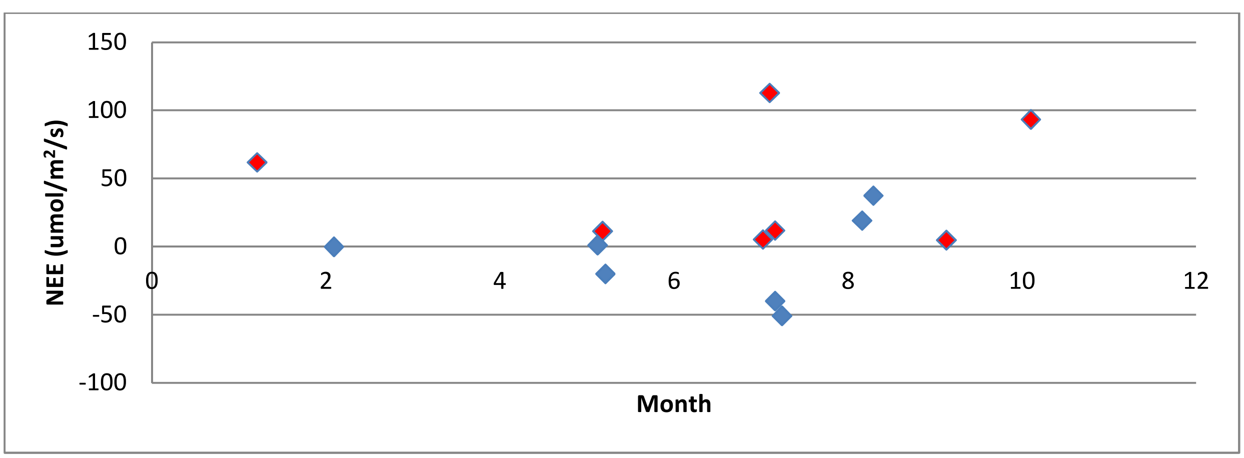


Figure 7 NEE values over the year (red bad data and blue good data)



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