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USING FLUX TOWERS TO INVESTIGATE CLIMATE VARIABILITY AND THE ROLE OF ECOSYSTEMS

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These lectures have scientific content, and should cover several areas of investigation in environmental disciplines of ecology, atmosphere and hydrology. As long as there is special interest in discussing about flux towers, we should see what is the use of it to study climate variability and the role of land terrestrial ecosystems. In the first Part we will focus how the technique of tower monitoring relates to a number of other scientific issues. In the second Part we will talk about implementation and monitoring techniques. This is a very specific issue and should help CIOMTA in his pioneering project in Argentina using flux towers. At a third Part it will be shown several examples of field observations in South America, so you can have an idea of current projects being developed in the continent. A summary of the lectures is given here:

- Using flux towers: its contribution.
    - Global and regional climate change.
    - The role of biosphere in global C cycle.
    - The mitigation of greenhouse gases and the C market.
    - Ecosystems and climate models.
- Examples of multidisciplinary scientific projects (in South America).

1. We will first see the how the surface exchanges are measured using the so called meteorological towers. We will talk about specifically the eddy covariance technique. Several theoretical aspects will give in order to level the audience. Then in a second issue we will talk about themes as surface balances of radiation, water and energy over the surface.

As a third issue, we will approach the instrumentation and the range of sensors and equipments often used. Many pictures will be shown to illustrate this talk.

The fourth issue will bring back again aspects of the second, specifying concepts of flux measurement such as the tower fetch, spectral relationships, and energy balance closure. Typical patterns often observed like the diel and seasonal variability will be focused, using several examples.

And finally we will see what has currently been developed in Brasil, where the given examples are located. Three particular experimental sites were selected for this: the tropical rain-forest, the savannas (Cerrado), and agroecosystem – in this particular case the sugar cane.

As a short introduction (presentation RUNNING FLUX TOWER SITES), it seems important to mention quickly six reasons why using flux towers is important. Namely, they are

1. The regional climate changes.
2. The global climate changes.
3. The role of the biosphere in the global C cycle.
4. The mitigation of greenhouse gases and the C market.
5. Ecosystems and climate models.
6. Interdisciplinary scientific activities.

(See page 3)

1. Regional climate changes

Let's first see the regional climate changes. We can think simply in the climate elements using five variables to describe it: the air temperature, the air humidity, the wind speed, the solar radiation and the precipitation. Put it simply, we can think in regional climate changes as a problem of how much, where, how often, these variables can change over a limited area, a limited region. Very often it is not easy to detect changes in these variables over urbanized areas – as they influence very particularly over a reduced scale of space. Regionally speaking, let's take an ultimate example (large region in this case) of the Amazonia. It is an example of an extense region where deforestation is taking place. Has there been a regional climate change due to deforestation? (See page 5)

Pioneer measurements in Amazonia started about 20 years ago (between US, England and Brasil), were searching for this kind of changes over pastureland areas, the most typical ones in Amazonia. A good example is how the air temperature at the surface changes over forest and over pasturelands. During the diel cycle, the maximum temperature over the grass is about 3° C larger than over the canopy forest. It is also observed that the minimum temperature is cooler over the forest. Next we see the specific humidity deficit, what means that over the pasture it is nearly zero at night, a condition suggesting mist, but not over the forest. From these points, we would wonder how the surface controls the incoming solar radiation, how is it used: for warming up the air or evaporating the water ? We'll see it later.

These findings, if extended to larger areas, will lead to a pattern of changing climate on a regional scale basis. Several studies, supported by these results, attempted to simulate how regional scale deforestation would impact the climate. They were conducted using numerical models, the so called General Circulation Atmospheric models, coupled with vegetation - or biosphere - models. Most of them agree that, with scenarios of homogeneous pasturelands over the Amazonia, there should a large reduction in regional evaporation. This reduction ranges around 200 to 400 mm per year.(See page6) And more important, there would be a reduction also in the precipitation, what is not obvious in a first moment. This reduction in rainfall would be between 10 to 20% on an annual basis, what can reach up to 800 mm per year over some regions.

This example shows how the consequence of deforestation can lead to reduction in precipitation and also in the soil moisture availability. Reducing soil moisture in the amazonian case can prevent the adapted biomas of tropical rain-forest to regrow again. Therefore only adapted species to lower amounts of water – as of savanna species – will compete under a better position. It would mean a process of 'savannazation', a result that is important to the biodiversity preservation and agriculture management.

I'd like to explain that using other words and a question: why should the rainfall change under those circunstances, as long it depends mostly of the large scale state of the atmosphere, like the humidity coming from the ocean, and the large masses of air from the south ? The evaporation, shown here as the blue arrow (See page7), is a source of humidity important to trigger cumulus clouds. But, conceptually, the precipitation has sources that depend also of the humidity transported horizontally from other regions – this term is called the advection transport, and a dynamic control from below – heat and mass convergence at the low levels of the atmosphere. Consequently a precipitating cloud (what simply a cumulus cloud is not strictly), needs several contributions. Therefore we have a balance: the precipitation is the addition of the water coming from the evaporation source plus that from the large scale convergence. So three hypothesis (See page 9) could be formulated: if evaporation is reduced (from deforestation), and the large convergence increases at the same rate, rainfall would not change; if evaporation reduces and the large scale convergence increases at a larger proportion, rainfall could increase; and finally, evaporation reduces, and the convergence also decreases or simply increases at rates lower than the evaporation decrease, then the precipitation would decrease – this last case is what presumably is going to happen with a scenario of large deforestation in the amazon basin. These results were much disseminated since 15 years ago.

Taking back the importance of the surface flux, and in this case the evaporation – an important source of water for cumulus clouds to trigger precipitation. The flux tower measures how the available energy at the surface is splitted into its two most important components – the sensible heat, that warms up the air, and the evaporation, that produces no warming at all, simply moist the air. The fraction how these two terms are splitted influences the growth of the planetary boundary layer, a region with between 1 to 3 km height above the surface, the height of the cumulus clouds, and consequently the probability of a precipitation cloud to be developed. These mechanisms are substantially important in the tropical regions, where the regime of convection – dominated by heating and availibity of humidity – prevails. At those belts (or latitudes) of the globe where there is intense action of cold fronts, called middle and high latitudes, this mechanism has less importance – in these regions the mechanical (or kinetic) energy of the winds is so strong that can overcome air movements raising from local sources by convection. It turns out we can make questions as – what has happened to the regions in South and Southeast Brasil (See page10-11), and also over many areas of Argentina, where deforestation took place along the last two centuries ? The current vegetation and land use is certainly very different from that at 100 or 200 years ago, therefore we can formulate the question: have these land use changes lead to changes in precipitation? would there be climate changes, regional climate changes, arisen from these changes in the vegetation cover ? We could guess two possible scenarios: the first is similar to what happens with the Amazonian case, as shown before – a reduction of precipitation. It means the crop- and pasturelands replacing the primitive forests would reduce local evaporation, and the there would be a positive feedback of the atmosphere, also reducing the rainfall. The other possibility is the atmospheric negative feedback: the cold fronts energetics would prevail over the convective mechanisms – it would mean the rainfall could increase, or simply does not change. We do not have definitive answers so far, but there are early investigations. This map shows the South and Southeast Brasil (states of São Paulo, Minas Gerais, Paraná, Santa Catarina e Rio Grande do Sul, Uruguay and the Missiones province in northern Argentina) – over this region the primitive vegetation was dominated by savanna (in brown), the Atlantic rain-forest (in black and blue), and mixed forests (light blue) (See page 10-11). Using atmospheric and biosphere models for climate simulations, we simulated conditions with this primitive vegetation, and alternatively, with the present vegetation, dominated by crops and grasslands (the green areas in the map, yellow areas mean sugar cane plantation which covers most of the northern part of São Paulo state). It resulted that over many regions the precipitation decreases, mostly during the wet season, with the present vegetation. The figure shows the difference between the primitive minus the present vegetation. Over orange and brown shading, the precipitation has reduced, but there are a few patches (in green) where precipitation increases. It turns out that, on the regional scale conception, the effect is highly non-linear, that is, the surface control and the atmospheric feedback are not always in the same sense. These mechanisms can only be simulated with complex atmospheric models. The results are notwithstanding preliminary: it is necessary to examine other conditions, for instance for periods when the El Niño is strong, or when there is its opposite phase, the La Niña, that can sometimes control the large scale dynamics of the atmosphere. The pattern of the sea surface temperature in the Atlantic Ocean is also important, and different from the El Niño influence.

We can talk now about the global climate changes.

2. Global climate changes

To talk about global changes, firstly we must understand what happened in the past, and try to understand what is happening in the present. For it, let's see how the temperature has been over the last million years. An oscillation, for more and less, of about 5° C (See page 13). The glacial period with the cooler temperatures, and the inter-glacial with warmer ones. Why is there such oscillation ? It has to be with paleoclimatological changes arisen from extra-terrestrial phenomena. These phenomena change the Earth position in relation to its movement around the sun, and control the input amount of radiation into the globe, and along its different latitudes. Using few words, it is a control called excentricity, how the orbit changes its shape, varying the excentricty of its ellipsoidal shape, more or less circular, in simple words. These changes vary about every 100.000 years. Other extra-terrestrials are the obliquity (how the tilt angle between the Earth and the orbital plane of translaction changes about every 20.000 years) and the precession change along several thousand years. These controls dominate situations where there is or there is not a glacial period, and are called the Croll-Milankovitch cycles.

Zooming in the last 15.000 years, we have left a glacial period at that time, and we are exactly in the inter-glacial, a warm period. We can guess to be about the turning point, when the temperature would begin to drop down. Nonetheless, we can not predict exactly when and how fast it is going to happen. So it is important to mention, that over the paleoclimatological perspective, we´re in a warm period, and moving towards a cold one. It is not well established how these glacial periods affects the whole globe: there are evidences the northern hemisphere was more affected (relatively colder) than the southern hemisphere, during the glacial. It is one more point of uncertainty.

, a cool atmosphere is not exactly what recent data is showing us, but exactly the opposite. Air is warming up. This well known result, reported in the IPCC reports, the Intergovernmental Panel on Climate Change, shows temperature changes along the last thousand years. During this period, the temperature has been nearly stationary, that is, its average is not apparently changing, although on the last 140 years the equilibrium was lost, and it appeared to increase significatively (See page 14)..

These results come from observational facts, consequently it is not imagination or artificial products. And it is supposed not to be contaminated by urbanization effects (local microclimate changes), that often also increases the temperature. It is the temperature supposed to be in equilibrium with all the dynamical and thermodynamical processes of the entire global atmosphere.

This other figure shows how some places have tended to be warmer than others along the last decades. All along the South America, there are big and small circles, all of them (in red) showing there is warming. The largest circles indicate there is about 1º C warming per decade, what is ranked as the largest rates. The positive trends are more emphasized in the northern hemisphere, but are widespread over continents and oceans in the whole globe (See page 15).

There is also observation of changes in precipitation over the last decades (See page 16). There are a few evidences the rainfall is increasing over the eastern region of Argentina. Very although over other places, as Africa, it is apparently reducing. These are distinct observations that both show there is something happening: the land use has changed, and the global atmosphere has changed.

This other graph (See page 17) shows how the temperatures were over the last 1000 years, and how they appear over the last decades. And at the right extreme of the graph there are various predicted scenarios showing how it can be in the next century. It all poses the temperature should increase dramatically, although it seems difficult to assess the consequences of this trend.

There is nowadays a strong agreement between the IPCC scientists the global warming development is real, and that it is caused by the greenhouse effect produced by increasing amounts of carbon dioxide and methane mostly, thus suggesting this relationship of cause and effect. The three next graphs (See page 18) were the ones that proved such relationship with a strong appeal – based on complex and powerful atmospheric models, coupling atmosphere, ocean and the surface, mostly in USA, Japan, Canada and England – they show in grey line, how the temperature would increase forced only by the natural variability (that is, without the increasing greenhouse gases concentration). On a second perspective, the models show how the temperature would be with only the increasing greenhouse gases, but without other natural forces. And third, keeping the two forcings: it appeared that the observations, in the red line, agreed noticeably the model predictions with the two forcing factors.

3. The role of the biosphere in climate changes

Moving to another point, what is the role of the biosphere in the global carbon balance ? How using flux towers help us to answer this question ? Very important at this point is to read the IPCC report on land use, land use change and forestry, LULUCF, as shown in the slide (See page 20). This report explains the terrestrial ecosystems can absorb carbon and keep stocks for several decades, being sensitive to the fertilization by atmospheric carbon dioxide, the nutrient availability and management. Although the carbon uptake by land terrestrial ecosystems is viable, it tends to reduce slowly with time. As well, in the perspective of increasing temperatures, as long as productivity usually increases, the emissions naturally developed in the soil (or heterotrophic) respiration accounts on the opposite way. The ecosystem's degradation is a factor that reduces its capacity to absorb carbon.

This figure shows schematically the global carbon balance. In present time, the atmosphere is a C reservoir that every year receives 3.2 million ton C (See page 21), coming from different sources in the surface. As well, along with the sources, there are sinks of C accounting on this net increase in the atmosphere. As shown in the red arrows, the fossil fuel burning and deforestation comprise respectively 5.5 and 1.6 million ton C of the source. Subtracted from these sources, the oceans nowadays are concerned as global C sinks. There is also a sink over the terrestrial biota. Remarkably in the northern hemisphere, changing the land use, and over tropical biomes as well, this C capture is about 1.9 million ton C, which is well significant. It explains well how the biosphere can play an important role in the global greenhouse effect.

It has been proposed that the terrestrial C sink increases, through the Kyoto Protocol, at rates of about 0.6 million ton C per year. It seems obvious that this amount has a significant scale, but will not solve the problem at all. It is not the ´Panacea´. It is necessary much more than that to zero the net increase in the atmosphere, and consequently level off, or even decrease, the current greenhouse gases concentrations in the atmosphere.

Still concerning how the biosphere is important, and remarkably in the tropical regions, a paper reported by D. Schimmel using inverse models has shown results indicating the tropics have indeed a substantial role in the biota C sink. What are inverse models ? They are transport models. Once they are fed by observations of CO2 over several stations in the world, and can calculated how the transport is developed, they can infer where the sources are, or as well where and if there sinks. It means they can localize where carbon is being generated and where it is being drained from the atmosphere. They found out that at latitudes southward of 30ºS there was a substantial sink, to be coherent with the dynamics of CO2 around the world. In other belts of latitude, more specifically northward of 30º N, the sink was even more noticeable. But, in the remaining belt of globe, that is, between 30º S and 30º S, nearly the intertropical region, there was apparently a balance, that is, no sink and no source. It means it is neutral on the surface ? Yes and No. As the deforestation and burning occurs mostly in the tropics, and it is a real source, there should be other mechanism taking place to compensate such emissions, and consequently zero the balance. This mechanism is possibly related to the terrestrial biota too, what makes its importance still more relevant in this context (See page 23).

4. Mitigation of the greenhouse effect

(See the presentation Mitigating the greenhouse effect, The carbon market)

We will talk now about the efforts to promote greenhouse gases mitigation and the current proposals of the so called C market. Some important definitions would fit well in here. The whole thing began with the creation of the IPCC, the Intergovernmental Panel on Climate Change, under the United Nations and its World Meteorological Organization, to measure the impacts and adaptations of global climate changes. It organized scientists, institutions, to advise the Conference of Parties (COP), created under a convention called UNFCCC, the United Nations Framework Convention on Climate Change. A sucession of COP meetings ended up in 1997 to propose the Kyoto Protocol, in 1997, to establish rules and conventions for mitigating the greenhouse effects with the help of trading responsibilities and costs. The article 1 says, between other things, the Annex I countries (mostly the developed countries) agree to limit greenhouse gases (GHG) emissions to 5% below 1990 levels in the commitment period 2008-2012 (See page2). The Article 3.3 says that that net fluxes of GHG resulting from direct human-induced activities of Land Use, Land Use Change & Forestry – LULUCF - limited to afforestation, reforestation and deforestation since 1990, measured as verified changes in C stocks, will be viable and eligible activities to meet the commitments. It means we can think in activities essentially related to the land terrestrial ecosystems to meet the achievements of reducing emissions to 5% below 1990 levels.

The Article 12.2 mentions that the purpose of the clean development mechanism (called CDM) shall be to assist non-Annex I parties (that is, the developing countries) to achievie sustainable development and contribute to the objectives of Convention. This link establishes well that the CDM means responsibilities (and resources invested) from a developed country to a non-developed one. As in Article 12.5(b), the mitigative activity must be real, measurable, and generate long-term benefits. Measurement of carbon uptake is a point i will focuse particularly while discussing the use of the flux tower platforms. And finally, the Article 12.5(c) – Reduction in emissions that are additional to any that would otherwise occur in the absence of project. This is the concept of the baseline (See page2).

Until recently, to use reforestation as a modality of CDM was not agreed as an eligible activity. There was not consensus that the benefits and longevity of these types of activities would accomplish the terms of the Protocol. Other types of activities were discussed, and many of them are eligible, for instance those using carbon removal through the ocean and geological reservoirs. It is in reported in a special IPCC publication. Other activities, like replacing fossil fuel used in power plants by other renewable fuels (e.g. from biomass) would promote C mitigation.

However it was decided in the last COP meeting, in Milan, Italy, the agreed rules about using LULUCF activities into the CDM, and more remarkably defined the activities of Afforesation and Reforestation (See page3). It has direct effects with all the community working with forests, silviculture and agriculture. There is now a much better position to view how C removal (from the atmosphere) can be planned to achieve the Protocol. With this, carbon credits would be generated.

The Annex A defines what is baseline (See page3-4), the sum of C changes that would result in the area of activity, and in increase in C emissions outside the project boundary. Consequently what is really important is the actual net C increase, defined as the sum of C changes with AR minus the baseline minus the leakage. The project is additional if actual net C increase is greater than baseline. And being additional, it is eligible.

Specifically concerning the C market, the eligible project should generate accreditation for the amount of C removed per period, and correspondent Certified Emission Reduction (CER), viable to be traded. These CERs are divided into tCER, or temporary, that expires at the end of comittment period (for example, between 2008 and 2012), and the lCER, or long term, that expires at the end of AR project (as specified in every particular proposal) (See page4).

Following, it defines small-scale AR project as those expected to result actual net C increase less than 8000 tons CO2 per year, and concerns those as eligible for CERs.

The next question would be practical. What are the steps to conduct an AR project and make it eligible for CERs. There are at least 5 important steps to observe (See page 5):

(i) (i) First would be writing and validating the project. The validation phase. It must be validated by an independent entity rather than the one who will conduct the project and receive the CERs. The project and the entity must be in accordance with the government laws, and possibly specific rules concerning CDM, being authorized by the government. Often specific official secretariats or bureaus (created by each government) give these authorizations.

(ii) After the validation phases, the project must be registered at the CDM Executive Board, a group of expertise who will accept it or not for accreditation. The successful approval and credit eligibility for AR projects in principle should comprise the evaluation of impacts in environment, in the hydrological component, soils, biodiversity, and regarding social-economic issues (it means for instance local communities must participate and interact positively with the

project). These constraints are somehow a practical implementation of the concept of sustainability.
(iii) At a third step, the project would implement, and consequently it should be necessary to start the measurements of possible carbon increments. All necessary data for this assessment must be archived.
(iv) Fourth: Verification. This is an independent review of the proposed project goals. Should be periodic to assess if the C increases have been in accordance with the planned expectations.
(v) There will be two independent entities: the verifier and the certifier. The certifier, at this point, will approve the written proposed achievements for the project development.

So it becomes important to emphasize a few points. The project involving land use and land use change for C sequestration ought to be sustainable, has characteristics of additionality, longevity, susceptible for measurements, and provides environment externalities. The measurement of the additional C increase must be a transparent action, so it is possible for everyone to see it, should be consistent, employing scientific methodologies, should be comparable (with other methodologies and similar projects), complete (cover all possible aspects of C variations in the project boundary), real, and verifiable. The data archiving must be efficient to provide verification for the periodic amount of C variation in the project.

The Kyoto Protocol is not ratified so far. It needs approval from 55% of all parties involved (what has been achieved), and parties involving 55% of the total global emissions – this latter constraint has not been completed so far, since USA has not ratified and neither Russia (See page 6) – anyone of these two countries would be enough for the final ratification and implementation. Notwithstanding, many companies in USA are already investing in initiatives of clean energy, compensating or not its own emissions, and despite they will be accredited or not. Similar to what happened with the tobacco industry, these companies would presumably not like to be suited in the future. If in the future, there is a proved correspondence between possible natural disasters and the global warming, this would be a very uncomfortable situation for the companies and countries who have not contributed to the greenhouse effect mitigation (See page 7).

6. Ecosystem and climate models.

An important reason why we work with flux towers has to be with the use of climate, and ecosystem models. The IPCC reports are strongly supported by experiments and studies driven by this type of models. I give an example of how an atmospheric climate model works. It is primarily driven by the input energy, given by the solar radiation. This input can be thought as of incoming into a column, over unit area, where several physical processes interact each other. Which are these processes ? Many of the processes i have mentioned before: reflection and absorption of energy at the surface, generation of water and energy at the surface followed by its diffusion along the boundary layer depth, triggering of shallow and cumulus clouds, precipitation. Horizontally, mass, temperature and humidity are transported accordingly to the balance equations of atmospheric dynamics. These atmospheric columns lie over a single cell, defined along the horizontal model grid at the surface. So it is at the surface where the vegetation (or ecosystem) model works, exchanging water, heat and CO2 with the atmosphere. How do these vegetation models work ? (See page 9).

These models are forced (or driven) by the atmospheric variables in the interface with the canopy height. These variables are namely the precipitation, the wind, air temperature and humidity, and radiation. This is for instance the Simple Biosphere Model. The importance of these models is that they represent mathematically (given some simplification) what is measured over a tower flux. We have the benefit to transport the data observed over the tower, to the model, in a process of validation, and thus make the model interact with the atmosphere (See page 10).

The first surface models working in the climate models were very simple indeed. In the 1970´s they were called *bucket* models: basically the water level in the bucket was reduced as long as there more evaporation than precipitation – concurrent with the level height, the evaporation was proportionally limited, as an attempt to control the evaporation limiting factors. Nowadays the vegetation models are much more complex. They calculate the limiting factors to transpiration and CO2 assimilation at the surface, dependent on the radiation, humidity, soil moisture and temperature. All these variables are measured at flux towers, and are used to calibrate the models to validate it for a specific biome. These validated models strongly increase our predictability about the ecosystem, related to climate dependencies. The coupled vegetation-climate models are powerful tools that provide us scenarios about future climates, and future state of vegetation (See page 11 to 15).

It is shown in this slide how satellite products can help the coupled ecosystem-atmosphere model to predictability. The normalized deviation vegetation index (NDVI) is a biophysical parameter that tell us about the state and type of vegetation. It can be monitored, and its information always feeding the model to update the status of vegetation. I show a scheme, called Mapper (reported by Sellers et al. 1996), that calculates several other biophysical variables derived from the NDVI, for instance the Leaf Area Index, the Greeness Fraction (Green leaf area index upon Total leaf area index), and many others. These parameters strongly influence the exchange of CO2 and water at the surface, and dramatically influence on the fluxes with the atmosphere (See Eco-Model-part2).

7. Interdisciplinary projects in South American (using flux towers)

(See presentation Participation in interdisciplinary scientific projects)

It is important to mention a project in Amazonia, entitled LBA (Large scale biosphere-atmosphere experiment in Amazonia) (See pag 4.), that is possibly the largest around the world in terms of multidisciplinary areas and number of researchers. It has 232 institutions, being 50 brazillians and the remaining mostly north-american and european. About 973 researchers are involved, where 380 are brazillians. LBA has two fundamental questions (See page5):

- How does Amazonia currently function as a regional entity ¿
- How will changes in land use and climate affect the biological, chemical and physical function of Amazonia, including the sustainability of development in the region and the influence of Amazona in the global climate ?

The example shown previously, about the impacts of deforestation in the amazonian climate, is excellent to demonstrate how its regional climate is dependent on its internal conditions and controls. Also, there are evidences, that i will limit to comment, that the regime of precipitation in Amazonia also controls the climate over remote areas: these areas can be as near as the South/Southeast Brazil, or even distant places like North America.

In LBA there are several lines of investigation (See page6), that are connected in the framework shown in the slide, that i will refer here: the climate physical system investigates the dynamics and balances of water and heat over the region and particularly in the surface; the atmospheric chemistry is directly related to the climate (with specific areas of pollution, aerossols, greenhouse gases, burnings, impacts of natural emissions as of volcanoes); carbon storage and exchange; biogeochemistry, mostly focusing trace gases and nutrient dynamics; the surface water hydrology (that has consequences to the atmospheric water cycle, impacts on croplands, forest sustainability, and others) and water chemistry; and land use cover and land use change – these aspects are strongly related to the emission of greenhouse gases, hydrological control (controlling evaporation, maximum surface runoff and discharge).

The LBA project is open to all amazonian countries (See page6), as well as others countries interested in investigating there. It is coordinated by Brasil, since its beginning in 1996, and the costs are covered mostly by brazillian funding agencies, north-american (mostly NASA), european (mostly funds of European Community), that at all must have reached about US$ 200 million over the last 7 years. Every two years there is a scientific meeting, usually hosted in Amazonia, where the project achievements are present, and future perspectives are discussed. The number of publications has increased over the years, and about 5 special issues of international journals have already been published.

There is a strong emphasys with works using flux towers in LBA. About 15 towers are operating nowadays at experimental sites where other approaches complement the research, for example, researchs are related to canopy studies, soil (isotopic measurements, nutrient dynamics), hydrology and remote sensing, besides others. The tower sites represent points of validation for surface and atmospheric models, and are the main references for the concept of studying the Amazonia along transects that attempt to represent its large spatial variability (See page8). The transects were strategically planed to combine the most typical types of climate, vegetation, soils, geomorphology and land use cover existent in the whole basin. Besides the continuous monitoring tower sites, there are intensive missions using sensos on board of satellites and airplanes to study the transport of gases from burnings and from natural emission. The models represent at the end a tool of integration between the several lines of investigation. We are using the models to increase the predictability about the region, understand changes in climate and hydrology in future scenarios of land use and global climate. They will fundamentally help to understand how the entire basin works as a sink or source of carbon to the atmosphere.

I show the slide of a tower in Santarém (See page10), state of Pará, 66 m height, that is near the Tapajós river, a main contributor to the Amazon river, and the list of the several towers currently operating. The towers are distributed along the transects, and are monitoring over particular biomas that complement the vast variability across the basin. Several of them are over terra firme rain-forest (Manaus, Santarém – two of them, Ji-Paraná, Caxiuanã), Cerrados (Brasília, Sinop), mangrooves (Bragança), ecotones (Bananal Island), crops (Santarém km77).

I mention the example of soybean production in Brasil, which is currently the largest world production together with USA. Farmers are now growing soybean over several areas in the amazonian region, where in the recent past it was concerned as useless for agriculture. They were attracted by cheap costs of land, and the reduced costs of transportation from the farms to the ports of exportation (in Santarém, for example). The LBA research is for instance also concentrated in studying this special land use change, with towers, social studies, and remote sensing, and trying to predict what impacts can arise, on the social and environmental levels.

Another example i mention and show slides is about initiatives of exploring the natural forests (federal reserves) using selective logging. This technique is supposed to bring minimum impact to the environment (on soil compaction, degradation of remaining trees, besides others). We are monitoring using flux towers, isotopic and forestry studies, the consequences of the logging on the forest regeneration, the CO2, water and energy fluxes.

This slide show the several sites worldwide where flux towers are being monitored over several different ecosystems (See page 11). They are currently organized into a network called Fluxnet, and is mostly concentrated in North America (Ameriflux), Europe (Euroflux), Japan and Brasil. Particularly in Brasil, there are three towers in southeast (Cerrado, sugar cane and eucaliptus) and one in Rio Grande do Sul state (over rice) monitored continuously. It seems interesting and relevant that CIOMTA is up to implement a tower in the Santa Fé Provincia, possibly a point at the highest south latitude (austral) ever having a tower flux.

Next is shown an example of other project multi-disciplinary, in the state of São Paulo, gathering many institutions, the Biota Fapesp Program (See page 13). It is sponsored by a state funding agency (Fapesp), and is mostly concerned with biodiversity studies, its conservation and strategies of sustainability. The towers currently working in São Paulo (savanna, sugar cane and eucaliptus) are supporting the biological studies of Biota Fapesp, thus complementing with physical information about ecophisiology and climate. Statistics by 2002 showed there were 39 projects and about 700 researchers. This program has a virtual journal since 2001, the Biota Neotropica, available at www.biotaneotropica.org.br, where per review articles are published.

Another more recent initiative is concentrating several investigators in the study of the Rio de la Plata basin (See page 15-16), the PLATEX/GEWEX, supported by the World Climate Research Program (WRCP), involving experiments with climate and hidrological studies. The project explores atmospheric models, existent data of meteorologicals networks and flux towers (the ones in São Paulo) to increase the predictability of hidrometeorology over La Plata basin. In this slide it's shown an output of an atmospheric model, the pattern of the atmospheric flow. I point in this flow pattern the wind coming from Amazonia, near the Andes, and reaching northern Argentina – there is therefore a remarkable connection between the humidity generated by evapotranspiration in Amazonia and the source for rainfall in southward areas of the continent, which suggests a relationship of dependence.

The surface energy balance

(1.See presentation Measuring ecosystem surface exchanges. The eddy covariance technique and

2. The surface energy and radiation Balances The energy balance closure)

To understand the complete relationships betwen flux of carbon over ecosystems and the climate, it's necessary to figure out how much energy is available, how much is exchanged, and what is the way how the vegetation shares its energy for a variety of processes (See page 1.3). The available energy comes from electromagnetic waves as radiation, and there are essentially two types of radiation available to the surface: one is from the sun (solar, called short waves, I will call K), and the other is from the atmosphere (the terrestrial, called long waves, I will call L), which is exactly the energy responsible for the greenhouse effect, that naturally happens in the atmosphere – without the natural greenhouse effect the average global surface temperature at the surface would be 33° C cooler than today, consequently too cold for many of organisms to survive, including the man. Not only the atmosphere, but all bodies in the planet continuously emit this type of radiation, also called thermal infra-red radiation. Short and long are so simply called as their wavelengths have relatively different scales. The main input to the surface is from the incoming solar radiation, Ki, and as the surface reflects back to the atmosphere part of that, Kr, the net solar radiation available is (Ki-Kr). On a global average, Kr is about 30% of Ki, what is called the average planetary albedo. Over terrestrial ecosystem, this proportion can vary from 5% to 25%. So a proper comment is that different ecosystems absorb different amounts of solar energy, and also, for one specific biome, it can vary strongly along the year given its phenology also changes seasonally. As well, incident long wave is always reaching the surface from the air (Li), and lost to the atmosphere as emergent radiation by its continuous emission (Le), what produces a budget of long wave radiation equal to (Le – Li). Consequently the total available radiation is the sum of those two, called net radiation (Rn, usually given in Wm^{-2}), or

$$Rn = (Ki - Ke) + (Le - Li)$$

A consequence of the increasing levels of GHG in the atmosphere is increasing the amount of LE component reaching the surface, as the atmosphere temperature will be larger.

The Rn component is a variable that is currently measured over flux towers. It is based on the radiation balance, but has an intrinsic relationship with the fluxes. It is called net radiation, and is the available energy at the surface. The question we do now is: what is this energy used for ¿ It will distribute into several processes. The first refers to warming up the air right above the surface. The amount of energy transferred per unit area and per unit time is called Sensible Heat Flux, usually called as H (in Wm^{-2}). As well, if there is liquid water available at the surface, in the soil surface, or over the leaves, there is evaporation; as well, if there are plants and these plants are making photosynthesis, there is transpiration – consequently for either processes, we call evapotranspiration, plenty of energy is required, and in this mechanism there is no change in temperature (as the change of water phase – liquid to vapour – does not alter the temperature by definition). This is why the evapotranspiration requires energy, in a term called Latent Heat Flux, called as LE (in Wm^{-2}). Over a green vegetated canopy, most of the energy is distributed into these two terms, so that the energy balance is approximately

$$Rn \cong H + LE$$

Often over most of vegetated surfaces about 90% of Rn is in (H+LE). The question arises in what is the proportion of H and LE ¿ Assuming Rn as constant, the higher the term LE, the lower the H, it is a balance. The denser and photosynthetically active the vegetation is, consequently enhancing evapotranspiration, the ratio of H upon LE decreases (this ratio is called the Bowen ratio = H/LE) (See page2.3 y 2.4). Over green forests or dense green crops it can be as low as 0.1. Over bare agricultural soil it can be as high as 10. Over crops it uses to range between 0.2 and 2 along the whole phenological cycle.

Strictly H and LE are called the turbulent fluxes (See page1.4), and they measured at the top of the tower at an average interface height between the canopy and the lower boundary layer. Often there is substantial energy coming in through the canopy, reaching the soil and warming its deeper layers – this term is called Soil Heat Flux (called G, in Wm-2) – so the energy balance can be more exactly

$$Rn \cong H + LE + G$$

As well, there is also energy used internally in the leaves during the photosynthetic reaction (transformation of CO2 and water into sugar) (See page2.6). This term, that we will call A, is often quite small, although significant in the concept of energy (can be as much as 2% of available net radiation), so the energy balance can be more precisely expressed as

$$Rn \cong H + LE + G + A$$

Additionally, over ecosystems such as dense-wood forest canopies, mostly as trunks, there is enough energy stored in the biomass, significant to alter (from 1 to 3%) the energy balance. Calling this storage term as S, the energy balance becomes

$$Rn \cong H + LE + G + A + S$$

It turns out that, since one of the objectives of a flux tower is measuring the turbulent fluxes H and LE, all the other terms (mainly Rn) must be measured too. It will make viable an analysis of how much the energy balance closes – and this means the turbulent fluxes are in principle being measured accordingly to what it is expected. In the field Rn is measured using net-radiometers, G is measured using soil heat flux plates (in the soil), while the turbulent fluxes are often measured with the eddy correlation technique (that we will talk about later). Since the measurements of Rn and G are often very local (a few meters scale), while the turbulent fluxes integrate the fluxes along hundreds to a thousand meters, often the energy closure is not expressed perfectly – it is possible that fluxes are transported from outside of the tower limits, and contaminates the closure. This is why a term called advection term that accounts for advective (horizontally transported) fluxes of water and/or heat, help to explain why the energy balance can not close. This problem can be reduced during the site selection, as long as the area around the tower is homogeneous to that along the tower fetch. Despite all, it is often seen in the literature that the turbulent fluxes underestimate the other terms between 5 to 25%.

Since the energy balance has a reasonable approximation, there is also reduction of uncertainties in interpreting the CO2 flux (measured at the flux tower too). If the energy closure is not satisfactory, there would also be reasons not to believe in the estimate of the turbulent CO2 flux, as the principal hypothesis of the theory could not be satisfied for the measurements.

The eddy covariance technique

(See presentation Measuring ecosystem surface exchanges. The eddy covariance technique)

We will see next a technique to measure the exchanges of gases and heat between the ecosystems and the atmosphere, called the eddy covariance method. It is emphasized the measurement of the CO2 flux, as CIOMTA is up to install a flux tower in the Provincia de Santa Fé, Argentina.

This figure explains some conditions of this meteorological technique (See page 3). The dashed line is supposed to be an interface between the atmosphere and the biosphere (that is, the ecosystem). Exchange of water (as water vapour), heat and gases (remarkably CO2) exist across this interface continuously. While water comes as precipitation and goes as evapotranspiration, heat is mostly generated during daytime and warms up the air.

Over a land terrestrial vegetated ecosystem, the exchange of carbon is mostly due to CO2, and several processes are defined in the CO2 flux. The plants uptake carbon by photosynthesis (called Gross Primary Productivity), and looses carbon by respiration. The difference between the two is called Net Primary Productivity, or NPP. As well, carbon is continuously lost by heterotrophic respiration, mostly in the soil, resulted from the activity of microorganisms decomposing organic matter. The subtraction of NPP minus the heterotrophic respiration results in the net ecosystem production. Once it is measured in the interface with the atmosphere, is often called the Net Ecosystem Exchange, or NEE.

It is important to stress how important the climate is for all the surface exchanges (as evapotranspiration, precipitation and CO2 flux). The climate controls the fluxes by net radiation, temperature, wind and air humidity, and ultimately also controlling soil moisture.

The eddy covariance method is a theoretical principle known since the 1950`s, but only in the last decade it became operationally viable for long term monitoring over remote areas, given that it depends on electronic midia to store large amounts of data, and sophisticated instrumentation (which also is expensive) – these combination followed parallel to the popularization of the microcomputer, its peripherals and electronic components as well.

I will show how the whole principle works. For example, during the daytime conditions, the large amounts of CO2 in the air are continuously depleted by photosynthesis.

It means that, if we measure CO2 concentration in the air above the canopy, it will be continuously decreasing proportional to the uptake by the net ecosystem exchange. In other words, the CO2 concentration near the canopy becomes a CO2-poor air parcel, while the height levels a little above the canopy height are CO2-rich air parcels. Well, if there is net flux of CO2 from the atmosphere to the surface, the CO2-rich parcels must go down, and the CO2-poor parcels must go up, thus characterizing the net exchange. It all suggests that the parcels need to be well mixed. This mixing is promoted by air turbulence. This is why we call the measured flux as a turbulent CO2 flux. Mathematically, it is expressed as the covariance between the vertical wind speed and the CO2 concentration.

Additionally, to estimate the CO2 net ecosystem exchange, it is often necessary to measure another term. It happens that, when there is not enough turbulence, the parcels are not well mixed, and consequently the principle should not work. For example, over a forest canopy, there can be CO2 being accumulated below the canopy during nighttime. During the night, there is continuous CO2 emission by heterotrophic respiration (and no photosynthesis – that is, the surface should be emitting CO2 and not uptaking). If this CO2 is trapped along the canopy height, and does not mix up with the air (as there is often small turbulence during the night), consequently there is a flux which is not measured at all at the interface line between the canopy and the atmosphere. This flux is real and is called a non-turbulent flux. It happens slowly nearly like a diffusive process, constrained to low turbulent air conditions.

Consequently the measurement of the entire ecosystem flux (See page 4), Fc, is the sum of a turbulent flux, i will call F, and a non-turbulent flux, i will call S. In these concepts, i am not regarding other ways to transport CO2 in the ecosystem, as for instance by water. The input or output of carbon by water by rivers, streams, flooding, is important over several landscapes and should be treated separately with proper and adequate methods. Other losses of carbon, for example as methane, are also not treated here and should be measured adequately, if relevant, for the estimation of the entire carbon balance.

Estimating the flux

Let's think about a surface area, called A, where the CO2 flux come from (or go to)(See page 5 and 6). This is the source-area where the flux Fc is associated with. The whole idea behind the method is how to measure the flux Fc having one point of observation or measurement. The theory concerns the point of observation is the tower. The turbulent flux is measured at the top of the tower, and is mixed by the wind, that transports the flux arising from the surface A, along the direction to the tower.

As expressed before, the CO2 concentration (or any other scalar, as temperature, water vapour concentration), I will call c, varies constantly along time resulting from the flux. As well, by theory, we will measure the vertical flux, perpendicular to the interface canopy-atmosphere. Consequently it is necessary to measure both the concentration c, and the vertical wind speed, i will call w that is responsible for the vertical air movement transporting the c-rich and c-poor air parcels.

Using the principle of mass conservation, i apply the equation for a control volume that comprises the area A, the tower at one of its lateral boundaries, and the top tower as approximately its height (to be exact, right above it, at a height h_v, called mixing height). The conservation requires that the rate of variation of c with time, measured at the top tower, must equalize the contribution from the transport promoted by the wind, plus the contribution from a source, or a sink, at the lower boundary (the surface).

Now we must simplify these terms in order to have a practical relationship, that is, so we can measure a few terms and isolate a specific one, for some conditions. First, the wind V is actually tridimensional: it is a vector decomposable in two horizontal components (an east-west one, in the direction, called u, and a north-south one, in the y direction, called v) and a vertical one, in the z direction, called w. To express the transport formally correct, the variations of the c transport by the wind, the tridimensional flux Vc, between the boundaries, are divided by the transport length in the x, y and z direction. This term is mathematically called the divergence. Algebraically the negative sign leads to that, if the term is negative, it contributes positively, as a converging flux increasing the variation of c in time.

There is in the equation a term concerning the variation of c with time, and the variation of c with height. As both the flux in the boundary, S, and the wind transport, contribute to the whole control volume, we integrate (or sum) in time and in height the terms of the equation. Consequently the fluxes like S bar are averaged in time. In this concept, we simplify that the horizontal fluxes are often neglect able, while the vertical one is the most significant.

The equation (after the simplifications of the scale analysis) shows a balance, that is, the variations of C with time (summed over a time period T, for instance 30 minutes), and along a height *hv*, must equal the sum of the product between *w* and *c* (the vertical flux or transport) over the time T (this term is called the covariance of *w* and *c*). The term S bar (averaged over a period T) is in this way the flux over the ecosystem we want to know about. Put S bar on left side of the equation, and it must equalize the covariance (or turbulent flux) plux the so called storage term (or non-turbulent flux).

The turbulent term is simplified furthermore. It is achieved using a concept called the Reynolds averaging. The variable w is decomposed into its temporal average, w bar, and the deviation from the average, w'. The same is used for the c concentration. It turns out that the product of w times c is decomposed into four terms, two of them equal to zero (as the time average over w', and over c', respectively, are identical to zero). The remaining terms is the average of the product between w' and c' (exactly equal to the covariance between w and c) and the product between w bar and c bar. The term w bar times c bar is neglected employing an artifical operation called axis rotation – this operation aligns the tridimensional axis along the prevailing wind, and the variable w bar becomes approximately equal to zero.

There are four possibilities about the turbulent term, that indicates about the air parcel movement as, respectively, w' positive (ascending movement) or w' negative (descending movement), and the CO2 concentration of the parcel, as being c' positive (rich-c parcel) or c' negative (poor-c parcel). The combinations of either w' and c' both positive (rich-c parcel going up) or w' and c' both negative (poor-c parcel going down) mean the flux is positive, or upward by definition, that is, carbon has been lost to the atmosphere. On the other hand, either w' positive and c' negative (poor-c parcel going up) or w' negative and c' positive (rich-c parcel going down) mean the flux is negative, or downard, that is, carbon has been sank into the surface.

If the product is zero, there is no net flux. It is often interpreted that, over the averaging period, the positive products algebraically cancel the negative ones. The case of a zero net flux would be, for instance, the case for measurements over a climax ecosystem. If the ecosystem reached its climax, it does not sink neither emit carbon on a long term average, what means years or many years. It can mean that, on a seasonal basis, there are patterns of sinks and emission alternating each other (which is by the way the most possible scenario).

Summarizing, the CO2 flux measurement over a land terrestrial ecosystem, we called F_c, can be measured approximately as $F_c = F + S$, where F is the turbulent flux, calculated as the covariance between the vertical wind speed (w) and the CO2 concentration (c) over a period of time T, and the non-turbulent flux, S, which means the temporal variation of the vertical storage of CO2 within a profile under the canopy, over the period T.

Another point I'd like to discuss is why atmospheric turbulence is a constraint for the eddy correlation method. In this concept turbulence is caused by two mechanisms: one called mechanica, where the wind shear mechanically mixes the air parcels; the second is thermodynamic, generated by the heating at the surface, thus associated with convective movements in an unstable atmosphere where warm parcels move up and cool parcels move down. Near the surface there is a zone of the atmosphere called the planetary boundary layer, or PBL. This zone is influenced by the fluxes generated at the surface within a short period of time, less than an hour. It means that the PBL can be warmed or cooled, moistened or dried, accordingly to what happens in the surface. The PBL height varies between a few hundred meters (usually at night) to up to about 2 km (mostly at daytime, when there is strong mixing or turbulence and the PBL is called convective mixed layer). Well, over the surface, when there is enough turbulence, there are eddies in the atmosphere structure. These eddies are tri-dimensional, and can be as small as scales of a few centimeters, ranging to meters and ultimately to the scale of 1 km. The latter ones are the thermals that exist along the PBL height during daytime. The lower (larger) the eddies, the faster (slower) they are. The eddies are the turbulent structures that transport heat, water vapour and gases, as the CO2, from the surface to the atmosphere. The small ones need seconds or seconds' fraction to move along a spatial direction similar to its dimension. The larger ones usually take around 15 or 20 min to move along the PBL. Because all eddies, small or large, contribute to the whole transport of scalars from the surface, it is necessary to measure the wind speed and scalar concentration at high frequencies (usually below 1 Hz) to capture the effect of the small ones, and calculate the fluxes for periods around the scale of 30 minutes, to capture the effect of the large eddies.

Instrumentation

(Presentation Instrumentation part I).

A flux tower with an eddy covariance system requires a sonic anemometer, that measures the wind speed with high frequencies (usually at 10 or 20 Hz), and also a high-frequency infra-red gas analyser, for measurements of H20 and CO2 air concentrations. These sensors are fixed at the top of a thin tower, over the average canopy height. The tower must be as thin as possible to minimize the flow distortion. (See page 2).

(Presentation The tower footprint)

A good question at this point would be: what is the height to set up the eddy system ? (See page 8-12)

Theoretically there is a zone, right above the average canopy height, called the surface region (within the PBL), that has a length scale of about 10% of the PBL height. In this region the surface fluxes are supposed to be constant with height. That means it would be OK to measure the flux at any height along the surface region. However, at the nearest levels near the canopy height the turbulence can be very strong. There is at these points roughness induced by the spatial variability of the vegetation, and the wind profile (supposed to vary logarithmically with height) can depart strongly from the theoretical log-adjustment curves. It is consequently helpful to fix the eddy covariance system above the roughness sub-layer. There is not a exact rule for that, however it is recommended that, having the canopy average height (hc) as the reference, fixing the sensors at heights of 1/3 hc or more, above hc.

For short canopies, like short grasslands, where hc vary between a few cm to ~m, other constraints need to be regarded, like the minimal height for the sonic operation. The sonic anemometer, over a flat surface, can provide a good flux estimate when fixed at a minimum of 1 meter height. Over rough surfaces, as grasslands, it is adviced to be fixed at a minimum of 3 meters above the average canopy height.

Often a meteorological weather station operates in the flux tower, together with the eddy covariance system. It is useful for several reasons. The sensors are more robust and comparable to other weather stations installed elsewhere. The weather stations also measure other variables rather than the turbulent fluxes, as the precipitation, solar and net radiation, and the data can be stored under smaller files, consequently distributed (and even transmitted).

This slide (See page 2) shows psicrometers, which measure the air temperature and humidity. These are radiometers, that measure incoming and reflected solar radiation, and the net radiometer (that measures the net radiation). Together with the solar radiometers, the PAR or photosynthetic active radiation (PAR radiometers) are also used. They measure the visible band of the solar radiation, where some specific wavelengths are responsible for the photosynthesis, very generally speaking.

In this slide (See page 3) sensors are shown to measure the soil moisture. These sensors, similar to the weather station and the eddy system, are electronic and automatically monitored. They are known as reflectometers, and work on the principle that electromagnetic waves, transmitted along its wave guides, change the velocity in response to the soil moisture condition. These sensors are available commercially, from a number of dealers. These sensors, when installed along vertical profiles, can identify the different zones of soil moisture root extraction. It is an important variable, correlated to the diel cycle of evapotranspiration, and with the seasonal patterns of the CO2 flux and evapotranspiration, for a number of ecosystems. Together with the reflectometers, soil temperature sensors and soil heat flux plates are also monitored to estimate the exchanges of heat in the soil.

This is an example of a micrometeorological tower (See page 4). It was first installed over a sugar cane plantation, in southeast Brasil, in 1996. At the top there is an eddy covariance system, profiles of wind and temperature, and a weather station. The wind profiles can be used to estimate the surface roughness, and the temperature profiles to estimate the fluxes using other methods, as for instance the Bowen ratio method (that i will only mention meanwhile). The roughness is variable along time, as the sugar cane height and density changes along the year in accordance to its phenology. This is a scaffolding tower, where it is easier to install additional instrumentation, and helpful under forest canopies as well to measure leaf photosynthesis using portable gas analysers. Nowadays over this sugar cane site a different concept of platform has been used, with triangle towers for the eddy system, and a smaller scaffolding tower to support the solar panels, the weather station and soil sensors. The eddy system is about 100 m apart of the remaining equipments. Towers with triangle sections are even thinners and prevent turbulence (induced by the structure) more efficiently, besides being cheaper.

These slides (See page 5) show three eddy covariance systems operating together, over the sugar cane site, for a few weeks. They had different regarding sensors type. Always when possible, when assembling a new system for field monitoring, it is desirable to test it against other systems previously installed and already verified.

This slide (See page 6) show a domeless net radiometer, solar and PAR radiometers, and an example of how they can be installed over a boom, fixed at the platform. Domeless net radiometers require less maintenance than those using domes. Domes often break and need to be replaced every 3 or 4 months.

It is the triangle tower installed at a tropical forest in Amazonia, in Santarém (See page 7) (km 83 site of Tapajós National Forest), which is part of the LBA project i have mentioned before. This tower is 66 m height, where at several levels there are air inlets for sampling. These samples are pumped to an infra-red gas analyser, at the base of the towers, and the CO2 concentration is measured. This strategy provides the evaluation of CO2 vertical profiles every 10 minutes, when the storage is estimated, and the variation of storage estimated at every 30 min, which is approximately the non turbulent flux, very useful at night for the estimation of the net ecosystem exchange of CO2.

Now we see in the illustration the sonic (See page 8) (or ultra-sonic) anemometer, a basic sensor for the eddy covariance system. It operates using the principle of Doppler effect. The tridimensional anemometers have three pairs of transducers. These transducers emit sound pulses, and are also receivers. Along an axis, where a pair of transducers are aligned, it is possible to measure the sound speed at high frequencies (say 10 measurements per second, or 10 Hz), and check how much it was increased or decreased by the wind speed. Consequently the wind speed is estimated by subtraction.

With three orthogonal axis, the 3-dimensional wind speed is easily decomposed, and the horizontal (u and v) and vertical (w) wind speed are calculated. As the sound speed in the air depends on the temperature (in a mathematical relationships proportional to the square root of the temperature), air temperature is also measured at the same 10 Hz frequency. It means the sonic anemometer is also a thermometer.

We will mention about the infra-red gas analysers, usually called by the acronym of IRGAs.

In this slide (See page 8) we see an open-path gas analyser. The CO2 and H20 concentration in the air are measured along the optical path, in its head fixed near the sonic anemometer. It is adviced to be installed along a slope to prevent dew formation and store water from precipitation over the optical cell. As well, the closed-path IRGAs (See page 9) can also be used to operate in the eddy covariance system (besides the profiler, as mentioned before). There is an air inlet, shown in this slide, near the sonic anemometer, where air is pumped to a closed chamber inside the IRGA, and the concentrations are measured. In this tower both concepts were used, however it is not strictly necessary for a eddy covariance system.

Differently from the weather station and soil sensors, the sonic anemometer and the IRGAs are much more expensive, they both are expensive as US$ 25 to 30 thousand. This is also why these systems are used for specific monitoring, usually research, and can not be easily implemented in networks. They also request more equipment for data collection, electronic control and sensor calibration. It all adds up to the whole system's cost.

It is also viable to separate the soil respiration component from the total CO2 flux measured at the top of the tower (See page 10). Understanding the heterotrophic respiration is important as long as the organic matter's decomposition depends on the temperature and the soil moisture, thus it is dependent on the climate. Soil respiration, also called soil CO2 efflux, can be measured using chambers. They are fixed on the soil surface, and work as dynamical or static chambers. In the dynamical chambers, there is an air inlet and an outlet; the chamber is ventilated from external air using these two paths. The soil respiration inside the chamber tends to increase the ouput concentration, the differential concentration between the input and output is measured by the IRGA, and an estimation of the efflux is provided. The static devices circulate the air inside the chamber through a closed system along the IRGA. Therefore the soil respiration will be increasing the CO2 concentration with time. The variation of CO2 concentration upon the period of measured time is the estimate of the efflux. This example (See page 11) shows measurements using automatic static chambers. Automatic chambers open and close at specified periods of time, usually 30 min or one hour or more. Portable chambers need to be operated manually. In this example hourly averages are shown, along period of days (day of year in the x-axis varies between 1 to 366). We observe soil respiration increases abruptly in the transition period between the dry and wet season.

This other picture shows a portable chamber. Using this approach, the next example of graph shows the soil respiration measurements over a woodland savanna (Cerrado) in southeast Brazil (See page 12). Using portable chambers constrain the frequency of measurements. In this case collections were made once a week. The pattern shows remarkably the seasonal pattern of soil respiration, with minima in the dry season and maxima in the wet season. The samples (See page 13-14) were collected at each week nearly at the same hour (of the day), what partly helped the whole lot of measurements to be comparable year round. This approach also provided a set of soil respiration data in good correlation with soil temperature and soil moisture, as seen in next slide. This correlation is physically sound, as those two variables control the plant metabolism and organic matter decomposition. It however depends on the ecosystem type, the site location and the climate variability. For instance, it is not trivial to find a good correlation (using sampling data) between soil respiration and soil temperature in the tropical forest, as the amplitude of temperatures (difference between maximum and minimum) is typically small on the seasonal basis.

The correlation with soil moisture is expected to happen. Soil respiration is limited by small soil moisture, and increases up to an optimal soil moisture – for large soil moisture it is again limited, given the air pore space in the soil is filled with water, and the gas emission can be reduced. At high and middle latitudes, where the variation of temperature is large, it is often found an exponential adjustment between soil respiration and soil temperature. Examples of these mathematical models are shown in next slide – they present linear and exponential dependences, and combinations between these two adjustments. These correlations help modelers to calibrate simple mathematical equations of soil respiration, dependent on soil temperature and moisture, for prediction and estimation of carbon balance when there are not measurements.

(Presentation Instrumentation part II)

Next slides (See page 2) we will see how a micrometeorologial tower, as an instrumental platform, can be designed. This tower was implemented in the region of Bananal Island, Central Brazil, over a seasonally flooded savanna site. In this region, surrounded by Araguaia river, the floods reach about 2 to 3 m height during 3 to 4 months in the year. This is an ecotone area, where there is a vast biodiversity, today threatened by farmer's occupation, mostly as croplands and pastures.

In this biome the trees reach about 20 m height, and a hut located at the middle of the tower is necessary to protect the power supply, a set of DC batteries recharged by solar pannels. In remote areas it is nearly impossible to reach AC power, thus it is an important step to design the power supply system to provide energy during all the year for the whole set of automatic instruments.

The photos on the right show the cabinets with CPUs of high frequency instrumentation (sonic anemometer and IRGA) and the datalogger. In this case the anemometer and IRGA sensors are located at 40 m height, and the cabinet fixed at a few meters below. Also, the other photo shows a second cabinet, with a datalogger and IRGA, in the middle of the tower. This latter set collects the canopy CO2 and temperature profile, and soil variables of temperature and moisture.

An important point about logistics: the site can visited on a monthly basis. Strictly, if there is data transmission by satellite to a reception station, there is no need to visit the site for data collection. However, maintenance is often necessary, as well as other ancillary measurements that are not automatic (for example dendrometry, litterfall, soil respiration, other parcel studies as mortality and recruitment, between others). To run the sites on a long term, cooperation with local institutions is encouraged. This cooperation promotes capacity building for local human resources.

The next slide (See page 3) shows an example of the CO2 profile's geometry. This is a 55.5 m tower of LBA Project, in Caxiuanã city, state of Pará, with several levels where CO2 concentration is measured for the purpose of estimating the storage term correction. Typically, near the ground, the CO2 vertical gradient is larger, thus it is advised that the spacing between levels is shorter at the bottom levels.

This picture (See page 4) shows the solar panels used for the batteries recharge. An eddy covariance system powered by solar energy, with a CO2 profile, today requires a solar pannel capacity of about 800 W for continuous operation. It is important to install the panels to optimize the position of solar height angle. This position varies year round, therefore the panel's system must change the geometry.

Next slide (See page 5) shows the example of a device for CO2 profile, over a surface that may flood. It is set over a buoy, with fixed levels of sampling above the buoy's surface. The CO2 sample goes into filter inlets. At the tower we see a profile of thermocouples: they measure the air temperature when the surface is dry, and once it floods, it will measure the temperature profile below the water.

Running a flux tower over agricultural lands can be more challenging than working over a natural ecosystem. This is an example of a tower over a sugar cane plantation (See page 6), in southeast Brazil, during the event to burn the dry leaves. This management using fire is still employed over more than half of the planted area in Brasil, and is developed right previous to the harvest. Generally, over agricultural lands, man made control over the ecosystem alters the surface balances of energy and CO2. Using machines for plowing, herbicides, irrigation, between others activities, changes drastically the surface characteristics, and influences on the fluxes. These transient disturbances need to be taken into account in the long term balances, as they are part of the whole cycle of agroecosystems.

The energy balance

(Presentation The surface energy and radiation Balances. The energy balance closure)

In this topic we will see examples of the turbulent fluxes measured with a flux tower. These fluxes are more usually estimated as the sensible heat flux, H, the latent heat flux or evapotranspiration, LE, the CO2 flux, Fc, and the momentum flux, expressed with the dependence of the friction velocity, u* (See page 2). All the fluxes depend, as said before, of covariances between the vertical wind speed, w, and a scalar expressing the variable exchanged in the turbulent transfer.

The example (See page 3) shows the entire set of measurements (of 30 min averages) of net radiation, Rn, the sensible heat and latent heat flux, measured over a tropical forest in Amazonia. The black and red solid lines represent the mean diel cycle average over the wet and dry season, respectively. It is seen, first, that the graph shows days of much and few solar radiation. The net radiation graph expresses that the red line (the dry season) has less cloud cover, and the black line (the wet season) more cloud cover. Near the equator the differences of height solar angle are small year round, thus is the cloud cover that controls most of the available energy. This is why in Amazonia during the wet season (December to June) the temperature is a little smaller (than in the dry season), and local people refer it as the winter. The dry season (July to November) on the other hand experiences higher temperatures (giving more solar radiation is available), and they call it as the summer, that are opposite to what it is called as the astronomical seasons of year.

The net radiation and the sensible heat are usually negative at night. This is expected, as the surface looses net infra-red thermal energy during the nighttime (thus Rn is negative) and the air is cooling (thus H is negative), what can be detected by the measurement devices, as shown in the graphs.

Average evapotranspiration peaks at 400 W/m2, not much lower than the peak of about 500 W/m2 of net radiation, and much larger than the sensible heat peak at 100 W/m2.

Absolute values can be as double as the average, for all the three variables. This simple comparison expresses how evapotranspiration prevails over the sensible heat in the energy balance over a tropical forest. The average Bowen ratio, the ration of sensible heat flux over latent heat flux, is about 0.17 year round.

It means that 1/0.17, or about 6, is how much larger the evapotranspiration is proportionally to the sensible heat at this ecosystem. It has not been found, using flux towers, that the tropical forests are stressed during the dry season. In these circumstances, the deep root system seems are capable to extract water from deep levels, possibly deeper than 10 m, and keep the transpiration at high rates.

Next slide (See page 4) shows the mean Bowen ratio diel cycle over the tropical forest, between 6 and 18 h local time. Despite the average is equal to 0.17 on the long term, there is a diurnal cycle well define, where maximum Bowen ratio, of about 0.3, happens during the morning. At this time the stomata are not completely opened, a condition that will happen over the next hours, thus decreasing the Bowen ratio. Having spoken before about the energy balance, that is, under some approximation, (See page 5) Rn. H +LE + G + S we can compare the energy measured with radiometers and flux plates on the left hand of the next equation, and compare with the turbulent fluxes, on the right hand, as Rn - (G + S) . H +LE and compare the two sides of the equation on a plot, seen in the next slide. The perfect comparison between would fit the 1:1 proportion (See page 6). This ideal condition does not happen in nature, even because we are using observational approaches, and the perfect closure of the energy balance would rarely be achieved. In this example the adjusted regression shows a slope of 0.923 in the left plot, and 0.945 in the right plot. The difference between the two plots is that, on the left case, the S term (energy storage in biomass and in the air column) is neglected, as long as it accounted on the right plot. It means the measured turbulent fluxes represent about 92 to 94 % of the available measured energy.

This is concerned as a good closure: in the literature it is observed that the closure varies between 70 and 100%.

The next slide shows the example of the energy closure at a site over sugar cane. In this case the closure is about 89%.

It is useful and necessary to check the energy closure. A low closure can indicate that the turbulent fluxes have not been estimated correctly, or that the fetch is not homogeneous (that is, the surface where the available radiation is measured is different from that where the turbulent fluxes come from), besides many other reasons. Although it does not regard explicitly about the CO2 flux, a good closure will prevent the aforementioned problems on the good estimation of the CO2 flux.

Filters and constraints

As said before, the estimation of the turbulent fluxes, using the eddy covariance method, requires that the turbulent transport integrate the influence of small and fast eddies through the large and slow eddies, in the planetary boundary layer. A mathematical tool to check how these hypothesis are satisfied is called the energy spectrum. The spectrum quantifies how much energy is involved at each band of energy, that is, how much energy the smaller frequencies (slow eddies) and the higher frequencies (fast eddies) respond to the total energy (or variance) of the estimated flux. It is also proved that the vertical flux of a scalar, expressed as the covariance between w and the scalar, is equal to the sum of all energy expressed in the co-spectrum between these two variables, that is, the sum of the energy associated to the entire range of frequencies. The co-spectrum is simply the cross covariance between the two variables.

For instance, the sensible heat flux, H, is expressed mathematically as the covariance between w and temperature è, that is equal to the integral (or sum) of the co-spectrum (between w and è) over all frequencies. The co-spectrum between w and è is shown in next slide (See page 9) (a figure of Kaimal and Finnigan's book, Chapter 2). In the x-axis, the frequencies (f, in Hz) are transformed to dimensionless frequency n. Several co-spectra are shown, varying the stability condition of the atmosphere, as expressed by a number of z/L values (z/L is called the stability parameter). Taking z/L = 0, for instance, the co-spectrum shows small energy for frequencies near 0.01, is maximum at frequency of 0.1, and then decreases towards the higher frequencies (> 0.1).

Theoretical co-spectra are useful to compare with measured co-spectra. It is possible that observations underestimate the low or the high frequencies, for a number of reasons, and it can be detected comparing to the theory. In this case, under some limitation, it is possible to correct the observed co-spectra, and consequently correct the flux.

As seen in the co-spectrum, the frequencies greater than n=10 are negligible to contribute to the fluxes. Strictly, the frequencies contributing to the co-spectra depend on the wind speed, height above the surface and surface roughness. For wind speed of about 10 m/s, measured at 10 m height, it is recommended that 5 Hz is necessary, or, on the safe side of it, have 10 to 20 Hz as the frequency required. As the infra-red gas analysers usually do not meet these requirements, it is often adviced to make corrections on the spectra.

Other uncertainty on the flux calculation arises from the period of time where the covariance is averaged. It is typically reported as 30 min fluxes. However, under some circumstances that are site-specific, the lower frequencies can be underestimated. Increasing the period of integration, it has been noticed at some cases that the energy closure improves. In next slide, a substantial improvement, near 100 %, appears at averaging period of about 100 min. This case is for instance calculated at Manaus forest.

Other issues:

- sonic anemometers are supposed to measure the turbulence and estimate the flux correctly at a minimum height of about 1 m, over flat surfaces; over rough surfaces it is recommended that a minimum height equal to 3 m is used, above the average canopy height; at tall dense forests, where the roughness sub-layer is thick, it is recommended that the sonic position is set much higher than the 3 m beyond the canopy height. Over towers in Amazonia it was set at about one third of canopy height beyond that.
- fix the anemometer facing the prevailing wind direction, in order to prevent the flow reaching the horizontal mast where it is fixed; in case of anemometers using vertical masts, the problem is minimized, but there is always flow distortion by the Sonics structure;
- Sample at 5 Hz or possibly higher frequency.

These recommendations are not rules strictly; on the other hand they are points to be regarded when designing the instrument platform and the observational approach.

Diel cycle, seasonal variability and annual sum

The eddy covariance technique has the advantage to estimate the diel cycle variability of the surface fluxes, and thus discriminate the controls like biome (site), climate and other surface controls. For example, next slide (See page 12) shows measurements over three different forest sites in Amazonia, and a pastureland – the measurements are shown as average diel cycle, on the dry (above) and wet (below) season. Different collors refer to different sites: black is for Manaus, red is for Jarú (Rondonia state) and green is for Caxiuana forest (Pará), while the yellow line is for the pastureland site in Rondonia (Fazenda NS). It appears clearly how the nighttime values are substantially different among the sites: during the night there is constant emission (thus the values are positive, ranging between zero and 8 μmolCO2 m-2s-1). During the dry season the pastureland is where the respiration is lower, and this same comparison appears on the wet season. It is also remarkable that the respiration rates during nighttime are higher during the wet season.

During daytime, the negative peaks indicate CO2 assimilation by the ecosystem: it is exactly the subtraction of the soil respiration (autotropic and heterotrophic) minus the net CO2 assimilation (photosynthesis minus above ground plant respiration) – consequently the more negative the values, the higher the CO2 uptake over the surface. In this case, comparing the forests, the red line (Jarú forest) appears absorbing more carbon than the other sites (of about -22 μmol CO2 m-2 s-1 in the wet season), while in Caxiuana (green light) the absorption is smaller in the dry season. Comparing all sites, the pastureland is where the absorption is smaller during daytime, for both seasons.

Generally, the eddy covariance technique represents fairly well the diel cycle and the seasonal variability. Errors arising from sampling and calibration are of about 5%, while errors from time-lag between velocity and the scalar are less than 2%. (See page 13)

It has been said before that the estimated ecosystem CO2 flux is the sum of a turbulent flux plus a non-turbulent flux, and that the non-turbulent term arises from the CO2 stored in the surface boundary layer during weak turbulent conditions. (See page 14) Keeping that in mind, a few recommendations are listed:

- design the observational system over a flat and uniform terrain
- measure the CO2 profile
- try to quantify the several components of the C cycle, using alternative measurements rather than the flux tower: over a land terrestrial ecosystem, measurements of soil respiration, sap flow, dendrometry, litterfall, are between those often reported.
- Gaps in the data, and data evolving much uncertainty, can be replaced for specific purposes, for instance the annual sum. This topic will be discussed furthermore.

Patterns of CO2 within the canopy

The next slide (See page 16) gives a nice example of how CO2 is stored under the canopy, and the importance to estimate the non-turbulent flux. This case was observed over a tropical forest in Caxiuana, Brasil (courtesy Y. Malhi), and shows the CO2 flux and concentration changing during the dawn transition, from 5:45 to 9:55 h (local time). Generally, the CO2 concentrations (bottom graph) are higher along the canopy before dawn, and start to decrease along the column after 6:05 h, resulting partly from the onset of canopy photosynthetic activity. However, CO2 flux is positive until 7:55 (emission), when it becomes negative (absorption). Right before 7:55 h, there is a pulse of CO2 emission, concurrent with a increase in the mechanical turbulence (sigma-w, the variance of the vertical wind speed, shown in the blue line). Thus there is a double mechanism of photosynthesis and mechanical turbulence controlling the CO2 flux measured at the top of the tower. Again, at 9:45 it is possible to see another pulse in CO2 concentration, and a little later, at 9:45 h, a positive CO2 flux arising from that pulse.

The next slide (See page 17), showing the CO2 concentration between the ground surface up to 70 m within a dense forest (in Santarem, km83 site), is the average CO2 concentration for several months.

It is clear how a strong gradient is defined up to 40 m, and a substantial storage appears during all the night, since 18 h (local time) through 9 h in the next morning. The CO2 storage within the canopy occurs due to the thermal stratification (that is, there is not mixing arising from thermodynamic static instability in the air column), and also due to lack of mechanical mixing, as wind shearing stress. In next slide (See page 18), also from data over the tropical forest in Santarem, we figure out how mechanical turbulence, as expressed by the pattern of the friction speed u* measured at the top canopy, changes during the diel cycle: it increases during daytime, resulted from the local circulations (forced by solar radiation), and decreases during nighttime, what gives the idea of calm nights, on average conditions.

The annual sum of the CO2 fluxes provides the accumulated amount of carbon that is absorbed or emitted from the ecosystem. It means, respectively, that during the period of the sum, the surface was a sink or a source of CO2. The use of eddy covariance data to estimate the annual sum has been reported over many sites worldwide, and compared to conventional biometric measurements. As explained previously, during nighttime it is possible that the weak turbulent conditions may not provide realistic absolute values. Even deviations as small as 0.5 μmol CO2 m-2 s-1, when summed over a period of a year, accumulate several hundreds kg C, thus biasing the result to indicate a sink (most of times) or source. It is a complex issue to sort out, depends on site-specific conditions. If the observational conditions were ideal, there should not be, in theory, no dependence between the ecosystem CO2 flux and the turbulence (for instance, expressed by the u* variable). In cases where the dependence is detected, it has been suggested that there is a threshold (minimum u*) indicating what data needs to be replaced (flux data associated to u* below the threshold) for the purposes of annual sum. There is not consensus about how the replacement must be done (See page 19): it is suggested that nighttime fluxes, one day before or after the event, associated to u* above the threshold, replace the data; other suggestions indicate the use of models that calculate the autotrophic and heterotrophic respiration, validated by eddy covariance and other data, to replace those nighttime data.

Using not the threshold for the annual sum can make a dramatic effect, as seen in next slide. This picture (See page 20) shows the accumulated ecosystem CO2 flux, in ton C ha-1, over the time, for data collected in Santarém km 83 tropical forest. When only the measured data is used, it ends up an annual sink of about –4 ton C ha-1 (blue line). However, when data are restricted to those with the threshold u* = 0.1 ms-1, the sink is reduced to –1 ton C ha-1. For this site, a threshold value equal to 0.2 ms-1 indicated no dependence between the flux and u*, where in the annual sum appeared as nearly zero (next slide, shown in the brown line). The next slide (See page 21-22) shows how the threshold was selected: the brown line (NEE or net ecosystem exchange) apparently increases with u* up to about 0.2 ms-1, from where on it does not show dependence.

With the new information, in synthesize a few topics, give some recommendations (See page 23-24), about site implementation, observational strategy, and data analysis, that might be helpful to remind important issues on using the eddy covariance data for the purpose of studying the carbon cycle over terrestrial land ecosystems:

a. Problems may exist with the ecosystem CO2 flux estimation:

- they are however site-specific, and might be prevented as much as possible (based on previous discussion);

b. Measured turbulent fluxes can underestimate the available energy, and several reasons (that should be minimized in the design implementation), can be:

- advection from heterogeneous areas outside the tower fetch;
- different footprints viewed by the tower and the radiation sensors, respectively;
- wind blowing from an undesirable wind sector (can be related to sonic position);
- flux calculation (period of time, underestimate some frequencies)

c. Recommendations about tower implementation:

- choose a platform that distorts the air flow as less as possible;

- place it on a position compatible with the eddy covariance hypothesis;
- height: maximum height compatible with the desired fetch, but constrained to minimum height of sonic position;
- ground all systems.

d. Sonic and IRGA

- position compatible with prevailing wind direction
- less disturbed as possible by tower;
- IRGA calibration, if closed path (automatic every 6h gives extreme accuracy; if every 15 days give moderate accuracy, but still viable for flux calculation since drifts are prevented); if open path (automatic calibration is less viable, 15 days viable if no other conditions discalibrate the device);
- Tend to be a place for birds watching the landscape (prevent it using non-toxic repellents), or others masts at higher levels. e. about site selection
- Hypothesis of homogeneous surface
- When working over agricultural lands, take notes and quantify the effects of irrigation, fertilization, burning, tillage, herbicides
- Keep good communication with owners;
- regional representativy: Is the site you're working with regionally representative ? Varieties of vegetation, soil type, climate and harvest management are representative ?

Processes of CO2 emission

(Presentation Using other methods to account other processes of CO2 emission)

Biometric approaches to account the carbon balance over terrestrial ecosystems have been used much before than the eddy covariance technique. They can be complementary, and comparable, since several hypothesis are accomplished. The biometric approach uses the concept of C stocks, and its variation on the long term – a long period of time can mean few weeks up to several years, depending on which stock we concern. The eddy covariance method works with nearly-instantaneous fluxes, on the scale of an hour. The biometric method works with long term fluxes.

If I add (to the conventional biometric method used in forestry) other ways to measure processes of CO2 input and output to the ecosystem, I could simply call it an alternative approach to the eddy covariance technique, and simply for the sake of making them comparable. The comparison brings benefits to understanding the CO2 cycle, and should be encouraged to be made over a tower flux site whenever as possible.

Put it simply, the temporal variation of C over a parcel is the sum of the variation from several terms, namely

$$\frac{\Delta C}{\Delta t} \cong \Delta C_b + \Delta(R_e - M_0 - N_c) + \Delta C_0 + \Delta C_w$$

The C allocation in the trunks, stems and roots are assessed by dendrometry and halometric studies (Cb). The variation of trunk's diameter at breast height (DBH), tree height (h) and crown diameters, as well as the prospection in destructive parcels (to measure below-ground biomass), are necessary to calibrate halometric equations that convert variations of DBH and h into C stock.

Other process of C exchange is in the soil, as organic carbon accumulation (Co). This processes is slow and difficult to measure over short periods of time, although can be significant over long periods of time. The recruitment rate refer to new species emerging over the parcel (that soon will be focused on a dendrometric approach), as long as the mortality rate refer to the species leaving the parcels (or leaving the dendrometric approach) (Re-Mo-Nc). The variation of C associated to dead species will move to another way of evaluation, called biomass decomposition. There are methods addressed to assess several levels of decomposed biomass in the field, and associated these levels to specific rates of C loss.

And complementing, as said before, soil respiration and litterfall are transient process that exchange C on a fast basis, and helpful to understand the C cycle over a terrestrial ecosystem.

This example (next slide) (See page 3) shows the quantification of these process over a tropical forest in Santarem km67, compared to the similar measurements taken in a boreal forest, the Harvard forest site, in Massassuchets, USA. Although the net fluxes of C over the sites look similar, the errors are larger over the tropical forest (as seen in the deviation over the bar). It happens partly because the process of the net flux have larger magnitude over the tropical forest: growth and recruitment account about 4 Mg C ha-1 yr-1 in the tropical forest, compared to less than 2 Mg C ha-1 yr-1 in the boreal forest; as well, mortality rate is approximately –2.5 Mg C ha-1 yr-1 in the tropical forest, compared to less than 0.5 Mg C ha-1 yr-1 in the boreal forest. In this case, the monitored parcel shows the net flux or Net Primary

Productivity (NPP) of about 1.0 Mg C ha-1 yr-1 in the tropical forest compared to about 0.7 Mg C ha-1 yr-1 in the boreal forest, therefore they have similar order of magnitude.

While the aforementioned processes of C allocation are feasible to take place in land terrestrial ecosystem, the C cycle becomes more complex when the hydrology controls the inputs and outputs (See page 4) of mass and gases to the parcel or control area. Exchanges of C as of dissolved organic carbon (Doc) and dissolved inorganic carbon (DIC) are controlled by river discharge and biogeochemical processes evolving on the river's tributaries. To measure these processes it is necessary to account on the full variability of river discharge, and measure the concentrations of Doc and DIC in the field (See page 5). It is called the term Cw in the previous equation. Another process of C emission refers to CO2 outgassing over aquatic systems.

Measurements of CO2 concentration down the water, near the surface, called pCO2, if larger than the CO2 concentration in the air right above the surface, indicate there is a next flux going out of the water. As seen in this slide (See page 6), the CO2 flux depends on the gradient between the surface (water) and the atmospheric equilibrium, and on a diffusive coefficient, that depends on the atmospheric stability, more remarkably the wind. The measurements are taken using domes to collect CO2 concentrations in the air, and syringes to extract CO2 from the water. The samples are taken to laboratories where chromatographers are used to analyze the gases.

Ecosystems like lakes, flooded areas, are in principle controlled by these mechanisms. The example i show in the next slide is an estimated carried out for the Amazon basin, using a number of samples, collected along many years in the basin's rivers (published in Nature 2002). The CO2 evasion appears more substantial on the tributaries, and less in the streams and the main channel of the basin. As well, the transport peaks concurrently with the peak of river discharge, usually near April and May. The maximum rates of CO2 evasion are as much as 30 Tg C per month. When integrated over the entire basin, an estimated of about 0.5 Gton C per year was estimated in the study, therefore a very substantial amount associated to fast C cycle.

Tower fluxes over ecosystems in South America (forest, savannah and crops) (See presentation Tower fluxes over ecosystems in South America).

To introduce this topic, it is useful to see a paper of synthesis about several observational sites (using eddy covariance) in the Northern hemisphere (Valentini et al. 2000, published in Nature). The picture in the slide shows (See page 2) proportionality between the Net Ecosystem Exchange (NEE) and the latitude, that is, the further the site is northward, the lower is the net uptake. It means that the differential heating by solar radiation influences the carbon uptake to a large extent. In the next slide (See page 3), a similar approach focus on only a few types of forests, in the northern hemisphere, and also shows that the variability between seasonal radiation and seasonal uptake is mostly linear. The information about these graphs is however limited to the latitudes between 40o and 65o N. There is not information about the tropical ecosystems, where there is a different equilibrium between temperature, rainfall and ecosystem, than that over middle and high latitudes.

This slide shows (See page 4) two latitudes in the southern hemisphere where there is a tropical forest site, at 3o S, a woodland savanna (Cerrado) and a sugar cane site, at 21o S. It is about these three ecosystems we will discuss next.

The woodland savanna (Cerrado)

The first site is the woodland savannah, also called the Cerrado vegetation in Brazil. As seen in the slide (See page 6), it is located in the northern state of São Paulo, Southeast Brasil. The reserve has about 1100 ha, and is called Gleba Pé de Gigante (as seen in the aerial photograph). The vegetation is composed by an herbaceous layer and a tree layer, with trees from 5 to 15 m height. Sparse trees can reach up to 20 m height. A micrometeorological tower with 22 m (in the photo) is where the turbulent fluxes and climate are measured.

A particularity about the Cerrado vegetation is the strong contrast between the seasons. These couple of photos (See page 7) in the side show the tower (from below) during the wet season (in the left) and during the dry season. The leaves senesce strongly, although not the total vegetation loose their leaves simultaneously. These four graphs in next slide (See page 8) show one year of measurements (in 2001), as (30 min averages of) precipitation (mm/day, in dark bars), solar irradiance (W/m2, in red), evapotranspiration (in blue), and CO2 flux (in green). Remarkably the dry season, between May and August, is marked by reduced solar radiation, less precipitation, and consequently the also evapotranspiration reduces substantially. The CO2 flux varies between –30 and +10 μmol CO2 m-2 s-1 during the wet season, thus suggesting a net negative CO2 flux (that is, a sink); the diurnal amplitude during the dry season is reduced, to vary between –5 and +5 μmol CO2 m-2 s-1.

Besides solar radiation and precipitation controlling the fluxes, the soil moisture appears as one of the most influencing factors controlling the fluxes. In this site the soil is quartz sand, and the soil moisture pattern along the year (seen in next slide) responds quickly to the variation of precipitation. The soil keeps very dry during the entire of the dry season, and also responds quickly to sparse events of precipitation during the dry season (as for example in May). The slide (See page 9) shows data during 2001 and 2002 for soil moisture, measured with frequency domain reflectometers displaced along a 2,5 m vertical profile.

The evapotranspiration measured over the Cerrado (See page 10) on the diel cycle (next slide) shows how the maxima reach about 400 W/m2 during the wet months, and reduce to 250 W/m2 during the dry months. On a seasonal perspective, it means the daily total vary between 6 mm/day to 1 mm/day (bottom graph in the slide). It is also remarkable how the evapotranspiration varies slower during the wet to dry season transition (April to June), than during the dry to wet transition (September to December). This pattern will be coherent with the variation in the surface albedo, consequently a response of the vegetation status of green leaf area index.

Having shown and discussed it before, the measurements of soil respiration (See page 11) (next slide) vary between 1.5 to 8 μmol CO2 m-2 s-1, with minimum and maximum in the dry and wet season, therefore concurrent with the CO2 flux measured at the top of the tower. These data were collected using portable chambers, and it is also suggested (have discussed before) the correlation between the CO2 efflux with soil temperature and soil moisture, giving the large dependency with these physical variables.

The diel cycle of the measured CO2 flux also vary substantially along the year. As seen in the slide (See page 12), during the wet months, 30 min averages vary from –30 (during daytime) to + 10 μmol CO2 m-2 s-1 (during nighttime). During the driest month, in August, these diurnal amplitude varied between – 10 to + 10 (during nighttime). It shows how during the late dry season there are active species making photosynthesis, thus compensation a number of other species that lost the leaves and are not active temporarily. This indication of active photosynthetic capacity concurs with small but still substantial evapotranspiration during the late dry spell. When the data are splitted into diurnal and nocturnal, it is possible to see how much carbon is lost (as daily averages): the green bars show the daytime uptake, varying between –60 kg C/ha/day, to zero in the late dry season. As well, during the night, the emissions vary from maxima of +20 kg C/ha/day in the wet season to less than +5 kg C/ha/day in the late dry season.

These days of minimum and maximum ecosystem photosynthetic capacity are exemplified in the next slide (See page 13). For the days 8-9 October 2001, in the late dry season, the CO2 flux appeared systematically positive (green curve in the graph), although the diurnal variation indicated the flux decreased around the noon time, what is possibly the response of a few species making photosynthesis over the tower fetch. The nighttime emissions were variable: these changes depended on the turbulence (u* speed, shown in the grey line). For the days 10-11 April 2001 (See page 14), in the late wet season, the nighttime fluxes were more stable, around 5 μmol CO2 m-2 s-1, and during the day it reached less than –20 μmol CO2 m-2 s-1.

For the purpose of describing the seasonal cycle, gaps in the data were filled using models' prognostics. The SiB2 model (Sellers et al. 1996) was calibrated and used to have a data set with the net ecosystem exchange (NEE), seen in this slide (See page 15). It is possible to see remarkably, in units of kg C/ha/day, how the Cerrado vegetation has a function of source during October to May, whereas during the remaining months (June to September) it is a source of carbon to the atmosphere. The source mode peaks in August, and decreases with the onset of the wet season. Next slide (See page 16) show the annual sum of CO2 flux using observed and modeled data year round. Using raw data, the sum reached about –3.2 ton C/ha/yr, and, similar to what was discussed for the tropical forest, using a threshold of 0.4 m/s, the fluxes changed dramatically and summed about – 0.05 ton C/ha/yr. We believe this threshold was the most appropriate to estimate the annual sum, based on comparisons between the soil respiration using chambers with the eddy covariance data during the night. The sum indicates the ecosystem is neither a sink nor a source, it is possible near the balance during this year. A word about the influence of climate interannual variability over this ecosystem. I pinpoint in the slide (See page 17), the CO2 flux during the 2001 dry season (in black bars) and the 2002 dry season (in green bars). Remarkably, the length of time with positive fluxes appeared larger during 2001 if compared to 2002. In other words, the question arises what would have caused this change ? The answer is partly due to the status of vegetation during these years: the PAR albedo, or the fraction of visible radiation reflected back to the atmosphere, was larger during 2001 (black line in the bottom graph) than during 2002 (red line in the bottom graph). Also in the bottom graph, there were in 2001 a few cold events (as shown by minimum temperature) during the wet to dry season transition, whereas in 2002 these early cold events were not observed – they were observed a little later in the year only. So the effect of the cold fronts, prior to the full leave's senescence, contributed to change the PAR albedo and consequentely change the flux during the late dry season. This effect was also observed in the evapotranspiration (See page 18) (next slide) during the dry season: in 2001 there were smaller daily rates than during 2002.

The sugar cane

(See presentation Agrosystem Sugar cane)

The sugar cane site is, similar to the Cerrado site, located in northern state of São Paulo, Brasil (See page 2). Sugar cane is a ratoon crop, with 5 to 7 annual cycles, and is planted with rows 1.4 m apart. The harvest is annual, mechanical, usually during April to November. This site is over a red latossol, usually fertile and proper for croplands. Along the full cycle during 5 to 7 years, the productivity decreases. Soil is plowed, prepared, and replanted again after this long cycle.

Sugar cane growth appears as a sigmoid curve (shape of Greek letter sigma) along time. In the picture (See page 3) the above-ground biomass is plotted against accumulated solar radiation, what gives a similar pattern.

Northern São Paulo state is the region with the highest production of sugar cane in Brasil. It is used for sugar and fuel-alcohol production. The slide shows (See page 4) a high-resolution image of SPOT satellite, showing a mosaic of plots where sugar cane is planted. Remarkably, the plots show different phenological stages of growth.

The solar albedo, or the fraction coefficient of solar radiation, varies much along the annual cycle. In the slide (See page 5), it is shown to range between 0.20 and 0.25 when the crop is dense and green, and decreases abruptly after the harvest, to about 0.15. In this particular case the soil is darker than the vegetation, and consequently more solar radiation (in the near-infra red band of spectra) is more absorbed when the soil is naked (or the vegetation cover fraction is minimum).

Next slide (See page 6) shows the variation of the energy fluxes over the surface (soil heat flux, G, in green line; sensible heat flux, H, in red line, and latent heat flux or evapotranspiration, LE, in thin black line), all in W/m2, for a site harvested in April. The lines are mean diel cycle, and in May, right after the harvest, the terms H and G are significant and prevail over the energy balance. This situation lasts until July, when the vegetation cover fraction is associated to leaf area index near 1 m2/m2. In October, the energy partition (between H and LE) has changed dramatically the pattern: evapotranspiration already overwhelms the sensible heat – this pattern will tend to be emphasized over the remaining months of the crop growth, until next March.

Next slide (See page 7) the daily average Bowen ratio (ratio of H upon LE) is shown (red circles) along the growth cycle: there is a marked difference between the early crop stages (high ratio), through the stages of denser vegetation (low ratios), and finally an increase during the late stages – this latter pattern can look surprising, but occurs due to the use of herbicides (about one month before the harvest) to accelerate the plant production of sugar.

The CO2 fluxes measured at the tower are shown in the bottom graph (See page 8) (thick black lines). In May, after the harvest, there is prevailing CO2 emission and no evidence of photosynthesis. This evidence appears in July, very tiny. In October not only the daytime amplitude of CO2 increases, but the CO2 uptake around noon reaches about –20 μmol CO2 m-2 s-1. The peak will increase later in January, to about –35 μmol CO2 m-2 s-1. These peaks in ecosystem CO2 absorption are larger than those observed over the Cerrado. This is expected since sugar cane is a C4 plant (compared to the prevailing C3 trees in the Cerrado), where the photosynthetic mechanisms are more efficient and the productivity is larger.

The perspective of seasonal variability shows a dry season from May to September (in 1998), and a period of substantial reduction in evapotranspiration, that is less than 2 mm/day. During the wet season the evapotranspiration vary up to 6 mm/day. The net ecosystem exchange (NEE, in kgC/ha/day) is positive through the early 4 months of growth, then becoming a source over the remaining months. The bottom graph shows the soil respiration, Rs, a estimation of models calibrated with data collected on soil chambers, and the difference between NEE and Rs, an estimate of the net primary productivity (NPP): assuming this calculation, NPP can be as high 150 kg C/ha/day, what shows one of the highest NPP rates observed over a number of crops.

Tropical rain-forest

(See presentation Amazon tropical rain forest)

This site is a tropical forest in Santarém, state of Pará, Brasil, located at about 3o S, 55o W (See page 3). The site monitoring was conducted by the LBA Project, since 1999 – in the implementation – at the Floresta Nacional do Tapajós, a federal reserve of about 6 million ha. A cooperation between the University of California at Irvine and the University of São Paulo was responsible for running the tower from the implementation so far, over a place that was kept in its primitive conditions during one year (Jul 2000-Jul 2001), and then managed with a selective logging. Another two micrometeorological towers were implemented nearby, one over a pristine forest, and a second one over a pastureland (that became cropland afterwards). The Floresta Nacional do Tapajós is at east of Rio Tapajós (as seen in the picture), and the logged-site tower at km83 (See page 4); the pristine forest is at km67. Also, we see the whole reserve is surrounded by roads and farms. The road is a federal highway (Cuiabá-Santarém, BR163), that is paved from Santarém and by about 80 km south.

The tower at km83 is a 66 m triangle Rohn aluminum tower, erected over a small clearing in the pristine forest. The region has about 2100 mm of annual rainfall, and is hot and humid.

There has been an increasing interest on planting soybean in the region. The regional costs (of transport) to trade the soybean are reduced as there is a port in Santarém for exportation.

Therefore the highway is planned to be paved over the next years, and it is expected that the deforestation is going to increase dramatically (See page 5).

Continuous measurements of precipitation and soil moisture (along a 10 m depth) show a nice clue about the root-zone hidrology. The slide shows (See page 6) measurements taken with the frequency domain reflectometers, based on collection of 30 min averages. The dry season happens climatologically between August and November. Severe storms with intensity larger than 50 mm/day is common to happen. The soil is a yellow-clayey latossol, a common soil type in the Central and Eastern Amazonia. This soil has good drainage, low fertility, high porosity, and substantial fraction of clay and silt. During the wet season, from December to July, it is seen in the soil moisture profile responds quickly in the first 30 cm – the red shade near the shallow surface indicate volumetric soil moisture larger than 0.5 m3/m3, that occurs partly by the large macroporosity (in the shallower layer), and by the easy infiltration. During the period of most regular rainfall (between January and April), the whole profile is wetted. After September the profile dries out systematically with time. It is seen how the deeper layers dry on a slower rates (See page 7) (than the surface and middle layers) – it is partly explained by the large concentration of roots between the surface and 5 m. Also it is seen that there is a tendency at the bottom of the profile for continuous drying, even after December – it suggests there is root activity of water extraction below the 10 m depth.

An interesting observation about the root-zone hydrology under the forest is how the surface layers dry out during the daytime and wet up during nighttime. It was observed remarkably for days in the late dry season (1 to 3 December – next slide). For depths at 5 cm, 10 cm, 40 cm the soil moisture diel cycle shows a recharge during the night, while at 60 and 200 cm there is not such effect. The shallow soil water content during rain-free periods decreased during daytime and recovered partially during nighttime, a pattern that is attributed to the nocturnal redistribution of water. The redistribution of soil water can occur either by flow through plant roots, a process referred to as hydraulic lift or flow through the bulk soil. Hydraulic lift occurs when root systems provide a low-resistance bridge between shallow dry soil and deep moist soil. Water flows through roots from moist, deep soil to shallow dry soil at night, resulting in an increase in shallow soil water content. Soil moisture redistribution can also occur by capillary flow through the bulk soil in response to strong vertical gradients in matric potential.

The nocturnal recharge integrated throughout the top 60 cm of soil was 0.3 mm day-1, a rate of recharge equivalent to 10% of the daily evapotranspiration, and may be important for forest function, helping the trees to avoid drought stress by increasing the efficiency with which deep roots extract water. Likewise, redistribution may increase microbial activity in the shallow soil by improving the local moisture status.

The slide shows a general climatology over the site (See page 8). About one-third of the annual precipitation fell from 15 July to 14 December, with the remainder falling from late December to July: There was a tendency for increased precipitation from 13 and 16 LT, as a result of increased convection. The wet season was marked by many consecutive days with moderate rainfall. Solar radiation at the top of atmosphere (Ktop) had two maxima (22 Sep and 22 Mar) and two minima (22 Jun and a secondary minimum on 22 Dec). Incoming solar radiation varied seasonally, reaching a maximum of about 24 MJm-2 day-1 in September and a minimum of 8 to 12 MJm-2 day-1 at the beginning of the wet season.

Seasonal change in cloud cover was the main controller of incident radiation, with solar angle playing a secondary role. The transition from dry to wet season coincided with a marked reduction in incoming radiation. The surface air temperature varied little over the year, a pattern that is typical for the region, that is, the maximum daily temperature was 24 to 32 °C and the minimum was 20 to 25 ºC. The dry season was only 1 to 3 ºC warmer on average than the wet season. The daily maximum and minimum temperatures and the daily temperature range were reduced during the 3 months centered on January, coincident with increased cloudiness. The water vapor content in the air was consistently 17 to 19 g kg-1 , and the daily average water vapor deficit decreased from 7 hPa in the dry season to 2 hPa in the wet season, coincident with the decline in daytime air temperature.

Next slide shows the seasonal patterns of net radiation (See page 9), evapotranspiration and sensible heat flux. Evaporation ranged from 1.5 to 6 mm day-1, with an annual average of 3.45 mm day-1. The annually integrated evaporation was about 1300 mm, or 60% of the observed precipitation. Evaporation and sensible heat flux increased in the dry season and decreased in the wet season, coincident with changes in cloudiness and net radiation. The net radiation was the main controller of day-to-day variation in latent and sensible heat flux, with high turbulent fluxes ºC currying on sunny days. The 24-hour average net radiation was 70 to 180 Wm-2, with an average of 140 Wm-2 in the dry season and 113 Wm-2 in the wet season. The inter- and intra- seasonal patterns of latent and sensible heat flux were similar to the trends in radiation. Evaporation was relatively high (≈ 4 mm day-1) and constant from day to day in the dry season, and low (≈ 3.2 mm day-1) and variable in the wet season.

Likewise, net radiation had a similar pattern. The 24-hour average heat flux was 21 Wm-2 in the dry season and 16 Wm-2 in the wet season.

But net radiation was not the only controller of daily evaporation. The next slide (See page 10) shows the evaporative fraction. It is calculated as the ratio of latent heat flux to net radiation. It appears to vary seasonally, reaching a minimum of 65 to 75% from May to October and a maximum of 75 to 100% from December to March. Likewise, the Bowen ratio varied seasonally, with a minimum coinciding with the maximum evaporative fraction. The increase in evaporative fraction from December to March cannot be explained based on a seasonal change in potential evaporation. The seasonal shift in energy partitioning may be partially related to the frequency of precipitation. Frequent, moderate to light intensity storms increase the overall fraction of precipitation retained on plant surfaces. This intercepted precipitation subsequently evaporates rapidly, since there is no stomatal limitation, resulting in higher overall rates of evaporation. In contrast, heavy, infrequent storms increase the fraction of precipitation that infiltrates into soil. The seasonal pattern of energy exchange was probably also controlled in part by changes in tree physiology. The decline in evaporative fraction in

May preceded the onset of the dry season, and the increase in evaporative fraction in November preceded the end of the dry season, indicating that the seasonal pattern of evaporative fraction cannot be explained entirely by changes in meteorology.

The seasonal patterns of evaporative fraction, Bowen ratio are similar to the seasonal pattern of daytime CO2 uptake described for the site (next slide, shown in a paper by Goulden et al. 2003 – Ecological Applications). They found that CO2 uptake at a given light intensity was greater from October to April than from May to September, a pattern attributed to a seasonal increase in LAI. It is likely that these observations are related, and that the October to April increases in canopy photosynthesis (See page 12), canopy conductance and evaporative fraction, and decrease in Bowen ratio, are mechanistically linked through seasonal changes in LAI.

The next slide (See page 14) will show measurements of biometric and eddy covariance data taken at the two towers at the Floresta Nacional do Tapajós, the km83 and the km67. It was shown in a recent paper published in Science by Saleska et al. (2003), that describes an objective synthesis of CO2 assimilation and emission processes in the eastern Amazonia rain forest. It was found that both soil respiration (Rtot) and gross ecosystem production (assessed by dendrometry) increase in the wet season. It was not obvious before that soil respiration had such patterns – the larger temperatures in the dry season could, in theory, also increase soil respiration, although it was not observed.

When looking over three years of measurements of the total CO2 flux measured at the top of the tower, there NEE (net ecosystem exchange) is more negative during the dry season (thus absorbing more CO2) and more positive during the wet season, relatively. So a different phasis of NEE was observed as compared to the GPP and soil respiration. The annual sum indicated that, year after year, there is a positive sign in CO2 flux, thus indicating there is emission on a yearly basis. It is also a little surprising, since other sites of LBA indicate a sink. That reveals how large is the spatial variability over the tropical forest, that is often concerned as homogeneous. It is explained that some places can be regenerating from previous natural disturbances that cause mortality (for instance during the El Niño events, that are associated to long dry spells). It is not known so far if the entire Amazon basin is a sink or a source – that is one of the issues that the LBA project will be aiming over the next years.

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