Carbon fluxes and soil moisture data assimilation

Tested at Siberian measuring locations

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Data contributed by TCOS-Siberia, GAME, Takeshi Ohta

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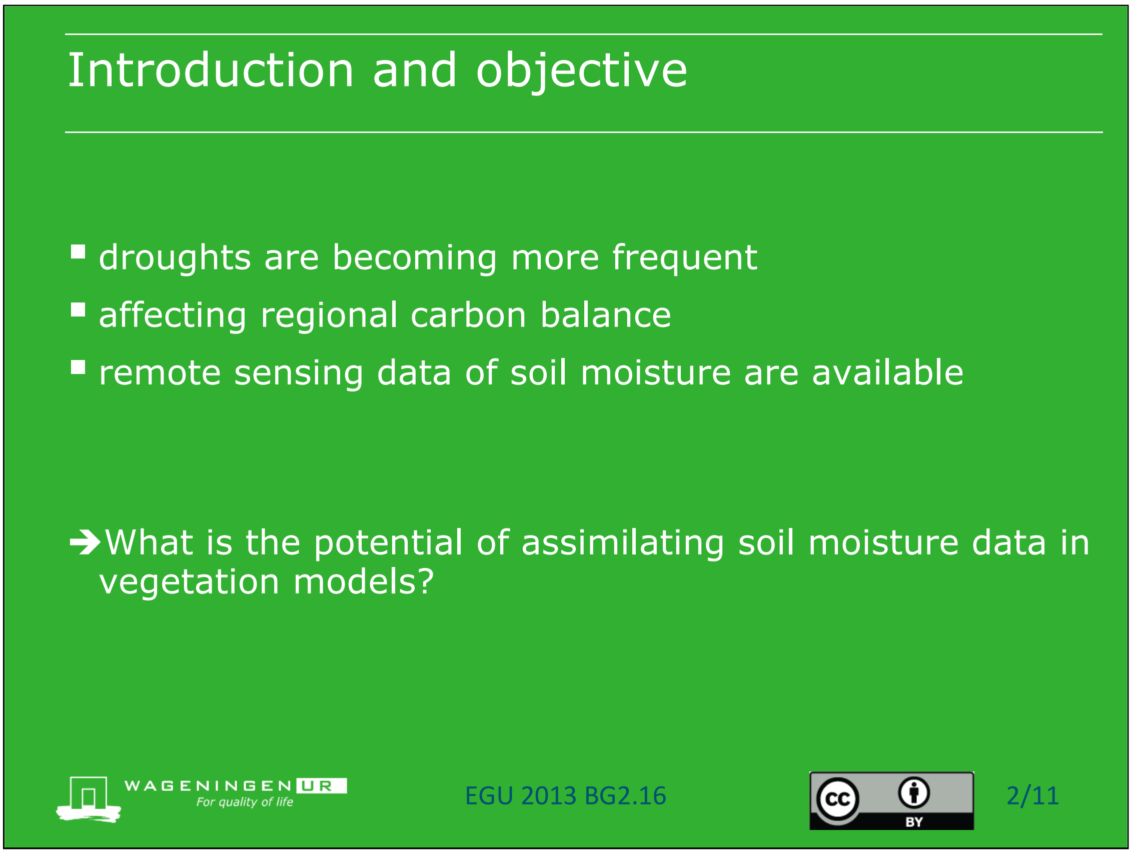
Title slide



- droughts are expected to become more frequent in the coming decades. Climate change does not only cause gradual changes, but also intermittent changes.

- droughts typically develop on a regional scale (100-1000km). As a result droughts significantly affect vegetation growth and decay on a continental scale, which is often measurable globally. Because droughts affect photosynthesis as well as respiration (decaying organic matter), droughts cause anomalies in the CO_2 uptake rate of vegetation.

- As background information: vegetation on land has removed about 30% of the anthropogenically emitted CO_2, from fossil fuel combustion and forest conversion, over the last few decades. As a result the CO_2 concentration in the atmosphere has not increased as fast as would be expected based on the emission rates alone. The vegetation therefore plays an important role in the global carbon cycle. However, it is uncertain if the vegetation will be able to continue to play this role if droughts affect the CO_2 uptake capacity.

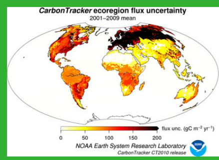
- remote sensing data of (top) soil moisture is now becoming available, and this could provide important information about temporal and spatial patterns in soil moisture in vegetation models. More about that on the next slide.

- The objective of my study is to investigate what the potential is of assimilating remote sensing derived soil moisture in vegetation models, on the performance of simulating carbon exchange.

Methods

- Passive microwave observations
  - 1982-now, 0.25°×0.25° lat, lon
  - Richard de Jeu, VU-Amsterdam (1)

- SiBCASA vegetation model (2)
  - vegetation model in CarbonTracker



- Tower-based NEE

(1) Owe et al., JGR, 2008, Liu et al., HESS, 2011, Miralles et al., HESS, 2011

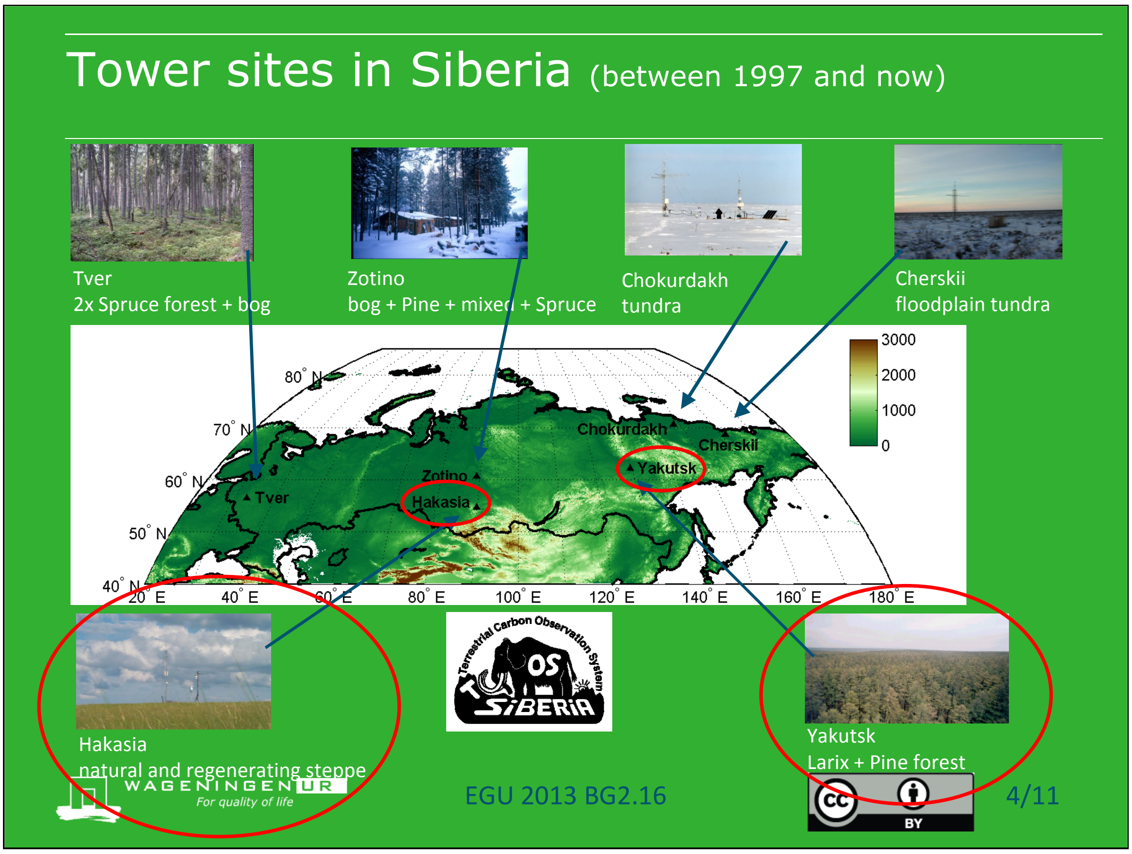
(2) Schaefer et al., JGR, 2008

- The remote sensing data of soil moisture is based on passive microwave observations from different satellite platforms, ranging from 1982 until now (continuing). In between the observations and derived soil moisture is a retrieval algorithm developed by Richard de Jeu c.s., who is based at the VU-University Amsterdam. The algorithm, called the Land Parameter Retrieval Model (LPRM, Over et al, 2008, Liu et al., 2011, Miralles et al., 2011) transforms the raw observations into a consistent database of top soil moisture with daily time step, 0.25 lat x lon resolution, and associated uncertainty.

- As the vegetation model, I use the SiBCASA model (Schaefer et al., 2008). This model simulates carbon fluxes with the classic Farquhar – Ball-Woodrow-Berry photosynthesis and stomatal conductance models, and then cycles the carbon through different pools with different turnover times. SiBCASA is the vegetation model used to provide a priori fluxes of CO2 in CarbonTracker.

- I developed a data assimilation routine in SiBCASA that takes the microwave soil moisture observations to improve the simulated soil moisture (more in the next slide).

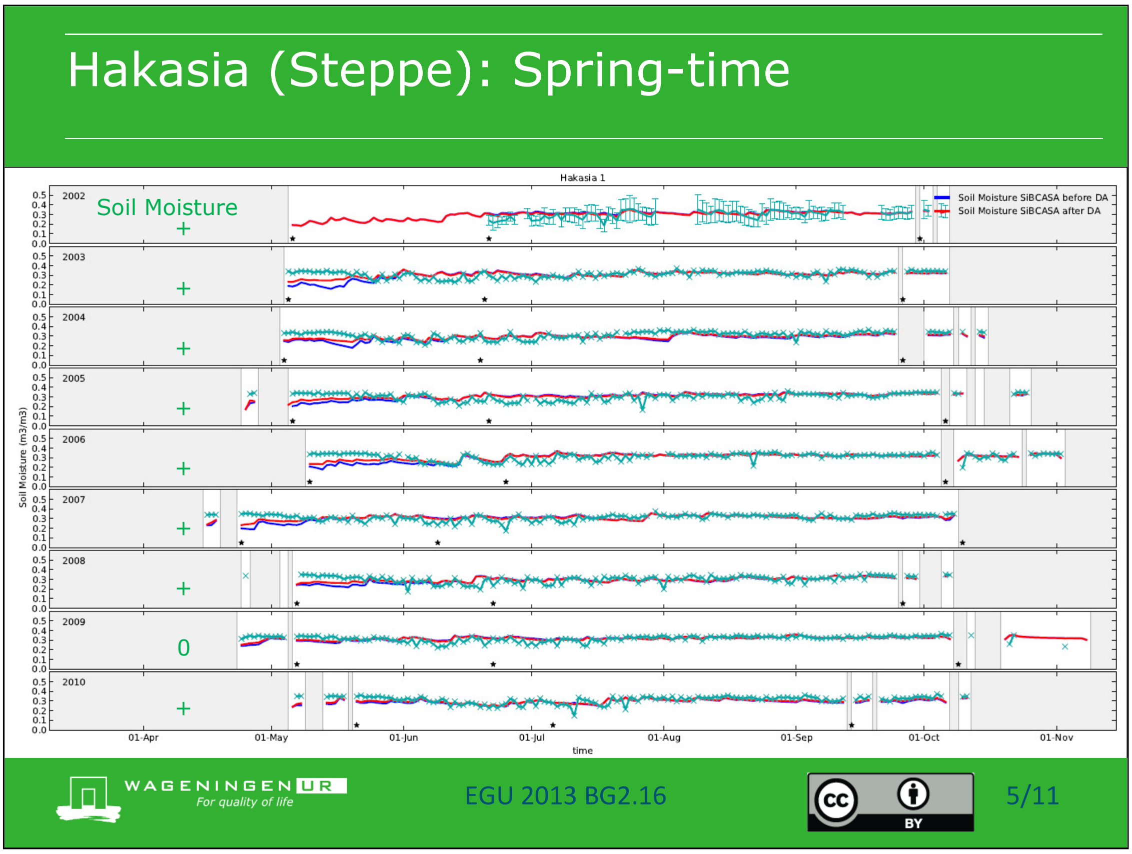
- To assess the impact this data assimilation has on the Net Ecosystem Exchange (NEE, the net carbon flux, composed of photosynthesis and respiration fluxes), I compare the simulated NEE with observations made in Siberia (next slide). Thus I run SiBCASA for selected gridpoints, where I manually change the vegetation type to match the vegetation type around the tower.



This slide summarizes the NEE data collected as part of TCOS-Siberia (EU), GAME-Siberia (JP), and several smaller programmes. There are in total 14 different tower sites, located over forest, steppe, tundra, and bogs. The period of record varies a lot between sites, the first measurements were collected in 1997, and some sites are still operational.

The reason for focussing on Siberia are:
-that it is still an understudied region and not many vegetation models are verified for the area
-soil moisture is hard to get right for vegetation models here, because of accumulation of snow in the long winter and the presence of permafrost in large parts of Siberia. I hypothesise that the models have a hard time getting the total accumulated snow pack in the spring period right. Consequently, the models do not know very well how much snow melt water will become available. Also the models do not know what happens with the melt water. Over permafrost regions, the melt water will not percolate into the soil, but runoff over hilly terrain or stay on site and waterlog the soil over flat terrain. In these conditions, soil moisture data assimilation may proof a useful tool to improve the simulated soil moisture at the start of the growing season.

In this study, I only focus on the Hakasia and Yakutsk Larix site.



Graphics

Now follow 4 slides with similar graphs. The first two show soil moisture for the steppe site Hakasia and the Larix forest site Yakutsk. The next two show NEE for those 2 sites.

-All graphs have 9 panels for the 9 years from 2002-2010. The x-axis shows date into the year.

-The blue line shows the temporal evolution of soil moisture / NEE without Data Assimilation

-The marine x's show the observations of soil moisture (from satellite) and NEE (tower based); Only the first panel shows the uncertainty range of observed soil moisture.

-The red line shows the temporal evolution of soil moisture / NEE after Data Assimilation

-the areas masked grey indicate periods when the soil is frozen.

-the first asterisk indicates the first day-of-year of the continuous soil thawing period

-the second asterisk indicates one month after the first asterisk

-the third asterisk indicatesthe last day-of-year of the continuous soil thawing period

-the green +/0/-'s indicate whether the data assimilation has a positive/no/negative effect on the simulated soil moisture.

Data assimilation methodology

-the absolute value of soil moisture in vegetation models is very model formulation dependent. E.g. it depends on soil type, porosity, wilting point, field capacity, rooting depth, transpiration and evaporation rates. The model finds a model dependent equilibrium soil moisture and the meaning of the simulated soil moisture depends on how the model formulates e.g. the stomatal conductance as a function of water stress. Similarly, the absolute value of the observed soil moisture depends on the formulation and accuracy of the retrieval algorithm. As a consequence, I cannot use observed soil moisture to change the absolute value of the simulated soil moisture. Otherwise, I would continuously pull the model out of equilibrium. Instead, I normalise the observed soil moisture to the simulated soil moisture. Normalisation would mean that I match mean and standard deviation. In practise I do a more advanced normalisation by matching the 10th, 20th, ... 90th percentile of soil moisture.

-in the previous slide I explained that I do not trust the model to have a valid soil moisture in the spring time, due to problems with amount and destiny of snow melt in permafrost regions. Therefore I do not use the first month of simulated soil moisture in the normalisation procedure. I normalise the observed soil moisture only towards the soil moisture simulated after the first month of the thawing period (the second asterisk) until the end of the thawing period (the third asterisk). However, I do apply the data assimilation to the entire thawing period.

-I use a one-dimensional Kalman filter approach for the data assimilation, which is similar to nudging. The relaxation time is a function of the uncertainty of the observations and of the model. The latter is supposed constant and small relative to the uncertainty of the obsertions. Because the uncertainty in the observations is larger than 0, the data assimilation does not result in a complete removal of the difference between observated and simulated soil moisture.

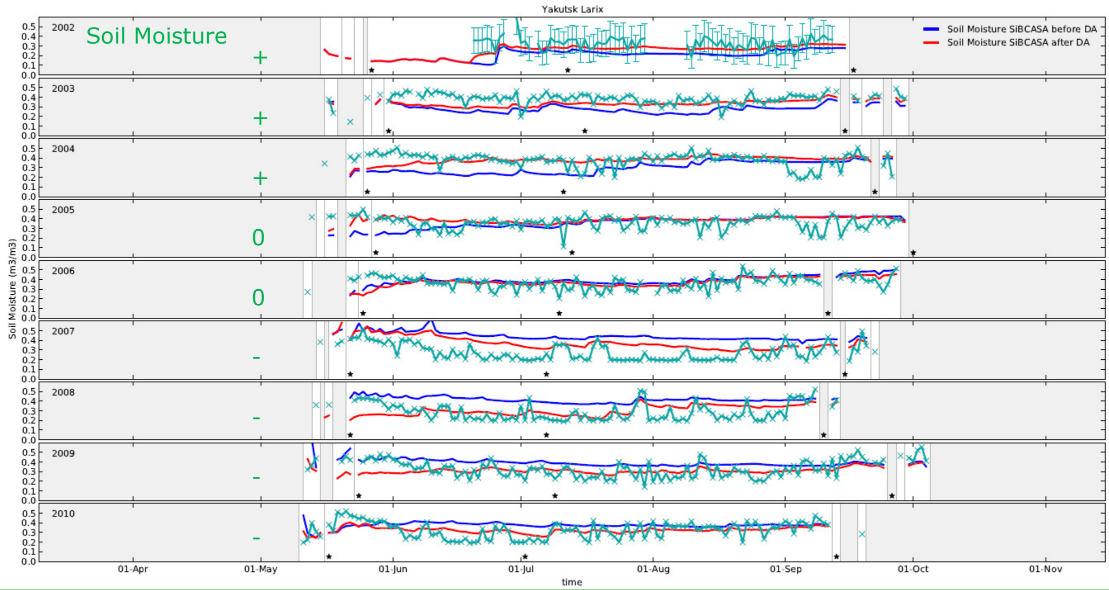
Results

-Conform the hypothesis that soil moisture in spring-time is hard to simulate, the comparison shows that SiBCASA consistently underestimates soil moisture after snow melt. The data assimilation improves the soil moisture, taking into account the uncertainty in observed soil moisture.

-For the rest of the year, the match between observed and simulated soil moisture is already good, and data assimilation does not have a further effect.

-I will show later what the effect is on NEE, but I first show this graph for Yakutsk Larix

Yakutsk (Larix): Inter-annual variability



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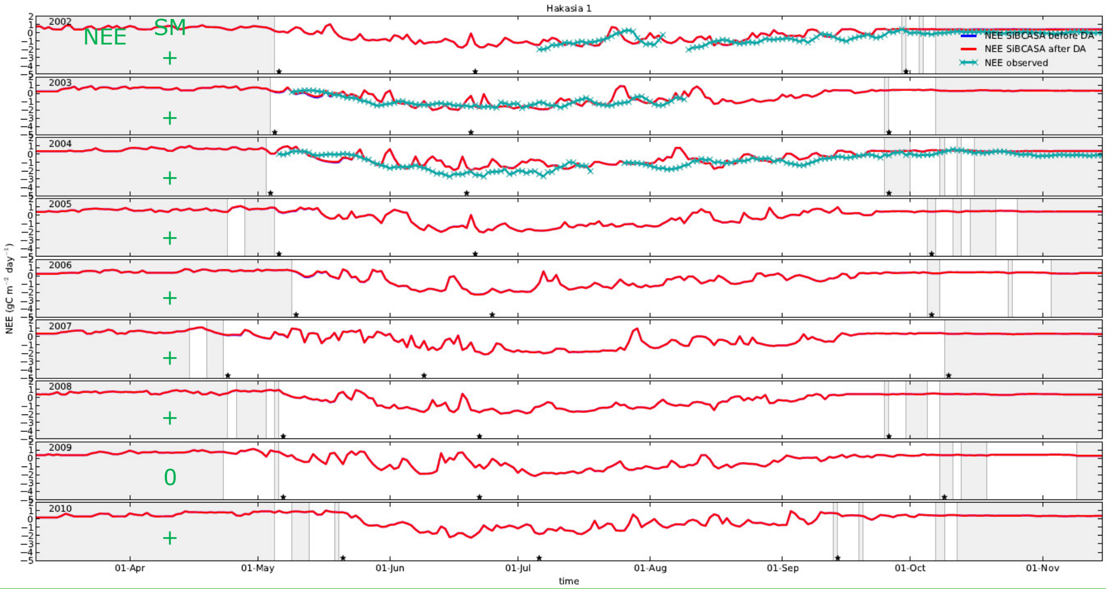
In the Yakutian Larix forest, the snow-melt-water hypothesis seems to be less relevant. Instead, the observed soil moisture seems to have a long-term interannual variability. In the first years (2002-2004), the soil is wet, in 2005-2006 it is ‘average’ and in 2007-2010, it is dry. SiBCASA does not appear to get this interannual variability at all.
The effect of data assimilation of soil moisture is that the simulated soil moisture compares better with the observed, as expected: a wetting trend in 2002-2004, no effect in 2005-2006, and a drying trend in 2007-2010.

Now we will look at the effects on NEE.

Hakasia 1 (Steppe): NEE



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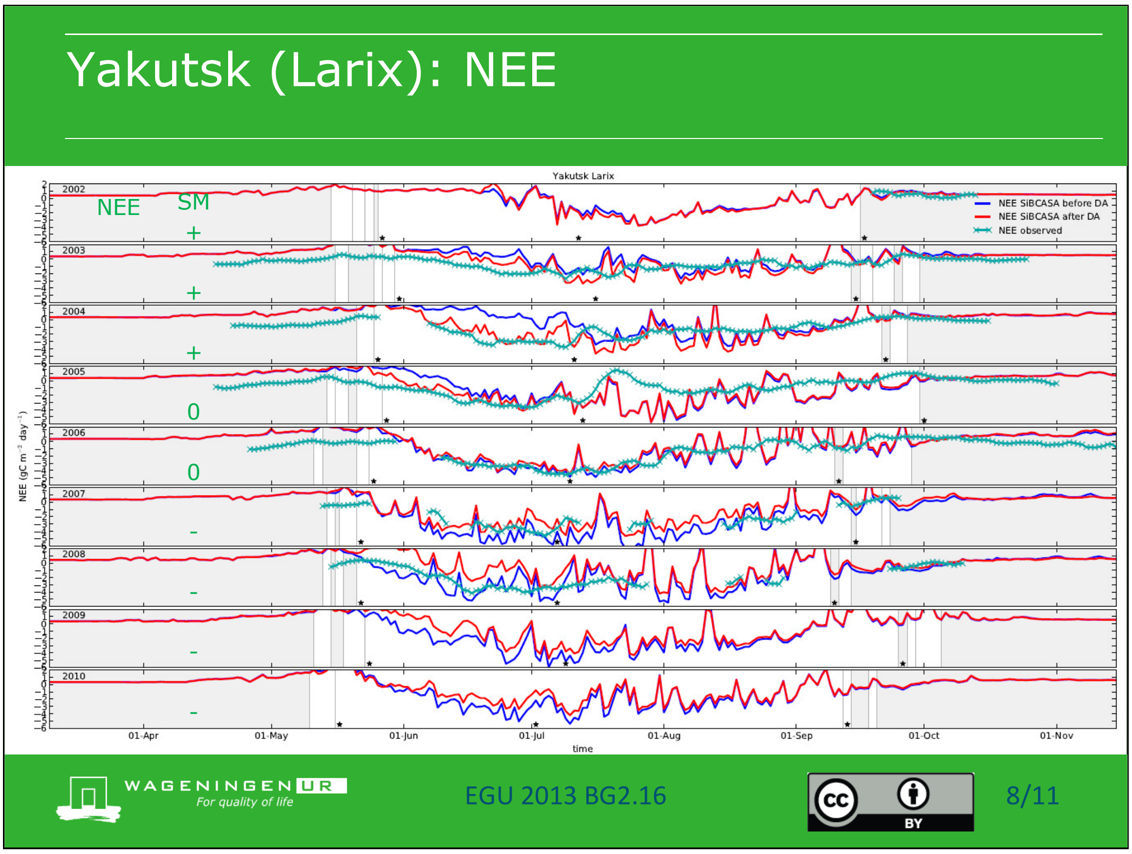
In Hakasia, there is hardly any effect of soil moisture data assimilation. Although there was a considerable effect of the assimilation on soil moisture in spring-time, this does not translate into a NEE effect.

This may be due to the changes to occur in spring-time, when NEE is usually small, but later I will show that there is a more fundamental reason for the lack of change in NEE.



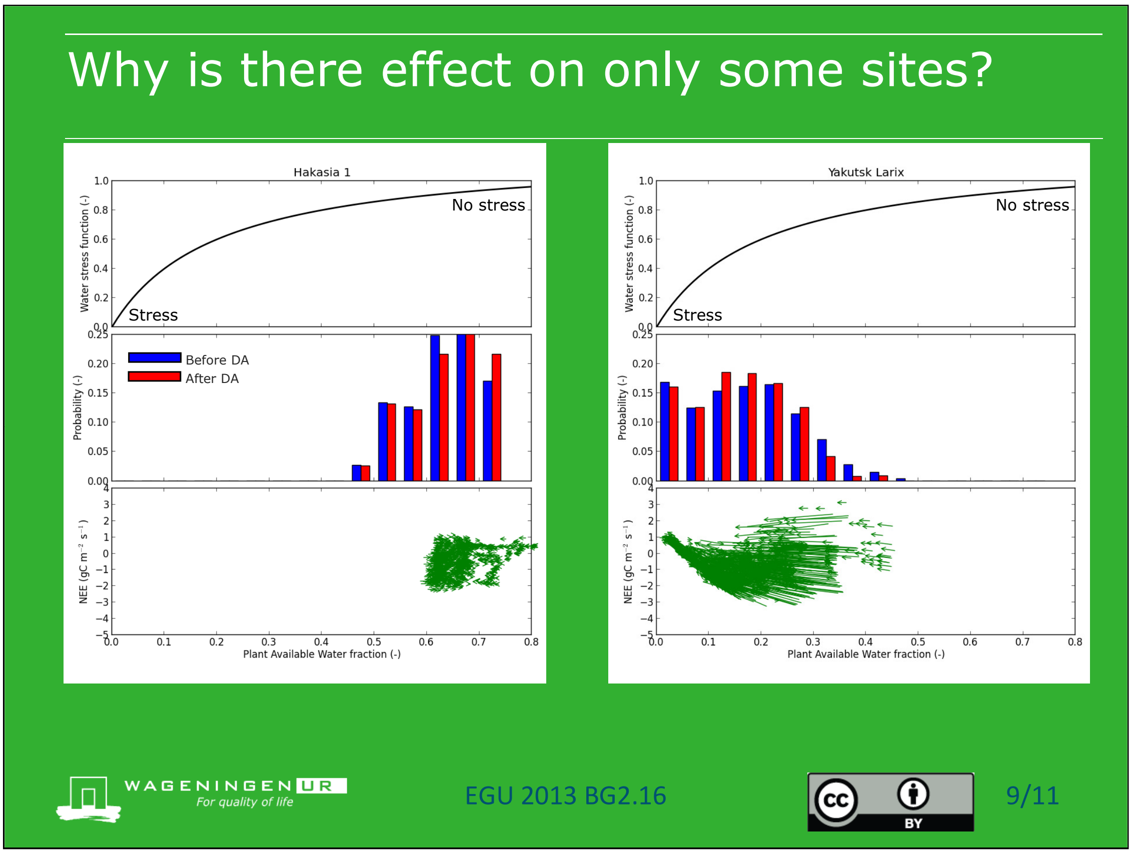
At the Yakutsk Larix site, data assimilation of soil moisture has a considerable effect on NEE.

However, I need to make a note first: NEE(simulated) was always a factor 2 smaller than NEE(observed). This is hardly surprising, as there are only very few data available to calibrate and constrain the NEE in vegetation models. Still this is a serious matter, because the majority of the Siberia east of the Yenissei river is covered with Larix forest, which probably accounts for about 50% of Siberia. If the NEE of this area is underestimated by a factor of 2, than this has an effect of the global estimate of NEE in SiBCASA. I have not yet studied this mismatch in more detail, but I will do this soon by comparing the light- and temperature responses of GPP, TER and NEE in SiBCASA and the observations. For now I 'normalised' NEE(simulated) by tuning it manually to NEE(observed) in the years 2005 and 2006, which needed a multiplication factor of 2.

In the years 2002-2004, the wetting effect of data assimilation results in an increase in NEE: the red curve is towards the marine curve, i.e. towards more uptake relative to the blue curve.
In the years 2005-2006, the data assimilation has no clear effect on NEE.
In the years 2007-2010, the drying effect of data assimimilation results in a decrease in NEE i.e. a smaller uptake rate.

At most times, the data assimilation of soil moisture moves the simulated NEE towards the observed NEE. I gently takes this as an indication that soil moisture data assimilation has a potential to improve the NEE in SiBCASA, although I still want to further investigate this for more sites and in more detail.

However, a question that comes to mind is: how can I explain why soil moisture data assimilation has no effect in Hakasia and a considerable effect in Yakutsk?



However, a question that comes to mind is: how can I explain why soil moisture data assimilation has no effect in Hakasia and a considerable effect in Yakutsk?

To answer this question, I show the water stress function in SiBCASA in the top panels of the figures. The water stress function is used to modify the stomatal conductance in SiBCASA and it varies from 1 (no stress) to 0 (complete stress). It is a function of plant available water fraction, i.e. the fraction of the maximum pore space filled with water that can be extracted by roots, as a function of wilting point, field capacity and root depth. SiBCASA's water stress function represents an agressive water use strategy: at large plant available water fraction (PAWfrac) the plants experience hardly any stress, and the stress only kicks in at PAWfracs of around 0.3-0.2, after when the water stress quickly increases.

The middle panels show the PAWfrac for the two sites before and after data assimilation, and it is clear that the Hakasia site always has a large PAWfrac, whereas Yakutsk Larix always has a small PAWfrac. As a result, the Hakasia site is in the unstressed zone. The bottom panels shows with arrows the change in PAWfrac and the associated change in NEE. Both changes are relatively small.

The Yakutsk Larix site in contrast is often in the water stressed zone, where small changes in soil moisture already have an effect on NEE. This is shown in the bottom panel, where the arrows show that the closer PAWfrac is to 0, the more a change in soil moisture has effect on NEE.

The formulation of the water stress function in combination with the simulated PAWfrac explains why soil moisture data assimilation has an effect at the Yakutsk site, but not in Hakasia. However, it important to mention that these things almost entirely occur in model space. It is unclear what the water stress function is based on. There are indications that the water stress function, which is in expression of the water use strategy, varies between species, but SiBCASA uses the same water stress function for all vegetation types (the PAWfrac calculation may vary between species due to variations in root depth). This is not particularly true for SiBCASA, but applies to many vegetation models.

In favor of SiBCASA: the model correctly predicts that changes in soil moisture hardly have an effect on NEE in Hakasia, where the model and observed NEE already match quite well. In Yakutsk Larix the model correctly predicts that changes in soil moisture should have an effect on NEE, and the changes in NEE are into the right direction.

Conclusions

- Use of soil moisture assimilation:
  - improvement of temporal variation
  - effect on NEE depends on drought sensitivity
- Better integration of carbon and water cycles is needed:
  - GLEAM and SiBCASA
  - key role for water stress sensitivity

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We conclude that the application of soil moisture data assimilation improves the temporal variation in soil moisture, whether in the first days after snow melt, or over long-term interannual variability. The associated changes in NEE are towards the observations.

The effect on NEE heavily depends on the formulation of the plant available water fraction and the water stress function, which are hardly constrained by observations. In order to achieve this, we argue that a better integration of the carbon and water cycles is still needed in vegetation models, to improve the correct prediction of droughts and their effects.

My plans are to study whether it is feasible and useful to integrate SiBCASA with GLEAM (Global Land Evaporation model – The Amsterdam Methodology, Miralles et al., 2011). GLEAM is a global water balance model almost entirely based on remote sensing data and is formulated as simple as possible while still representing the relevant processes, a.o. rainfall interception. GLEAM is also extensively tested and verified using multiple sources of data (ground data, time series, annual totals and biases, ET, runoff). As such it provides As such it provides a first globally consistent observations-based estimate of the water balance. The simplicity and use of remote sensing data match very well with the concepts of SiBCASA. The data assimilation methodology used in this study is actually taken from GLEAM.

A first comparison of SiBCASA and GLEAM precipitation has already been performed. This showed that precipitation is generally similar, but that significant differences occur in some areas. Because precipitation is really the starting point of the water cycle in vegetation models, I decided to force SiBCASA with the same precipitation data as GLEAM. Next steps will be to compare evaporation rates and their sensitivity to water stress, temperature and radiation for the different sites in Siberia.

I also plan to test the performance of SiBCASA with different water stress functions. In these tests, I want to see how the absolute value of soil moisture changes, and how this affects the associated water stress.

A third plan is to study how the water and carbon pools are disturbed during and after a drought period. There are indications that carbon pools may remain disturbed until years after the drought ended, and this would impact the carbon uptake and respiration, as well as the water use efficiency. The microwave retrieval algorithm also provides a time-varying estimation of the vegetation optical depth, which is to a large extent a function of the vegetation water content. It would be timely to also engage the vegetation optical depth in this plan.

The end

Questions,
comments?

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I appreciate any comments or feedback you may have. Thanks,
Michiel