Advancing land data assimilation science to monitor terrestrial water and vegetation dynamics

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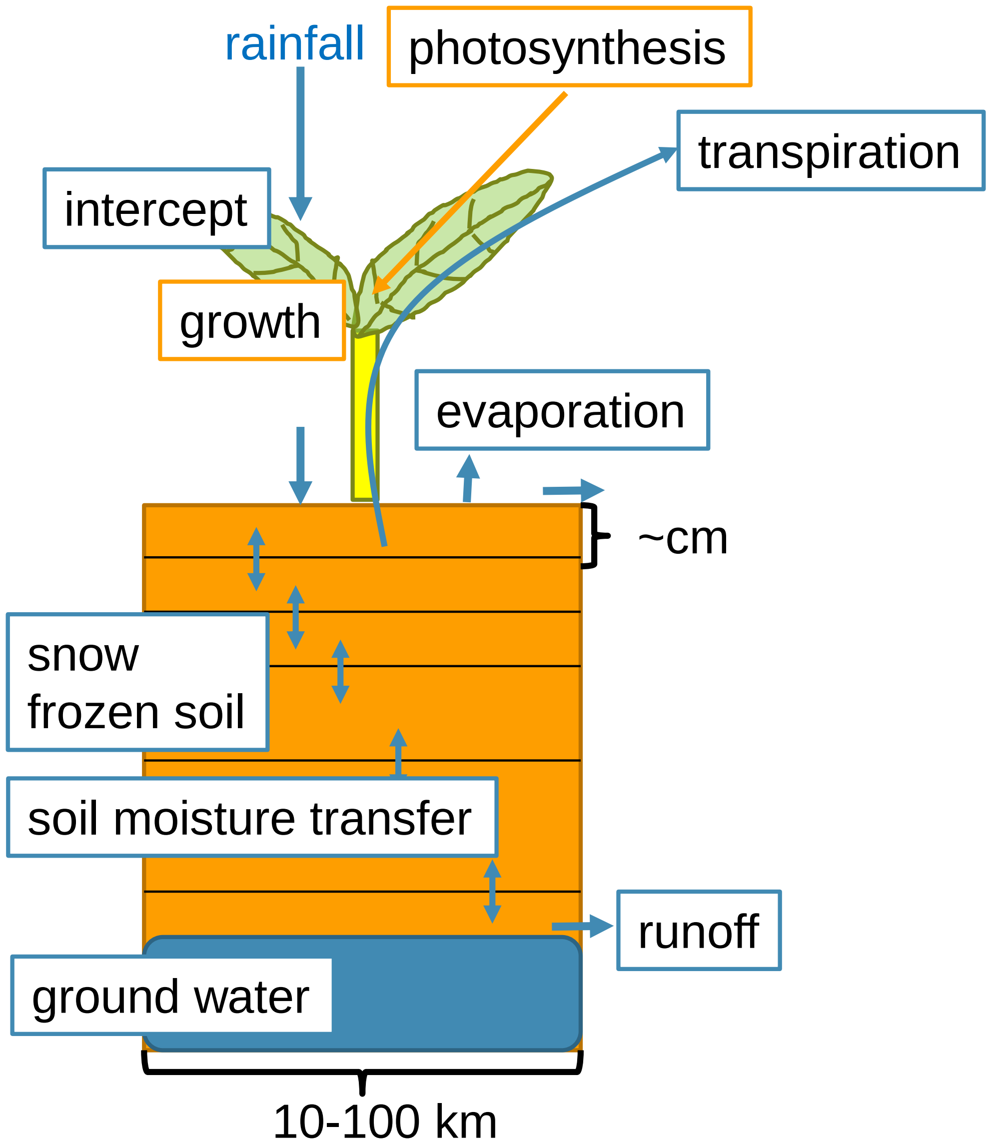
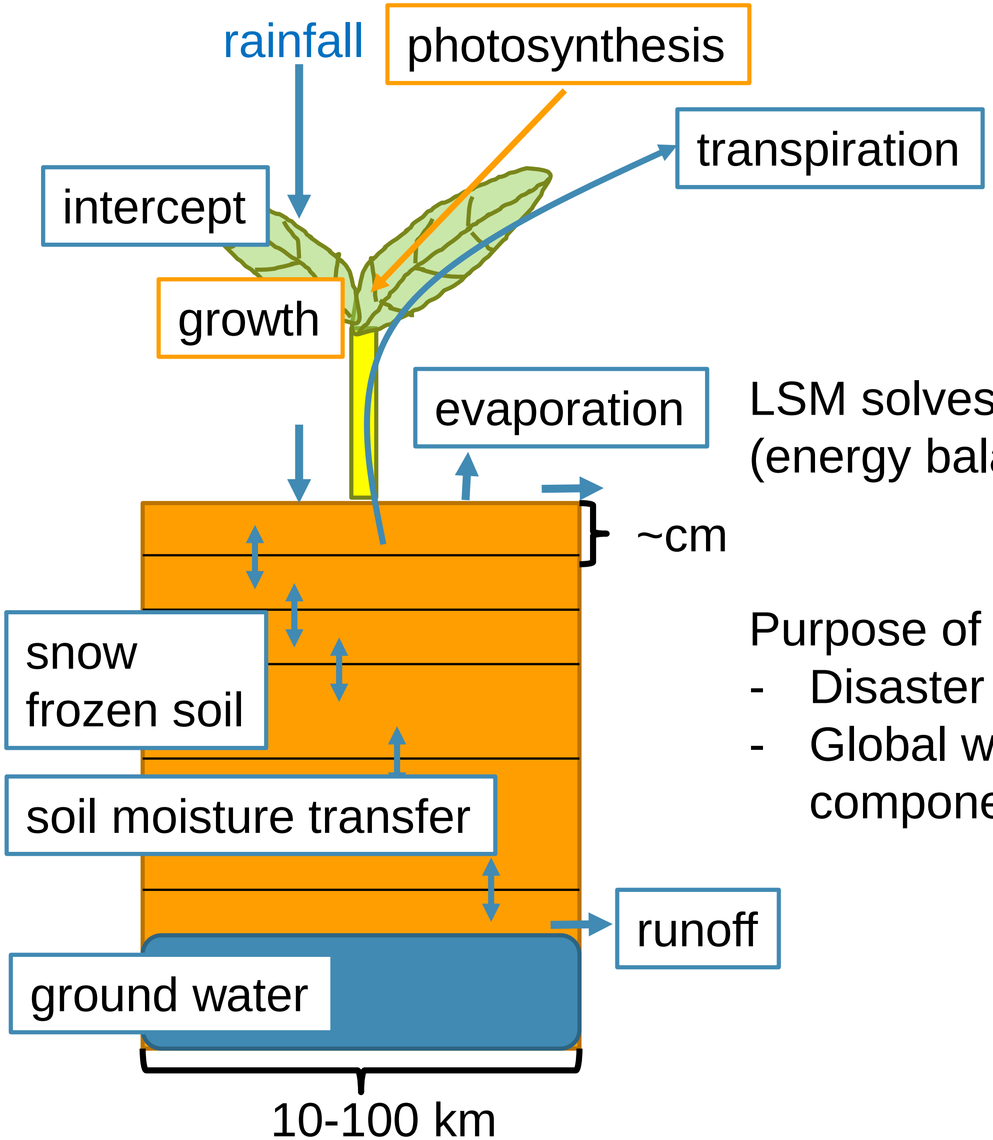


1. Introduction

1.1. What is Land Surface Model (LSM)?



LSM solves water, carbon, energy balance of land (energy balance is not described in the figure).

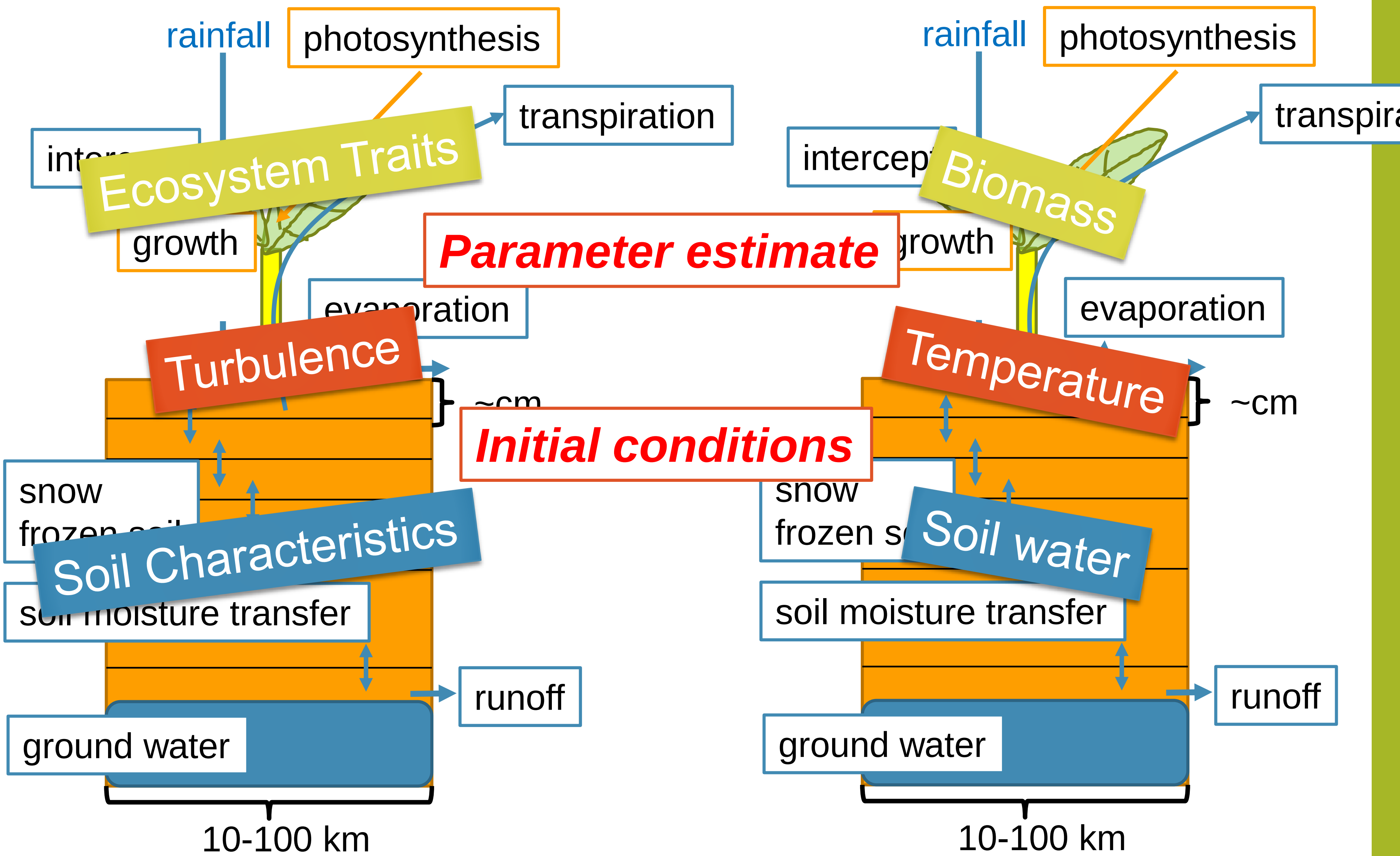
Purpose of LSM:

- Disaster modeling (flood and drought)
- Global water, carbon, and energy cycle (as a component of ESM)

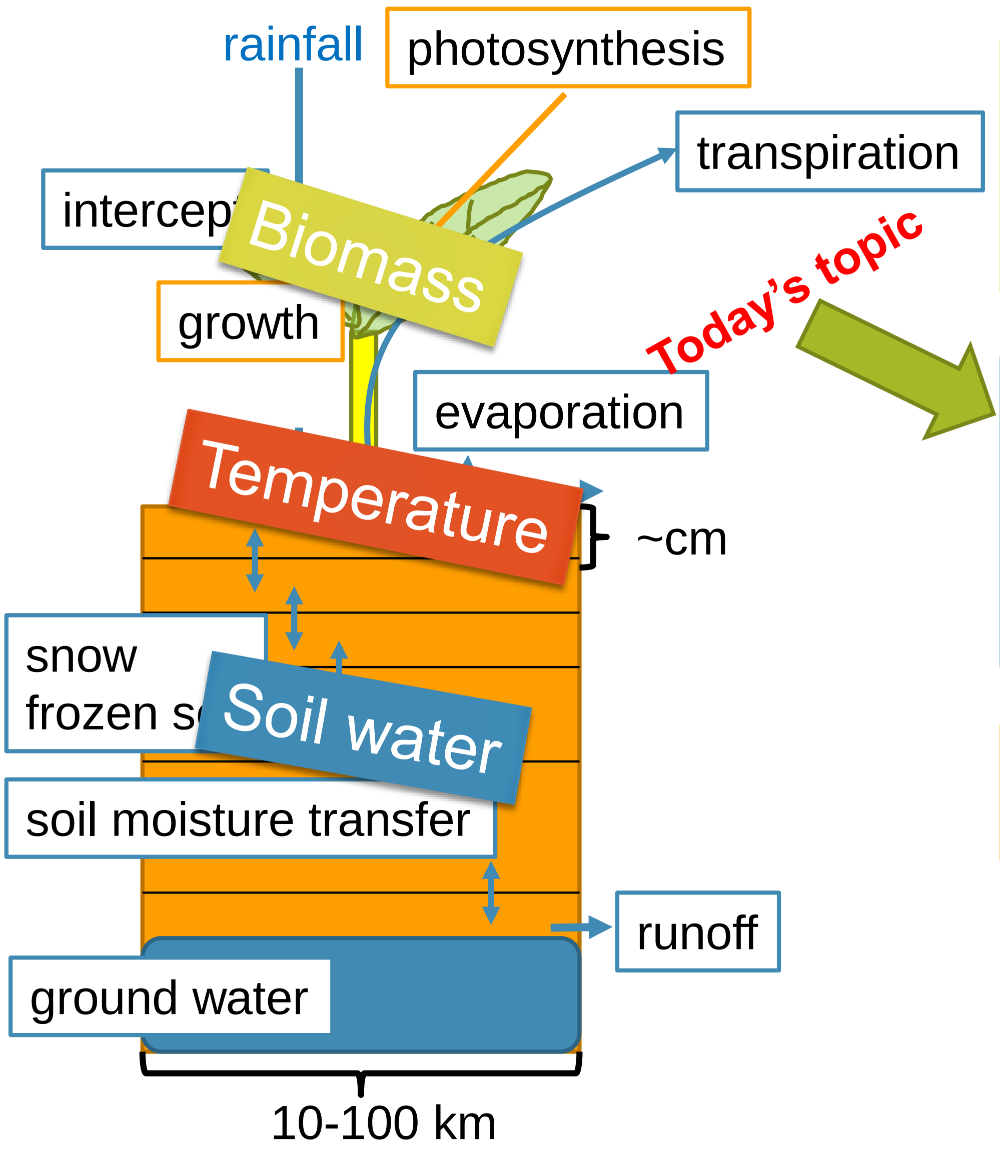
Most of LSMs are vertical one dimension model.

Runoff is parameterized and passed to the different model (river routing model)

1.2. Purpose of Land Data Assimilation System (LDAS)



1.3. Satellite-based LDAS



Visible/infrared (e.g., MODIS)

- Land surface Temperature
- Photosynthetic activities (LAI)
- Snow cover

Microwave (e.g., AMSR-E, SMOS)

- Land surface temperature
- **Soil Moisture**
- Vegetation water content
- Snow depth

Gravity (GRACE)

- Total water storage

1.4. Outline

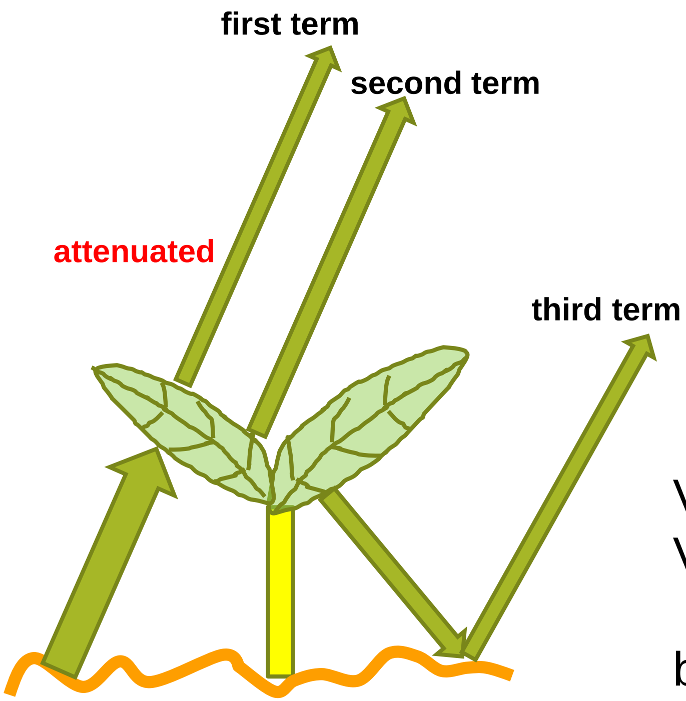
1. Capability and limitation of passive microwave observation of land

2. A land data assimilation system for simultaneous estimation of soil moisture and vegetation dynamics based on microwave observations

3. Application of LDAS to mega-drought monitoring and prediction

2. Capability and limitation of passive microwave observation of land

2.1. Microwave radiative transfer of land



Canopy radiative transfer
(tau-omega model)

$$T_{bp} = (1-R_p)T_s \exp(-VOD_p) +$$
$$(1-\omega_p)T_c(1-\exp(-VOD_p) +$$
$$R_p(1-\omega_p)T_c(1-\exp(-VOD_p))\exp(-VOD_p)$$

VOD: Vegetation optical depth
VOD = b × (vegetation water content)

b is species-dependent parameter [Jackson and Schmugge, 1991]

Q1:How large?

Land surface emission

$$T_B = \varepsilon T$$
$$\varepsilon = f(soil\ moisture, roughness)$$

Q2:Can we observe soil moisture under dense canopy? How dense?

2.2.1. Field Experiment (1)

Brightness temperature
(multi-frequency, multi-polarization)

Vegetation properties
(Biomass amount, vegetation water content, leaf area, ……)

→ The set of observations has been carried out for 4 years

Meteorological forcings
(rain, radiation, wind speed,…)

Land surface properties
(soil moisture, temperature, roughness,…)

2.2.2. Field Experiment (2)

We planted various kinds of crops & tree.

oat

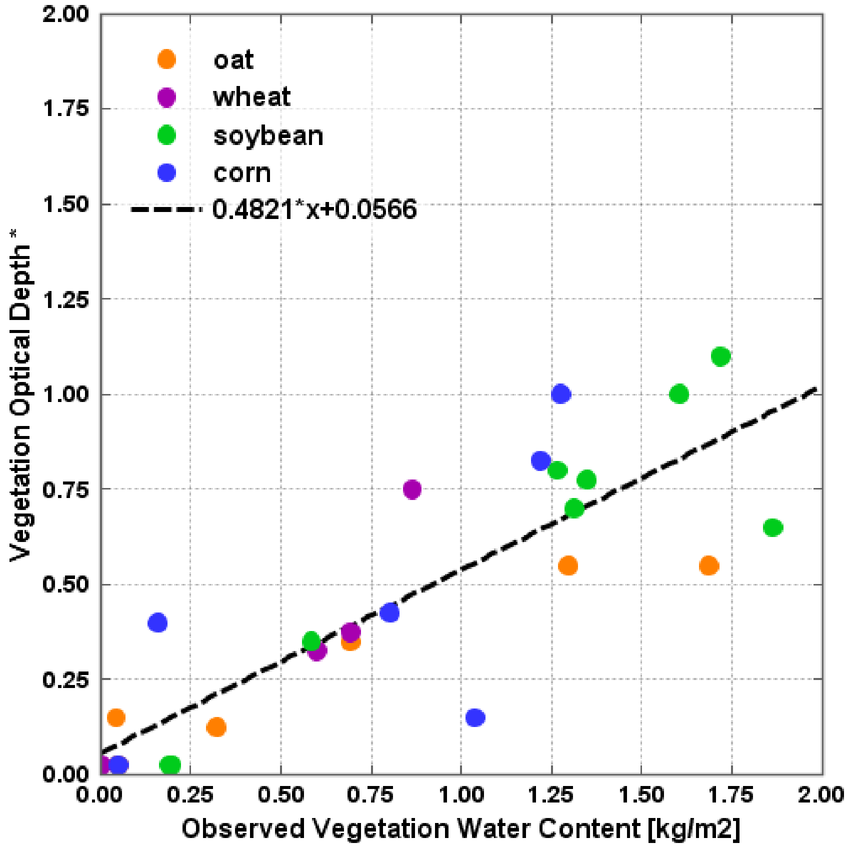
wheat

corn and soybean

olive

[Sawada et al., 2016 IEEE TGARS]
[Sawada et al., in prep]

2.3. Species dependent



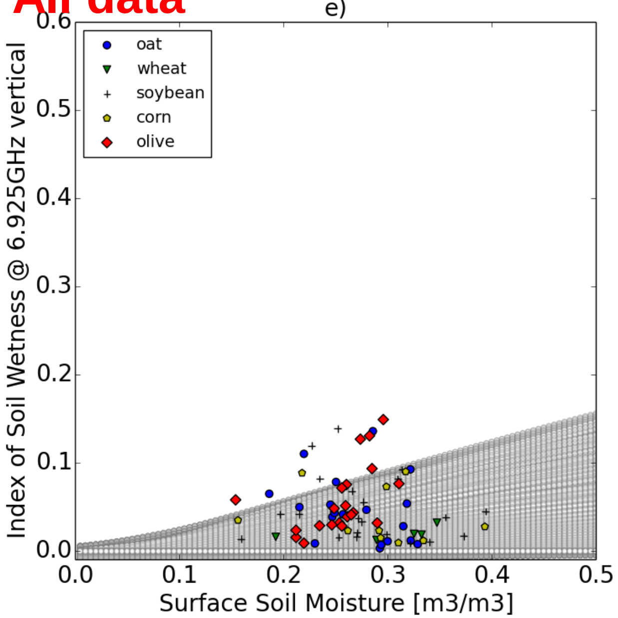
VOD: Vegetation optical depth
VOD = b × (vegetation water content)
b is species-dependent parameter [Jackson and Schmugge, 1991]

Vegetation effects are species-independent to vegetation type in C-band!

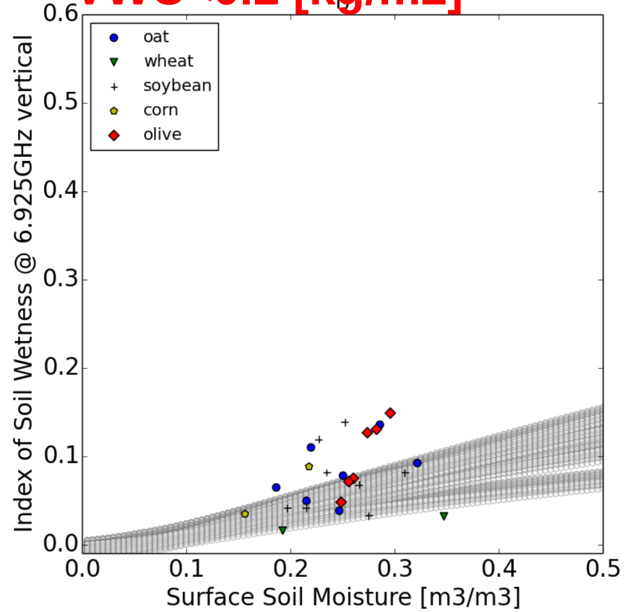
[Sawada et al., 2016 IEEE TGARS]
[Sawada et al., in prep]

2.4. Effect of soil moisture under canopy

All data



VWC<0.2 [kg/m2]



Index of Soil Wetness (ISW: Koike et al. [2004]) is the proxy of soil moisture and operationally used by JAXA.

We have believed that soil moisture can be retrieved under VWC < 2.0 [kg/m2]

We believe that soil moisture can be retrieved under VWC < 0.5 [kg/m2]

[Sawada et al., 2016 IEEE TGARS]
[Sawada et al., in prep]

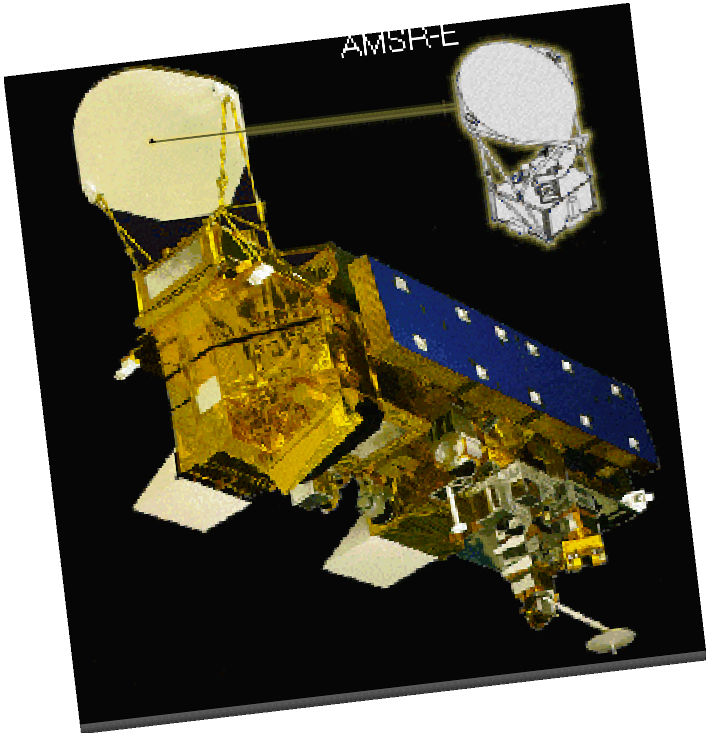
2.5. Summary of this section

Q1: How strongly is passive microwave radiative transfer dependent to vegetation type and structure?

→ In C-band, the effect of vegetation structure is minimal

Q2: Can we observe soil moisture under dense canopy? How dense?

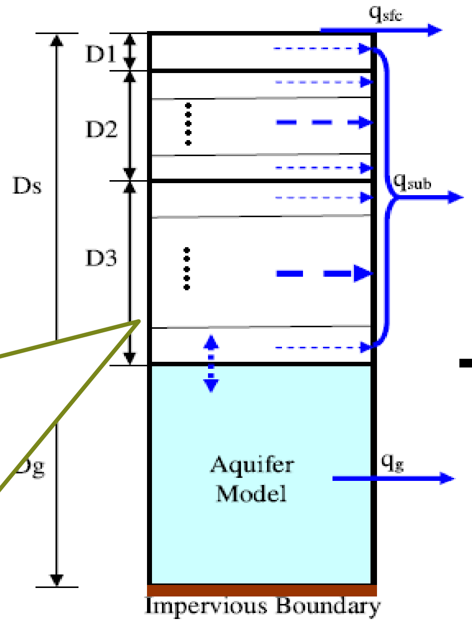
→ In C-band, the capability to observe soil moisture under dense canopy is smaller than we expected.



3. A land data assimilation system for simultaneous estimation of soil moisture and vegetation dynamics

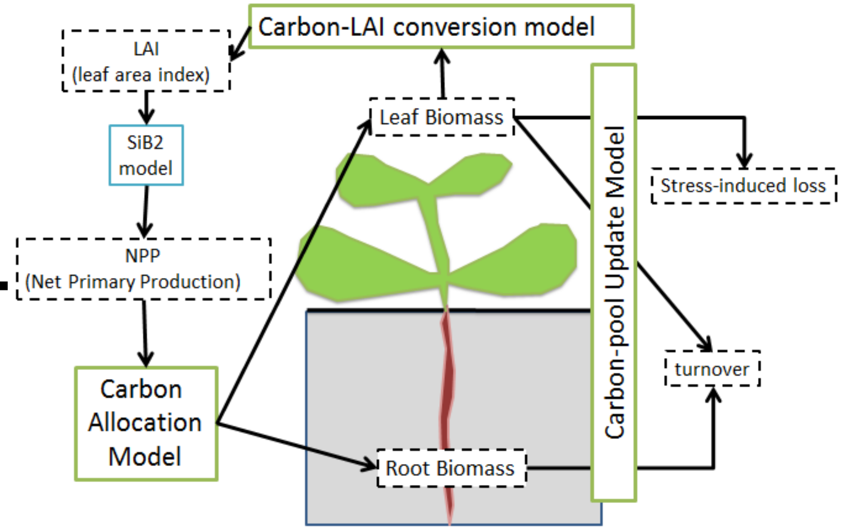
3.1. LSM - EcoHydro-SiB

- Multi-layer transpiration
- Modified V-G water retention curve
- Multi-layer soil parameter distribution



hydro-SiB
[Wang et al., 2009]

+

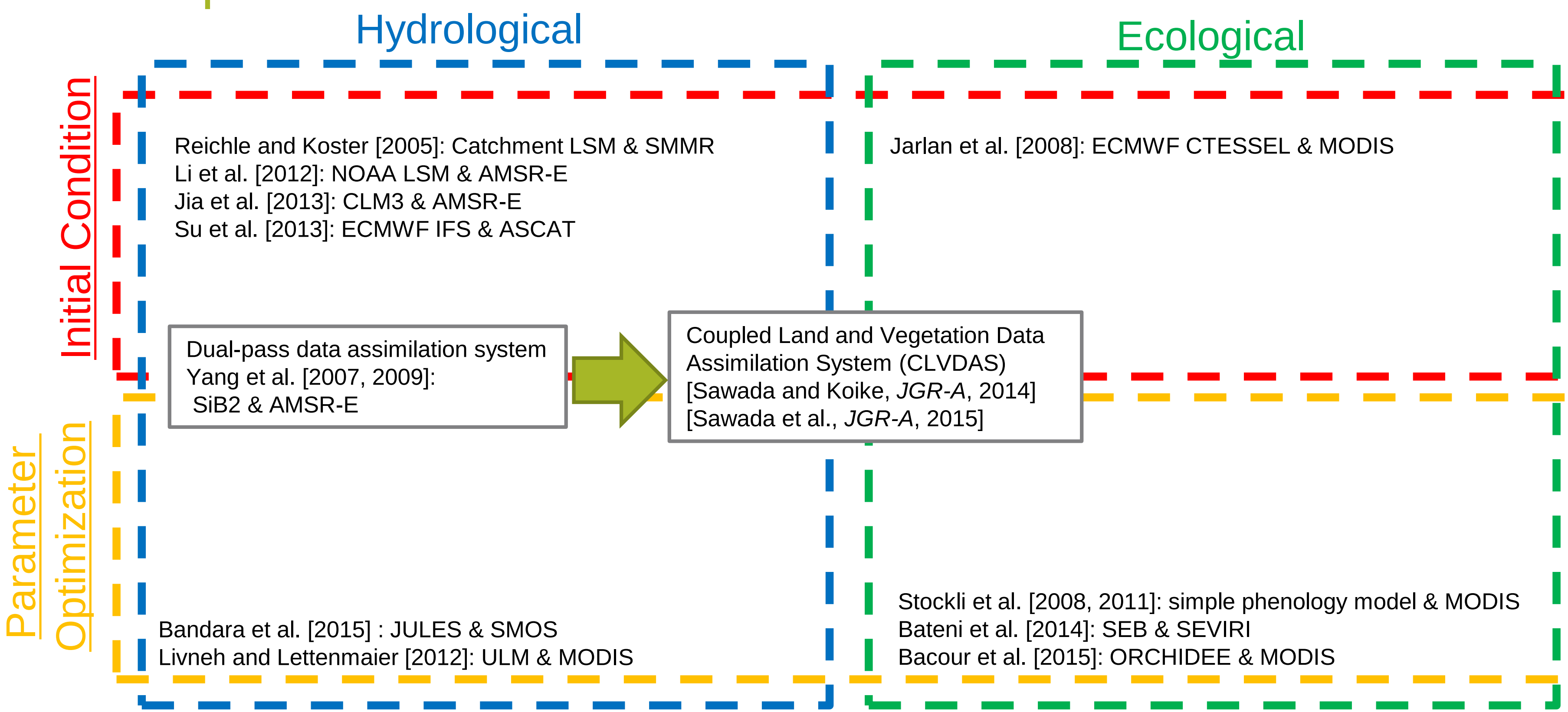


Dynamic Vegetation Model (DVM)

- Based on SiB2 [Sellers et al., 1996]
- Including precise hydrological scheme [Wang et al., 2009] with Dynamic vegetation model.

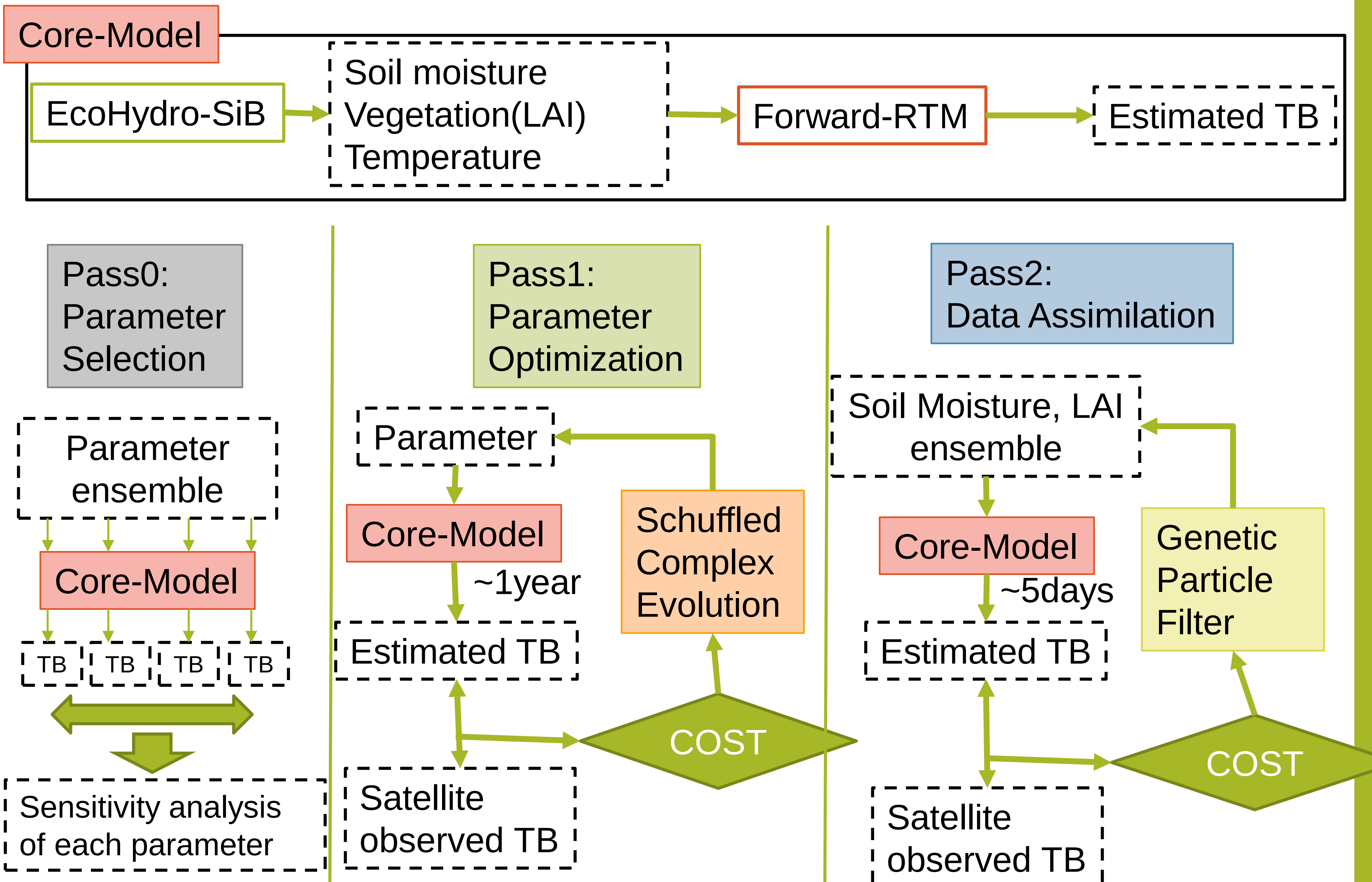
→ We have already confirmed that this model can simulate water cycle and vegetation dynamics (crop productions) correctly in the data rich basin
[Sawada et al., 2014, Water Resour. Res.]

3.2. Purpose of our LDAS



→ LDAS for parameter optimization and state valuable adjustment of both hydrological and ecological part of LSM is developed.

3.3. Coupled Land and Vegetation Data Assimilation System (CLVDAS)

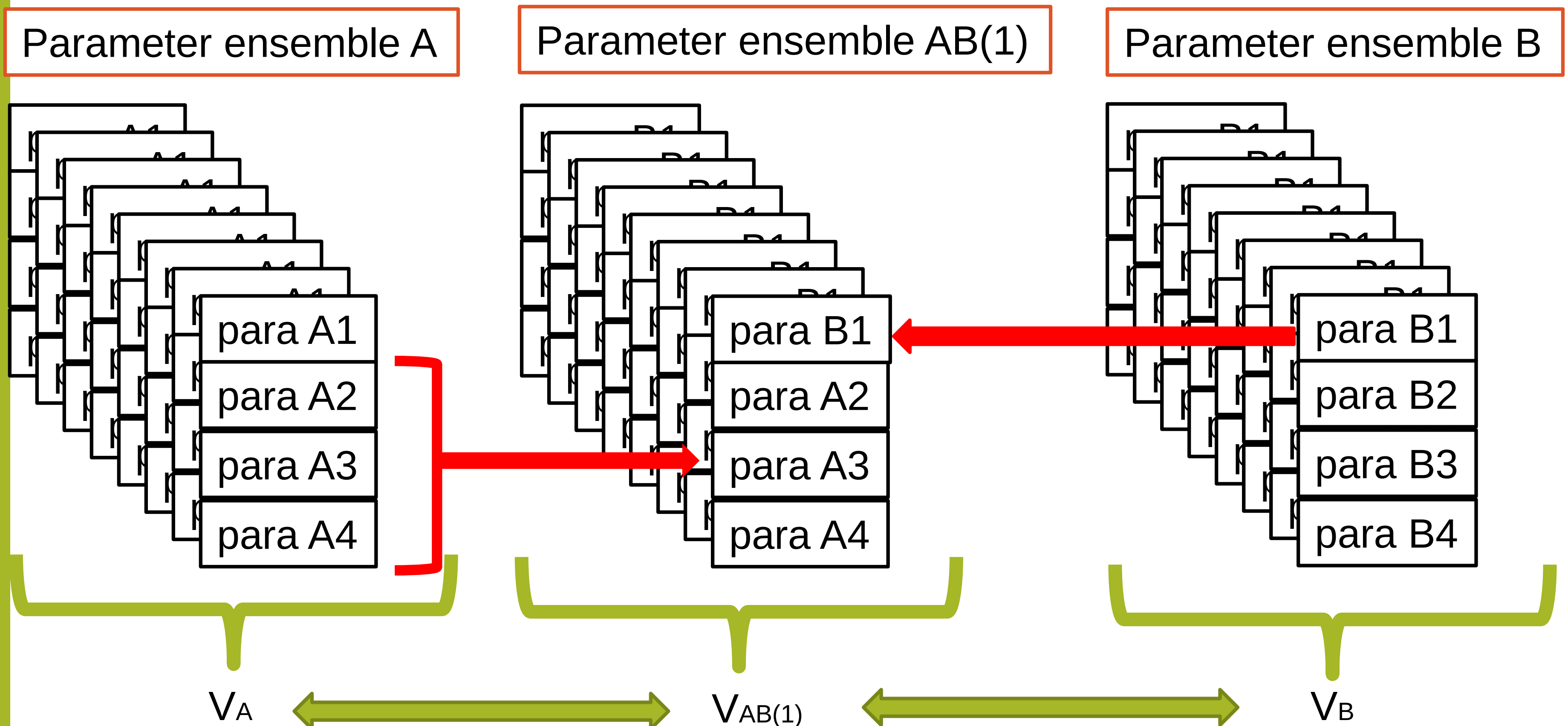


3.4.1. Parameter selection (1) - algorithm

Variance-based global sensitivity analysis (Sobol's method) [Saltelli et al. 2010]

$$V_Y = \sum_i V_i + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \ldots\ldots + V_{12\ldots n}$$

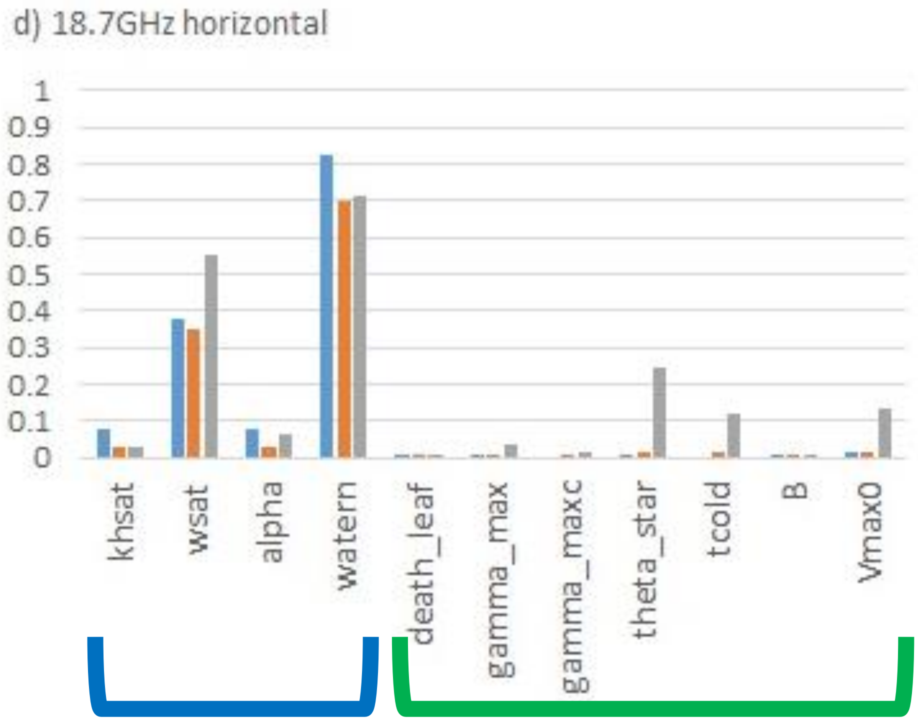
→ Total variance of the model's output is decomposed to the variance that come from each parameter uncertainty.



(Recently, some researchers indicated this method is very inefficient and some other useful methods are proposed [e.g., Razavi and Gupta, 2016])

3.4.2. Parameter Selection (2) - Results

Parameter Sensitivity to TBs (18.7GHz Horizontal)



Hydrological parameters （e.g., hydraulic conductivity）

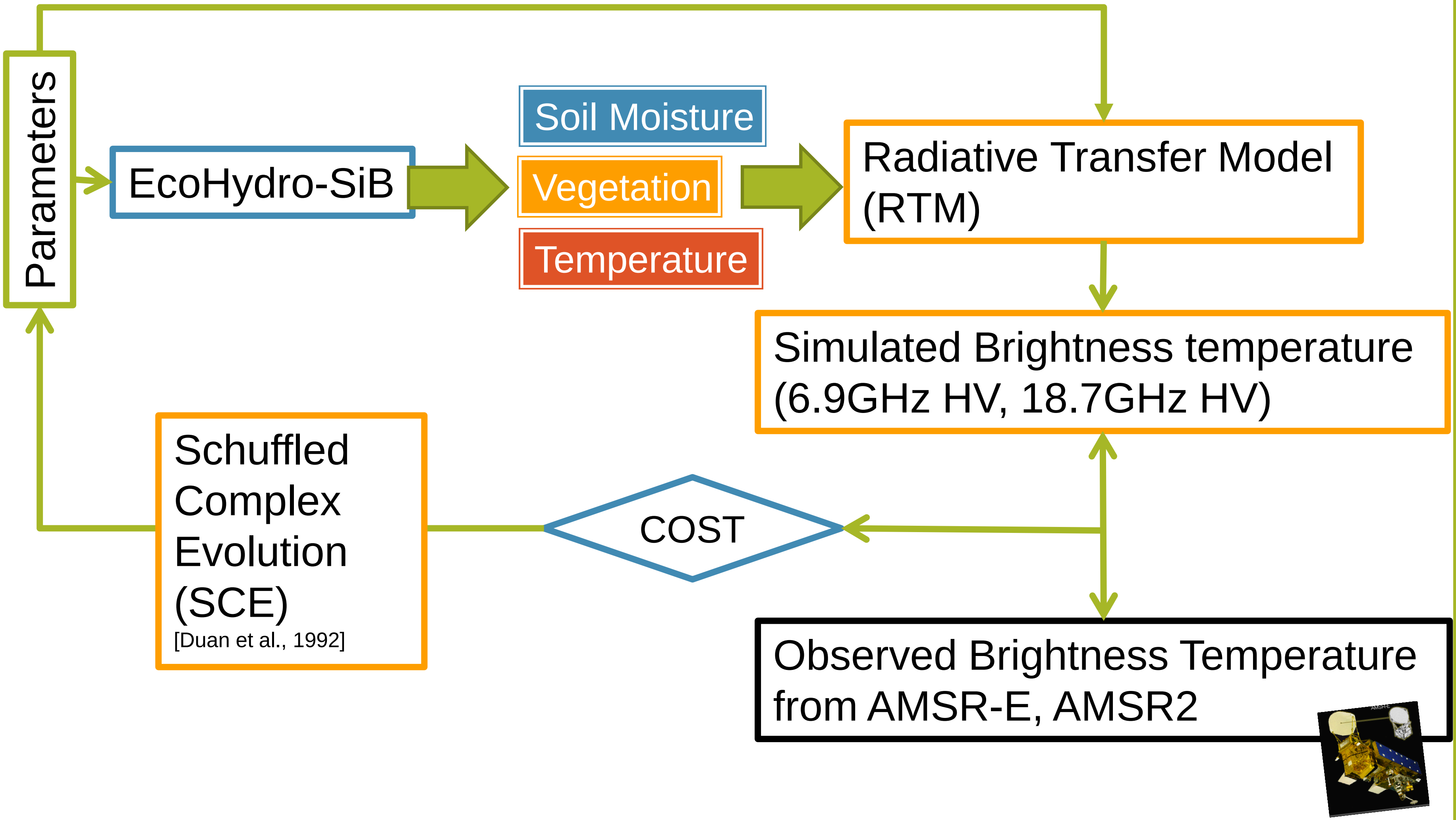
Ecological parameters （e.g. Maximum efficiency of Rubisco）

Blue：West Africa (Hot and dry)
Orange：Mongolia (cold and dry)
Gray：California (US) (temperate)

→ In dry area, we can improve the performance by tuning only hydrological parameters
→ We can reduce the number of the calibrated parameters by using this method.

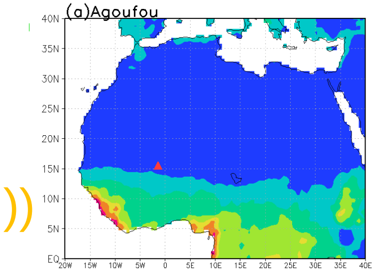
[Sawada and Koike, *JGR-A*, 2014]

3.5.1. Parameter Optimization (1) - algorithm



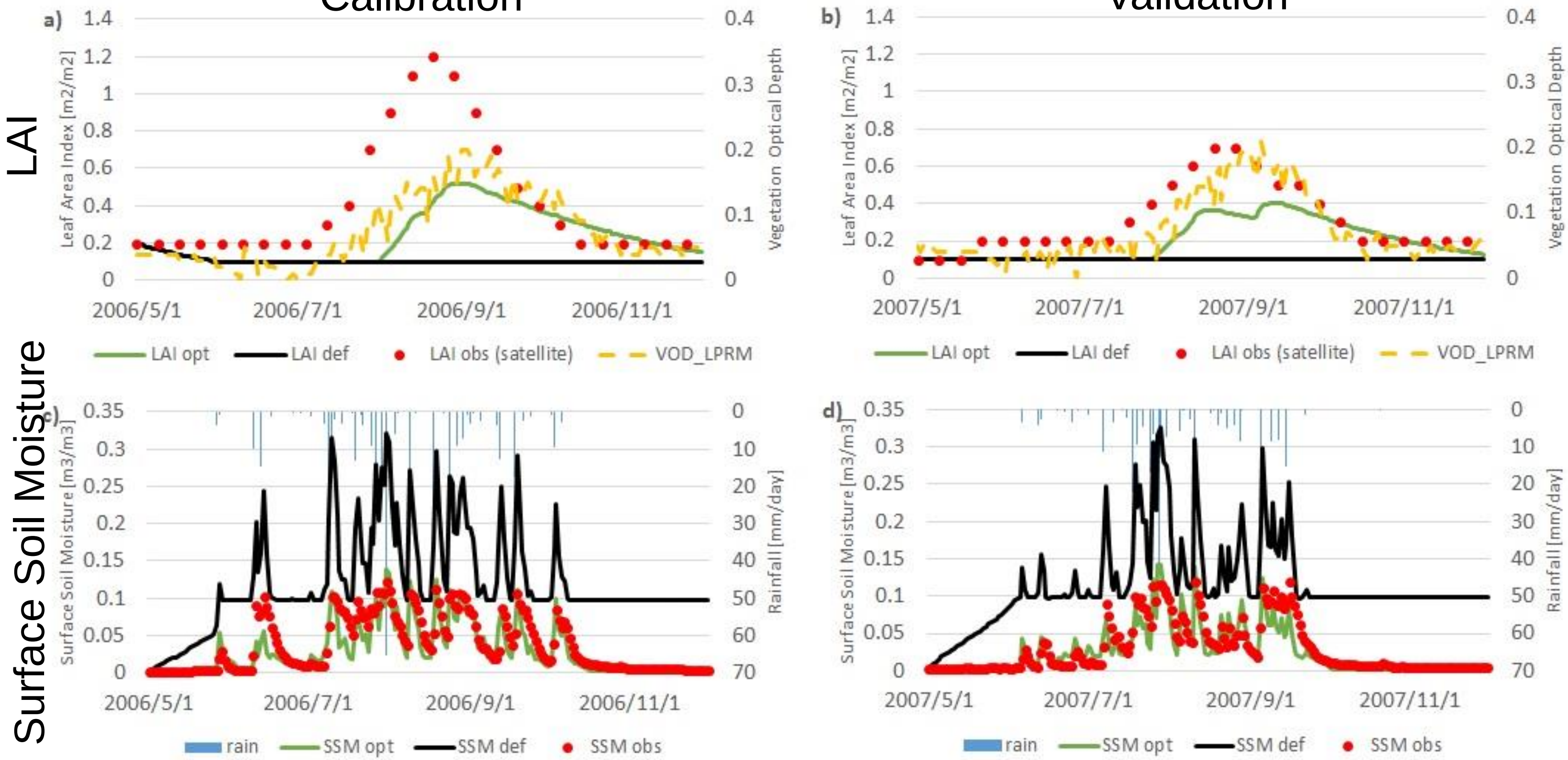
→ CLVDAS optimizes parameters by minimizing the difference between modeled and observed brightness temperature.

3.5.2. Parameter Optimization (2) -Results @ West Africa



Green: Optimized, Black：Default,
Red：Observed, Yellow：Observed (Microwave VOD (NASA LPRM))

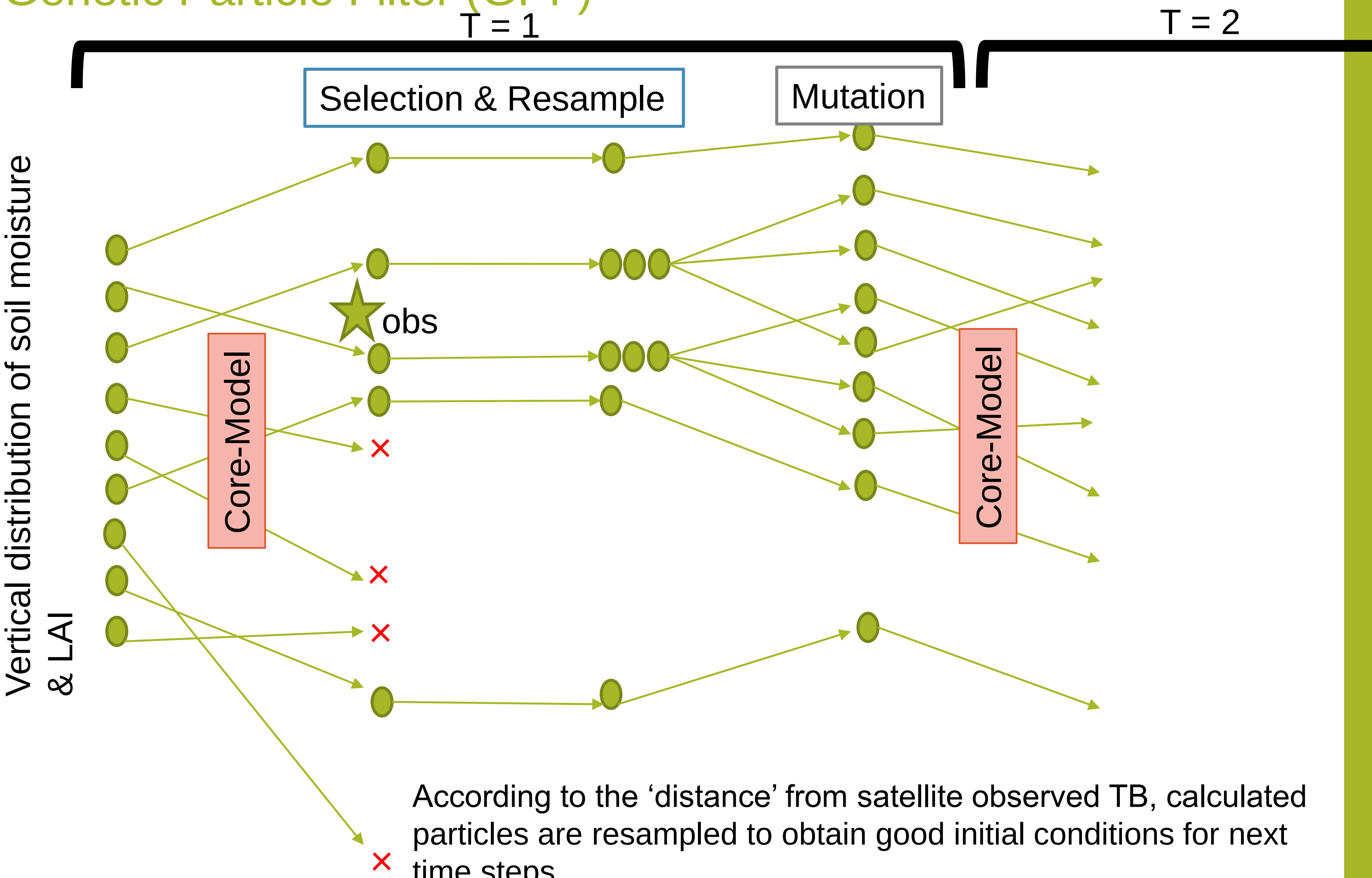
Calibration — Validation



[Sawada and Koike, *JGR-A*, 2014]

→ Optimization improves the skill of estimating surface soil moisture and vegetation dynamics at the same time.

3.6.1. State adjustment (1) - algorithm
Genetic Particle Filter (GPF)

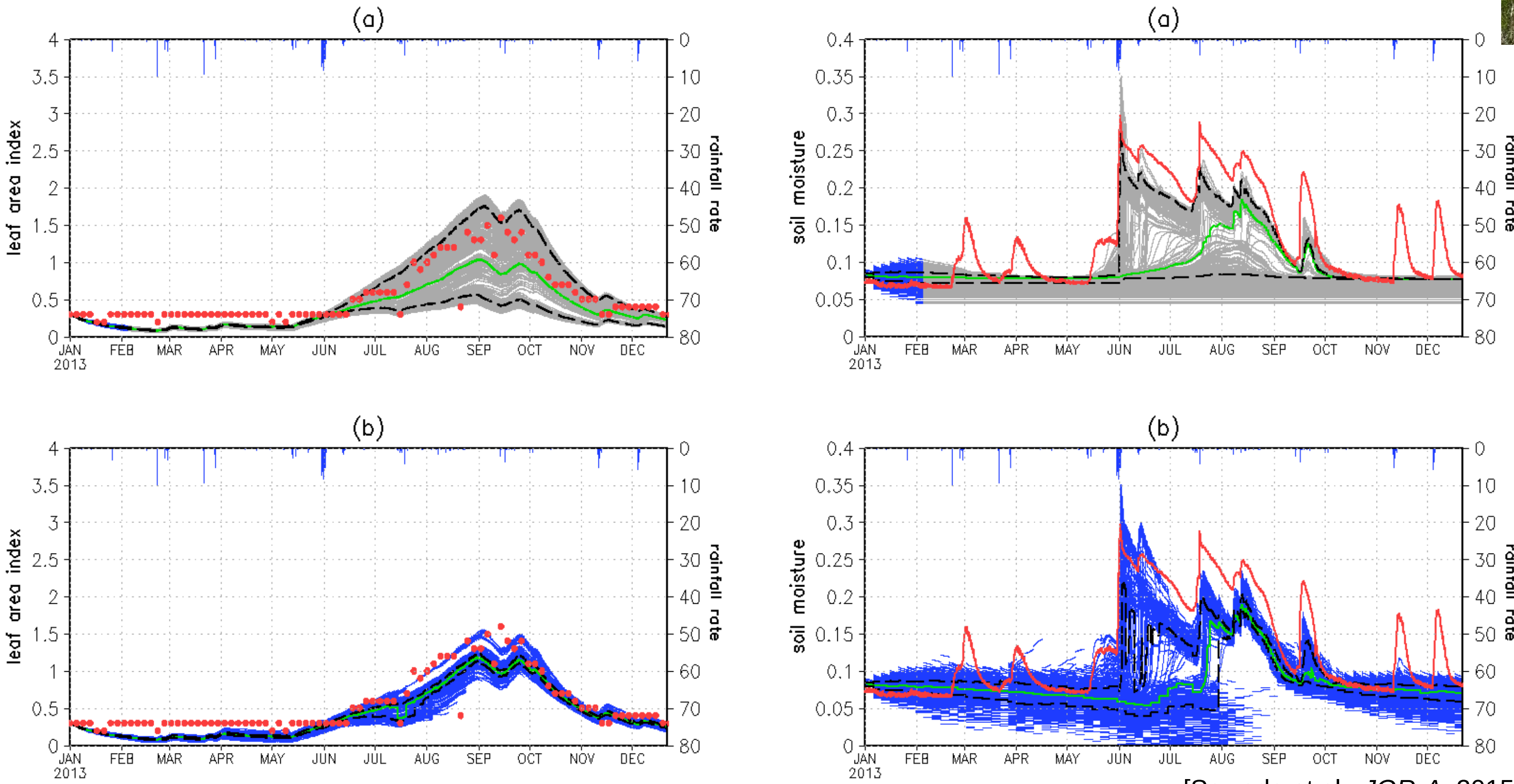


According to the ‘distance’ from satellite observed TB, calculated particles are resampled to obtain good initial conditions for next time steps

3.6.2. State adjustment (2) - Results @ Yanco, AUS

Grey: Open loop
Blue: Genetic Particle Filter
Red: observation

Leaf Area Index **10-15cm Soil Moisture**

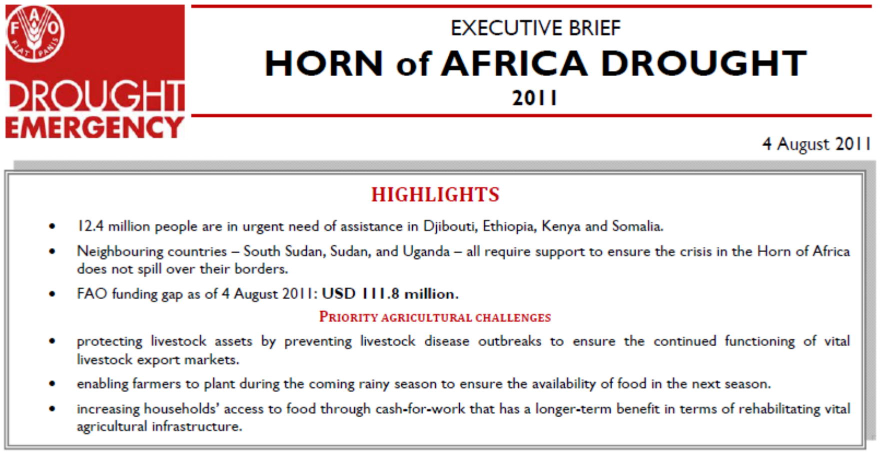


[Sawada et al., *JGR-A*, 2015]

→ We can dramatically reduce the uncertainty of LAI estimation
→We can inversely estimate root-zone soil moisture from the observation of vegetation dynamics on land surface.

4. Application to disaster monitoring and prediction

4.1. Case study: Horn of Africa drought



DROUGHT EMERGENCY

EXECUTIVE BRIEF

HORN of AFRICA DROUGHT

2011

4 August 2011

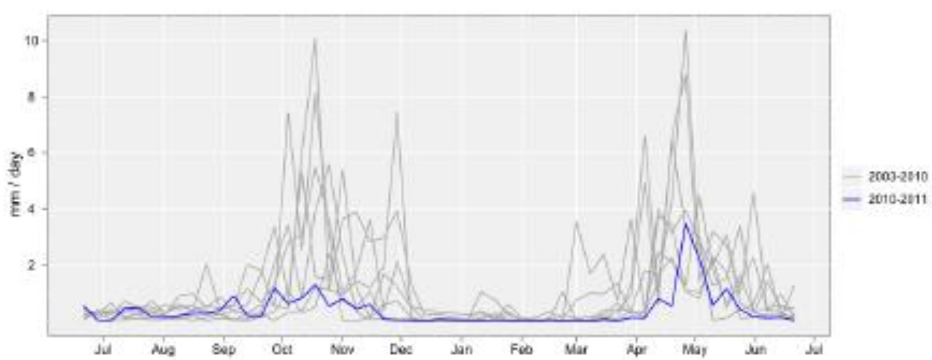
HIGHLIGHTS

- 12.4 million people are in urgent need of assistance in Djibouti, Ethiopia, Kenya and Somalia.
- Neighbouring countries – South Sudan, Sudan, and Uganda – all require support to ensure the crisis in the Horn of Africa does not spill over their borders.
- FAO funding gap as of 4 August 2011: **USD 111.8 million.**

PRIORITY AGRICULTURAL CHALLENGES

- protecting livestock assets by preventing livestock disease outbreaks to ensure the continued functioning of vital livestock export markets.
- enabling farmers to plant during the coming rainy season to ensure the availability of food in the next season.
- increasing households' access to food through cash-for-work that has a longer-term benefit in terms of rehabilitating vital agricultural infrastructure.

[FAO, 2011]

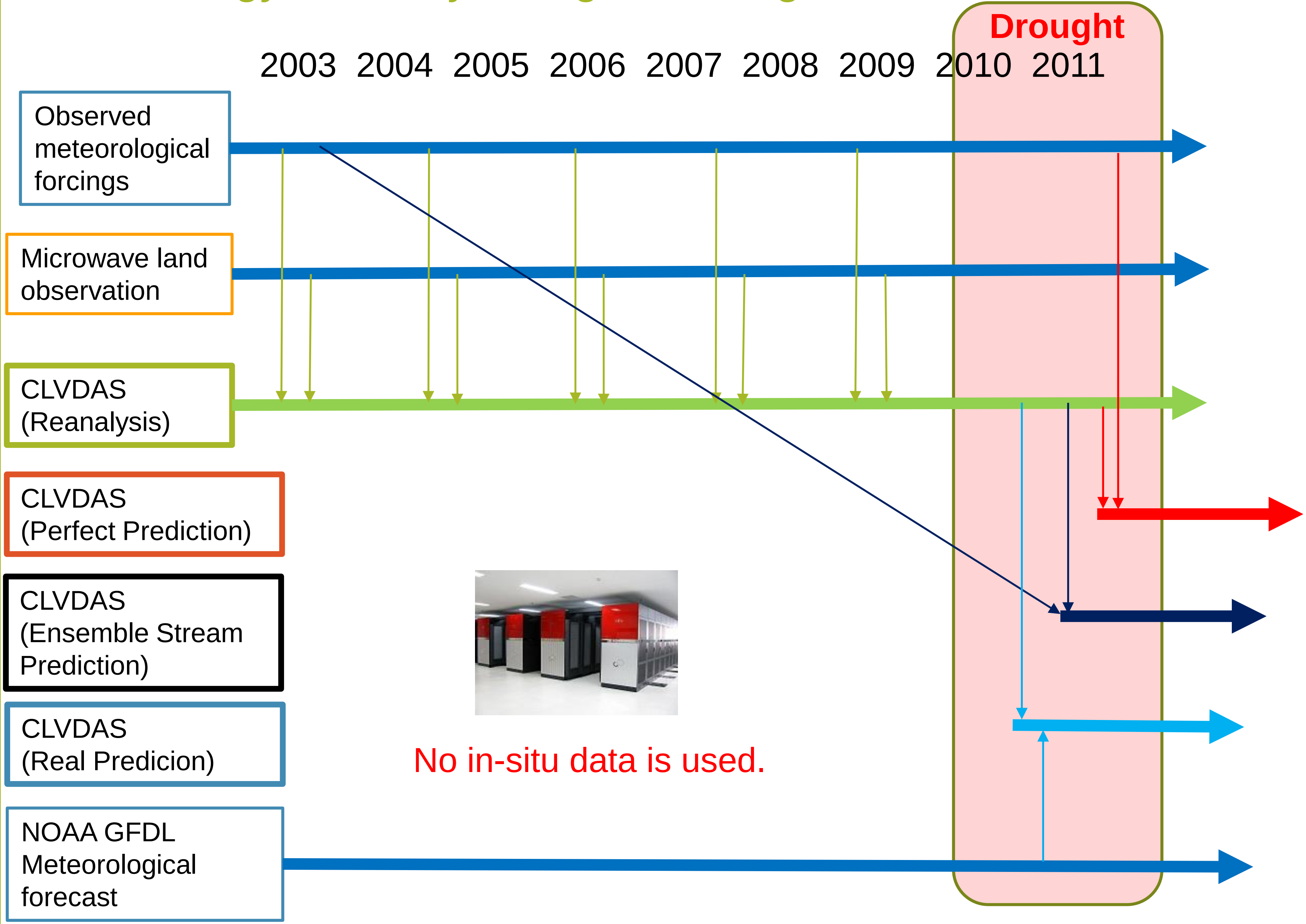


[Anderson et al., 2012]

→ Totally, 12.4 million people suffered from food shortage.

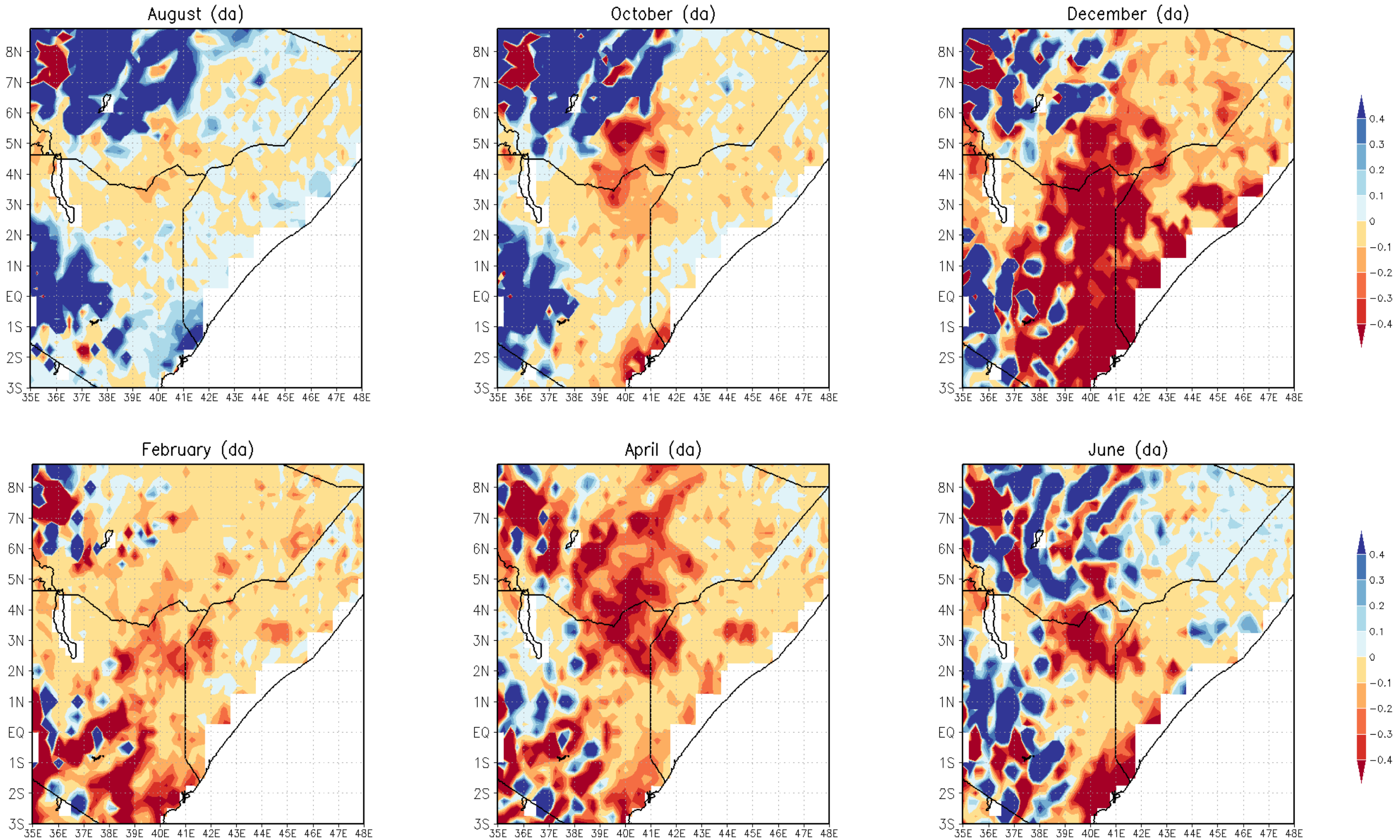
→ We cannot have the access to many ground observations to develop the drought prediction system.

4.2. Strategy of ecohydrological drought forecast



4.3.1. Results (1) 2010-2011 drought in reanalysis

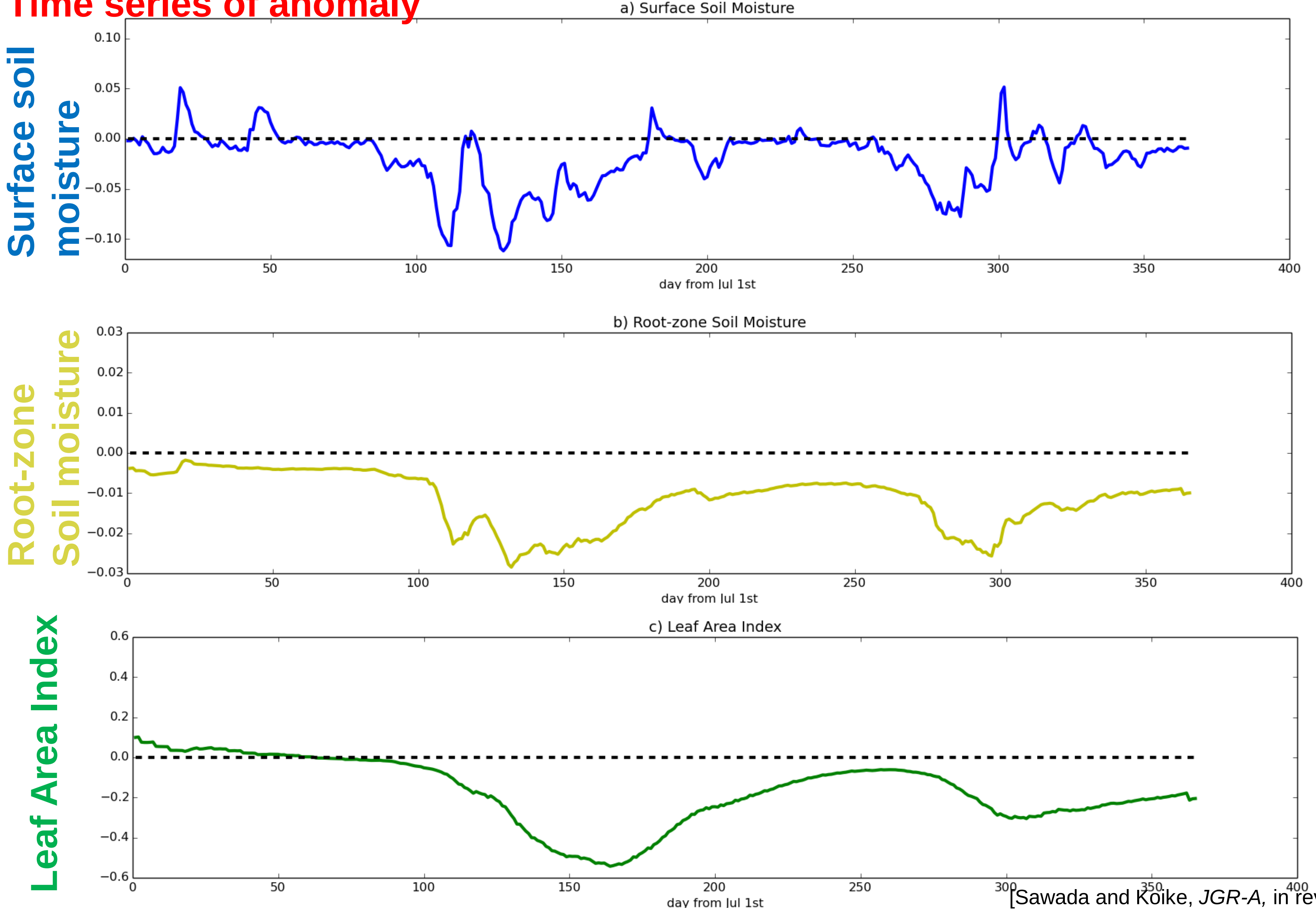
LAI anomaly of 2010-2011 droughts in “reanalysis”.



[Sawada and Koike, *JGR-A,* in revision]

4.3.2. Results (2) 2010-2011 drought in reanalysis

Time series of anomaly



[Sawada and Koike, *JGR-A*, in revision]

→ Root-zone soil moisture and LAI have longer memory of the past precipitation deficit than surface soil moisture.

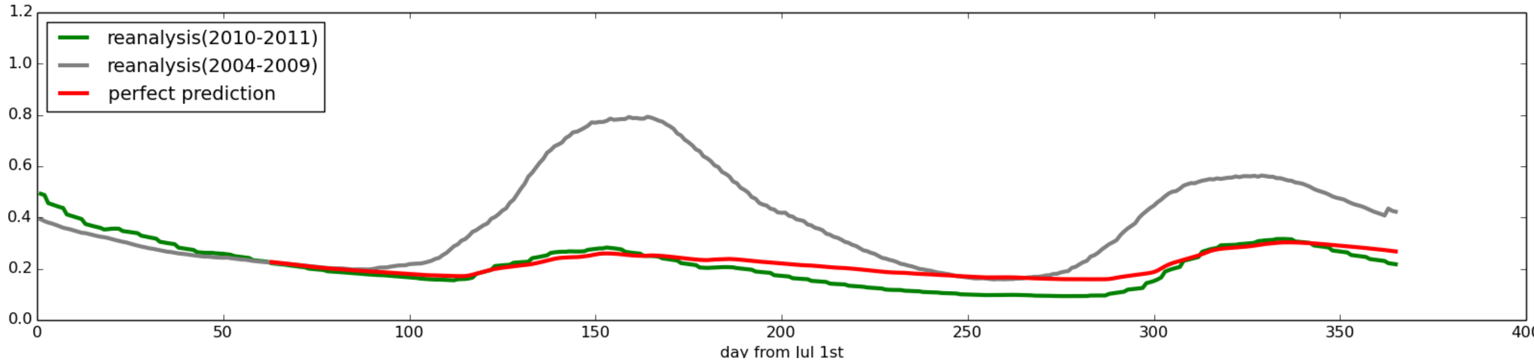
4.3.3. Results (3) Predictions: starting from 1 Sep 2010

Leaf Area Index timeseries

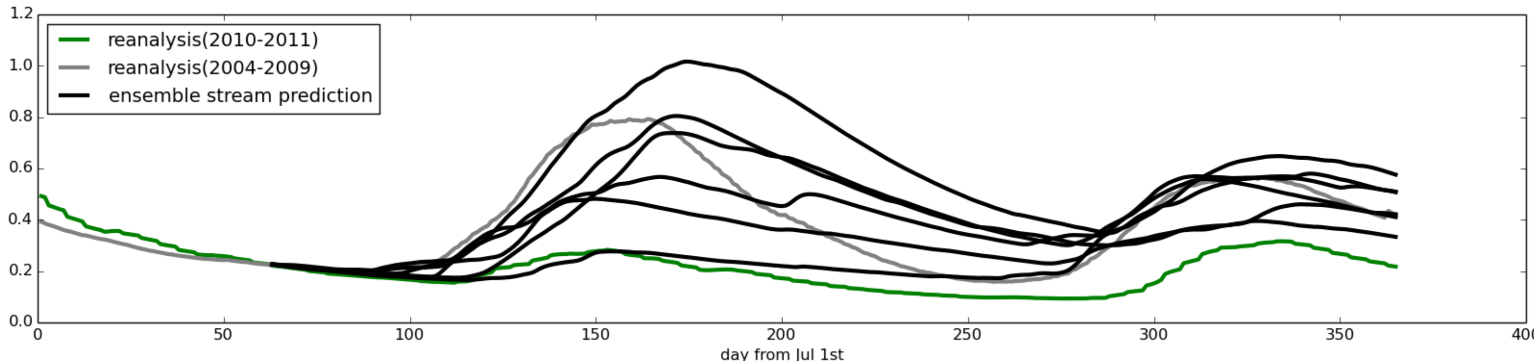
Gray: Climatorogy

Green: Horn of Africa drought (reanalysis)

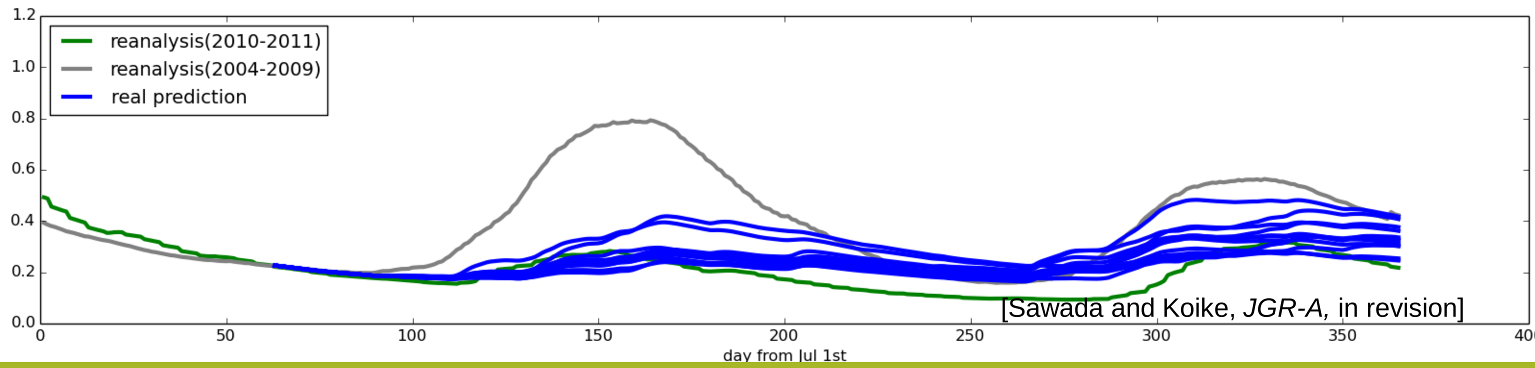
CLVDAS
(Perfect Prediction)



CLVDAS
(Ensemble Stream
Prediction)



CLVDAS
(Real Predicion)



[Sawada and Koike, *JGR-A*, in revision]

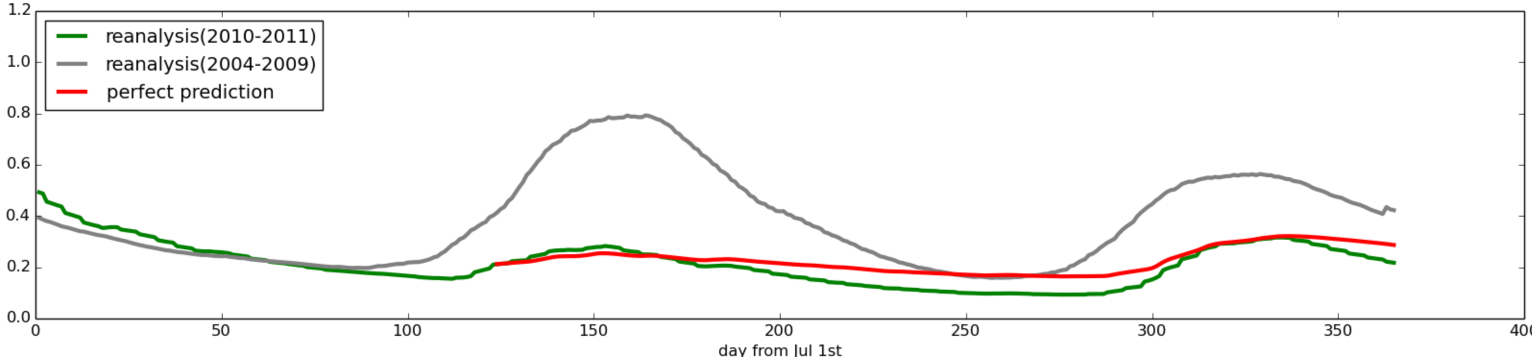
4.3.3. Results (3) Predictions: starting from 1 Oct 2010

Leaf Area Index timeseries

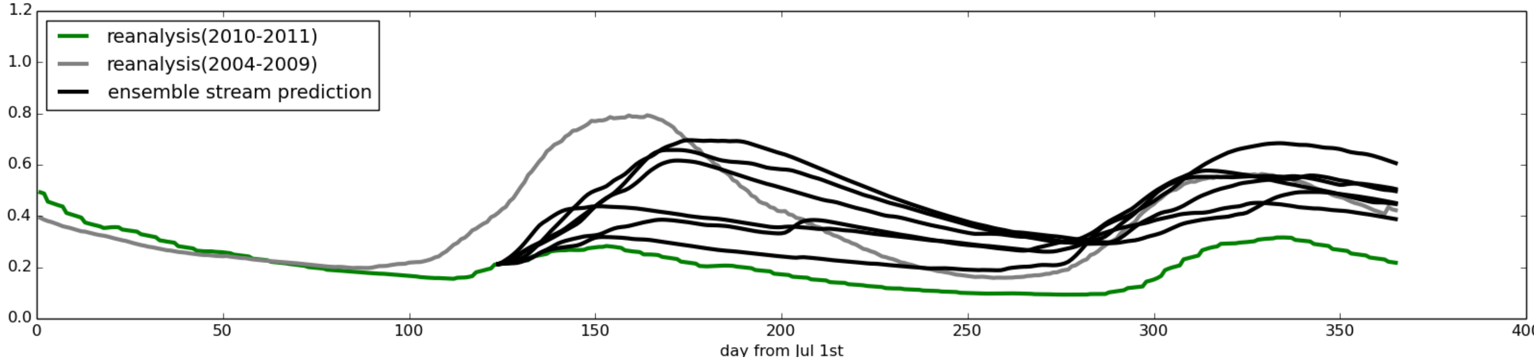
Gray: Climatorogy

Green: Horn of Africa drought (reanalysis)

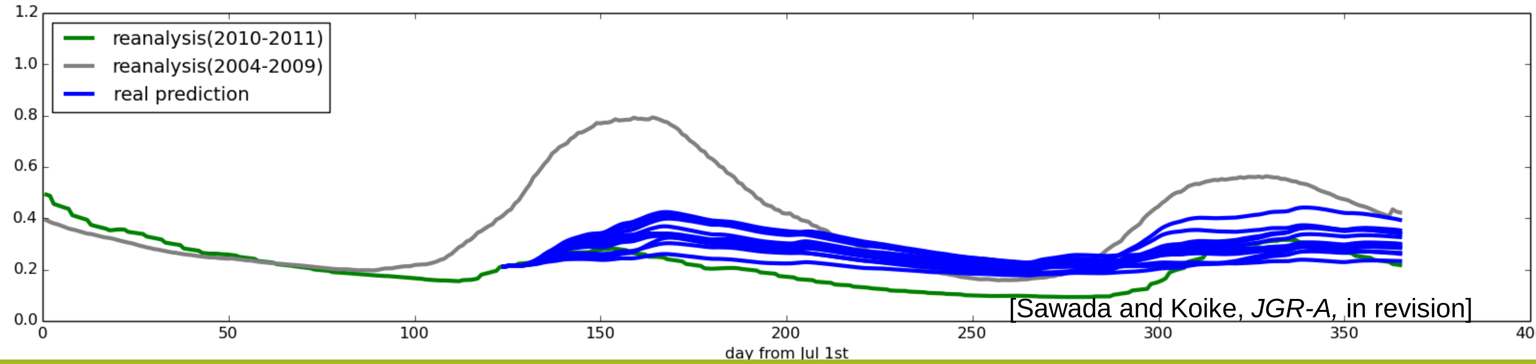
CLVDAS
(Perfect Prediction)



CLVDAS
(Ensemble Stream
Prediction)



CLVDAS
(Real Predicion)



[Sawada and Koike, *JGR-A*, in revision]

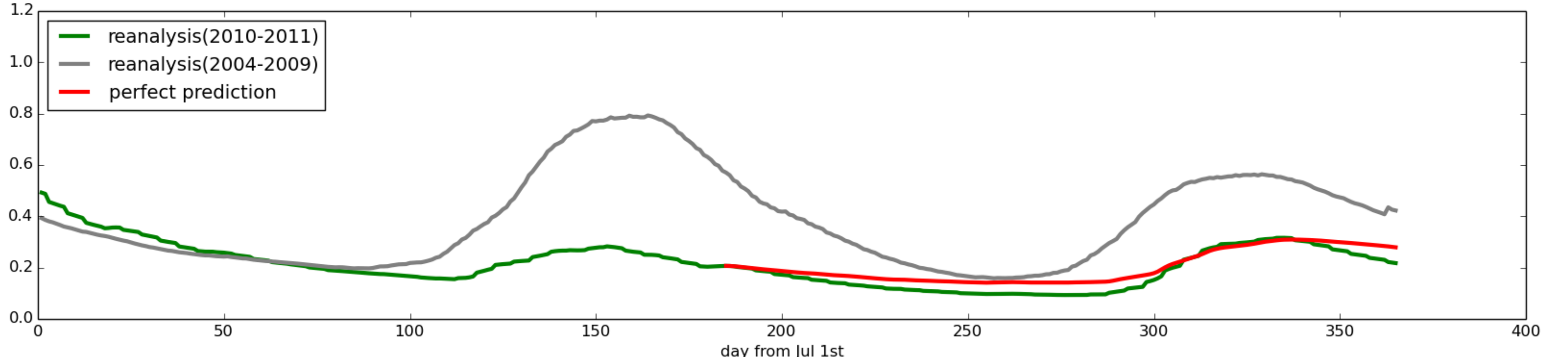
4.3.3. Results (3) Predictions: starting from 1 Jan 2011

Leaf Area Index timeseries

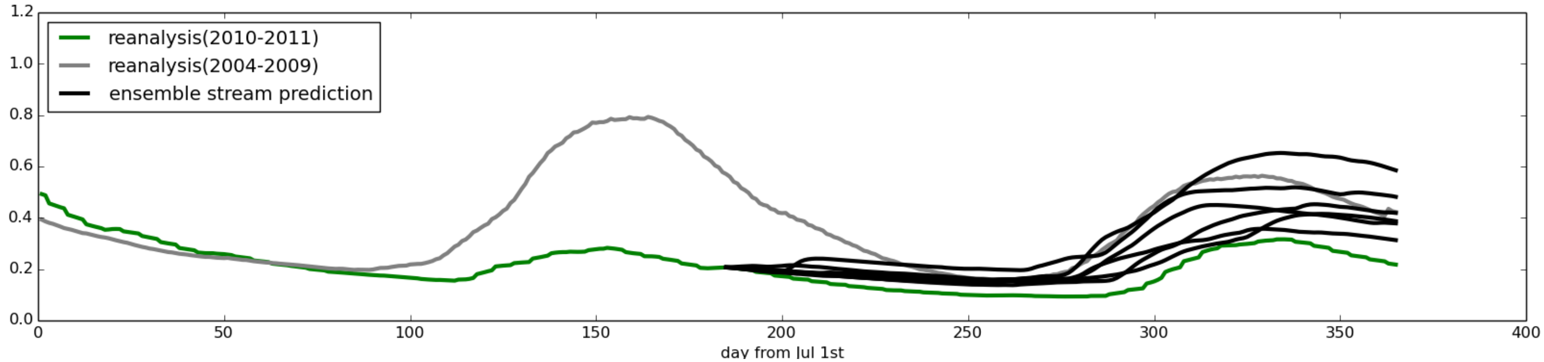
Gray: Climatorogy

Green: Horn of Africa drought (reanalysis)

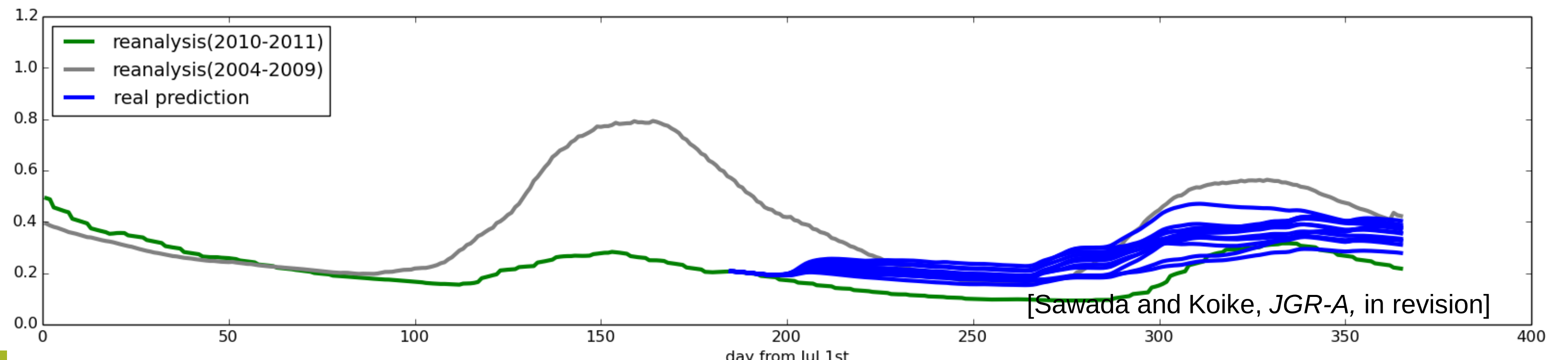
CLVDAS (Perfect Prediction)



CLVDAS (Ensemble Stream Prediction)



CLVDAS (Real Predicion)



[Sawada and Koike, *JGR-A*, in revision]

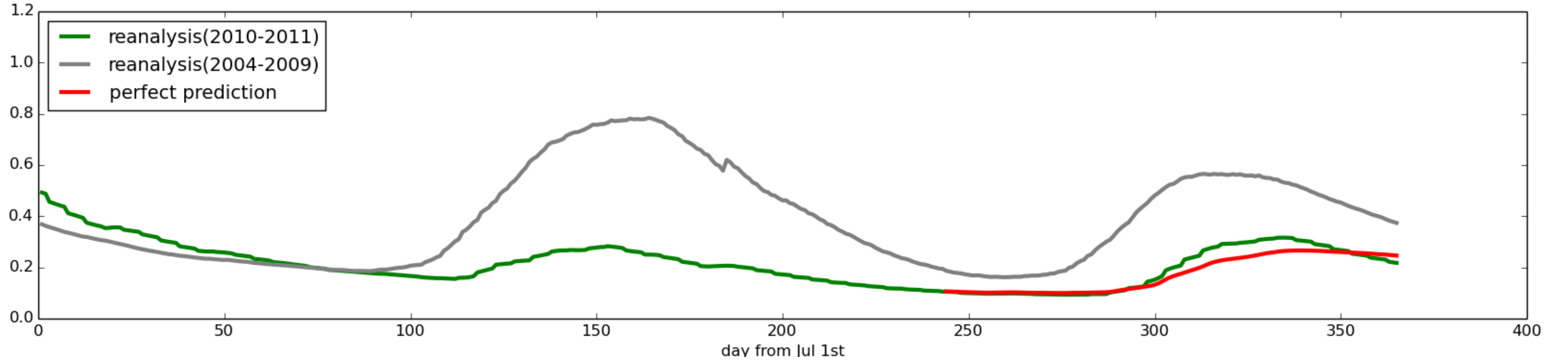
4.3.3. Results (3) Predictions: starting from 1 Mar 2011

Leaf Area Index timeseries

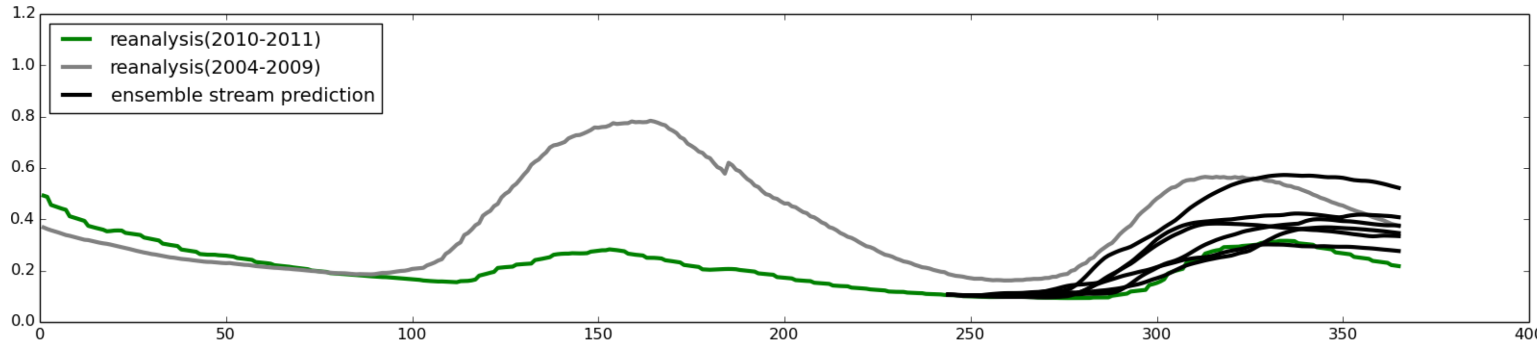
Gray: Climatorogy

Green: Horn of Africa drought (reanalysis)

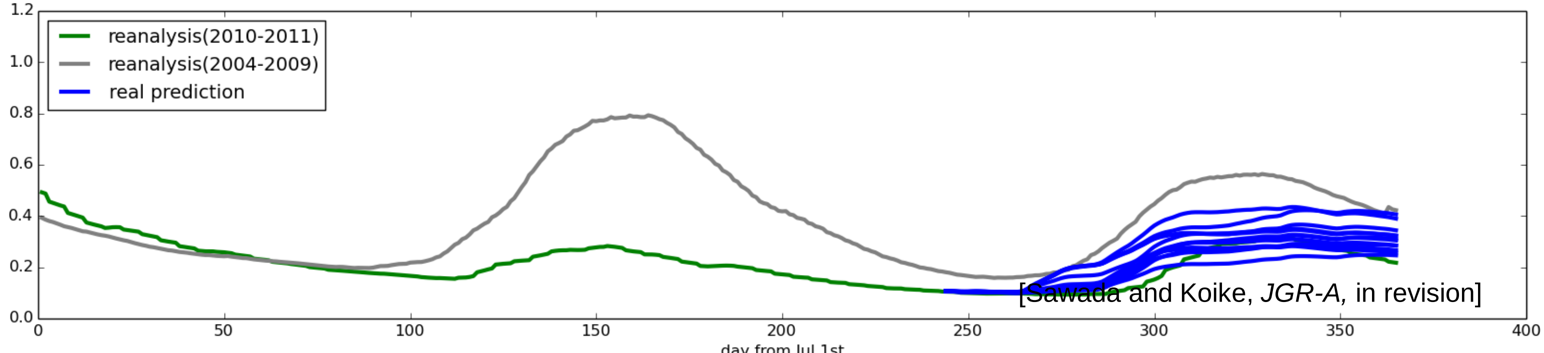
CLVDAS
(Perfect Prediction)



CLVDAS
(Ensemble Stream Prediction)



CLVDAS
(Real Predicion)



[Sawada and Koike, *JGR-A*, in revision]

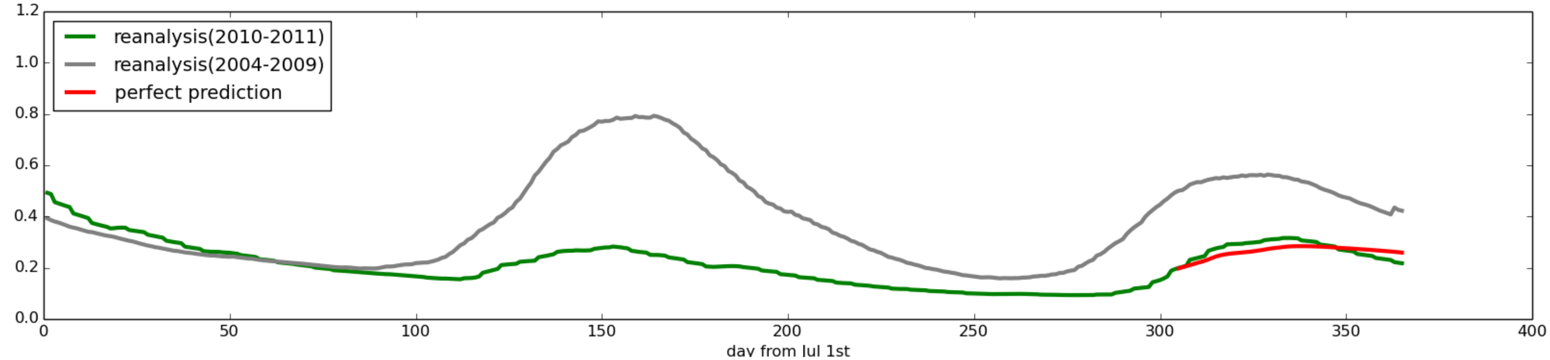
4.3.3. Results (3) Predictions: starting from 1 May 2011

Leaf Area Index timeseries

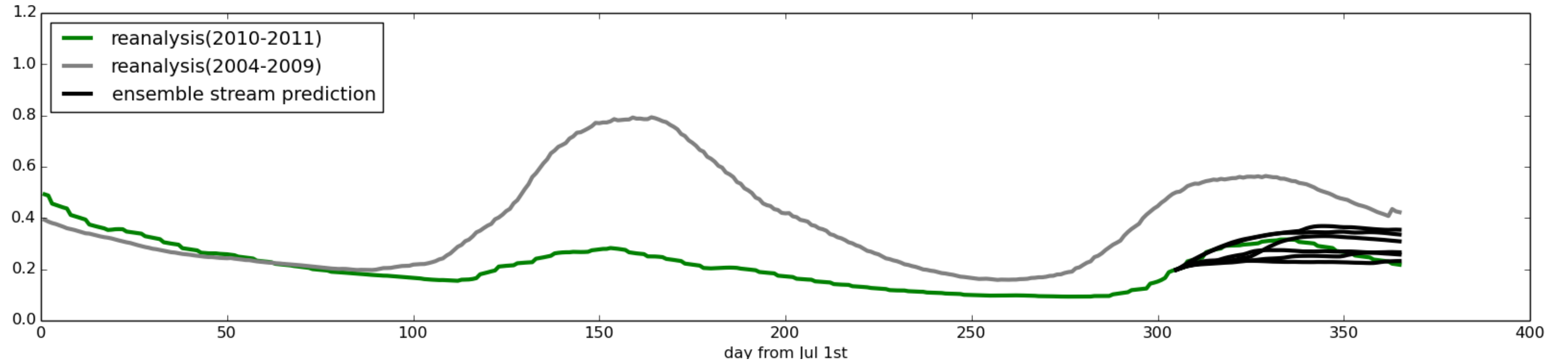
Gray: Climatorogy

Green: Horn of Africa drought (reanalysis)

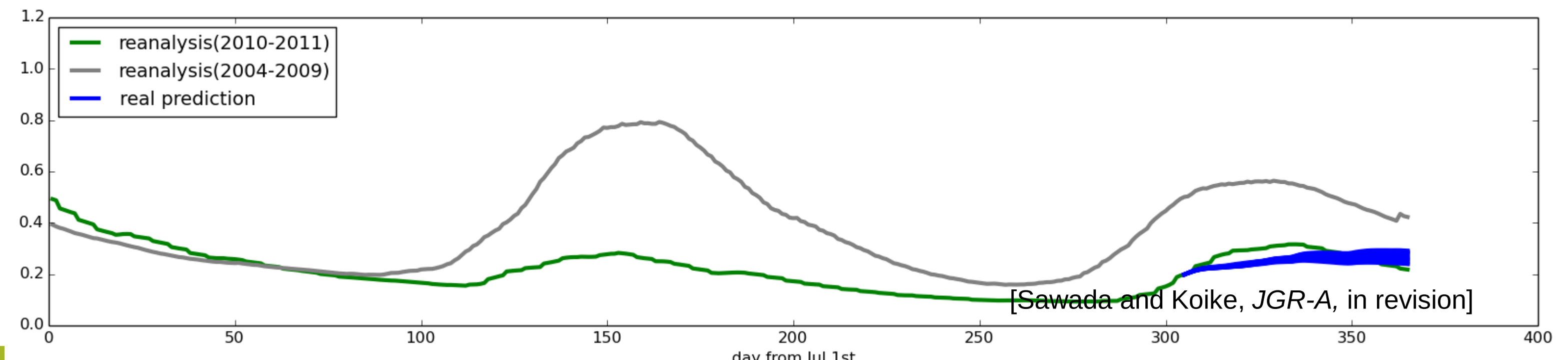
CLVDAS
(Perfect Prediction)



CLVDAS
(Ensemble Stream
Prediction)

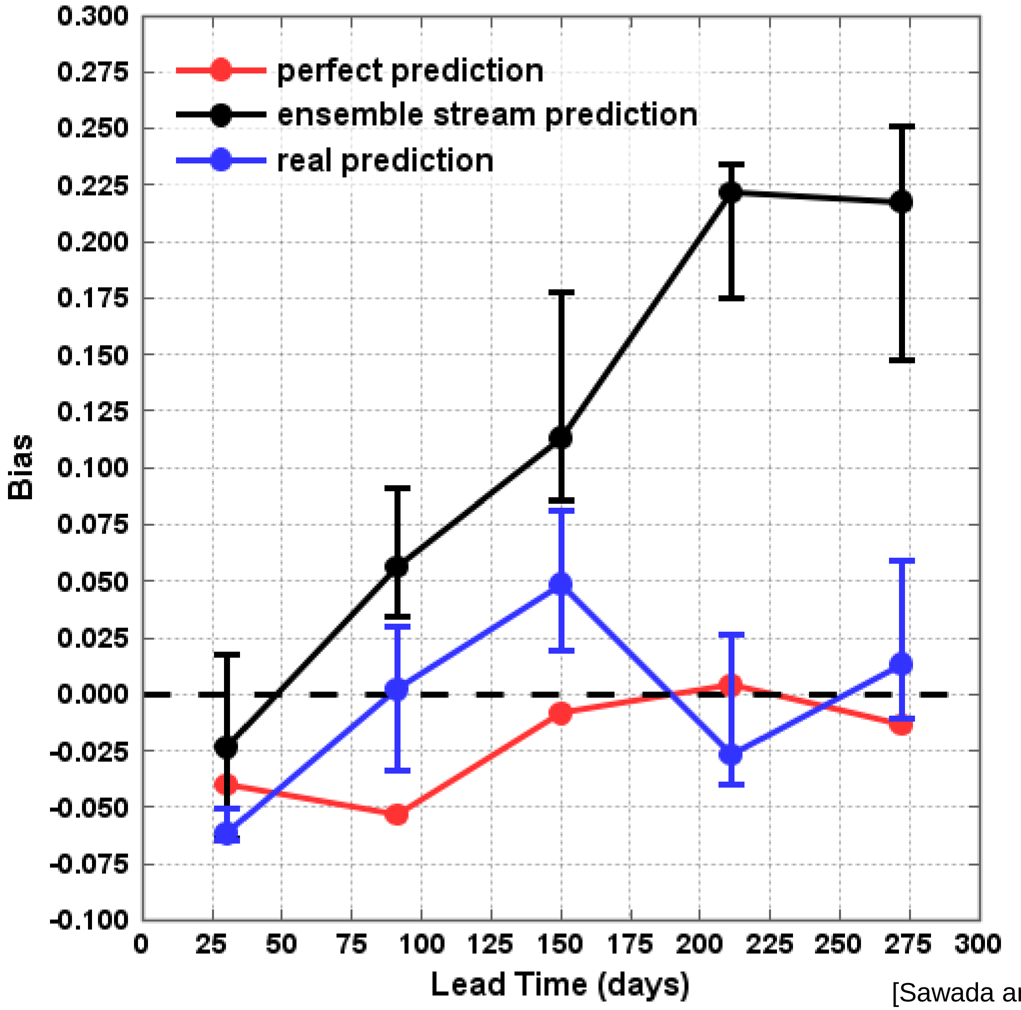


CLVDAS
(Real Predicion)



[Sawada and Koike, *JGR-A*, in revision]

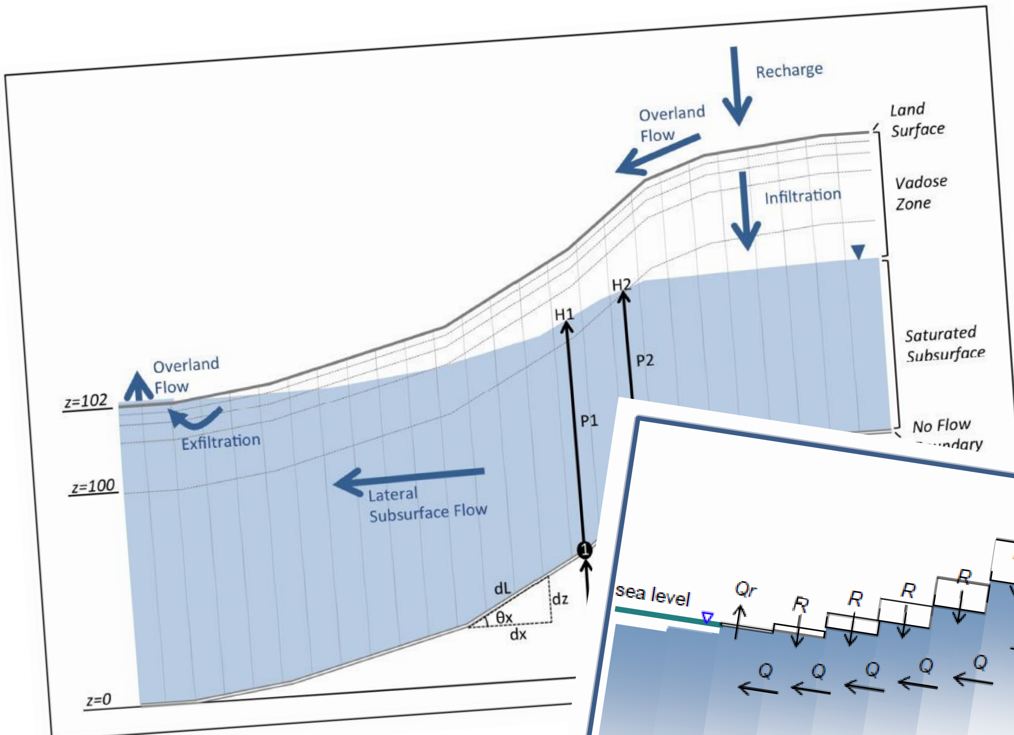
4.3.4. Summary of the skill of predicting LAI

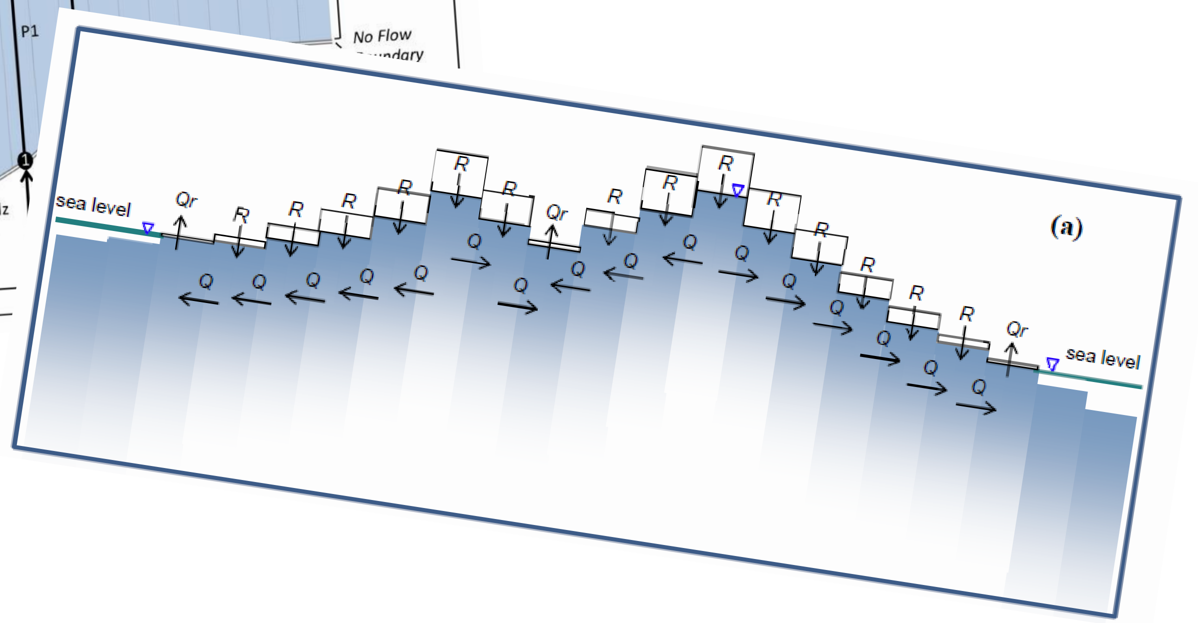


[Sawada and Koike, *JGR-A,* in revision]

→ In the prolonged drought, obtaining the initial conditions significantly contributes to predict ecological conditions in drought.

→ We can say it has already been drought before the UN's alart.



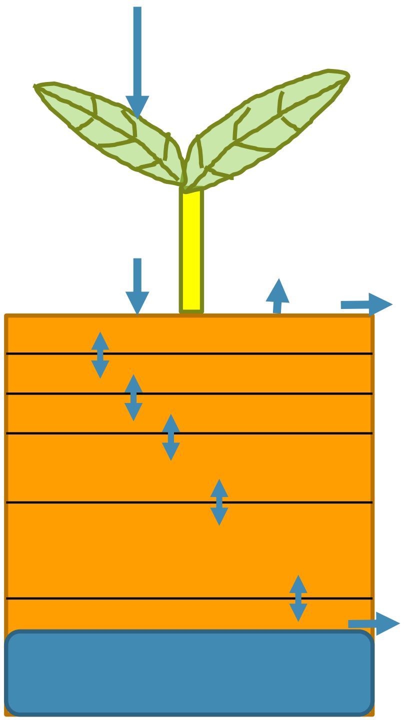


5. Future suggestion

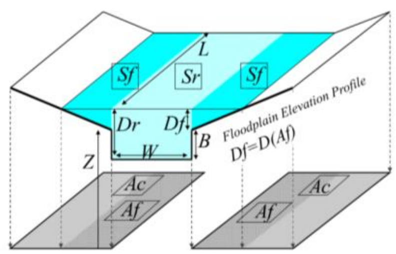
5.1. Hydrological modeling complexity

complexity

1-D LSM	1-D LSM & River routing model (offline)	1-D LSM & River routing model (online)	3-D LSM 1-D soil moisture & 2-D groundwater

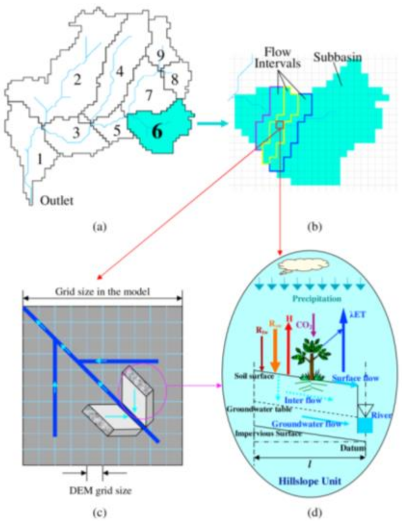


10-100km



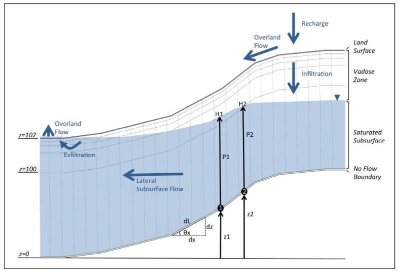
[Yamazaki et al., 2010]

10-100km
With river routing (<1km)



[Wang et al., 2009]

1km
With river routing
River-groundwater interaction



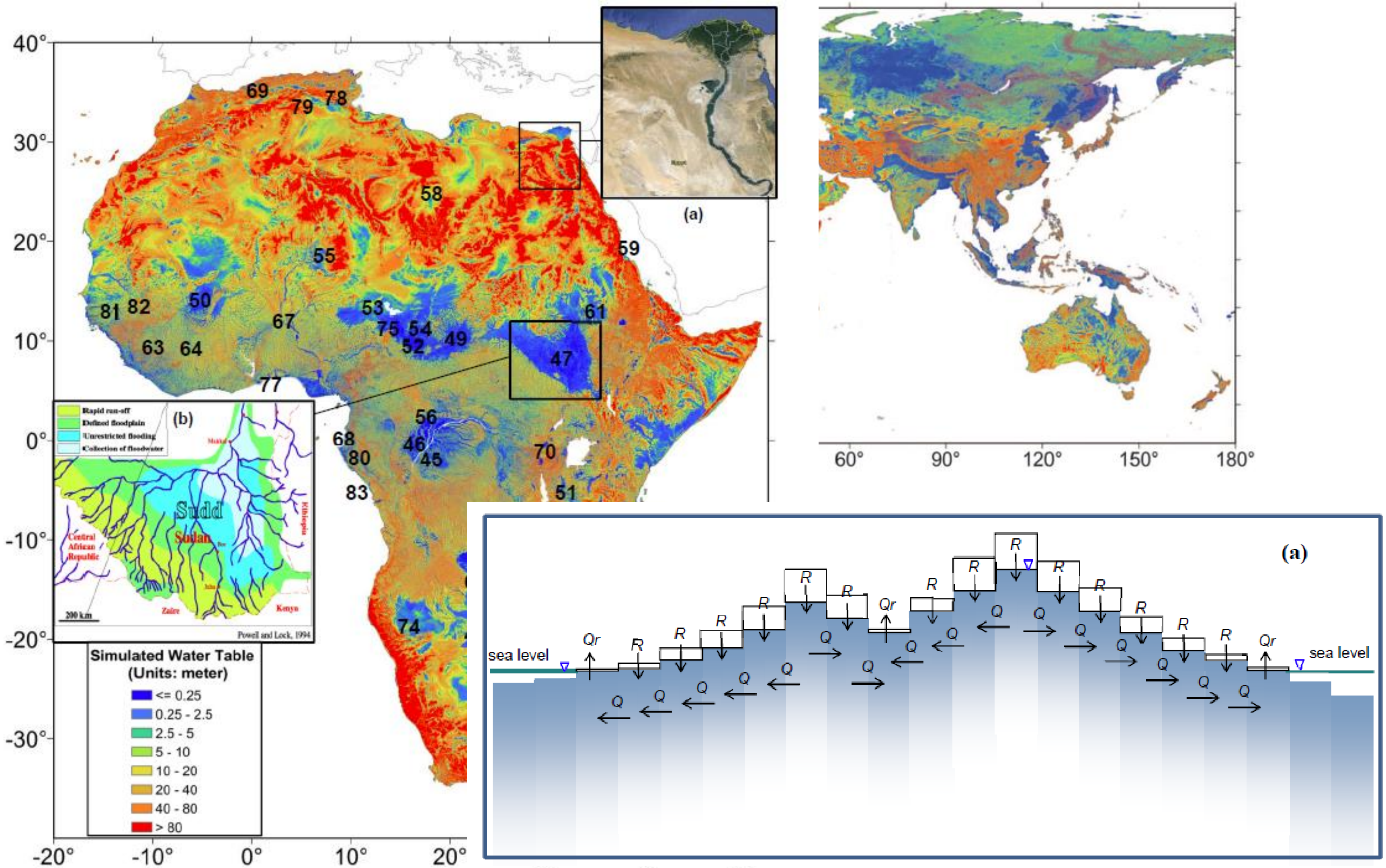
[Condon and Maxwell, 2013]

<1km
With river routing
Explicit groundwater flow

LDAS researches have focused only on simplest 1-D LSM

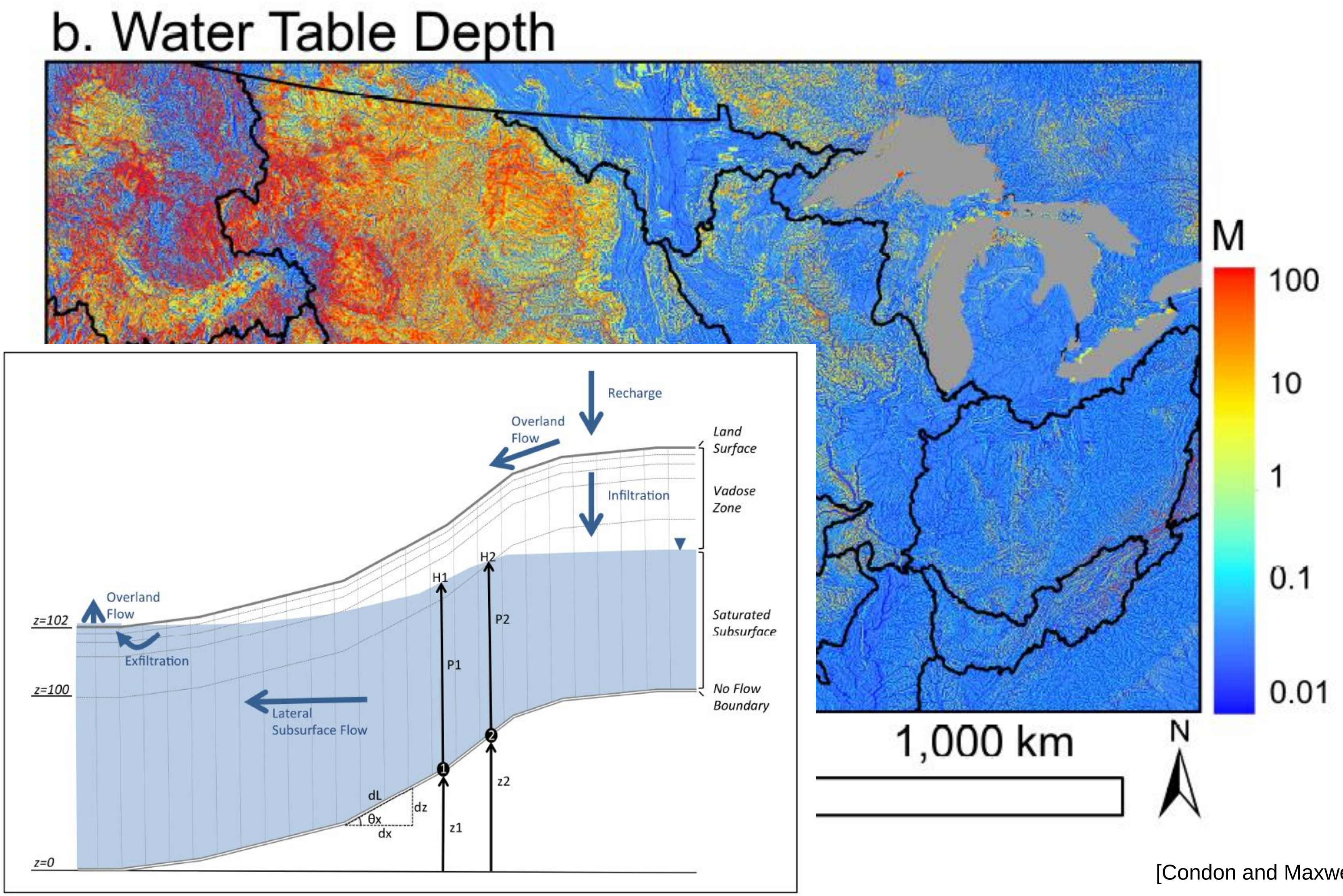
5.2.1. Hyper-resolution hydrological modeling (1)

Global groundwater simulation with horizontal resolution of 1km



[Fan et al., 2013]

5.2.2 Hyper-resolution hydrological modeling (2)



[Condon and Maxwell, 2015]

5.3. Potential benefits of hyper-resolution LDAS

- Horizontal impact of data assimilation.
- Maximizing the potential of high resolution satellite data
- Important processes which are not explicitly considered in the traditional LSM (e.g., slope driven water-plant interactions)
- Counterpart of high resolution atmospheric model (e.g., NICAM) and contribution to a study on land-atmosphere interactions.

6. Summary

- Microwave satellite observations are very useful for LDAS because of their sensitivity to soil moisture and all-weather capability.
- However, there are still many uncertainties in microwave radiative transfer on vegetated land surfaces and the products issued by JAXA and NASA may have large systematic bias.
- Our CLVDAS can improve the skill of ecohydrological LSM to simulate both soil moisture and vegetation dynamics by directly assimilating microwave brightness temperatures. We found the assimilation of vegetation dynamics positively impacted to sub-surface soil moisture estimations
- CLVDAS is useful to monitor and predict droughts in data-scarce regions.
- We are heading to hyper-resolution hydrological modeling era. Hyper-resolution LDAS might be useful to deepen our understanding of land processes.