MODELLING OF THE CARBON CYCLE IN THE GEOLAND PROJECT
Modelling of the carbon cycle in the geoland project

Contents

• Overview of geoland/ONC

• Models used in geoland/ONC
  ➢ ISBA-A-gs / C-TESSEL (Météo-France / ECMWF)
  ➢ ORCHIDEE (LSCE)

• Representation of land surface patchiness

• VALIDATION:
  ➢ LAI
  ➢ FaPAR
  ➢ water flux comparison with operational models
  ➢ ground based flux measurements
  ➢ crop production

• Data Assimilation
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Overview

The geoland project

Operational Scenario

Regional Monitoring

Global Monitoring

Core Services

Generic Land Cover

Bio-physical Parameters

Observatories

Natural Carbon Fluxes

Natural Carbon Fluxes

- Habitat Directive
- Wetlands
- ESPON
- Water Framework Directive
- Soil Protection Initiative
- Sustainable Development
- Fight against Poverty
- Global Change (Kyoto)
- Global Environment Protection

Directives Implementation

Policy Support

06.09.2005

Observatory Natural Carbon Fluxes

Jean-Christophe Calvet
Météo-France
Overview

The Observatory of Natural Carbon Fluxes of geoland

Partners

• Research partners: KNMI, LSCE, ALterra
• Service providers: ECMWF, Météo-France
• Associated user: LSCE

Objectives

• Kyoto protocol
• Transpose the tools used for weather forecast to the monitoring of vegetation and of natural carbon fluxes:
  
  Near real-time monitoring at the global scale (ECMWF) based on
  ➢ modelling,
  ➢ in situ data,
  ➢ assimilation of satellite data.
• Scientific validation of the system
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Overview

The products

• The terrestrial biospheric CO₂ flux at the soil-vegetation-atmosphere interface
• The water flux at the soil-vegetation-atmosphere interface
• The vegetation biomass
• The leaf area index
• The root-zone soil moisture
• The carbon storage.

SPATIAL RESOLUTION: ½ degree

The anthropogenic fluxes are not accounted for here: to be treated in atmospheric analysis projects (e.g. GEMS).

The fluxes produced by geoland will be used by GEMS.
STRONG PHYSICAL LINKS BETWEEN THE PRODUCTS:
All these quantities interact and need to be fully consistent, i.e. produced at the same time by a physically-based model.
Overview

Usefulness of remote sensing data

- Land use maps (e.g. ECOCLIMAP)
- Analysis of the above-ground biomass by assimilation
- Model error ➔ Bias reduction
- Atmospheric forcing ➔ Precipitation + Radiation
- Model parameters ➔ Assimilation
- Scaling issues ➔ Tiling
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Overview

Maturity

- Assimilation of Ta & qa to analyse soil moisture already operational at ECMWF and Météo-France

- Assimilation of NDVI to analyse vegetation biomass is well advanced at LSCE

- ELDAS FP5 project

- New versions of operational land surface models are able to simulate the CO₂ fluxes

- Modelling: ISBA-A-gs at Météo-France, ORCHIDEE at LSCE, both involved in the PILPS-Carbon international intercomparison exercise
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Models

Land-surface modelling: the energy budget
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Land-surface modelling: the water budget

\[ \Delta W = P - R - D_r - E \]

- Precipitation
- Runoff
- Transpiration
- Interception
- Drainage
- Soil moisture (W)
The stomatal aperture controls the ratio: 

**Photosynthesis/Transpiration** 

according to the environment conditions: 

- Light, temperature, air humidity, soil moisture, atmospheric [CO₂]
- \( qa \), \( Ta \), \( qsat \), \( Ci \), \( Cs \), \( H₂O \), \( PAR \), \( q_s \), \( T_s \)

*Land-surface modelling: the role of stomatal control*
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Models

A new version of the operational SVAT of Météo-France

**C-TESSEL (Voogt et al. 2005)**
A new version of the operational SVAT of ECMWF, based on ISBA-A-gs

**ORCHIDEE (Krinner et al. 2005)**
A research dynamic vegetation model with a high level of complexity
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Models

Met. forcing  LAI

ISBA / TESSEL  LE, H, Rn, W, Ts...

Met. forcing  LAI

ISBA-A-g_s / C-TESSEL  Active Biomass  LE, H, Rn, W, Ts...

[CO_2]_{atm}  CO_2 Flux

*ISBA-A-g_s / C-TESSEL are CO_2-responsive land surface models, new versions of operational schemes used in atmospheric models.*

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Météo-France

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Models

**Observatory Natural Carbon Fluxes**

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**ORCHIDEE is a research dynamic global vegetation model**

- **Atmosphere**
  - Prescribed or calculated by LMDZ General Circulation Model
  - Meteorological variables
    - rainfall, temperature, solar radiation, CO2 concentration...
  - Sensible and latent heat fluxes, albedo, roughness, surface temperature, CO2 flux...

- **Biosphere**
  - ORCHIDEE
    - STOMATE
      - Vegetation and soil Carbon cycle
        - Prognostic phenology and allocation
        - NPP, biomass, litterfall...
        - LAI, roughness, albedo
        - Δt = 1 day
  - SECHIBA
    - Energy budget, Hydrology + Photosynthesis
      - Soil profiles of water and temperature, GPP
      - Δt = 1 hour
  - LPJ
    - Dynamic Vegetation Model
      - Vegetation types, biomasses
      - Vegetation distribution
      - Prescribed or calculated by
        - Δt = 1 year

- **Models**
  - LMDZ
    - General Circulation Model
    - LAI, roughness, albedo
    - Soil profiles of water and temperature, GPP
    - Sensible and latent heat fluxes, albedo, roughness, surface temperature, CO2 flux...
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    - Meteorological variables
    - Vegetation distribution
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    - Δt = 1 hour, Δt = 1 day, Δt = 1 year

- **Prescribed or calculated by**
  - Meteorological variables
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  - Δt = 1 hour, Δt = 1 day, Δt = 1 year
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ISBA-A-gs / C-TESSEL

Photosynthesis

- SVAT approach (time step = minutes)

- Biochemical approach (explicit simulation of photosynthesis): *Jacobs et al. 1996*

- Big-leaf but radiative transfer within the canopy for photosynthesis and stomatal conductance
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Photosynthesis

Other global models using a biochemical approach:

SiB2 (Sellers et al. 1996)
IBIS (Foley et al. 1996)
BATS (Dickinson et al. 1998)
MOSES (Cox et al. 1998-2001)
BETHY (Knorr 2000)
ORCHIDEE (Krinner et al. 2005)
Soil water stress

- Key parameters of the photosynthesis model are affected by drought: the well-watered value are adjusted by using the Soil Wetness Index (SWI)
- 2 possible strategies: drought-avoiding / drought-tolerant:

**DROUGHT-TOLERANT**

**DROUGHT-AVOIDING**

**Crops, Grasslands**

- Mesophyll conductance $g_m$
- Max leaf-to-air saturation deficit $D_{max}$

**Trees, Shrubs**

- Mesophyll conductance $g_m$
- Max $C_i$ coupling factor $f_0$

Calvet 2000, Calvet et al. 2004
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Respiration

- Ecosystem respiration is calculated by using a simple $Q_{10}$ function depending on soil temperature.
  
  *this is enough to calculate a net CO$_2$ flux but NPP cannot be simulated*

- Autotrophic respiration is calculated for the above-ground biomass only.
- Heterotrophic respiration is not explicitly calculated in the present version.
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ISBA-A-gs / C-TESSEL

Allocation

- The **active biomass** (= leaves) is a reservoir fed by the net CO₂ uptake by leaves (i.e. An = Photosynthesis – Leaf respiration). It looses carbon following an exponential law whose e-folding time depends on the daily maximum An (parameter = max leaf span time).

- The **above-ground biomass** (non-woody) is derived from the active biomass:
  - Growing period: a logarithmic nitrogen dilution equation is used
  - Senescence: respiration losses and exponential decline
Phenology

- LAI is linearly related to the active biomass (parameters = leaf nitrogen concentration and 2 plasticity parameters)
- A minimum value of LAI is prescribed (e.g. 0.3 for annual vegetation), permitting a self restart of the vegetation when photosynthesis becomes active
- Possibility to cut the vegetation or to maintain LAI at its minimum value, for agricultural applications
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ISBA-A-gs / C-TESSEL

Phenology

*Merits of this methodology*

- Simple
- Leaf onset and offset dates don’t have to be prescribed (permitting to simulate the interannual variability and climate change effects)
- No use of empirical degree-day sums (all the factors are accounted for, not only temperature)

*Other models using this approach*

AVIM (Ji 1995, Dan et al. 2005)
STEP (Mougin et al. 1995)
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**ISBA-A-gs / C-TESSEL**

## Parameters at a global scale for the ECOCLIMAP vegetation types

<table>
<thead>
<tr>
<th>Vegetation type</th>
<th>Photosynthesis</th>
<th>Allocation/Phenology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( g_m ) (mm s(^{-1}))</td>
<td>( g_c ) (mm s(^{-1}))</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>C3 Crops</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>C4 crops</td>
<td>9</td>
<td>0.15</td>
</tr>
<tr>
<td>C3 grasslands</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>C4 grasslands</td>
<td>6</td>
<td>0.15</td>
</tr>
<tr>
<td>Coniferous forests</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Evergreen forests</td>
<td>2</td>
<td>0.15</td>
</tr>
<tr>
<td>Deciduous forests</td>
<td>3</td>
<td>0.15</td>
</tr>
</tbody>
</table>

- **Mesophyll conductance**
- **Cuticular conductance**
- **Max leaf span time**
- **Critical SWI**
- **N Plasticity parameters**
- **Leaf N**

Gibelin et al. 2005
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ISBA-A-gs / C-TESSEL

Example of Carbon flux simulations by ISBA-A-gs for Southwestern France (Toulouse)

Jean-Christophe Calvet
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<table>
<thead>
<tr>
<th>ORCHIDEE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photosynthesis</strong></td>
<td>• Biochemical approach (Farquhar, Ball &amp; Berry)</td>
</tr>
</tbody>
</table>
| **Autotrophic respiration** | • Maintenance respiration: linear response to temperature (Ruimy et al.), and possible adaptation to climate change
|                          | • Growth respiration: a fixed part of net assimilation         |
| **Heterotrophic respiration** | • CENTURY-like model                                           |
| **Allocation**          | • Allocation to leaves/stems/roots function of resources: water, light, nutrients (Tilman 1998)
|                          | • 8 pools of living biomass                                    |
| **Phenology**           | • Degree-day model for leaf onset, accounting for soil moisture, tuned at a global scale by using satellite data
|                          | • Senescence: soil moisture and temperature are accounted for  |
| **Competition**         | • Grass/tree competition and competition between tree species described in LPJ |
| **Fires**               | • Fire occurrence described in LPJ                            |
| **Carbon storage**      | • Litter (above/below ground, structural/metabolic, natural/agricultural)
|                          | • 3 soil organic matter pools (active, slow, passive)          |
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Representation of land surface patchiness

- Usefulness of tiling

Herbaceous classes of ECOCLIMAP: Mainly 4 ‘metaclasses’

- Type 1
- Type 2

Image showing maps of herbaceous classes with color-coded areas indicating different types of vegetation. The maps are labeled with coordinates and a legend indicating various types of vegetation.
Usefulness of tiling

Herbaceous classes of ECOCLIMAP:
Fraction of type 2 can be high

8 tiles:
- bare soil (and rock/snow)
- Deciduous forests
- Coniferous forests
- Evergreen forests
- grass C3
- grass C4
- crops C3
- crops C4
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VALIDATION: LAI

Yearly maximum of LAI

Gibelin et al. 2005

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VALIDATION: LAI

Zonal mean of the maximum of LAI

Gibelin et al. 2005
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VALIDATION: LAI

Correlation of the monthly LAI anomaly (difference between monthly LAI and the mean annual cycle) between ISBA-A-gs and the ISLSCP-II data (1986-1995).

Gibelin et al. 2005

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VALIDATION: LAI

Monthly time series of LAI from ISBA-A-gs and ISLSCP-II over Southern Africa [-35°N:-15°N, 10°E:40°E]

Gibelin et al. 2005

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VALIDATION: LAI

Sahel

Relative anomaly of LAI (%) versus precipitation anomaly (mm d⁻¹)
(blue boxes: ISLSCP2 ; red dots: ISBA-A-gs ; green bars: precipitation)

Southern Africa

Gibelin et al. 2005

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VALIDATION: LAI

Start of the growing season (mean 1986-1995) simulated by ISBA-A-gs and observed in ISLSCP-II

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VALIDATION: FaPAR

2003 FaPAR anomaly:

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VALIDATION: water flux comparison with operational models

**ISBA standard**

**ISBA standard – ISBA-A-gs**

Comparison of the evapo-transpiration flux (JJA) of ISBA and ISBA-A-gs

A.-L. Gibelin

Jean-Christophe Calvet

Météo-France
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VALIDATION: ground-based flux measurements

Validation of the ORCHIDEE fluxes by using more than 30 FLUXNET sites: Average diurnal cycle
Validation of the ORCHIDEE fluxes by using more than 30 FLUXNET sites: Average seasonal cycle
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VALIDATION: crop production

1900-2000 crop production simulated by the STICS module of ORCHIDEE over Europe: the management effect

N. Viovy
06.09.2005
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VALIDATION: crop production

Wheat yield (t ha\(^{-1}\)) estimated by ISBA-A-gs for the area of Toulouse, by assuming a Harvest Index of 0.5

<table>
<thead>
<tr>
<th>Year</th>
<th>Spring Wheat</th>
<th>Winter Wheat</th>
<th>Observation for Midi-Pyrénées</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>5.3</td>
<td>6.2</td>
<td>-</td>
</tr>
<tr>
<td>2002</td>
<td>6.2</td>
<td>6.2</td>
<td>5.9</td>
</tr>
<tr>
<td>2003</td>
<td>4.2</td>
<td>4.8</td>
<td>4.6</td>
</tr>
<tr>
<td>2004+</td>
<td>4.6</td>
<td>5.8</td>
<td>5.7</td>
</tr>
</tbody>
</table>
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geoland project

VALIDATION: crop production

Maize yield (t ha\(^{-1}\)) estimated by ISBA-A-gs for the area of Toulouse, by assuming a Harvest Index of 0.5
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Data Assimilation

The variational approach

Formalism: Minimization of a cost function

\[ J(x) = J^b(x) + J^o(x) \]

\[ = \frac{1}{2} (x - x^b) \mathbf{B}^{-1} (x - x^b) + \frac{1}{2} (y - H(x))^T \mathbf{R}^{-1} (y - H(x)) \]

- \( x \) is the control variables vector
- \( y \) is the observation vector
- \( H \) is the observation operator

The analysis is obtained by the minimization of the cost function \( J(x) \)

- \( \mathbf{B} \) is the background error covariance matrix
- \( \mathbf{R} \) is the observation error covariance matrix

⇒ Literal solution for linear model:

\[ x^a = x^b + K(y-Hx^b) \]

with \( K = BHT(HBH^T+R)^{-1} \)
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Data Assimilation

A simplified algorithm (adapted from Balsamo and Bouyssel)

From a perturbation of the initial total biomass $\delta B_{\text{init}}$ applied on each model land grid-point.

Guess $G$

Guess $G'$

$\delta B_{\text{init}}$

$B_{\text{init}} = B_{\text{init}} + \delta B_{\text{init}}$

$\delta \text{LAI (i)} = \text{LAI}_G(i) - \text{LAI}_G'(i)$

Numerical linearization of the observation operator $H$
Two main hypotheses have to be validated

- **TL** (linearity)
  - Minimization of the cost function with a look up table ...
  - ... + comparison to a sequential stochastic approach
    (Ensemble Kalman Filter, not shown)

- **2D** (horizontal decoupling)
  - Verified at our spatial scale?
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Data Assimilation

Application to the SMOSREX fallow

- Analysis of Biomass thanks to in situ LAI observations (10 days analysis period)
  - Perfect LAI correction
  - Overall good Biomass analysis (particularly in 2002)
  - Low impact on w2 (different LAI → different root water extraction and transpiration rates)

L. Jarlan

Observatory Natural Carbon Fluxes

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Data Assimilation

Application to the SMOSREX fallow

- Analysis of Biomass and \( \text{w2} \) thanks to in situ LAI observations (10 days analysis period)

- Perfect LAI correction
- Overall good Biomass analysis
- High scattering of analysed \( \text{w2} \) ...
- ... but \( \text{w2} \) better in agreement with observations during high water stress period
Prospects

• ISBA-A-gs / C-TESSEL (Météo-France / ECMWF)
  ➢ Roots
  ➢ Wood
  ➢ Soil carbon
  ➢ NPP

• Representation of land surface patchiness
  ➢ Regional applications (5-10 km) at Météo-France and LSCE

• VALIDATION:
  ➢ Test of C-TESSEL global simulations of LAI
  ➢ Test of ISBA-A-gs and C-TESSEL using the FLUXNET data

• Data Assimilation
  ➢ Global assimilation of LAI products in ORCHIDEE and C-TESSEL
Thank you for your attention!

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Co-funded by the European Commission within the GMES initiative in FP-6