JULES meeting on forest processes 19-20 June 2013

JULES and CTESSEL: Representing carbon and energy fluxes in forests

Andrea Manrique Suñén

University of Reading
Emily Black, Anne Verhoef
Gianpaolo Balsamo and Souhail Boussetta
Outline

1. Model descriptions JULES vs CTESSEL
   • Tiles
   • Surface energy balance
   • Photosynthesis

2. Model results for a forest site
   • Energy fluxes
   • Carbon fluxes
1. Model description: Tiles

<table>
<thead>
<tr>
<th>Index</th>
<th>Vegetation type</th>
<th>H/L</th>
<th>$r_{s,min}$ (sm$^{-1}$)</th>
<th>$c_{veg}$</th>
<th>$gD$ (hPa$^{-1}$)</th>
<th>$a_r$</th>
<th>$b_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crops, mixed farming</td>
<td>L</td>
<td>100</td>
<td>0.90</td>
<td>5.558</td>
<td>2.614</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Short grass</td>
<td>L</td>
<td>100</td>
<td>0.85</td>
<td>10.739</td>
<td>2.608</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Evergreen needleleaf trees</td>
<td>H</td>
<td>250</td>
<td>0.90</td>
<td>6.706</td>
<td>2.175</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Deciduous needleleaf trees</td>
<td>H</td>
<td>250</td>
<td>0.90</td>
<td>7.066</td>
<td>1.953</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Deciduous broadleaf trees</td>
<td>H</td>
<td>175</td>
<td>0.90</td>
<td>5.990</td>
<td>1.955</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Evergreen broadleaf trees</td>
<td>H</td>
<td>240</td>
<td>0.99</td>
<td>7.344</td>
<td>1.363</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Tall grass</td>
<td>L</td>
<td>100</td>
<td>0.70</td>
<td>8.235</td>
<td>1.627</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Desert</td>
<td>–</td>
<td>250</td>
<td>0</td>
<td>4.372</td>
<td>0.978</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Tundra</td>
<td>L</td>
<td>50</td>
<td>0.50</td>
<td>8.992</td>
<td>8.992</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Irrigated crops</td>
<td>L</td>
<td>180</td>
<td>0.90</td>
<td>5.558</td>
<td>2.614</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Semidesert</td>
<td>L</td>
<td>150</td>
<td>0.10</td>
<td>4.372</td>
<td>0.978</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Ice caps and glaciers</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Bogs and marshes</td>
<td>L</td>
<td>240</td>
<td>0.60</td>
<td>7.344</td>
<td>1.363</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Inland water</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Ocean</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Evergreen shrubs</td>
<td>L</td>
<td>225</td>
<td>0.50</td>
<td>6.326</td>
<td>1.567</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Deciduous shrubs</td>
<td>L</td>
<td>225</td>
<td>0.50</td>
<td>6.326</td>
<td>1.567</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Mixed forest/woodland</td>
<td>H</td>
<td>250</td>
<td>0.90</td>
<td>4.533</td>
<td>1.631</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Interrupted forest</td>
<td>H</td>
<td>175</td>
<td>0.90</td>
<td>4.533</td>
<td>1.631</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Water and land mixtures</td>
<td>L</td>
<td>150</td>
<td>0.60</td>
<td>0</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

CTESSEL
- High vegetation
- Low vegetation
- Snow on high vegetation
- Exposed snow
- Interception reservoir
- Bare ground
- Lake (LAKEHTESSEL)
Surface energy balance

**JULES**

\[
\frac{C_s}{\partial t} \delta T^*_s = (1 - \alpha) S_w \downarrow + \varepsilon (L_w \downarrow - \sigma T^*_s^4) - H - LE - G
\]

\[
H = \frac{\rho c_p}{r_a} (T_s - T_A)
\]

\[
G = \nu [\sigma \varepsilon \varepsilon_s T_s^4 - \sigma \varepsilon \varepsilon_s T_{s1}^4] + \frac{\rho c_p}{r_{a,con}} (T_s - T_{s1}) + (1 - \nu) \lambda_{sat} (T_s - T_{s1})
\]

\[
E = \frac{\rho}{r_a + r_s} (q_{sat}(T_s) - q_1)
\]

**CTESSEL**

\[
0 = (1 - f_{Rs}) (1 - \alpha) S_w \downarrow + \varepsilon (L_w \downarrow - \sigma T_{sk}^4) + H + LE - G
\]

\[
H = \frac{\rho c_p}{r_a} \left( T_A - \frac{g z}{c_L} - T_{sk} \right)
\]

\[
G = A_{sk} (T_{sk} - T_{s1})
\]

\[
E = \frac{\rho}{r_a + r_s} (q_1 - q_{sat}(T_{sk}))
\]

Radiative

Turbulent

Conductive

Skin conductivity
# Photosynthesis

## JULES
- A-\(g_s\) scheme
- Differentiates C\(_3\) and C\(_4\) photosynthesis
- Soil moisture stress applied to leaf level net assimilation
- T dependence with \(Q_{10}\) functions
- Scaling from leaf level photosynthesis:
  1. Big leaf approach
  2. Multilayer approach

## CTESSEL
- A-\(g_s\) scheme
- Only one type
- Soil moisture stress applied to mesophyll conductance
  - Low vegetation formulation
  - High vegetation formulation
- T dependence with \(Q_{10}\) functions
- Big leaf approach with differentiation between direct and diffuse radiation
Leaf level photosynthesis

**JULES:** Potential gross photosynthesis is obtained combining 3 regimes:

1. **Rubisco-limited rate**

   \[
   W_c = \begin{cases} 
   V_{c_{\text{max}}} \left( \frac{c_i - \Gamma}{c_i + K_c + \left( 1 + \frac{Q_o}{K_o} \right) \alpha} \right) & \text{for } C_3 \\
   V_{c_{\text{max}}} & \text{for } C_4 
   \end{cases}
   \]

   - \( V_{c_{\text{max}}} \): max rate of carboxylation of Rubisco
   - \( c_i \): Internal \( CO_2 \) partial pressure
   - \( Q_o \): Partial pressure of \( O_2 \)
   - \( c_i \): Compensation point
   - \( K_c, K_o \): Michelis-Menten parameters

2. **Light-limited rate**

   \[
   W_l = \begin{cases} 
   \alpha(1 - \omega)I_{\text{par}} \left( \frac{c_i - \Gamma}{c_i + 2\Gamma} \right) & \text{for } C_3 \\
   \alpha(1 - \omega)I_{\text{par}} & \text{for } C_4 
   \end{cases}
   \]

   - \( \alpha \): Quantum efficiency of photosynthesis
   - \( I_{\text{par}} \): Incident photosynthetically active radiation
   - \( \omega \): leaf scattering coefficient

3. **Rate of transport of photosynthetic products (C\(_3\)) and PEPCarboxylase limitation (C\(_4\))**

   \[
   W_e = \begin{cases} 
   0.5 V_{c_{\text{max}}} & \text{for } C_3 \\
   2 \times 10^4 V_{c_{\text{max}}} \left( \frac{c_i}{P_s} \right) & \text{for } C_4 
   \end{cases}
   \]

   - \( P_s \): Surface air pressure

\( V_{c_{\text{max}}}, \Gamma, K_c, K_o \) depend on temperature according to \( Q_{10} \) functions
Leaf level photosynthesis

**JULES**

Soil moisture stress

\[ A_l = \beta A_p \]

\[
\beta = \begin{cases} 
1 & \text{for } \theta > \theta_c \\
\frac{\theta - \theta_w}{\theta_c - \theta_w} & \text{for } \theta_w < \theta \leq \theta_c \\
0 & \text{for } \theta \leq \theta_w 
\end{cases}
\]
Canopy level photosynthesis

1. **Big leaf** (can_rad_mod=1)
   - Radiation is attenuated according to Beer’s law
   - Photosynthetic rate integrated to LAI
   \[
   A_c = \int_0^{L_c} A_t dL
   \]

2. **Multi-layer** (can_rad_mod=2)

3. **Multi-layer** (can_rad_mod=3)
   - Differentiation of shaded and sunlit leaves

4. **Multi-layer** (can_rad_mod=4)
   - Exponential profile of canopy nitrogen
   - Inhibition of leaf respiration in the light

5. **Multi-layer** (can_rad_mod=5)
   - Sunfleck penetration
   - Inhibition of leaf respiration in the light
Leaf level photosynthesis

1. **Radiation limiting regime**

\[ A_n = \varepsilon I_a - R_d \]

\( \varepsilon \): Quantum efficiency

2. **CO₂ limiting regime**

\[ A_m = \frac{c_i - \Gamma}{g_m} \]

\( c_i \): Internal CO2 concentration
\( \Gamma \): Compensation point
\( g_m \): Mesophyll conductance
Leaf level photosynthesis


Driven by:
• Mesophyll conductance
• Maximum specific humidity deficit tolerated by the vegetation
• Ratio $c_s/c_i$

Different formulation for high and low vegetation
Canopy level photosynthesis

Radiation attenuation according to Beer’s law with differentiation between diffuse and direct radiation

\[ I_a(z) = I_0 (1 - K(z)) \]

**\( K(z) \)** Extinction function

\[ K(z) = \delta(\mu_s)K_{df}(z) + (1 - \delta(\mu_s)K_{dr}(z)) \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_0 )</td>
<td>Radiation above the canopy</td>
</tr>
<tr>
<td>( K_{df} )</td>
<td>Extinction coeff. for diffuse light</td>
</tr>
<tr>
<td>( K_{dr} )</td>
<td>Extinction coeff. for direct light</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Ratio of diffuse to total radiation at the top of the canopy</td>
</tr>
<tr>
<td>( \mu_s )</td>
<td>Solar zenith angle</td>
</tr>
</tbody>
</table>

\[ A_{nl} = LAI \int_0^1 A_n d(z/h) \]
Respiration

**JULES**

Dark respiration

Plant respiration = maintenance + growth
(nitrogen contents of stem, roots and leaves)

\[ R_d = f_{dr} V_{cmax} \]

\[ R_p = R_{pm} + R_{pg} \]

**CTESSEL**

Dark respiration (leaves only)

\[ R_d = A_m / 9 \]

Soil and structural biomass respiration:
(T, snow cover, soil moisture, vegetation)

\[ R_{soilstr} = R_0 (25) Q10 R_0 \left( \frac{T_{soil} - 25}{10} \right) f_{sm} f_{sn} \]

Soil moisture attenuation
Snow cover attenuation
2. Model results

Hyytiälä forest (SMEAR II) (61°51’N, 24°17’E, 179 m a.s.l)
Vegetation: Scots pines (Needle leaf trees)
Observations: FLUXNET
- Fluxes: eddy-covariance measurements
- Respiration estimated according to Reichstein (2005)
- NEE gapfilled with marginal distribution sampling (MDS)

Meteorological forcing: Half-hourly FLUXNET data

JULES
- Big leaf approach (crm1) and multilayer approach (cmr3)
- Phenology and TRIFFID off
- Prescribed LAI

CTESSEL
- without coupling $A_g$ to evaporation
- Prescribed LAI
Energy fluxes
Carbon fluxes

\[ \text{NEE} = \text{Reco} - \text{GPP} \]
Diurnal GPP

GPP, Hyytiala 1998

The graphs show the diurnal pattern of Gross Primary Production (GPP) over the months from January to December. The data is compared with observations (obs) and simulations using different models (CT, JULES cm3, JULES cm1). The x-axis represents hours of the day, ranging from 0 to 21, while the y-axis represents GPP in μmolC m⁻² s⁻¹.
Diurnal NEE

\[ \text{NEE} = \text{Reco-GPP} \]
GPP, NEE, Reco Accumulations 1998

Cumulative plots (gC m^-2 day^-1): NEE = -202 (MDS), -232 (ANN); GPP = 969 (MDS), 979 (ANN); Reco = 696
Accumulated NEE-initial soil carbon

Soil respiration is very sensitive to initial soil carbon pool. Values of soil carbon above 15 kg/m² will result in a positive NEE (net source of CO2).

Measured NEE 1998:
-282 g C/m² day
Concluding remarks

1. Model comparison: JULES and CTESSEL

   • Physical processes involving energy and water are very similar

   • The carbon module presents more differences: treatment of vegetation, soil moisture stress

2. Model performance in boreal needle leaf site:

   • Energy fluxes are similar, both overestimate latent heat

   • The use of multilayer photosynthesis in JULES improves the diurnal cycle of GPP compared to the big leaf approach.

   • CTESSEL is able to reproduce the diurnal cycle with the big leaf approach by differentiating between direct and diffuse radiation

   • Soil respiration in JULES presents high sensitivity to initial soil carbon pool