Carbon fluxes and LAI evolution in the ECMWF land surface scheme (C-TESSEL)
Part B: Global evaluation

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[1] NB: the latent heat flux is positive downward, so in the calculation of the difference a positive value is less evaporation.

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Chapter 1

Introduction

1.1 Background of the project

In the scope of future climate change, the climate discussion and the Kyoto protocol an accurate representation of large-scale CO2 fluxes from and to atmosphere, ocean, land and biosphere is needed. In situ-measurements are indispensable but also the modelling of these fluxes deserves attention. Currently many groups are active in this research field and many projects are executed.The current research is performed within the framework of two projects, **GEOLAND** and **GSWP2**.

Context GEOLAND is carried out in the context of GMES, a joint initiative of European Commission (EC) and European Space Agency (ESA), which aims to build up a European capacity for Global Monitoring of Environment and Security. The ambition of the GEOLAND consortium is to develop and demonstrate a range of reliable, affordable and cost efficient European geo-information services, supporting the implementation of European directives and their national implementation, as well as European and International policies.[1]

GEOLAND is an integrated GMES project on landcover and vegetation, and consists of various observatories. One of those is the Observatory of Natural Carbon (ONC). Its participants are METEO France, the European Centre for Medium-Range Weather Forecasts (ECMWF), the Royal Dutch Meteorological Institute (KNMI[2]), LSCE (a French research center of the Commissariat a l'Energie Atomique and of the Centre National de la Recherche Scientifique) and Alterra (Wageningen University and Research center). The goal of ONC is modelling of the carbon cycle to get (3):
- 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.

The second Global Soil Wetness Project (GSWP2) is an ongoing environmental modelling research activity of the Global Land-Atmosphere System Study (GLASS), a contributing project of the Global Energy and Water Cycle Experiment (GEWEX)

[1] http://www.gmes-geoland.info/PROJ/index.php
[2] http://www.knmi.nl

in the World Climate Research Programme (WCRP) (7). GSWP2 has a number of goals (8):
- to produce state-of-the-art global data sets of land surface fluxes, state variables and related hydrologic quantities
- to develop and test large-scale validation, calibration and assimilation techniques over land
- to provide a large-scale validation and quality check of the ISLSCP data sets[3]
- to compare land surface schemes and conduct sensitivity studies of specific parameterisations and forcings.

Land Surface Schemes Modelling groups from around the world run their Land Surface Scheme (LSS) on the standard GSWP2 forcing data. Within the scope of GSWP, standards for LSS input and output are formulated by GLASS. These standard procedures are called ALMA (Assistance for Land-surface Modeling Activities) and are also applied in the current study [(19) and (14)].

The first results of GSWP2 are promising (7). However, a large variability exists among LSSs driven by the same forcing data. This points out that there is still much uncertainty in the understanding of land-atmosphere interactions at these large scales. So there is much room for improvement in the modelling of this part of the earth system (7).

One of the factors that is missing in many LSSs are plant processes such as photosynthesis and respiration. Some do include a prescribed seasonal cycle in vegetation cover, but usually there is no active biomass increase and decrease based on photosynthesis and respiration. Consequently, the contribution of the vegetation to water and CO2 fluxes is not based on the actual use and production of the plant. It is estimated that the addition of these processes might significantly improve the outcome of LSS.

The ECMWF and the KNMI use a LSS named TESSEL[4]. This LSS also lacks a module on plant processes and does not have a seasonal variation in vegetation cover. Bart van den Hurk and Marita Voogt of KNMI adjusted TESSEL to include these processes to make it a so-called 'third generation' model (7). They tested the new LSS, called C-TESSEL (the C stands for CO2), for one specific point in Europe for which an extensive data set was present. Some first results of this analysis are presented in Voogt et al. (2005, (18)).

Goal The purpose of the current study is to apply C-TESSEL to a global run and to test this global application. C-TESSEL is run for a 10-year period and the results are compared with a 10-year run of TESSEL. Emphasis is put on the respiration, which is a major uncertainty in 'third generation' models. A validation of the global C-TESSEL output with satellite products (biomass) will be done by Alterra in 2006.

1.2 Research questions

The subject of this study is an analysis of plant processes in the land surface scheme of climate and forecast models. Since this is an extensive topic, the scope of this research needs to be narrowed. A central objective and research questions are formulated to cover the relevant elements of the system.

[3]ISLSCP = International Satellite Land Surface Climatology Project
[4]TESSEL = Tiled ECMWF Surface Scheme for Exchange Processes over Land

1.2.1 Central objective

The central objective of this study is **to evaluate the results of the global modelling of carbon fluxes and vegetation evolution in the ECMWF land surface scheme**. With that purpose the results of C-TESSEL are compared with those of ISBA-A-gs. ISBA[5] is the land surface scheme of the French climate model ARPEGE (METEO-France, (12)). ISBA-A-gs is the same LSS including interactive vegetation development and carbon fluxes [(4) and (6)].

The ultimate goal is to make the new C-TESSEL model operational at the ECMWF, so that photosynthesis and CO2-fluxes are included in future modelling, together with data assimilation. Therefore, it is important that the radiation balance and water balance of C-TESSEL are comparable to those of TESSEL. Major changes in, for example, the latent heat flux (LE) induces unwanted feedbacks in the model which can significantly change cloud patterns and precipitation. Differences between TESSEL and C-TESSEL should be explicable based on the diagnostics vegetation type, Leaf Area Index (LAI) and CO2 assimilation. The final test of C-TESSEL is by comparing the latent heat flux with the GSWP2 ensemble mean, which is the average over all LSS's participating in GSWP2 (7).

1.2.2 Research questions

The research questions of this study are formulated as follows:

1. Are the global energy balances of TESSEL and C-TESSEL closed?

2. What are the differences between the results of C-TESSEL (including plant processes) and that of TESSEL? Are the spatial patterns of various fluxes (like latent heat, interception, etc) in C-TESSEL comparable to that of TESSEL, and are the differences explicable?

3. Is the reference respiration calculated with C-TESSEL comparable to literature values? Can the spatial pattern of the reference respiration be explained by vegetation patterns?

For the research questions a zero-hypothesis is formulated based on the central objective.

1. The remainder of the energy balances of TESSEL and C-TESSEL should be less than 10^{-2} W/m^2.

2. The difference between TESSEL and C-TESSEL of the globally averaged latent heat (Qle in W/m^2), averaged over the 10 year of the run should not be more than 10 %.

3. The globally averaged reference (residual) respiration calculated with C-TESSEL should have the same order of magnitude as literature values of the reference (ecosystem) respiration.

[5]ISBA = Interactions between Soil Biosphere Atmosphere

Chapter 2

Theory

Many textbooks exist on the interactions between soil, vegetation and atmosphere. In this chapter this extensive information will not be repeated. I will only give a short overview of the most important principles and mechanisms relevant for this study.

2.1 Land-atmosphere interactions

The earth radiation balance consists of incoming and outgoing radiation and products of conversion at the surface.

$$K^{\downarrow}(1-a) + (L^{\downarrow} - L^{\uparrow}) + \lambda E + H = G \tag{2.1}$$

where
$K^{\downarrow}$ = incoming shortwave radiation in $W/m^2/s$
a = albedo of the earth surface $(-)$
$L^{\downarrow}$ = incoming longwave radiation in $W/m^2/s$
$L^{\uparrow}$ = outgoing shortwave radiation in $W/m^2/s$
λE = latent heat in $W/m^2/s$
H = sensible heat in $W/m^2/s$
G = ground heat flux in $W/m^2/s$
(all fluxes positive downward)

The water balance at the surface is a combination of the fluxes in and out of the surface and storage in the soil.

$$\partial W/\partial t = P - E - R_s - D \tag{2.2}$$

where
$\partial W/\partial t$ = change in soil moisture in mm/d
P = precipitation in mm/d
E = evaporation in mm/d
R_s = direct runoff in mm/d
D = drainage in mm/d

These two important balances are coupled by the latent heat flux or evaporation (λE). In this coupling the wind speed and the roughness of the surface play an important role.

2.2 Plant processes

2.2.1 Vegetation development

To include plant processes in land-atmosphere models a parameter needs to be specified indicating the amount of vegetation present in a certain region. A parameter used in vegetation science is coverage. The coverage of a certain species is the percentage of the region covered by that species. Another well-known parameter is the Leaf Area Index (LAI). The LAI represents the total area of leaves per unit surface area. The development of the LAI over time is determined by photosynthesis and respiration processes.

2.2.2 Photosynthesis and Respiration

A plant leaf contains stomata through which gas exchange with the atmosphere takes place. CO2 goes in for photosynthesis, and O2 and water vapour are emitted through the stomata. The stomatical aperture is regulated actively by the plant based on various environmental conditions, including light, temperature, air humidity, soil moisture and atmospheric CO2 concentration (3). This stomatical aperture determines the stomatal resistance for gas exchange between the stomata and the atmosphere. According to Jacobs (1994, (9)) the total canopy resistance for transpiration is determined by the atmospheric resistance between the surface and a reference height, the surface resistance, and the stomatal resistance.

For the parametrisation of photosysthesis two different approaches are developed. One is the phenomenological or Jarvis-Stewart approach and the other is the (semi)physiological approach. The main difference is that the (semi)physiological models include a description of stomatal responses to CO2 and the synergistic interaction between CO2 and other stimuli (9).

Ecosystem respiration is the total respiration, a combination of the dark respiration, the belowground respiration and the soil respiration (from decomposition). Respiration is dependent on temperature and moisture: a higher temperature or more moisture will result in more respiration. More explanation of these processes is given in Section 3.2.

Chapter 3

Methodology

3.1 TESSEL

TESSEL is a tiled land surface scheme, which is operational in the ECMWF forecast model (17).

Vegetation TESSEL allows one low and one high vegetation type per grid box, so only the dominant types within the grid box are accounted for. The other sub-grid fractions over land represent bare soil, interception, snow on low vegetation/bare soil and snow underneath high vegetation (see the scheme of Figure 3.1). The stomatal conductance is calculated using the Jarvis-type parameterisation. It is scaled up to the canopy by dividing it by the leaf area index (LAI). Values of the LAI are prescribed and do not have a seasonal variation.

Experimental setup The spatial resolution and the model period used in this study are set by the GSWP2 prescriptions. The spatial resolution is 1 degree and it includes all land points except Antarctica (19). In this study TESSEL is run for 10 years, from 1 January 1986 to 1 January 1996, and has a spinup period of 3,5 years (8). A time step of 30 min is chosen for the computations.

Input and output The input of TESSEL consists of (atmospheric) forcing data from GSWP2 [(8) and (11)]. The forcing data are global gridded analysis series at 3-hourly time resolution and 1 degree spatial resolution from July 1982 through December 1995. The series are based on the ISLSCP Initiative II global data effort[1] [(19), (11), (16) and (1)] and observational data from in situ-measurements and remote sensing.

Additionally, land use maps of remote sensing data (e.g. ECOCLIMAP[2]) are used in TESSEL. The ECOCLIMAP database includes values for the albedo, the LAI, the roughness length and a number of other environmental variables. At the moment two different versions of ECOCLIMAP are in use, named after their year of birth. In this study the 2003 version of ECOCLIMAP is used, which is described in Masson et al. (2003, (13)). One of the differences between this ECOCLIMAP version and the 2004 version used by ISBA-A-gs are the vegetation types in the Eastern USA.

[1] ISLSCP Initiative II: ten-year gridded global surface data set of the near-surface meteorology at a 3-hourly interval as a combination of various reanalysis products.

[2] http://www.cnrm.meteo.fr/gmme/PROJETS/ECOCLIMAP/page_ecoclimap.htm

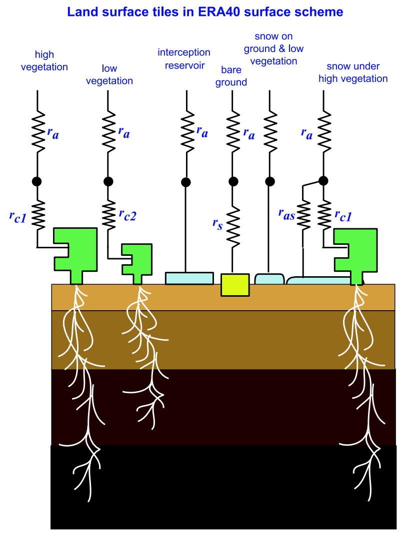


Figure 3.1: Sub-grid fractions in TESSEL (Source: (17)).

The C4 crops in Florida and the rest of the Southeastern USA in the 2003 version (Figure 3.2A) are in the 2004 version replaced by C3 crops (Figure 3.2B). The same conversion was performed in India.

The output files of TESSEL are in NetCDF[3] format. The analysis of the model outcomes is mainly done with NetCDF tools and GMT.

3.2 C-TESSEL

The main difference between C-TESSEL and TESSEL is an active, CO2 responsive vegetation, resulting in a dynamic vegetation cover (LAI). This introduces for example a seasonal cycle of the vegetation in the model. C-TESSEL is created by the implementation of the A-gs and biomass evolution module from the land surface scheme ISBA-A-gs in TESSEL. Therefore we will first describe the relevant characteristics of ISBA-A-gs.

3.2.1 ISBA-A-gs

ISBA-A-gs[4] is the CO2-responsive version of the land surface scheme ISBA (4). The model simulates the stomatal conductance based on the A-gs scheme proposed by Jacobs (1996, (10)), in which the relation between stomatal aperture and photosynthesis is addressed. The ratio photosynthesis/transpiration is controlled by stomatal aperture according to the environmental conditions light, temperature, air humidity, soil moisture and atmospheric CO2 concentration (3).

The model includes a biomass evolution module. The growth of active biomass (leaves) directly depends on net CO2 assimilation, whereas the mortality is based on an exponential law whose efolding time depends on the daily maximum net CO2 assimilation. During the growing period, a logarithmic nitrogen dilution equation is

[3]NetCDF = Network Common Data Format

[4]In ‘A-gs‘ the ‘A‘ stands for ‘assimilation‘ and the ‘gs‘ means ‘stomatal conductance‘.

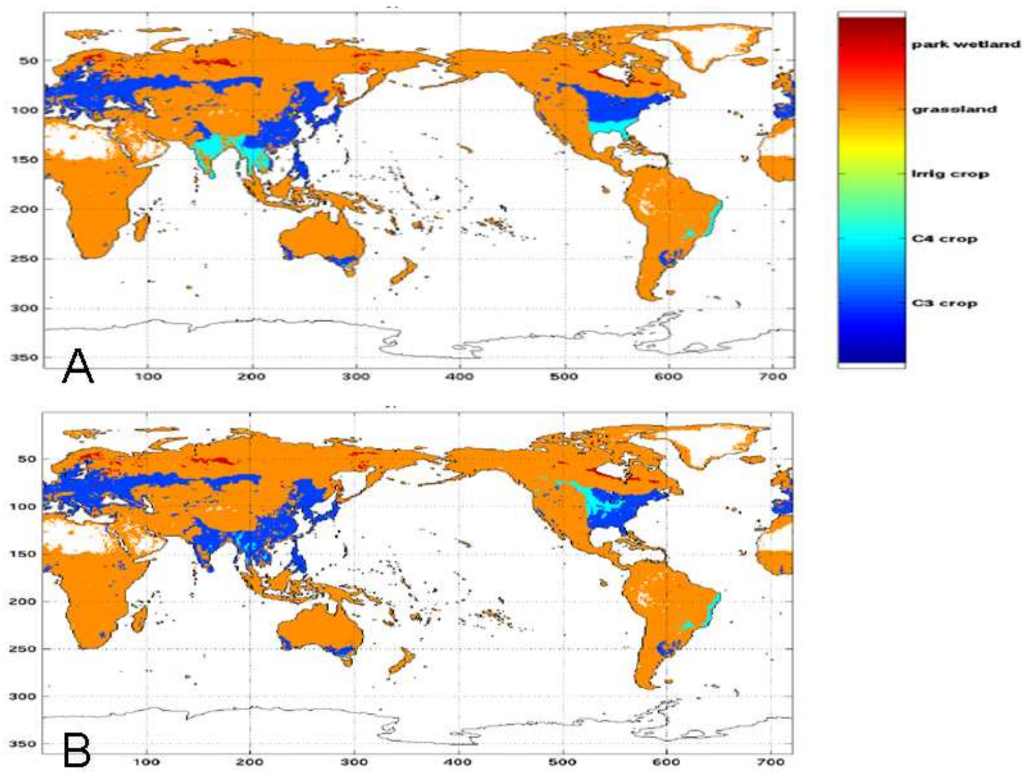


Figure 3.2: Dominant low vegetation type of ECOCLIMAP, A = 2003 version, used in C-TESSEL, B = 2004 version, used in ISBA-A-gs (Source: S. Lafont).

used to relate aboveground structural biomass[5] to active biomass and vice versa (6). Wood and soil carbon reservoirs are not (yet) included.

The LAI is linearly related to the active biomass and has a prescribed minimum value. Through the dynamic representation of the LAI, the model can account for seasonal and inter annual variability, droughts in particular. Soil moisture stress affects the stomatal aperture. The model distinguishes two types of soil moisture stress strategies that either low, herbaceous vegetation or high, woody vegetation can adopt. Those are drought-avoiding (or defensive) and drought-tolerant (or offensive) strategies [(2) and (5)]. In ISBA-A-gs all vegetation classes use the drought-avoiding strategy.

The ISBA-A-gs model is also initialised by the ECOCLIMAP global surface parameter database (13). ECOCLIMAP distinguishes 215 vegetation types that can be grouped into 7 vegetation classes with respect to the photosynthesis parameterisation. There are 3 classes for high vegetation (deciduous, coniferous and evergreen forests) and 4 classes for low vegetation (C3 grass, C3 crops, C4 grass, C4 crops), each having a distinctive set of vegetation parameter values. A meta-analysis was performed in order to determine the parameter values. Calvet (2000, (2) and 2004, (5)) gathered the values for a great number of species by optimizing the simulated water fluxes. The mean values from the meta-analysis are slightly adapted to optimise global LAI simulations (pers.comm. M. Voogt).

3.2.2 C-TESSEL

In the conversion from TESSEL to C-TESSEL the number of vegetation types in the model was increased to represent the 7 vegetation classes from ISBA-A-gs. In that way, not only dominant vegetation types are accounted for. A grid box is filled with percentages of all vegetation types to include sub-grid variations. In C-TESSEL only one tile with snow underneath high vegetation is kept, and the dominant high vegetation type is assigned to it. In total, 14 tiles are present in C-TESSEL. These include the 7 vegetation tiles (deciduous forest, coniferous forest, evergreen forest, C3 grassland, C4 grassland, C3 crops, and C4 crops), the 'bare soil' tile, some water, ice and snow tiles (water, ice, exposed snow, shaded snow, and wet skin), and an 'urban' tile which is not yet developed (see Figure 3.1).

It is assumed that wet leaves assimilate CO2 in the same way as dry leaves, since the stomata are located at the bottom side of the leaves. Snow covered vegetation does not assimilate any CO2. In C-TESSEL coniferous forest has a defensive stress strategy, while the rest of the vegetation types has an offensive soil moisture stress strategy. The same biochemical approach as in ISBA-A-gs is used in C-TESSEL. This approach is characterised by an explicit simulation of photosynthesis (10).

Respiration The Net Ecosystem Exchange (NEE) is the sum of the gross CO2 assimilation (A_g) and the ecosystem respiration (R_{eco}). In C-TESSEL the long-term NEE is equal to zero, because an equilibrium is assumed between the long-term R_{eco} and the long-term A_g. The gross CO2 assimilation is calculated directly by running the 10-year period 1986-1995 from the GSWP2 project (8). The total CO2 ecosystem respiration (R_{eco}) is split into two terms. The first is dark respiration (R_d), which is the autotrophic respiration from the leaves (3). It is parameterised as a fraction of the CO2 assimilation that would take place if radiation is not limited (A_m).

[5] The aboveground structural biomass is the non-woody, non-photosynthetic part of the aboveground vegetation (pers.comm. A. Gibelin).

The second respiration term represents both heterotrophic respiration from the soil and autotrophic respiration from the above- and belowground structural biomass. It is in this report called the residual respiration (R_s). A Q10 function[6] is used for its parameterisation (Equation 3.1).

$$R_s = R_{eco} - R_d = R_0 \cdot Q_{10}^{((T-T_0)/10)} \tag{3.1}$$

where
R_s = residual respiration in $kg/m2/s$
R_{eco} = ecosystem respiration in $kg/m2/s$
R_d = dark respiration in $kg/m2/s$
R_0 = residual respiration at reference temperature T_0 in $kg/m2/s$
Q_{10} = exponential factor $(-)$
T = soil temperature of the second soil layer in °C
T_0 = reference temperature in °C

Soil moisture is not taken into account in Equation 3.1 because respiration is found to be principally determined by soil temperature (pers.comm. M. Voogt). For T_0 a temperature of 25 °C is chosen. For the factor Q_{10} the value 2 is chosen based on available literature (pers.comm. M. Voogt). This means that the residual respiration doubles when the soil temperature increases by 10 degrees.

The reference respiration (R_0) is the only unknown parameter in Equation 3.1. No general parameterisation has yet been proposed for R_0. In C-TESSEL it is determined per vegetation type in a specific grid box, assuming an equilibrium between the multi-annual net CO2 assimilation, harvest and the residual respiration (pers.comm. M. Voogt). The calculation is given by:

$$A_{n,acc} - harvest_{acc} = R_{s,acc} = R_0 \cdot (Q_{10}^{((T-T_0)/10)})_{acc} \tag{3.2}$$

where
$A_{n,acc}$ = 10 yr accumulated net assimilation (= A_g - R_d) in $kg/m2/s$
$R_{s,acc}$ = 10 yr accumulated residual respiration in $kg/m2/s$
$(Q_{10}^{((T-T_0)/10)})_{acc}$ = 10 yr accumulated Q_{10} function in $kg/m2/s$
$harvest_{acc}$ = an estimate of the 10 yr accumulated harvest in $kg/m2/s$

The terms $A_{n,acc}$ and $(Q_{10}^{((T-T_0)/10)})_{acc}$ in this CO2 exchange equilibrium are calculated in the 10 year model run. The determination of the accumulated harvest ($harvest_{acc}$) is less straightforward. We only dispose of the rough yearly harvest estimates per vegetation class. These are based on a 40% carbon content of dry biomass (Table 3.1, adopted from an estimate of METEO-France) and assumed to be valid as an average over the globe (pers.comm. M. Voogt). The accumulated harvest, however, is not similar for all climatic zones. It is dependent on the amount of assimilation in a climatic zone, because when assimilation is low in the northern latitudes due to little radiation, the harvest will also be low. To distribute the accumulated harvest realistically over the globe, it is calculated as a fraction of $A_{n,acc}$ for each vegetation type in a specific grid box (Equation 3.3).

$$harvest_{acc} = f_{vc} \cdot A_{n,acc} \tag{3.3}$$

where
f_{vc} = the harvest factor of each vegetation class, calculated by: globally averaged

[6] Q10 = ratio of the respiration rate at one temperature to that at a temperature 10 degrees lower

harvest/ globally averaged A_n

Table 3.1: Table harvest estimates from METEO-France (pers.comm. J.C. Calvet).

Vegetation class	harvest estimate METEO-France
Deciduous forest	3.2 tCO2/ha/yr
Coniferous forest	2.3 tCO2/ha/yr
Evergreen forest	3.2 tCO2/ha/yr
C3 grass	2.3 tCO2/ha/yr
C4 grass	3.2 tCO2/ha/yr
C3 crops	2.3 tCO2/ha/yr
C4 crops	3.2 tCO2/ha/yr

The globally averaged A_n per vegetation class is again determined from the outcomes of the run of the GSWP2 project (8).

Input and output Some differences exist between the input of TESSEL and that of C-TESSEL. In C-TESSEL the LAI is not taken as a constant value from ECOCLIMAP but calculated interactively by the model. Effects are expected in the amount of evaporation and interception. Since in C-TESSEL, the 7 vegetation classes from ECOCLIMAP are represented, ECOCLIMAPs monthly values of the roughness length for each vegetation type are introduced. In TESSEL, the roughness length was a grid-averaged constant value. As a consequence, the aerodynamic conductance increased for high vegetation and decreased for low vegetation. After calculation, the reference respiration is treated as input for the model as a surface climatology variable.

The output of C-TESSEL is also in NetCDF-format.

Chapter 4

Results

4.1 Analysis TESSEL

Balances To check the outcomes of TESSEL the energy balance at the surface is calculated with Equation 2.1. When all components of the equation are added up, the outcome must be zero for every point on the globe for every time step. Every month of the 10 year period is tested and the maximum remainder of the balance is determined. This maximum is $4.41 \cdot 10^{-5}$ $W/m^2/s$ which is very close to zero. The zero-hypothesis of Section 1.2.2 is confirmed.

Further analysis of TESSEL is done by students at the University of Utrecht.

4.2 Analysis C-TESSEL

Balances Also for C-TESSEL the energy balance is checked, and comparable results are found. The maximum remainder of the balance of C-TESSEL is $4.34 \cdot 10^{-5}$ $W/m^2/s$. Also for C-TESSEL the zero-hypothesis of Section 1.2.2 is confirmed.

Assimilation and respiration The yearly maximum LAI is calculated and averaged over the model period of 10 years. The results are given in Figure 4.1A and are compared with data from ISBA-A-gs, ISLSCP-II, MODIS (Moderate Resolution Imaging Spectroradiometer) and ECOCLIMAP (see Figure 9.1 in the Appendix). In general the LAI of C-TESSEL seems somewhat higher, but it is certainly in the correct order of magnitude. The pattern of C-TESSEL resembles that of ISBA-A-gs (Figure 4.1B). However, some differences are observed. In Southeastern USA the LAI is higher in C-TESSEL than in ISBA-A-gs, because the vegetation in C-TESSEL mainly consisted of C4 crops and that in ISBA-A-gs of C3 crops (see Section 3.1). The assimilation of C4 crops is higher, so the LAI increases more for C4 crops. When the tropical regions are compared, we see that the LAI in Africa is comparable for the two LSS's. However, in South America and Indonesia the LAI of C-TESSEL is higher. This could be caused by differences in the underlying forecast models. The difference in soil moisture stress strategy between ISBA-A-gs and C-TESSEL can not be the cause of the LAI difference in the tropics, because no moisture stress is expected in this region.

We also looked at the average yearly maximum LAI of the various vegetation classes. The total LAI is principally determined by the LAI of the forest types; coniferous forest on the Northern Hemisphere, evergreen forest in the tropics and

(a) (b)

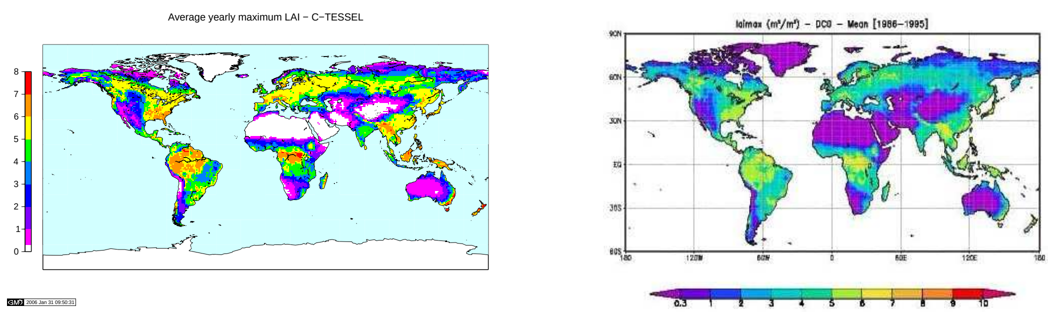


Figure 4.1: Average yearly maximum LAI of C-TESSEL (a) and ISBA-A-gs (b) (Source ISBA: A. Gibelin).

deciduous forest in both regions. C3 grassland and C3 crops occur on almost the entire globe and also contribute largely to the LAI. C4 grassland and crops are only present in warm regions, the tropics and sub-tropics.

The 10 year (1986 - 1995) averaged net CO2 assimilation of C-TESSEL is given in Figure 4.2A. The assimilation is low in dry areas as the Sahara, central Asia, central Australia, the western USA, and in the cold regions around the Arctic. In the tropics the assimilation is highest, but when Figure 4.2A is compared with Figure 4.1A it is found that the regions with the highest LAI (central South-America, central Africa and Indonesia) do not show the highest assimilation. The maximum assimilation occurs in the areas *around* the maximum LAI. The same can can be seen in the net assimilation of ISBA-A-gs in Figure 4.2B. An explanation for this mechanism is not yet found. Possibly, it has a relation with the predominance of evergreen forest in the regions with maximum LAI. Figure 9.2C in the Appendix shows the coverage of evergreen forest. In the considered regions with maximum LAI, the coverage of evergreen forest is almost 100 %. In the tropical regions around the dominant evergreen forest, also other vegetation types are present. Consequently, the low net assimilation of Figure 4.2A can not be caused by a meteorological forcing, like the temperature (higher in tropics, possibly resulting in a higher respiration and a lower assimilation) or the cloud cover (high in tropics due to convection, resulting in a reduced incoming radiation), because if that was the case the assimilation would be lower in the entire tropical zone and not just in the regions with a dominance of evergreen forest. At the GEOLAND symposium[1] the influence of shading by the canopy was suggested as a possible cause. However, no difference in vertical distribution of leaves exists between the vegetation types, so shading occurs equally in evergreen forest and in the other forest types. The difference must be caused by the parameters of evergreen forest specified in the model. The g_m, an important parameter in the calculation of assimilation (17), is somewhat lower for evergreen forest than for

[1] Vienna, 7-10 February 2006

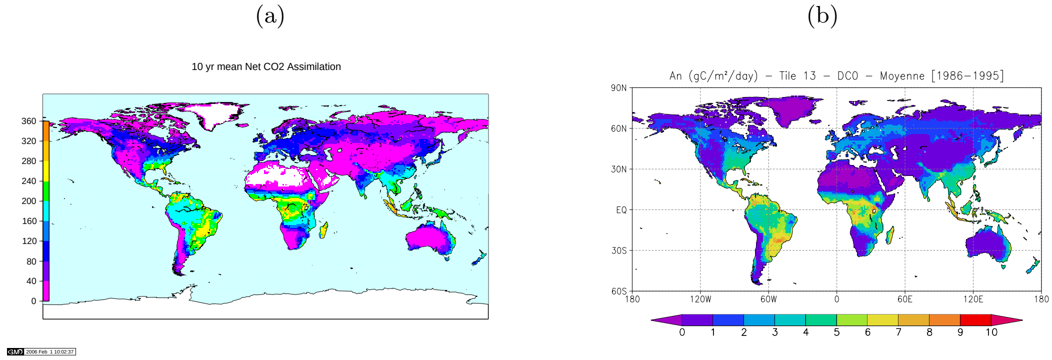


Figure 4.2: 10 year average net CO2 assimilation of C-TESSEL in $kgC/ha/day$ (a) and ISBA-A-gs in $gC/m^2/day$ (b) (Source ISBA: A. Gibelin).

i.e. deciduous forest, which means that under similar circumstances the assimilation of evergreen forest is lower than that of deciduous forest. In evergreen forest the loss of biomass is minimal, so probably little assimilation is needed to maintain a high LAI. For further research on the modelling of carbon fluxes this is an interesting phenomenon.

The gross assimilation is a more realistic variable than the net assimilation (= gross assimilation - dark respiration), because it has a physical meaning and is used also by ecologists. In the 10 year (1986 - 1995) averaged gross CO2 assimilation the dip in assimilation in the tropics is less conspicuous than in the net assimilation (Figure 4.3A). This leads to the suspicion that the main problem in evergreen forest is the dark respiration. The pattern of the gross assimilation is comparable to the pattern of ISBA-A-gs (Figure 4.3B).

The reference respiration ($R0$) is the parameter that is determined from the long-term equilibrium between assimilation and respiration. According to Equation 3.2, $R0$ is dependent on the 10 yr accumulated net assimilation and the 10 yr accumulated Q10-function. Consequently, the spatial pattern of $R0$ is determined by these factors. $R0$ is higher in regions with higher assimilation (see Figure 4.2) and in regions with a lower Q10-function. In Figure 9.3 of the Appendix the maps of $R0$ per vegetation type are given. The correlation of the spatial pattern of $R0$ with that of the LAI of a vegetation class is high and is mainly due to the relation of the LAI with the net assimilation. Since the Q10-function is determined by soil temperature, low Q10-functions occur mostly in the cold areas around the Arctic. Figure 4.4 shows the temperature dependency of the Q10-function with different values for the Q10-base rate and the reference temperature. The soil temperature in the Arctic regions is around 0 °C which lays in the lower reach of Q10-function. The gradient is low and the Q10-function is not very sensitive for temperature.

The values of $R0$ are compared with values used for the $R0$ of the ecosystem respiration in ISBA-A-gs, which are based on an analysis of Rivalland (2003, (15)). Only a rough comparison is possible because the values are an estimate and are not

(a) (b)

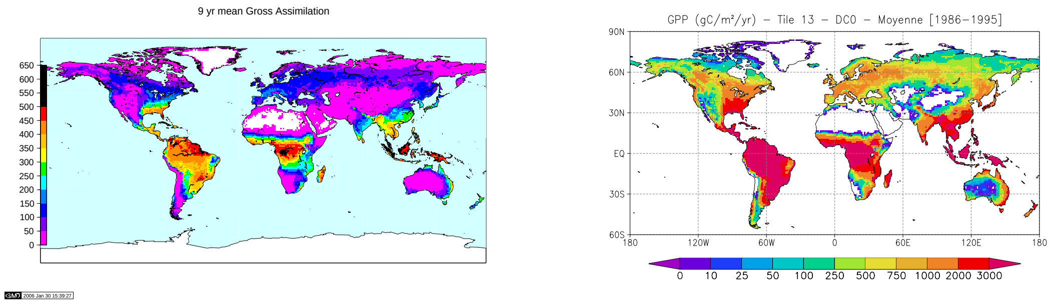


Figure 4.3: 10 year average gross CO2 assimilation of C-TESSEL in $kgC/ha/day$ (a) and ISBA-A-gs in $gC/m^2/day$ (b) (Source ISBA: A. Gibelin).

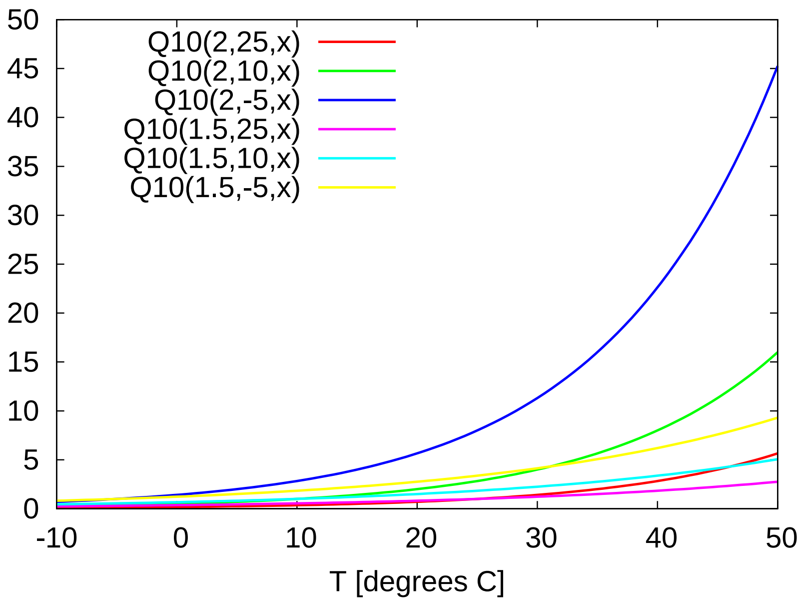


Figure 4.4: Q10-function as a function of temperature (the first value between brackets is the Q10 base rate and the second value is the reference temperature) (Source: M. Voogt).

Table 4.1: Comparison reference respiration C-TESSEL with estimates from ISBA-A-gs.

	ISBA-A-gs	ISBA-A-gs	C-TESSEL
Vegetation class	$R0$ of R_{eco}	$R0$ of R_s	$R0$ of R_s
	$kgC/ha/day$	$kgC/ha/day$	$kgC/ha/day$
Deciduous forest	311	156	147
Coniferous forest	156	78	276
Evergreen forest	311	156	138
C3 grass	311	156	85
C4 grass	311	156	190
C3 crops	311	156	181
C4 crops	259	130	259

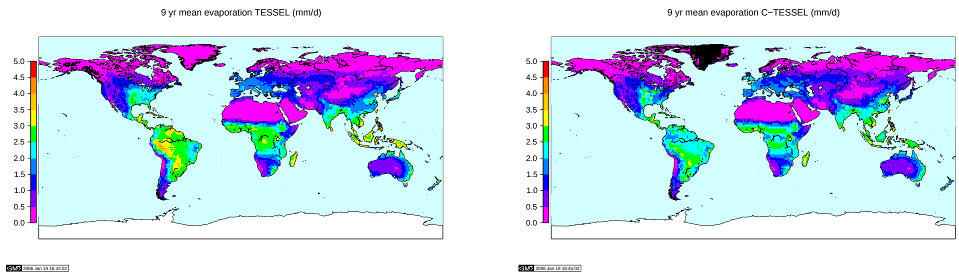
used the same way in the model. The second column of Table 4.1 shows the $R0$ of ISBA-A-gs for the ecosystem respiration. As R_d and R_s are of about the same order of magnitude, the $R0$ of the residual respiration can be regarded as half the $R0$ of the ecosystem respiration (pers.comm. M. Voogt). This value is given in the third column of Table 4.1. The global averaged values of C-TESSEL (the last column of Table 4.1) are of the same order of magnitude as the estimate of ISBA-A-gs, which agrees with the zero-hypothesis formulated in Section 1.2.2. From Table 4.1 it is conspicuous that in ISBA-A-gs the $R0$ is lower for coniferous forest than for the other vegetation types, while in C-TESSEL the $R0$ of coniferous forest is higher than the other types. Probably, the estimate made for each vegetation type, that the $R0$ of the residual respiration is equal to half the $R0$ of the ecosystem respiration, is not valid for coniferous forest.

4.3 Differences TESSEL and C-TESSEL

The difference between TESSEL and C-TESSEL is mainly evaluated from the evaporation, because it is expected to change due to the interactive vegetation development in C-TESSEL and because it is an important parameter in the operational forecast model of the ECMWF.

Evaporation The evaporation or latent heat is an important variable in both the energy and water balance (Equation 2.1 and 2.2). Large differences can induce unwanted feedbacks in the land-atmosphere system.

The evaporation in TESSEL (Figure 4.5A) shows a spatial pattern as expected, with maximum values in the tropics and high also in eastern USA and Europe. In the evaporation in C-TESSEL (Figure 4.5B) some differences are observed. The regions where the evaporation is negative have extended, in C-TESSEL they include almost all of Greenland. The evaporation in the sub-tropical and temperate zones is comparable in TESSEL and C-TESSEL (Figure 4.6). Only in the Eastern part of the USA, the C4 crops of ECOCLIMAP (Figure 3.2a) result in a lower evaporation in C-TESSEL. In the tropics differences are larger. The evaporation in C-TESSEL is much lower in the Amazon and the African and Indonesian rainforest. When we look at the seasonal mean evaporation of a specific year within the period 1986-1995, we see that also there the evaporation in some regions of the tropics is lower in C-TESSEL then in TESSEL. The reasons for this difference are still unknown, but the



(a) (b)

Figure 4.5: 10 year average evaporation of TESSEL (a) and C-TESSEL (b) in mm/d.

pattern corresponds with the lower net assimilation found in the tropical regions with a 100 % coverage of evergreen forest. The stomatal resistance of evergreen forest apparently is too high in C-TESSEL, resulting in both a lower net assimilation and a lower evaporation in that specific region. The cause of this high stomatal resistance is unknown and is an important subject for further research.

In Figure 4.7 the difference between TESSEL and C-TESSEL is divided by the standard deviation of TESSEL. The green areas have a value between -1 and 1 times the standard deviation. Here, the latent heat flux of C-TESSEL is within the amplitude of the interannual variability of TESSEL. This Figure shows that also in the temperate zones there is a significant difference between TESSEL and C-TESSEL, although the differences in the tropics are higher (up to 10 times the standard deviation of TESSEL). The differences in the temperate zone are caused by the properties of the boreal forest in that zone (pers.comm. S. Lafont). However, the exact mechanisms are still unsure and no difference is found with the ensemble mean of GSWP2 (Figure 9.5).

The average difference between TESSEL and C-TESSEL in percentage of TESSEL is -3.72 %. This value is lower than the zero-hypothesis formulated for this study (Section 1.2.2) and therefore the difference is acceptable.

When we compare these results with the latent heat flux of ISBA and ISBA-A-gs (Figure 9.6), we see that ISBA-A-gs has less evaporation in the tropics, just as in C-TESSEL. However, in the temperate zones ISBA-A-gs also a lower evaporation is observed, while in C-TESSEL the evaporation in that zone was (slightly) higher than in TESSEL. Consequently, the tropical anomaly is caused by the formulations in the model.

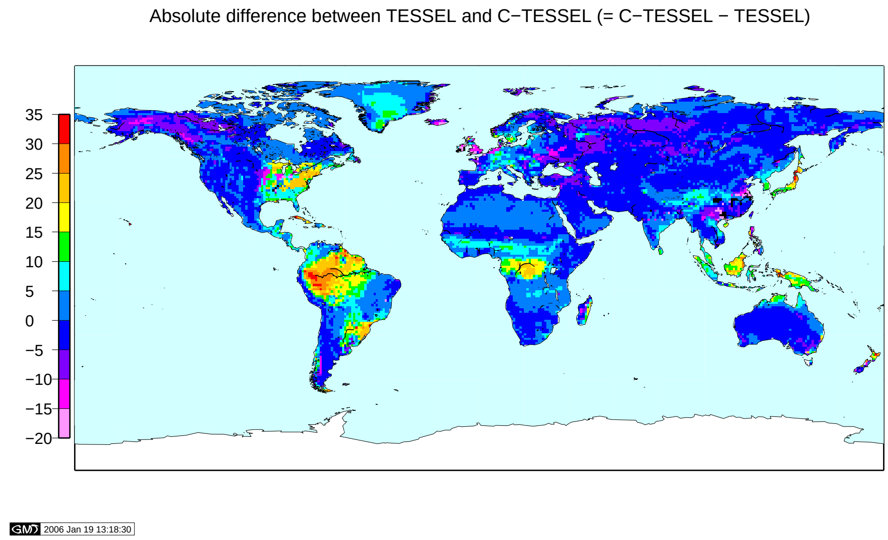


Figure 4.6: Difference between the 10 year average net latent heat flux of C-TESSEL and that of TESSEL in $W/m2$.[3]

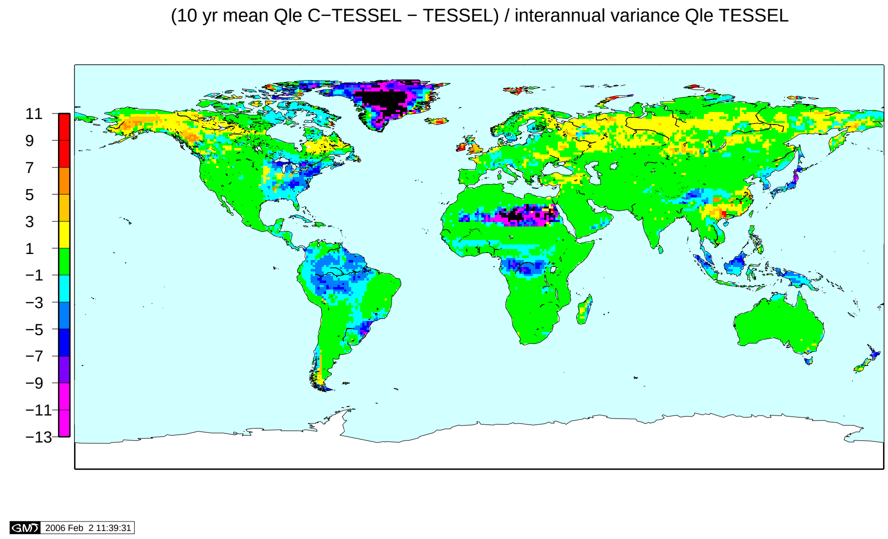


Figure 4.7: Difference between the 10 year average latent heat flux of C-TESSEL and that of TESSEL, divided by the interannual standard deviation of TESSEL.

Chapter 5

Discussion

Despite the numerous improvement made in C-TESSEL, the model is not perfect. The method to calculate the Q10-function and the reference respiration (described in Section 3.2.2) still contains many uncertainties. For example, there is no agreement that the use of a Q10-function is the best method to calculate the respiration. Furthermore, probably the Q10 base rate is not a fixed value (2 in this study), but changes in time and space. Also in the calculation of harvest many assumptions are made that are probably not permitted. The difficulty with the calculation of the respiration is that the results can not be validated, because no global data are available on respiration. Currently, measurement sites are developed to measure CO2-fluxes at a fluxtower. The first data are compared with point-values of the model by Alterra and these show promising results. However, much more data is needed for a real global validation.

In the analysis of the model we found an anomaly in the daily outcomes. The net assimilation in C-TESSEL showed high negative daily values both in summer and winter for certain regions. The regions with negative values changed each day, but occurred primarily in the tropics, in the USA and in India. These are areas where the radiation is high so negative assimilation should not occur. In the average monthly net assimilation the negative values are eliminated. The mechanisms behind this anomaly are unknown and deserve some attention in further research.

To make C-TESSEL operational in the ECMWF forecast model some adaptations are needed. The ECMWF wants to include only two dominant vegetation types in stead of 7, to reduce the difference with the current LSS (TESSEL) to a minimum. Further development is done by the ECMWF (pers.comm. S. Lafont).

Chapter 6

Conclusion

- The remainder of the energy balance is below 10^{-2} W/m^2 for the global run of both TESSEL and C-TESSEL.
- On a global scale the spatial pattern of the LAI calculated with C-TESSEL is comparable to that of ISBA-A-gs and to satellite observations. The LAI in the Southeastern USA and in the tropical areas of South-America and Indonesia is a little higher in C-TESSEL.
- The net assimilation of C-TESSEL has the correct order of magnitude for most of the world. Only in some tropical regions an anomaly occurs. In regions where the coverage of evergreen forest is almost 100 % the net assimilation is lower than in the rest of the tropics. Probably, this anomaly is caused by the parameters of the vegetation type evergreen forest prescribed in the model.
- The spatial pattern of the reference respiration is as expected, based on temperature and net assimilation. The order of magnitude over the global average per vegetation type is comparable to the values used in ISBA-A-gs.
- The difference between the latent heat flux of TESSEL and C-TESSEL is less than 10 % (global average difference = 3.72 %). However, the evaporation of C-TESSEL was significantly lower in the tropical regions where the net assimilation was low. This is caused by a high stomatal resistance.

Chapter 7

Recommendations

- The parameterisation of the respiration needs to be improved and validation of the respiration with measurement data deserves more attention.
- The mechanisms leading to a high stomatal resistance of evergreen forest in the tropics need to be analysed to determine the causes of the difference in net assimilation and evaporation in that regions. The parameters of the vegetation type evergreen forest can be adjusted.
- The difference in evaporation in the boreal forest needs some extra attention.
- The negative values in the daily values of the net assimilation need to be investigated in more detail.

Chapter 8

Glossary

Abbreviations:
* GSWP2 = second Global soil Wetness Project
* GMES = Global Monitoring of Environment and Security
* ONC = Observatory of Natural Carbon
* ECMWF = European Centre for Medium-Range Weather Forecasts
* KNMI = Royal Dutch Meteorological Institute
* LSCE = Laboratoire des Sciences du Climat et de l'Environnement
* GLASS = Global Land-Atmosphere System Study
* GEWEX = Global Energy and Water Cycle Experiment
* WCRP = World Climate Research Programme
* ISLSCP = International Satellite Land Surface Climatology Project
* ALMA = Assistance for Land-surface Modeling Activities
* LSS = Land-Surface Scheme
* TESSEL = Tiled ECMWF Surface Scheme for Exchange Processes over Land
* C-TESSEL = TESSEL extended with a module on CO2 fluxes
* ISBA = Interactions between Soil Biosphere Atmosphere
* LAI = Leaf Area Index
* C3 plant = plant that fixes CO2 in the molecule 3-fosfoglycerate, which consists of three carbon atoms
* C4 plant = plant that fixes CO2 in the molecule oxaloacetate, which consists of four carbon atoms, and makes use of the enzyme fosfo-enolpyruvate carboxylase, which is very sensitive to CO2
* Q10 = ratio of the respiration rate at one temperature to that at a temperature 10 degrees lower
* NetCDF = Network Common Data Format
* LAI = Leaf Area Index
* Qle / LE = latent heat
* H = sensible heat
* R0 = reference respiration

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Chapter 9

Appendix

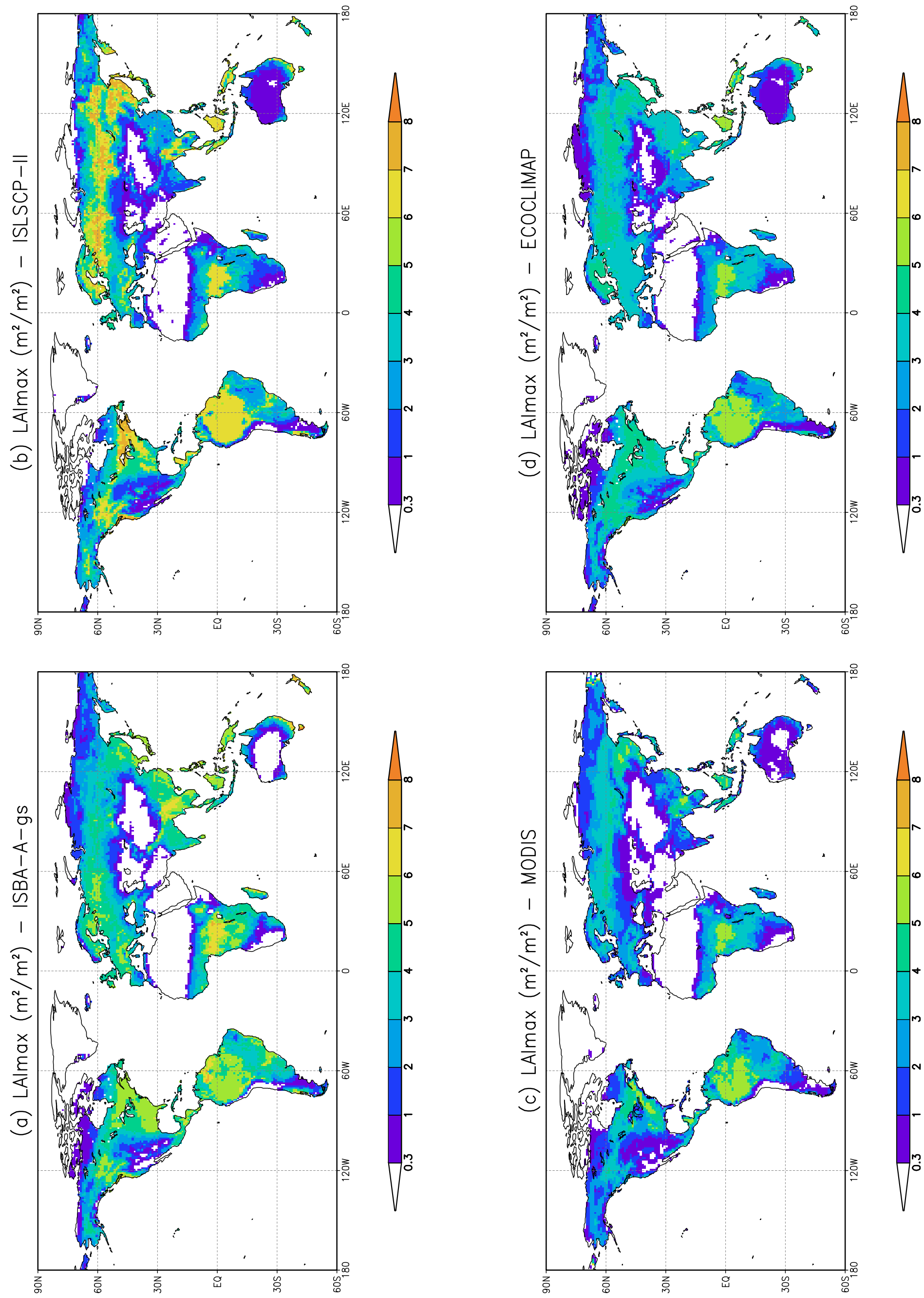
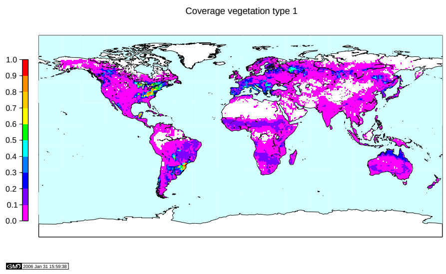


Figure 9.1: Average yearly maximum of the LAI of ISBA-A-gs, ISLSCP-II, MODIS and ECOCLIMAP (Source: A. Gibelin).



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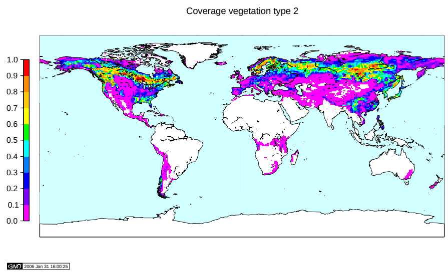
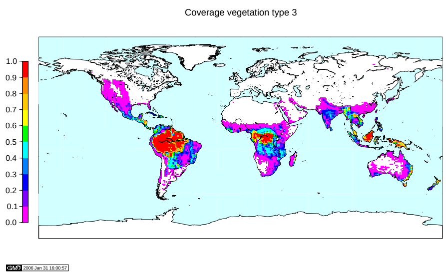


(b)



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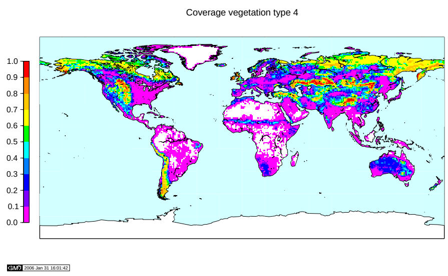
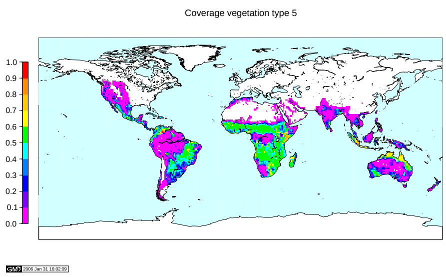
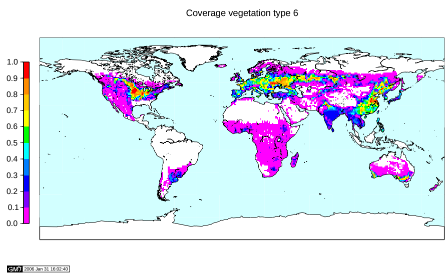


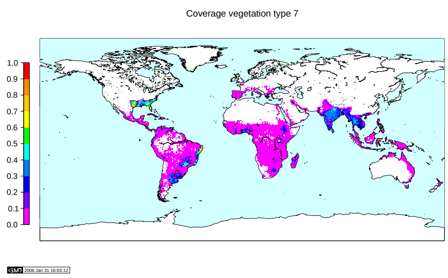
(d)



(e)



(f)



(g)

Figure 9.2: Coverage per vegetation type.

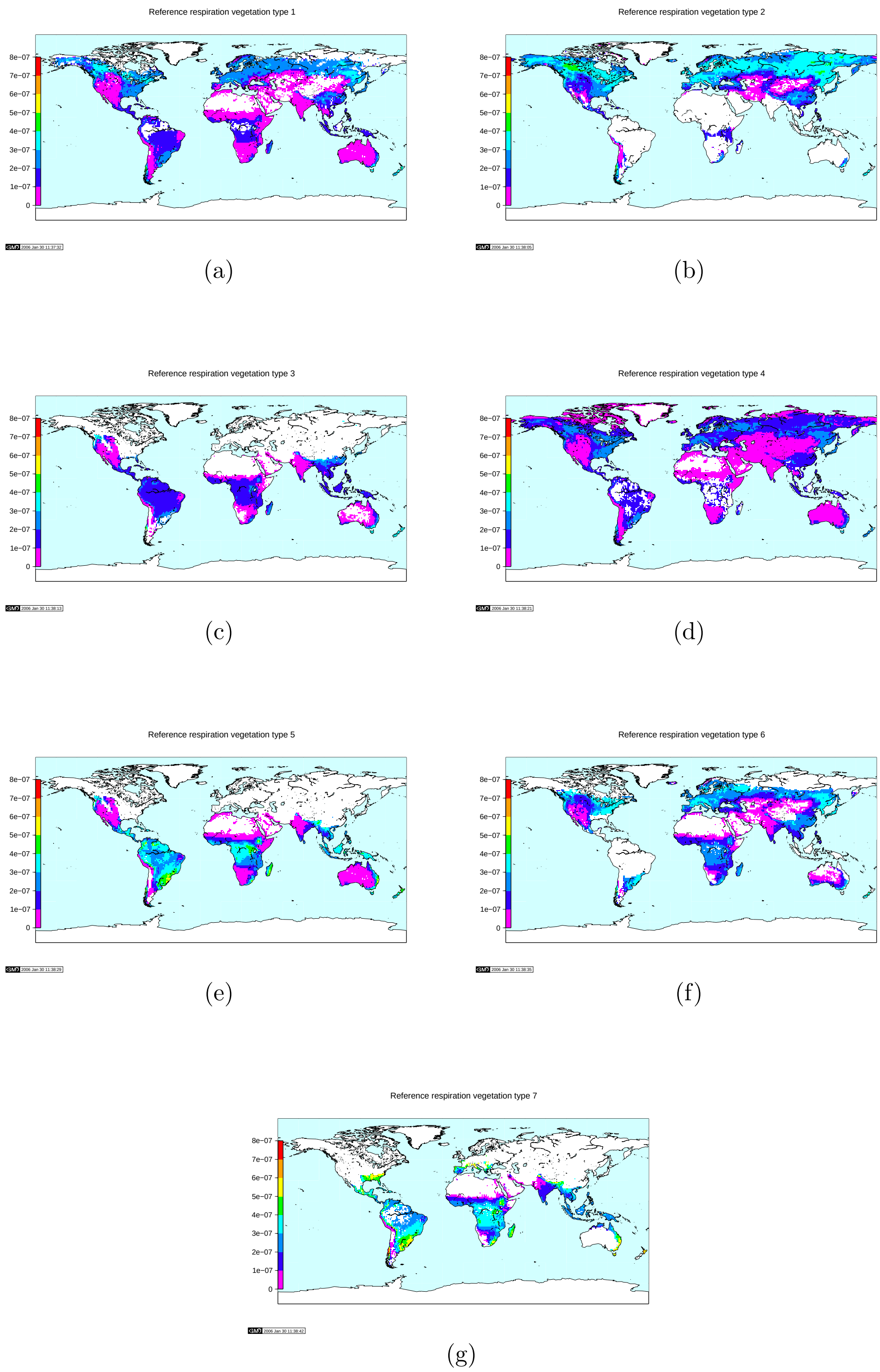


Figure 9.3: Reference respiration per vegetation type in $kgC/m^2/s$.

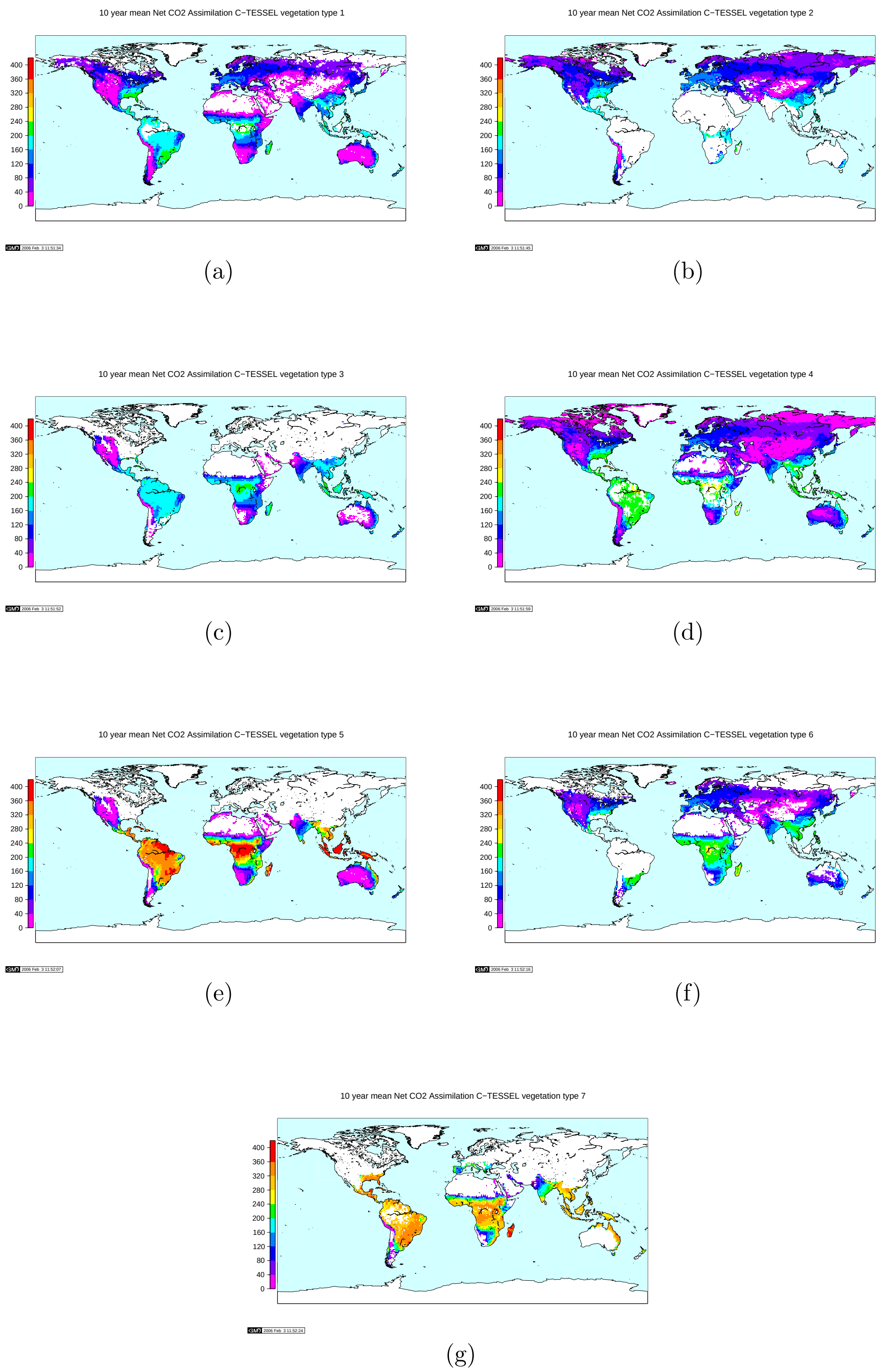


Figure 9.4: Net CO2 Assimilation per vegetation type in $kgC/ha/day$.

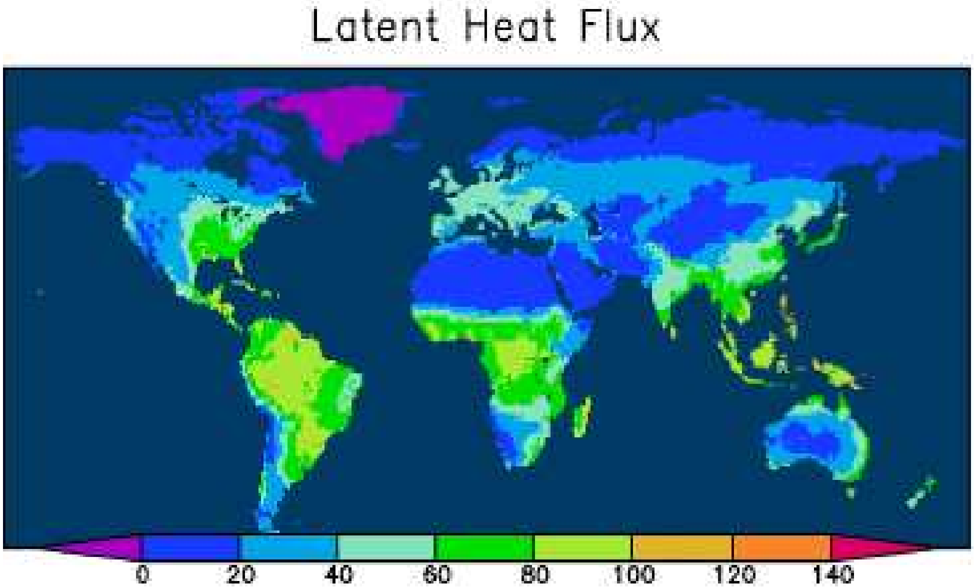


Figure 9.5: 10 year average latent heat flux of the ensemble mean of GSWP2 in W/m^2 (Source: (7)).

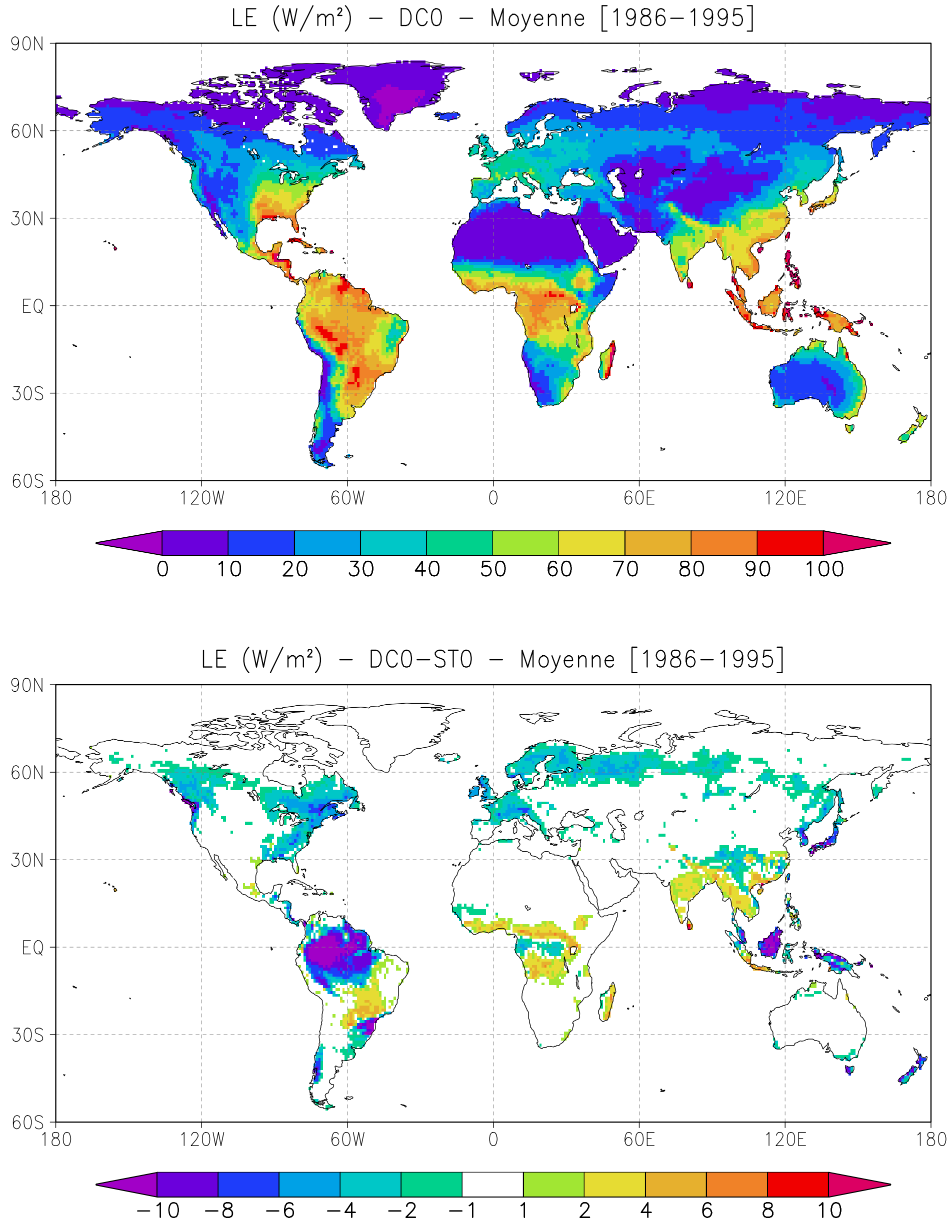


Figure 9.6: Difference between the 10 year average net CO2 flux of ISBA-A-gs (upper map) and that of ISBA (Source: A. Gibelin).