

# **Climate effects of land use changes and anthropogenic impact on surface radiation**

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By Maria Malene Kvalevåg

Department of Geosciences

Section of Meteorology and Oceanography

University of Oslo

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# Table of Contents

<b>Acknowledgements .....</b>	<b>2</b>
<b>Chapter 1 General introduction .....</b>	<b>3</b>
1.1 Background .....	3
1.2 Objectives .....	5
1.3 Thesis outline.....	5
<b>Chapter 2 Scientific Background.....</b>	<b>6</b>
2.1 Land use changes.....	6
2.2 Solar dimming and brightening .....	8
2.3 UV – radiation.....	9
<b>Chapter 3 Modeling tools.....</b>	<b>11</b>
3.1 The Global Climate Model (GCM) .....	11
3.2 The Radiative Transfer Model.....	12
<b>Chapter 4 Summary of papers.....</b>	<b>15</b>
4.1 Anthropogenic land cover changes in a GCM with surface albedo change based on MODIS data.....	15
4.2 Human impact on direct and diffuse solar radiation during the industrial era.....	16
4.3 Extensive reduction of surface UV radiation since 1750 in worlds populated regions .....	17
<b>References.....</b>	<b>18</b>

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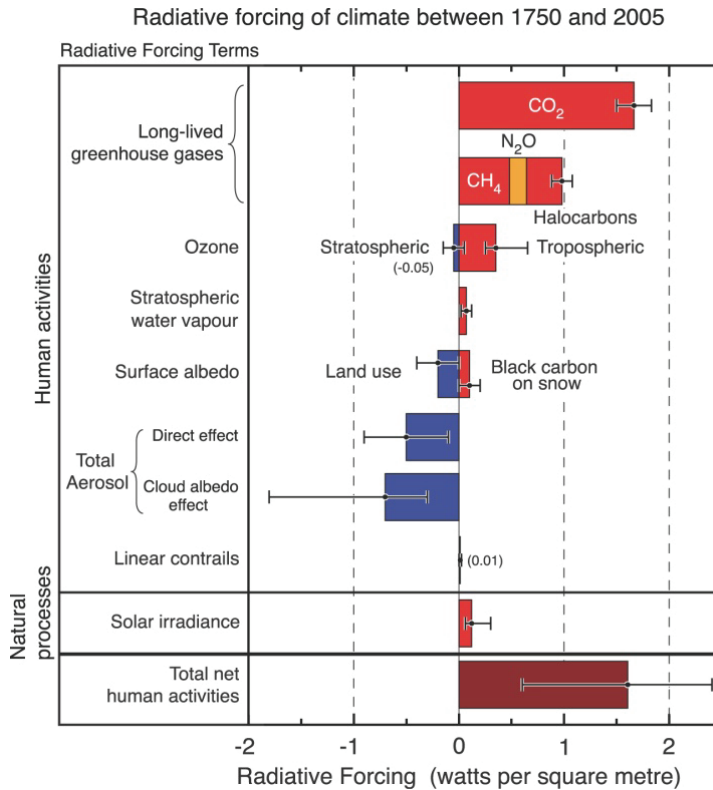
# Chapter 1 General introduction

## 1.1 Background

The fourth assessment report on climate change (AR4) was released in 2007 and the Intergovernmental Panel of Climate Change (IPCC) derive an increase of  $0.74 \pm 0.18^\circ\text{C}$  in the 100 year global mean surface temperature linear trend between 1906 – 2005. IPCC state further that “there is *very high confidence* that the global average net effect of human activities since 1750 has been one of warming” (IPCC, 2007). The observed global warming has occurred during the same period as a considerable increase of greenhouse gases in the atmosphere. The most important anthropogenic greenhouse gas is carbon dioxide ( $\text{CO}_2$ ) and the global concentration of  $\text{CO}_2$  has increased by 35% from 280 parts per million (ppm) since pre industrial times to 379 ppm in 2005. The sources of increasing  $\text{CO}_2$  in the atmosphere are related to human activity through fossil fuel combustion and deforestation. Other important greenhouse gases that have increased since pre industrial times are  $\text{N}_2\text{O}$  and  $\text{CH}_4$  and their sources are primarily from agriculture. At the same time as the observed global warming, there has been an increasing amount of anthropogenic emissions of particles into the atmosphere. These particles are known as aerosols and have mainly caused global cooling by scattering and absorbing solar radiation. It is proposed that the aerosols have partly masked the warming caused by the greenhouse gases (Charlson *et al.*, 1992, Ramanathan *et al.*, 2001, Kaufman *et al.*, 2002, Chung *et al.*, 2005).

Radiative forcing (RF) is a common concept of measuring the effect of different drivers on climate. IPCC describe RF as “a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered”. RF is especially used for comparison of the effect between different anthropogenic and natural drivers on climate. It is calculated as the change in net radiative flux at the tropopause for two different climate conditions. The first simulation is usually a control simulation for current conditions, whereas the second simulation to be compared with has been perturbed with a modification that influences the climate system. Typically, the RF is calculated as the difference between the climate today (i.e. 2005 in the latest IPCC report) compared to the climate in pre industrial times (year 1750) for a wide range of climate forcing mechanisms. A negative RF is associated with loss of energy between the two different climate conditions and is related to a cooling of the Earth-Atmosphere system. A positive RF occurs when more energy is added and results in a warming of the system. Factors that can possibly influence climate through a positive or negative RF are compared as seen in Figure 1.

Atmospheric  $\text{CO}_2$  absorbs infrared radiation emitted by the Earth’s surface, effectively trapping heat in the atmosphere and is accordingly an important greenhouse gas. The natural abundance of  $\text{CO}_2$  in the atmosphere is therefore necessary for the greenhouse effect on our planet, but the increase during the last centuries has contributed to imbalance the Earth-Atmosphere system. Due to human activities,  $\text{CO}_2$  is contributing to a positive RF of  $1.66 \text{ Wm}^{-2}$ . The radiative forcing of  $\text{CO}_2$  is the strongest term among the long-lived greenhouse gases and also the strongest contributor among all the forcing mechanisms compared here. Other long-lived greenhouse gases such as  $\text{CH}_4$ , Halocarbons and  $\text{N}_2\text{O}$  are



**Figure 1:** Overview of the radiative forcing components due to human activities and natural processes since pre industrial times (IPCC, 2007).

contributing to a total positive RF of  $0.98 \text{ Wm}^{-2}$ . Ozone is an important greenhouse gas as well as being crucial for protecting life on Earth against UV radiation. A negative RF is associated with the stratospheric ozone depletion ( $-0.05 \text{ Wm}^{-2}$ ) while the increased ozone in the troposphere causes a positive RF ( $+0.35 \text{ Wm}^{-2}$ ).

Aerosols influence the climate system through the direct effect of scattering and absorbing solar radiation. Global mean radiative forcing is  $-0.50 \text{ Wm}^{-2}$  with an estimated error of  $\pm 0.40 \text{ Wm}^{-2}$  for the direct effect of aerosols. Aerosols also influence climate indirectly when acting as cloud condensation nuclei (CCN) in the formation of clouds. More numerous aerosols as CCN enhance the reflectivity of the cloud compared to fewer aerosols when sharing the same amount of cloud liquid water and the indirect effect of aerosols is thus called the cloud albedo effect. The effect of aerosols on cloud formation is very uncertain and has the greatest uncertainty range among the RF components in Figure 1.

Surface albedo is the ratio between reflected and incident solar radiation at the surface. Changes in surface albedo due to land use since year 1750 produce a negative RF due to increased reflectivity of agricultural land compared to forest. The estimated forcing since pre industrial time caused by land use is  $-0.20 \text{ Wm}^{-2}$  with an uncertainty range of  $\pm 0.20 \text{ Wm}^{-2}$ . Nevertheless, deforestation started long time before the industrial era. About  $\frac{1}{4}$

of the radiative forcing caused by agricultural activity occurred prior to 1750 (Betts *et al.*, 2007).

Stratospheric water vapour and contrails are considerable smaller forcing mechanisms than the other discussed here but are still important for understanding the anthropogenic influence on climate change. Increase of stratospheric water vapour is an indirect effect of increased atmospheric CH<sub>4</sub> with a best RF estimate of 0.07 Wm<sup>-2</sup>. The aviation induce contrail cover contribute to climate change by reflecting solar radiation and absorbing long wave radiation which are counteracting effects in terms of forcing. The best RF estimate of contrails is 0.01 Wm<sup>-2</sup>.

The total net radiative forcing presented in Figure 1 is the overall forcing from all the compounds resulting from anthropogenic activity. The global mean effect of all anthropogenic compounds is a positive RF of 1.60 Wm<sup>-2</sup>, thus a global warming effect. Compared to the natural forcing of changes in solar irradiance, human activity is suggested as a much stronger driver of climate change than the natural change of incident solar radiation.

## 1.2 Objectives

This thesis includes three major subjects concerning anthropogenic influence on climate which alter the radiation balance at the surface. The motivation is to quantify radiative processes that are causing climate change and to study their influence on global climate. Man-made clearing of forest for agricultural purposes is analyzed in a global climate model to study the climate change due to changes in surface albedo from deforestation and agricultural activity. The global surface temperature change and changes in the hydrological cycle are parameters of particular interest. A radiative transfer model is used to calculate the anthropogenic influence of changes in surface solar and ultraviolet radiation due to human emissions of gases and aerosols and aviation induced contrails and cirrus.

## 1.3 Thesis outline

Parts I – III contain the three papers included in the scientific work:

- Kvalevåg, M. M., G. Myhre, G. Bonan and S. Levis, 2008: Anthropogenic land cover changes in a GCM with surface albedo changes based on MODIS data, *submitted to International Journal of Climatology for a special issue on land cover change*.
- Kvalevåg, M. M. and G. Myhre, 2007: Human impact on direct and diffuse solar radiation during the industrial era. *Journal of Climate*, **20**, 4874-4883.
- Kvalevåg, M. M. , G. Myhre, C. L. Myhre, 2009: Extensive reduction of surface UV radiation in world's population regions since 1750, *submitted to Proc. Natl. Acad. Sci., USA*.

## Chapter 2 Scientific Background

### 2.1 Land use changes

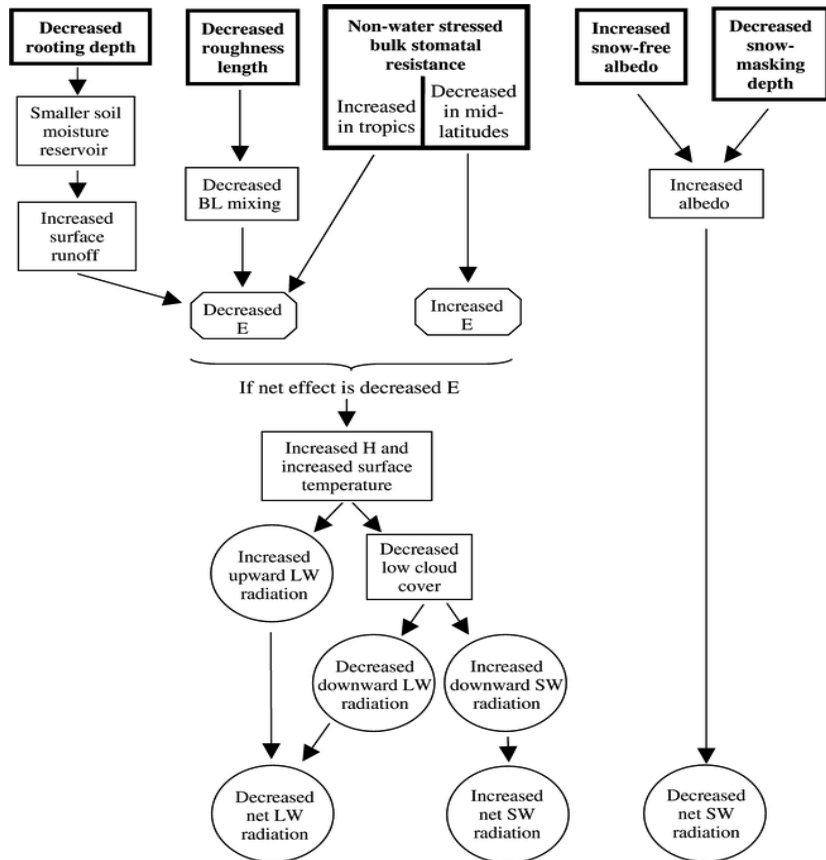
Humans have disturbed the properties of the Earth's surface substantially by removing large areas of forest. Land-use activities, primarily for agricultural expansion, covers 15 million km<sup>2</sup> of the Earth which equals 12% of the Earth's ice-free land surface (Ramankutty *et al.*, 2008). The influence of deforestation on climate is uncertain due to the many factors that contribute to climate change. *Biogeophysical* processes are altered through modified hydrological cycles and surface energy fluxes. *Biogeochemical* processes are changed through the carbon cycle. The possible climate effects resulting from these two different processes can potentially offset each other and the net effect of land cover change is still not very well known (Forster *et al.*, 2007). The atmospheric carbon concentration is fixed to present day in our climate simulations and there are no carbon cycle feedbacks, thus we only consider the biogeophysical processes in the following discussion.

Figure 2 is showing a schematic overview of the biogeophysical effects of land use caused by different land surface parameters (Findell *et al.*, 2007). Deforestation alters these land surface parameters and the effect on climate differs for each of them. The flow of water vapour in and through the canopy and from the ground is controlled by the rooting depth, roughness length and stomatal resistance. The net effect of reducing rooting depth and roughness length and increasing stomatal resistance is most likely leading to decreased evaporation and reduced transpiration from the canopy, and consequently reduced latent heat flux. An increase in snow free albedo and the reduced vegetation masking of snow increase the surface albedo. The surface albedo determines the amount of reflected solar radiation from the canopy and the ground and is important for the net radiative balance at the surface.

Figure 3 shows a vegetation map of the “potential natural” vegetation cover that would most likely have occurred before agriculture began (upper panel) and the global distribution of land that is used for agricultural purposes (lower panel) (Foley *et al.*, 2005). Large areas in North America, Europe and in South Asia as well as minor regions in South America, Africa and Australia are used for agricultural activity. These regions are associated with forest or grassland in the map of potential natural vegetation in pre agricultural times.

Previous studies have calculated the global radiative forcing of the surface albedo effect due to land cover change (Hansen, J. E. *et al.*, 1998, Betts, 2001, Myhre and Myhre, 2003, Myhre *et al.*, 2005, Betts *et al.*, 2007). Myhre *et al.* (2005) found a weaker forcing than previously estimated of  $-0.09 \text{ Wm}^{-2}$  using satellite retrieved surface albedo values from the Moderate Resolution Imaging Spectroradiometer (MODIS). Myhre and Myhre (2003) claim that the surface albedo value of cropland is a crucial parameter in calculating radiative forcing estimates of land cover change. If the surface albedo effect is the dominant driver of climate change, the response of deforestation will be a surface cooling. Hansen *et al.* (2005) found a global mean annual surface temperature decrease of  $-0.20 \pm 0.20 \text{ K}$  based on five ensemble mean simulations from a global climate model. Betts (2001, 2007) also argue that the surface albedo effect is the most dominant effect in land use changes, and calculates a decrease over land of  $-0.06 \text{ K}$ . According to Figure 3, extensive agriculture occurs in mid

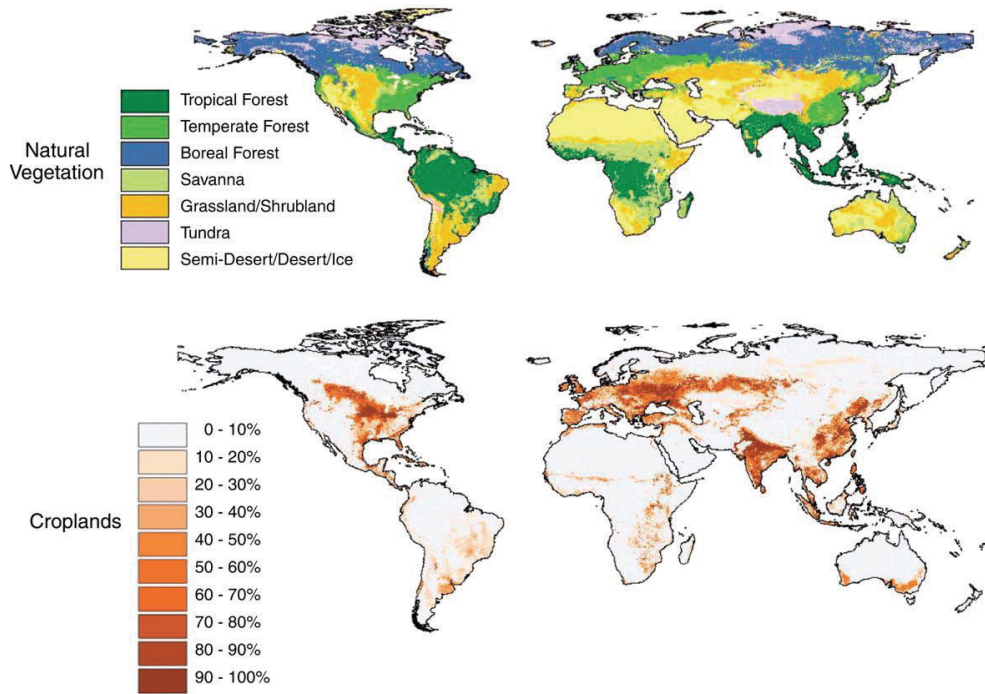




**Figure 2:** Idealized schematic overview of processes influenced by deforestation in a model; *E* (evapotranspiration), *H* (sensible heat), *BL* (boundary layer), *LW* (long wave) and *SW* (short wave). Circles: Surface fluxes, Bold squares: Prescribed model parameters (Findell *et al.*, 2007).

latitudes in the Northern Hemisphere (NH), and this is a region that is covered with snow during NH winter. Snow covered forests have a much lower albedo than snow covered crops and is the main reason for the calculated global surface cooling (Betts, 2000).

Land cover conversions can potentially impact the water flow through the canopy and disturb the surface water balance and the partitioning of precipitation into evapotranspiration and runoff. Surface runoff and river discharge generally increase when natural vegetation is removed. According to a study on deforestation and irrigation, deforestation is alleged to have decreased water vapor flow from the land surface to the atmosphere by 4%, an amount which is almost compensated for by an increase due to irrigation (Gordon *et al.*, 2005).

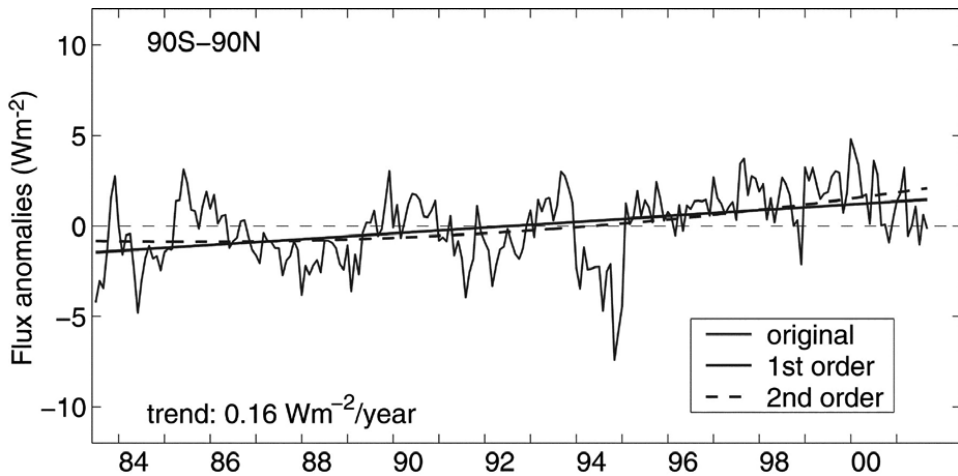


**Figure 3:** *Vegetation cover in pre agricultural times (upper panel). Percent area covered with cropland in present day (lower panel) (Foley et al., 2005).*

## 2.2 Solar dimming and brightening

Scattering and absorbing constituents in the atmosphere have a great impact on the incident surface solar radiation (Stanhill and Cohen, 2001, Wild *et al.*, 2005). Satellite retrievals during the last two decades have observed a recent solar brightening, i.e. a trend of increasing incident solar radiation at the surface (Pinker *et al.*, 2005). Figure 4 shows the time series of surface solar radiation from 1983-2001 retrieved from satellite measurements with a first and second order least square fit. The linear trend shows an increase in surface solar radiation throughout the period and is estimated as  $0.16 \text{ W/m}^2/\text{year}$ . The second order fit shows a decreasing trend up to 1992, and then a reversal with an increasing trend towards 2001. The period of decreasing surface solar radiation, is the last part of a period of global dimming which started in the 60's and lasted for about three decades. This trend is also supported by ground based measurements from world wide sites where the calculated decline in surface solar radiation is estimated to 4% during 1961-1990 (Liepert, 2002). The dimming is most likely caused by the strong emissions from expanding transport and industry in mid 20<sup>th</sup> century. When better technology and restrictions on emission were introduced in the 80's and 90's, the emissions were reduced and the air became cleaner. Alpert *et al.* (2005) argue that cities with large populations have a much stronger effect on the total solar radiation at the surface compared to rural regions. They estimated that urban activities reduce the surface solar radiation by  $-0.41 \text{ W/m}^2/\text{year}$  between 1964 and 1989.

The solar radiation is divided into two components: The solar radiation that penetrates the atmosphere directly to the Earth's surface without being obstructed is called *direct solar radiation*. The radiation that has been scattered out of the direct beam by either clouds, aerosols or other atmospheric constituents is called *diffuse solar radiation*. The *total solar radiation* is the sum of the component of direct sunlight and the diffuse component of scattered light. The distinction between direct and diffuse radiation is important because it is claimed that increasing amount of diffuse light can increase the photosynthesis because diffuse radiation penetrates deeper into the forest canopy than direct radiation (Roderick *et al.*, 2001).



**Figure 4:** Satellite retrieved total solar radiation at the surface from 1983 – 2001 (Pinker *et al.*, 2005)

### 2.3 UV – radiation

Ultraviolet (UV) radiation is very important for all biological life on Earth. UV radiation is defined as wavelengths between 280 – 400nm; the shortest wavelengths are UV-B radiation (280-320nm), while UV-A radiation exists of wavelengths between 320 and 400nm. There have been major concerns regarding increasing UV-radiation since the beginning of 1980s when scientists first discovered the indication of ozone depletion. The stratospheric ozone concentrations experienced a rapid decrease during the 80's and early 90's due to rising chlorine and bromine amounts in the atmosphere, with lowest values occurring during 1992 to 1993 (~6% below the 1964 to 1980 average) (WMO, 2007). The ozone level has by now reached steady values and is most likely being recovered due to global limitations on emissions of ozone destroying gases. Global ozone values for the time period 2000 - 2003 was ~4% below the 1964 to 1980 average (WMO, 2007). In nearly unpolluted regions, especially in the Southern Hemisphere, reduced UV radiation has currently been observed, as expected from the recovering of the Antarctic “ozone hole” and from measurements of increasing ozone (Bais *et al.*, 2007). At mid- and low latitudes, changes in surface UV radiation are harder to quantify because it is difficult to separate ozone changes from those

due to other causes, such as changes in aerosols and clouds, because of higher concentrations of air pollutants.

Satellite measurements started in early 1990s and have contributed to an increased understanding of the ozone depletion and the relation to increased UV-radiation. Retrievals from space are also of great importance regarding global coverage of the ozone column. Major effort has been made in recent years to improve the satellite measurements (Krotkov *et al.*, 1998, Krotkov *et al.*, 2001). It is especially the absorbing gases and aerosols that produce the largest biases in the calculation of surface UV radiation based on satellite retrievals (Arola *et al.*, 2005). Combined with ground based measurements, satellite observations are important tools to investigate UV changes.

During the last decades, the importance of air pollutants on global and local UV radiation has received more attention (Bais *et al.*, 2007) and some studies have indicated that emissions from anthropogenic activity can counteract the effect of stratospheric ozone depletion on surface UV-radiation (Liu *et al.*, 1991, Sabziparvar *et al.*, 1998, Barnard *et al.*, 2003). The concentrations of air pollutants have been increasing due to anthropogenic emission of aerosols and gases since pre industrial times and is therefore of interest when estimating long term changes in UV during the industrial era. Strong spatial, temporal and spectral variations in aerosol and gas properties are the most challenging issues when estimating the effect of air pollutants on UV radiation. While ozone depletion has been the most important factor for surface UV the last decades, anthropogenic emissions of aerosols and gases have influenced surface UV during centuries.

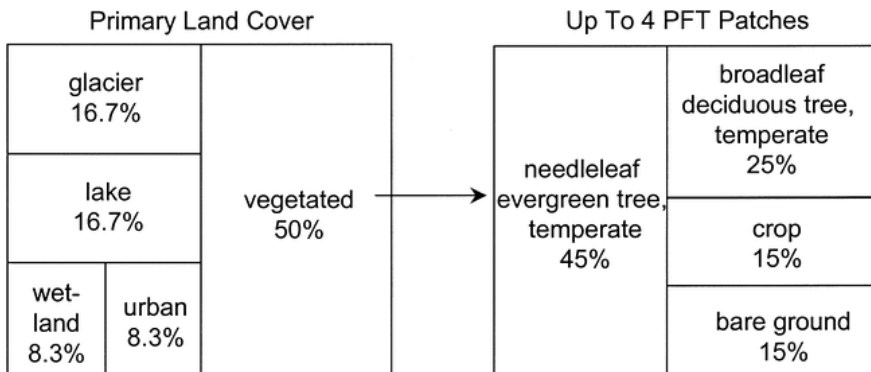
McKinlay and Diffey (1987) defined an action spectrum which relate UV radiation to skin damages and is denoted as UV-E (erythemally weighted UV radiation). UV-B is weighted close to unity, while the action spectrum decreases toward lower values for longer wavelengths. Shorter wavelengths penetrate deeper into the skin and are responsible for more dangerous skin damage than longer UV wavelengths. The concept of UV-E radiation is used in Kvalevåg *et al.* (2009).

## Chapter 3 Modeling tools

### 3.1 The Global Climate Model (GCM)

The climate simulations for studying the surface albedo effect from land cover changes are performed with the National Center for Atmospheric Research (NCAR) Community Land Model 3.5 (CLM3.5) coupled to the Community Atmosphere Model 3 (CAM3) (Collins *et al.*, 2006) and a slab ocean model (Kiehl *et al.*, 2006). All modifications performed to study land cover changes are made within the CLM3.5. The land model is an upgraded version of the CLM3 (Dickinson *et al.*, 2006), where the most important modification for our purpose is an improved hydrology cycle (Oleson *et al.*, 2008). The spatial horizontal resolution is T42 (2.8° x 2.8°) and with 26 atmospheric vertical layers. The time integration is averaged into monthly means. The 30 last years of a 40 year integration are used to calculate annual global mean changes in climate parameters such as surface temperature, latent and sensible heat fluxes, cloud cover, precipitation and water vapor column.

A remotely sensed fractional vegetation cover data set is used as current vegetation in CLM3.5 (Bonan *et al.*, 2002, Oleson *et al.*, 2008). This data set includes seven primary plant functional types (PFT) (needleleaf evergreen/deciduous tree, broadleaf evergreen/deciduous tree, shrub, grass and crop) and seven variants within the primary types (arctic/boreal/temperate/tropical trees, C<sub>3</sub>/C<sub>4</sub> grasses, and evergreen/deciduous shrubs). Every PFT is associated with biogeophysical parameters to describe the vegetation structure. CLM3.5 operates with a constant vegetation fraction throughout the year, where the leaf/stem area index (LAI/SAI) for each PFT describes the seasonal change. The vegetated part of a grid cell, as shown in Figure 5, can possibly hold 4 PFT's in CLM2, but is increased in CLM3.5 to allow for 16 PFT's within one grid cell. The non vegetated part of a grid cell contains glacier, lake, wetland or urban classifications. When we study land cover change, the anthropogenic vegetated part of the grid cell, cropland, is replaced with the natural vegetation based on a data set of natural vegetation by Ramankutty and Foley (1999) (Figure 3 upper panel). Consequently, the vegetation parameters, such as roughness length, rooting depth, LAI/SAI are changed.



**Figure 5:** Sketch of the land cover structure of a grid cell in CLM2 (Bonan *et al.*, 2002). CLM3 introduced up to 16 PFT patches instead of 4 as shown in box to the right.

The surface albedo simulated in CLM3.5 varies with snow cover, soil moisture, leaf and stem optical properties, and LAI/SAI. The parameterization of surface albedo is based on Dickinson (1983). The surface albedo is a combination of ground, vegetation and soil albedo and is calculated using a two stream approximation (Oleson *et al.*, 2004). Kvalevåg *et al.* (2008) overwrite the calculated surface albedo with satellite retrieved snow free surface albedo from MODIS. In this way, the surface albedo in the model is constrained to observed values of surface albedo.

### 3.2 The Radiative Transfer Model

We use a multistream radiative transfer model to calculate the irradiances at the surface for direct and diffuse solar radiation (Kvalevåg and Myhre, 2007) and UV radiation (Kvalevåg *et al.*, 2009). The model contains the discrete ordinate radiative transfer (DISORT) algorithm (Stamnes *et al.*, 1988, Myhre *et al.*, 2002) adopted with eight streams. It includes absorption by atmospheric gases, clouds, and Rayleigh scattering. A spectral resolution of four bands in the total solar radiation is used in the model (Myhre *et al.*, 2002). UV calculations are performed with a five nanometer spectral resolution in the UVB (280-320 nm) and UVA (320-400 nm) regions, and thereafter integrated over the two intervals. The meteorological data of temperature and cloud cover are from the European Centre for Medium-Range Weather Forecasts (ECMWF) for the year 2000. The model uses the same cloud cover for preindustrial times as for present day; thus inter-annual variation is not taken into account. Radiative transfer calculations are performed with 3-h time step on monthly mean data. Calculations for the indirect aerosol effects are performed on daily data with 3-h time step. Annual means are averaged based on the monthly mean (daily data for the indirect aerosol effect). The model resolution is T42 (approximately  $3^\circ \times 3^\circ$ ) and with 40 vertical layers.

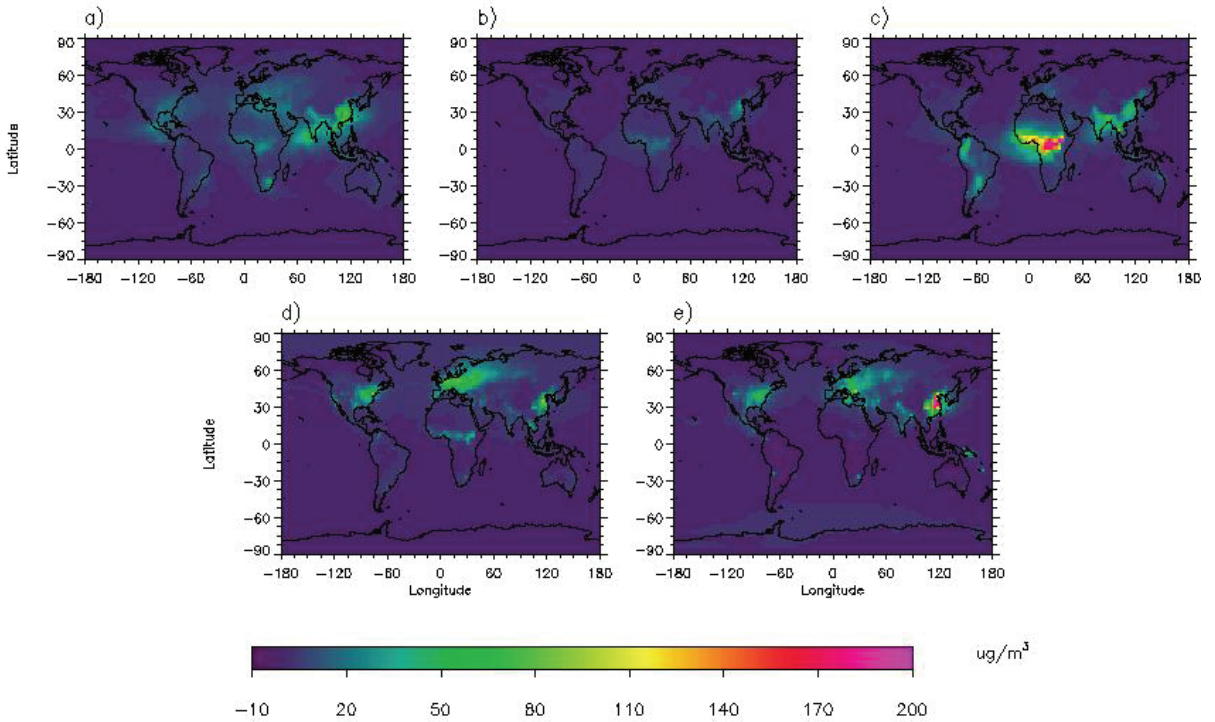
#### 3.1.1 Compositional changes

Anthropogenic activity has increased the aerosol content in the atmosphere. In this respect, the most important aerosol components are sulfate, black carbon (soot), and organic carbon (OC) from both fossil fuel combustion and biomass burning. Aerosol datasets for both present and preindustrial times are based on simulations from the Oslo CTM2 chemistry transport model, which has been part of a global aerosol comparison study (AEROCOM; <http://nansen.ipsl.jussieu.fr/AEROCOM/>) (Textor *et al.*, 2006). The aerosol simulations include background aerosols, such as mineral dust and sea salt. Anthropogenic dust is not included in this study.

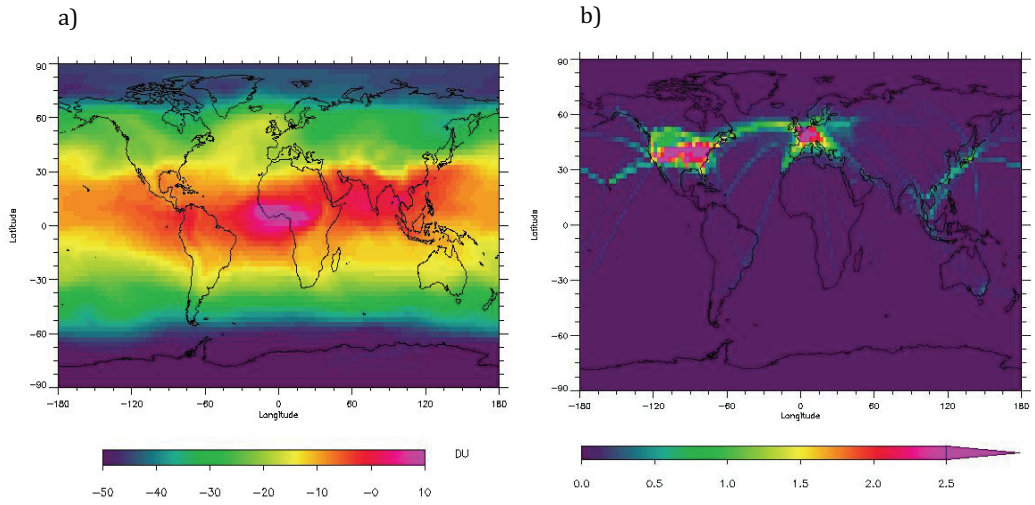
The amount of atmospheric gases that influence surface solar and UV radiation has also increased as a result of anthropogenic activity. We include O<sub>3</sub>, NO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>O and CO<sub>2</sub> in Kvalevåg and Myhre (2007), while concentrating on O<sub>3</sub>, NO<sub>2</sub> and SO<sub>2</sub> in Kvalevåg *et al.* (2009). Figure 6 shows the global atmospheric compositional changes in aerosols (sulphate, soot and OC) and gases (NO<sub>2</sub> and SO<sub>2</sub>) during the industrial era. The strong increase of aerosol and gas emissions is related to highly populated regions. However, the largest changes of aerosol load have occurred over bio mass regions in central Africa. Figure 7a shows that ozone has been reduced close to the poles due to ozone depletion in the

stratosphere, but increased at lower latitudes caused by increasing tropospheric ozone. Figure 7b shows the increase in contrail cover from intensified aviation. Contrails and subsequent evolving cirrus clouds can influence the NH climate, most over North America and Europe (Forster et al., 2007). These thin clouds consist of ice particles that reflect solar radiation but are also trapping long wave radiation which increase the greenhouse effect (Myhre and Stordal, 2001).

CH<sub>4</sub> and CO<sub>2</sub> concentrations have had a relatively homogenous and vertical well mixed increase (not shown here) throughout the atmosphere compared to NO<sub>2</sub> and SO<sub>2</sub>. CH<sub>4</sub> has changed from a pre industrial level of 0.700 ppmv to 1.745 ppmv in year 2000. CO<sub>2</sub> has increased from 278 to 365 ppmv during the same period (Ramaswamy, 2001). We also calculate the effect on total solar radiation at the surface due to an estimated increase in the H<sub>2</sub>O optical depth during the last two decades by 2.8% in the troposphere (Trenberth *et al.*, 2005).



**Figure 6:** Changes in aerosol and gas content ( $\mu\text{g}/\text{m}^3$ ) between present and preindustrial times used in the radiative transfer model for a) sulphate aerosols, b) soot (bc), c) organic carbon (oc), d) NO<sub>2</sub>, and e) SO<sub>2</sub>.



**Figure 7:** Same as Figure 6 but for a) ozone (DU) and b) contrails (%).



## Chapter 4 Summary of papers

### 4.1 Anthropogenic land cover changes in a GCM with surface albedo change based on MODIS data

M. M. Kvalevåg<sup>1</sup>, G. Myhre<sup>1,2</sup>, G. Bonan<sup>3</sup> and S. Levis<sup>3</sup>

[1] Department of Geosciences, University of Oslo, Norway

[2] Center for International Climate and Environmental Research – Oslo (CICERO), Norway

[3] National Center for Atmospheric Research, Boulder, Colorado, USA

Simulations with CLM3.5 coupled to CAM3.0 and a slab ocean model have been performed to study land cover changes in a global climate model. We have used the MODIS surface albedo product to represent current surface albedo and to reconstruct a surface albedo data set for pre-agricultural times. This is done for the purpose of imposing a satellite based surface albedo change from the land cover changes into the climate model. Our main findings are:

- A small global warming since pre industrial times when both vegetation cover and surface albedo have been changed. However regionally the results vary: In the main regions of land use change we find surface warming of India, but North America and Europe have cooler surface temperatures today than before deforestation.
- When we exclude the change in vegetation cover and only take account of the satellite based surface albedo change in the model, the annual global mean warming is reduced. Further, while the surface temperature change in North America and Europe remains a cooling, India is in this case experiencing reduced surface temperature.
- The changes associated with the replacement of temperate forests with agricultural land are broadly similar in North America and Europe. In both cases there is surface cooling, decreased sensible heat, increased latent heat, cloud cover and precipitation. In India where the tropical forests have been replaced by crops, the surface temperature increases, while all other parameters discussed here are reduced. The surface albedo change is most dominant in temperate regions while the change in evapotranspiration drives the climate response in the tropics (Bonan, 2008).
- The satellite based surface albedo changes due to land cover change are not large enough to produce major differences between the climate in present day and pre-agricultural times. When the surface albedo value for cropland is increased in a sensitivity simulation, the climate response through surface temperatures in all three regions becomes significant at the 95% level.

- We find a total reduction in global surface water flow of -0.6% when considering both vegetation changes and surface albedo changes. This small decrease is a combination of reduced evapotranspiration through the modified canopy (-2.3%) and an increase of evaporation from the surface (+1.8%).
- The surface albedo value for cropland is of major importance in climate simulations of land cover change. The surface albedo effect is the main driving mechanism when the change in surface albedo between agricultural and natural land is substantial. In the sensitivity study where the surface albedo value for cropland was increased, the surface temperature change between current and pre-agricultural land is closer to previous estimates (Betts, 2001, Hansen, J. et al., 2005, Betts et al., 2007). Using satellite retrieved surface albedo for cropland, the surface albedo effect becomes smaller and the climate response due to land cover change is weaker.

#### 4.2 Human impact on direct and diffuse solar radiation during the industrial era

M. M. Kvalevåg<sup>1</sup> and G. Myhre<sup>2</sup>

[1] Department of Geosciences, University of Oslo

[2] Center for International Climate and Environmental Research – Oslo (CICERO)

This study investigates the change in direct and diffuse surface solar radiation due to anthropogenic emissions of gases and aerosols and aviation induced cirrus and contrails. Calculations of incident solar radiation at the surface are performed in a radiative transfer model. We include anthropogenic changes since pre industrial times in five different gases: O<sub>3</sub> (stratospheric decrease and tropospheric increase), NO<sub>2</sub>, H<sub>2</sub>O, CO<sub>2</sub> and three types of aerosols: sulphate, organic and black carbon from fossil fuel combustion and bio mass burning. The compositional change in gases and aerosols is considered as the difference in atmospheric concentration between present (year 2000) and pre industrial times (year 1750). We also study the effect of aviation induced cirrus and contrails.

- We find that gases contribute to a total reduction of direct and diffuse radiation with  $-0.22 \text{ Wm}^{-2}$  and  $-0.09 \text{ Wm}^{-2}$ , respectively.
- The only gas that contributes to *an increase* of the solar radiation at the surface is stratospheric ozone. Its effect on solar brightening dominates over the decrease of solar radiation caused by increase tropospheric ozone, except in the Tropics.
- The greatest contributor to solar dimming is the direct effect of aerosols. We include both absorbing and scattering aerosols that decrease direct radiation with  $-2.77 \text{ Wm}^{-2}$  and increase diffuse radiation with  $1.42 \text{ Wm}^{-2}$ . Thus the direct effect of aerosols reduces the total solar radiation at the surface globally by  $-1.35 \text{ Wm}^{-2}$ . Global dimming is to a large degree constrained to certain land areas and the surrounding

oceanic regions. The reduction of direct solar radiation is as large as 40% in the most industrialized and populated regions in North America, Europe and South East Asia.

- Because of the coarse horizontal resolution of the model, it does not fully resolve the maximum values where the strongest dimming occurs. Using MODIS aerosol optical depths (AOD) retrievals, it is shown that the dimming may be higher than a factor of two in the centre of maximum dimming than in an averaged region.

#### **4.3 Extensive reduction of surface UV radiation since 1750 in world's populated regions**

M. M. Kvalevåg<sup>1</sup>, G. Myhre<sup>1,2</sup> and C. E. L. Myhre<sup>3</sup>

[1] Department of Geosciences, University of Oslo, Norway

[2] Center for International Climate and Environmental Research – Oslo (CICERO), Norway

[3] Norwegian Institute of Air Research, NILU, Kjeller, Oslo, Norway

Human activities influence the wide range of components that affect the surface UV radiation levels, among them ozone at high latitudes. In this study we use a global radiative transfer model to investigate the changes in erythemally weighted UV radiation (UV-E) since 1750 caused by anthropogenic changes in three gases (ozone, NO<sub>2</sub>, and SO<sub>2</sub>), aerosols (sulphate, organic and black carbon from fossil fuel combustions and biomass burning), the cloud albedo effect due to aerosols, surface albedo changes due to deforestation and snow cover changes, and aviation-induced contrails and cirrus. Our aim is to investigate the changes between year 1750 and 2000 and to what extent there are regional variations for the components. We use erythemally weighted UV radiation (UV-E) that relates UV radiation and skin damages.

- The results show an *increase* of surface UV-E in polar regions, most strongly in the Southern Hemisphere. Moreover, our study also shows an extensive surface UV-E *reduction* over most land areas; a reduction up to 20% is found in some industrialized regions.
- Our analysis shows that currently 95% of the world's population lives in regions where surface UV-E has been reduced during the industrial era, and only 0.3% lives in locations with more than a 5% increase.
- The model results are validated against ground based measurements and satellite derived surface UV-E. The model correlates well with the observations from 14 sites ( $r^2 = 0.98$ ), but overestimates UV-E during summer months at stations in lower latitudes. The model is as least as good as the satellite derived surface UV-E provided by TOMS.

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