

**Analysis of the spatial heterogeneity of land surface  
parameters and energy flux densities**

**DISSERTATION**

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## Zusammenfassung

Die vorliegende Arbeit wurde auf der Grundlage begutachteter Publikationen als kumulative Dissertation verfasst.

Klimaprognosen basieren im Allgemeinen auf den Ergebnissen numerischer Simulationen mit globalen oder regionalen Klimamodellen. Eine der entscheidenden Unsicherheiten bestehender Modelle liegt in dem noch unzureichenden Verständnis von Wechselwirkungsprozessen zwischen der Atmosphäre und Landoberflächen und dem daraus folgenden Fehlen entsprechender Parametrisierungen. Um das Problem einer unsicheren Modell-Parametrisierung aufzugreifen und zum Beispiel subskalige Heterogenität in einer Art und Weise zu beschreiben, dass sie für Modelle nutzbar wird, werden für die Bestimmung und Evaluierung von Modell-Parametrisierungsansätzen so viele Datensätze wie möglich benötigt. Die Arbeit trägt zu diesem Thema durch die Verwendung verschiedener Datensätze unterschiedlicher Plattformen bei. Ziel der Studie war es, aus Satellitendaten verschiedener räumlicher und zeitlicher Auflösung sowie aus in-situ Daten die räumliche Heterogenität von Landoberflächenparametern und Energieflussdichten zu bestimmen. Die Untersuchungen wurden für zwei Zielgebiete in Deutschland durchgeführt. Für das LITFASS-Gebiet (Lindenberg Inhomogeneous Terrain - Fluxes between Atmosphere and Surface: a longterm Study) wurden Satellitendaten der Jahre 2002 und 2003 untersucht und validiert. Zusätzlich wurde im Rahmen dieser Arbeit eine NDVI-Studie (Normalisierter Differenzen Vegetations Index: Maß zur Detektierung von Vegetationsflächen, deren Vitalität und Dichte) auf den Testflächen des FLUXNET Clusters um Tharandt in den Jahren 2006 und 2007 realisiert.

Die Grundlage der Arbeit bildete die Bestimmung von Landoberflächeneigenschaften und daraus resultierenden Energieflüssen, auf Basis dreier optischer Sensoren (ETM+ (Enhanced Thematic Mapper), MODIS (Moderate Resolution Imaging Spectroradiometer) und AVHRR 3 (Advanced Very High Resolution Radiometer)) mit unterschiedlichen räumlichen (30 m – 1 km) und zeitlichen (1 – 16 Tage) Auflösungen. Unterschiedliche Sensorcharakteristiken, sowie die Verwendung verschiedener, zum Teil ungenauer Datensätze zur Landnutzungsklassifikation führen zu Abweichungen in den Ergebnissen der einzelnen Sensoren. Durch die Quantifizierung der Sensorunterschiede, die Anpassung der Ergebnisse der Sensoren aneinander und eine Qualitätsanalyse von verschiedenen Landnutzungsklassifikationen, wurde eine Basis für eine vergleichbare Parametrisierung der Oberflächenparameter und damit auch für die daraus berechneten Energieflüsse geschaffen.

Der Schwerpunkt lag dabei auf der Bestimmung des latenten Wärmestromes ( $L.E$ ) mit Hilfe des Penman-Monteith Ansatzes (P-M). Satellitendaten liefern Messwerte der spektralen Reflexion und der Oberflächentemperatur. Die P-M Gleichung erfordert weitere Oberflächenparameter wie zum Beispiel den NDVI, den Blattflächenindex (LAI), die Windgeschwindigkeit, die relative Luftfeuchte, die Vegetationshöhe oder die Rauheitslänge, die jedoch aus den Satellitendaten nicht bestimmt werden können. Sie müssen indirekt aus den oben genannten Messgrößen der Satelliten oder aus in-situ Messungen abgeleitet werden. Stehen auch aus diesen Quellen keine Daten zur Verfügung, können sogenannte Standard- (Default-) Werte aus der Literatur verwendet werden. Die Qualität dieser Parameter hat einen großen Einfluss auf die Bestimmung der Strahlungs- und Energieflüsse. Sensitivitätsstudien im Rahmen der Arbeit zeigen die Bedeutung des

## Zusammenfassung

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NDVI als einen der wichtigsten Parameter in der Verdunstungsbestimmung nach P-M. Im Gegensatz dazu wurde deutlich, dass z. B. die Vegetationshöhe und die Messhöhe einen relativ kleinen Einfluss auf  $L.E$  haben, so dass für diese Parameter die Verwendung von Standardwerten gerechtfertigt ist.

Aufgrund der Schlüsselrolle, welche der NDVI in der Bestimmung der Verdunstung einnimmt, wurden im Rahmen einer Feldstudie Untersuchungen des NDVI über fünf verschiedenen Landnutzungstypen (Winterweizen, Mais, Gras, Buche und Fichte) hinsichtlich seiner räumlichen Variabilität und Sensitivität, unternommen. Dabei wurden verschiedene Bestimmungsmethoden getestet, in welchen der NDVI nicht nur aus Satellitendaten (spektral), sondern auch aus in-situ Turmmessungen (breitbandig) und Spektrometermessungen (spektral) ermittelt wird. Die besten Übereinstimmungen der Ergebnisse wurden dabei für Winterweizen und Gras für das Jahr 2006 gefunden. Für diese Landnutzungstypen betrugen die Maximaldifferenzen aus den drei Methoden jeweils 10 beziehungsweise 15 %. Deutlichere Differenzen ließen sich für die Forstflächen verzeichnen. Die Korrelation zwischen Satelliten- und Spektrometermessung betrug  $r=0.67$ . Für Satelliten- und Turmmessungen ergab sich ein Wert von  $r=0.5$ .

Basierend auf den beschriebenen Vorarbeiten wurde die räumliche Variabilität von Landoberflächenparametern und Flüssen untersucht. Die unterschiedlichen räumlichen Auflösungen der Satelliten können genutzt werden, um zum einen die subskalige Heterogenität zu beschreiben, aber auch, um den Effekt räumlicher Mittelungsverfahren zu testen. Dafür wurden Parameter und Energieflüsse in Abhängigkeit der Landnutzungs-kategorie untersucht, um typische Verteilungsmuster dieser Größen zu finden. Die Verwendung der Verteilungsmuster (in Form von Wahrscheinlichkeitsdichteverteilungen – PDFs), die für die Albedo und den NDVI aus ETM+ Daten gefunden wurden, bietet ein hohes Potential als Modellinput, um repräsentative PDFs der Energieflüsse auf größeren Skalen zu erhalten. Die ersten Ergebnisse in der Verwendung der PDFs von Albedo, NDVI, relativer Luftfeuchtigkeit und Windgeschwindigkeit für die Bestimmung von  $L.E$  waren sehr ermutigend und zeigten das hohe Potential der Methode.

Zusammenfassend lässt sich feststellen, dass die Methode der Ableitung von Oberflächenparametern und Energieflüssen aus Satellitendaten zuverlässige Daten auf verschiedenen zeitlichen und räumlichen Skalen liefert. Die Daten sind für eine detaillierte Analyse der räumlichen Variabilität der Landschaft und für die Beschreibung der subskaligen Heterogenität, wie sie oft in Modellanwendungen benötigt wird, geeignet. Ihre Nutzbarkeit als Inputparameter in Modellen auf verschiedenen Skalen ist das zweite wichtige Ergebnis der Arbeit. Aus Satellitendaten abgeleitete Vegetationsparameter wie der LAI oder die Pflanzenbedeckung liefern realistische Ergebnisse, die zum Beispiel als Modellinput in das Lokalmittel des Deutschen Wetterdienstes implementiert werden konnten und die Modellergebnisse von  $L.E$  signifikant verbessert haben. Aber auch thermale Parameter, wie beispielsweise die Oberflächentemperatur aus ETM+ Daten in 30 m Auflösung, wurden als Eingabeparameter eines Soil-Vegetation-Atmosphere-Transfer-Modells (SVAT) verwendet. Dadurch erhält man realistischere Ergebnisse für  $L.E$ , die hoch aufgelöste Flächeninformationen bieten.

## Summary

This work was written as a cumulative doctoral thesis based on reviewed publications.

Climate projections are mainly based on the results of numeric simulations from global or regional climate models. Up to now processes between atmosphere and land surface are only rudimentarily known. This causes one of the major uncertainties in existing models. In order to reduce parameterisation uncertainties and to find a reasonable description of sub grid heterogeneities, the determination and evaluation of parameterisation schemes for modelling require as many datasets from different spatial scales as possible. This work contributes to this topic by implying different datasets from different platforms. Its objective was to analyse the spatial heterogeneity of land surface parameters and energy flux densities obtained from both satellite observations with different spatial and temporal resolutions and in-situ measurements. The investigations were carried out for two target areas in Germany. First, satellite data for the years 2002 and 2003 were analysed and validated from the LITFASS-area (Lindenberg Inhomogeneous Terrain - Fluxes between Atmosphere and Surface: a longterm Study). Second, the data from the experimental field sites of the FLUXNET cluster around Tharandt from the years 2006 and 2007 were used to determine the NDVI (Normalised Difference Vegetation Index for identifying vegetated areas and their "condition").

The core of the study was the determination of land surface characteristics and hence radiant and energy flux densities (net radiation, soil heat flux, sensible and latent heat flux) using the three optical satellite sensors ETM+ (Enhanced Thematic Mapper), MODIS (Moderate Resolution Imaging Spectroradiometer) and AVHRR 3 (Advanced Very High Resolution Radiometer) with different spatial (30 m – 1 km) and temporal (1 day – 16 days) resolution. Different sensor characteristics and different data sets for land use classifications can both lead to deviations of the resultant energy fluxes between the sensors. Thus, sensor differences were quantified, sensor adaptation methods were implemented and a quality analysis for land use classifications was performed. The result is then a single parameterisation scheme that allows for the determination of the energy fluxes from all three different sensors.

The main focus was the derivation of the latent heat flux ( $L.E$ ) using the Penman-Monteith (P-M) approach. Satellite data provide measurements of spectral reflectance and surface temperatures. The P-M approach requires further surface parameters not offered by satellite data. These parameters include the NDVI, Leaf Area Index (LAI), wind speed, relative humidity, vegetation height and roughness length, for example. They were derived indirectly from the given satellite- or in-situ measurements. If no data were available so called default values from literature were taken. The quality of these parameters strongly influenced the exactness of the radiant- and energy fluxes. Sensitivity studies showed that NDVI is one of the most important parameters for determination of evapotranspiration. In contrast it could be shown, that the parameters as vegetation height and measurement height have only minor influence on  $L.E$ , which justifies the use of default values for these parameters.



## Summary

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Due to the key role of NDVI a field study was carried out investigating the spatial variability and sensitivity of NDVI above five different land use types (winter wheat, corn, grass, beech and spruce). Methods to determine this parameter not only from space (spectral), but also from in-situ tower measurements (broadband) and spectrometer data (spectral) were compared. The best agreement between the methods was found for winter wheat and grass measurements in 2006. For these land use types the results differed by less than 10 % and 15 %, respectively. Larger differences were obtained for the forest measurements. The correlation between the daily MODIS-NDVI data and the in-situ NDVI inferred from the spectrometer and the broadband measurements were  $r=0.67$  and  $r=0.51$ , respectively.

Subsequently, spatial variability of land surface parameters and fluxes were analysed. The several spatial resolutions of the satellite sensors can be used to describe subscale heterogeneity from one scale to the other and to study the effects of spatial averaging. Therefore land use dependent parameters and fluxes were investigated to find typical distribution patterns of land surface properties and energy fluxes. Implying the distribution patterns found here for albedo and NDVI from ETM+ data in models has high potential to calculate representative energy flux distributions on a coarser scale. The distribution patterns were expressed as probability density functions (PDFs). First results of applying PDFs of albedo, NDVI, relative humidity, and wind speed to the *L.E* computation are encouraging, and they show the high potential of this method.

Summing up, the method of satellite based surface parameter- and energy flux determination has been shown to work reliably on different temporal and spatial scales. The data are useful for detailed analyses of spatial variability of a landscape and for the description of sub grid heterogeneity, as it is needed in model applications. Their usability as input parameters for modelling on different scales is the second important result of this work. The derived vegetation parameters, e.g. LAI and plant cover, possess realistic values and were used as model input for the LokalmodeLL of the German Weather Service. This significantly improved the model results for *L.E*. Additionally, thermal parameter fields, e.g. surface temperature from ETM+ with 30 m spatial resolution, were used as input for SVAT-modelling (Soil-Vegetation-Atmosphere-Transfer scheme). Thus, more realistic *L.E* results were obtained, providing highly resolved areal information.

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## Publication List

1. *Tittebrand A.*, A. Schwiebus, F.H. Berger (2005): The influence of land surface parameters on energy flux densities derived from remote sensing data. Meteorol. Zeitschrift, Vol. 14, No.2, 227-236.
2. *Tittebrand A.* and F.H. Berger (2009): Spatial heterogeneity of satellite derived land surface parameters and energy flux densities for LITFASS-area. ACP, 9, 2075-2087
3. *Tittebrand A.*, U. Spank, C. Bernhofer (2009): Comparison of satellite-, spectrometer- and ground-based NDVI above different land-use types. Theor. Appl. Climatol, 98:171–186
4. Heret, C., *A. Tittebrand*, F.H. Berger (2006): Latent heat fluxes simulated with a non-hydrostatic weather forecast model using actual surface properties from measurements and remote sensing. Bound.—Lay. Meteorol, 121, 175–194

## 1. Introduction

For climate research worldwide the ongoing challenge is to provide forecasts of global climate in sufficient accuracy for reliable estimations of biological and social-economical consequences of climate change and for political agreements. Climate forecast in general is based on numerical simulations of global or regional models. One of the major uncertainties of current climate models is given by deficits in the knowledge of the atmosphere-land relationships and the inherent errors due to the uncertain parameterisations (Mengelkamp et al., 2006).

Land surfaces are characterised by a significant heterogeneity regarding the spatial scale of climate models. This subscale heterogeneity has to be solved using adequate averaging methods or by the determination of regional representative parameters, before they can be used as input for a model.

Recognising these deficits the *Deutsches Klimaforschungsprogramm* (DEKLIM) proclaimed the project EVA-GRIPS (Evaporation at Grid/Pixel Scale) and the question of the influence of heterogeneous land surfaces on the water cycle as well as on the energy balance for the area of the Baltic Sea. Thus, the project is a contribution to the Global Energy and Water Cycle Experiment (GEWEX) within the World Climate Research Program (WCRP). The objective in EVA-GRIPS was to determine the entirety of components of the energy and water balance above heterogeneous land surfaces based on observations and numeric modelling. Based on these data the overall aim of EVA-GRIPS was outlined to develop a parameterisation scheme for the determination of the exchange between land surface, vegetation and atmosphere for weather forecast and climate modelling, as well as for hydrological models. This included the implementation of the parameterisation into regional models e.g. *LokalmodeLL* (LM: Doms et al., 2007; Schulz und Schättler, 2009). The spatial scale was given by a numerical model grid or a satellite pixel and in-situ data. Besides, boundary layer observations were used, as well as satellite data and numerical simulations.

Exchange processes on the Earth's surface influence heat and water fluxes between terrestrial ecosystems and the atmosphere. The energy-balance equation:

$$R_n = H + L.E + G \quad (1)$$

describes the equilibration between the turbulent processes of transport in the atmosphere (sensible heat flux  $H$ , latent heat flux  $L.E$ ), heat transport into the soil ( $G$ ) and net radiation ( $R_n$ ). The natural variability of land surfaces and the spatial heterogeneity of water availability influence the partitioning of the quantities of the energy balance (Berger and Schwiebus, 2004). Within EVA-GRIPS the focus was on the investigation of evapotranspiration, which closely links the energy cycle of the climate system with hydrology.

Evapotranspiration is one of the most fundamental processes, which influence climate and weather from local to global scale. It is always interlocked with the other components of the surface energy

balance, mostly net radiation, absorbed by the surface. In combination with rainfall and runoff, it controls the amount and distribution of water at the Earth's surface, and is of significance to a number of water-related research and application areas (McCabe and Wood, 2006).

There are a number of techniques to determine evapotranspiration by in-situ measurements. The Bowen ratio method (Bowen, 1926) or the direct measurements of the turbulent transfer process by the eddy covariance (EC) method for measurements at selected points (Grünwald and Bernhofer, 2007; Spank and Bernhofer, 2008; Lee, 2004) are only some examples. Airborne measurements using eddy-covariance can be used to extrapolate the point measurements to a larger area, but they give only a glimpse of regional evapotranspiration (Braun et al., 2001). However, satellite data provide area integrated information at a range of temporal and spatial scales.

Thus, the increasingly available arrays of remotely sensed variables entailed significant developments in estimating  $LE$  from space (Carlson et al., 1977; Matson et al. 1978; Price, 1979), providing detailed information on land- and atmospheric properties. However, previous studies which use remotely sensed data to estimate evapotranspiration, primarily focus on measurements of solar reflection and thermal emission of the surface-atmosphere system. Eymard and Taconet (1995) give a very general overview of these and other techniques.

A critical limitation using remotely sensed data is the lack of necessary atmospheric variables, such as wind speed, air temperature and humidity, normally utilized to estimate  $LE$  over large heterogeneous areas. Consequently, many studies integrate remote sensing products with ancillary surface and atmospheric observations, or use variables simulated by models (Norman et al., 1995; Bastiaansen et al., 1998a; Jiang and Islam, 2001; Su, 2002). Empirical or semi-empirical models directly integrate remotely sensed data, alone or in combination with ground-based meteorological data. The models use ground-based air temperature and remotely sensed surface temperature (based on Jackson et al., 1981), or the relationship between surface temperature and NDVI (Carlson et al., 1994; Moran et al., 1994a; Moran et al., 1996). This relationship is used due to differences in the amount of vegetation where the leaf transpiration rate and the soil evaporation rate result in variability in surface temperature measurements due to evaporative cooling. For dense vegetation with a complete canopy, the slope of the temperature/NDVI relation has been related to canopy resistance (Sellers, 1987; Hope, 1988; Nemani et al., 1993). For land surfaces with fractional vegetation cover, Nemani et al. (1993) found that the slope of this relation was negatively correlated to a crop-moisture index (Moran et al., 1996).

Other approaches use a combination of empirical relationships and physically-based models. Most of the current operational models (e.g. Surface Energy Balance Algorithm for Land (SEBAL), Bastiaansen et al., 1998a) have been designed to calculate evapotranspiration at the regional scale with a limited number of ground data. Semi-empirical methods are used to estimate soil heat flux, net radiation and sensible heat flux, with evapotranspiration computed as the residual of the energy balance. Finally, physically based methods integrate complex land surface models, which compute the land surface energy budget and remotely sensed data. These data are used either to force the model, or in assimilation procedures (Mitchell et al., 2004; Rodell et al., 2004; Hogue et al.,

2006). As shown, there is a significant variability in  $LE$  methods that incorporate remotely sensed data.

This work is focussed on land surface parameters and surface flux densities as given in Eq. (1) (with special focus on  $LE$ ) determined from satellite data with different spatial and temporal resolution. Therefore, data from Landsat 7 ETM+ (Enhanced Thematic Mapper), NOAA 16-AVHRR 3 (National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer) and Terra/Aqua MODIS (Moderate Resolution Imaging Spectroradiometer) are used, differing in their spatial (30 m up to 1 km) and temporal resolution (16 days to 1 day).

However, a routinely monitoring for  $LE$  at a high spatial and temporal frequency is difficult due to the various limitations (frequency, spatial coverage, cloud coverage etc.) of satellite sensors and available model outputs. For example, high resolution (~30 m) satellite products derived from Landsat ETM+ are limited in their temporal frequency (~16 days). Products from the AVHRR satellite are available on a daily basis, but have lower spatial resolution. Furthermore, the AVHRR satellite does not have the increased spectral resolution currently available from MODIS (6 vs. 36 channels, respectively) and other sensors. While using a low spatial resolved data set as provided by AVHRR, the heterogeneity of the observed surface could get lost (Garrigues et al., 2006), because the landscape is represented as a mosaic of objects that are often smaller than the pixel size at a moderate resolution.

Cloud-related issues are also a primary factor in preventing the development of high-resolution temporal products (i.e. cloud coverage is problematic for visible or infrared sensors not transmitting clouds). Thus, most remote sensing methods are designed to apply primarily to clear days (Nemani and Running, 1989; Goward and Hope, 1989; Moran et al., 1994; Bastiaanssen et al., 1998a; Li and Lyons, 1999).

The publications presented here are dealing with the topics mentioned above. The overall working plan of the present work is shown in Fig. 1: The framed key words are the working packages described in the several papers. To close the gap between the determination of land surface parameters to resultant radiant and energy flux densities the four following working steps are described in detail in the Appendix A:

- Quantification of sensor differences
- Sensor adaptation
- Validation of resultant fluxes
- Comparison of land use classifications

These topics are essential for the determination of a comparability of the energy fluxes (validated with in-situ data) and thus for the analysis of the spatial variability of the results.

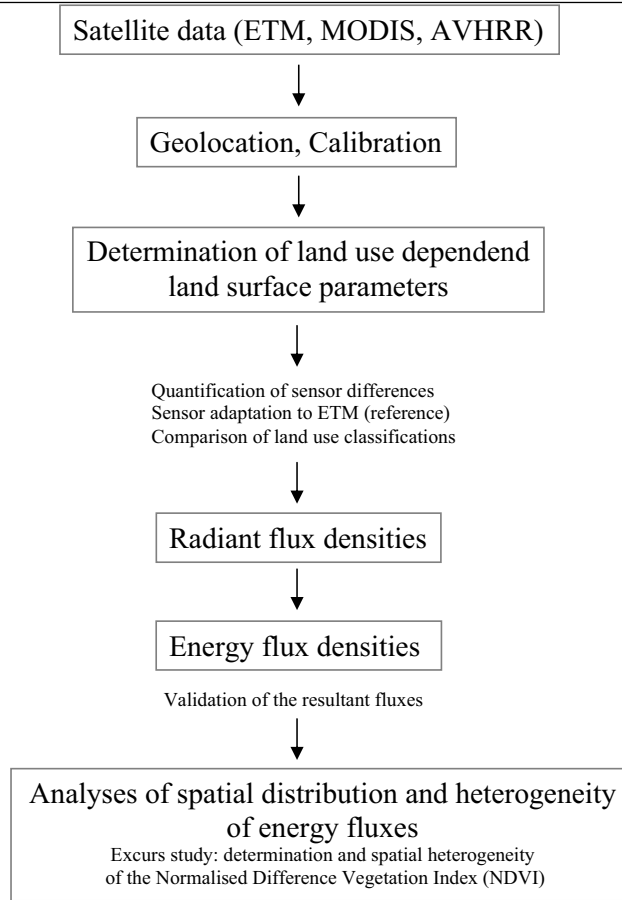


Fig. 1: PhD overview, working plan

The published researches in the front part of this paper can be differentiated into three work packages:

(1) The first part describes the determination of land surface characteristics (as albedo, surface temperature, NDVI, roughness length, canopy resistance etc.) applied for three optical satellite sensors (ETM+, MODIS and AVHRR 3). Based on this information radiant and energy flux densities can be inferred for each sensor. The main focus is on the derivation of latent heat flux ( $L.E$ ), using the Penman-Monteith approach. The method refers to the use of an equation for computing water evaporation from vegetated surfaces. Historically, the majority of evaporation models were developed for well-watered agricultural crops. Probably, the most rigorous of these models is the Penman (1948) equation, which led to the use of the term “potential evapotranspiration” (Stannard, 1993). To generalize the Penman equation for crops that were water stressed, Monteith (1965) incorporated a canopy resistance term,  $r_c$ , to describe the effect that partially closed stomates have on transpiration. As water availability to a canopy decreases, the values of  $r_c$  increases and  $L.E$  decreases. The Penman-Monteith equation (P-M) is described in detail in the accompanying papers Tittebrand et al., 2005 and Tittebrand and Berger, 2009).

Satellite data only provide measurements of spectral reflectance and surface temperatures. Further surface parameters as e.g. LAI, wind speed, relative humidity, vegetation height or roughness length that are needed for P-M, but not offered by satellite data, has to be derived indirectly from these properties or in-situ measurements. Additional information could also be extracted from land use classifications or literature (see default vegetation values by Hagemann, 2002). The quality of these parameters strongly influences the exactness of the radiant- and energy fluxes. Sensitivity studies were carried out to investigate the influence of the used parameters according to the resultant fluxes (Tittebrand et al., 2005).

(2) The second part of the work focuses on sensor differences of ETM+, MODIS, AVHRR and land use classifications. Latter are needed as base for the land use dependent parametrisation for P-M. Both topics are seen as sources for uncertainties for a correct and comparable determination of the energy fluxes between the sensors. Parameters and flux distinctions result from differences of the sensor filter response functions, sensor characteristics, calibration techniques and correction methods of atmospheric effects (van Leeuwen et al., 1999; Teillet et al., 1997; Venturini et al., 2004; Huete et al., 2002; Trishchenko et al., 2002) among the sensors. Differing in range, shape and different influences by water vapor – the variances in the filter response functions have a strong impact on the determination of the spectral reflectance or temperature. For a long time the determination of effective techniques to make use of data from various sensors has been the focus of considerable research (Jackson, 1997; Kustas, 1990; Wan & Dozier, 1996). However, only little actual inter comparison between sensors was undertaken, with main focus on individual satellite platforms (McCabe and Wood, 2006). As recently as in the last years there are increasing activities quantifying sensor differences, at least for the so called NDVI-channels (visible and near infrared domain of the spectra) or for albedo (Trishchenko et al., 2002; van Leeuwen et al., 2006; Fang et al., 2004 and Liang et al., 2001). Further important work is provided by Steven et al. (2003), offering intercalibration of vegetation indices (as NDVI) from 15 different sensor systems, and from Teillet et al. (2007), using ETM data as reference for the calibration of 20 sensors. Based on now calibrated and comparable data of albedo, NDVI, or surface temperature for the sensors, the further parameterisation for the P-M approach is land use dependent.

Correctly specifying the underlying land cover is particularly critical, since many of the aerodynamic and plant-physiological properties (vegetation height, roughness length, displacement height) are related to the surface type (McCabe and Wood, 2006). There are a lot of land use classifications presented in the literature differing in their quality and quantity concerning the represented classes. A comparison and validation was needed to find a useful dataset for the satellite applications in this study. The approach was improved by applying the Coordinated Information on the European Environment (CORINE) land use classification for AVHRR and MODIS data, and a Landsat based classification by Prechtel (2007) for the ETM data (according to their spatial resolutions, respectively). As a conclusion, a consistent base for the comparison of the resultant fluxes and furthermore for analysis of spatial heterogeneity (as analysed in Tittebrand and Berger, 2009) was enabled.

(3) The third part of the work describes the analysis of the derived parameters and fluxes according to their spatial variability. The Earth's surface is characterized by spatial heterogeneity over a



wide range of scales. Especially the several spatial resolutions of the satellites can be used to describe subscale heterogeneity from one scale to the other, and to study the effects of spatial averaging. Therefore, land use dependent parameter- and flux investigations were carried out in order to find typical distribution patterns of land surface properties and energy fluxes. The spatial variability was analysed by the characterisation of frequency distribution functions (PDF) of the satellite based parameters and fluxes in different spatial resolutions. The data were averaged using different methods (Tittebrand and Berger, 2009).

The results of the investigations showed, that NDVI is the key-parameter for *L.E* determination from space. On the one hand, regarding PDFs from NDVI and *L.E*, the same distribution pattern (in contrast to other parameter distributions) were found, a direct relationship suggested. On the other hand, NDVI has a significant influence on the determination of LAI and on canopy resistance (see the sensitivity study in Tittebrand et al., 2005). Thus, for further investigations of the spatial variability and sensitivity of NDVI, a field study was carried out testing methods to determine this parameter not only from space, but also from in-situ tower measurements, providing highly resolved temporal data without any atmospheric effects. Therefore, routine measurements of global radiation and photosynthetically active radiation (PAR) over different land use types were used. To close the gap between spectral and broadband measurements, spectrometer data were measured, providing highly resolved spectral reflectance patterns. These patterns were useful for the determination of NDVI, as well as for the validation of satellite data. Based on the radiation measurements, three methods of NDVI determination for the different platforms were carried out and compared.

In addition to the analysis, mentioned above, satellite derived parameters are also useful for model applications, to reach more realistic evapotranspiration results. Within the project EVA-GRIPS satellite derived parameters as LAI and plant cover, together with in-situ soil moisture, were included in the numerical weather prediction model Lokalmmodell of the German Weather Service: *LM* (Doms et al., 2007; Schulz und Schättler, 2009). The parameters are poorly represented in the model and the adaptation on satellite derived parameters and in-situ measurements resulted in significant improvements of the *L.E*-output (Heret et al., 2006).

Summarising, knowledge about the vegetation properties is essential for the determination of heat and water fluxes between terrestrial ecosystems and atmosphere. Remote sensing data provide area integrated information of surface properties in different spatial and temporal resolution and they are a helpful tool to investigate spatial variability of a landscape.

To take up the problem of an uncertain parameterisation for modelling and the difficulties to describe sub grid heterogeneity in a way that it becomes useful for modelling, the determination and evaluation of parameterisation schemes for modelling require as many datasets from several spatial scales of process parameters as possible. This work contributes to the topic by the application of different datasets from different platforms (satellite and in-situ measurements) in different temporal resolution. The determination and analysis of land surface parameters and energy fluxes is realised for typical land use classes on the regional scale that are representative for Central-Europe: for grass, forest and crop. For this reason, this work fills a gap within international investigations. Up to

now previous studies concentrated either on different climate zones (and thus different land use types) or on different spatial scales (e.g. the Hydrologic Atmospheric Pilot Experiment and Modélisation du Bilan Hydrique, HAPEX-MOBILHY (André et al. 1986, 1988); the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment, FIFE (Sellers et al., 1988); the Northern hemisphere climate Processes land-surface Experiment, NOPEX (Lundin and Halldin, 1994a,b); the European Field Experiment in a Desertification-threatened Area, EFEDA (Bolle et al., 1993) or the Boreal Ecosystem-Atmosphere Study, BOREAS (Sellers et al. 1997). Based on these new analyses the following questions should be answered: Can an appropriate dataset for model input be offered? How much information in time and space is needed for the description of a regional or bigger target area? How to deal with area averaging of surface parameters and energy fluxes to solve sub grid heterogeneity for a model or data on a coarser scale?

This work was submitted as cumulative thesis according to the promotion regulations of the department of Hydrosience of the Technische Universität Dresden. Table 1 gives an overview of paper content of the four papers. A publication list of the author complements the dissertation.

Table 1: Short overview of the paper contents and investigations

<b>Article 1</b> Tittebrand et al., 2005 published	Determination of surface parameters and surface flux densities from satellite data - Determination of energy fluxes for NOAA-AVHRR and Landsat ETM data - Sensitivity study of land surface parameters to $L.E$ - Validation of the results
<b>Article 2</b> Tittebrand and Berger, 2009 published	Study of the spatial heterogeneity of the satellite derived parameters and fluxes - Improvement of the Penman-Monteith approach for $L.E$ determination - Enhancement of the flux determination to Terra/Aqua MODIS data - Correction of the variations of sensor based differences and land use classifications - Application of averaging methods (arithmetical, dominant land use, PDF) - Analysis of the results according to spatial variability
<b>Article 3</b> Tittebrand et al., 2009 published	Special study for determination methods of NDVI and its spatial variability - Combination of satellite-, tower- and spectrometer measurements over five different land use types - Application of determination methods of NDVI from different sources/platforms - Investigation of spatial variability - Investigation of seasonal changes - Influence of angular dependence of spectrometer measurements
<b>Article 4</b> Heret et al., 2006 published	Improvement of Lokalmmodell (LM) input with assimilated averaged satellite and in-situ surface parameters - Sensitivity study of model input parameters to $L.E$ - Averages of soil moisture (PDF) and LAI/plant cover from satellite (arithmetic mean) to 7x7 km <sup>2</sup> for LM input - Comparing standard model output $L.E$ to modified model-output with integrated soil moisture from in-situ measurements and plant parameters from NOAA- AVHRR data.



## 2. Target Area and Data

### 2.1 LITFASS-Area

#### Study area

The study area, carried out in Tittebrand et al. (2005), Tittebrand and Berger (2009) and Heret et al. (2006) is situated in the north-east of Germany and represents the lowlands with little relief, formed by inland glaciers with differences of only 80 - 100 m over distances of about 10 - 15 km. Investigating an area of 20 km × 20 km area around the Richard Aßmann Observatory (MOL-RAO) of the German Meteorological Service (Deutscher Wetterdienst, DWD, the land use is dominated by forest and agricultural fields with approximately 45 % each, 7 % lake coverage and nearly 4 % villages. The forest dominates the western part of the area while agriculture is mainly situated in the eastern part). Detailed information is given in the papers.

#### Data

As already introduced, the analysis is carried out with satellite data of optical sensors with different spatial and temporal resolution. While in paper 1 the first analyses were realised with Landsat 7 ETM+, and NOAA 16-AVHRR 3 data the investigations and methods are enhanced also to Terra/Aqua MODIS data in Tittebrand and Berger (2009). Characteristics of the three sensors are summarised in Table 2.

Landsat-7 ETM+ data were provided as Level-1B data. First they had to be corrected for the atmospheric effects using the radiative transfer code 6S (Second Simulation of the Satellite Signal in the Solar Spectrum, Vermote et. al., 1995, 1997b). The determination of brightness, temperature and spectral reflectance as base for the determination of further surface parameters and fluxes was applied after the Landsat User Handbook (2004).

NOAA 16-AVHRR 3 data were processed with the modularic scheme SESAT (Strahlungs- und Energieflüsse aus Satellitendaten, Berger, 2001; Tittebrand et al., 2005) including an atmospheric correction. Surface reflectance, top of atmosphere (TOA)-NDVI and surface temperature were used for further determination of own heat and water fluxes with a spatial resolution of 1 km.

From MODIS surface temperature and reflectance products from the Earth Observing System Data Gateway were used (EOS, 2007) for the determination of NDVI as well as for further parameters needed for the calculation of the energy fluxes. The surface reflectance product *MOD09GHK* (collection 004) was given for each band to produce a measurement equivalent to a ground-level measurement with no atmospheric scattering or absorption. These reflectance products are provided as a grid-level-2G product in the sinusoidal projection. *MOD11* (coll. 004) data provide surface temperature data, also given as a gridded product corrected for the atmospheric effect.

To study variability effects of a natural surface with optical sensors, cloud free scenes are necessary because, in contrast to microwave remote sensing, optical sensors are not able to measure within or under clouds. A simulation of cloud effects would be very challenging. However, because of

the low interval of overpass of Landsat ETM+ (16 days) the number of cloud free scenes is rare.

The evaluation of satellite data purposed a field experiment (LITFASS-2003, Beyrich et al., 2004), which was carried out from May until June in 2003. For this period the measured flux data were compared with AVHRR and modelled *LM*-data (Heret et al., 2006). Comparisons for ETM data were planned but could not be realised, although during LITFASS-2003 two cloud free Landsat-overpasses were recorded. Reason for the non-ability of these data was a problem with Landsat's scan line corrector (Landsat, 2003) from 31th of May in 2003 on. Thus, these scenes were not available for the analysis of spatial heterogeneity. Hence, for the main study four cloud free scenes outside of the LITFASS-2003 period were found and used for the analysis: data from spring and summer 2002 and 2003: 09/05/02, 28/07/02, 20/08/02 and 17/04/03. To validate and compare these data to in-situ data, half-hourly measurements of the routine observations in Lindenberg (Beyrich et al., 2004) were provided by the DWD.

Table 2: Overview over the satellite characteristics of ETM, MODIS and AVHRR

Sensor	ETM+	MODIS	AVHRR-3
Satellite	Landsat-7	Terra/Aqua	NOAA-16
Orbit	Sun synchronous, near-polar	Sun synchronous, near-polar	Sun synchronous, near-polar
Height	705 km	705 km	833 km
Equator crossing time	10:00 – 10.15 a.m. descending node	Terra: 10:30 a.m. descending node Aqua: 1:30 p.m. ascending node	2 p.m.
Channels	7 (+1 panchromatic band)	36	6
Spatial resolution	30 m (bands 1-5, 7) 60 m (band 6) 15 m (band panch.)	250 m (bands 1-2) 500 m (bands 3-7) ~1 km (bands 8-36)	~ 1 km
Temporal resolution	16 day	1 day	1 day

## 2.2 FLUXNET-Testsite

### Study area

The target area investigated in the NDVI study (Tittebrand et al., 2009) represents a hilly area with elevations above 300 m. The sites cover the land use types spruce (at the Anchorstation Tharandt), grassland (in Grillenburg), crop rotation (in Klingenberg) and beech (at Landberg) represented by the research stations of the Department of Meteorology of the Technische Universität Dresden (Table 3). This cluster includes continuous observation sites in Central Saxony/Eastern Ore Mountains with an outstanding data base of carbon and water fluxes, biomass and soil data, climate data and all kinds of auxiliary data starting in 1996.

Table 3: Characteristics of the four measurement sites (data from Mellmann et al., 2003; Grünwald and Bernhofer, 2007; Göckede et al., 2008). Data in [ ] show values during the campaign measurements; LAI from harvest (Grillenburg, Klingenberg), harvest based allometric functions (Tharandt), and measurements with the Plant Canopy Analyser LI2000 (Landberg).

Station	Land use type and patch size	Vegetation height	LAI	Specific feature
Grillenburg 50°56'58"N, 13°30'45"E, 385 m a.s.l (above see level)	grass (62 ha)	10 - 75 cm [25 cm, 2006] [15 - 70 cm, 2007]	0.5 - 6 [1.97, 2006] [2.6 - 4.64, 2007]	Management: unfertilised, 2 - 4 cuts/year
Klingenberg 50°53'34"N, 13°31'21"E, 480 m a.s.l	winter wheat (2006) corn (2007) (55 ha)	[55 cm, 2006] [0 - 220 cm, 2007]	[2.55] [0.3 - 2.17 for April-August; 4.6 in July]	Crop rotation Management: Mineral/Organic fertiliser, Herbicides, Tillage, 1 harvest/year
Tharandter Wald, Anchor station 50°47'N, 13°43'E, 735 m a.s.l	spruce (150 ha)	29 m (117 years old, 2008)*)	7.6 (2007)*)	Management: commercial thinning in April 2002, disturbance: storm "Kyrill" on 18.01.2007 (windspeed_max = 9.5 m/s)
Landberg 50°59'33"N, 13°29'25"E, 400 m a.s.l	beech (36 ha)	30 m (100 years old, 2008)*)	0 - 3.9 (2007)	

\*) values refer to the vicinity of the tower

## Data

For all test sites radiation components from the FLUXNET towers (Baldocchi, 2001; Fluxnet 2007) were measured. Overall data availability at the permanent stations was given every 10 minutes, except the data of global radiation in Grillenburg in 2006 with measurements every 30 minutes. Table 4 gives an overview of the instruments used for the study.

In addition to the fixed tower measuring devices of the stations, a hand-held measuring set-up for global radiation and PAR (broadband) was established to investigate spatial variability within one specific land use type (for grass and winter wheat, respectively) realising five measurements within a 25 x 25 m<sup>2</sup> grid. To avoid influences disturbing the other flux measurements, the mobile measurements were accomplished about 20 m away from the permanent stations, still measuring the same land use characteristics.

Spectrometer data of spectral reflectance are provided by an adapted newly designed spectrometer with an excellent spectral accuracy. The set-up uses a UV/VIS-Spectrometer getSpec-PDA, a Y-optical fiber with 400 µm core diameter, a collimating lens Col-UV/VIS and a white standard Spectralon (getReflex) with 99 % reflection as reference material.

Table 4: Instrumentation and characteristics

Station	Spectrometer measurements	Tower measurements	Hand-held measurements	Satellite measurements
Grillenburg grass	UV/VIS- Spectrometer getSpec-PDA  spectral range 380-1100 nm	- 1 pyranometer CM5 (by Kipp&Zonen) for incoming radiation - 2 Licor LI-190SA, quantum sensors for incoming and reflected PAR, spectral range 400 - 700 nm	- pyranometer CM7B - 2 Quantum SKP 215 sensors by Sky for incoming and reflected PAR  spectral range 400 - 700 nm	Aqua/ Terra MODIS  daily overpass data and sampling products  250 m up to 1 km
Klingenberg winter wheat (2006) corn (2007)		- CRN1 net radiometer (by Kipp&Zonen) - Licor LI-190SA quantum sensors		
Tharandter Wald spruce		- pyranometer CM7 (by Kipp&Zonen) for incoming and reflected radiation - 2 Licor LI-190SA quantum sensors		
Landberg beech		- CRN1 net radiometer (by Kipp&Zonen) - 2 Licor LI-190SA quantum sensors		

Finally, satellite products of spectral reflectance and NDVI from Aqua/Terra MODIS are used for comparison. Therefore, daily overpass-values as well as sampling products (16 day-sampling) were used with a spatial resolution of 250 m up to 1 km. The data were collected in June 2006, and in the period from April to September in 2007.

In Table 4 the different headline-colors (from white to dark grey) represent the different measurement systems and platforms. Tower measurements provide broadband data every 10 minutes, given as point measurements above a land use type. One question was to find out their representativeness for the entire area, covered by this land use type. Therefore, the hand-held measurements were used. Satellite data (dark grey) were area integrated spectral measurements, but with a lower temporal resolution. Spectrometer measurements provide highly resolved spectral data in also a high temporal resolution (in dependence on the weather conditions and therefore calibration time). All three systems were used for the determination of NDVI, using a special approach for each data base.



### 3. Summary of the Results

#### Article 1

In Tittebrand et al. (2005) the determination of satellite derived land surface characteristics and energy flux densities from NOAA 16 AVHRR 3 and Landsat 7 ETM+ data for LITFASS-area is described. The first results were presented using a determination scheme for ETM data based on SESAT (Berger, 2001 developed for AVHRR). The aim was to infer similar and comparable  $L.E$  results from ETM data using the Penman-Monteith approach compared to the AVHRR results. SESAT needs variables for the determination which base on satellite data (spectral reflectance, surface temperature), are derived from the NDVI (LAI,  $rc$ ) or taken from literature (e.g. roughness length  $z_0$ , Hagemann, 2002). The algorithm is given in detail in the accompanying paper.

The analyses showed that AVHRR evapotranspiration correlates better with in-situ measurements (provided by the DWD) than ETM results. An exception is given for very dry periods (Beyrich et al., 2005) where a significant overestimation of  $L.E$  is obvious for both sensors. Using radiative transfer models with given atmospheric profiles for the correction of atmospheric effects can be one reason for that mismatch, assumed that these profiles do not always correspond well to the prevailing conditions. The SESAT scheme, developed for AVHRR and applied for ETM to some degree, showed at least good agreements for global radiation ( $r^2=0.81$  compared to in-situ measurements), whereas  $R_n$ ,  $G$  and  $L.E$  are overrated and do not result in matchable good findings with  $r^2<0.25$  in comparison to in-situ data. However, note that the verification for ETM  $L.E$  was limited to one date, so these results could not really be evaluated.

The main part of Tittebrand et al. (2005) dealt with sensitivity investigations of the input parameters for P-M. The sensitivity study shows that leaf area index LAI (based on NDVI) is regarded as one of the most important parameters for the determination of evapotranspiration. A correct estimation especially for lower vegetation is necessary. Otherwise errors of up to  $80 \text{ Wm}^{-2}$  in  $L.E$  may occur. In contrast, default parameter values for vegetation height or measurement height as used in the study show only a minor influence on  $L.E$ , so their application is legitimated. The use of constant stomatal resistances for each land use type causes high uncertainties inferring latent heat, because of the wide range of potential values of  $rc$ , especially for the forest class. Thus, a land use dependent parameterisation is essential with representative values for each land use class.

The P-M parameterisation in Tittebrand et al. (2005) is based on the modified U.S. Geological Survey database USGS (for AVHRR, Kautz 1999) and a downscaled CORINE classification for ETM (30 m grid). Differences between these land use classifications can also result in obvious differences in the energy fluxes. Thus, a quality check and a comparison of land-use classifications was one of the next important working steps to improve the overall calculation of  $L.E$ .

#### Article 2

An investigation of the heterogeneity of land surface parameters (e.g. albedo, NDVI) and energy

fluxes ( $R_n$ ,  $G$ ,  $H$  and  $L.E$ ) for LITFASS-area was carried out in Tittebrand and Berger (2009). To realise these investigations, based on the results of Tittebrand et al. (2005) with major differences between AVHRR and ETM results, the objective was to create a comparable database for the different sensors.

This includes:

- (a) To demonstrate the problem of sensor differences between AVHRR and ETM+, quantify them and find possible adaptation methods to reduce these differences (enhanced to MODIS data).
- (b) To evaluate land use classifications and quantify differences, using the in-situ reference classification of the MOL-RAO (Beyrich et al., 2004; Beyrich et al., 2005). Based on these analyses, an appropriate classification for our parameterisation schemes was to be found.

Both objectives are presented only very shortly in Tittebrand and Berger (2009), but are essential for this work. Thus, Appendix A2 and A4 give information in detail.

After sensor adaptation (using regressions and histogram stretching) and the application of new land use classifications, an ETM based calculation scheme was applied for all three sensors to determine the energy fluxes. The classifications used were CORINE in 1 km resolution for the MODIS and AVHRR parameterisation and a new developed Landsat based classification by Prechtel (2007) in 30 m resolution for the ETM data. Reasonable agreements with in-situ data of the MOL-RAO confirm the methods.

For comparison of the sensor related results and for further analyses the mean for LITFASS-area (LITFASS-mean) and standard deviations were investigated for the data, averaged to AVHRR resolution. Two averaging methods were tested and compared, the simple mean and the dominant land use method. It was demonstrated that the LITFASS-mean of the fluxes of the different sensors agrees well, no matter the data are arithmetically averaged or with respect to the dominant land use type. However, the histograms of the data averaged using the dominant land use preserve the actual distribution patterns as found in the original highly resolved data. Whereas the arithmetically means cause a smoothing of the actual distribution.

Nevertheless, it is assumed that using probability density functions (PDF) and thus the entire range of the surface characteristics, including extremes as well as the mode instead of the mean, should provide more realistic conditions for the determination of energy fluxes. Further, they can improve the description of subscale heterogeneity within pixel on coarser scale or a model grid. Li and Avissar (1994) confirmed that the results of determined fluxes depend on the shape of the spatial distribution of the land surface parameters, used for the calculation. They found the more skewed the distribution within the range of values, the larger their error (for nonlinear relationships between parameter and flux e.g. for LAI, inferred nonlinear from NDVI). The errors increase with larger differences for lognormal distributed land surface parameters. Thus, the pattern of the distribution is essential for the determination of accurate fluxes.

The heterogeneity analysis was carried out with respect to frequency distributions:

(1) For LITFASS-area: Regarding the frequency distributions for the energy fluxes  $Rn$ ,  $H$ ,  $G$  and  $LE$  determined from the three sensors in their original spatial resolution, it can be outlined, that with the exception for  $Rn$  the patterns as well as their ranges (caused by the adaptation method) are very similar to each other. Thus, the adaptation methods work successfully.

(2) For different land use classes: The analysis with respect to the land use classes grass, crop and forest show obvious differences in the distribution patterns. Note that results differ not only between grass and forest but also between grass and crop. One question of the study was to investigate whether it is possible to summarise both classes to one group e.g. lower vegetation. Thus, for further studies using PDFs for  $LE$ -determination, it is suggested to differentiate between crop and grass. Here, a second peak for crop, showing the bare soil conditions in the distributions of NDVI and thus  $LE$ , appears (in three different seasonal states of summer), that can not be neglected.

(3) For highly resolved data within pixel on coarser scale: Selecting MODIS pixels with known land use classes and analysing their included ETM-distributions, allowed for conclusions with respect to subscale-heterogeneity, provided that they offer the same land use type (at least 80 %). The distribution variability of  $LE$  is shown to be higher than for  $Rn$  except for the crop class where an evident difference in the distribution patterns can be found. The best distribution agreement can be outlined for forest. According to spatial variability of  $LE$  former studies also showed that the latent heat flux was the most sensitive parameter for that issue (Li and Avissar, 1994). Thus the results indicate that it is very important to consider the spatial variability of NDVI and, therefore, LAI, stomatal resistance and further important parameters of the Penman-Monteith approach.

### Article 3

NDVI was seen as the key parameter in the Penman-Monteith based determination of  $LE$  from satellite data. Regarding distribution patterns (histograms) of satellite based NDVI and  $LE$ , nearly identically structures were found. Thus, the third article is an excursion to NDVI. Different methods of NDVI determination for different platforms were tested, together with an analysis of NDVI heterogeneity. MODIS radiances were used as well as highly resolved ground spectrometer data and measurements from broadband micrometeorological sensors. Satellite and spectrometer data offer spectral- or band information, whereas the micrometeorological sensors measure a broader range of the spectra (broadband). Differing in these characteristics, for each of the three platforms/instruments a specific NDVI determination method was applied.

The objective was to find out whether ground-based data (spectral and broadband) can complement satellite based vegetation information by offering highly resolved temporal resolution without any atmospheric effect or background noise.

This study compared values derived from five experimental (FLUXNET) field sites (grassland, winter wheat, corn, spruce and beech) in Germany in June 2006 and April-September 2007.

The NDVI determination methods are described in short, for details see Tittebrand et al. (2009):

(1) *Satellite NDVI* is determined from spectral radiance in the Visible or Red (VIS) and Near Infrared (NIR) channels using Eq. (2) (Rouse et al. 1974).

$$NDVI = \frac{(NIR - VIS)}{(NIR + VIS)} \quad (2)$$

(2) For *broadband- or tower NDVI* Huemmrich et al. (1999), Wang et al. (2004) and Wilson and Meyer (2007) replaced the VIS domain with the photosynthetic active radiation (PAR) and the near-infrared domain with the difference of the shortwave radiation minus PAR. Shortwave radiation is provided by the sensors in the range of 305 – 2800 nm. The broadband NDVI uses a PAR wavelength band of 400 – 700 nm and an NIR band that is effective between 700 – 2800 nm with little perturbation due to a minor influence of the 280 – 305 nm sensitivity of the shortwave instrument (Huemmrich et al., 1999).

(3) NDVI from *spectrometer data* was inferred by convolution of e.g. the MODIS filter response functions of the NDVI-channels with the according land use class (see in detail in Appendix A1).

In addition, the spatial variability of in-situ NDVI values within one specific land use class (for grass and winter wheat) was investigated. We wanted to find out the representativeness of the FLUXNET tower values for the land use types. It can be pointed out that variability within one land use class is smaller than the differences caused by the different NDVI-determination methods. Thus, the in-situ tower NDVI is seen as representative for the land use type and comparable to the areal measurement of MODIS.

Finally, the angular dependence of spectrometer values on viewing angles was determined, in order to enhance the spatial representativeness of spectrometer measurements. Spectrometer measurements, especially above trees, are affected by soil parts and the tower structure when measured in nadir. They offer a hyperspectral dataset, but detailed ground-based time series of spectrometer measurements (and thus for NDVI) are rare. Further, to compare the data to broadband or satellite derived NDVI, nadir-view measurements are common. As shown by the results, the nadir measurements provide comparable results to other methods only for closed low canopies (grass and winter wheat) measured under ideal sunny conditions. For more open vegetation or for tower measurements above trees, the soil parts, as well as the effect of the tower construction, significantly influence the NDVI. To enhance the spatial representativeness for these measurements, angular measurements were carried out using viewing angles of 30° and 60° in forward observation direction. The influence of the angular measurements was marginal for grass, whereas for corn and beech the viewing angle significantly influenced the resulting NDVI. This was mainly caused by the NIR measurements with strong increases for reflectance. The effect of the uncertainties caused by overlapping trees that appear denser observed under larger angles compared e.g. to a satellite view, is known but accepted for the analysis. However, for measurements at 30° and 60°, the patterns are typical for vegetation spectra, providing smaller reflection in the VIS part but significantly larger

reflection in the NIR part as compared to the nadir view (Disney et al., 2004). The resulting NDVI for corn and beech were in good agreement to satellite derived NDVI.

The comparison of NDVI of one satellite and two ground based methods resulted in good agreements, perfect measuring conditions and a cloudless day assumed. Best results were found for the winter wheat and grass measurements in 2006 with maximum differences of 10 % and 15 %, respectively, for the different methods. Obvious differences were obtained for the forest measurements. Correlation between in-situ and satellite measurements was found to be  $r=0.67$  for spectrometer NDVI and  $r=0.51$  for broadband NDVI compared to MODIS (daily) NDVI. Correlation to MODIS sampling NDVI was much better for the spectrometer based NDVI ( $r=0.91$ ) but significantly lower for broadband NDVI ( $r=0.41$ ). A detailed analysis of the uncertainties resulting in different NDVI is provided in the discussion part of Tittebrand et al. (2009).

Summarising all results, a ground-based network of NDVI measurements (enhanced by special spectrometer data) provides a very powerful tool for supporting remote sensing NDVI estimates. Ground-based NDVI results may be more related to canopy physiology and offer the potential to overcome some of the challenges associated with the satellite products (Wang et al., 2004). Another advantage of the ground-based NDVI is the possibility to realise a temporally detailed NDVI time series at each location. Wang et al. (2004) use the broadband NDVI directly as input for models that simulate ecosystem functions. Existing tower-based networks (FLUXNET, Baldocchi et al., 2001) provide anchor stations for similar works. Their potential is improved by instruments being installed at an increasing number of sites.

#### Article 4

In Heret et al. (2006) the influence of land surface parameters on latent heat fluxes simulated with the numerical weather prediction model *Lokalmodell* (*LM*, grid size: 7x7 km<sup>2</sup>) of the DWD is investigated. The area of interest is the LITFASS-area (see Tittebrand et al., 2005 and Tittebrand and Berger, 2009) during the LITFASS-2003 (May-June 2003) campaign. Based on simulations varying soil and vegetation properties it is shown, that simulated latent heat fluxes are significantly overestimated and that they strongly depend on soil moisture and leaf area index. Both parameters are difficult to obtain from in-situ measurements with sufficient spatial resolution over heterogeneous land surfaces. Therefore, a procedure was provided to determine area averages of soil moisture from Time Domain Reflectometry (TDR) measurements performed at a limited number of sites within the LITFASS-area. Furthermore, satellite inferred plant parameters from AVHRR were used to initialise model runs. The derived vegetation parameters showed notable differences to the standard input of *LM*. The latent heat fluxes from the *LM* were compared with aggregated eddy-covariance in-situ-measurements (Beyrich et al., 2005). While the operational *LM* showed a strong overestimation of latent heat fluxes, it was demonstrated that the application of land surface parameters derived from measurements (in-situ and satellite) can significantly reduce the deviation between the simulated and measured latent heat fluxes.

For the PhD work the focus is on the satellite part of the publication providing *LE* results for

comparison and satellite derived vegetation parameters (LAI and plant cover) to improve the model-input and, moreover, the modelled  $LE$  results. The parameters were averaged to the model grid using arithmetic mean and were then used as model input. Combining the measured soil moisture and the vegetation parameters as derived from AVHRR for the implementation into the  $LM$  accomplished a remarkable improvement of the simulated  $LE$ . The former  $LE$ -overestimation was reduced significantly (e.g. the bias between measurements and model decreased significantly from  $49 \text{ Wm}^2$  to  $12 \text{ Wm}^{-2}$ ).

#### 4. Concluding Remarks and Outlook

In the context of the BMBF-project EVA-GRIPS that investigates sub surface heterogeneity on model grid or pixel scale the aims of this study were:

- (1) To determine all components of the energy balance with focus on  $LE$  on satellite pixel scale
- (2) To use known concepts of averaging for turbulent fluxes or parameters and
- (3) To find a method based on these analyses which manage spatial heterogeneity according to vegetation (albedo, NDVI, LAI) and to the boundary layer (radiation, temperature, wind etc.).

An excursion study to the key-parameter NDVI enhances the investigations with the overall objective of the PhD work, to contribute to the question of appropriate scales in time and space, for an adequate description of surface characteristics and processes on regional or a coarser scale.

(1) The work presented here offered evapotranspiration data determined from satellites with different spatial (30 m – 1 km) and temporal (1 day – 16 days) resolution. The method to infer  $LE$  was realised applying the Penman-Monteith approach by using spectral reflectance and temperature based on the satellite data of AVHRR, MODIS and ETM+. Further parameters, offered from in-situ measurements (wind speed, relative humidity) or from literature (e.g. roughness length by Hagemann, 2002), were necessary to calculate actual evapotranspiration for heterogeneous surfaces. The method was not applicable for water reservoirs, thus, for water bodies a default value for  $LE=125 \text{ Wm}^{-2}$  was assumed.

The satellite derived fluxes were compared to in-situ values showing the successful application of P-M. The algorithm depends on the addition of measured in-situ data or default values for quantities which are not available from the satellite data but necessary for the parameterisation scheme. Thus, the adaptation to other regions bases on the availability of such in-situ measurements or useful default values. However, the sensitivity studies showed that NDVI (LAI) is regarded as one of the most important parameters for the determination of evapotranspiration. In contrast, the fixed values for e.g. vegetation height or measurement height only show minor influence on  $LE$  so their application is legitimated.

The advantage of the method is the easy adaptation to other sensors by correcting sensor differences using one of the various correction methods (Trishchenko et al., 2002 ; van Leeuwen et al., 2006; Fang et al., 2004; Liang et al., 2001; Steven et al., 2003; Teillet et al., 2007), or as realised in this study: by regressions and histogram stretching. Thus, the overall method is recommended for derivation of radiant- and energy flux densities for heterogeneous land surfaces. However, the provided atmospheric profiles used in radiative transfer codes as *6S* (Vermote et. al., 1995, 1997b) or *LOWTRAN* (Low Transmission Model, Kneizys and Selby, 1988) and *STREAMER* (Key and Schweiger, 1988; Key, 1999) to calculate the atmospheric attenuation of the radiance seem to

differ much from real conditions that might be resulting in an overestimation of the resultant water fluxes. Usage of radio soundings can solve this problem, depending on the area size of the target.

(2) For the description of spatial heterogeneity averaging methods were investigated, using arithmetic mean and averages with respect to the dominant land type. Comparing the area mean (for LITFASS-area) from both methods, they only differ marginally from each other. However, regarding their frequency distribution in comparison to the un-averaged data in original resolution, the dominant land use method maintains the distribution pattern whereas the simple mean smoothes the distribution function. For description of sub grid heterogeneity and to find an appropriate, representative parameterisation in modelling, both methods are assessed to result in sufficient representative fluxes assumed that the parameter – or flux distribution functions of the sub grids provide comparable mean and mode values. As shown in the paper of Tittebrand and Berger (2009) which analyses the parameters albedo, NDVI and  $L.E$  for grass, crop and forest respectively, this assumption was only achieved for albedo. Significant deviations between mean and modal value were found especially for grass and crop regarding NDVI and  $L.E$ . Therefore, a method was needed that takes the entire range of the function and the different values for mean and mode as well as extreme values into account especially in a skewed distribution (e.g. for lognormal PDF). Thus, the pattern of the distribution is essential for the determination of accurate fluxes.

(3) Using PDF showed the highest potential to describe sub grid heterogeneity providing an accurate method that preserves patterns and structures and also statistical properties without losing important information on the moderate or a coarser scale. Applying the distribution patterns found here for albedo and NDVI as input in models has high potential to calculate representative energy flux PDFs on coarser scale. Our first results in applying PDFs of albedo, NDVI, relative humidity and wind speed for  $L.E$  determination are encouraging (MAGIM, 2006) and show the high potential of this method. Assuming  $\chi^2$  distributions with a different range and mode for grass and forest for the four input parameters, the method was applicable as a first approximation. The approach could now be improved by the results of the new distribution patterns (described in Tittebrand and Berger, 2009) for the two land use types and by the enhancement for the often represented land use type “crop” with different distribution characteristics compared to grass. Until now only pixel mean and standard deviation were compared to in-situ measurements often resulting in marginal deviations. Taking the entire PDF (or at least some more supporting points) of the resulting energy flux, into account, the point measurement can be different from mean or mode and nevertheless be representative for the pixel. And this allows a new interpretation of areal results concerning their accuracy.

Supplemental to (1) - (3) spatial heterogeneity was investigated for NDVI as one of the key parameters for the  $L.E$  determination based on the P-M approach. It was shown that different methods work well to infer an in-situ NDVI that is not influenced by any atmospheric effect and that provides a high temporal resolution. These data can contribute to understand and to use vegetation indices, and support the determination of NDVI from satellite data. Validation of diurnal variations with flux tower data as started in the NDVI-study would be an interesting extension as well.



Summarising, the method of satellite based surface parameter- and energy flux determination has been shown to work reliable on different temporal and spatial scales. The data are useful for detailed analyses of spatial variability of a landscape and for description of sub grid heterogeneity, as it is needed in model applications. Their usability as input parameters for modelling on different scales is the second important result of this work. The derived vegetation parameters as e.g. LAI and plant cover possess realistic results usable for modelling input for the *Lokalmodell* (Heret et al., 2006), improving significantly the model results of *L.E.* But also thermal parameters, as surface temperature fields from ETM+ in 30 m spatial resolution, were used as input for SVAT-modelling (Soil-Vegetation-Atmosphere-Transfer scheme) within the EVA-GRIPS group for improving the *L.E.* results, providing highly resolved areal information.

Thus, the work contributes to enhance knowledge of the atmosphere-land relationship and the development of parameterisations schemes for modelling, in order to provide forecasts of climate in sufficient accuracy for reliable estimations of biological and social-economical consequences of climate change.



## **Appendix A: Methodical Considerations**

In this section some aspects of the methods used in the publications will be presented in more detail as well as discussed in general and regarding their application in this work.

As shown in Fig. 1 the framed key words are the working steps described in the several papers. In this appendix the focus is on the four main points:

- (1) Quantification of sensor differences
- (2) Sensor adaptation
- (3) Validation of resultant fluxes
- (4) Comparison of land use classifications

These topics are essential for the determination of comparable energy fluxes (validated with in-situ data) and thus for the analysis of the spatial variability of the results.

## A.1 Quantification of Sensor Differences

The topic of sensor differences is of increasing importance especially concerning long-term studies (20 years of monitoring) of NDVI based on AVHRR data. For ongoing investigations and monitoring with other sensors such as MODIS it is important to understand the relationship between the AVHRR-derived results and NDVI derived from other current and future sensors.

As pointed out by McCabe and Wood (2006), Jackson (1997), Kustas (1990) and Wan & Dozier (1996), determining effective techniques to make use of data from various sensors has been the focus of considerable research but little actual inter comparison between sensors has been undertaken, with most analysis focused on individual satellite platforms. There are increasing activities quantifying sensor differences, at least for the so called NDVI-channels or for albedo-determination. Important work was done by Trishchenko et al. (2002), van Leeuwen et al. (2006), Fang et al. (2004), Liang et al. (2001) and as an outstanding work Steven et al. (2003) offering intercalibration of vegetation indices (NDVI) from 15 different sensor systems. Finally the work of Teillet et al. (2007) should be mentioned, using ETM data as reference for the calibration of 20 sensors.

In this study the spectral reflectance of the NDVI-channels (VIS and NIR) as well as the NDVI of eight several sensors in dependence of 22 (5 land use types in Inner Mongolia and 17 provided by the National Aeronautics and Space Administration (NASA), see Fig. A1 and A4) different land use types are compared.

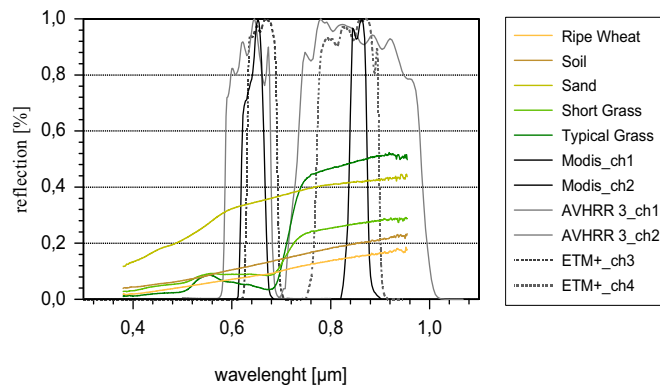


Fig. A1: Case study: NDVI-channels of MODIS and measured spectral reflectance above several land use types in Inner Mongolia

Figure A1 shows exemplarily the filter response functions of the VIS (red domain) and NIR channels of ETM+, MODIS and AVHRR used for the calculation of the NDVI and exemplarily the spectral reflectance of five different land use types: wheat, soil, sand, short grass and typical grass. They were measured in Inner Mongolia (in August 2005 by L. Fan (pers. communication) in the context of “MAGIM” (Matter fluxes of grasslands in Inner Mongolia).

Based on these spectral values two methods are common to infer the channel dependent reflectance and thus NDVI. Both use the filter response functions of the satellite sensors according to the NDVI-channels and the spectral signature of different land use types. A fast and easy way to estimate the channel dependent reflectance is to use the central wavelengths of the filter response functions in order to choose the point of intersection from this value with the spectral land use signal. As an example, for MODIS corresponding wavelengths are 0.645  $\mu\text{m}$  for channel 1 and 0.855  $\mu\text{m}$  for channel 2, respectively. On these wavelengths one can take the accordant values of the land use reflections and thus the channel-specific reflections for this special land use type.

However, this method works only for very high frequent spectrometer measurements (increment 2 nm).

A more precise spectral reflectance estimate can be obtained by the convolution of the filter response functions with a broad range of land use types. This channel-specific spectral reflectance  $\rho$  can be inferred by weighting the spectrum of the land use  $\psi(\lambda)$  stepwise with the filter response function  $\varphi(\lambda)$  of the satellite for the given range ( $\lambda_1 \dots \lambda_2$ ) of the filter response function:

$$\rho = \frac{\sum_{i=1}^N \varphi(\lambda_i) \cdot \psi(\lambda_i)}{\sum_{i=1}^N \varphi(\lambda_i)} \quad (\text{A1})$$

Here, N is the number of sampling points of  $\psi(\lambda)$  between  $\lambda_1$  and  $\lambda_2$ . This weighted sum is divided by the sum of the weighting factors to get the spectral reflectance of the respective channel, taking the shape of the response function into account. After calculating the reflectance of MODIS channel 1 (for  $\lambda$ : 610 nm – 680 nm) and channel 2 (for  $\lambda$ : 820 nm – 900 nm) using equation (A1), the NDVI is derived according to equation (2).

In Table A1 the results of the comparison for both methods referring to MODIS channels, are shown. On the left side and in the mid the inferred reflections of channel 1 and 2 are shown. On the right side the resulting NDVI values are displayed. Although there are differences in the channel based reflections the agreement in NDVI is good with nearly identically values. The example outlines the alternative to use the central wavelength to get a fast result, especially for field studies. And it also offers the possibility for validating satellite channel reflections easily.

Table A1: Case study Inner Mongolia: determined band-reflection and NDVI according to MODIS channels, using the method with the central wavelength (left side of the columns;  $v_c$ ) and weighting the spectral graph with the filter response functions (right side of the columns; convolution)

Land use type	Reflectance referring to MODIS channel 1		Reflectance referring to MODIS channel 2		NDVI referring to MODIS sensor	
	$v_c$	convolution	$v_c$	convolution	$v_c$	convolution
Ripe wheat	8.3187	8.2771	15.2978	15.2646	0.2955	0.2968
Soil	12.115	12.1266	20.0852	19.2646	0.2475	0.2444
Sand	34.508	34.4483	41.9921	41.8586	0.0978	0.0971
Short grass	8.8427	8.8145	27.0442	26.9996	0.5072	0.5078
Typical grass	4.6666	4.3605	49.4182	48.2418	0.8274	0.8281

In Figure A2 NDVI results based on the convolution method for MODIS, AVHRR 3 and ETM+ (left side) are shown for the land use types as used in Fig. 1. While there are differences in the shape, range and position of the filter response functions that are compared, the deviation in NDVI between the sensors seems to be small.

As mentioned above, the work was continued for further satellite sensors (AVHRR 2, ATSR 2, TM, ASTER and Seviri) and 17 land use types e.g. spruce, pine, water, snow (see Fig. A4, NASA, 1985). Figure A3 displays the results for a) VIS channel reflectance, b) NIR channel reflectance and c) the resultant NDVI.

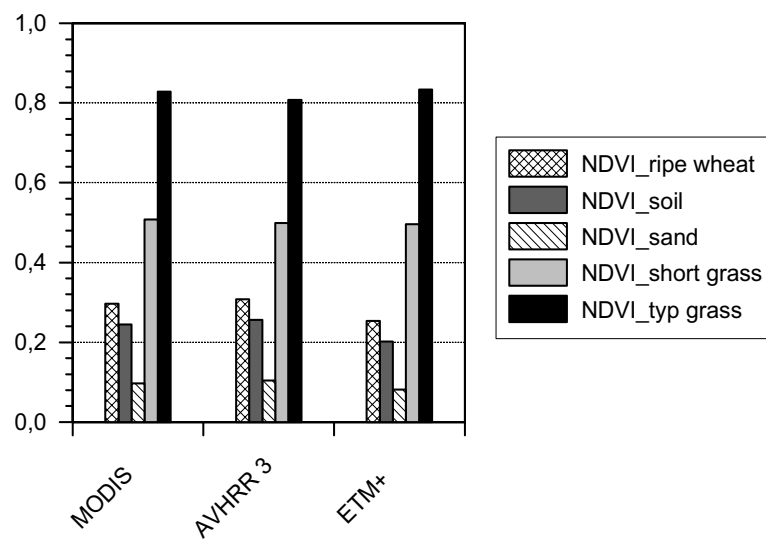


Fig. A2: Case study Inner Mongolia: Sensor-dependent NDVI

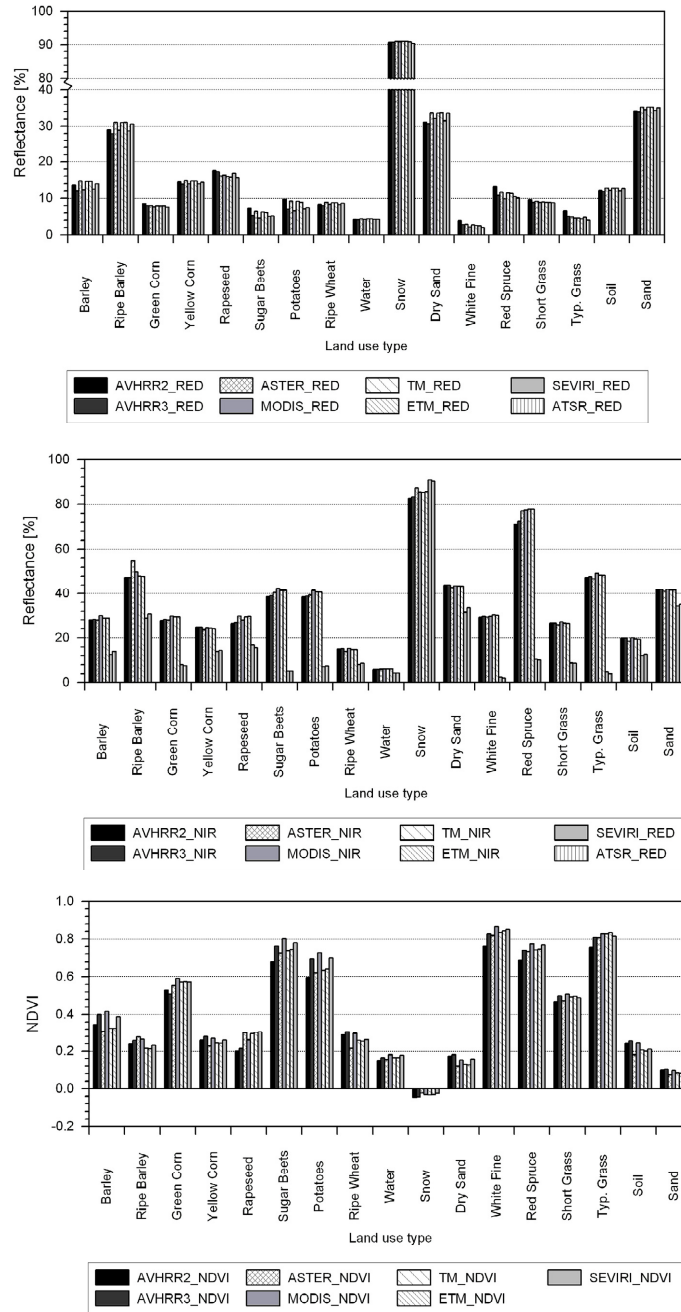


Fig. A3: Sensor differences of VIS-, NIR- and NDVI-values for various land use types, determined by convolution of the spectral response functions of the sensors and the spectral reflectance of different land use types

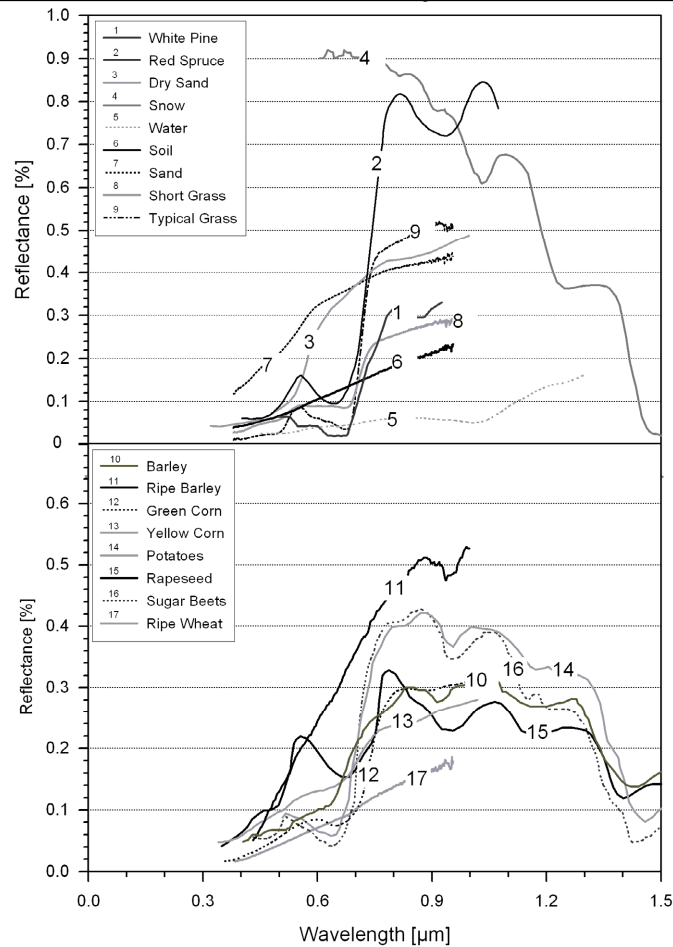


Fig. A4: Used land use types for convolution with filter response functions

Regarding all NDVI results of the land use types: with exception to the AVHRR values, (especially AVHRR 2) the differences of the sensor dependent results remain relatively stable to each other: with overall less values for ATSR (with exception to rapeseed), often followed by the ETM and TM results and then by Sevir. ATSR and MODIS mostly provide the highest values for NDVI only topped by AVHRR 3 for some land use types. On the other hand AVHRR 3 values are often lower compared to the other sensors and it can be outlined that NDVI from AVHRR 2 show the highest variability with very high values for ripe wheat, dry sand and snow (negative) but also with extremely low NDVI results for most of the land use types. Therefore the values are just lower than the ASTER-NDVI, actually showing the lowest NDVI.

Including the channel dependent reflection of the VIS and NIR channels it can be outlined that high reflectance values in the VIS and lower reflectance in the NIR results in low NDVI (green corn, rapeseed, sugar beets and potatoes). Differences in NDVI of MODIS and AVHRR 2 are in the same range as shown for Inner Mongolia, but for MODIS and AVHRR 2 differences can reach up to 0.12 (sugar beets) or 0.13 (potatoes).



NDVI differences between MODIS and AVHRR could be even higher, if the sensor derived data are used instead of the ground based spectrometer data. A major cause of these differences can be attributed to the influence on water vapour content in the atmosphere, which strongly effects the AVHRR NIR-band (0.71-0.98  $\mu\text{m}$ ) and caused NDVI values to decrease. The narrow MODIS band 2 (0.82  $\mu\text{m}$ -0.90  $\mu\text{m}$ ) avoids the water absorption regions of the spectrum and is nearly unaffected by seasonal variations in the atmospheric water vapour contents (Fensholt, 2004) and the red band of MODIS is rendered more sensitive to chlorophyll absorption.

Using the convolution method and quantifying the differences provide one possibility of adaptation from one sensor to the other. Steven et al. (2003) also used this method for their investigations and offered a table of conversion coefficients for all sensors. They found out that the values are strongly linearly related, allowing vegetation indices from one sensor to be intercalibrated against another.

Based on the given land use types (see Fig. A4), Fig. A5 and Table A2 show the relationship of the NDVI inferred for the seven sensors compared to the reference NDVI from ETM, using Eq. (A1). Linear relationships are found and the accordant correction coefficients calculated.

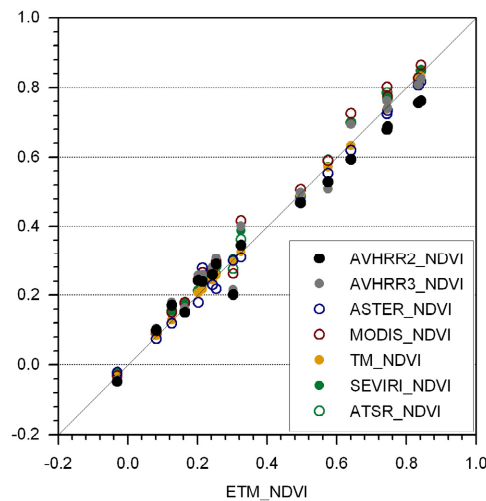


Fig. A5: Scatter plot of NDVI resulting from the 17 land use types for all sensors, reference: ETM onboard Landsat 7

Table A2: Correction functions and regression coefficients, (x = reference Landsat ETM)

Sensor	Linear function	Regression coefficient
AVHRR 2	$y=0.8791x+0.0286$	$r=0.9914$
AVHRR 3	$y=0.9542x+0.0301$	$r=0.9875$
ASTER	$y=0.9673x+0.0019$	$r=0.9972$
MODIS	$y=1.0126x+0.0237$	$r=0.9937$
TM	$y=0.9879x+0.0028$	$r=0.9999$
SEVIRI	$y=0.998x+0.017$	$r=0.9971$
ATSR	$y=0.0012+0.0163$	$r=0.997$

However, within the scope of this study a correction method using these theoretical relationships was difficult to realise, because of the different quality of the satellite databases.

ETM data were provided by calculating surface temperature and spectral reflectance from Landsats User Handbook (2004) and by using radiative transfer codes (6S and STREAMER) for atmospheric correction. From MODIS given products of surface reflectance and -temperature (MOD09 and MODA11) are used, already corrected for atmospheric effects. Finally the AVHRR *top-of-atmosphere* NDVI (TOA-NDVI), *surface* temperature and albedo (both corrected for atmospheric effects using LOWTRAN and 6S, respectively) were provided by using the SESAT scheme of Berger (2001). Thus, an appropriate correction/adaptation method had to be found to deal with the different data bases.

## A.2 Application of Sensor Adaptation

### MODIS

The determined ETM results are treated as reference because the sensor is radiometrically well-understood (Markham et al., 2004) and the more important reason here: In comparison to in-situ measurements the best validation results were obtained for all ETM derived parameters and fluxes. Thus, the MODIS parameters were adapted to the reference to realise then a consistent, sensor independent, parameterisation for the flux determination.

Comparing (averaged) ETM- and MODIS-albedo, NDVI and surface temperature pixel by pixel for the four investigated scenes 09/05/02, 17/04/03, 20/08/02 and 28/07/02, high correlation coefficients were found: surface temperature  $T_s$  ( $r=0.66, 0.79, 0.78$  and  $0.75$  for each scene respectively), albedo ( $r=0.95, 0.97, 0.90$  and  $0.93$ ) and  $NDVI$  ( $r=0.79, 0.92, 0.89$  and  $0.89$ ). This allowed the usage of the regression equations for shifting the MODIS data approximate to the 1:1 agreement. Especially the MODIS surface temperatures showed much lower values pre-corrected and could be seen as the reason for the deviations e.g. for  $R_n$  (Fig. A6:  $T_s$  (lower left) and Fig. A7:  $R_n$ , (upper left) between ETM and MODIS.

Scatter plots of albedo, NDVI and surface temperature (in MODIS resolution) are displayed in Fig. 6, exemplarily shown for the 20th of August in 2002. As mentioned above MODIS- $T_s$  shows strong deviation compared to the ETM values ( $r=0.78$ ) while albedo and NDVI are in good agreement ( $r=0.9$  and  $r=0.89$ , respectively). The parameters were then corrected according to the 1:1 agreement (for albedo:  $y=0.8469+0.8628x$ , for NDVI:  $y=0.1304+0.8429x$  and for surface temperature:  $y=177.7614+0.4008x$  as it can be seen in Fig. A6 on the right side.

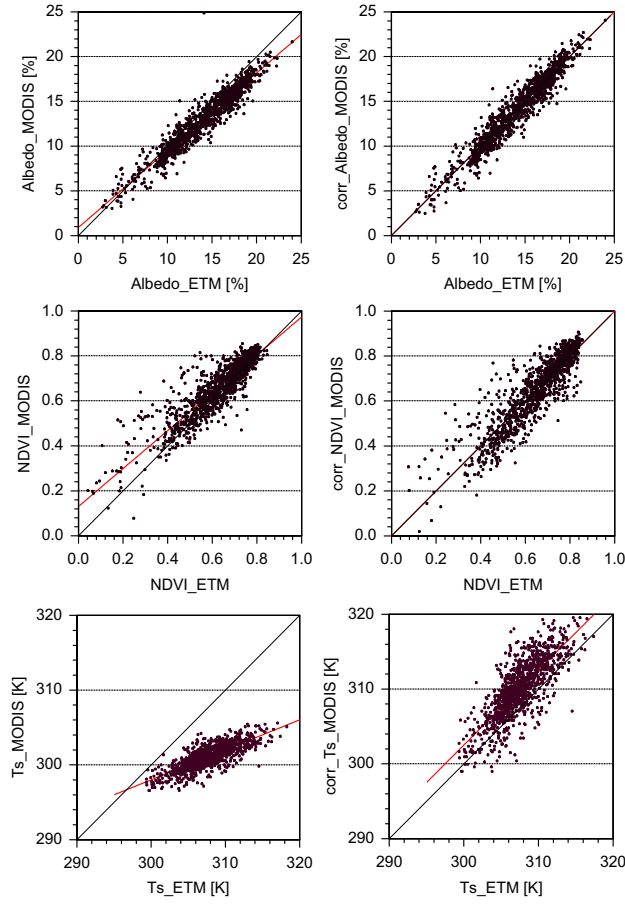


Fig. A6: Comparison of uncorrected (left) and corrected MODIS (right) to ETM results of albedo, NDVI and surface temperature for 20/08/02

The resultant fluxes, calculated after the Penman-Monteith equation by using the corrected values of  $T_s$ , albedo and NDVI are shown in Fig. A7. A significant improvement especially for  $Rn$  is obvious, mainly on the basis of the corrected temperatures. Values decreased more than  $100 \text{ Wm}^{-2}$ , now well corresponding to the ETM value range. Correlation coefficients remain nearly in the same range compared to the uncorrected fluxes ( $Rn$ :  $r=0.89$  to  $0.9$   $LE$ :  $r=0.83$  for both,  $H$ :  $r=0.61$  to  $0.6$ , only soil heat flux  $G$  shows a marginal improvement of correlation from  $r=0.75$  to  $0.78$ ).

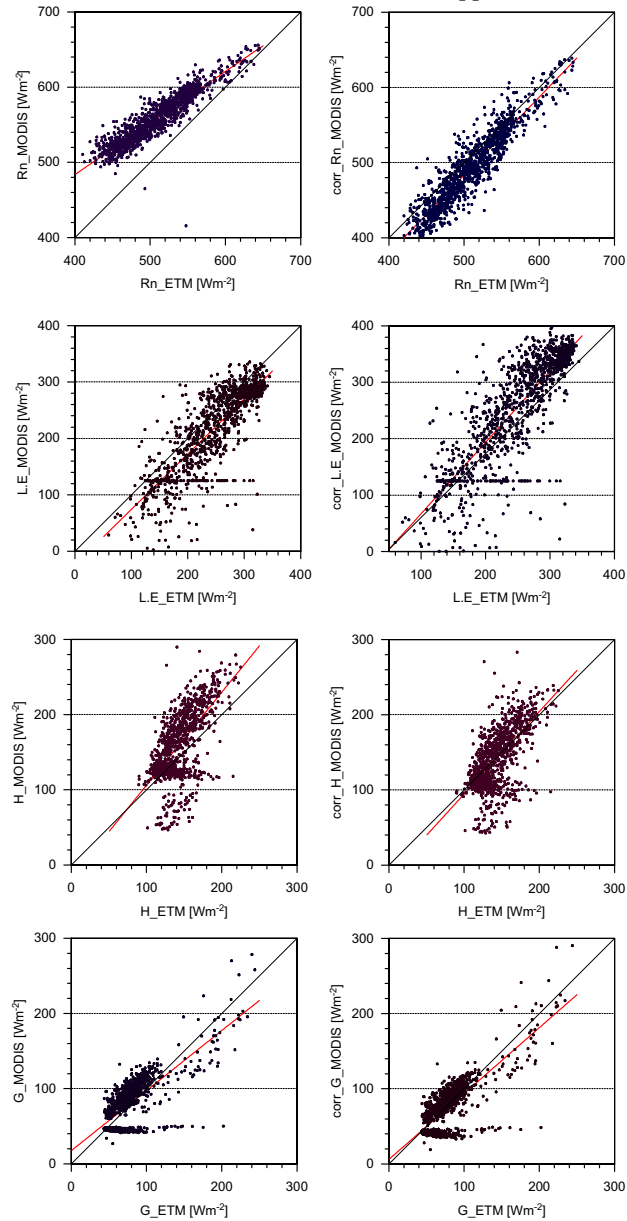


Fig. A7: Comparison of uncorrected (left) and corrected MODIS (right) to ETM results of the energy fluxes for 20/028/02, note especially the improved  $Rn$  agreement (upper panel).

## NOAA

From AVHRR surface temperature, albedo and TOA-NDVI were inferred using the SESAT scheme (Berger, 2001). Taking into account the two hour delay of the AVHRR overpass (AVHRR measurements are closed to the noon maximum in contrast to ETM and MODIS

measurements around 10:00 UTC) the regression-adaptation-method should not be used to correct sensor differences. The data analysis showed that an adaptation of the NDVI - which is significantly lower for AVHRR (Buheaosier et al., 2003; van Leeuwen et al., 2006) than for ETM and MODIS - is sufficient to infer comparable energy fluxes.

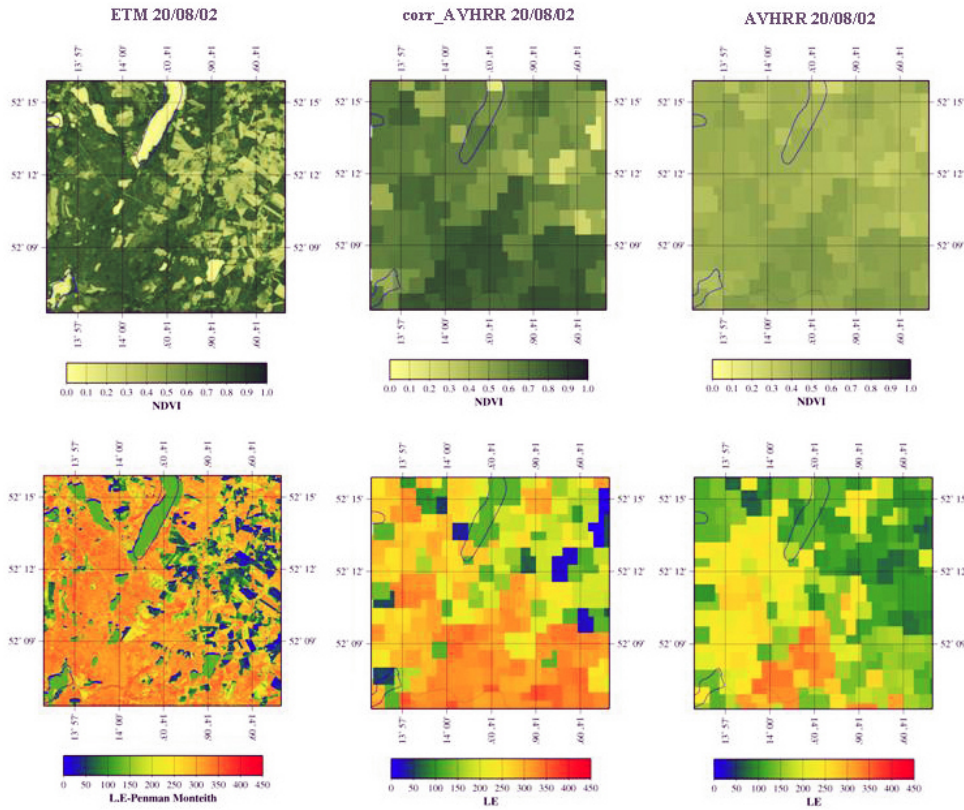


Fig. A8: Comparison of the spatial distribution of ETM (left), corrected AVHRR (middle) and uncorrected AVHRR (right): NDVI (upper panel) and  $L.E$  (lower panel) for 20/08/02

This NDVI adaptation was realised by stretching AVHRR-NDVI histograms: A comparison between AVHRR- and ETM-histograms was made investigating the values of 10 classes, respectively. At the first view the values differed strongly in their range as well as in the pattern. However, splitting the AVHRR histogram into 40 classes showed then a similar shape allowing the reallocation of the AVHRR-values into histogram classes according to the ETM distribution. Then a second comparison between the given 10 ETM-classes and the new summarised 10 AVHRR-classes was realised. As a result nearly the same distribution, in shape and range for both sensors was found. Thus, only a correction of one parameter (NDVI) was necessary to eliminate the sensor differences between AVHRR and MODIS.

Figure A8 shows the spatial distribution in NDVI (upper panel) and  $L.E$  (lower panel) exemplarily for 20th of August in 2002: ETM reference on the left side, corrected AVHRR-NDVI and  $-L.E$  in

the middle and on the right side the pre-corrected TOA-NDVI and  $L.E$  originally based on SESAT (Berger, 2001). Note the same spatial distribution of higher and lower values showing the direct influence of the NDVI on the  $L.E$  determination.

After correcting MODIS and AVHRR parameters by regressions or histogram stretching the energy fluxes are recalculated with one common parameterisation scheme for all sensors. The resultant flux distributions (in original spatial resolution) are shown in Fig. A9. It can be pointed out that for  $G$ ,  $H$  and  $L.E$  nearly the same distribution-patterns for all sensors can be found as well a comparable data range. Especially the peaks obvious for  $H$  are nearly the same with 20-25 % frequency for the class 100-120  $Wm^{-2}$ . The peak at 125  $Wm^{-2}$  that can be seen for  $L.E$  is the water constant as mentioned above. Further higher frequencies are found for the classes from 300-340  $Wm^{-2}$ . For  $G$  the peaks for the three sensors are comparable but the further frequencies differ marginal in the shape. While for ETM the values slightly rises after the peak found for 48-50  $Wm^{-2}$ , they descend for MODIS and AVHRR.  $Rn$  offers a somewhat different behaviour between the sensors not only in the distribution pattern but also in the range. As expected the range becomes narrower with a coarser spatial sensor-resolution.

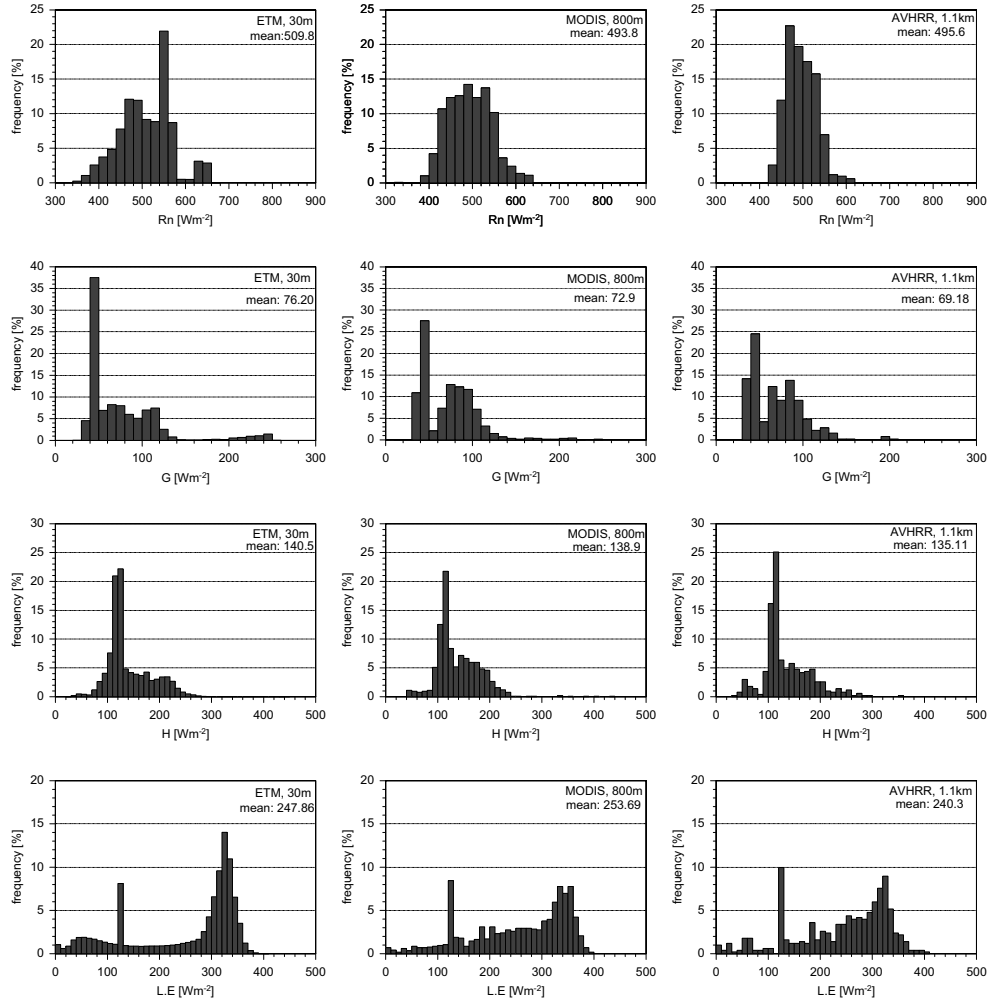


Fig. A9: Histograms of the energy flux densities for 20/08/02 after applying the correction methods for ETM (left), MODIS (middle) and AVHRR (right side) in their original spatial resolution.



### A.3 Validation

In the study of Tittebrand and Berger (2009) exemplarily for the 20<sup>th</sup> of August 2002 the validation results of original ETM- corrected MODIS- and corrected AVHRR data (averaged to 5 x 5 km<sup>2</sup> each) are shown in comparison to in-situ measurements above grass in Lindenberg (Beyrich et al., 2004).

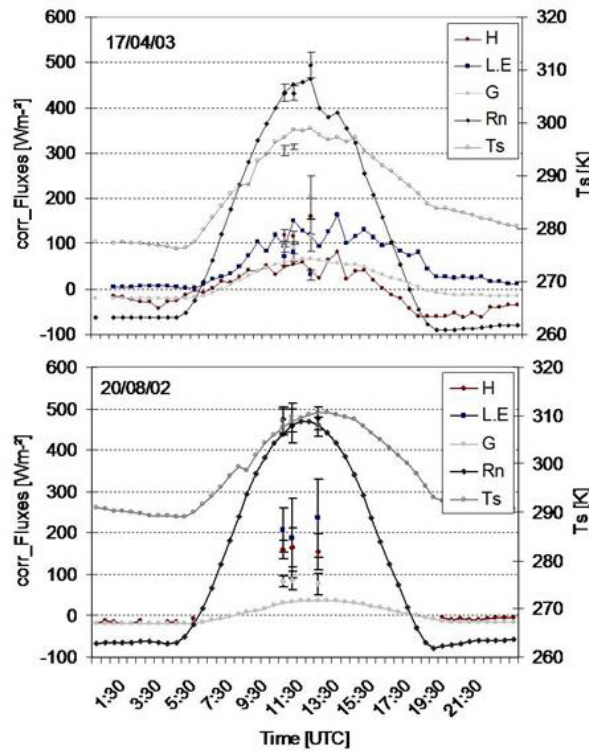


Fig. A10: Daily course of energy flux densities and surface temperature provided from the MOL-RAO as reference measurements. Instantaneous measurements of ETM, MODIS and AVHRR (starting left) are included according to their time of overpass with standard deviation respectively, for 17/04/03 (upper panel) and 20/08/02 (lower panel)

Figure A10 shows the daily course of the in-situ measurements for the 20<sup>th</sup> of August (lower panel) but also for the 17<sup>th</sup> of April in 2003, the only day with available energy fluxes. The data are added by the satellite results according to their time of overpass (from left: ETM, MODIS, AVHRR). For 20/08/02 an excellent agreement for  $R_n$  and surface temperature can be outlined. Soil heat flux remains an uncertain and hard to derive quantity with overestimations of 40-50 Wm<sup>-2</sup> for all sensors. Values for the turbulent fluxes are missing for this day but taking the other quantities into account - the evapotranspiration can be assumed to fit well, especially for these very wet conditions in August 2002, although LITFASS-area is dominated by sandy soils with high infiltration.  $H$  is computed according to Tittebrand et al. (2005) and not the remaining quantity of the energy balance. So

the system is open, but with only small gaps in the energy balance (ETM:  $23.22 \text{ Wm}^{-2}$ , MODIS:  $19.32 \text{ Wm}^{-2}$  and AVHRR:  $11.04 \text{ Wm}^{-2}$ ). For 17/04/03 data of all energy fluxes as well as for surface temperature were available showing again a good agreement for  $R_n$  and  $T_s$ , at least for ETM and MODIS. Surface temperature from AVHRR shows an underestimation of nearly 10 Kelvin. One reason can be found in the assumed beginning cloud coverage with strong influence on the sensor. The decrease in net radiation corroborates this theory. The turbulent flux  $H$  also differs from the in-situ measurements, overestimated by around  $100 \text{ Wm}^{-2}$  by all sensors. Latent heat inferred from ETM fit very well the in-situ measurement of evapotranspiration whereas both, MODIS and AVHRR derived  $LE$  are underestimated by about  $100 \text{ Wm}^{-2}$ . Analysing the turbulent fluxes for only this day they seem to be interchanged compared to the in-situ measurements. As outlined for 20/08/02 soil heat flux  $G$  is again overestimated by 40 -  $50 \text{ Wm}^{-2}$  by all sensors.

## A.4 Land Use Classifications

As mentioned in Tittebrand and Berger (2009) the application of a correct land use classification for flux determination is seen as a base for accurate results. In Tittebrand et al. (2005) the USGS land use classification (Anderson et al., 1976) and later a modified version of USGS (Kautz, 1999) were used for the processing of AVHRR data (SESAT, Berger, 2001) whereas the ETM data were parameterised in dependence on a downscaled CORINE classification. The comparison showed that USGS and also modified USGS are not recommended for the calculations due to wrong classifications and mapping and due to mixed classes as: "crop and grass", "crop and pasture" or "crop and forest" that make a parameterisation difficult. Thus this kind of classification was not suitable for the study target.

For further studies classifications as *CORINE* or a new Landsat-classification developed in the scope of the research project EVA-GRIPS (Tittebrand and Berger, 2009) were tested and assumed to improve spatial distribution and determination of the parameters and their resulting fluxes. The comparison to a reference classification is shown in Table A3.

Table A3: Comparison of land use classifications

Classification/ Satellite	25m_Landsat- classification [%]	CORINE [%]	Modified USGS [%]	Field study reference [%]
water	7	8	10	7
deciduous forest	4	-	-	-
mixed forest	7	2	44	-
coniferous forest	29	36	-	43
grass	24	8	8 (unsure: agriculture and grass and pasture)	13
crop	27	43	37 (unsure: grass and forest)	32
urban areas	2	3	1	5

For this comparison consistent classes had to be found. Therefore classes containing for example different field fruits were summarised to one class: crop. Problems with this method occur for the USGS because of mixed groups like "crop and grass", "crop and pasture", and "crop and forest". Nevertheless, there are huge differences between not only the percental representation of each class but also for the classification itself. A good agreement can only be found within the water classes, also in comparison to the reference classification.

Actually in LITFASS-area there is no deciduous forest. The CORINE and Landsat-classification match this well and give coniferous forests as dominant land use type for high vegetation. However, coniferous forest is underestimated by CORINE and the Landsat-classification with differences of 14 % and 7 % respectively, compared to the reference. The modified USGS show high values for mixed forest, not recognizing the coniferous forests as own group. Another problem using USGS is

found for the mixed groups and the question, how they can be summarised or how to assign them within the classification? Classes including grass and pasture are classified in the grass-class otherwise there were no values representing this group. Classes, including crop and forest, are dedicated to the agriculture-class otherwise this land use type would be strongly underrepresented. Most uncertainties can be outlined for crop and grass assumed that they are sometimes interchanged, due to their similar spectral behaviour.

Realising the four important working packages A1-A4 the basis for the investigations according to spatial heterogeneity – as provided in the paper of Tittebrand and Berger (2009) – was given.

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## Abbreviations

6S	Second Simulation of the Satellite Signal in the Solar Spectrum
AVHRR	Advanced Very High Resolution Radiometer
BOREAS	Boreal Ecosystem-Atmosphere Study
CORINE	Coordinated Information on the European Environment
DEKLIM	Deutsches Klimaforschungsprogramm
DWD	German Meteorological Service, Deutscher Wetterdienst
EC	Eddy covariance
EFEDA	European Field Experiment in a Desertification-Threatened Area
ERS	European Remote sensing Satellite
ETM	Enhanced Thematic Mapper
EVA-GRIPS	Evaporation at Grid/Pixel Scale
FIFE	First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment]
GEWEX	Global Energy and Water Cycle Experiment
HAPEX-MOBILHY	Hydrologic Atmospheric Pilot Experiment and Modélisation du Bilan Hydrique
LITFASS	Lindenberg Inhomogeneous Terrain - Fluxes between Atmosphere and Surface: a longterm Study
LM	Lokalmodell
LOWTRAN	Low Transmission Model
MODIS	Moderate Resolution Imaging Spectroradiometer
MOL-RAO	Richard Aßmann Observatory
MSG	Meteosat Second Generation
NASA	National Aeronautics and Space Administration
NIR	Near infrared (domain in the solar spectrum)
NOAA	National Oceanic and Atmospheric Administration
NOPEX	NORthern hemisphere climate Processes land-surface EXperiment
PAR	Photosynthetically active radiation
PDF	Frequency distribution functions
P-M	Penman-Monteiths
SEBAL	Surface Energy Balance Algorithm for Land
SESAT	Strahlungs- und Energieflüsse aus Satellitendaten
TM	Thematic Mapper
TOA	Top of Atmosphere
USGS	U.S. Geological Survey
VIS	Visible (domain in the solar spectrum)
WCRP	World Climate Research Program

## Symbols

$\rho$	reflectance	(%)
$\lambda_1$	spectral wavelength	( $\mu\text{m}$ )
$\lambda_2$	spectral wavelength	( $\mu\text{m}$ )
$\varphi(\lambda)$	weighting function of the filter response function	
$\psi(\lambda)$	weighting function of the land use spectrum	
$G$	soil heat flux	( $\text{Wm}^{-2}$ )
$H$	sensible heat flux	( $\text{Wm}^{-2}$ )
$LE$	latent heat flux / evapotranspiration	( $\text{Wm}^{-2}$ )
LAI	Leaf Area Index	( $\text{m}^2/\text{m}^2$ )
NDVI	Normalised Difference Vegetation Index	
$r$	regression coefficient	
$rc$	canopy resistance	( $\text{sm}^{-1}$ )
$Rn$	net radiation	( $\text{Wm}^{-2}$ )
$T_s$	surface temperature	(K)
$vc$	central wavelength	( $\mu\text{m}$ )

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**Erklärung:**

Hiermit erkläre ich, die vorliegende Arbeit selbstständig und ohne die Hilfe anderer Personen angefertigt zu haben. Weiterhin versichere ich, nur frei zugängliche oder lizenzierte Software verwendet zu haben, welche mir im Rahmen einer Anstellung als wissenschaftlicher Mitarbeiter des Institutes für Hydrologie und Meteorologie der Technischen Universität Dresden und des Institutes für Meereskunde der Universität Hamburg zur Verfügung stand.

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Antje Tittebrand

Hamburg, 30.10.2009