Deriving Normalized Difference Vegetation Index based on remotely sensed AVHRR and MODIS data

Thesis of PhD dissertation

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Introduction and aim of the study

Satellite-based remote sensing provides valuable information that can be used in meteorology, climatology, atmospheric environment, geophysics, biology, ecology, agronomy and environment protection related studies. The importance of this information is continuously increasing, and by today remote sensing became an essential tool in many scientific areas.

By the combination of data measured by the different channels of satellite-based radiometers different vegetation indices were constructed for the quantification of the state and amount of terrestrial vegetation. One of the most popular indices is the Normalized Difference Vegetation Index (NDVI), which is calculated from measurements of the Advanced Very High Resolution Radiometer (AVHRR) sensor onboard the NOAA meteorological satellites. The derived NDVI time series can be used in a wide range of research fields (e.g., in relation to weather, climate, plant phenology, etc.; *Kern et al., 2007a*). Ideally NDVI is calculated from remotely sensed and atmospherically corrected radiances. Atmospheric correction means the removal of the atmospheric effects on the measured radiance. This procedure requires several different variables related to the meteorological conditions. Atmospheric correction can be performed using a variety of models with the exploitation of the different meteorological information. The high resolution, multispectral information acquired by the MODerate resolution Imaging Spectroradiometer (MODIS) sensor of the National Aeronautics and Space Administration (NASA) can theoretically be used as information source for the atmospheric correction. The main aim of the present study was the synergistic use of the AVHRR and MODIS data acquired by the receiving station of the Faculty of Science, Eötvös Loránd University, Budapest. The synergistic use means that in order to obtain NDVI for Hungary the atmospheric correction of the received AVHRR data is performed exclusively (i.e., independent from other data sources) on the basis of the meteorological products derived from the MODIS data. The results of the atmospheric correction are used to estimate NDVI for Hungary.

Materials and methods

The primary data sources of the study are the AVHRR and MODIS data recorded by the receiving station of the Faculty of Science, Eötvös Loránd University (*Timár et al., 2006; 2008*). AVHRR data were processed by self-developed software, while MODIS data were preprocessed by freely available, public domain software developed by NASA scientists for the implementation of the official NASA MODIS products (the applied software version corresponds to the Collection 5 MODIS products).

Two, basically different models were adapted for the accurate determination of the NDVI fields. (1) Atmospheric correction model was adapted for eliminating the atmospheric effects on the radiances. (2) Bidirectional Reflectance Distribution Function (BRDF) model was adapted to decrease the angular effects of the measured radiances, which procedure means the normalization of radiances by the different angles. The primary aim of the research was to perform atmospheric correction based exclusively on MODIS data, independently from other data sources (e.g., results of numerical weather prediction models). Consequently, all four meteorological variables needed for atmospheric correction (aerosol optical depth at 550 nm, total precipitable water, vertically integrated ozone and surface pressure) were estimated from MODIS data. In case of missing MODIS data, monthly or annual climatology of the meteorological fields were used on the basis of public or previously derived direct broadcast datasets. The irregularly gridded meteorological fields were resampled and transformed into the grid of each AVHRR fields using bilinear interpolation and multiple step, adaptive sampling. The resampled meteorological fields were used for the application of the atmospheric correction. The quality and reliability of the calculated MODIS-based meteorological products were investigated, providing information about their applicability to atmospheric correction. The quality of the calculated NDVI fields was also evaluated, and a case study was accomplished to demonstrate the usefulness of the AVHRR-based NDVI results.

Results

The most important results of the dissertation are as follows.

1. This is the first study in Hungary where MODIS measurements are applied to perform atmospheric correction of AVHRR data.
2. The AVHRR and MODIS data recorded by the direct broadcast receiving station was processed by a complex, multiple step data processing chain, with the atmospheric correction as a final product. In case of the MODIS data the implemented data processing chain is fully automatic. The processing includes reception, calibration, archiving, and near real-time calculation of meteorological products. Additionally, the meteorological fields are assimilated into numerical weather prediction software. Data processing is performed with state-of-the-art software developed by NASA engineers (*Kern et al., 2008d; 2009; 2010a; 2010b*).
3. Sensitivity analysis of the adapted Simplified Method for the Atmospheric Correction (SMAC) model was performed using the Least Squares Linearization method, where the latter is a Monte Carlo based technique. The results indicate that the relative importance of the meteorological parameters needed for the atmospheric correction is as follows (from the

most important to the least important): (1) aerosol optical depth (at 550 nm), (2) vertically integrated water vapor, (3) vertically integrated ozone, (4) surface pressure.

4. All four meteorological variables needed by the atmospheric correction were derived from MODIS data. Accuracy of the three most important fields was evaluated in detail. The results presented in the followings clearly support their applicability, making the atmospheric correction of the NOAA/AVHRR data independent of other data sources.
   4.1. The variability of the aerosol optical depth at 550 nm (AOD) was quantified for Hungary based on two years of MODIS data with a total of 306 Terra/Aqua overpasses. The average spatial mean of AOD is ~0.17, and the average spatial variability is ~0.23, based on the 0.05 and 0.95 percentiles. The spatial mean is close to the continental average of 0.2, but this value can significantly change due to industrial processes or natural phenomena (*Kern and Bartholy, 2006; Timár and Kern, 2007*). The daily variability of AOD represented by the difference between the daily absolute maximum and minimum values was found to be ~0.41. The average AOD value for Budapest was ~0.3. The average AOD field for the Carpathian Basin at a 0.125° × 0.125° spatial resolution was also calculated based on two years of data (2007 and 2008) separately, which are considered to be representative for the AOD climatology of the region during the investigated years. Based on the results it is strongly suggested to use the most reliable data source for AOD, which should refer to the specific time. The MODIS-based AOD is currently the best available data source for this purpose.
   4.2. Vertically integrated water vapour (IWV) values were calculated from MODIS data based on 152 Terra/Aqua overpasses with two different (infrared (IR) and near infrared (NIR)) techniques. The MODIS based estimates were compared to the IWV values retrieved both from radiosonde measurements, and from the European Centre for Medium Range Weather Forecast (ECMWF) numerical analysis and short-term weather forecast for the Carpathian Basin. Comparing to the IWV values derived from 356 radiosonde measurements during 124 mostly clear days, the MODIS NIR IWV provides better estimations (the root mean square error (RMSE) is lower and R^2 is higher), but with more negative bias (i.e., underestimation) than the MODIS IR IWV (*Kern et al., 2007b; 2008c*). However, taking into account the dry underestimation of the daytime radiosonde measurements, the MODIS NIR IWV results in smaller bias than the MODIS IR IWV. Therefore the MODIS NIR IWV seems to have better quality than the MODIS IR IWV. Comparing the IWV values obtained from radiosonde measurements to IWV values retrieved from ECMWF (analysis and forecast fields at different times),

better results were obtained (due to the good temporal match between the radiosonde measurements and model results), but this difference is not significant (from the point of view of their use for atmospheric correction). Analysis of the IWV diurnal variation (which can affect the combination of the data from different satellites) concluded to a similar IWV growth rate to those reported in the previous publications in the case of NIR IWV (0.54 mm h^{-1}) and the ECMWF forecast (0.21 mm h^{-1}). In contrast, the results of IR IWV and ECMWF analysis data resulted in much lower values (0.02 and 0.025 mm h^{-1}, respectively). These results suggest that both NIR and IR MODIS IWV values are appropriate for the atmospheric correction of AVHRR data. However, due to the finer spatial resolution and the better temporal characteristics, MODIS NIR IWV is recommended as the primary data source.

4.3. Vertically integrated ozone values derived from MODIS and the Ozone Monitoring Instrument (OMI) onboard the satellite Aura were validated with surface observations of the Brewer spectrophotometer located in Budapest for the year of 2007 (*Borbás et al., 2010*). The results show that the relationship between the surface observations (interpolated to the time of every MODIS measurements) and the MODIS ozone values is weaker than the relationship between the surface observations and the OMI ozone values. However, this difference is negligible from the point of view of the atmospheric correction, which supports the use of the MODIS ozone values. Better results were obtained using the new, so-called Collection 6 algorithm (especially for the MODIS/Aqua data; *Borbás et al., 2010*). Our validation results contributed to the development and theoretical description of the new C6 official NASA algorithm of the MOD07 ('Atmospheric Profiles') products, as well (*Borbás et al., 2011*).

5. A BRDF model was adapted in order to decrease the angular dependence of reflectance measured in the visible and near infrared channel of the AVHRR sensor. A new land cover database was constructed for the application of the BRDF model (simplified to follow the logic of the BRDF model), based on the MODIS land cover product (MOD12) and improved by the Corine Land Cover 2000 database. The new database has better quality – especially in case of grasslands – than the MODIS land cover database used previously as primary data source.
6. AVHRR data from 153 satellite overpasses (including data from NOAA-16, -17, and -18) were corrected with the SMAC and the BRDF model based on the derived MODIS products. The AVHRR overpasses covered the region of the Carpathian Basin. NDVI was calculated from the atmospherically corrected, and angular geometry corrected reflectances of channels

1 and 2. The effects of MODIS-based atmospheric correction and BRDF normalization were quantified based on the 153 overpasses. Atmospheric correction increased NDVI by 0.197, while BRDF correction increased NDVI by only 0.0046 in average. It was pointed out that the effect of alternative meteorological fields used for the atmospheric correction is negligible on the calculated NDVI values. It means that the uncertainty of NDVI caused by the choice of the meteorological input data is negligible. Experiences with the land cover dependent BRDF model suggest that inappropriate selection of the land cover type has small effect on the calculated NDVI, even though in some extreme cases the bias is comparable with the magnitude of the correction of the BRDF model itself.

7. Causes of uncertainties present in the temporal courses of NDVI were specified, and different methods for possible reduction of this uncertainty (i.e., noise) were also discussed. One of these methods is the discrete wavelet transform, which was implemented and applied in the dissertation. Through the application of the wavelet transform noise filtering and interpolation was performed on the original, noisy time series (*Kern et al., 2008b; Barcza et al., 2009; Tóth et al., 2010*).
8. The calculated NDVI fields were resampled into regular grids with different horizontal resolution. Advantages and disadvantages arising from the different grid resolutions were evaluated. Derived NDVI values were analyzed using $0.1° \times 0.1°$ horizontal resolution, mostly to quantify the uncertainty of the indices. Resampled NDVI fields acquired during the same day from different NOAA satellites were compared. The strongest relationship was found between NOAA-17 and NOAA-18, while the weakest relationship occurred between NOAA-16 and NOAA-17. These results – together with other issues described in the dissertation – suggest that the received AVHRR data from NOAA-16 are not recommended for any use in case of 2007. Mean difference between NDVI fields of the different NOAA sensors during the same day was also estimated using $0.1° \times 0.1°$ horizontal resolution and 100% data coverage. The mean difference was 0.009, which means that the overall uncertainty of the derived NDVI values is about 0.01. This uncertainty can be used for the estimation of error propagation in further studies that utilize the calculated NDVI values.
9. An attempt was made to verify the calculated NDVI values based on the official MOD13 NDVI dataset (derived from MODIS data), which contains composite data in 16 days temporal resolution. During the experiment we acknowledged that (1) even the MOD13 NDVI can not be considered as absolute reference; and (2) it is virtually impossible to reach perfect agreement between data of the two sensors (MODIS and AVHRR) due to their different channel bandwidth, different spectral response, and different spatial coverage (i.e.,

grid definition). Verification was first performed based on NDVI time series representative to selected locations with homogeneous vegetation cover. Then, MOD13 and AVHRR NDVI values using 16 days composite technique were compared for the same locations and same days. The resulting mean difference was -0.01 and 0.005 for Aqua/MODIS and Terra/MODIS, respectively. For the sake of completeness Terra/MODIS and Aqua/MODIS NDVI results were also compared using 1 km × 1 km resolution. Here the mean difference was 0.009. This difference is almost equal to the estimated values from AVHRR data using 0.1° × 0.1° grid resolution. The results suggest that due to the better illumination conditions and better geolocation it is always recommended to use AVHRR data from „younger" satellites, which in our case are NOAA-17 and NOAA-18 – but not NOAA-16.

10. Based on the calculated AVHRR/NDVI dataset, effects of the heat wave occurred in the Carpathian Basin in July 2007 were discussed. In spite of the uncertainties associated with the derived NDVI fields, it was possible to detect the impact of the heat wave on the selected regions with homogeneous vegetation. In these selected regions (forests, and arable lands with summer crops) it was even possible to follow the phenological effects of the heat wave from day to day. During a 9-day-long time period centered around the heat wave the mean decrease of NDVI was 0.053. The impact of the heat wave was also evaluated based on the MOD13 NDVI dataset (*Kern et al., 2008a*). It was found that the composite images with 16 days temporal resolution are less useful for detecting the phenological response of the vegetation. This weather event demonstrates that – independent of the precipitation amount – a single extreme event may cause significant damage in the standing biomass that can affect the yield of some crops.

Conclusions

The results of the dissertation summarized above clearly demonstrate the usefulness of the well-known and widely used AVHRR sensor. There is a significant added value in the temporal resolution of the received AVHRR data, and this value is further enhanced by the throughout knowledge of the derivation method. In the present case, due to this added value, the derived AVHRR/NDVI fields are preferred if one has to choose between MODIS NDVI and AVHRR NDVI. Uncertainty of the NDVI values were quantified, which further enhances the applicability of the results. The dissertation proved that it is worth studying the synergistic use of different remotely sensed data in order to better exploit the information content of the sensors.

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