Spatial variability of the atmosphere across southern England and the resulting error in assuming a uniform atmospheric correction

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Abstract

There is an increasing trend towards the use of large-swath satellite sensors, such as those on the Disaster Monitoring Constellation (DMC), for monitoring environmental change due to their significant advantages over systems such as Landsat. Before imagery can be used quantitatively it must undergo atmospheric correction, where most techniques assume a uniform atmosphere across the image – an assumption that is likely to be invalid for 600km wide images from DMC. To assess the significance of the error caused by this assumption, spatial variability over southern England on a clear day is assessed from a number of data sources and the results are used in simulations with the 6S Radiative Transfer Model to examine the effects on NDVI, and Net Primary Productivity values calculated from these NDVI data using the CASA ecosystem model.
Results show that the AOT variation during the study period was approximately 0.1-0.5 and that this could cause an error in NDVI of 2.9-4.5%. A conservative estimate of the error in NPP values which could be caused by this over southern England is 7.6Mt C, or 3%. Further work should focus on spatially-variable atmospheric correction techniques.

Keywords: *atmospheric correction, NDVI, radiative transfer model, error analysis*

1. Introduction

Remote sensing provides an important method for assessing environmental change over large areas. Much of this work has been performed using images from the Landsat series of satellites, the archive of which stretches back to the 1970s. However, in many areas of the world it can be difficult to analyse large areas with Landsat images as issues with cloud cover and the 16-day revisit period mean that images from different dates or even different years need to be combined. In the UK context this has presented problems for each of the three land cover maps produced to date (LCM1990, LCM2000 and LCM2007) (Morton et al. 2011).

Sensors on the Disaster Monitoring Constellation (DMC) provide data with a nominal 22m or 32m ground resolution element (GRE) in green, red and NIR bands spectrally matched to the Landsat TM, but with a two-day revisit period and considerably larger images (600km swath), which reduces the need for mosaicking. This high revisit frequency and the large area coverage make these images ideal for synoptic survey and for examining environmental change, for example as part of a UK Environmental Change Observatory.

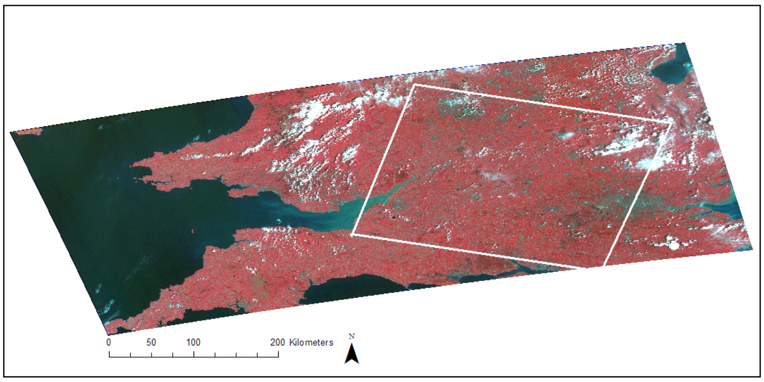

Figure 1: *A DMC image of southern England on the 17th June 2006. The white rectangle indicates the typical Landsat image size. © DMCii*

In order to produce useful information for analysis, satellite images require atmospheric correction. Several methods can be used such as Dark Object Subtraction (Chavez, 1988), the Empirical Line Method (Smith and Milton, 1999) or simulation modelling using Radiative Transfer Models (RTMs). However, all of these methods assume that the atmosphere is uniform across the image, which may be reasonable for small images but is unlikely to be true for 600km wide images such as those from DMC.

This paper aims to assess the spatial variability of the atmosphere over southern England and model the effects of performing a uniform atmospheric correction over this area.

2. Spatial variability of the atmosphere

The two key atmospheric parameters required for correcting satellite images using RTMs are the Aerosol Optical Thickness (AOT) and Precipitable Water Content (PWC). This paper will focus on AOT, as modern multi-spectral satellite bands generally exclude wavelengths that exhibit high water vapour absorption, and therefore water vapour content has very little effect on such data.

Spatial variability of AOT over southern England on a generally clear day (16th June 2006) was assessed using data from ground-based instruments and satellite imagery (Table 1). AERONET produces the most accurate AOT measurements (Holben et al., 1998), but during the study period only one site was operating in southern England. Many Met Office meteorological stations record horizontal visibility, from which AOT can be estimated using the Koschmieder equation (Horvath, 1971; Koschmieder, 1925). Satellite data products provide high spatial coverage, but with lower accuracy. We used two satellite products: the MODIS AOT product and the GlobAerosol merged satellite product, which produces AOT estimations from the combined data of four satellites.

Table 1: *Summary of AOT data sources used*

Source	Type	Spatial Resolution	Temporal Resolution	Accuracy
AERONET	Ground	One location	Every 15 minutes	±0.02
Met Office	Ground	36 stations	Hourly	RMSE=0.05-0.47[1]
MODIS M?D04	Satellite	10km	Daily merged or Once per orbit	±0.05 ±0.15τ
GlobAerosol	Multi-Satellite	10km	Daily	RMSE=0.12

Although AERONET data are the most accurate, in this study they were derived from a single location, so we used a time-for-space substitution to estimate the AOT across the study site by assuming an air mass was moving constantly over the AERONET site during the day. Thus AERONET measurements from the entire day (approximately 10 hours of measurements, as AERONET only records during sunlight hours) were compared with the other data sources.

Considering the entirely different measurement techniques used by the four data sources, Figure 2 shows that they produce similar results for the range of AOT values over the study area. Both satellite data sources have a larger range, and show a minimum AOT of almost zero, which is unlikely to be the case, and AERONET shows one AOT measurement over 1.0, which is likely to be caused by incorrect cloud screening.

Overall it appears that the range of AOT was approximately 0.1-0.5, although it could be as high as 0.01-0.5 or as low as 0.18-0.4, depending on the data source used. All analysis of the effects of this AOT variability was carried out using the 5% and 95% quantiles of the data as this excludes extreme values which may be erroneous, and allows statistical inference

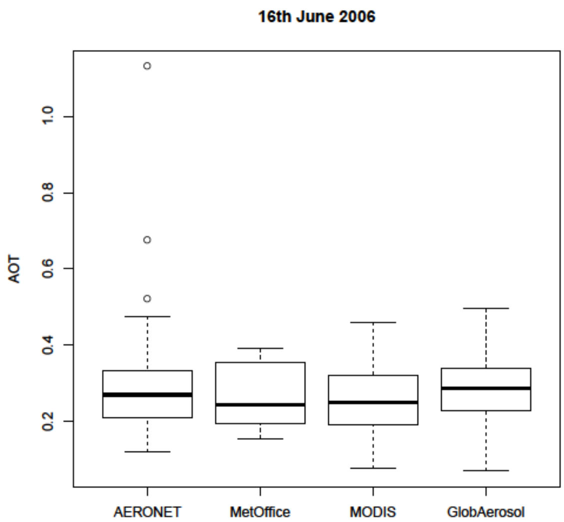

Figure 2: *Boxplots showing AOT measurements from the four data sources*

[1] The RMSE error of the Koschmieder estimation varies from 0.05 for a visibility of 40km to 0.47 for a visibility of 10km.

based upon the assumption that 10% of the pixels in the image will have AOTs outside of the 5% and 95% quantiles.

3. Effect of uniform atmospheric correction

The effects of performing a uniform atmospheric correction over an area with the spatially variable atmosphere described above were simulated using the 6S Radiative Transfer Model (Vermote et al., 1997). Functions were written using the Py6S interface to 6S (Wilson, 2012) to run the model twice: firstly in the upward direction to calculate the top of atmosphere radiance for a given surface reflectance under a specific AOT (τ_u), and secondly in the downward direction to atmospherically correct that top of atmosphere radiance using a different AOT (τ_d), producing a corrected surface reflectance. To simulate uniform atmospheric correction under a spatially-variable atmosphere, the top of atmosphere radiance was calculated with τ_u set to the 5% or 95% quantile of the AOT, and this radiance was then corrected using a τ_d set to the mean AOT value, thus simulating a uniform atmospheric correction performed for all pixels in an image using the average AOT. All other parameters in 6S were set to suitable values for the location and time of year and the surface reflectance spectrum was set to a standard green vegetation spectrum.

The effect of uniform atmospheric correction on NDVI was then assessed using the surface reflectance values from the 6S simulations. The simulations were carried out using each data source described above, and the percentage differences in the resulting NDVIs from the true NDVI of the green vegetation spectrum were calculated. (see Table 2). A sensitivity analysis showing the percentage error in NDVI for a range of AOT errors was also performed (see Figure 3).

Table 2: *Effect of uniform atmospheric corrections on NDVI values*

	NDVI			% difference	
Source	**Actual**	**95%**	**5%**	**95%**	**5%**
AERONET	0.612	0.586	0.639	-4.48	4.28
Met Office	0.612	0.595	0.634	-2.94	3.46
MODIS	0.612	0.594	0.639	-3.00	4.20
GlobAerosol	0.612	0.593	0.636	-3.20	3.80

NDVI is often used as an input to ecosystem models which produce outputs such as Net Primary Productivity (NPP), which is an important input for climate models. The CASA model (Potter et al., 1993) was used to analyse the effect of these NDVI differences on estimates of NPP for the study area. Default parameterisations at one degree resolution were used for the CASA model (see van der Werf et al., 2003 for details). To produce the input data for the CASA simulation, 6S simulations were run with τ_u set to each value from the data source in turn, and τ_d set to the average of the AOT from that data source, thus producing a distribution of NDVI errors caused by the variation in AOT from that data source. The CASA model was altered to allow random errors from this distribution to be applied to the NDVI values in the model before simulation commenced. The model was run 500 times and the total yearly NPP of the study area was calculated for each run.

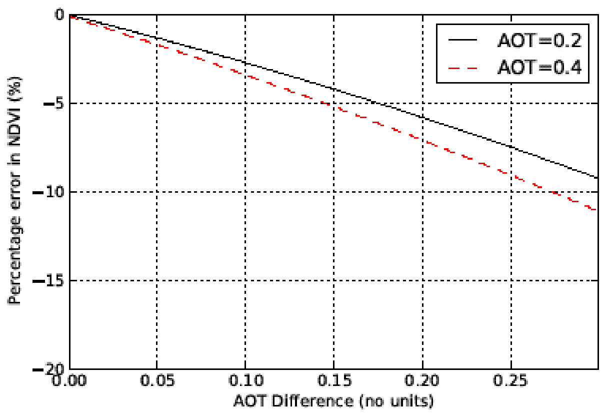

Figure 3: *Sensitivity analysis showing effect of AOT error on NDVI*

The results using the Met Office dataset (which has the lowest range of NDVI differences and would thus produce the most conservative estimates of NPP change) produced NPPs from 0.271 to 0.284 Gt C an error of approximately 3% (7.6 Mt C) compared to the true value.

The 6S simulations show that the NDVI error caused by performing a uniform atmospheric correction over this area could be up to 4.5%. This is high enough to be significant in terms of final remote sensing product output. The modelled error in NPP was up to 7.6Mt C, which is around 0.3% of the global yearly carbon uptake rate on land from 1990-2000 (Le Quéré et al., 2009). The study area for this paper is only 0.07% of the world's land area, and if this magnitude of error were present in atmospheric corrections used to produce NDVI values for global NPP estimates then the overall error could be very significant.

The 6S simulations also show an issue with the available AOT data sources. The majority of spatially-distributed AOT data sources have high uncertainty, so acquiring any data of high-enough quality to perform a spatially-variable atmospheric correction is likely to be difficult. The official validation for the MODIS AOT product states that 67% of the pixels should be within, $\pm 0.05 \pm 0.15\tau$ which is ±0.08 for an AOT of 0.2 and ±0.11 for an AOT of 0.4, but the sensitivity analysis shows that these can produce errors in NDVI of 2.1% and 2.7% respectively. This suggests that the common practice using MODIS AOT data as inputs to atmospheric correction models may produce results with a significant error.

4. Conclusions

Overall, this study shows that there can be significant spatial variability in AOT (0.1-0.5) across southern England, even on a visually clear day. Most current atmospheric correction techniques assume a uniform atmosphere across the image; this is an invalid assumption for the study area during the study period, and is likely to be invalid at many other times and places. Future work should focus on spatially-variable methods of atmospheric correction, although given the uncertainty associated with AOT data it is likely to be difficult to parameterise them effectively.

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