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Spatial variability of the atmosphere over southern England, and its effect on scene-based atmospheric corrections

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Earth observation data acquired in the optical region require atmospheric correction before they can be used quantitatively. Most operational methods of atmospheric correction assume that the atmospheric properties are uniform across the image, but this assumption is unlikely to be valid for large images. This study aims to characterise the spatial variation in atmospheric properties over a typical mid-latitude area (southern England), and assess the errors that would result from applying a scene-based atmospheric correction to data collected under this variable atmosphere. Two key atmospheric properties - Aerosol Optical Thickness (AOT) and Precipitable Water Content (PWC) - are assessed over two clear days in June 2006, and results show an AOT range of approximately 0.1-0.5, and a PWC range of 1.5-3.0cm. Radiative transfer modelling shows that errors in reflectance of up to 1.7 percentage points, and up to a 5% change in NDVI, can be caused by the AOT variability, but the PWC variability has minimal effects. Sensitivity analyses also show that the high uncertainty of many data sources used to provide AOT values for atmospheric correction may also lead to significant errors in the resulting products. The spatial variability of the atmosphere cannot be ignored, and we are in need of operational, generic methods to perform a spatially-variable atmospheric correction.

Keywords: Atmospheric correction; Error & Uncertainty; Radiative Transfer Modelling

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1. Introduction and Background

Remotely sensed data are typically used to generate quantitative products which require a high degree of accuracy, for example, satellite sensor data are applied to estimate the Global Climate Observing System Essential Climate Variables (GCOS 2004) such as snow cover (Hall, Riggs, and Salomonson 1995), sea-surface temperature (Brown et al. 1999), albedo (Wielicki et al. 2005), water vapour (Gao and

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Kaufman 2003) and net primary productivity (Running et al. 2004). To produce these variables, remotely-sensed data must undergo atmospheric correction to remove the perturbing effects of the atmosphere from the data, and thus allow results to be determined accurately in physical units (Slater 1980). A range of atmospheric correction methods can be used with satellite sensor data but most methods assume that the atmosphere is spatially-uniform across the image. However, over large images such as those from Landsat (185km x 185km) or DMC (a swath width of 650km) the atmosphere is likely to vary and so uniform correction methods may introduce significant errors in the resulting data products.

This paper investigates errors associated with uniform atmospheric correction over large images of southern England. We first quantify the spatial variability of the atmosphere over southern England on a clear (cloud-free) day, and then assess the magnitude and range of errors associated with uniform atmospheric correction over this area, both in terms of radiance and NDVI.

1.1 *Study area and period*

The study used data over southern England (the grey area in Figure 1) from the 16th and 17th June 2006. These were typical mid-latitude clear days during the NCAVEO Field Campaign (Milton et al. 2011), when a range of ground and satellite data were available.

The meteorological situation changed significantly during these two days, as a high-pressure system migrated from the southern Atlantic Ocean, over southern England to Germany. The passage of this weather system caused significantly different wind directions on the two days (with average directions of 287° on the 16th and 192° on the 17th). Field observations confirm that conditions on the 17th were more variable than the 16th (Milton et al. 2011), with an increase in cloudiness and a reduction in sky clarity after 11:00 UTC.

1.2 *Background*

In the early days of satellite remote sensing, simple scene-based atmospheric correction techniques such as Dark Object Subtraction were generally used. In the 1990s and 2000s there was significant development in per-pixel approaches designed for use with hyperspectral imagery. However, there is a lack of true pixel-based correction methods for multispectral imagery. Tools such as ATCOR (Richter 2004) and FLAASH (Cooley et al. 2002) can be used to perform a pseudo-pixel-based correction of multispectral images, but the methods that are used for extracting spatially-variable atmospheric information from multispectral imagery are limited. Thus, the majority of multispectral atmospheric corrections performed today are scene-based, using constant values of atmospheric parameters across the scene and not taking into account the spatial variability of the atmosphere over the image.

It is particularly important to quantify errors resulting from these scene-based atmospheric corrections due to a number of recent developments within remote sensing. First, the use of large images with a variety of spatial resolutions in environmental studies is becoming increasingly common, due both to the increased availability of large images and the policy-driven need for large area studies, particularly those relating to environmental change. Typical sensors include MODIS (500m resolution) and the Disaster Monitoring Constellation (30m resolution), which both produce images that cover very large areas (a single DMC image can cover approximately half the area of England). Second, with the incorporation of atmospheric correction tools into image processing software, atmospheric correction can now be performed by users who may have little knowledge of the possible uncertainties of the results. Third, data obtained from quantitative analysis of remotely-sensed images are now in widespread use for a variety of important scientific projects and errors in this data could have serious consequences. In climate modelling, significant errors in input data caused by incorrect atmospheric correction could result in misleading predictions being reported to policymakers. For example, Saleska et al. (2007) stated that the Amazon rainforest was more resilient to short-term climatic fluctuations than previously thought (as shown by a significant increase in Enhanced Vegetation Index), but Samanta et al. (2010) showed that these inferences were due to the use of cloud- and aerosol-contaminated satellite data in the original study.

1.3 *Atmospheric parameters of interest*

The primary atmospheric constituents which affect remotely-sensed measurements are mixed gases, ozone, aerosols and water vapour. Concentrations of atmospheric mixed gases are controlled by atmospheric pressure, and ozone concentrations can be modelled effectively by latitude and season (Van Heuklon 1979). However, aerosol and water vapour concentrations vary significantly both spatially and temporally, and thus contemporaneous data on these must be provided when atmospherically-correcting satellite images.

The *Aerosol Optical Thickness* (AOT), also known as the *Aerosol Optical Depth* (AOD), is a dimensionless measure of the degree to which aerosols restrict the transmission of light through the atmosphere, defined as the integrated extinction coefficient due to aerosols through a vertical column of unit area in the atmosphere (Iqbal 1983).

Water vapour in the atmosphere can be quantified in two ways: Integrated Water Vapour (IWV), the vertically integrated mass of water per unit area ($\mathrm{kg\,m^{-2}}$), or Precipitable Water Content (PWC), the height of an equivalent column of liquid water (mm) (Iqbal 1983).

1.4 *Previous work*

Previous studies that have assessed AOT variability have typically used i) low resolution data or ii) daily, weekly or monthly composites which are relevant for climate-related studies but not for assessing the spatial variability in AOT at the specific instant of satellite image acquisition.

González et al. (2003) and Koelemeijer, Homan, and Matthijsen (2006) both examined the spatial variation of AOT across Europe using MODIS and ATSR-2 data respectively. These data were averaged to monthly or yearly periods, and so only provide estimates of an average variability of 0.2–0.5. González et al. (2003) found a wide range in AOT values across Europe, with values of 0.5–0.6 in industrialised areas of Germany and northern Italy, and values of 0.1 in rural areas of France, Spain and Norway, which suggests that local emissions are particularly important in determining AOT values. Koelemeijer, Homan, and Matthijsen (2006) also found significant local effects, with a number of cities easily distinguishable as peaks in the data, and particularly low AOT in mountainous areas. The AOT values in southern England from the same study reflect this, with high values around London and the Thames Estuary and generally low values in rural Cornwall. González et al. (2003) also found that AOTs can increase by up to 300% over relatively short distances (along a transect from Germany to Belgium), and similar gradients occurred in their data for the UK (eg. an increase of 275% from east Kent to mid Oxfordshire). AOTs also vary temporally, both diurnally (Smirnov et al. 2002) and over weekly periods (Bäumer and Vogel 2007). These anthropogenic variations, along with the prevailing meteorological situation, significantly impact the spatial variability of AOT, and thus yearly or monthly averages do not provide the information required for assessing the effect of uniform atmospheric correction procedures.

1.5 *Uniformity assumptions in atmospheric correction methods*

Very few implementations of atmospheric correction methods take into account the spatial variability of the atmosphere, even though these methods are conceptually able to work with a variable atmosphere. Typical relative or empirical methods, such as Dark Object Subtraction (Chavez 1975; Moran et al. 1992) and the Empirical Line Method (Smith and Milton 1999), use averages of measurements taken across the image, thus ignoring the data on spatial variability which would be present in these measurements. Physical correction methods involve running a Radiative Transfer Model (for example, Berk et al. 1999; Vermote et al. 1997b) on each pixel in the image, and thus could easily take into account spatial variability in atmospheric parameters.

The Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS; Masek et al. 2006) partially accounts for spatial variability by estimating AOT over areas of dense dark vegetation (DDV) in the image using the Kaufman et al. (1997) method. The AOT data are then interpolated to 1km resolution and used to parameterise 6S (Vermote et al. 1997a) to perform the atmospheric correction. However, there are a number of problems with this method: i) it does not take into account fine-scale variability in AOT; ii) it can only estimate AOT over areas of DDV thus making it impossible to use over areas without DDV, such as deserts; and iii) it is only implemented for Landsat images as the AOT retrieval method requires the use of the Landsat short-wave infra-red bands.

There has been discussion within the community as to whether atmospheric correction is required in all situations. Song et al. (2001) state that atmospheric correction is not required for applications which require only a single image and do not need the data to be in physical units. For example, they argue that performing a maximum likelihood classification of a single Landsat image using training samples derived from the image data itself would give exactly the same result with and without atmospheric correction. This is because a uniform atmospheric correction would simply apply the same correction to each pixel in each band, thus changing the mean of each land cover class, but not altering the covariance of the classes. However, if a spatially-variable atmospheric correction were to be performed the correction applied each pixel would be different (based upon the atmospheric conditions over that pixel), and thus the covariances of the classes would change. Similarly, if the image was acquired through a spatially-variable atmosphere but a uniform atmospheric correction was performed there would be a different error for each pixel, which would affect the covariances of the classes. Thus, if the atmosphere is spatially-variable, a full spatially-variable atmospheric correction is required even for the uses specified in Song et al. (2001).

2. Data Sources & Validations

AOT and PWC can be measured using a variety of ground instruments and satellite products with a range of spatial and temporal resolutions (Table 1). The uncertainty of these methods depends on the location they are used in, with factors such as land cover and aerosol type having a large effect, so it is important to perform validation for the study site.

Validation of satellite measurements against ground measurements is challenging for a number of reasons including: i) the lack of exactly coincident measurements, ii) differences in cloud screening, iii) different measurement variables, and iv) the fundamental difference between areally integrated measures from satellites and point-based measurements from ground instruments. The Ichoku et al. (2002) spatio-temporal subset approach for validation is used here, comparing a spatial subset from the satellite data (5 x 5 pixels) with a temporal subset from ground measurements (±30 minutes). Ichoku et al. (2002) justified the size of these subsets based upon an estimate of average aerosol front speed, the requirement to obtain a statistically-significant sample size, and the observation that larger window sizes could introduce errors from cloudy pixels and changing topography.

2.1 *AERONET Sun Photometry*

Sun photometers estimate AOT and PWC based upon measurements of solar irradiance in a number of wavelengths. Here we use automatically cloud-screened data (Level 1.5) collected by the AERONET Cimel CE-318 sun photometer situated at the Chilbolton Faciity for Atmospheric and Radio Research (CFARR) (Holben et al. 1998). We used a simple time-for-space substitution to obtain an estimate of the spatial variability over the whole area from this single point measurement, by taking the AERONET measurements over the entire daylight period and assuming that they are representative of the AOT across the whole study area.

Sun photometers are used as reference data within this study, as they are currently the most accurate method for measuring AOT (Wang et al. 2009). Errors are low: approximately ±0.02 for AOT (Eck et al. 1999), and with an PWC RMSE of 2.9 mm (Liu et al. 2011).

The time-for-space assumption was examined by modelling the passage of aerosol particles across the UK during the study period using the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT; Draxler and Rolph 2003), using gridded one degree resolution meteorological data from the NCEP Global Data Assimilation System archive (Kalnay et al. 1996). The model was parameterised to simulate an ensemble of possible back-trajectories for a single particle located above the AERONET site at 19:00 UTC back to its starting location at 05:00 UTC (the start and end times of the AERONET data during the study period). Simulations were run for particles at heights of 500m, 1000m and 1500m to capture the differing trajectories produced by height-varying winds. These heights were chosen based upon the finding of Matthias et al. (2004) that 80–90% of the AOT is produced by aerosols in the planetary boundary layer, which was found to be at a height of 1204 ± 481m at the Aberystwyth station, located approximately 100km outside the study area.

A simple 'contributing area' for the AERONET site was then calculated as the concave hull of the resulting trajectories. These estimated areas for the 16th and 17th June 2006 (Figure 1) show that the time-for-space substitution covered 23% and 19% of the study area on the 16th and 17th respectively. The contributing

Table 1. Summary of characteristics and accuracy of all data sources considered

Source	Type	Spatial Resolution	Temporal Resolution	Official validation	Study area validation	Closest aquisition time
AERONET	Ground	One location	Every 15 minutes, in good weather	±0.02	—	09:37
Met Office	Ground	36 stations across study area	Hourly	—	RMSE: 0.05–0.47 (for visibilities 40–10km)	10:00
MODIS AOT (MOD04)	Satellite	10km	Daily merged *or* once per orbit	$\pm 0.05 \pm 0.15\tau$	No sig difference	16th: 11:34 17th: 10:38
GlobAerosol	Multi-Satellite	10km	Daily	RMSE: 0.12	16th: No sig difference 17th: Sig difference	Daily
MODIS PWC (MOD05)	Satellite	1km	Daily merged *or* once per orbit	RMSE: 1.7mm	16th: No sig difference 17th: Sig difference	16th: 11:34 17th: 10:38
BIGF Water Vapour	Ground	25 stations across study area	Hourly	—	RMSE: 1.5mm	10:00

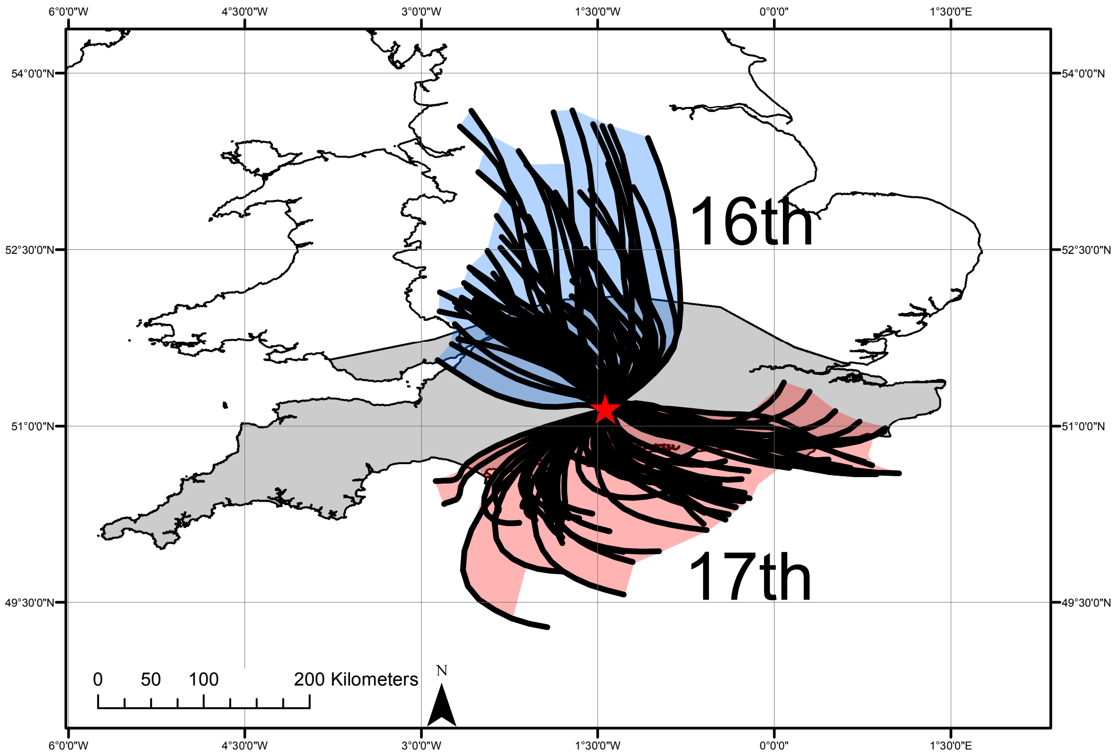


Figure 1. Estimates of 'contributing areas' for the Chilbolton AERONET site for the 16th and 17th June 2006 in blue and red respectively, with the study area shown in grey. The black lines show the individual trajectories towards Chilbolton, Hampshire (marked with a red star) computed by HYSPLIT using the ensemble mode with heights of 500m, 1000m and 1500m above ground level.

area for each day was very different due to contrasting meteorological conditions, and a large proportion of the contributing area was outside of the study area (62% and 63% respectively).

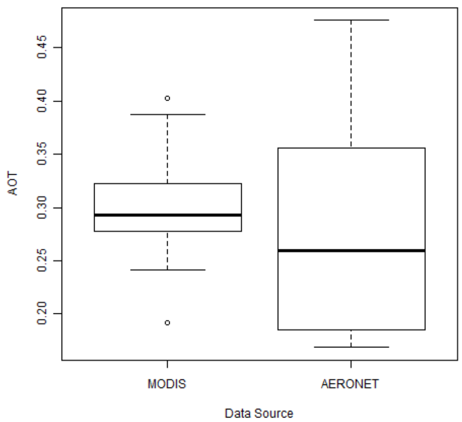
2.2 *Met Office Visiometry*

AOT was estimated from hourly measurements of horizontal visibility (accurate to ±10%) acquired by a network of UK Met Office stations across the study area (UK Met Office 2006) using Koschmieder's equation (Koschmieder 1925; Horvath 1981):

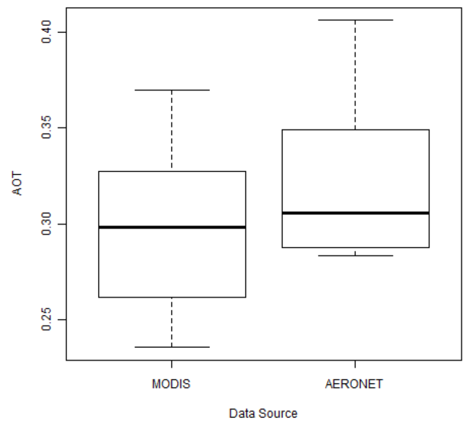
$$V = \frac{3.912}{\tau} \quad (1)$$

where V is the visibility in km and τ is the AOT.

Koschmieder's equation relates horizontal visibility and horizontal extinction coefficient measurements, but is now widely used for calculating vertical extinction coefficients (that is, AOT) from horizontal visibility. This mixing of horizontal and vertical measurements relies on many assumptions which are often invalid (Chan 2009), and there are broader issues with the choice of coefficients in the equation (Middleton 1952; Horvath 1971, 1981). Previous studies comparing AOT and visibility-based estimates of AOT, have found correlations ranging from 0.38 (So, Cheng, and Tsui 2005) to 0.89 (Chen et al. 2009). However, despite these limitations, visibility-based estimates of AOT are still useful due to their high spatial



(a) 16th June 2006



(b) 17th June 2006

Figure 2. Boxplots showing the summary statistics for the validation of the MODIS AOT product against AERONET

and temporal resolutions as well as the wide availability of data collected according to World Meteorological Organisation standards.

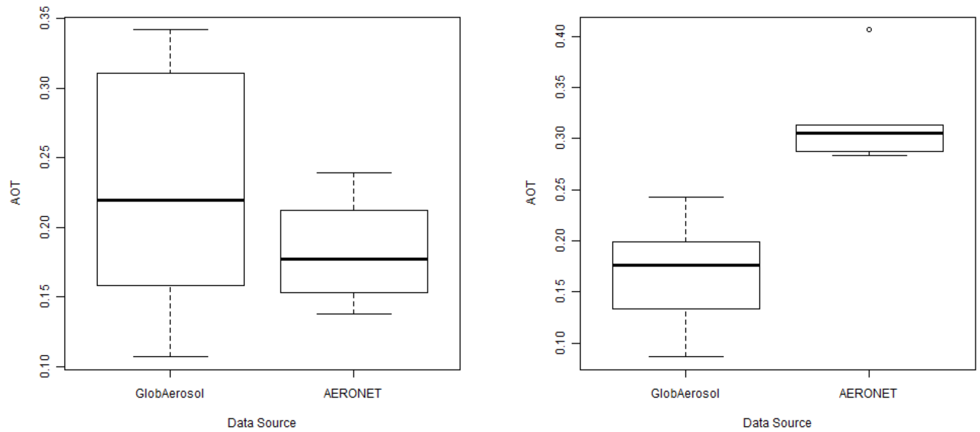
2.3 *MODIS AOT (MOD04)*

The MOD04 product from the MODIS sensors on the Terra and Aqua satellites provides AOT estimates at 10km resolution using an algorithm based on short-wave infra-red measurements and the use of a Radiative Transfer Model lookup table (Remer et al. 2006). The official MODIS validation report for the latest version of the algorithm (Collection 5.1) (Remer et al. 2006) states that 67% of the retrievals were within the expected uncertainty ($\pm 0.05 \pm 0.15\tau$), which has been confirmed by independent validations (Levy et al. 2010). Results improve when only pixels with the highest Quality Assurance Confidence were used, as in this study. Many assessments of MOD04 accuracy in the literature are based upon previous versions of the algorithm (Collection 4), but the current algorithm (Collection 5.1) has significantly improved the accuracy. The accuracy is seasonally-variable (El-Metwally et al. 2010), likely due to the seasonal changes in aerosol types present over some of the sites used in their study.

Validation for the study area was performed between the MOD04 product and the AERONET site at Chilbolton using the Ichoku et al. (2002) method (Figure 2). Results from t-tests showed that there was no significant difference between the samples obtained from MODIS and AERONET ($p = 0.83$ and $p = 0.28$ for the 16th and 17th respectively), and thus they are likely to have come from the same distribution of AOT values.

2.4 *GlobAerosol*

The GlobAerosol product is produced by merging AOT products from the ATSR-2, AATSR, MERIS and SEVERI sensors (Thomas et al. 2010), at a 10km resolution. Poor data are excluded based upon a number of checks, and merging is performed using temporal interpolation, with observations weighted by their error estimates (Siddans et al. 2007). The official validation against AERONET measurements found that the AATSR-derived dataset was most accurate, with a RMSE of 0.07



(a) 16th June 2006 (b) 17th June 2006

Figure 3. Boxplots showing the summary statistics for the validation of the GlobAerosol product against AERONET

(Poulsen et al. 2009). Although the merged product has a lower accuracy (Poulsen et al. 2009), the major advantage is that the merging process ensures higher spatial coverage of the area.

A comparison between the GlobAerosol merged product and the AERONET site at Chilbolton (Figure 3) show a smaller difference between AERONET and GlobAerosol measurements on the 16th than on the 17th June. Results from t-tests indicate that there was a significant difference between the AOT samples from MODIS and AERONET on the 17th ($p = 0.0008$), but no significant difference on the 16th ($p = 0.20$).

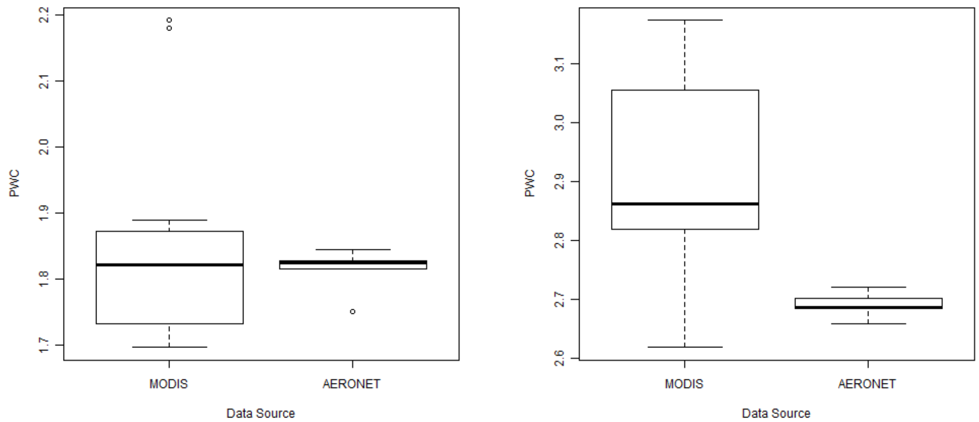
2.5 *MODIS PWC (MOD05)*

The MOD05 product provides PWC estimates at 1km resolution, based upon a ratio of adjacent bands with and without water absorption features. Official validation for the MODIS water vapour product is limited (Gao and Kaufman 2003), with a RMSE based on a microwave radiometer dataset of 1.7mm, corresponding to an approximate 5–15% error for the PWC range found over southern England (10–40mm). Comparisons of the MOD05 PWC estimates to radiosonde and GPS-based measurements at Herstmonceux in southern England (50.889 N, 0.324 E) found a positive bias of 10% and 7% respectively (Li, Muller, and Cross 2003), and comparisons in the Tibetan Plateau produced a similar result to the official validation (1.95mm RMSE).

Validation between the satellite data and the AERONET PWC measurements at Chilbolton (Figure 4) indicated similar relationships between the spatial and temporal subsets on the 16th ($p = 0.437$), but not on the 17th ($p = 0.004$, as found with the other datasets. Again, the satellite data has a larger range, but on both days the AERONET data were encompassed within this range.

2.6 *GPS Water Vapour*

Measurements of delays in the GPS L-band radio signals passing through the atmosphere can be used to quantify the water vapour in the atmosphere above the GPS receiver (Bevis et al. 1992). The British Isles Continuous GNSS Facility (BIGF;



(a) 16th June 2006 (b) 17th June 2006

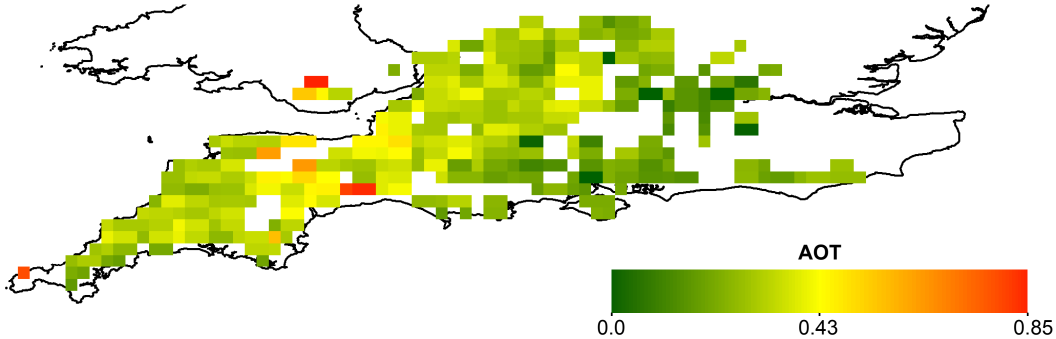
Figure 4. Boxplots showing the summary statistics for the validation of the MODIS Water Vapour product against AERONET

Natural Environment Research Council 2012) uses these methods to provide estimates of integrated water vapour at all BIGF stations on an hourly basis. Previous validations of GPS-derived water vapour estimates against radiosonde and satellite data have generally produced errors of 1–2mm (Becker et al. 2003; Wang et al. 2007; Wolfe and Gutman 2000; Tregoning et al. 1998). However, all the data used in these validations were processed from the GPS data by the authors, with specific parameterisations for the area of study. The BIGF product is a national operational product, and thus may be expected to have a lower accuracy.

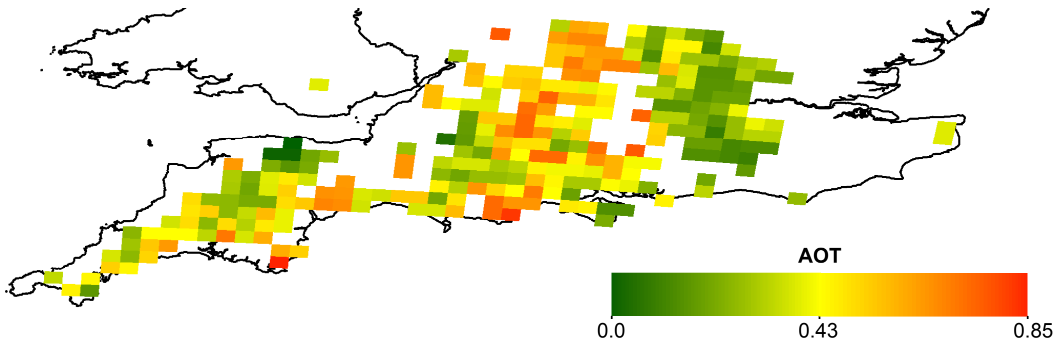
A BIGF measurement site is co-located with the AERONET site at Chilbolton, and validation for all days with at least two matching measurements in the period August 2009–November 2010 produced an average daily RMSE of 1.5mm, with a maximum of 6.3mm, and a Pearson correlation coefficient of 0.976, showing a good agreement between GPS-derived and AERONET-derived estimates.

3. Simulation of uniform atmospheric corrections

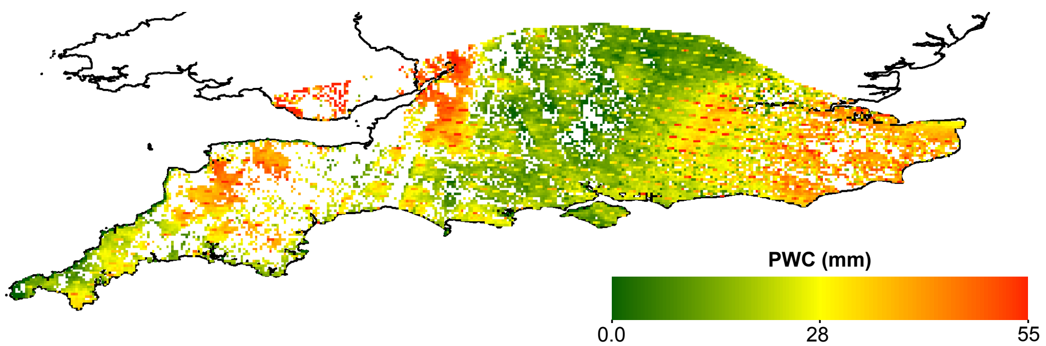
The 6S radiative transfer model (Vermote et al. 1997b) was used to simulate a uniform atmospheric correction over southern England, using the data on spatial variability described above. The Py6S (Wilson 2012) interface to 6S was used to allow hundreds of individual simulations to be run in an automated manner. Simulations were run in two stages: first to generate a top-of-atmosphere (TOA) radiance from a representative vegetation spectrum under a given set of atmospheric parameters (P_{up}), and second to atmospherically correct the TOA radiance to a ground reflectance under a different set of atmospheric parameters (P_{down}). P_{up} was set to the 5% or 95% quantile of the AOT or PWC values and P_{down} was set to the mean of the AOT or PWC values (from Tables 2 and 3), thus simulating the uniform atmospheric correction of a pixel measurement which was actually acquired in extreme conditions. Simulations were performed for Landsat bands 1-4, and 6S parameters other than AOT and PWC were set to appropriate values for southern England. Results from the simulations were retrieved as reflectance values. To assess the effect on a standard remote-sensing product, NDVI was also calculated from these reflectances.



(a) GlobAerosol



(b) MODIS AOT (MOD04)



(c) MODIS PWC (MOD05)

Figure 5. Examples of the three satellite data products used in this study. All images are from the 16th June 2006.

The errors resulting from a uniform atmospheric correction are conceptually the same as the errors resulting from uncertainty in the atmospheric parameters: both are caused by differences between the true parameter value and the value used for correction. Thus, a sensitivity analysis was also performed to assess the effects of the uncertainties of the data sources (as listed in Table 1) on remote sensing products.

Table 2. Summary statistics showing the range of AOT values across southern England during the study period for each data source. Q05 and Q95 are the 5% and 95% quantiles respectively.

(a) 16th June 2006

Source	Min	Max	Mean	Q05	Q95
AERONET	0.120	1.130	0.291	0.156	0.464
Met Office	0.156	0.391	0.260	0.156	0.391
GlobAerosol	0.071	0.496	0.287	0.155	0.417
MODIS	0.078	0.460	0.258	0.139	0.398

(b) 17th June 2006

Source	Min	Max	Mean	Q05	Q95
AERONET	0.153	0.436	0.216	0.160	0.332
Met Office	0.145	0.559	0.296	0.175	0.489
GlobAerosol	0.050	0.338	0.164	0.082	0.258
MODIS	0.063	0.440	0.223	0.090	0.386

Table 3. Summary statistics showing the range of PWC (in cm) across southern England during the study period for each data source. Q05 and Q95 are the 5% and 95% quantiles respectively.

(a) 16th June 2006

Source	Min	Max	Mean	Q95	Q05
AERONET	1.433	2.257	1.859	2.236	1.486
BIGF	1.750	2.820	2.138	2.565	1.813
MODIS	0.212	5.588	2.180	2.772	1.646

(b) 17th June 2006

Source	Min	Max	Mean	Q95	Q05
AERONET	1.892	2.724	2.433	2.688	1.975
BIGF	1.820	3.250	2.676	3.190	1.904
MODIS	1.458	6.218	2.763	3.379	1.995

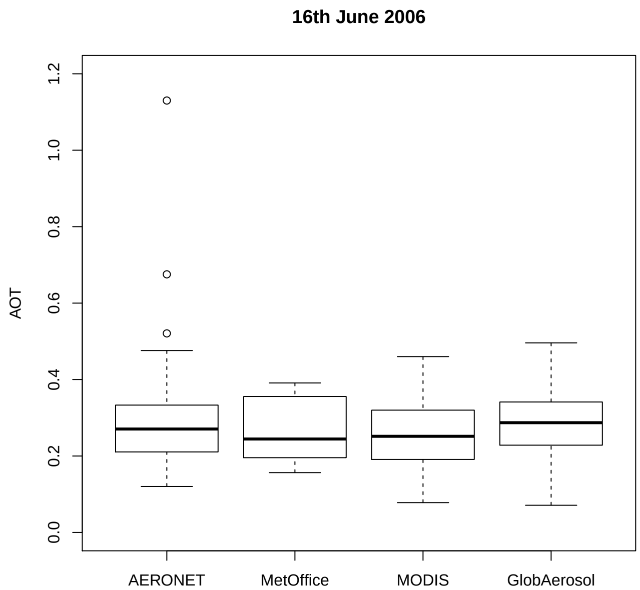
Table 4. Effects of a uniform atmospheric correction performed over an area with the AOT variability from each data source. Values in the table are the reflectance differences for [95% perturbation; 5% perturbation], with reflectance values in percent. Note that increases in AOT (using the 95% percentile of the AOT data from the datasource) cause increases in reflectances for all bands, but a decrease in NDVI.

(a) 16th June 2006

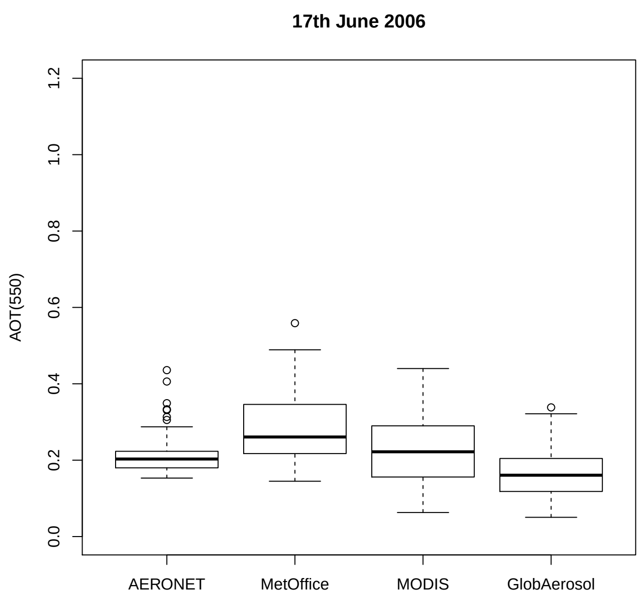
Source	$\rho_{\mathbf{B}}$	$\rho_{\mathbf{G}}$	$\rho_{\mathbf{R}}$	$\rho_{\mathbf{NIR}}$	NDVI
AERONET	+1.3; -1.0	+1.1; -0.8	+1.0; -0.8	+0.1; -0.1	-0.026; 0.027
Met Office	+1.0; -0.8	+0.8; -0.6	+0.7; -0.6	+0.1; -0.1	-0.017; 0.022
GlobAerosol	+1.0; -1.0	+0.8; -0.8	+0.7; -0.7	+0.1; -0.1	-0.018; 0.027
MODIS	+1.1; -0.9	+0.9; -0.7	+0.8; -0.7	+0.1; -0.1	-0.019; 0.024

(b) 17th June 2006

Source	$\rho_{\mathbf{B}}$	$\rho_{\mathbf{G}}$	$\rho_{\mathbf{R}}$	$\rho_{\mathbf{NIR}}$	NDVI
AERONET	+0.9; -0.4	+0.7; -0.4	+0.6; -0.3	+0.1; -0.1	-0.014; +0.014
Met Office	+1.5; -0.9	+1.2; -0.8	+1.1; -0.7	+0.1; -0.1	-0.030; +0.025
GlobAerosol	+0.7; -0.6	+0.6; -0.5	+0.5; -0.5	+0.1; -0.2	-0.009; +0.017
MODIS	+1.2; -1.0	+1.0; -0.8	+0.9; -0.7	+0.1; -0.2	-0.022; +0.025



(a) 16th June



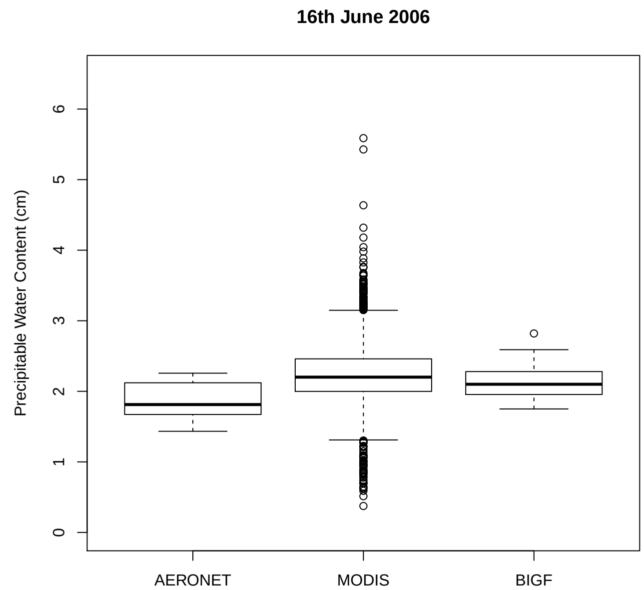
(b) 17th June

Figure 6. Boxplots showing the range of AOT values found over southern England during the study period according to each data source.

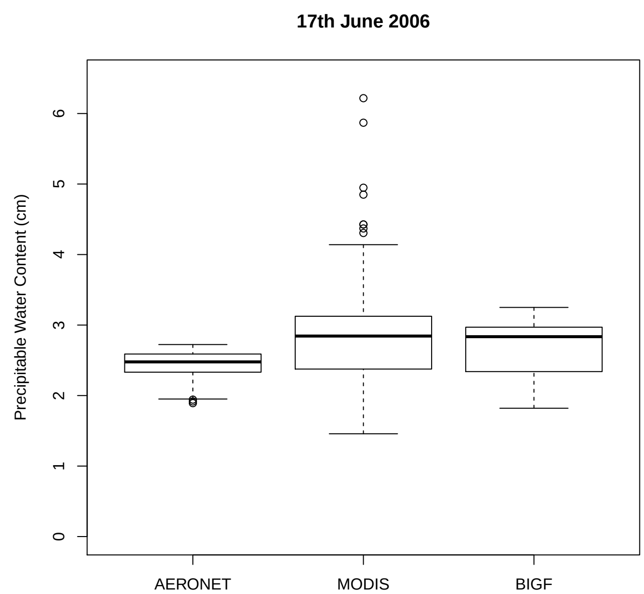
4. Spatial variability over the study area

4.1 *Aerosol Optical Thickness*

The AOT range over the study area on the 16th and 17th June 2006 was approximately 0.1–0.5 (Table 2). This is large, given that these measurements were acquired on days which had mostly clear skies across the study area, and shows that



(a) 16th June



(b) 17th June

Figure 7. Boxplots showing the range of PWC values found over southern England during the study period according to each data source.

there is more spatial variability in AOT than visual examination of sky conditions suggests.

The overall range in AOT was similar each day, but all data sources have significantly higher variability on the 17th (Figure 6). This is consistent with the more changeable weather conditions on the 17th, as noted by the records from the NCAVEO Field Campaign (Milton et al. 2011). Similarly, the median values for

Table 5. Effects of a uniform atmospheric correction performed over an area with the PWC variability from each data source. Values in the table are the differences from the true results for [95% perturbation; 5% perturbation], and reflectance values are in percent. ρ_{B}, ρ_{G}, ρ_{R} and ρ_{NIR} are the reflectances in the Landsat blue, green, red and NIR bands respectively.

(a) 16th June 2006

Source	$\rho_{\mathbf{B}}$	$\rho_{\mathbf{G}}$	$\rho_{\mathbf{R}}$	$\rho_{\mathbf{NIR}}$	**NDVI**
AERONET	0.00; 0.00	-0.02; +0.02	-0.02; +0.02	-0.37; +0.40	-0.002; +0.002
BIGF	0.00; 0.00	-0.02; +0.01	-0.02; +0.02	-0.39; +0.32	-0.002; +0.002
MODIS	0.00; 0.00	-0.03; +0.02	-0.03; +0.02	-0.49; +0.44	-0.003; +0.006

(b) 17th June 2006

Source	$\rho_{\mathbf{B}}$	$\rho_{\mathbf{G}}$	$\rho_{\mathbf{R}}$	$\rho_{\mathbf{NIR}}$	**NDVI**
AERONET	0.00; 0.00	-0.01; +0.02	-0.01; +0.02	-0.22; +0.43	-0.001; +0.002
BIGF	0.00; 0.00	-0.02; +0.04	-0.02; +0.04	-0.41; +0.72	-0.002; +0.004
MODIS	0.00; 0.00	-0.03; +0.03	-0.03; +0.04	-0.49; +0.70	-0.003; +0.007

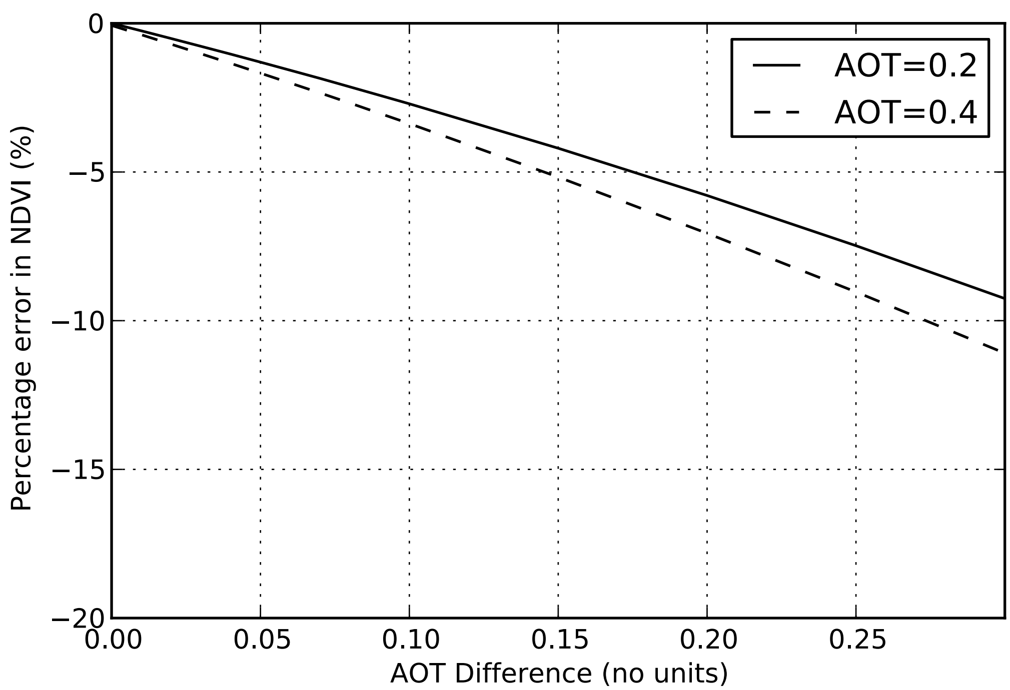


Figure 8. Sensitivity analysis showing percentage change in NDVI caused by correcting a standard green vegetation spectrum with a erroneous AOT value, for two standard AOT values (0.2, corresponding to a visibility of around 20km; and 0.4, corresponding to a visibility of around 10km). The x-axis shows the difference between the true AOT and the AOT used for correcting, and the y-axis shows the resulting error.

each dataset are very similar on the 16th, but not on the 17th. In all cases the satellite-based datasets (MODIS and GlobAerosol) have a lower minimum, which is likely to be due to errors in separating the at-sensor radiance into the ground reflectance and aerosol scattering components.

The AOT data obtained from Met Office visibility measurements has a similar range to the other datasets on the 16th, but over-estimates the AOT on the 17th. This is likely caused by failure of the assumptions inherent in the visibility to AOT conversion due to the meteorological conditions. For example, local conditions could reduce horizontal visibility at ground-level, but not significantly affect the vertical extinction coefficient measured by AOT.

Generally the AERONET measurements have the lowest inter-quartile range (16th: 0.12, 17th: 0.04) due to the time-for-space substitution not capturing the variability across the entire study area, but have a number of high outliers (including a value of 1.13 on the 16th). These outliers are likely to be due to poor performance of the automated cloud screening algorithm used for the level 1.5 data, which performs relatively poorly for large areas of temporally and spatially homogeneous cloud (Smirnov et al. 2000).

4.2 *Precipitable Water Content*

The range agreement between the data sources for PWC is weaker than for the AOT datasets (Figure 7), but an approximate range for PWC, taking into account expected values (Randel et al. 1996) and obvious outliers on the 16th is approximately 1.5–3.0 cm on the 16th and around 2.0–3.5 cm on the 17th (Table 3). The larger values on the 17th were likely caused by the southerly/south-westerly winds bringing moist air-masses from the Atlantic Ocean over the study area. Again, the satellite data had the largest range, with many outliers for MODIS on the 16th June. High outliers may have been caused by incorrect cloud-screening (as clouds will have a significantly higher PWC) but the very low values (a minimum of 0.2 cm for MODIS) may be plausible in certain areas (a maximum PWC of 3 mm was found in Norway by Mook 1978). The MODIS PWC dataset has a significantly higher resolution than the AOT datasets (1 km compared to 10 km) and is likely to record more small-scale variation that would be averaged out in a lower-resolution dataset, and thus have a larger range. The BIGF data compares well with the other datasets, with a smaller range than MODIS but similar inter-quartile ranges, showing the utility of this relatively-new measurement approach.

4.3 *Summary*

All data sources confirm that the AOT and PWC over the study area was not uniform during the study period. As there were mainly clear skies during this time it is likely that the measured variability is a ‘best case’ scenario and that AOT variability will be greater in other situations. Thus, the assumption of atmospheric spatial uniformity made by atmospheric correction methods is not valid across a large area in southern England, and probably other mid-latitude areas.

5. Effects of uniform atmospheric correction

To estimate the implications of uniform atmospheric correction we used the 5% and 95% quantiles of AOT and PWC measured over the study period (as they represent the ‘extreme’ values that affect 10% of the pixels in the image) to simulate the effects of a uniform atmospheric correction for these ‘extreme’ pixels.

5.1 *Aerosol Optical Thickness*

The results of the Radiative Transfer Model simulations show that atmospheric correction of data acquired under a high AOT and corrected with a lower AOT

Table 6. Noise Equivalent Delta Radiance (NEΔL) and Noise Equivalent Delta Reflectance (NE$\Delta\rho$) for the visible and near infra-red Landsat bands under the simulation conditions.

	Blue	**Green**	**Red**	**NIR**
NEΔL	1.11	0.85	0.89	0.61
NE$\Delta\rho$	0.056	0.046	0.057	0.058
NE$\Delta\rho$/Error	26.6	26.1	19.1	3.4

produces erroneously high reflectances (Table 4). This is due to the increased scattering caused by the aerosols which was not corrected by the atmospheric correction. The error has a significant spectral dependence, with higher errors for lower wavelengths (blue) and very low errors for high wavelengths (NIR), and an overall range of 0.1-1.3 percentage points of reflectance. In this situation, the NDVI decreased, as the red reflectance increased relative to the NIR reflectance. The absolute NDVI difference was low, but the percentage error reached 5% for the Met Office dataset on the 17th June. Even relatively small errors in NDVI may affect derived products such as estimates of biomass production, for example, Kaufman and Holben (1993) found that a NDVI difference of 0.04 corresponded to biomass production errors of 11–30%.

To put these errors in context: the Noise Equivalent Delta Radiance ($NE\Delta L$) and equivalent Noise Equivalent Delta Reflectance ($NE\Delta\rho$) were calculated for each Landsat band under the simulation conditions, using the $NE\Delta\rho$ formula and data in Scaramuzza et al. (2004) (Table 6). The errors due to a uniform atmospheric (Table 4) are significant, at almost thirty times more than the NE$\Delta\rho$ for bands 1 and 2, approximately twenty times more for band 3 and three times more for band 4.

5.2 *Precipitable Water Content*

The reflectance differences caused by PWC perturbations are significantly smaller than those for AOT perturbations, with a maximum error of 0.5 percentage points in the NIR and 0.02 percentage points in the visible (Table 5). They have the opposite spectral dependence to the differences due to AOT, with low errors at short wavelengths, but high errors at longer wavelengths. This is because most multi-spectral satellite bands are deliberately located away from areas of the spectrum which experience significant water absorption, but Landsat band 4 (NIR, 0.76-0.90μm) covers a water absorption feature (Gao and Goetz 1990). Although there is a differing effect between the NIR and red bands, it is not as significant as with the AOT perturbations, and thus the NDVI differences are much lower (with a maximum of 0.007).

5.3 *Sensitivity Analysis*

The sensitivity analysis (Figure 8) shows the how errors in AOT propogate to the resulting NDVI values for a range of errors. Comparing the results to the uncertainties of each dataset (Table 1) shows that there is a serious problem in using these datasets to provide AOT values for use in atmospheric correction procedures. The NDVI changes resulting from the official error estimates for each of the AOT data sources (Table 7), generate errors ranging from 2% to 7% for all data sources except AERONET. The effect of the AERONET error on NDVI is acceptable at less than 1%. This suggests that only AERONET data should be used for parameterising atmospheric correction models, but this research has also shown that a fully spatially variable correction is needed, and as AERONET sites are sparsely distributed this is not possible. The errors shown in this sensitivity analysis are a result of inaccuracies in the AOT data sources, and have no relationship to the uniform atmospheric correction issues that our main study focuses on. Thus, these errors could occur in any atmospheric correction that uses visibility, MODIS or GlobAerosol data to obtain the AOT input, regardless of whether the atmosphere is spatially uniform or variable.

5.4 *Summary*

Performing a uniform atmospheric correction for water vapour does not introduce unacceptable errors in reflectance or NDVI, with a maximum error of 0.7 percentage points and 0.6% respectively. Further simulations have shown that even in areas with very high water vapour amounts, such as tropical rainforests, NDVI values are unlikely to be significantly affected by variability in water vapour unless that variability approaches 80% of the mean value.

In contrast, performing a uniform atmospheric correction over a spatially-variable AOT distribution may cause errors in reflectance of up to 1.5 percentage points, and errors of 5% in NDVI values. Overall 5% of the pixels in the image may have a reflectance error $> +1.5$ percentage points, and another 5% of the pixels may have an error < -1.0 percentage points. To put this in context, 10% of the pixels in a Landsat image is approximately 3.8 million pixels, covering an area of approximately 3,500km^2.

Table 7. Resulting error in NDVI caused by AOT uncertainties (according to the official validation) for each data source, for AOTs of 0.2 and 0.4

	NDVI Error (%)	
Data Source	**AOT = 0.2**	**AOT = 0.4**
AERONET	0.51	0.70
MetOffice	3.37	7.06
GlobAerosol	3.29	4.08
MODIS	2.13	3.72

6. Conclusions

The spatial variability of the atmosphere over southern England was investigated by acquiring data on the Aerosol Optical Thickness (AOT) and Precipitable Water Content (PWC) from a wide range of ground- and satellite-based sources on two clear days. All data sources except the AERONET network of ground-based sun photometers had high uncertainty, but it was possible to extract a range of AOT and PWC over the study area for each day of 0.1–0.5 and 1.5–3.0 cm respectively. These ranges show that there is significant variation in these properties across this area.

The errors which would be caused by performing a uniform atmospheric correction over the study area were assessed through simulations using Py6S. These showed that ignoring the spatial variation in AOT when performing atmospheric corrections could cause errors in reflectance and NDVI of up 1.3 percentage points and 5% respectively, but that ignoring spatial variation in PWC caused maximum errors of 0.7 percentage points and 0.6% respectively (an acceptable error primarily due to the strategic location of multispectral sensor bands away from water absorption features).

In conclusion, the results from this study show that there is significant variation in AOT and PWC across southern England during clear days.The variation in PWC is not significant in terms of the errors resulting from a uniform atmospheric correction, but ignoring the variation in AOT by performing a uniform atmospheric correction could cause significant errors (reflectance errors of over twenty times the NE$\Delta\rho$, and NDVI changes > 0.03). (reflectance errors of over twenty times the NE$\Delta\rho$, and NDVI changes > 0.03). The widespread availability of scene-based atmospheric correction procedures in modern image processing systems invites users to disregard spatial variability in the atmosphere and risks introducing significant errors into key derived products.

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