Observation of the Earth system with Meteosat Second Generation

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ABSTRACT
The geostationary location of the Meteosat Second Generation (MSG) satellites is ideal for examining the properties of the Earth’s surface and atmosphere over both long and short timescales. The high temporal resolution of the SEVIRI instrument aboard MSG provides a unique opportunity to examine diurnal trends in soil moisture, land surface temperature, cloud cover and also highly dynamic events such as floods and dust storms. On a longer timescale the fixed satellite position is useful for monitoring seasonal vegetation growth and drought events as well as climatic changes such as shifting land cover and differences in the amount of water vapour present in the atmosphere. Here we summarise the use of SEVIRI products generated at the University of Copenhagen and external data from the Land-SAF and NWC-SAF facilities for examining such variables. The new possibilities opened up by the upcoming Meteosat Third Generation (MTG) satellites are also discussed.

INTRODUCTION
The Spinning Enhanced Visible and InfraRed Imager (SEVIRI) aboard Meteosat Second Generation (MSG) is a multi-spectral sensor, imaging across the visible and near-IR, which provides data with a high temporal resolution of one image per 15 minutes (Schmetz et al, 2002). Because the MSG satellites are located in geostationary orbit the SEVIRI has a very wide field of view that covers Europe, Africa, South America and the Atlantic Ocean. Although the main use of MSG is to provide data of use to meteorologists it also serves a broad range secondary purposes that include analysis of surface albedo (Geiger et al, 2008), plant growth (Proud and Rasmussen, 2011), sea surface characteristics (Merchant et al, 2009) and flood detection (Proud et al, 2011). The use of MSG data for these purposes is helped by the EUMETCAST system that allows SEVIRI data to be received by interested parties in near-real-time. The University of Copenhagen (KU), Denmark, operates a EUMETCAST receiving station that has, over time, built up an archive of over 7 years of SEVIRI data. Initially this data was limited to coverage of the African continent but in recent years the field of regard has been expanded to include the full SEVIRI disk. Efforts are ongoing to back-process the archived data for this expanded region. At KU the main use for this data is in land surface analysis, with a focus on plant and crop growth in Africa and Southern Europe. A second major area of research is the effects of climate change – particularly in sub-Saharan Africa where small changes in environmental conditions can induce a large change in the characteristics of the land surface itself. Our research requires estimates of a number of variables that includes: Land Surface Temperature (LST), surface reflectance (BRDF), soil moisture, evapotranspiration and rainfall.

PRE-PROCESSING
Before use in estimating these variables, the SEVIRI data received at KU is converted into reflectance values (for channels 1, 2 and 3, the solar channels) or brightness temperature values (for the remaining channels except HRV, which is unused). Data from the solar channels is then atmospherically corrected using a substantially modified version of the SMAC algorithm (Proud et al, 2010) in order to minimise the effects of both atmospheric gases such as ozone and of aerosol contamination. It has been found that the SMAC algorithm can be unsuitable for use on data where the View Zenith Angle (VZA) is greater than 65°, which for MSG would mean that data gathered for Northern Europe, parts of South America and parts of the Middle East is invalid. Nevertheless, this high-VZA region still produces accurate results under many atmospheric conditions and so we have chosen not to mask-out this area but rather to indicate in the associated quality analysis that the results may be sub-nominal.
In addition to this data processing, KU also operates the software package maintained by the Satellite Applications Facility in support of Nowcasting and very short-range Weather forecasting (NWCSAF). This software uses both SEVIRI data and weather forecasts (NWP) to produce a variety of data products describing the state of the Earth’s atmosphere (Fernandez et al, 1999). The package is
modular, meaning that the user can choose which data products to produce as well as the region of interest. At KU we produce the cloud mask (PGE01); cloud type and phase (PGE02); cloud temperature, height and pressure (PGE03); precipitating clouds (PGE04); convective rainfall rate (PGE05); rapid development thunderstorms (PGE11) and atmospheric clear-sky physical retrieval (PGE13) products. We use these products for analysis of land-atmosphere interactions and flood prediction, and plan to expand into using this data for analysis of the atmosphere itself — primarily in deep convective storms. As well as this we also use the NWC-SAF data within the SMAC and LST algorithms as they requires an estimate of the atmospheric water vapour content. Lastly, the cloud mask is used to ensure that only clear-sky pixels are included in our land-surface analyses. We have slightly modified the land/water mask used by the SAF-NWC software in order to produce better results in areas with many small rivers or lakes, such as central Africa. Aside from that we have not modified the software from the standard v2012 distribution and we use the recommended NWP data that is provided by the European Centre for Medium range Weather Forecasting (ECMWF).

Land Surface Reflectance
Due to the prevalence of clouds, polar orbiting sensors, such as MODIS, have great difficulty in retrieving clear-sky solar reflectances in regions such as central Africa and the South American rainforests. In some cases several months may pass between consecutive clear-sky images. The high temporal resolution of SEVIRI can help overcome this problem as, in the same amount of time, it will produce many more images of a given area than a polar orbiting sensor — thus increasing the chance of gaining at least one clear-sky image (Fensholt et al, 2011). However, the geostationary location does present a problem: Regions that are far from the sub-satellite point can have large view zenith angles (VZA), something that can dramatically affect the measured reflectance — known as anisotropy. It is therefore necessary to normalise these VZAs to a common scene geometry, so minimising the reflectance anisotropy. At KU we use a customised version of the MODIS Bidirectional Reflectance Distribution Function (DB-BRDF) to normalise the scene geometry (Schaaf et al, 2002).

The BRDF algorithm for SEVIRI has been modified to work with a time series of 5-days of data, with the most recent day being at full temporal resolution (15min) and the remaining days at half resolution (30min) to give a total of 288 input images. Atmospherically corrected reflectances in the three solar channels (Ch 1, 2 and 3) are ingested alongside data on the view and solar angles for each pixel. The algorithm then outputs a series of BRDF-parameters that describe how the reflectance varies as a function of scene geometry, a process known as BRDF inversion. Finally, the parameters are used to generate a set of normalised reflectances for each pixel in which we set the viewing angle to nadir and the solar angle equal to local solar noon — an example of this is shown in Figure 1. Validation is
ongoing but initial results are promising – the relative error compared to the MODIS BRDF is less than 12% for all channels and the majority of pixels in Africa display errors of less than 5%. Pixels at very high VZA, such as Northern Europe, show the largest difference to MODIS – something that suggests that the BRDF algorithm is not entirely successful at normalising reflectances under these extreme scene geometries. It is possible that by assimilating data from polar sensors, such as those aboard the NOAA and MetOp satellites, the accuracy can be improved in these high VZA areas. Aside from the good accuracy of the SEVIRI normalised reflectances another important point is that the high temporal resolution does indeed produce more frequent clear sky images than is possible with MODIS. The BRDF algorithm requires a minimum number of looks at the land surface in order to function correctly, so by analysing the number of successful BRDF inversions it is possible to compare the relative success of SEVIRI and MODIS. MODIS generates a BRDF using 16-days of data, yet over the whole of 2008 can only retrieve a BRDF successfully in 50.12% cases, averaged over all pixels in the SEVIRI full disk. The SEVIRI BRDF operating on a daily basis retrieved a successful BRDF in 64.01% of cases whilst on a 16-day timescale the success rate increases to 87.09%.

Vegetation Indices

An important use for SEVIRI data at KU is vegetation analysis with a focus on monitoring the spatial and temporal trends in vegetation growth across Africa as well as the driving forces behind any changes that are found. By using indices such as the Normalised Difference Vegetation Index, NDVI (Tucker, 1979), it is possible to measure the amount of green-ness on the land surface and hence estimate vegetation activity. We generate NDVI from the normalised reflectances produced by the BRDF, giving us a daily vegetation estimate across the full SEVIRI disk. As well as the validation that is ongoing for the BRDF products we are also performing a separate validation of NDVI in comparison to data both from other satellites and from a number of field sites across Africa. Figure 2 shows the NDVI for a KU field site in Dahra, Senegal – a semi arid region that displays strong seasonal trends in vegetation growth. Overall there is very good agreement between the field and satellite measurements with very little noise being shown in the SEVIRI data series. However, there are numerous points where there are large disagreements in the data. During the rainy season these are likely due to cloud contamination that has not been identified by the MPEF or NWCSAF cloud-masks. Towards the end of the season there is a period where the SEVIRI NDVI is substantially higher than the field values; this is due to scaling issues between the field site and the much larger MSG pixel.

Figure 2: A time series for the Dahra field site that compares in-situ NDVI to that from SEVIRI for 2008.

The PGE13 SEVIRI Physical Retrieval

The NWCSAF PGE13 SPhR product contains a physical retrieval of atmospheric profiles of temperature and moisture. One of its outputs is the Total Precipitable Water vapour (TPW) from the surface to the top of the atmosphere. PGE 13 SPhR is based on an error minimization between the observed brightness temperatures of the 6 thermal channels of SEVIRI and the brightness temperatures simulated with RTTOV (Saunders et al. 2005). This process consists on an iterative
minimization procedure which is initialized based on a first guess profile from a Numerical Weather Prediction (NWP) model. Also required are surface emissivity for the SEVIRI thermal channels and the PGE01 CMs. Further details about the algorithm can be found in Martínez et al. (2011). PGE13 was run every 15 minutes for the full year of 2008 with a field-of-regard of 7x7 pixels. The TPW was validated against two different free online datasets for an area to the South of 40°N latitude, thus avoiding high view zenith angles. The first dataset comprises of radiosonde data that was acquired from the NOAA’s Integrated Global Radiosonde Archive (IGRA, http://www.ncdc.noaa.gov/oa/climate/igra/index.php). The density of the radiosonde stations is considered acceptable to represent the spatial variability of TPW in the area, however radiosondes are usually launched twice a day and hence its temporal resolution is not comparable with 15 minute SEVIRI data. On the other hand, the second dataset is sun photometer data obtained from the AERONET network (Holben et al. 1998). This dataset provides estimates of TPW at very high temporal resolution, but the station density for the chosen area is much poorer compared to IGRA. Therefore, both datasets can be considered complementary in order to validate the spatio-temporal performance of PGE 13 TPW.

After cross-tabulating the valid TPW retrievals by PGE13 with the two validation datasets a total of 11342 cases were available for IGRA (from a total of 64 radiosonde stations) and 71055 for AERONET (23 stations). Error measurement and observed vs. predicted scatter plots are depicted in Figure 5. Results show that error ranges from 0.57 g cm⁻² in the case of IGRA and 0.38 g cm⁻² for AERONET, with R² coefficients of 0.76 and 0.91, respectively. Such values are slightly higher than the results obtained in Martínez et al. (2011) of 0.29 g cm⁻² for the year 2009 although the accuracy obtained in this study is still within the product requirements document threshold of 0.6 g cm⁻².

Assuming that both validation datasets provide accurate estimates of TPW, the difference in performance of PGE 13 in both cases can be attributed to a better ability to explain the short-term temporal variability of TPW, which in any case is usually low, rather than the spatial variability. Indeed, we believe that the lower performance in explaining the spatial variability is mainly caused by the dependency on the NWP profile forecast, which has a spatial resolution of 0.5°. On the other hand, Sobrino et al. (2008) obtained a RMSE of 0.4 g cm⁻² for retrievals of TPW using the SEVIRI split-window channels at two different times. However, their validation dataset could be considered less representative given that they used a total of 59 radiosonde cases. Furthermore, Schroedter-Homscheidt et al. (2008) validated a similar algorithm to Sobrino et al. (2008) and they obtained an accuracy of 0.68 g cm⁻² for 2583 radiosondes.

The Total Precipitable Water vapour estimated with the NWCSAF PGE13 Physical Retrieval Algorithm has been validated against radiosonde and sun photometer data for one full year. The validation was performed for land pixels with SEVIRI view zenith angles small enough to avoid extreme geometric and atmospheric effects. PGE 13 has shown good performance in estimating TPW, especially when dealing with temporal variation in TPW. However, PGE 13 shows a poorer performance in estimating the spatial variability, although its accuracy is still within the expected ranges. Further study, using higher resolution NWP data, will help to understand the PGE13 performance over varying spatial scales.
Land Surface Temperature

A Land Surface Temperature (LST) estimate is produced every 15 minutes for the full SEVIRI disc using two thermal infrared channels: one centred at 10.8 µm (ch09) and the other centred at 12.0 µm (ch10). Depending on whether the data comes from MSG1 or MSG2, it is processed by a semi-empirical split window algorithm developed either by Sobrino & Romaguera (2004) or Atitar et al. (2008), respectively. Both algorithms take the satellite VZA into consideration, which is particularly important when calculating LST away from the centre of the SEVIRI disc.

Aside from the two thermal channels and the VZA, the algorithms also require the surface emissivity in each of the two channels and the total column atmospheric water vapour content (WV). The emissivity is estimated in a two-step process. First, yearly emissivity base-maps are produced from the MODIS MCD12Q1 land cover product (Strahler et al. 1999) and the emissivity values proposed by Trigo et al. (2008) for each International Geosphere-Biosphere Program (IGBP) land cover class. Four base-maps are produced for each year, two for each thermal channel: one for full vegetation cover and one for bare ground case. In the second step daily emissivity values are estimated by a linear combination of the full vegetation cover and bare ground emissivities, based on the fraction of vegetation cover (FVC). The FVC is calculated as:

\[
FVC = \frac{(NDVI - NDVI_{\text{min}})}{(NDVI_{\text{max}} - NDVI_{\text{min}})}
\]

Where NDVI_{\text{min}} represents NDVI of bare soil and has a value of 0.12 and NDVI_{\text{max}} represents the NDVI of full vegetation cover and has a value of 0.65 (Stisen et al. 2007). The WV data is produced by the NWCSAF PGE13 (SPPhR) algorithm. The PGE01 cloud mask is combined with the MPEF cloud mask to ensure high reliability of the final product. Validation of the LST estimates is in the preliminary stage, due to the data still being processed. However early results that compare the 15 minute LST with ground based measurements from the Dahra field station in Senegal for 2008, indicate that the LST algorithm performs well — as shown in Figure 3. Once more data is available a more thorough validation will be undertaken.

![Graph showing the comparison of SEVIRI derived LST to that measured by instruments at the Dahra field site.](image)

**Figure 3**: A comparison of SEVIRI derived LST to that measured by instruments at the Dahra field site.

Estimating Evapotranspiration in semiarid climates

Evapotranspiration, or the amount of water returned to the atmosphere from the surface, is a key variable linking the energy, water and carbon cycles. In water-limited ecosystems evapotranspiration represents up to 90% of the annual rainfall and is the main determinant of net primary productivity (Glenn et al., 2007). Availability of regional estimates of daily evapotranspiration in water-scarce regions like the Sahel is critical for improving agricultural and hydrological information. The general aim of this study was to obtain accurate yet operational estimates of daily evapotranspiration from SEVIRI at the point level for a site in the Sahel (Agoufou, Mali) (15.34°N, 1.48°W). This site is an open woody savanna instrumented within the Monsoon Multidisciplinary Analyses (AMMA) project. Particular objectives were (i) compare two different formulations of a soil moisture constraint and (ii) compare SEVIRI model outputs with the performance of a global-coverage evapotranspiration product (MOD16A2).

LST and broadband surface albedo products were acquired from the Satellite Application Facility for Land Surface Analysis (Land-SAF) that has developed a wide suite of datasets based on SEVIRI.
measurements. Data acquired from MODIS included $LAI$ and $f_{PAR}$ (MCD15A3), and daily surface reflectance from Terra (MOD09GA) to estimate albedo (Liang et al., 2001). Incoming solar radiation, relative humidity and air temperature were obtained from the NASA-power database. For model evaluation, eddy covariance data from the AMMA project were used (Mougin et al., 2011).

The evapotranspiration model used here is a modified version of the PT-JPL (Priestley-Taylor Jet Propulsion Laboratory) evapotranspiration model of Fisher et al., (2008). The soil moisture constraint, required to get soil evapotranspiration, was estimated using an Apparent Thermal Inertia (ATI) Index (Verstraeten et al., 2006) instead of an atmospheric water deficit index (ATM) (Garcia et al., 2012) as in the original version. The ATI is based on broadband albedo and the difference between maximum daytime ($T_{S,D_{max}}$) and minimum nighttime ($T_{S,D_{min}}$) surface temperature as well as a solar correction factor that normalizes for changes in solar irradiance. Daily evapotranspiration estimates from the PT-JPL model and eddy covariance data were aggregated to an 8-day time-scale to compare with the MODIS global evapotranspiration product (MOD16) (Mu et al., 2011).

As shown in Table 1 there is a good correlation between both SEVIRI and MODIS evapotranspiration estimates and data collected in the field. Although biases were lower for MODIS than for SEVIRI, fewer observations were available due to its lower frequency of acquisition. For this reason the global MODIS 8-day evapotranspiration product (MOD16) failed to capture the dynamics of evapotranspiration in this Sahelian savanna. The results using JPL-PT model with an ATI index are very promising for regional applications relying as it is mostly based on available satellite products and using relative humidity estimates is not longer needed as in the original JPL-PT version (Atm-MSG).

<table>
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<th>Model</th>
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<th>$r$</th>
<th>$N$</th>
<th>slope</th>
<th>MAE</th>
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<td>ATI-MSG</td>
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<td>1.38</td>
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<td></td>
<td>Atm-MSG</td>
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<td>16</td>
<td>1.49</td>
<td>1.06</td>
<td>-0.96</td>
</tr>
</tbody>
</table>

Table 1: Evaluation of model evapotranspiration with eddy covariance at 8-day time scale. MOD16A2 is the global MODIS evapotranspiration product. Three versions of the PT-JPL were used: (i) ATI-MODIS (Apparent Thermal Inertia estimated with MODIS), (ii) ATI-MSG (Apparent Thermal Inertia estimated with MSG-SEVIRI), and (iii) Atm-MSG (uses an atmospheric water deficit index estimated with MSG-SEVIRI). Units are in mm/day.

**Soil Moisture**

Soil moisture plays a very important role in plant growth; with plants obtaining nutrients dissolved in the water contained in soil pores. A wide variety of models, such as those used in Hydrology and Meteorology, use soil moisture as a key input and it is therefore important to obtain accurate estimates of this variable. Microwave remote sensing has provided useful information on soil moisture in the first centimeters of the soil surface; however, in many vegetated areas these estimates can be inaccurate. Due to the link between soil moisture and vegetation status, a relationship between optical and combined optical-thermal remote sensing has been studied, showing high correlation values with soil moisture (Wang et al. 2007).

Due to the importance of soil moisture in different models and to the relationship with the vegetation status, we examined the applicability of a sensor like MSG-SEVIRI to monitor intraday soil moisture variations at a wooded grassland in Las Majadas del Tietar, in Spain. When plotting LST against NDVI in an area containing a full range of fractional vegetation covers and soil moisture, and assuming homogeneous atmospheric forcing, a triangular scatter plot emerges in which a dry edge and wet edge limit can be defined. The position of each point in that space is determined by the fractional vegetation cover and its surface temperature and this can be related to soil moisture (Friedl & Davis 1994). However, this method works well in semi-arid ecosystems and is not valid in all environments, given that a full range of conditions (bare wet and dry soil to stressed and unstressed full cover vegetation) has to be present in the scene. The Temperature Vegetation Dryness Index (TVDI) (Sandholt et al. 2002) was obtained using NDVI and LST from SEVIRI between 06:00 and 18:00 UTC for 2009. A window of 50 by 50 pixels was used to calculate the TVDI for each image and the method proposed by Tang et al. 2010 was used to determine the dry edge. Figure 4 shows the temporal evolution of the soil moisture measured with a TDR sensor at 4 cm depth for each day (DOY) during 2009 (Lower graph). The middle plot shows the slope values of the dry edge obtained from the triangle method and in the upper plot the TVDI values are illustrated. The results show a pattern in the in the temporal evolution of the dry edge slope that can be appreciated in two stages: one with very low soil moisture values (DOY 125 to 270) and a second stage with wetter soils for the rest of the year. For
The pattern is not as clear, but higher TVDI values correspond to the period ranging from DOY 125 to 270, season with very low precipitation and therefore low soil moisture values.

Figure 4: A comparison of soil moisture indicators for the Las Majadas del Tietar field site in Spain. The left-most figure shows in-situ soil moisture measured at ground level whilst the centre and right-most figures show SEVIRI estimates of the dry edge slope and the TVDI.

These early stage results are very promising and a much deeper analysis of the data is being carried out to reduce the noise in the TVDI and calibrate a usable model. Using TVDI from SEVIRI to monitor soil moisture can be a very powerful tool due to the high temporal resolution of the sensor. This can help to produce wide-scale soil moisture estimates with a 15 min sampling interval that can be used as an input to land surface models.

Conclusions and Future Perspectives
In this paper we have shown a broad range of applications for data gathered by the SEVIRI sensor. Most of the results presented here are preliminary and we are currently performing ongoing validation efforts in order to maximise the accuracy of these land and atmosphere products. Whilst the methods presented in this paper are well-established there is still scope for additional improvement, particularly in high VZA areas such as Northern Europe and parts of South America. To this end we are also working on the integration of polar orbiting data from MetOp into our processing chain. This should increase accuracy in these regions and also allow extended coverage of the poles, an area in which SEVIRI observations are not well suited.

Looking to the future there are also new possibilities with the upcoming Meteosat Third Generation platform. Increased temporal resolution will allow an even greater chance of gaining clear-sky images whilst the increased spatial resolution will enable more detailed analysis of the land surface. This will be particularly useful in examining vegetation growth in marginal areas, such as the African Sahel and South American rainforest, and will also allow much greater precision for tasks such as flood mapping.

References


