SURFACE ALBEDO DATABASES DETERMINED FROM PMD MEASUREMENTS PERFORMED BY THE GOME-2 INSTRUMENT

Lieuwe G. Tilstra, Olaf N.E. Tuinder, Ping Wang, and Piet Stammes
Royal Netherlands Meteorological Institute (KNMI), Utrechtseweg 297, De Bilt, The Netherlands

Abstract
In this paper we introduce a new spectral surface albedo database which was based on Polarisation Measurement Device (PMD) measurements performed by the GOME-2 instrument. This GOME-2 PMD-LER database contains the Lambertian-equivalent reflectivity (LER) of the Earth’s surface, and is meant to support satellite retrieval of trace gases and of cloud and aerosol information. The database consists of 12 PMD bands that span the wavelength range from 330 to 800 nm. The database is made for each month of the year, and its spatial resolution is 0.5° × 0.5°. In this paper we introduce the PMD-LER database and its properties, provide examples of the surface reflectivity fields inside the product, and present the results from comparisons with other, comparable surface LER databases.

DESCRIPTION OF GOME-2
The spectrometer GOME-2 (the 2nd Global Ozone Monitoring Experiment) (Munro et al., 2016) was launched on 19 October 2006 on board the MetOp-A satellite. The MetOp-A satellite was brought in a polar sun-synchronous orbit at an altitude of about 800 km, with a local crossing time of the equator of 9:30 a.m. for the descending node. MetOp-A was launched as the first satellite in a series of three Meteorological Operational (MetOp) satellites. The second satellite platform, MetOp-B, was launched successfully in September 2012, and placed in the same orbit as MetOp-A but with a head start of 50 minutes (half an orbit) on MetOp-A. The third MetOp satellite, MetOp-C, is scheduled to be launched in 2018. All three MetOp satellites host or will host identical versions of the GOME-2 instrument.

GOME-2, like its predecessor GOME on the ERS-2 satellite (Burrows et al., 1999), measures the sunlight reflected by Earth in the wavelength range between about 240 and 790 nm, with a spectral resolution (FWHM) ranging from 0.2 nm in the UV to 0.4 nm in the NIR. The instrument scans the Earth from east to west in 4.5 s and back in 1.5 s by rotating an internal scanner mirror. The orbit swath sensed this way is 1920 km wide. The typical measurement footprint is 80 km × 40 km (across track × along track) in the forward scan. Global coverage is achieved in 1.5 days. Since 15 July 2013 the orbit swath of the GOME-2 instrument on the MetOp-A satellite has been reduced to 960 km, leading to a measurement footprint of 40 km × 40 km and global coverage in three consecutive days.

The four spectral channels of GOME-2 are not only sensitive to the intensity of the detected light, but also to the polarisation of the light. As a result, a correction for this polarisation sensitivity is needed. To be able to do this the GOME-2 instrument has been equipped with two Polarisation Measurement Device (PMD) detector arrays. These PMDs combined are able to measure the state of polarisation of the detected light in 15 programmable bands. Apart from being able to detect the state of polarisation, these 15 PMD bands also provide usable broadband measurements of the solar irradiance and the Earth radiance (Tilstra et al., 2014). The footprint size of the PMD measurements is a factor 8 smaller than that of the Main Science Channel (MSC) measurements, amounting to 10 km × 40 km.

DESCRIPTION OF THE PMD-LER DATABASE
The PMD-LER database contains the Lambertian-equivalent reflectivity of the Earth's surface, derived from GOME-2 PMD measurements, for each month of the year, for the entire globe in a grid of 1440 × 720 grid cells. The intrinsic spatial resolution, however, is not 0.25° × 0.25° but 0.5° × 0.5°. The higher
The spatial resolution of the database grid is only achieved near coastlines, via explicit dynamical gridding. The lower intrinsic resolution for the bulk of the grid leads to more reliable surface LER values and decreases the amount and impact of residual cloud contamination. Surface LER values are available for PMD bands 4–15, covering the wavelength range between 330 and 800 nm. Since May 2017, databases are available which are based on either GOME-2A or GOME-2B observations.

Next to the GOME-2 PMD-LER databases introduced in this paper, we also create GOME-2 surface LER products based on Main Science Channel (MSC) measurements (Tilstra et al., 2017b). These MSC-LER databases are based on the same retrieval algorithm as the PMD-LER databases. As compared to the MSC footprints, the PMD footprints have an eight times smaller footprint size which results in a reduction of residual cloud contamination and allows a higher spatial resolution. However, because the PMD bands are not monochromatic, spectrally fixed, and governed by a radiometric calibration which is specific to the PMD bands and not necessarily consistent with the radiometric calibration of the main science channels, this database is mostly suited to support GOME-2 PMD band retrievals, such as the Polar Multi-sensor Aerosol product (PMAp) retrieval. The spectral characteristics of the PMD bands are summarised graphically in Figure 1. Note that only PMD bands 4–15 are part of the PMD-LER database. For PMD bands 1–3 a reliable retrieval is not possible.

Instrument degradation is a very serious problem that normally directly affects the retrieved surface LER values. However, instrument degradation was handled using the method introduced in Tilstra et al., 2012a. This method was applied to the GOME-2 Earth reflectance in the way as explained in Tilstra et al., 2012b. All details about the retrieval algorithm and the algorithm setup can be found in Tilstra et al., 2017b. More information about the databases themselves can be found in the Product User Manual (PUM) of the GOME-2 surface LER products (Tilstra et al., 2017a).

**EXAMPLES OF THE PMD-LER DATABASE**

In Figure 2 we present global maps of the surface LER retrieved by GOME-2A for the month February for PMD bands 6, 9, 11, and 15. For PMD 6 (~369 nm) there are a lot of structures visible over the ocean. These structures are related to spatial variations in the concentration of phytoplankton, coloured dissolved organic matter, and detritus. All these organic components absorb radiation in the UV, unlike pure water which absorbs most radiation at the longer wavelengths. Over land, the diversity in surface types is large and this is reflected in the spatial variation and spectral dependence found in Figure 2. For PMD 6 the surface LER of most land surfaces is quite a bit lower than that of the ocean. Exceptions are desert areas, such as the Sahara, the Arabian Peninsula, and the Gobi desert, and the snow/ice-covered surfaces near the poles and northern latitudes. For PMD 9 (~460 nm) the surface...
Figure 2: Global maps of the surface LER retrieved by GOME-2/MetOp-A for PMD 6, 9, 11, and 15 for the month of February. The surface LER type presented here is the MODE-LER. More details are provided in the main text.

Figure 3: Colour composite images of the Earth’s surface constructed from GOME-2/MetOp-A surface LER values for the months of March, June, September, and December. The three PMD bands that are used for the images are PMD 9 (serving as the blue component), PMD 11 (green component), and PMD 13 (red component). These three PMD bands correspond to central wavelengths of 461, 555, and 639 nm, respectively.
LER over land is more or less similar to that of PMD 6, but over desert areas it is higher, and over the wet tropical rainforests it is slightly lower. At PMD 11 (~554 nm) the surface LER for all land surfaces is larger, with peak values reached over the Sahara desert. Already, some spatial structure related to (differences in) vegetation can be seen. The presence of vegetation is most pronounced, however, for PMD 15 (~799 nm). At this wavelength the absorption by chlorophyll for vegetation is much lower, resulting in much higher surface LER values. The images in Figure 2 are very similar to the images that were presented in Tilstra et al., 2017b for the GOME-2A MSC-LER database.

Figure 3 presents colour composite images of the Earth’s surface for the four months of March, June, September, and December. These images were based on the GOME-2A surface LER grids from PMD bands 9, 11, and 13, serving as the blue, green, and red components, respectively. As the images are essentially true colour images, they provide information on the surface (water, soil, and vegetation), snow/ice cover, and the seasonal variation and also on potential residual cloud contamination. Indeed, some mild cloud structures can be discerned in Figure 3. They are most easily found over the dark ocean surface, but also over land certain areas can be found where residual cloud contamination is an issue. Note that no attempt is made in the surface LER retrieval algorithm to correct for residual cloud contamination over land. This can be verified by studying the „flag“ field provided in the databases.

This flag field is presented in Figure 4 for the months March, June, September, and December. A flag value of 0 means that no flags were raised and that the reported surface LER values are to be trusted. A flag value of 1 indicates that residual cloud contamination was detected but successfully handled by searching for a nearby donor cell to act as replacement. A flag value of 2 means that residual cloud contamination was detected but that a suitable donor cell could not be found. In practice, this rarely happens. Grid cells with flag value 1 occur less frequent than for the MSC-LER database. This is directly related to the smaller footprint size of the PMD measurements. The red colour in Figure 4 is linked to a flag value of 3. These are typically grid cells that were observed during polar night. Under such conditions the surface LER cannot be retrieved. To complete the surface LER fields, they were replaced by grid cells for the same location but from different months (Tilstra et al., 2017b). A flag value of 4 means that such a replacement could not be found. This does not occur in practice.

Figure 4: Global maps of the flag fields that are provided in the GOME-2/MetOp-A PMD-LER database. Flag values that can occur range from 0 (optimal) to 5 (suspicious). The exact meaning of the flag values is given in the main text.
The black pixels, belonging to a flag value of 5, point to non-physical surface LER values for at least one of the PMD bands. In Figure 4 this happens mostly for the months June and December. These grid cells turn out to have slightly negative surface LER values for PMD 4 and 5. This is related to a small (negative) offset in the surface LER values for these PMDs, to be discussed in the next section.

COMPARISONS WITH OTHER DATABASES

In this section we first compare the GOME-2 PMD-LER database with the OMI surface LER database (Kleipool et al., 2008). Using the OMI surface LER database as a reference makes sense. It has the same intrinsic spatial resolution as the GOME-2 PMD-LER database and has wavelength bands close enough to the PMD wavelength bands. The downside is that the list of wavelength bands in the OMI surface LER database only goes up to 499 nm. This means that we can only study PMD bands 4–9.

Some typical results from the comparison between the GOME-2A PMD-LER database and the OMI surface LER database are presented in Figure 5, which presents global maps of the differences between the GOME-2A PMD-LER and OMI surface LER databases for PMD bands 4, 7, 8, and 9 (which were linked to the OMI wavelength bands at 335, 380, 416, and 463 nm). The results that are shown apply to the month of March, and the comparisons were performed for the MIN-LER products contained in the two databases. For PMD 8 and 9 the agreement is good, with differences rarely exceeding the 0.01 boundaries, except for snow/ice situations near the poles. For PMD 7 the result is slightly less good, with differences generally within the 0.02 boundaries. For PMD 4, however, the agreement is only just about fair, with a clear negative offset of about –0.02 in the studied differences.

To study the differences more closely, we analyse histograms of the differences. The (normalised) histograms are presented in Figure 6 and are based only on the grid cells between 60°S and 60°N. Grid cells that were flagged for residual cloud contamination were not filtered out. Such grid cells were copied from nearby donor cells by the retrieval code (Tilstra et al., 2017b) and are not considered “bad”. All four histograms are symmetric, as expected. To explain, we expect the histograms to be symmetric because the differences are governed by statistical fluctuations in two very similar quantities which both should follow more or less similar statistics. The histogram of the differences in surface LER for PMD 4 (~335 nm) is found to be offset by –0.02, while the offset found for PMD bands 8 and 9 is on the order of –0.005, in magnitude much smaller than the spread of the histograms.

In Figure 7 we present the results from the comparison between the GOME-2A PMD-LER database and the GOME-2A MSC-LER database. This time PMD bands 7, 9, 11, and 13 are studied, and linked to the MSC wavelength bands at 380, 463, 555, and 640 nm. The agreement is very good for PMD 9, 11, and 13. However, for PMD 7 (~380 nm) there seems to be a negative offset of about –0.03. Histograms of the differences are shown in Figure 8. The histograms for PMD 9, 11, and 13 are very narrow, and only a very small negative offset can be found. For PMD 7 (~380 nm) we find again the negative offset of about –0.03. It should be noted that the GOME-2A MSC-LER band at 380 nm was shown to be suffering from a positive offset of ~0.017 (Tilstra et al., 2017b). Taking this into account the GOME-2A PMD-LER seems to be suffering from an offset for PMD 7 between –0.01 and –0.02.

In summary, for the longer wavelength bands (PMD bands 8–15) we found a very good agreement. For the shorter wavelength bands (PMD bands 4–7) we did find indications of offsets, but these are acceptable. This leads us to the conclusion that the GOME-2 PMD-LER agrees well with the GOME-2 MSC-LER database and the OMI surface LER database, which were used as references.

SUMMARY

The GOME-2 PMD-LER databases provide global spectral surface albedo for 12 wavelength bands between 330 and 800 nm, for each month of the year. These databases are especially suited for retrievals that make use of the GOME-2 PMD bands, such as the Polar Multi-sensor Aerosol product (PMAp) retrieval does. Comparisons with the OMI surface LER database and the GOME-2 MSC-LER database show in general good agreement. Some discrepancies are found, though, which are most likely related to imperfections in the radiometric calibration of the PMD bands. The radiometric calibration of the PMD detectors of the GOME-2 instrument is expected to be improved in the future.
Figure 5: Global maps of the differences between the surface LER derived from the GOME-2A PMD bands and the OMI surface LER database for the four indicated GOME-2A PMD bands. The associated (nearby) OMI wavelength bands are also indicated. The differences that are presented are based on the MIN-LER products from the month of March. The agreement is satisfactory except for PMD 4 (associated OMI wavelength band: 335 nm).

Figure 6: Histograms of the differences between the GOME-2A PMD-LER and the OMI surface LER databases. The results are obtained for the month of March, for PMD bands 4, 7, 8, and 9, which were compared to the four (nearby) OMI surface LER wavelength bands indicated. The histograms were based on all grid cells between 60°S and 60°N, thereby excluding the polar regions and observations taken at high solar zenith angles.
Figure 7: Global maps of the differences between the surface LER derived from the GOME-2A PMD bands and from the main science channels for the four indicated PMD-LER bands. The associated (nearby) MSC-LER wavelength bands are also indicated. The differences that are presented are based on the MIN-LER products from the month of March. The agreement is satisfactory except for PMD 7 (associated MSC-LER wavelength band: 380 nm).

Figure 8: Histograms of the differences between the GOME-2A PMD-LER and the GOME-2A MSC-LER databases. The results are obtained for the month of March, for PMD bands 7, 9, 11, and 13, which were compared to the four (nearby) MSC-LER wavelength bands indicated. The negative offset of about ~0.04 found for PMD 7 (~380 nm) is partly due to a positive offset in the GOME-2A MSC-LER that was already reported earlier (Tilstra et al., 2017b).
The PMD-LER databases can be downloaded from the TEMIS website via the following URL:

http://www.temis.nl/surface/gome2_ler.html

The databases are free to use for commercial and non-commercial purposes. When the databases are used for a publication (research or otherwise), please refer to the following paper:


REFERENCES


Copyright ©EUMETSAT 2017

This copyright notice applies only to the overall collection of papers: authors retain their individual rights and should be contacted directly for permission to use their material separately. Contact EUMETSAT for permission pertaining to the overall volume.

The papers collected in this volume comprise the proceedings of the conference mentioned above. They reflect the authors' opinions and are published as presented, without editing. Their inclusion in this publication does not necessarily constitute endorsement by EUMETSAT or the co-organisers.

For more information, please visit www.eumetsat.int