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# Benchmarking of essential climate variables: Gamma index theory and results for surface albedo and aerosol optical depth

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ABSTRACT

This paper proposes a benchmarking method for assessing the level of spatio-temporal variability of Essential Climate Variable (ECV) products against a reference taking into account acceptance criteria in terms of intensity and physical distance tolerances. This is based on a modified version of the gamma index that could be suitable for fitness-for-purpose assessment given that one can choose various criteria depending on applications.

The method is first presented and then applied to both land and atmospheric ECVs. The terrestrial analysis concerns the global surface albedo, using monthly white-sky surface albedo in the visible, near-infrared and shortwave broadband spectral ranges at a spatial resolution of 0.05° using three sources of products. The latter study is conducted using monthly aerosol optical depth (AOD) products at 550 nm at a spatial resolution of 1° with four different datasets at the global scale. The analysis shows how the values of the gamma criteria impact the spatial and temporal results.

As an example, if the Global Climate Observing System (GCOS) actual target measurements uncertainty is used as an acceptance criteria for the intensity tolerance the results show that: 1) the seasonal agreement for the surface albedo products varies over 20% to 40% of the terrestrial surface in the shortwave and near-infrared broadband and from 10% to 30% in the visible one and 2) the three aerosols optical depth products agree with the reference one for over 50% of the land surface only when the tolerance distance term is at 224km.



## 1. Introduction

Earth Observation (EO) using space remote sensing technique has become one of the primary means for monitoring climate change impacts at regional and global scale (Bojinski et al., 2014; Blunden and Arndt, 2016). In recent years, many programs, including the European Space Agency (ESA) Climate Change Initiative (CCI) (Hollmann et al., 2013; CCI, 2016), the Copernicus Climate Change Service (C3S) (Raoult et al., 2017; C3S, 2016) and the Global Observing Systems Information Center (GOSIC) (Diamond, 2013; GOSIC, 2016) among others, have been created to increase the number, and to enhance the capabilities of satellites in providing Essential Climate Variables (ECVs) data (GCOS, 2011, 2016).

The most critical challenge is now to ensure the quality control and to assess the fitness for purpose of these space products. For example, the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) Land Product Validation (LPV) subgroup is actually devoted to proposing updated or new frameworks for validating some of the land ECV whereas the CEOS WGCV Atmospheric Composition SubGroup (ACSG) is responsible for ensuring accurate and traceable calibration of remotely-sensed atmospheric composition radiance data.

The Global Climate Observing System (GCOS) specifies that the surface albedo is required as one of the land ECVs for climate change monitoring purposes with a required measurements uncertainty defined as *max* (5%, 0.0025), *i.e.* whichever is the greater between 5% (relative) of the surface albedo value and 0.0025 (absolute). Another crucial ECV for climate change monitoring as specified in GCOS, is represented by the aerosol optical depth (AOD), in this case the requirement is max (10%, 0.03) (GCOS, 2016).

The surface albedo represents the fraction of the back-scattered sunlight radiation reflected by the surface and is defined as the non-dimensional ratio of the reflected radiation flux and the incoming irradiance. Surface albedo can be defined with 1) the directional-hemispherical reflectance (DHR) 2) the isotropic bidirectional-

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hemispherical reflectance ($BHR_{iso}$) and 3) the bidirectional-hemispherical reflectance (BHR). DHR describes albedo solely in terms of direct illumination, assuming that the solar energy is coming from only one direction and is the integration of the bi-directional reflectance over the viewing hemisphere. $BHR_{iso}$ assumes a completely diffuse illumination, and is the integration of the DHR over the upper hemisphere. Finally, BHR is a combination of the two.

Land surface albedo is currently provided by several projects or organisations in a large number of spatial, temporal and spectral resolutions. A non-exhaustive list of available surface albedo products includes the Moderate Resolution Imaging Spectroradiometer (MODIS) (Schaaf et al., 2002), Multi-angle Imaging Spectro-Radiometer (MISR) (Diner et al., 1998), Spinning Enhanced Visible and InfraRed Imager (SEVIRI) (Aminou, 2002), Satellite Pour l'Observation de la Terre (SPOT) VEGETATION (VEG) (Geiger and Samain, 2004), GlobAlbedo (Muller et al., 2012; Lewis et al., 2012), Meteosat (Pinty et al., 1998), Global Land Surface Satellite (GLASS) (Liang and Liu, 2012) and the Copernicus Global Land Service (C-GLS, 2013).

Several previous studies intercompare some of these products. Taberner et al. (2010) and Pinty et al. (2011) show that MISR and MODIS white-sky albedo values in the visible, near-infrared and shortwave broadbands spectral ranges deviate within 0.02 with a slight bias from 0.01 to 0.03 depending on the broadband domain. Direct comparison against ground-based measurements is often used, even so there is a need to make them more reliable (Wang et al., 2014; Chen et al., 2008; Cescatti et al., 2012; Adams et al., 2016b; Loew et al., 2016). For example, root mean square error (RMSE) is found to be less than 0.03 (0.02) over agriculture/grassland (forest) sites and less than 0.05 (0.025) during the snow-covered periods for MODIS Collection 6 (Wang et al., 2014). Past research projects on surface albedo quality assessment explain that one of the major sources of uncertainties comes firstly from detection of snow events (Wang et al., 2014; Chen et al., 2008) and secondly the atmospheric correction which may, or may not, depend on retrieval of the aerosols products (Zelazowski et al., 2011). One additional difference arises from different cloud masks that could provide less or more measurements during the kernel model inversion and then impact the overall quality of surface albedo products (Jin et al., 2003; Lattanzio et al., 2015).

Contemporaneously, the aerosols actively influence the global radiative-balance by scattering solar radiation and influencing cloud reflectivity, cloud cover and cloud lifetime. The Intergovernmental Panel on Climate Change (IPCC) identifies also the aerosol properties as one of the most uncertain variables in our understanding of the climate system (Griggs and Noguer, 2002). The aerosol optical depth (AOD) is nowadays operationally retrieved from several space sensors like the Ozone Monitor Instrument (OMI) (Levelt et al., 2006), Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) (Sassen et al., 2008), Advanced Along-Track Scanning Radiometer (AATSR) (Holzer-Popp et al., 2013), MODIS Aqua and Terra (Remer et al., 2005) and MISR (Martonchik et al., 2004; Kahn et al., 2010). The validation of such products is mainly done by comparing them against the ground-based AERONET sun photometer network (Holben et al., 2001). For example, de Leeuw et al. (2015) present results of round robin exercises between seven CCI aerosols retrieval algorithms using both Level 2 and Level 3 products. In these latter studies, the benchmarked metrics provide two performance indicators for spatial variability and temporal or seasonal variability using bias against reference data. More recently, the uncertainties of three CCI AOD products are also validated and benchmarked using reference ground-based data (Popp et al., 2016). Other methods, devoted to the benchmarking of ECVs products, can be found in the literature. Among them, Meroni et al. (2012) proposed 1) correlation metrics such as Geometric Mean Functional Relationship (GMFR) regression analysis and 2) systematic and unsystematic agreement components using Fraction of Absorbed Photosynthetical Active Radiation (FAPAR) datasets at regional level. Mueller et al. (2013) evaluated land evapotranspiration products through merged global products in order to evaluate their trends.

Here we propose a complementary benchmarking method which can infer the global spatio-temporal consistency between several sources of one ECV using a modified version of the gamma index method. The gamma index ($\gamma$), originally developed as a methodology to quantitatively compare treatment planning system derived dose distributions for external beam radiotherapy with measured dose distributions (Low et al., 1998), is routinely used in medical physics although some work can be also found in the remote sensing literature (see e.g. Voyant et al. (2014) ).

The gamma test provides a pass-fail criterion and two distributions are considered in agreement when $\gamma$ values $\leq 1$. This method can be applied to any ECV as it requires one reference product and takes into account the level of intensity and distance criteria of interest.

## 2. Materials and methods

### 2.1. ECV: surface albedo

The European Space Agency (ESA) Data User Element (DUE) GlobAlbedo (Lewis et al., 2012), MODIS MCD43C3 Collection 6 (Schaaf and Wang, 2015) and Copernicus Global Land Service (Copernicus-GLS) (Samain et al., 2006) albedo products are included in this study as the latter two are the newer products among the list given in the introduction. Each project provides different levels of global surface albedo products therefore the spatial and temporal resolutions differ among them.

On the one hand, the global MODIS MCD43C3 Collection 6 provides daily products in lat/lon projection at 0.05° for which the original retrieval algorithm uses 16 days of clear-sky Bidirectional Reflectance Factors (BRFs) at 30 arcsec grid for fitting the parametric (kernel) model. If the kernel parameters are well estimated, they are used to compute the daily albedo or, conversely, "a pixel based updated from the latest full inversion is used" (Schaaf and Wang, 2015). Each specific file represents the central date of the retrieval period. On the other hand, Copernicus Global Land Service strategy is to provide only surface albedo products every 10 days, for which the retrieval uses 30 days to fit the same kernel model, at 1/112° in lat/lon projection. For the latter, the given date is the centre of the accumulation period. The GlobAlbedo project gives 8-day global surface albedo products at 1 km but also monthly aggregated products at 0.05° and 0.5° in lat/lon projection.

Due to these inherent differences of the spatial-temporal resolution, a direct comparison of the products "as-they-are" is not possible. Nevertheless, the analysis can be achieved by rescaling all the products to a unique spatial-temporal resolution, chosen at 0.05° spatially for monthly aggregation. As GlobAlbedo is the only project that provides this combination, the daily products generated from MODIS Collection 6 are processed to provide monthly products, while the daily Copernicus-GLS products are also aggregated spatially and combined on a monthly basis. The next paragraphs summarise the methodologies to produce the monthly products at 0.05°. In order to perform spatial and/or temporal aggregation of the products, other alternate methods exist such as the one reviewed and proposed in Smith et al. (2013) .

In the case of MODIS, the temporal composite is achieved by averaging all daily products that belong to the month of interest. However, the average value is calculated for each grid-cell only if more than 50% of the time a valid observation is associated to the grid-cell, failing this a "non-valid" value is assigned (Sun et al., 2017). MODIS products contain a quality layer with values from 0 (best quality) to 5 (50% or more fill values in the 0.05 grid cells). We are aware that we should take into account this information for validation purposes: however if we take into account only grid-cells with a quality flag

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