Phenology Estimation From Meteosat Second Generation Data

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***Abstract*—Many studies have focused on land surface phenology, for example as a means to characterize both water and carbon cycles for climate model inputs. However, the Spinning Enhanced Visible Infra-Red Imager (SEVIRI) sensor onboard Meteosat Second Generation (MSG) geostationary satellite has never been used for this goal. Here, five years of MSG-SEVIRI data have been processed to retrieve Normalized Difference Vegetation Index (NDVI) daily time series. Due to existing gaps as well as atmospheric and cloud contamination in the time series, an algorithm based on the iterative Interpolation for Data Reconstruction (IDR) has been developed and applied to SEVIRI NDVI time series, from which phenological parameters have been retrieved. The modified IDR (M-IDR) algorithm shows results of a similar quality to the original method, while dealing more efficiently with increased temporal resolution. The retrieved phenological phases were then analyzed and compared with an independent MODIS (Moderate resolution Imaging Spectrometer) dataset. Comparison of SEVIRI and MODIS-derived phenology with a pan-European ground phenology record shows a high accuracy of the SEVIRI-retrieved green-up and brown-down dates (within days) for most of the selected European validation sites, while differences with MODIS product are higher although this can be explained by differences in methodology. This confirms the potential of MSG data for phenological studies, with the advantage of a quicker availability of the data.**

***Index Terms*—Meteosat second generation (MSG), normalized difference vegetation index (NDVI), phenology, spinning enhanced visible infra-red imager (SEVIRI), time series analysis.**

I. Introduction

LAND surface phenology consists in the study of vegetation phases, such as greening (corresponding to leafing) and browning (senescence) from space [1], [2]. It has the advantage of regional to global coverage of our planet, as well as the relatively low cost of its retrieval when compared with the tedious field work needed to retrieve equivalent parameters [3]. It is also a key parameter for research in water and carbon cycles, since it characterizes vegetation behavior through time, and therefore part of the respiring biomass of the Earth, which is of utmost importance to assess carbon pit locations as well as carbon balance. This is also valid for the water balance of whole regions, since evapotranspiration, a mandatory driver of hydrological models, is determined by vegetation activity. Moreover, changes in vegetation phenology have been linked with climate change, mainly through earlier greening and later browning of the vegetation [1], whether from ground observations [3]–[5] or remotely sensed studies [3], [6]–[10].

In the literature, numerous studies have dealt with the retrieval of phenological phases from remotely sensed data (for a complete review of phenology detection methods, see [1], [3], [11] and references therein). These retrievals have focused on the use of data retrieved by polar orbiting satellites, due to both their spatial resolution and their revisit time. However, recent geostationary platforms such as Meteosat Second Generation (MSG) have improved on previously available spatial resolutions, while retrieving data at high temporal resolution. For example, the Spinning Enhanced Visible Infra-Red Imager (SEVIRI) instrument onboard MSG has a nominal spatial resolution of 3 by 3 km at the Equator, with acquisitions every 15 minutes, and provides information in the red and near-infrared wavelengths, widely used by the scientific community to retrieve phenology phases through the time series analysis of Normalized Difference Vegetation Index (NDVI).

However, most previous approaches have been based on composited time series, which have the advantage of fewer gaps as well as lower cloud and atmospheric contamination on daily time series, although these composited time series have been shown to influence the accuracy of land surface phenology phase estimation [12]. Therefore, recent approaches focus on the use of daily time series for the retrieval of green-up and brown-down dates [13], [14], for which a previous reconstruction of the time series is mandatory to remove eventual gaps and atmospheric contamination. Here, the iterative Interpolation for Data Reconstruction (IDR [15]) method has been chosen to reconstruct each pixel temporal profile of MSG-SEVIRI NDVI between 2008 and 2012. Since the IDR method was developed for composited NDVI time series, a modified version of this method (M-IDR) is presented here to cope more efficiently with daily data. From these reconstructed time series, green-up and brown-down dates for the longest growth cycle (for eventual cases of vegetation with several growth cycles per year) are identified, and then compared to independently retrieved MODIS (Moderate resolution Imaging Spectrometer) phenology, and also to a Pan-European phenological dataset. These results are then discussed thoroughly to assess the validity of this approach.

II. Data

The MSG-SEVIRI sensor is located on a geostationary orbit above the (0° N, 0° E) latitude and longitude coordinates. There-

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fore, it has an observation disk of half the world, and is mainly used for weather observation and forecast, especially in Europe. This sensor acquires data in 3 channels dedicated to visible and near-infrared, centered at 0.6, 0.8 and 1.6 μm, 8 channels for the infrared, centered at 3.9, 6.2, 7.3, 8.7, 9.7, 10.8, 12.0 and 13.4 μm, and finally a broad band (0.5 to 0.9 μm) in the visible, called High-Resolution Visible (HRV) channel. Its spatial resolution at nadir is 1 km by 1 km for the High-Resolution Visible channel (HRV) and 3 km by 3 km for the other channels.

The MSG-SEVIRI data used in this study have been acquired using a direct broadcast HRPT (High Resolution Picture Transmissions) system implemented at the Global Change Unit of the University of Valencia since mid-2007. This system consists of a parabolic dish, a Personal Computer with the hardware and software to decode L-band data and a set of storage devices to save all the SEVIRI data. Taking into account the temporal resolution of SEVIRI, an image is acquired every 15 min amounting to 96 images per day for each channel. The storage space needed is 1TB of data per month, more than 50 TB for the five years of data used in this study. Only data from the red and near-infrared channels (Vis06 and Vis08) acquired at 12:00 GMT over land for years 2008 to 2012 have been used in this work.

For validation purposes, we also used data from the Pan European Phenology Project PEP725 for years 2008 to 2010. PEP725 is a project funded by the Austrian Meteorology and Geodynamics Center (ZAMG), the Austrian Ministry for Science and Research (BM:W_F) and EUMETNET (the network of European meteorological services)—with the goal to establish an open access database with plant phenology data sets for science, research and education. Seventeen European meteorological services and five partners from different phenological network operators are integrated in PEP725. This database includes different phenological indicators on plant leafing, flowering, maturity, harvesting and senescence for 54 different species. More information on the PEP725 database can be found on the project website: http://www.pep725.eu/ (last accessed 4 December 2012).

III. Methods

In order to retrieve yearly land surface phenology parameters from MSG-SEVIRI data, several pre-processing steps have to be carried out. These pre-processing steps (NDVI estimation, time series extraction, time series reconstruction) are presented here, before the method for yearly land surface phenology parameter estimation is presented.

A. NDVI Estimation

Visible and near-infrared data are first calibrated using standard calibration coefficients. NDVI is then estimated from these calibrated data through the approach developed by [16]. Although other vegetation indexes have been presented in the literature to estimate phenology, NDVI has been chosen here since it is easily estimated from MSG-SEVIRI data at continental scale. Please note that the data have been kept in the original hemispherical view characteristic of MSG data, and no atmospheric correction has been carried out on the data. The influence of this lack of atmospheric correction on the results will be analyzed in the discussion section. The NDVI estimation is part of an automatic processing scheme implemented at the University of Valencia to estimate biophysical parameters (NDVI, land and sea surface temperature) from MSG data.

B. Time Series Extraction

Since MSG NDVI values have been shown to vary with illumination geometry [17], we use a configuration with a geometry as stable as possible: observation angle fixed by SEVIRI orbital characteristics, and illumination closest to satellite nadir (12:00 GMT). Since the time series reconstruction method (see next section) deals with data gaps as well as atmospheric and cloud contaminated values, no other considerations on data quality have been taken into account.

C. Time Series Reconstruction

Due to transmission errors or antenna maintenance, NDVI time series may present gaps which have to be corrected to estimate phenological parameters. Additionally, cloud presence or atmospheric contamination tend to decrease NDVI values, which also hinder land surface phenology retrieval. Therefore, we chose to reconstruct the NDVI time series through the IDR (iterative Interpolation for Data Reconstruction [15]) method.

The IDR method consists in a pixel by pixel linear fit of composited data from its two temporal neighbors, which is compared to the actual observation. Then, the highest of these two values is selected for the interpolated time series. This procedure is iterated until the difference between interpolated and original values is below a given threshold (0.02 NDVI units, corresponding to the accuracy of NDVI estimation [15]). However, since this method is based on an iterative correction of single date estimations, its application to several years at daily temporal resolution for half the globe would be time-consuming. Therefore, a modification of this method is presented here:

1) To reduce the time of the fitting procedure, this revised version of the IDR method starts with a MVC (Maximum Value Compositing [18]) compositing of the original daily NDVI data at eight day temporal resolution. This step allows the reduction of the dimension of the yearly time series. Dates corresponding to the selected observation for each composite are saved for data reconstruction and posterior interpolation to daily resolution.
2) The IDR method is applied to the time series of 8-day-composited data, although a major change to its implementation has been carried out in order to fasten its application: a time series is constructed using for each single date its two closest temporal neighbors to interpolate linearly the value at the selected date by taking into account the date of each composited acquisition, and then this time series is compared to the original composited time series. All interpolated values which are above the original composited time series increased by a given threshold are replaced in the original composited time series.
3) This time series is used for successive iterations of this procedure, until the difference between time series stays below the given threshold. Here, this threshold has been fixed empirically at 0.005 NDVI units.
4) The IDR composited time series is interpolated back to daily resolution through linear interpolation. A spline in-

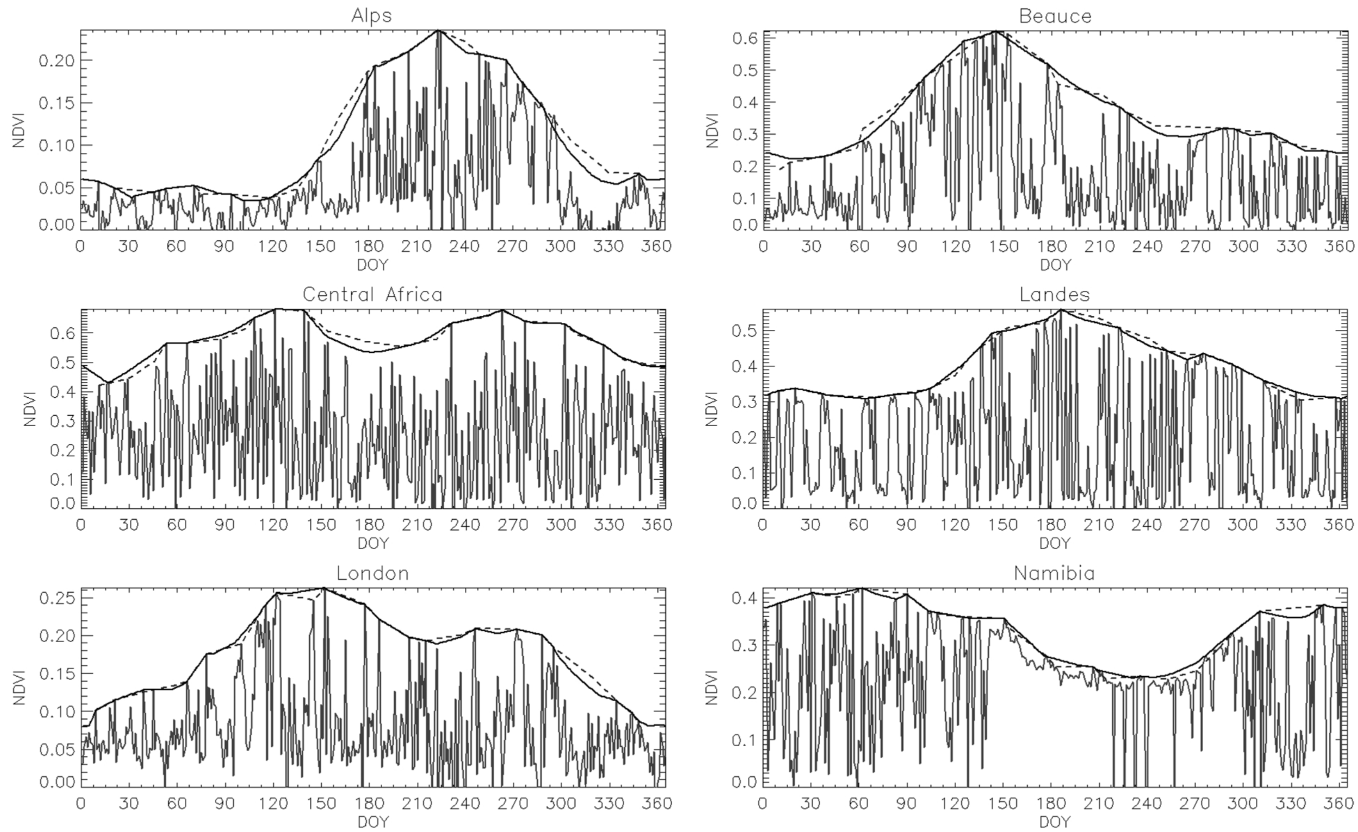

Fig. 1. Comparison of raw (grey), IDR (dotted black) and M-IDR (continuous black) NDVI time series for different pixels corresponding to different land covers: Alps (46.05°N, 8.03°E), Beauce (48.12°N, 1.73°E), Central Africa (0.62°N, 20.18°E), Landes (44.20°N, 0.37°W), London (51.46°N, 0.02°W), Namibia (17.92°S, 16.93°E). These pixels correspond respectively to alpine, crop, evergreen rainforest, evergreen needle leaf vegetation, urban, and semi-arid areas.

terpolation has been tested; however it has been discarded due to over- and undershoots in the reconstructed time series.

Fig. 1 shows an example of such modified IDR (M-IDR) reconstruction, compared with the standard IDR reconstruction, for pixels with different vegetation covers. This comparison shows that the obtained time series are similar, with a closer fit to the upper envelope of the original time series in the case of the M-IDR approach.

D. Phenology Parameter Estimation

In this paper, we estimate green-up (increase in NDVI) and brown-down (decrease in NDVI) dates pixel by pixel on a yearly basis, except for pixels with less than 0.1 annual NDVI amplitude, which have been masked out. Ref. [1] compared different phenological parameter estimation techniques, and identified the midpoint technique as preferable for green-up and brown-down date estimations. Therefore, this technique is applied here to retrieve phenological dates, green-up date corresponding to the date for which 50% of the annual amplitude is reached through an increase in NDVI values, while brown-down date corresponds to the date for which 50% of the annual amplitude is reached through a decrease in NDVI values. In case several green-up or brown-down dates are identified within a same year, the longest growing-period (largest difference between adjacent brown-down and green-up dates) is selected.

IV. Results

Green-up and brown-down dates have been retrieved for years 2008 to 2012. Fig. 2 presents these parameters for year 2012. As regards green-up dates (Fig. 2(a)), high variability can be observed over low-seasonality land covers such as evergreen rain forest (central Africa, Amazon region). Green-up starts earlier in Southern Europe than in Northern Europe, and later in altitude (Alps, Pyreneans). Brown-down dates (Fig. 2(b)) show a later occurrence in the Sahel as well as in most of Europe, while the rest of the Southern Hemisphere shows early brown-down dates. All areas observed under high viewing angles show lower than expected VI values (not shown), especially in the Amazon region, due to the increased path of the signal through the atmosphere, although retrieved phenology phases remains consistent. The comparison of NDVI-retrieved parameters from 2008 to 2012 (not shown) reveals a good stability of the observed phenology, although some annual differences can be observed locally.

V. Validation

Two approaches have been chosen to validate these results. The first one is based on comparison with an independent land surface phenology product, while the second one is based on ground data.

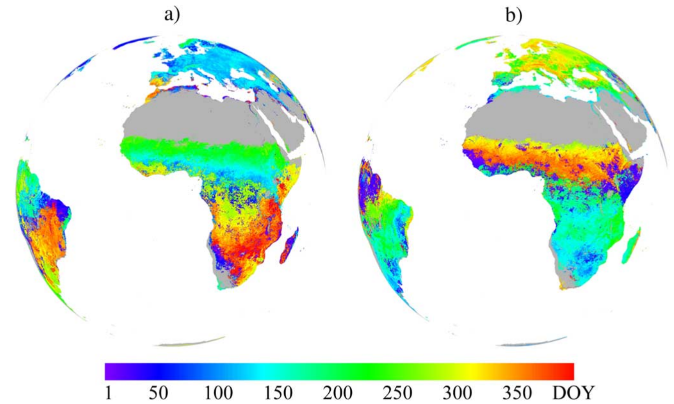

Fig. 2. Retrieved NDVI parameters for year 2012 based on MSG-SEVIRI NDVI data: (a) green-up date (NDVI increase), and (b) brown-down date (NDVI decrease).

A. Comparison With MODIS Phenology Product

We used independent phenological data retrieved by MODIS sensor, based on the yearly analysis of the temporal evolution of a different vegetation index, the Enhanced Vegetation Index (EVI [19]). For all emerged areas, green-up and brown-down dates are available as a standard MODIS product (MCD12Q2 Collection 5 [20]), which includes two eventual growth cycles (two green-up and two brown-down dates per year) from 2001 to 2010. When different versions of this product were available for a given year, we always selected the latest. Since this product is provided as MODIS tiles, we projected MCD12Q2 data to a 0.05° lat/lon grid ("plate carrée" projection) with MODIS Reprojection Toolkit. Please note that the MODIS phenology product green-up and brown-down dates are retrieved differently than with the method presented for MSG-SEVIRI data: MODIS green-up date corresponds to the onset of greenness increase (start of VI increase), while MODIS brown-down date corresponds to the onset of greenness decrease (start of VI decrease). Therefore, MODIS-retrieved phenological phases are expected to occur earlier than SEVIRI-retrieved phases.

For comparison purposes, we selected the longest MODIS growth cycle and then projected the corresponding green-up and brown-down dates to the Meteosat observation "grid". Then, we estimated the agreement between MODIS phenology product and green-up and brown-down dates from MSG-SEVIRI data. Table I presents the statistics obtained from this comparison: R^2, bias, σ and RMSE (Root Mean Square Error) for 2008 and 2009. The obtained values are quite high with RMSE in green-up date estimation of the order of one month and a half, and for brown-down date of the order of two months. However, if we look at the spatial repartition of these errors (through a comparison of 3×3 pixels of MSG and MODIS derived phenology events) for green-up, these are concentrated in central Africa (Fig. 3(a)). For example, most of Europe shows RMSE below one month for green-up. On the contrary, brown-down dates show higher RMSE in Europe, with lower values concentrated in the Sahel and northern Maghreb (Fig. 3(b)).

TABLE I
RETRIEVED STATISTICS FROM THE COMPARISON BETWEEN MSG-SEVIRI AND MODIS BASED PHENOLOGY. BIAS, Σ AND RMSE (ROOT MEAN SQUARE ERRORS) VALUES ARE IN DAYS

Year	Phenology	R^2	bias	σ	RMSE
2008	Green-up	0.921	22.6	37.4	43.7
	Brown-down	0.874	47.6	43.2	64.2
2009	Green-up	0.918	22.7	37.3	43.7
	Brown-down	0.868	48.0	44.4	65.3

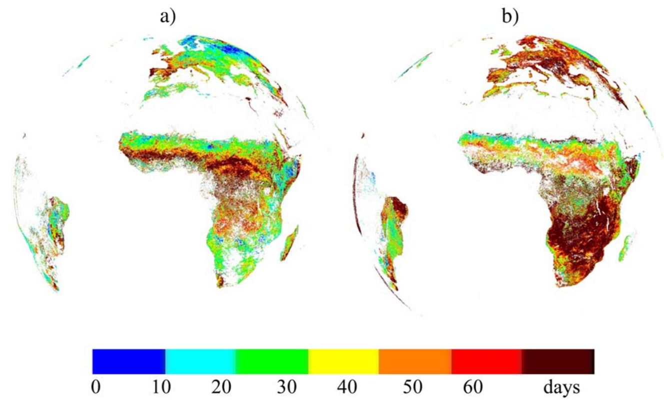

Fig. 3. RMSE between MODIS- and MSG-retrieved green-up (left) and brown-down (right) dates for year 2008. White areas correspond to sea and areas without data for MODIS dataset. (a) 2008 green-up RMSE. (b) 2008 brown-down RMSE.

B. Validation With Ground Data

Although PEP725 phenology network covers most of Europe, observations made at any station may not be representative of the surrounding vegetation. Therefore, we focused our validation on a few areas with relatively homogeneous vegetation for year 2008. Table II presents these areas, with corresponding PEP725 station numbers and species, as well as observed phenological dates to compare to SEVIRI and MODIS green-up and brown-down dates.

A general observation for all these sites is that brown-down dates are generally retrieved with a high accuracy by SEVIRI (within days), while errors for green-up dates are higher. As expected, MODIS-retrieved phenology shows earlier dates than SEVIRI. For example, the Rohrbrunn area, located in North western Bavaria (Germany), is 93% forested, the forests corresponding to oaks (*Quercus robur*, 28%), beech (*Fagus sylvatica*, 46%) and conifers (26%) [21]. Since the influence of the conifers (evergreen) on NDVI amplitude can be neglected, the SEVIRI-retrieved brown-down date is within one day of the ground observations for the main species of the area (beech). Unfortunately, for green-up metrics, no corresponding phenological observations are available for these species (only first flower opening), even though SEVIRI and MODIS-retrieved dates correspond to the greenness related PEP725 metrics in the area. As for Saxony, it is a German agricultural area, which production consists mainly of wheat (*Triticum aestivum*, 28% of cultivated surface), rye (*Secale cereale*, 5%), barley (*Hordeum*

TABLE II
VALIDATION OF SEVIRI AND MODIS PHENOLOGY METRICS FROM PEP725 DATA FOR DIFFERENT COVERS AND AREAS FOR YEAR 2008. DOYS CORRESPOND TO MEDIAN VALUES (IN DAYS), VALUES IN PARENTHESES CORRESPOND TO STANDARD DEVIATIONS (IN DAYS)

Area (Land Cover)	Phenology indicator	PEP725 station number	PEP725 species	PEP725 DOY	SEVIRI DOY	MODIS DOY
Rohrbrunn, Germany (deciduous broadleaf)	Beginning of sprouting, 25 % green in spring	3070, 3161, 3172, 4278, 4279, 4286, 4290, 4291, 4292, 4398, 4400, 4401, 4403, 4406, 4407, 4421, 4423, 8246	Meadow Vitis vinifera	84 (11) 123 (8)	107 (3)	98 (15)
Rohrbrunn, Germany (deciduous broadleaf)	Autumnal colouring of leaves (50%)	3070, 3161, 3172, 4278, 4279, 4286, 4290, 4291, 4292, 4398, 4400, 4401, 4403, 4406, 4407, 4421, 4423, 8246	Aesculus hippocastanum Betula pendula Fagus sylvatica Quercus robur Larix decidua Vitis vinífera Prunus avium (late cultivar)	278 (11) 281 (11) 282 (9) 287 (10) 295 (11) 285 (7) 292 (5)	283 (23)	210 (31)
Eastern Slovenia (deciduous broadleaf)	Autumnal colouring of leaves (50%)	6863, 6870, 6875, 19297	Aesculus hippocastanum Betula pendula Tilia cordata Prunus avium (early cultivar) Prunus avium (late cultivar) Fagus sylvatica Quercus robur Prunus domestica (late cultivar)	281 (15) 287 (9) 289 (8) 282 (12) 283 (12) 289 (9) 293 (8) 289 (8)	288 (3)	218 (13)
Southern Finland (evergreen needleleaf)	Autumnal colouring of leaves (50%)	7153, 7158, 7159, 7171	Betula pendula Betula pubescens Sorbus aucuparia Populus tremula	255 (10) 251 (9) 263 (4) 263 (8)	265 (20)	215 (23)
Central Finland (evergreen needleleaf)	Autumnal colouring of leaves (50%)	7043, 7173, 7174, 7175, 7176, 7177, 7178, 7187	Betula pendula Betula pubescens Sorbus aucuparia Populus tremula	248 (10) 247 (9) 252 (9) 251 (10)	286 (9)	209 (15)
Saxony, Germany (crops)	First node just above surface detectable	5661, 5678, 5687, 5693, 5698, 5699, 5707, 5732, 5735, 5740, 5741, 5830, 5832, 5839, 5844, 5851, 5854, 5862, 5863, 5866, 5870, 5871, 5911, 5918, 5921, 5922, 5924, 5942, 5949, 5958, 5995, 6077, 6088, 6285, 6358, 6359, 6406, 6416, 8215	Hordeum vulgare (winter) Triticum aestivum (winter) Zea mays	111 (10) 119 (10) 155 (9)	84 (14)	68 (19)
Saxony, Germany (crops)	Harvest	5661, 5678, 5681, 5682, 5683, 5687, 5688, 5690, 5693, 5694, 5697, 5698, 5699, 5701, 5702, 5703, 5704, 5705, 5706, 5707, 5711, 5714, 5715, 5732, 5733, 5734, 5735, 5736, 5737, 5738, 5739, 5740, 5741, 5742, 5743, 5800, 5801, 5802, 5804, 5807, 5830, 5832, 5833, 5835, 5836, 5837, 5838, 5839, 5840, 5844, 5845, 5846, 5847, 5848, 5849, 5850, 5851, 5852, 5853, 5854, 5855, 5856, 5858, 5859, 5860, 5861, 5862, 5863, 5864, 5865, 5866, 5867, 5869, 5870, 5871, 5911, 5912, 5913, 5916, 5917, 5918, 5920, 5921, 5922, 5923, 5924, 5925, 5926, 5942, 5949, 5951, 5952, 5957, 5958, 5960, 5961, 5964, 5965, 5966, 5989, 5990, 5991, 5993, 5993, 5995, 6026, 6029, 6036, 6037, 6038, 6066, 6067, 6077, 6078, 6079, 6080, 6088, 6200, 6210, 6285, 6355, 6356, 6358, 6359, 6362, 6363, 6405, 6406, 6416, 6417, 8215	Hordeum vulgare (winter) Triticum aestivum (winter) Beta vulgaris Helianthus annuus Avena sativa (spring) Secale cereale (winter) Zea mays	196 (7) 224 (8) 282 (9) 270 (11) 224 (9) 208 (9) 266 (10)	201 (18)	168 (31)

vulgare, 16%) and maize (*Zea mays*, 13%) [22]. SEVIRI-retrieved brown-down dates are within the range of the harvesting dates of these crops, while MODIS-retrieved dates are earlier by one month. As for green-up dates, both SEVIRI and MODIS dates are earlier than the observed phenological metric (first node detectable) by one and two months respectively, although the retrieved phases may correspond to surrounding vegetation (no other than flowering metrics were available).

The only area for which MSG-derived brown-down is more than 10-day away from ground observations is for Central Finland, where the effect of snow on evergreen vegetation in addition to the high observation angle (and therefore longer atmospheric path) may have been mistaken for vegetation brown-down. However, it is interesting to note that the browning of underrepresented deciduous trees within an evergreen forest in Southern Finland is adequately captured by our method.

VI. DISCUSSION

The differences observed between SEVIRI and MODIS-retrieved phenology can be explained by the definition of the phenological phases for both methods. For example, [1] reported differences up to 60 days for detection of phenological events depending on the method used for retrieval. Since the PEP725 phenological database do not include many observations of early season phases, the validation of MODIS green-up and brown-down dates cannot be carried out as thoroughly as in the case of SEVIRI. The fact that both approaches are based on different vegetation indexes may also play a role in these differences [13], [23]–[25].

Moreover, the differences between our NDVI based phenology estimates and MODIS-EVI phenology product can be due to inherent variability in land surface phenology. Ref. [26] showed that the variability within one scene is higher for brown-down than for green-up dates, and could reach two weeks in autumn, in agreement with the DOY standard deviations observed in Table II. Finally, validation of MODIS phenology product with two forest sites in North America shows that errors in green-up date estimation are below 20 days, while errors for brown-down date estimation can reach 38 days [20]. In comparison, the good accuracy of the brown-down dates retrieved from SEVIRI data represents a strong improvement on existing land surface phenology.

In the case of Central Finland, both snow and atmospheric effects cannot be ignored. First, the biophysical meaning of green-up and brown-down date is different for winter-snow-covered areas. However, snowmelt and vegetation green-up have been shown to be correlated, vegetation green-up occurring shortly after snowmelt (as shown for example in [27]). As for the influence of the atmosphere for high viewing angles, the absence of atmospheric correction of NDVI may result in error-prone estimates of phenological phases, explained by the compressed NDVI amplitude due to increased optical path. An atmospheric correction could therefore be beneficial to the approach, although algorithms for an atmospheric correction are usually limited to low viewing angles (below 50° for SMAC [28]; 5 S [29]; and 6 S, which also performs for higher viewing angles, although with lower accuracy [30]) so atmospheric correction would be highly difficult for these areas (outer portion of MSG observed disk).

Finally, the validation has only been carried out for European vegetation, due to the lack of publicly available phenology data over Africa. Should such a dataset become available, the validation of this method in Africa would be carried out by the authors.

VII. Conclusion

In this paper, a modified method, based on the IDR approach, has been presented to reconstruct time series affected by both data gaps and atmospheric and cloud contamination. This method (M-IDR) has been shown to provide temporal profiles with similar characteristics to the original method, while dealing efficiently with higher temporal resolution (daily versus bimonthly). This M-IDR methodology has been applied to SEVIRI NDVI time series for estimation of phenological phases such as green-up and brown-down of vegetation for years 2008 to 2012. When compared with MODIS-retrieved phenology, green-up dates show on average a one and a half month difference, while for brown-down dates this difference amounts to two months. Observed differences can be explained by methodology differences (different vegetation indexes are used). Direct comparison of both SEVIRI and MODIS retrieved phenology with pan-European phenological data show a better agreement of phenology retrieved from SEVIRI than from MODIS, again due to methodological choices. However, the high accuracy (within days) of the developed method in the case of brown-down dates for most validation sites represents a strong improvement on existing methods.

Since a key point for phenology studies is the rapid availability of observations for the scientific community, processing times between complete year of data retrieval and phenological phases availability should be minimized. At the moment this paper was redacted, the latest phenological retrievals from MODIS data were from year 2010, with a more than two year lag between complete year data acquisition and phenology parameter extraction, while MSG-retrieved phenology is available within weeks of yearly data completion.

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References

[1] M. A. White, K. M. De Beurs, K. Didan, D. W. Inouye, A. D. Richardson, O. P. Jensen, J. O'Keefe, G. Zhang, R. R. Nemani, W. J. D. Van Leeuwen, J. F. Brown, A. De Wit, M. Schaepman, X. Lin, M. Dettinger, A. S. Bailey, J. Kimball, M. D. Schwartz, D. D. Baldocchi, J. T. Lee, and W. K. Lauenroth, "Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982–2006," *Global Change Biology*, vol. 15, pp. 2335–2359, 2009.

[2] M. Friedl, G. Henebry, B. Reed, A. Huete, M. White, J. Morisette, R. Nemani, X. Zhang, and R. Myneni, *Land Surface Phenology*, A Community White Paper Requested by NASA, 2006.

[3] Y. Julien and J. A. Sobrino, "Global land surface phenology trends from GIMMS database," *Int. J. Remote Sens.*, vol. 30, no. 13, pp. 3495–3513, 2009.

[4] A. Menzel, "Trends in phenological phases in Europe between 1951 and 1996," *Int. J. Biometerol.*, vol. 44, pp. 76–81, 2000.

[5] R. Ahas, A. Aasa, A. Menzel, V. G. Fedotova, and H. Scheifinger, "Changes in European spring phenology," *Int. J. Climataol.*, vol. 22, pp. 1727–1738, 2002.

[6] M. D. Schwartz, R. Ahas, and A. Aasa, "Onset of spring starting earlier across the Northern Hemisphere," *Global Change Biology*, vol. 12, pp. 343–351, 2006.

[7] R. B. Myneni, C. D. Keeling, C. J. Tucker, G. Asrar, and R. R. Nemani, "Increased plant growth in the northern high latitudes from 1981 to 1991," *Nature*, vol. 386, pp. 698–702, 1997.

[8] C. J. Tucker, D. A. Slayback, J. E. Pinzon, S. O. Los, R. B. Myneni, and M. G. Taylor, "Higher northern latitude NDVI and growing season trends from 1982 to 1999," *Int. J. Biometerol.*, vol. 45, pp. 184–190, 2001.

[9] L. Zhou, C. J. Tucker, R. K. Kaufmann, D. Slayback, N. V. Shabanov, and R. B. Myneni, "Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999," *J. Geophys. Res.*, vol. 106, pp. 20069–20083, 2001.

[10] J. Bogaert, L. Zhou, C. J. Tucker, R. B. Myneni, and R. Ceulemans, "Evidence for a persistent and extensive greening trend in Eurasia inferred from satellite vegetation index data," *J. Geophys. Res.*, vol. 107, no. D11, 2002, 10.1029/2001JD001075.

[11] B. Tan, J. T. Morisette, R. E. Wolfe, F. Gao, G. A. Ederer, J. Nightingale, and J. A. Pedelty, "An enhanced TIMESAT algorithm for estimating vegetation phenology metrics from MODIS data," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 4, no. 2, pp. 361–371, Aug. 2011.

[12] D. Pouliot, R. Latifovic, R. Fernandes, and I. Olthof, "Evaluation of compositing period and AVHRR and MERIS combination for improvement of spring phenology detection in deciduous forests," *Remote Sen. Environ.*, vol. 115, pp. 158–166, 2011.

[13] B. Tan, J. T. Morisette, R. E. Wolfe, G. Gao, G. Ederer, J. Nightingale, and J. Pedelty, "Vegetation phenology metrics derived from temporally smoothed and gap-filled MODIS data," *Proc. IGARSS*, vol. 3, pp. III-593–III-596, 2008, 10.1109/IGARSS.2008.4779417.

[14] B. Tan, J. T. Morisette, R. E. Wolfe, G. Gao, G. Ederer, J. Nightingale, and J. Pedelty, "An enhanced TIMESAT algorithm for estimating vegetation phenology metrics from MODIS data," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 4, no. 2, pp. 361–371, Aug. 2011.

[15] Y. Julien and J. A. Sobrino, "Comparison of cloud-reconstruction methods for time series of composite NDVI data," *Remote Sen. Environ.*, vol. 114, pp. 618–625, 2010.

[16] C. J. Tucker, "Red and photographic infrared linear combinations for monitoring vegetation," *Remote Sen. Environ.*, vol. 8, pp. 127–150, 1979.

[17] R. Fensholt, I. Sandholt, S. Stisen, and C. Tucker, "Analyzing NDVI for the African continent using the geostationary meteosat second generation SEVIRI sensor," *Remote Sen. Environ.*, vol. 101, pp. 212–229, 2006.

[18] B. N. Holben, "Characteristics of maximum values composite images from temporal AVHRR data," *Int. J. Remote Sens.*, vol. 7, pp. 1417–1434, 1986.

[19] X. Zhang, M. A. Friedl, and C. B. Schaaf, "Sensitivity of vegetation phenology detection to the temporal resolution of satellite data," *Int. J. Remote Sens.*, vol. 30, no. 8, pp. 2061–2074, 2009.

[20] J. B. Thayn and K. P. Price, "Julian dates and introduced temporal error in remote sensing vegetation phenology studies," *Int. J. Remote Sens.*, vol. 29, no. 20, pp. 6045–6049, 2008.

[21] K. W. Gottschalk, "Oak silviculture, management, defoliation effects in France and Germany," in *Proc. 9th Central Hardwood Forest Conf.*, A. R. Gillespie, G. R. Parker, P. E. Pope, and G. Rink, Eds., 1993, pp. 23–45.

[22] Ernaehrungs Landwirtschaft 2011, Feb. 13, 2013 [Online]. Available: https://publikationen.sachsen.de/bdb/artikel/15890/documents/19940

[23] A. Huete, K. Didan, T. Miura, E. P. Rodriguez, X. Gao, and L. G. Ferreira, "Overview of the radiometric and biophysical performance of the MODIS vegetation indices," *Remote Sen. Environ.*, vol. 83, pp. 195–213, 2002.

[24] S. Ganguly, M. A. Friedl, B. Tan, X. Zhang, and M. Verma, "Land surface phenology from MODIS: Characterization of the collection 5 global land cover dynamics product," *Remote Sen. Environ.*, vol. 114, pp. 1805–1816, 2010.

[25] S. R. Garrity, G. Bohrer, K. D. Maurer, K. L. Mueller, C. S. Vogel, and P. S. Curtis, "A comparison of multiple phenology data sources for estimating seasonal transitions in deciduous forest carbon exchange," *Agricul. Forest Meteorol.*, vol. 151, pp. 1741–1752, 2011.

[26] A. R. Huete, H. Q. Liu, K. Batchily, and W. van Leeuwen, "A comparison of vegetation indexes over a global set of TM images for EOS-MODIS," *Remote Sen. Environ.*, vol. 59, pp. 440–451, 1997.

[27] K. Hufkens, M. Friedl, O. Sonnentag, B. H. Braswell, T. Milliman, and A. D. Richardson, "Linking near-surface and satellite remote sensing measurements of deciduous broadleaf forest phenology," *Remote Sen. Environ.*, vol. 117, pp. 307–321, 2012.

[28] A. D. Richardson, B. H. Braswell, D. Y. Hollinger, J. P. Jenkins, and S. V. Ollinger, "Near-surface remote sensing of spatial and temporal variation in canopy phenology," *Ecolog. Appl.*, vol. 19, no. 6, pp. 1417–1428, 2009.

[29] H. Steltzer, C. Landry, T. H. Painter, J. Anderson, and E. Ayres, "Biological consequences of earlier snowmelt from desert dust deposition in alpine landscapes," *PNAS*, 10.1073/pnas.0900758106, 2009.

[30] H. Rahman and G. Dedieu, "SMAC: A simplified method for the atmospheric correction of satellite measurements in the solar spectrum," *Int. J. Remote Sens.*, vol. 15, no. 1, pp. 123–143, 1994.

[31] D. Tanré, C. Deroo, P. Duhaut, M. Herman, J. J. Morcrette, J. Perbos, and P. Y. Deschamps, "Technical note description of a computer code to simulate the satellite signal in the solar spectrum: The 5 S code," *Int. J. Remote Sens.*, vol. 11, no. 4, pp. 659–668, 1990.

[32] S. Y. Kotchenova and E. F. Vermote, "Validation of a vector version of the 6 S radiative transfer code for atmospheric correction of satellite data. Part II. Homogeneous Lambertian and anisotropic surfaces," *Appl. Opt.*, vol. 46, no. 20, pp. 4455–4464, 2007.

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