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Validation of Global LAnd Surface Satellite (GLASS) leaf area index product

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Abstract: Long time series Global LAnd Surface Satellite (GLASS) Leaf Area Index (LAI) product (1981—2012) is generated from time-series MODIS and AVHRR reflectance data using general regression neural network method. This study assesses the performance of the GLASS LAI product in two ways: (1) by comparing the spatial and temporal characteristics of the GLASS LAI product with those of other moderate-resolution LAI global products and (2) by comparing the GLASS LAI values with ground measurement data. The results show that the GLASS LAI product achieved a good consistency with the MODIS and CYCLOPES LAI products at the global scale, although with differences in magnitude of LAI values. The largest differences occur between the GLASS and CCRS LAI products in high northern latitudes and close to the equator, followed by differences between the GLASS and MODIS LAI products and the GLASS and CYCLOPES LAI products. The GLASS and MODIS LAI products have more complete temporal trajectories than the CYCLOPES LAI product, while the GLASS and CYCLOPES LAI products have more continuous and realistic trajectories than the MODIS LAI product. The GLASS LAI product maintains reasonable profiles in c ontrast to the MODIS LAI product, which shows dramatic fluctuations, particularly during the growing seasons. Compared with 20 ground-measured LAI reference maps at 17 sites, the GLASS LAI product shows lower uncertainty, with an R-square of 0.76 and RMSE of 0.51, than the MODIS and CYCLOPES LAI products.

Key words: Leaf Area Index (LAI), GLASS, validation, MODIS, long time series

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1 INTRODUCTION

Leaf Area Index (LAI), defined as the single-sided leaf area per unit horizontal ground area (Chen & Black, 1992), is a key biophysical variable in land surface processes related to vegetation dynamics, such as photosynthesis, transpiration, and energy balance (Sellers, et al., 1997).

Long-term global or regional LAI products are urgently needed for the study of global change, climate modeling, and many other problems. Currently, multiple global LAI products have been produced from various types of satellite remote sensing data: MODerate resolution Imaging Spectroradiometer (MODIS) (Knyazikhin, et al., 1998; Myneni, et al., 2002; Yang, et al., 2006), Carbon Cycle and Change in Land Observational Products from an Ensemble of Satellites (CYCLOPES) (Baret, e t al., 2007), Canada Centre for Remote Sensing (CCRS) (F ernandes, et al., 2003), ECOCLIMAP (Masson, et al., 2003), and GLOBal Biophysical Products Terrestrial CARBON Studies (GLOBCARBON) (Deng, et al., 2006). Validations and comparisons among these LAI products demonstrate that these products have common problems of limited temporal continuity, spatial i ntegrity, and accuracy. The uncertainties (within ±1.0) of current global LAI products remain incapable of meeting the threshold accuracy requirements (±0.5) stipulated by the Global Climate Observing System (Fang, et al., 2012).

To meet the demand for long time series and high-quality global LAI products, Xiao, et al. (2013) developed an operational method to generate a long-time-series Global Land Surface Satellite (GLASS) LAI product (1981—2012) from time series MODIS and AVHRR reflectance data , with support from the

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Project "Study on the generation and application of global land surface characteristic parameter products."

This study aims to assess the performance of the GLASS LAI product derived from time series MODIS reflectance. An a nalysis and comparison with MODIS, CYCLOPES, and CCRS LAI products are performed to evaluate the spatial and temporal consistencies of the GLASS LAI product. The global distributions and frequency histograms of the GLASS, MODIS, CYCLOPES, and CCRS LAI products, as well as the spatial d istribution of differences between GLASS and the other three LAI products, are used to evaluate the spatial consistency of the GLASS LAI product. Time-series analysis of the GLASS, M ODIS, and CYCLOPES LAI products from 2001 to 2007 are performed to compare the GLASS LAI with other LAI products over time, and direct comparisons with the LAI field measurements are conducted to evaluate the accuracy and precision of the GLASS LAI product.

The GLASS LAI product, along with other global LAI products used in this study, and the field LAI measurements are briefly described in Section 2. The methods to evaluate and validate the GLASS LAI product are presented in Section 3. The spatial and temporal consistencies of the GLASS LAI product are discussed in Section 4, and the accuracy of the GLASS LAI product is also evaluated against the LAI field measurements in this section. Conclusions are then presented in the final section.

2 DATA

2.1 Global LAI products

MODIS, CYCLOPES, and CCRS LAI products are compared with the GLASS LAI product in this study. The main characteristics of these global LAI products are described below.

2.1.1 GLASS LAI product

The GLASS LAI product with a temporal resolution of 8 d has been available since 1981 from the Center for Global Change Data Processing and Analysis of Beijing Normal University ([2010-07-10] http://www.bnu-datacenter.com/). From 1981 to 1999, the product was generated from AVHRR surface reflectance and provided in a geographic projection at the spatial resolution of 0.05°. Since 2000, the product has been generated from MODIS surface reflectance (MOD09A1) and provided in an I ntegerized Sinusoidal projection at a spatial resolution of 1 km. The latest version of the GLASS LAI product is Version 3.0 and is used in this study.

To exploit the potential of multi-temporal remote sensing data fully, the GLASS LAI product (since 2000) was produced from time-series MODIS surface reflectance data using general regression neural networks (GRNNs) (Xiao, et al., 2013). A database was generated to train the GRNNs from MODIS and C YCLOPES LAI products and MODIS surface reflectance products of the BELMANIP sites (Baret, et al., 2006) from 2001 to 2004. The BELMANIP is a global network that includes 402 sites that can properly represent the variability of surface types and conditions. A 3×3 subset of MODIS and CYCLOPES LAI products and MODIS reflectance product was extracted for each BELMANIP site. The effective CYCLOPES LAI values were first converted to true LAI values using the clumping index d erived from POLDER data. The true CYCLOPES LAI values were then combined with the MODIS LAI according to the u ncertainties as determined from the ground-measured true LAI (Xiao, et al., 2013). The MODIS surface reflectance was reprocessed to remove the remaining effects of cloud contamination and other factors by using temporal-spatial filtering algorithms and to fill the missing data by using an optimum interpolation a lgorithm. Finally, to retrieve the GLASS LAI (since 2000) from time series MODIS surface reflectance data, GRNNs were trained using the fused LAI and reprocessed MODIS surface reflectance for each biome type, and the reprocessed MODIS reflectance data from an entire year were then input into the GRNNs to estimate one-year LAI profiles.

2.1.2 MODIS LAI product

The MODIS LAI product has been available since 2000 ([2010-06-10] http://reverb.echo.nasa.gov/reverb/). The product comes in a sinusoidal projection at a 1 km spatial resolution and an 8 d time step. The latest version of the combined TERRA-AQUA MODIS LAI product, Collection 5, is used in this study.

The MODIS LAI retrieval algorithm consists of a main a lgorithm and a backup algorithm. The main algorithm is based on Lookup Tables (LUTs) simulated using a three-dimensional radiation transfer model, whereas the backup algorithm is based on the biome-specific LAI-NDVI relationships (Knyazikhin, e t al., 1998). When the main algorithm fails, the backup algorithm is used to estimate LAI.

In addition to providing the LAI value for each pixel, the MODIS LAI product also provides quality control (QC) information to state the quality of the LAI value. If $QC < 32$, the main algorithm successfully retrieves the LAI value without saturation, and the LAI value is with the best possible quality. If $32 \leqslant QC < 64$, the LAI value is calculated from the main algorithm with s aturation. If $64 \leqslant QC < 128$, the main algorithm fails because of poor geometry or other problems, and the back-up algorithm is triggered to estimate LAI. If $QC \geqslant 128$, the back-up algorithm fails, no LAI value is retrieved, and a filled value is assigned a ccording to the land cover types.

2.1.3 CYCLOPES LAI product

The CYCLOPES LAI product comes in an equirectangular projection at a spatial resolution of 1/112° and a temporal resolution of 10 d. The product was available from 1999 to 2007.

The CYCLOPES LAI product is estimated from the SPOT/VEGETATION sensor observations. The retrieval algorithm uses a neural network trained on a one-dimensional radiative SAIL transfer model simulation (Baret, et al., 2007). Clumping at the plant and canopy scales is not represented, although it is considered at the landscape scale by regarding mixed pixels as having fractions of pure vegetation and pure bare soil.

2.1.4 CCRS LAI product

The CCRS LAI product is also retrieved from the SPOT/VEGETATION sensor observations and provided at 10 d temporal sampling and a spatial resolution of 1/112°. The SPOT/VEGETATION surface reflectances for the shortwave i nfrared bands, along with the red and near-infrared bands, are used to generate the CCRS LAI product. The LAI product is e stimated based on the relationships between LAI and RSR for forest pixels and between LAI and SR for all other land cover types (Deng, et al., 2006). The Four-Scale bidirectional reflectance model (Chen & Leblanc, 1997) is used to simulate the bidirectional reflectance and establish the empirical relationships between LAI and vegetation indices for each land cover type. Variations in the solar zenith angle are also considered in the algorithm.

2.2 Field LAI

The Validation of Land European Remote sensing Instrument (VALERI) project ([2010-06-10] http://w3.avignon.inra.fr/valeri/) developed a globally distributed network of sites and a standard method to measure the biophysical variables of interest directly at the proper spatial and temporal scales. This network contains 33 sites and 52 LAI reference maps. The LAI reference maps were derived from the determination of the transfer function between the reflectance values of the high-spatial-resolution SPOT images and the LAI ground measurements. The SPOT image was acquired by HRVIR1 on SPOT 4 during or near the ground campaign. The LAI ground measurements were obtained using the LAI-2000 Plant Canopy Analyzer (Welles & Norman, 1991) or hemispherical photographs which were p rocessed using the CAN-EYE software (Version 3.6) developed at INRA-CSE (Demarez, et al., 2008). In this study, only 20 LAI reference maps, which provide true LAI values, were selected from the 52 LAI reference maps to validate the accuracy of the GLASS LAI and the other LAI products. The characteristics of the selected validation sites are shown in Table 1.

Table 1 Characteristics of the selected validation sites (17 sites with 20 LAI reference maps)

Site	Country	Latitude/°	Longitude/°	Biome type	DOY	Year	Mean LAI
Alpilles	France	43.810	4.715	Grasses/cereal crops	204	2002	1.691
Camerons	Australia	-32.598	116.254	Savannah	63	2004	2.13
Demmin	Germany	53.892	13.207	Broadleaf crop	164	2004	4.15
Donga	Benin	9.770	1.778	Savannah	172	2005	1.85
Fundulea	Romania	44.406	26.585	Grasses/cereal crops	144	2002	1.53
Gilching	Germany	48.082	11.320	Grasses/cereal crops	199	2002	5.39
Gnangara	Australia	-31.534	115.882	Savannah	61	2004	1.01
Larzac	France	43.938	3.123	Savannah	183	2002	0.81
Nezer	France	44.568	-1.038	Evergreen needleleaf forest	107	2002	2.38
Plan-de-Dieu	France	44.199	4.948	Grasses/cereal crops	189	2004	1.13
Puechabon	France	43.725	3.652	Savannah	164	2001	2.85
Sonian	Belgium	50.768	4.411	Deciduous broadleaf forest	174	2004	5.66
Sud-Ouest	France	43.506	1.238	Broadleaf crop	189	2002	1.96
Zhangbei	China	41.279	114.688	Grasses/cereal crops	221	2002	1.26
Counami	French Guyana	5.343	-53.237	Evergreen broadleaf forest	269	2001	4.93
Counami	French Guyana	5.343	-53.237	Evergreen broadleaf forest	286	2002	4.37
Laprida	Argentina	-36.990	-60.553	Broadleaf crop	311	2001	5.82
Laprida	Argentina	-36.990	-60.553	Broadleaf crop	292	2002	2.81
Turco	Bolivia	-18.235	-68.184	Shrub	208	2001	0.31
Turco	Bolivia	-18.235	-68.184	Shrub	240	2002	0.04

3 METHODS

To assess the performance of the GLASS LAI product, an analysis and comparison with MODIS, CYCLOPES and CCRS LAI products are performed in this study. Field measurements are also used to validate these global LAI products.

An inter-comparison with the MODIS, CYCLOPES, and CCRS LAI products was performed to examine the spatial and temporal consistency of the GLASS LAI product. These global LAI products have a different spatial and temporal resolution and use different projection systems. Thus, the projections of the C YCLOPES and CCRS LAI products were first transformed into sinusoidal projection by using the GCTP library and resampled to a 1 km spatial resolution by using the nearest neighbor resampling method. Then, all these LAI products were aggregated into a monthly time step using the averaging method. Since the quality of LAI values retrieved by the backup algorithm is poor, we selected good quality MODIS LAI from the main algorithm with QC less than 64 in the intercomparisons.

Global spatial distributions and histogram of the GLASS, MODIS, CYCLOPES, and CCRS LAI values for January and July, 2003 are used to analyze the range and distribution of LAI values from each global LAI product, and to evaluate the spatial consistency of these products. Furthermore, spatial distributions of the differences between the GLASS LAI product and other global LAI products for July, 2003 and their frequency distributions were produced to analyze more deeply the discrepancies between these global LAI products. Moreover, the temporal c onsistency and seasonal variations are evaluated by comparing the temporal profiles of the GLASS, MODIS (with main algorithm), and CYCLOPES LAI products for several VALERI sites with different vegetation types.

The GLASS, MODIS (main algorithm), and CYCLOPES LAI products are also compared directly with the same data set of LAI reference maps at several VALERI sites to quantify the o verall performance of the GLASS LAI product. The LAI reference maps, with the spatial resolution of 30 m or so, are upscaled into 1 km spatial resolution. Then, the aggregated average values of the LAI reference maps are used to validate the GLASS, M ODIS, and CYCLOPES LAI products. Difference in the julian date and measuring time of field LAI are observed among the three LAI products. In this study, the LAI values closest to the field measurement time are compared with the field LAI values.

4 RESULTS

4.1 Spatial consistency analysis

Fig. 1 shows the spatial distribution of the GLASS, MODIS, CYCLOPES, and CCRS LAI products at a global scale for January, 2003 and July, 2003. All products followed the seasonality effect, which shows opposite properties in the two hemispheres. In the northern Hemisphere, the LAI values in July were significantly higher than those in January. The LAI values in January for the northern Hemisphere were between 0 and 1, and the spatial variation was generally very low. In July, the northern Hemisphere showed large spatial variations, with higher LAI values in Canada, Russia, and southeast Asia. In contrast to the variation of the northern Hemisphere, the LAI values in January for the southern Hemisphere were generally larger than those in July.

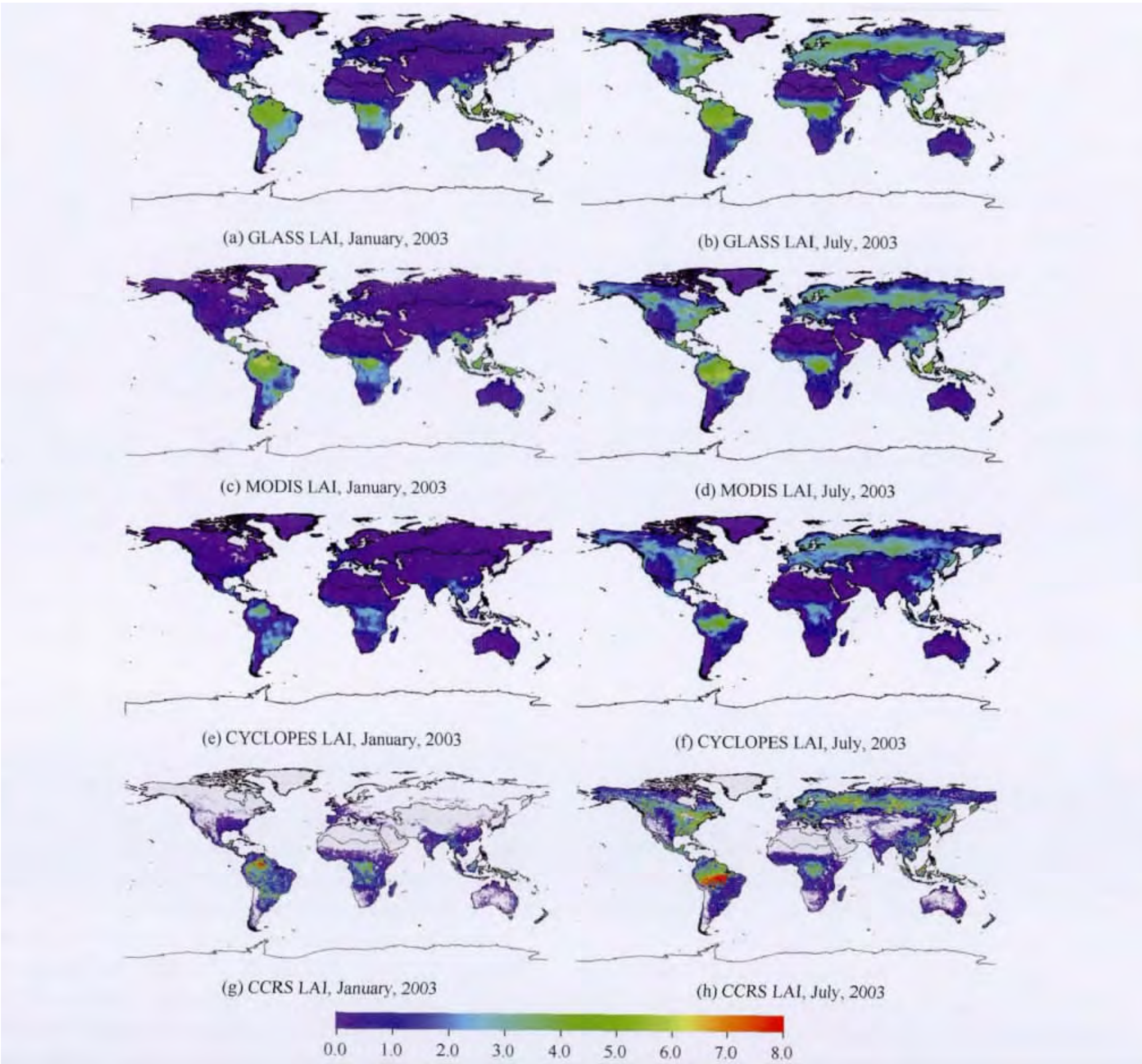


Fig. 1 Global spatial distribution of the GLASS, MODIS, CYCLOPES and CCRS LAI products for January 2003 and July 2003

The GLASS and MODIS LAI products achieved better s patial completeness than the CYCLOPES and CCRS LAI. The CYCLOPES and CCRS LAI products were observe to contain a large number of missing pixels, and some missing pixels were present in the MODIS LAI product. By contrast, the GLASS LAI product was the most spatially complete.

Comparatively speaking, the GLASS LAI product achieved better agreement with the MODIS LAI product both in January and July. A relatively large discrepancy between the LAI products was observed in the tropical forest regions. The CCRS LAI product maintained a higher LAI values than the GLASS and MODIS LAI products, whereas the CYCLOPES LAI product maintained the lowest LAI values over these regions.

Fig. 2 shows histogram distributions of the GLASS, MODIS, CYCLOPES, and CCRS LAI values for July 2003. When the LAI values were larger than 4.0, the frequency of the CYCLOPES LAI approached zero, indicating a significant u nderestimation of the CYCLOPES LAI product for the broadleaf and needle forest biome types attributed to the characteristics of the CYCLOPES algorithm (Garrigues, et al., 2008).

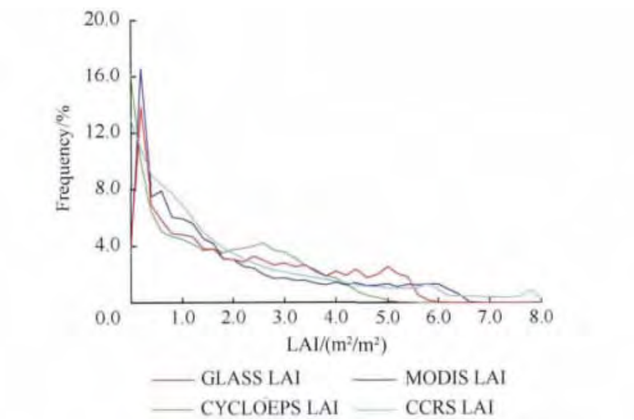


Fig. 2 Histogram distributions of the GLASS, MODIS, CYCLOPES, and CCRS LAI values for July 2003

The highest LAI value of the GLASS LAI product reached 6.0, and the highest LAI value of the MODIS LAI product e xceeded 6.5. By contrast, the CCRS LAI product with the highest LAI value reaching 8 had the largest dynamic range of LAI compared with the GLASS and MODIS LAI products to d escribe the global variability of LAI. The CYCLOPES LAI product showed the smallest dynamic range of LAI. When the LAI values were smaller than 2.0, the higher frequencies were a chieved by the MODIS LAI product, and when the LAI values were larger than 2.0, the GLASS product achieved higher f requencies. A possible explanation is that many of the MODIS LAI values are significantly underestimated because of clouds and other poor atmospheric conditions, and the GLASS LAI v alues are generally larger than the MODIS LAI values during the growing season over northern latitudes.

Fig. 3(a) shows the spatial distribution of differences between GLASS LAI and the MODIS LAI retrieved by the main algorithm for July 2003 and Fig. 4(a) shows the histogram distribution of the differences between the GLASS and MODIS LAI products for the same period. The difference values were calculated by subtracting the MODIS LAI from the GLASS LAI. The GLASS LAI was in a good agreement with the MODIS LAI with good quality (QC < 64). More than 80% of the difference values shown in Fig. 4(a) were between −0.5 and 0.5, and the percentage of the difference values between −0.1 and 0.1 reached 35%.

By contrast, Fig. 4(a) shows the histogram distribution of the differences between GLASS LAI and the MODIS LAI retrieved by the backup algorithm for July 2003. Larger discrepancies a ppeared when the quality of MODIS LAI was poor (QC ≥ 64). On one hand, the MODIS LAI for some pixels with poor quality was slightly larger than the corresponding GLASS LAI. The difference values were between −2.0 and 0.0, and the histogram distribution of the differences between the GLASS LAI and M ODIS LAI with poor quality exhibited a small peak approximately −0.5 (Fig. 4(a)). The negative difference was attributed to the overestimation of the MODIS LAI values associated with broadleaf forests (Garrigues, et al., 2008). On the other hand, the MODIS LAI values with poor quality were significantly lower than the corresponding GLASS LAI values. For these pixels, the MODIS LAI values were poorly retrieved because of consistent cloud contamination in the observation data. The GLASS LAI values were generally higher, approximately 3.0 to 5.0, than the MODIS LAI values. The properties of the differences between GLASS and MODIS LAI products described above suggest that the GLASS LAI has improved upon the unrealistically high or low values of the MODIS LAI with poor quality, especially for the forest biome types.

Fig. 3(b) displays a map of differences between the GLASS and CYCLOPES LAI for July 2003. The difference values were calculated by subtracting the CYCLOPES LAI values from the GLASS LAI values. The CYCLOPES LAI significantly underestimates the GLASS LAI for the broadleaf and needle forest biome types because of the lack of clumping representation in the CYCLOPES algorithm (Garrigues, et al., 2008). Fig. 4(b) shows a histogram of the differences. The histogram had only one peak near zero, and the percentage of the differences at the zero value was 45%. More than 70% of the difference values shown in Fig. 4(b) were between −0.5 and 0.5. The positive differences were significantly larger than the negative ones. The difference values between 1 and 3 were observed near the equator and in the higher latitudes of the northern Hemisphere. Compared with the histogram distributions of the differences b etween the GLASS and MODIS LAI, the GLASS LAI product achieved a good consistency with the CYCLOPES LAI and M ODIS LAI retrieved from main algorithm.

A map of differences between the GLASS and CCRS LAI products is shown in Fig. 3(c), and a histogram of the differences is shown in Fig. 4(c). The difference values were calculated by subtracting the CCRS LAI values from the GLASS LAI values. We observed that the GLASS LAI values were larger than the CCRS LAI values in the most of areas. The differences of more than 2.0 were mainly distributed in the areas near the equator, where the GLASS and MODIS LAI had consistently higher LAI values (approximately 6.0), and the CCRS LAI values were in the range of 2.0 to 4.0. The differences of less than −2.0 were mainly distributed in southern Brazil, where the CCRS

LAI maintained a higher LAI values (8.0 to 9.0) in contrast to the GLASS LAI values of 5.0 to 6.0. Generally, the differences b etween the GLASS and CCRS LAI products were significantly larger than the differences between the GLASS and MODIS LAI products or the differences between the GLASS and CYCLOPES LAI products.

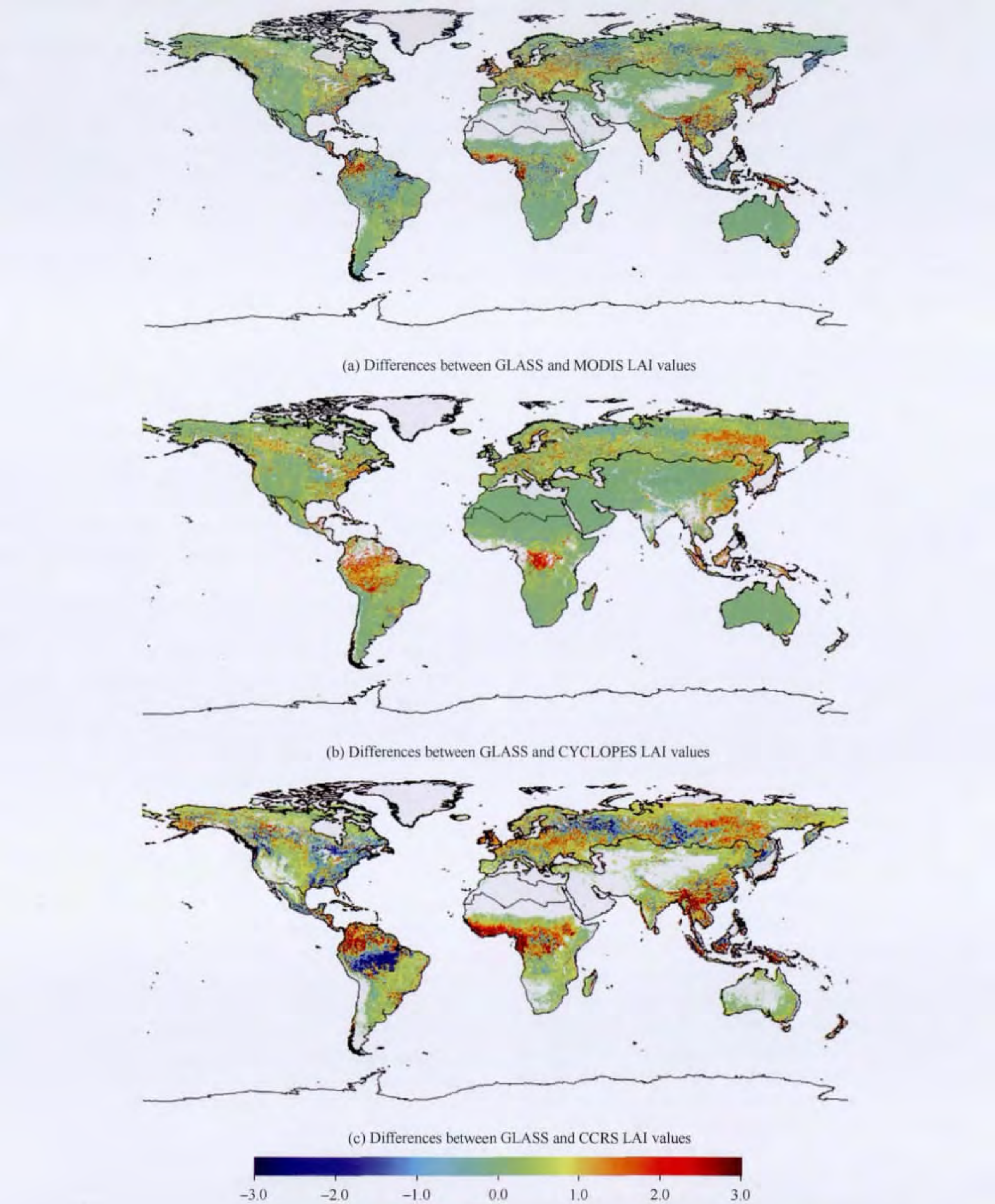


Fig. 3 Spatial distribution of differences between the GLASS LAI and MODIS, CYCLOPES, CCRS LAI in July 2003

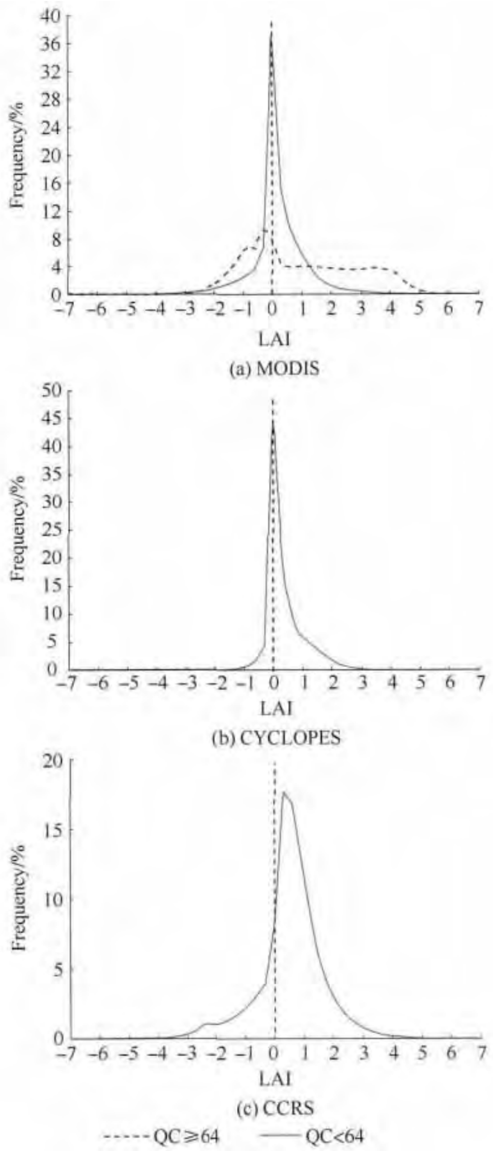


Fig. 4 Histograms of the differences between the GLASS LAI and the MODIS LAI, the CYCLOPES LAI and the CCRS LAI for July 2003

4.2 Temporal consistency analysis

Temporal profiles of the GLASS, MODIS (with main algorithm), and CYCLOPES LAI products for some sites in Table 1 were compared to analyze temporal consistency and seasonal variations from 2001 to 2007 during which all the three LAI products provided valid data. The main biome classes of the s elected sites included broadleaf crops, grasses and cereal crops, needleleaf forests, broadleaf forests, shrubs, and savannahs a ccording to MODIS land cover. In addition, the temporal profiles of these LAI products were also compared with the mean LAI of the reference maps available for each selected site to e valuate the quality of each product in the time series.

Fig. 5 shows the temporal LAI trajectories over the Zhangbei and Wankama sites. The biome type for these sites is grasses and cereal crops according to MODIS land cover. At the Zhangbei site, the GLASS, MODIS, and CYCLOPES LAI products captured similar temporal trajectories. The three products all yielded complete and continuous profiles. The interannual variation of the GLASS and CYCLOPES LAI values was low, but a s ignificantly larger magnitude of the MODIS LAI was observed during the growing season of 2006. At the Wankama site, the GLASS and CYCLOPES LAI profiles were relatively smooth but the MODIS data were invalid or retrieved by the backup a lgorithm. The CYCLOPES LAI profile maintained lower LAI values compared with the GLASS and MODIS LAI profiles. Comparatively speaking, the GLASS LAI values were closer to the mean LAI of the reference maps than the MODIS and CYCLOPES LAI values.

Fig. 6 shows the temporal LAI trajectories over the Plande-Dieu, Fundulea, and Gilching sites with broadleaf crop biome types according to MODIS land cover. The GLASS and CYCLOPES LAI products over these sites provided smooth and continuous trajectories, whereas the profile of the MODIS LAI showed dramatic fluctuations especially in the Gilching site. All the LAI profiles at the PlandeDieu and Fundulea sites exhibited similar seasonal variations and good consistency. Exceptionally on PlandeDieu, GLASS LAI retrieved higher LAI during the 2002 growing season than other years and MODIS LAI achieved higher interannual variations on 2001 and 2004. At the Gilching site, large discrepancies were observed between the GLASS LAI values and the MODIS and CYCLOPES LAI estimates. The GLASS LAI values were generally larger than the CYCLOPES and MODIS LAI estimates throughout the entire growing seasons. Owing to the fluctuations of MODIS LAI, GLASS LAI was less than MODIS LAI at some choppy time plot. At the Gilching and PlandeDieu sites, the GLASS, CYCLOPES, and MODIS LAI values became underestimates in comparison with the mean LAI of the reference maps. The CYCLOPES and GLASS LAI values were generally in good agreement with the mean LAI of the reference maps at the Fundulea site.

Fig. 7 shows the temporal LAI trajectories over the Puechabon, Larzac and Donga sites, which are of the savannah biome type according to MODIS land cover. The GLASS and CYCLOPES LAI profiles were smoother, whereas the profile of the MODIS LAI showed dramatic fluctuations, with sudden peak and valley values during the growing season, particularly over the Donga site. All the products captured the seasonal variation and low interannual variation. At the Puechabon site, the GLASS, MODIS, and CYCLOPES LAI values showed similar temporal trajectories and were all underestimates when compared with the mean LAI of the reference map. At the Larzac site, the GLASS and MODIS LAI products were in good agreement, whereas the CYCLOPES LAI profile maintained lower LAI v alues. Meanwhile, the three LAI products became overestimates compared with the mean LAI of the reference map. At the Donga site, the GLASS and CYCLOPES LAI profiles achieved a good agreement with envelope of the time series MODIS LAI values, although many of the CYCLOPES LAI values were missing d uring the peak of the growing seasons. Moreover, excellent a greement was achieved between the GLASS LAI values and the mean LAI of the reference map.

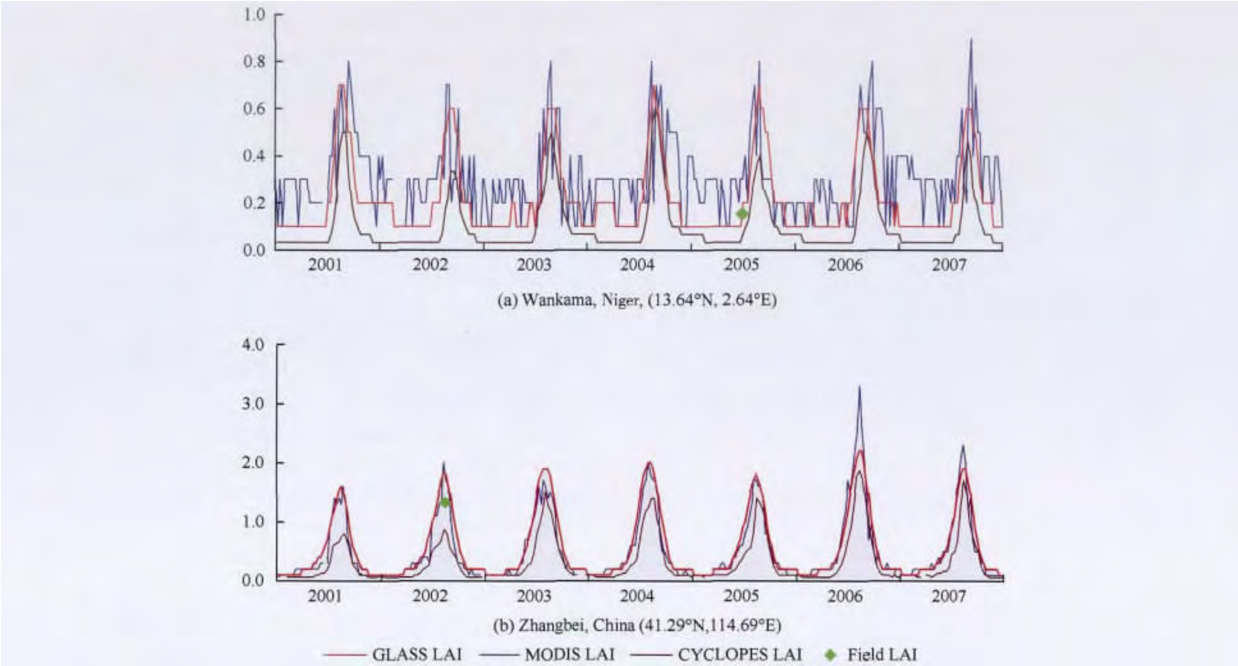


Fig. 5 Temporal profiles of GLASS, MODIS (with main algorithm) and CYCLOPES LAI over the Zhangbei and Wankama sites of grasses and cereal crops

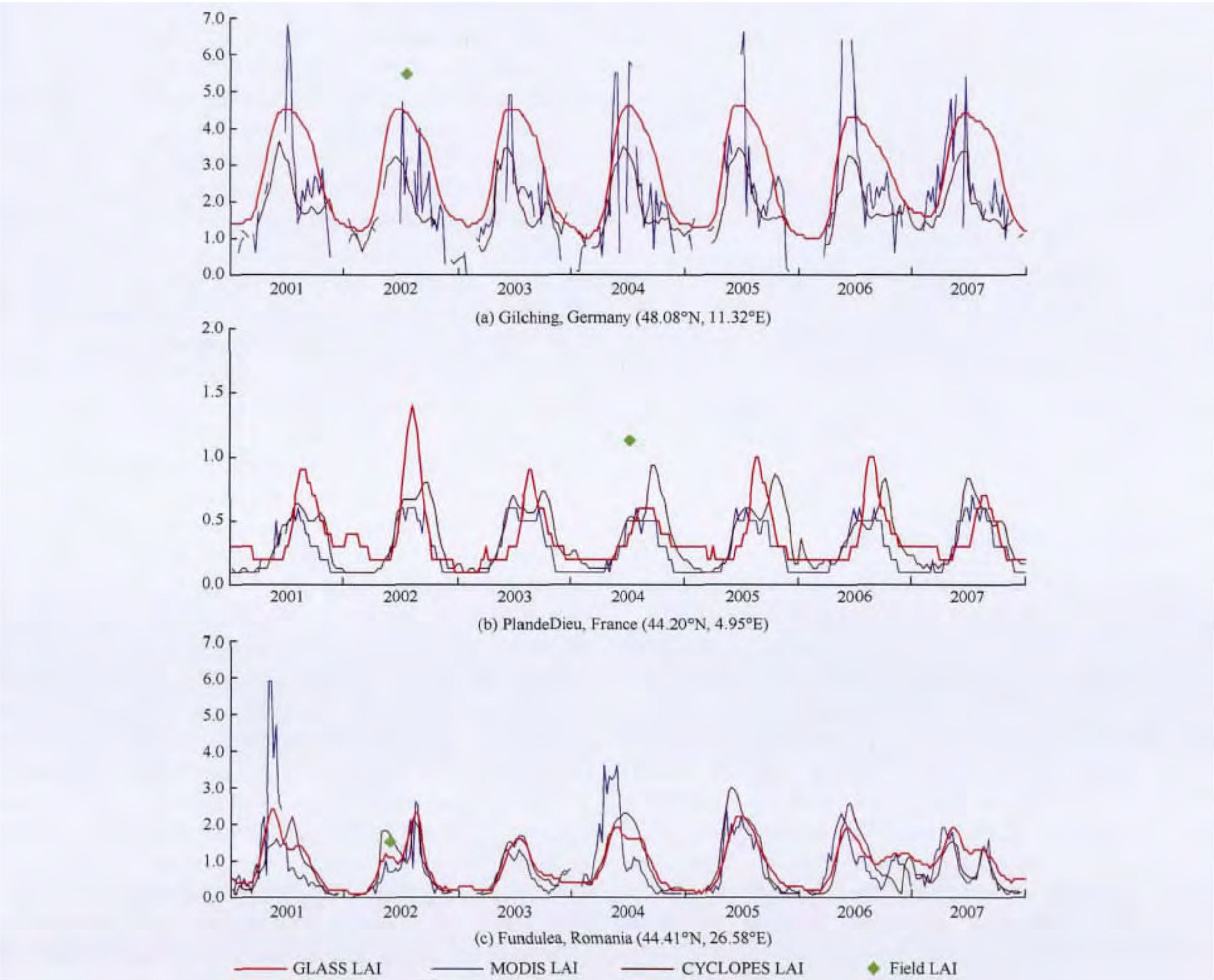


Fig. 6 Temporal profiles of GLASS, MODIS (with main algorithm), and CYCLOPES LAI over the PlandeDieu, Fundulea and Gilching sites of broadleaf crops

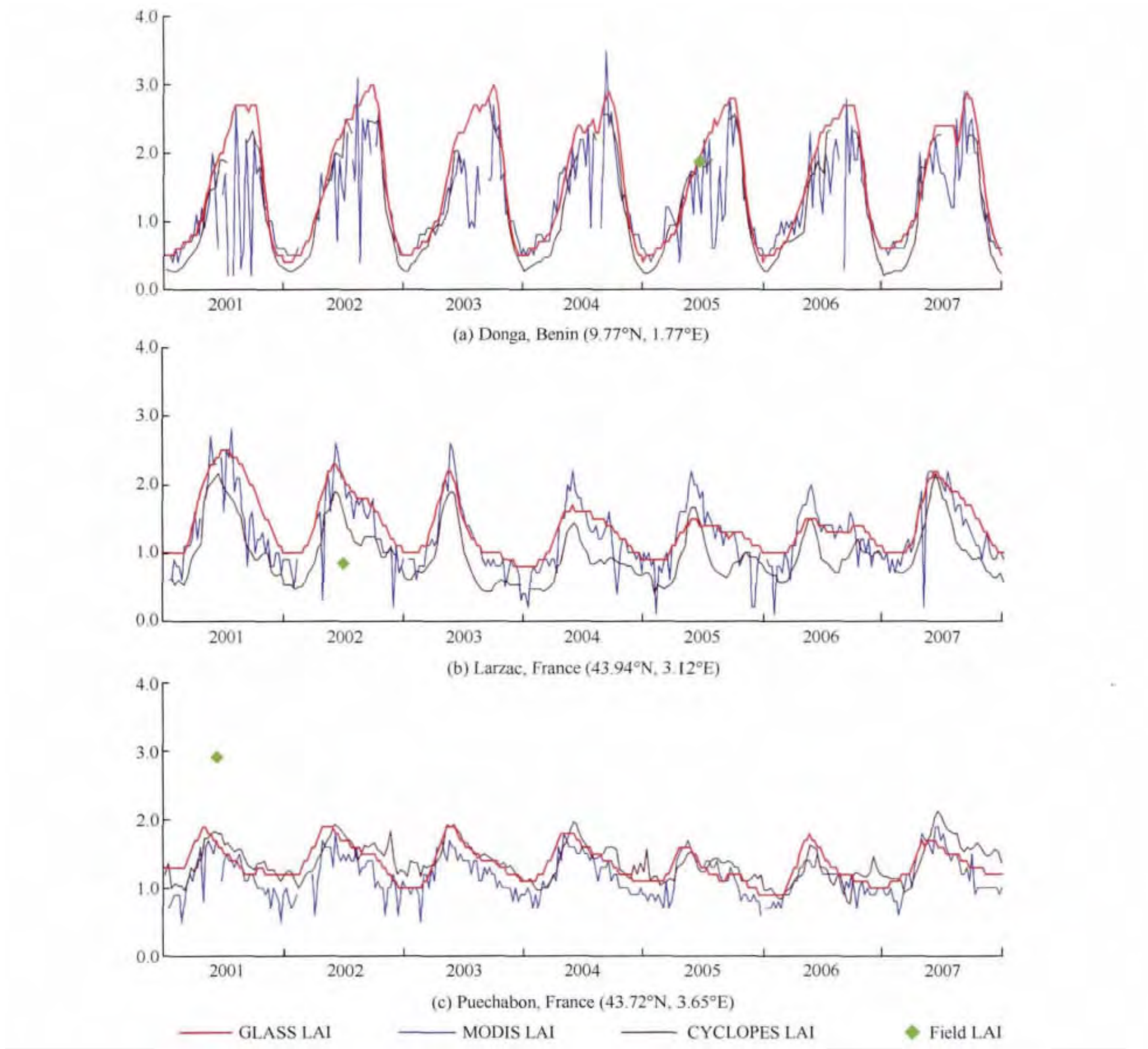


Fig. 7 Temporal profiles of GLASS, MODIS (with main algorithm) and CYCLOPES LAI over the Puechabon, Larzac and Donga sites of Savannah

The temporal profiles of the GLASS, MODIS, and CYCLOPES LAI values at the Nezer, Counami, Sonian and Larose sites with forest biome type according to MODIS land cover are provided in Fig. 8. At the Nezer site with evergreen needleleaf forest biome type, the MODIS LAI profile exhibited dramatic fluctuations. By contrast, the temporal profile of the GLASS LAI values was smooth and continuous. The GLASS, MODIS, and CYCLOPES LAI products generally depicted similar temporal trajectories with differences in magnitude. A good agreement was achieved between the GLASS and MODIS LAI values, but the CYCLOPES LAI values were significant underestimates throughout the entire growing season. The GLASS LAI values were in very good agreement with the mean LAI of the reference map at this site.

The biome type of the Counami site is evergreen broadleaf forest. The temporal profile of the MODIS LAI values at this site was extremely shaky, and most of the CYCLOPES LAI estimates were missing. In contrast to the temporal profiles of the MODIS and CYCLOPES LAI products, the GLASS LAI captured a c omplete and reasonable temporal profile which was relatively smooth and stable. Meanwhile, the GLASS LAI values were close to the mean LAI of the reference map.

At the Sonian and Larose sites, the biome type is deciduous broadleaf forests. Most of the MODIS LAI estimates were missing for fill value or backup algorithm retrieval. GLASS and CYCLOPES LAI had similar seasonal and interannual variability with differences in magnitude. In contrast to the GLASS and MODIS LAI values, the CYCLOPES LAI values were significant underestimates during the growing seasons because clumping at the plant and canopy scales, which could produce a difference of approximately 50% between true and effective estimates, was not considered in the CYCLOPES algorithm. The GLASS and CYCLOPES LAI profiles were relatively smooth, whereas the MODIS profile showed dramatic fluctuations with sudden peaks and valleys. The GLASS LAI values were in best agreement with the mean LAI of the reference maps at both sites.

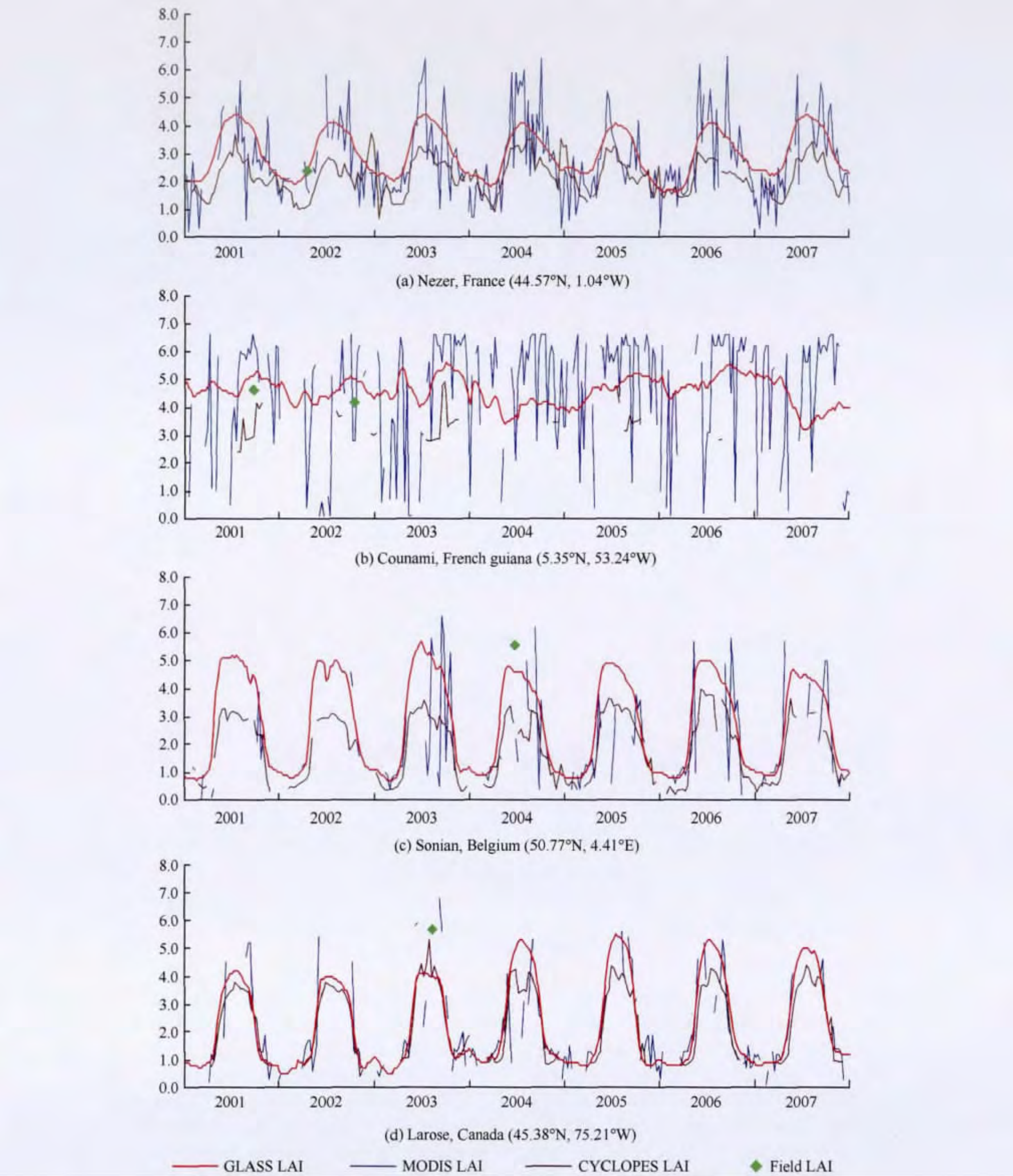


Fig. 8 Temporal profiles of GLASS, MODIS (with main algorithm) and CYCLOPES LAI over the Nezer, Counami, Sonian and Larose sites of forest

Regarding shrubs, the LAI temporal profiles at the Turco site are illustrated in Fig. 9. The GLASS, MODIS, and CYC-LOPES LAI products all showed good completeness, except for some missing data from MODIS LAI in 2001 and 2002. The LAI values were less than 0.5 for all the three LAI products from 2001 to 2007. The profiles of the LAI products exhibited no s ignificant interannual and seasonal variation. Compared with the MODIS and GLASS LAI estimates, the CYCLOPES LAI values were underestimates throughout the same period. Generally speaking, the GLASS, MODIS, and CYCLOPES LAI values were in very good agreement with the mean LAI of the reference map at the site.

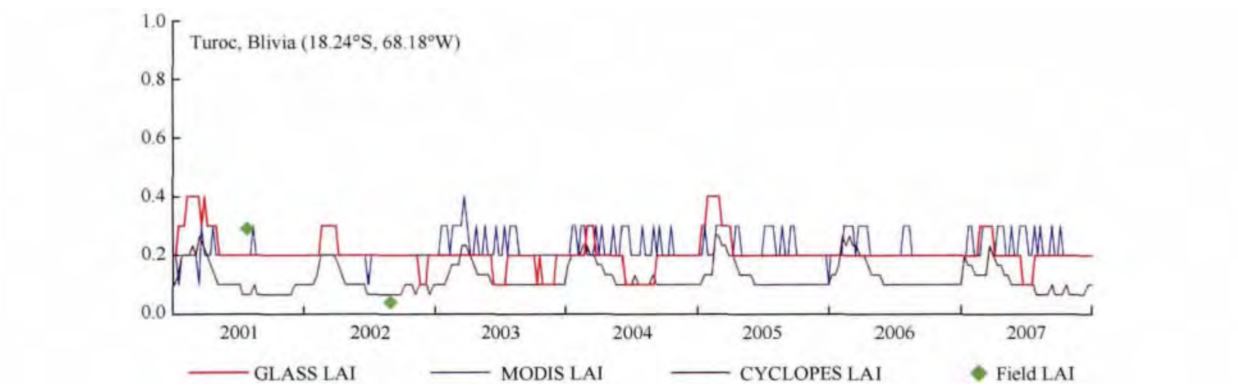


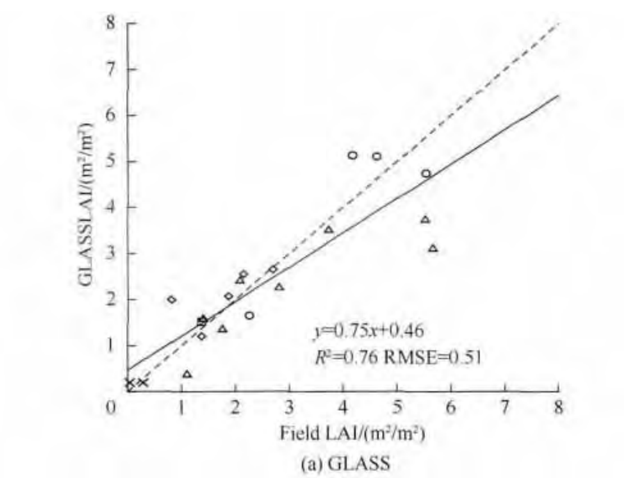
Fig. 9 Temporal profiles of GLASS, MODIS (with main algorithm) and CYCLOPES LAI over the Turco site of shrubs

4.3 Direct validation

The GLASS, MODIS, and CYCLOPES LAI products were compared with LAI reference maps to evaluate differences in LAI magnitude between products (Fig. 10). Fig. 10(a) and F ig. 10(b) show 20 LAI reference maps for which the GLASS and MODIS LAI with main algorithm provide valid data. H owever, the CYCLOPES LAI products provided valid data for only 18 LAI reference maps in Fig. 10(c). The discrepancies of each product were quantified by the regression function, R -square, and RMSE.

The GLASS (RMSE = 0.51) and CYCLOPES LAI (RMSE = 0.41) products provided better accuracy and precision with the LAI reference maps when compared with the MODIS LAI product (RMSE = 1.11). The correlations between the GLASS LAI values and the LAI reference maps ($R^2 = 0.76$) was also superior to the correlations of the CYCLOPES LAI product ($R^2 = 0.59$) and the MODIS LAI product ($R^2 = 0.46$) with the LAI reference maps.

The GLASS LAI product also achieved the best agreement across the whole range of LAI values, although a slight underestimation for the highest values was observed. The CYCLOPES LAI product significantly underestimated the LAI reference maps, especially for the highest LAI values over forests. In fact, the C YCLOPES LAI product rarely produced LAI values larger than 4 for the broadleaf and needle forest biome types due to the characteristics of the CYCLOPES algorithm (Garrigues, et al., 2008).



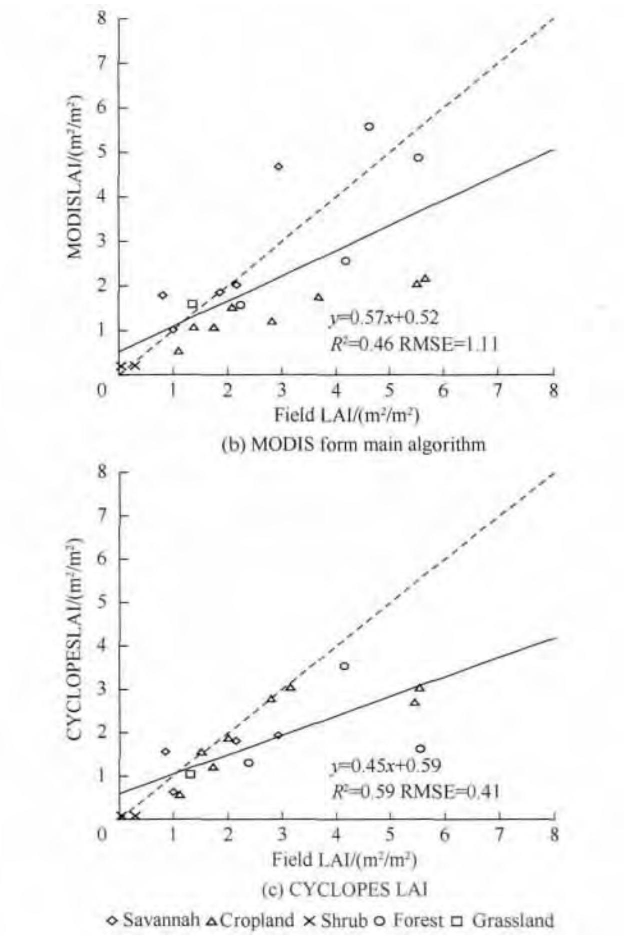


Fig. 10 Scatterplot comparison of the GLASS, MODIS from main algorithm, and CYCLOPES LAI products with mean LAI of the reference maps

Generally speaking, all these LAI products showed better performances for low LAI values than for high LAI values. M oreover, these products are all more or less underestimates compared with the LAI reference maps for the high LAI values.

5 CONCLUSIONS

In this study, the GLASS LAI product has been evaluated both through comparative and direct validation methods. The spatial distributions of the GLASS LAI were reasonable and c onsistent with the MODIS LAI with good quality (retrieved by the main algorithm) and the CYCLOPES LAI. By contrast, the GLASS and CCRS LAI products showed the largest discrepancies. The results of temporal variations showed that the GLASS LAI product has the best temporal continuity and c ompleteness compared with the others. GLASS and CYCLOPES LAI had smoother trajectories compared with the erratic fluctuations of the MODIS LAI. GLASS LAI had i mproved upon the unrealistically high or low values of the M ODIS LAI, particularly for the forest biome types. By computing for the RMSE and R^2 of each product over the LAI reference maps, the accuracy of the GLASS LAI product was found to be clearly better than that of MODIS and CYCLOPES LAI products.

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GLASS 叶面积指数产品验证

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摘 要:在国家高技术研究发展计划(863 计划)重点项目的支持下,已利用 MODIS 和 AVHRR 地表反射率数据生成了 1981 年—2012 年的 GLASS(Global LAnd Surface Satellite)叶面积指数(LAI)产品。本文从两个方面对 GLASS LAI 产品的质量进行分析和评价:(1)与现有的全球 LAI 产品进行比较,分析 GLASS LAI 产品的时空变化特征;(2)利用 LAI 的地面测量数据,对 GLASS LAI 的精度进行评价。研究结果表明:GLASS LAI 与 CCRS LAI 在高纬度和赤道附近区域的差异较大;相对而言,GLASS LAI 与 MODIS(主算法反演)和 CYCLOPES LAI 在空间分布上具有更好的一致性;GLASS 和 CYCLOPES LAI 的时间序列曲线连续平滑,MODIS LAI 在一些区域的植被生长季节存在剧烈的跳跃;与 LAI 的地面测量数据进行比较,GLASS LAI 产品的 R^2 为 0.76,RMSE 为 0.51,结果明显优于 MODIS 和 C YCLOPES LAI 产品。

关键词:叶面积指数(LAI),GLASS,验证,MODIS,长时间序列
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1 引 言

叶面积指数 LAI 定义为单位地面面积上叶子的单面面积之和(Chen 和 Black,1992)。它是地表生态系统的重要生物参数,和植物的光合作用、蒸散以及能量平衡等过程密切相关(Sellers 等,1997)。

全球变化、气候模拟等研究迫切需要长时间序列的区域及全球尺度的 LAI 产品。目前,利用不同卫星观测数据,生成了多个全球 LAI 产品,例如:MODIS(Knyazikhin 等,1998;Myneni 等,2002;Yang 等,2006),CYCLOPES(Baret 等,2007),CCRS(Fernandes 等,2003),ECOCLIMAP(Masson 等,2003)和 GLOBCARBON(Deng 等,2006)。对不同 LAI 产品之间的相互比较和验证的结果表明,现有的 LAI 产品在时间上不连续、在空间上不完整,产品的精度也有待进一步提高。现有 LAI 产品的精度(±1.0)不能满足全球气候观测系统 GCOS(Global Climate O bserving System)的应用需求(±0.5)(Fang 等,2012)。

为了生产长时间序列、高质量的全球 LAI 产品,Xiao 等人(2013)发展了业务化运行的从卫星观测数据中反演 LAI 的方法,并利用时间序列的 M ODIS 和 AVHRR 地表反射率数据,生成了从 1981 年—2012 年的全球陆表卫星 GLASS LAI 产品。

本文对利用 MODIS 地表反射率数据反演的 GLASS LAI 产品进行质量评价与精度检验。通过 GLASS 和 MODIS、CYCLOPES 以及 CCRS LAI 产品的相互比较和分析,评价 GLASS LAI 产品的时间和空间一致性。在空间尺度上,本文分析了 GLASS、MODIS、CYCLOPES 和 CCRS LAI 产品全球的空间分布和频率分布,以及 GLASS 与其他 3 种产品差值的

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全球空间分布和频率分布。在时间尺度上,对 GLASS、MODIS 和 CYCLOPES LAI 产品在 2001 年—2007 年进行时间序列分析,比较 GLASS 和其他 LAI 产品的异同。另外,利用地面测量数据与 GLASS LAI 直接验证,评价 GLASS LAI 的精度。

2 数 据

2.1 全球 LAI 产品

2.1.1 GLASS LAI 产品

GLASS LAI 产品的时间分辨率是 8 天,时间范围是 1981 年—2012 年。1981 年—1999 年的 GLASS LAI 产品由 AVHRR 地表反射率数据反演得到,采用等角度投影方式,空间分辨率为 0.05°;2000 年—2012 年的 GLASS LAI 产品由 MODIS 地表反射率数据(MOD09A1)反演得到,采用 ISIN 投影方式,空间分辨率为 1 km。该产品由北京师范大学全球变化处理与分析中心发布([2010-07-10] http://www.bnu-datacenter.com/)。

GLASS LAI 反演算法采用多输入—多输出的广义回归神经网络 GRNN 反演 LAI(Xiao 等,2013)。选取 BELMANIP 站点 2001 年—2004 年预处理后的 MODIS 地表反射率数据和 MODIS 与 CYCLOPES LAI 产品融合后的 LAI 数据,构造 GRNN 的训练数据集。BELMANIP 包含了全球范围 402 个地面验证站点,对不同植被类型,这些站点都具有较好的代表性(Baret 等,2006)。利用 GRNN 反演 LAI 时,输入一年 MODIS 或 AVHRR 地表反射率的时间序列数据,GRNN 的输出为一年的 LAI 时间序列曲线。

2.1.2 MODIS LAI 产品

MODIS LAI 产品采用 ISIN 投影方式,其空间分辨率是 1 km,时间分辨率是 8 天。本文使用目前最新的第 5 版 MODIS LAI 产品(MCD15A1)进行比较分析。

MODIS LAI 反演算法包含一个主算法和一个备用算法。主算法基于 3 维辐射传输模型构造的查找表反演 LAI。备用算法利用特定地类的 LAI 和 NDVI 之间的经验关系反演 LAI(Knyazikhin 等,1998)。当主算法失败的时候,使用备用算法。

除了提供每个像元的 LAI 值,MODIS LAI 产品还提供了质量控制信息(QC),用以说明 LAI 的反演质量。如果 QC < 32,说明主算法反演成功并且没有饱和。如果 32 ≤ QC < 64,主算法反演成功但是存在饱和。如果 64 ≤ QC < 128,主算法反演失败,利用备用算法反演 LAI。如果 QC ≥ 128,备用算法反演失败,算法根据地表类型分配一个填充值。

2.1.3 CYCLOPES LAI 产品

CYCLOPES LAI 是利用搭载在 SPOT 卫星上的 VEGETATION 传感器数据反演的全球 LAI 产品。CYCLOPES LAI 的时间跨度为 1999 年—2007 年,采用等距柱面投影方式。其空间分辨率是1/112°,时间分辨率是 10 天。

CYCLOPES LAI 反演算法利用 SAIL 模型模拟数据训练的神经网络反演 LAI。反演算法没有考虑冠层和植被尺度的聚集效应,反演的结果是有效 LAI。

2.1.4 CCRS LAI 产品

CCRS LAI 产品也是利用搭载在 SPOT 卫星上的 VEGETATION 传感器数据反演的。其空间分辨率是 1/112°,时间分辨率是 10 天。CCRS LAI 反演算法利用四尺度模型(Chen 和 Leblanc,1997)的模拟数据建立不同植被类型的 LAI 和植被指数之间的经验关系。对于林地像元,采用 LAI 和植被指数 RSR 之间的关系反演 LAI,而其他植被类型的像元,采用 LAI 和植被指数 SR 之间的关系反演 LAI(Deng 等,2006)。算法中同时考虑了太阳天顶角的变化。

2.2 LAI 地面测量数据

由欧洲空间局资助的 VALERI 项目([2010-06-10] http://w3.avignon.inra.fr/valeri/),旨在对中低分辨率的地表参数产品进行真实性检验。该项目在全球范围内选择了 33 个站点对 LAI 等生物物理参数进行测量。LAI 地面测量数据是利用 LAI-2000 植被冠层分析仪(Welles 和 Norman,1991)或者由 INRA-CSE 发明的带有鱼眼镜头的半球摄影方法(Demarez 等,2008)测量得到。通过建立高分辨 SPOT 影像的反射率和 LAI 地面测量数据之间的转换函数,生成各个站点的 LAI 高分辨率影像图。本文选择 17 站点提供的 20 个真实 LAI 高分辨率影像数据对 GLASS LAI 产品进行真实性检验。这些验证站点的信息及 LAI 高分辨率影像数据聚合到 1 km 尺度 LAI 的均值在表 1 中列出。

表 1　验证站点信息

站点	国家	纬度/°	经度/°	地表类型	儒略日	年份	LAI 均值
Alpilles	法国	43.810	4.715	草地/粮食作物	204	2002	1.69
Camerons	澳大利亚	-32.598	116.254	稀树草原	63	2004	2.13
Demmin	德国	53.892	13.207	阔叶作物	164	2004	4.15
Donga	贝宁	9.770	1.778	稀树草原	172	2005	1.85
Fundulea	罗马尼亚	44.406	26.585	草地/粮食作物	144	2002	1.53
Gilching	德国	48.082	11.320	草地/粮食作物	199	2002	5.39
Gnangara	澳大利亚	-31.534	115.882	稀树草原	61	2004	1.01
Larzac	法国	43.938	3.123	稀树草原	183	2002	0.81
Nezer	法国	44.568	-1.038	常绿针叶林	107	2002	2.38
Plan-de-Dieu	法国	44.199	4.948	草地/粮食作物	189	2004	1.13
Puechabon	法国	43.725	3.652	稀树草原	164	2001	2.85
Sonian	比利时	50.768	4.411	落叶阔叶林	174	2004	5.66
Sud-Ouest	法国	43.506	1.238	阔叶作物	189	2002	1.96
张北	中国	41.279	114.688	草地/粮食作物	221	2002	1.26
Counami	法属圭亚那	5.343	-53.237	常绿阔叶林	269	2001	4.93
Counami	法属圭亚那	5.343	-53.237	常绿阔叶林	286	2002	4.37
Laprida	阿根廷	-36.990	-60.553	阔叶作物	311	2001	5.82
Laprida	阿根廷	-36.990	-60.553	阔叶作物	292	2002	2.81
Turco	玻利维亚	-18.235	-68.184	灌木	208	2001	0.31
Turco	玻利维亚	-18.235	-68.184	灌木	240	2002	0.04

3　方　法

将 GLASS LAI 与现有的全球 LAI 产品进行比较分析，实现对 GLASS LAI 产品的质量评价，并使用地面测量数据对 GLASS LAI 精度验证。

由于 GLASS、MODIS、CYCLOPES 和 CCRS LAI 产品的时空分辨率不同、投影方式也不一样，先利用 GCTP 库函数将 CYCLOPES 和 CCRS LAI 产品转换到 ISIN 投影，再使用最邻近采样的方法将空间分辨率重采样到 1 km。MODIS 的备用算法反演的 LAI 质量低。因此，在产品相互比较中仅选择主算法反演得到的质量较好的 MODIS LAI（QC < 64）。为了降低随机误差的影响，在时间尺度上将 GLASS、MODIS 和 CYCLOPES LAI 产品聚合到 1 个月。

利用 GLASS、MODIS、CYCLOPES 和 CCRS LAI 在 2003 年 1 月和 7 月的全球空间分布和频率分布，分析了每一种产品的 LAI 变化范围和取值分布，并对产品之间的空间一致性进行评价。利用 GLASS LAI 与其他产品之间差值的空间分布以及频率分布，进一步分析产品之间的空间差异。此外，利用 GLASS、MODIS 和 CYCLOPES LAI 产品在 VALERI 站点上的时间序列曲线，对 LAI 产品之间的时间一致性和季节变化特征进行分析和比较。

通过对 GLASS、MODIS 和 CYCLOPES LAI 产品与 VALERI 站点的 LAI 高分辨率影像数据进行比较，定量地评价 GLASS LAI 产品的精度。LAI 高分辨率影像数据和 LAI 产品的空间分辨率以及投影方式不同。对 LAI 高分辨率影像数据进行投影转换并升尺度到 1 km 分辨率。由于 LAI 产品的儒略日期和地面测量的时间可能存在差异，本研究选择最靠近地面测量时间的 LAI 产品和地面测量数据进行比较。

4　结　果

4.1　空间一致性分析

图 1 为 GLASS、MODIS、CYCLOPES 和 CCRS LAI 在 2003 年 1 月份和 7 月份的全球空间分布图。所有产品的空间分布均遵循植被生长的季节变化规律，即南北半球呈现相反的季节特征。在北半球，7 月份的 LAI 值普遍比 1 月份高。事实上，北半球 1 月份的 LAI 值大部分分布在 0—1，几乎没有空间变化。而北半球 7 月份的 LAI 值的空间变化明显，在加拿大、俄罗斯和东南亚等地区的 LAI 值是较高的。相反地，在南半球 1 月份的 LAI 值普遍比 7 月份高。

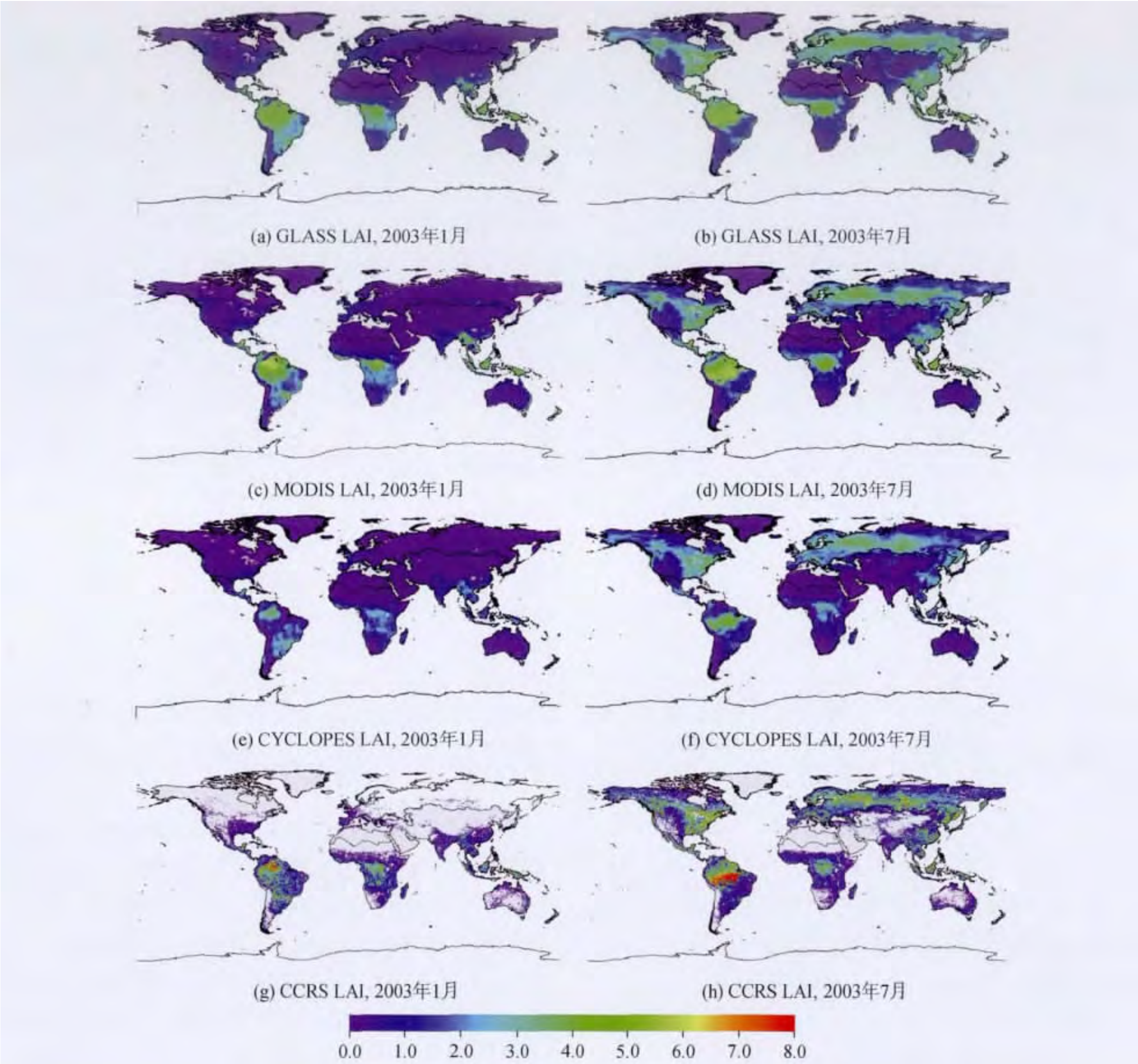


图1 GLASS、MODIS、CYCLOPES和CCRS LAI在2003年1月和7月的全球空间分布图

GLASS和MODIS LAI产品相比CYCLOPES和CCRS LAI有更好的空间完整性。CYCLOPES和CCRS LAI存在大量的数据缺失,MODIS在一些区域也有数据缺失的情况,而GLASS LAI产品在空间上是最完整的。

相对来说,GLASS和MODIS LAI有更好的空间一致性。LAI产品之间空间差异显著的区域主要集中在森林地类的一些地区。在这些区域,CCRS LAI产品有较高的LAI值,而CYCLOPES LAI产品的LAI值则较低。

图2为2003年7月份GLASS、MODIS、CYCLOPES和CCRS LAI产品的全球频率分布图。当LAI值大于4的时候,CYCLOPES LAI的频率几乎为0,表明CYCLOPES LAI产品对森林地类的LAI值有明显的低估(Garrigues等,2008)。

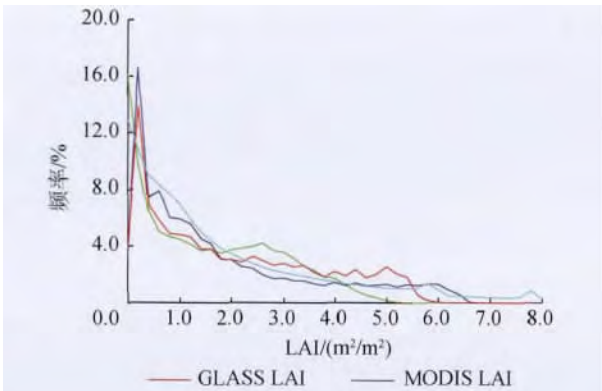
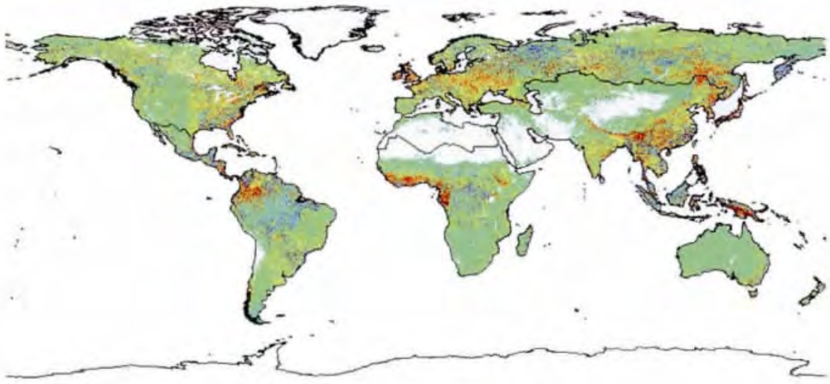


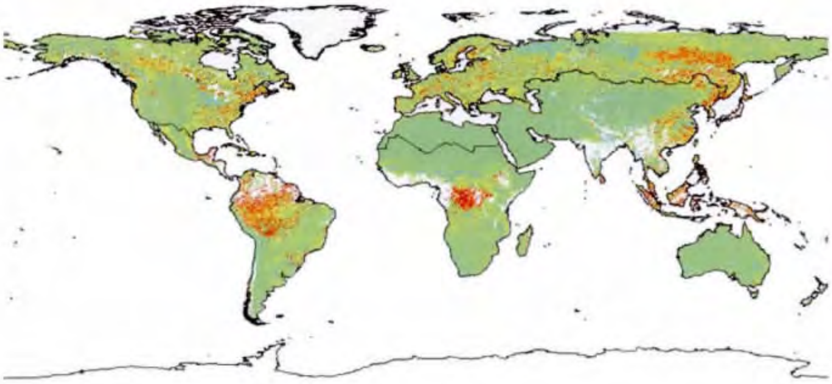
图2 GLASS、MODIS、CYCLOPES和CCRS LAI在2003年7月的频率直方图

GLASS LAI 的最高值达到了 6，MODIS LAI 的最高值超过了 6.5，而 CCRS LAI 的最高值达到了 8。这说明 CCRS LAI 比 GLASS 和 MODIS LAI 有更大的动态取值范围来描述 LAI 的全球变化。CYCLOPES LAI 的动态取值范围最小。比较 GLASS 和 MODIS LAI 的频率分布，当 LAI 值小于 2.0 的时候，MODIS LAI 的频率较大，而当 LAI 值大于 2.0 的时候，GLASS LAI 的频率较大。这主要是因为受云等因素影响的像元，MODIS LAI 值有明显的低估。

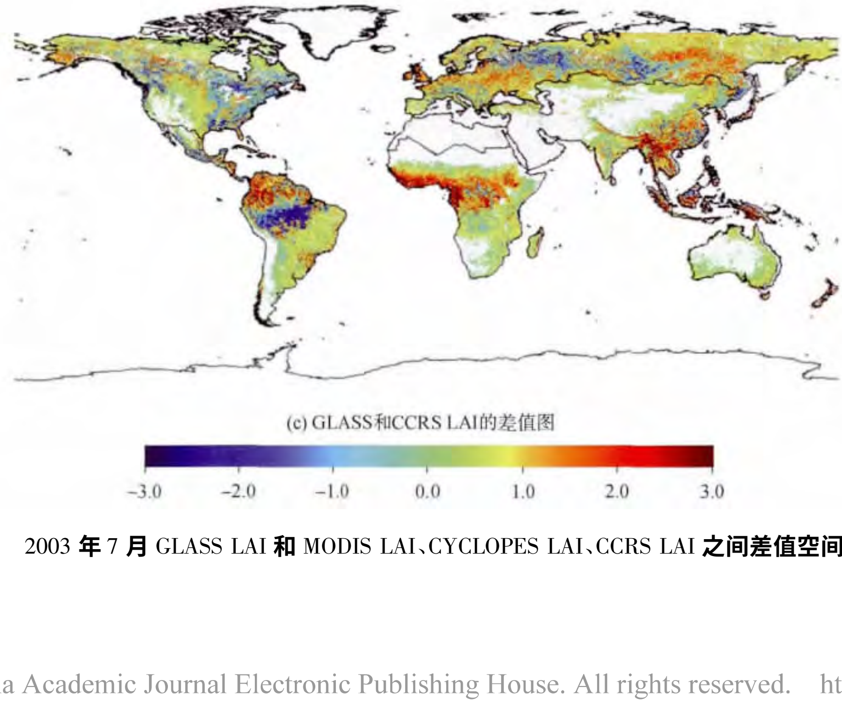
图 3(a)为 2003 年 7 月份 GLASS LAI 和 MODIS LAI(主算法反演)之间差值的全球空间分布图，差值是用每个像元的 GLASS LAI 值减去 MODIS LAI 值计算的。当 QC < 64 的时候，MODIS LAI 的质量较



(a) GLASS和MODIS LAI的差值图



(b) GLASS和CYCLOPES LAI的差值图



(c) GLASS和CCRS LAI的差值图

图 3 2003 年 7 月 GLASS LAI 和 MODIS LAI、CYCLOPES LAI、CCRS LAI 之间差值空间分布图

好,GLASS LAI 和 MODIS LAI 有很好的空间一致性。图4(a)为差值的全球频率直方图。超过80%的像元差值分布在-0.5—0.5。差值直方图的峰值在0处,并且差值为0的频率超过了35%。图4(a)也给出了GLASS LAI 与 MODIS 备份算法反演的 LAI(QC≥64)差值的频率直方图。很显然,备份算法反演的 LAI 与 GLASS LAI 之间有较大的差异。一方面,一部分像元的 MODIS LAI 值比 GLASS LAI 值大。这些像元的差值主要分布在-2.0—0。在图4(a)中,GLASS LAI 和质量不好的 MODIS LAI 的差值频率直方图在接近-0.5的地方有一个波峰。小于0的差值主要是由于 MODIS LAI 对于阔叶森林像元 LAI 的高估造成的(Garrigues 等,2008)。另一方面,一些像元的 GLASS LAI 值比 MODIS LAI 值大。这些像元的 GLASS LAI 值大多数分布在3.0—5.0,而 MODIS LAI 值受云等因素的影响,明显偏低。GLASS 和 MODIS LAI 之间差值的频率直方图的分布特性表明,GLASS LAI 产品一定程度地改进了当 MODIS LAI 反演质量不好的时候产生的不合理的高值和低值现象。

图3(b)为2003年7月份 GLASS LAI 和 CYCLOPES LAI 差值的全球空间分布。差值利用 GLASS 减去 CYCLOPES 对应像元的 LAI 值计算得到。由图可知,由于 CYCLOPES 反演算法无法表达冠层和植被的聚集效应,LAI 有明显的低估现象,并且大多出现在林地覆盖的区域(Garrigues 等,2008)。图4(b)为差值的频率直方图。这个直方图只有一个波峰分布在 LAI 差值为0的位置上,波峰处的频率达到了45%。超过70%的差值都分布在-0.5—0.5。大部分的差值均大于0,取值在1—3的差值集中分布在北半球高纬度地区和赤道附近。

图3(c)为2003年7月份 GLASS LAI 和 CCRS LAI 差值的空间分布图,图4(c)是差值的频率直方图。差值利用 GLASS 减去 CCRS 对应像元的 LAI 值计算得到。GLASS LAI 值在大部分区域都比 CCRS LAI 值大。差值超过2.0的区域主要分布在赤道附近。在这些区域,GLASS LAI 和 MODIS LAI 的值较高(约为6),而 CCRS LAI 取值为2.0—4.0。差值小于-2.0的区域主要分布在巴西南部,CCRS LAI 取值在8.0—9.0的高值,对应的 GLASS LAI 分布在5.0—6.0。总体来看,GLASS LAI 与 CCRS LAI 的空间差异比 GLASS 与 MODIS LAI 以及 GLASS 与 CYCLOPES LAI 的空间差异更大。

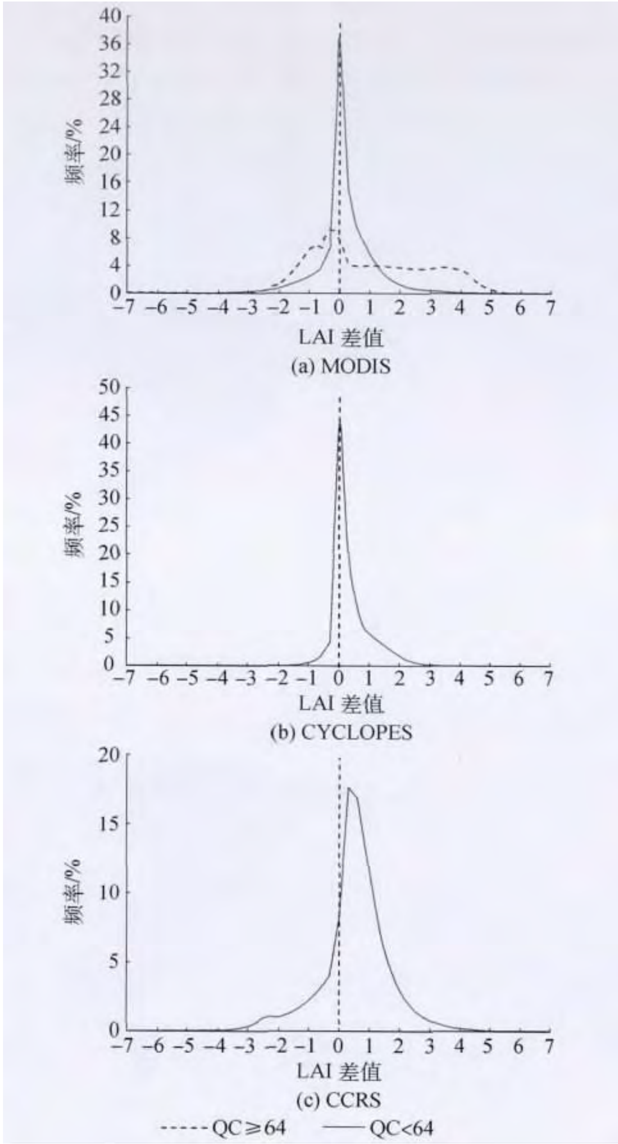


图4　2003年7月 GLASS LAI 和 MODIS LAI、CYCLOPES LAI、CCRS LAI 之间差值的频率直方图

4.2　时间一致性分析

选择表1中不同植被类型 VARELI 站点的 GLASS、MODIS(主算法反演)和 CYCLOPES LAI 产品做时间序列曲线进行比较,分析2001年—2007年不同 LAI 产品的时间一致性和季节变化特点。本文根据 MODIS 的地表分类产品选择了几种主要的地表类型,分别是阔叶作物、草地和粮食作物、针叶林、阔叶林、灌木和稀树草原。

图5为张北和 Wankama 站点的时间序列曲线。根据 MODIS 分类产品,这两个站点的地表类型为草地和粮食作物。在 Zhangbei 站点,GLASS、MODIS 和 CYCLOPES LAI 的时间序列曲线非常相似,均完整

而平滑。GLASS 和 CYCLOPES LAI 的年际变化较小，但在 2006 年的生长期，MODIS LAI 值明显高于其他年份。在 Wankama 站点，MODIS LAI 的时间序列曲线大部分都是缺失值，这是因为 MODIS LAI 产品提供了填充值或反演使用了备用算法。GLASS 和 CYCLOPES LAI 曲线的变化规律有较好的一致性。CYCLOEPS LAI 表现出了一定的年变化，在 2002 年和 2005 年的 LAI 值较低。CYCLOPES 在整个时间序列上比 GLASS 和 MODIS 的 LAI 值小一些。相比较而言，GLASS LAI 曲线在这两个站点更接近 LAI 的地面测量值。

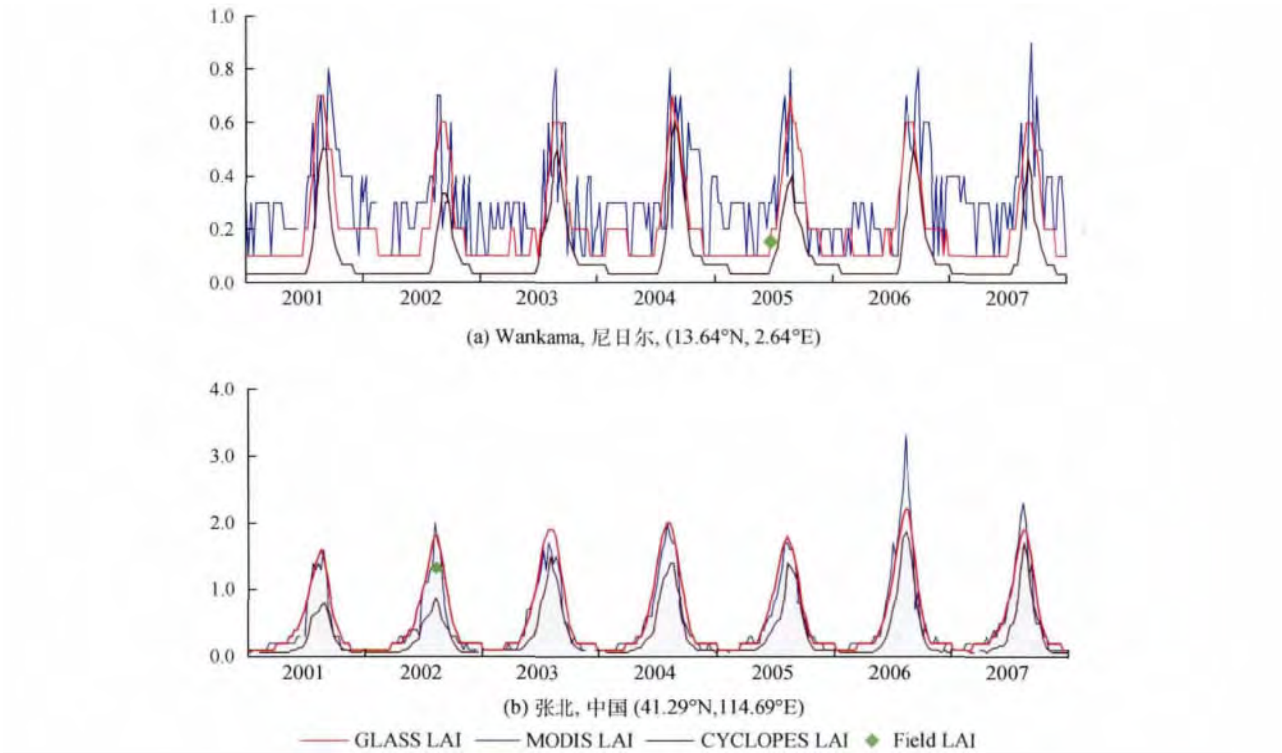


图 5　GLASS、MODIS（主算法反演）和 CYCLOPES LAI 在张北和 Wankama（草地/粮食作物）站点的时间序列曲线

图 6 为 PlandeDieu、Fundulea 和 Gilching 站点的时间序列曲线。根据 MODIS 分类产品，这 3 个站点的地表类型为阔叶作物。GLASS 和 CYLOPES LAI 的曲线平滑且连续，但是 MODIS 的时间序列曲线有非常明显的跳跃性。特别是在 Gilching 站点上，MODIS LAI 的波动特别大。在整个生长期，GLASS LAI 值一般比 MODIS 和 CYCLOPES LAI 值都要大。但由于 MODIS LAI 的跳跃性，在一些 LAI 值突变的时间点上 GLASS LAI 值比 MODIS LAI 值小。GLASS、MODIS 和 CYCLOPES LAI 的时间一致性在 Gilching 上较差。而在 PlandeDieu 和 Fundulea 站点上，所有的产品都展现了相似的季节变化和较好的一致性。PlandeDieu 站点是一个例外，GLASS LAI 在 2002 年的生长期比其他年份 LAI 值高。在 Fundulea 站点，MODIS LAI 在 2001 年和 2004 年也表现了明显的年变化。在 Gilching 和 PlandeDieu 站点上，所有的 LAI 产品都比地面测量值低。在 Fundulea 站点，GLASS 和 CYCLOPES LAI 和地面测量数据有更好的一致性。

图 7 为 Puechabon、Larzac 和 Donga 站点的时间序列曲线。根据 MODIS 分类产品，这些站点的地表类型为稀树草原。GLASS 和 CYCLOPES LAI 的曲线平滑，但 MODIS LAI 曲线有明显的波动，在生长期分布了很多突变的波峰和波谷。这种情况在 Donga 站点特别明显。所有产品都有相似的季节变化规律和较低的年际变化特点。在 Puechabon 站点，GLASS、MODIS 和 CYCLOPES LAI 有相似的时间变化曲线，并且都比 LAI 地面测量值小。在 Larzac 站点，GLASS LAI 和 MODIS LAI 有很好的一致性，CYCLOPES LAI 在时间序列上比 GLASS 和 MODIS 低。和 LAI 地面测量值相比，3 种 LAI 产品均高估。在 Donga 站点，尽管 CYCLOPES LAI 在生长期有很多

缺失值,但是 GLASS 和 CYCLOPES LAI 与 MODIS LAI 时间序列曲线的包络线有很好的一致性。在这个站点,GLASS LAI 和 LAI 地面测量值有非常好的一致性。

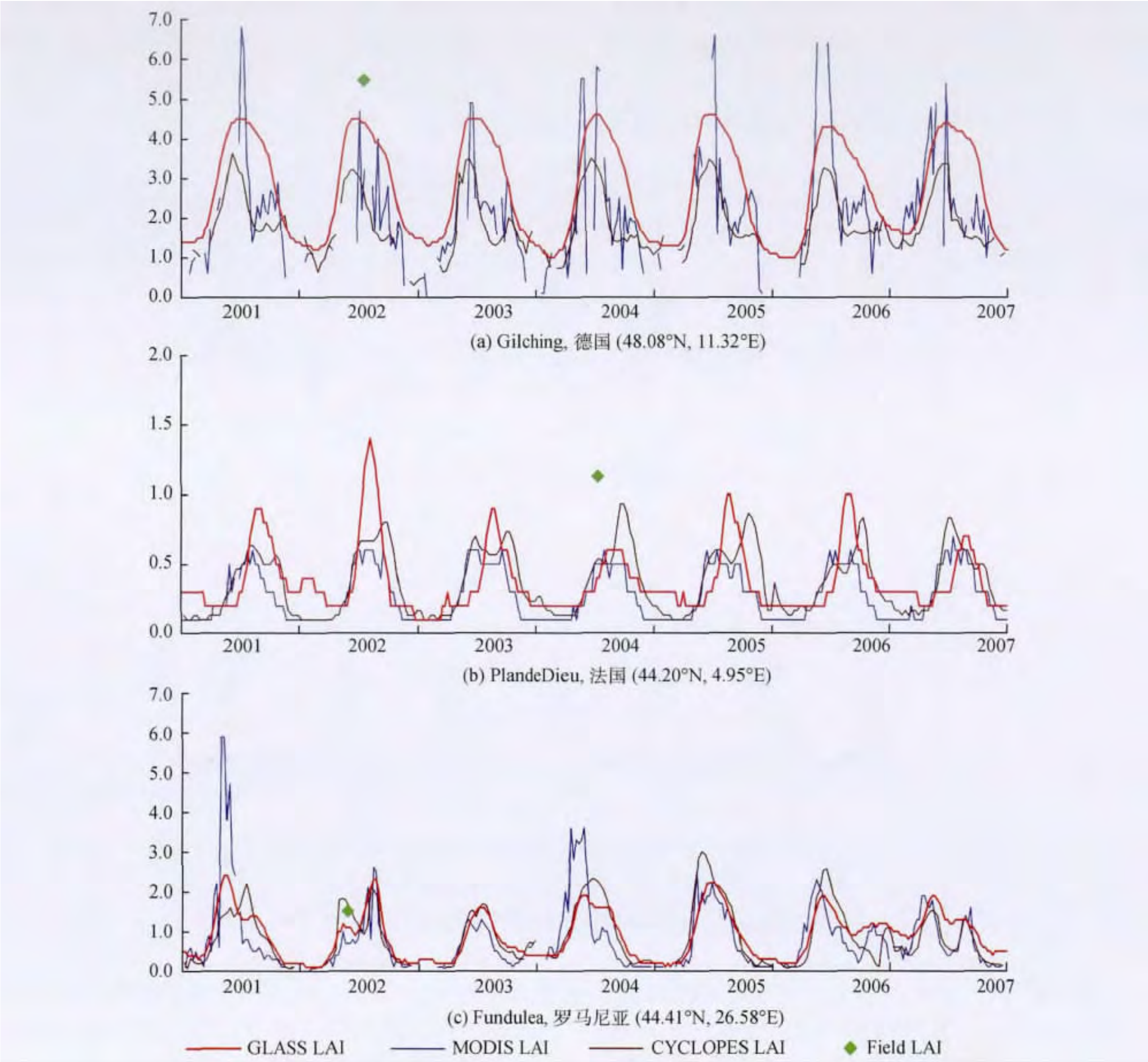
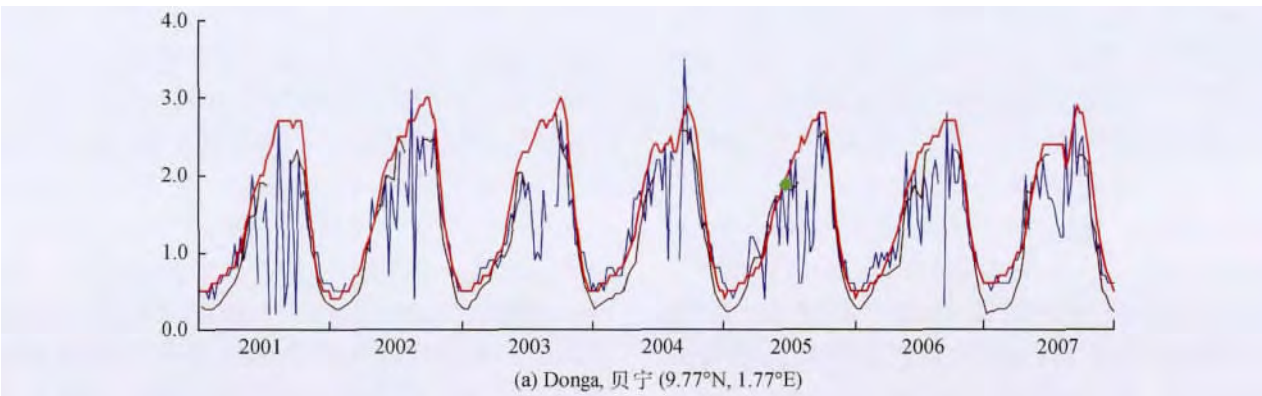


图 6 GLASS、MODIS(主算法反演)和 CYCLOPES LAI 在 PlandeDieu、Fundulea 和 Gilching(阔叶作物)站点的时间序列曲线



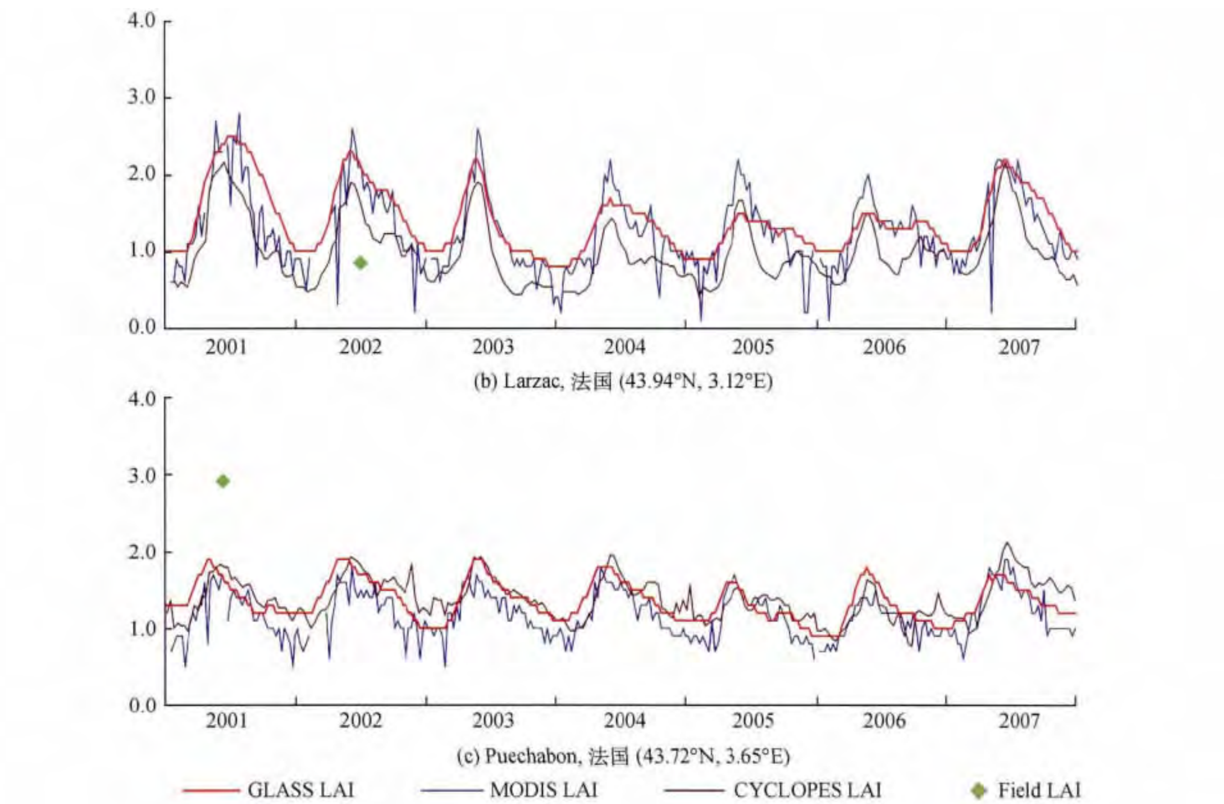
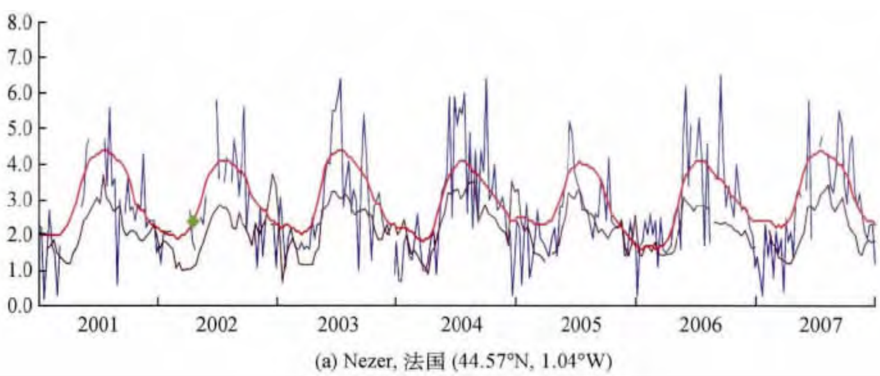


图 7　GLASS、MODIS（主算法反演）和 CYCLOPES LAI 在 Puechabon、Larzac 和 Donga（稀树草原）站点的时间序列曲线

Nezer、Counami、Sonian 和 Larose 站点的时间序列曲线如图 8 所示。这 4 个站点均为森林地类。Nezer 站点的地表类型是常绿针叶林。GLASS、MODIS 和 CYCLOPES LAI 呈现出相似的曲线变化趋势，但是在 LAI 值的大小上有明显的差异。GLASS 和 MODIS LAI 有较好的一致性，CYCLOPES LAI 在整个生长期都比它们更小。MODIS LAI 的时间序列曲线有明显的波动，而 GLASS LAI 的曲线平滑而连续。相对来说，GLASS LAI 和地面测量值更加接近。Counami 站点的地表类型属于常绿阔叶林。在这个站点，MODIS LAI 的跳跃性非常剧烈。大部分的 CYCLOPES LAI 值缺失。相比之下，GLASS LAI 呈现了完整而合理的时间序列变化特点，并且时间序列曲线平滑而稳定。同时，GLASS LAI 更加接近 LAI 地面测量值。在 Sonian 和 Larose 站点，地表的类型是落叶阔叶林。GLASS 和 CYCLOPES LAI 有相同的季节变化和年际变化，但在数值上存在差异。由于受到填充值或备用算法的影响，MODIS LAI 的时间序列曲线大部分是缺失的。与 MODIS 和 GLASS LAI 相比，CYCLOPES LAI 在生长期存在明显的低估。因为它没有考虑植被和冠层尺度的聚集效应，这会导致真实 LAI 和有效 LAI 值之间约 50% 的差异。GLASS 和 CYCLOPES LAI 的曲线是相对光滑的，而 MODIS LAI 存在明显的波动以及突然的波峰和波谷。这两个站点的 GLASS LAI 和 LAI 地面测量值有更好的一致性。



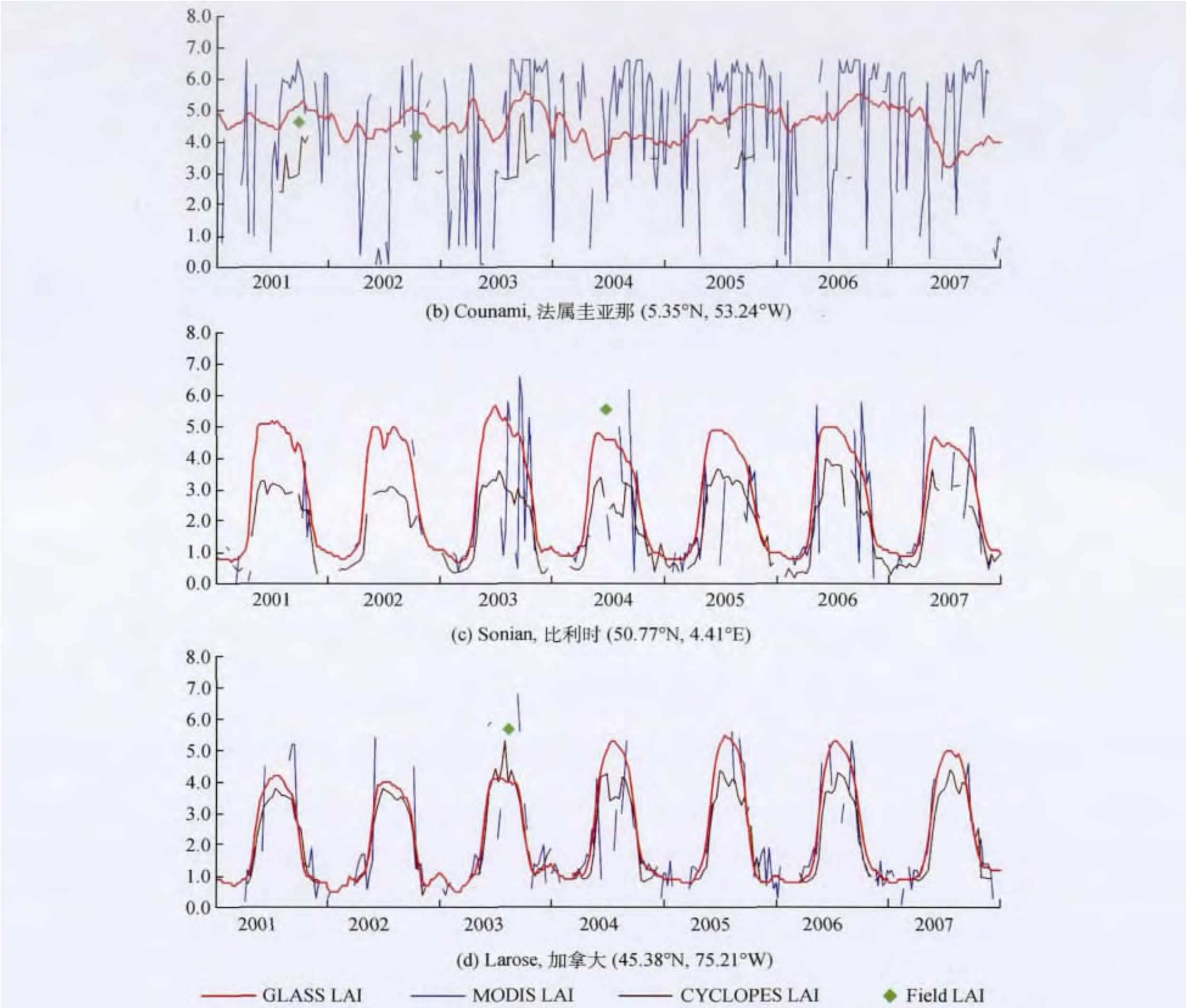


图 8 GLASS、MODIS(主算法反演)和 CYCLOPES LAI 在 Nezer、Counami、Sonian 和 Larose(森林)站点的时间序列曲线

图 9 为 Turco 站点 GLASS、MODIS 和 CYCLOPES LAI 的时间序列曲线。该站点为灌木类型。2001 年—2007 年,3 种产品的 LAI 值都小于 0.5,并且时间序列的曲线没有明显的年际变化和季节变化。GLASS、MODIS 和 CYCLOPES LAI 的曲线都有很好的完整性,但 MODIS LAI 在 2001 年和 2002 年的时候有一些数据缺失。和 MODIS 和 GLASS LAI 相比,CYCLOPES LAI 在 2001 年—2007 年都存在低估的现象。GLASS、MODIS 和 CYCLOPES LAI 均与 LAI 地面测量值有很好的一致性。

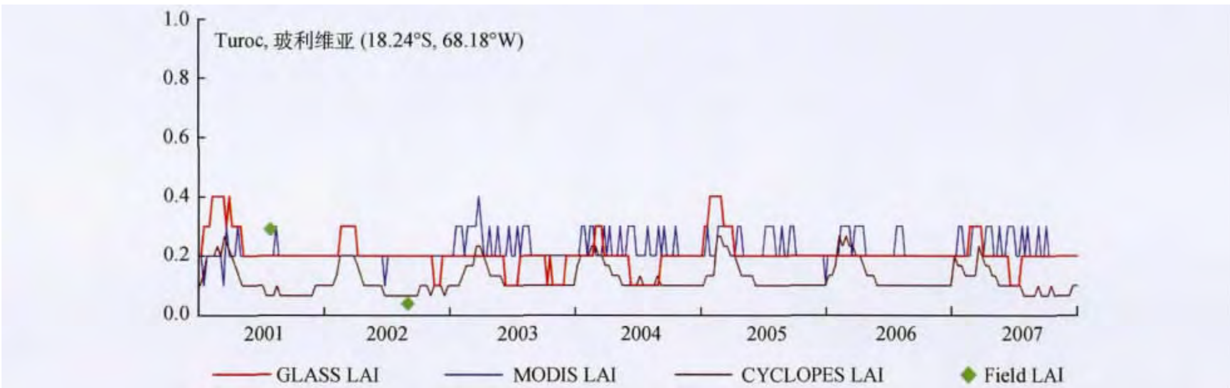


图 9 GLASS、MODIS(主算法反演)和 CYCLOPES LAI 在 Turco(灌木)站点的时间序列曲线

4.3 直接验证

利用 VALERI 站点的 LAI 地面测量数据对 GLASS、MODIS 和 CYCLOPES LAI 产品进行直接验证，图 10 显示了不同 LAI 产品和 LAI 地面测量值的散点图。在图 10(a)和(b)中，均有 20 个 LAI 地面测量数据与对应的 MODIS LAI(主算法反演)和 GLASS LAI 数据，而图 10(c)中只有 18 个 LAI 地面测量数据及相对应的 CYCLOPES LAI 数据。不同 LAI 产品的质量可以通过回归方程、均方根误差和相关系数来衡量。

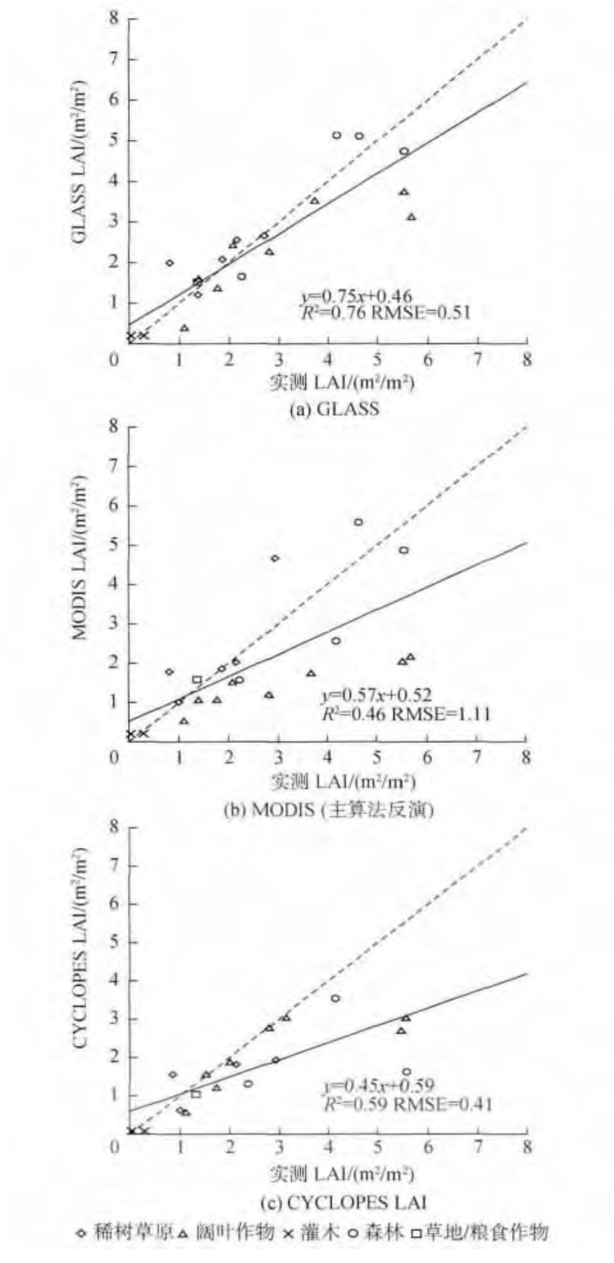


图 10 GLASS、MODIS(主算法反演)、CYCLOPES LAI 与地面测量 LAI 的散点图

与 LAI 地面测量数据比较，GLASS LAI (RMSE = 0.51)和 CYCLOPES LAI (RMSE = 0.41)比 MODIS LAI (RMSE = 1.11)有更好的精度和准确性。GLASS LAI (R^2 = 0.76)与 LAI 地面测量数据的相关性比 MODIS (R^2 = 0.46)和 CYCLOPES (R^2 = 0.59) LAI 更好。

GLASS LAI 产品在整个取值变化的范围内，都和 LAI 地面测量数据有较好的一致性。它的回归直线方程与 1∶1 线最接近。大部分的样点都均匀地分布在 1∶1 线的两边。只是在高值时，有个别样点的偏离较远，出现了低估。CYCLOPES LAI 对 LAI 地面测量数据有明显的低估，尤其是在 LAI 值较大的森林地类。CYCLOPES LAI 反演算法的饱和是导致 CYCLOPES LAI 值明显低估的主要原因。事实上，针对针叶林和阔叶林地类，CYCLOPES LAI 很少有大于 4 的 LAI 值 (Garrigues 等，2008)。

5 结 论

通过 LAI 地面测量数据的直接验证和 LAI 产品之间的相互比较两种方法对 GLASS LAI 的质量进行分析评价。GLASS LAI 的空间分布合理，并且和 MODIS LAI(主算法反演)的全球空间分布有很好的一致性。GLASS LAI 和 CYCLOPES LAI 之间存在少量小于 0 的差值，但大部分的差值均大于 0 且取值较高。GLASS 和 CCRS LAI 一致性最差。

不同 LAI 产品的时间序列曲线的对比分析表明 GLASS LAI 具有最好的时间连续性和完整性。GLASS 和 CYCLOPES LAI 的时间序列曲线更平滑，MODIS LAI 的曲线有明显的波动性。

3 种 LAI 产品和 LAI 地面测量数据之间的相关系数和均方根误差定量地表明了 GLASS LAI 产品的精度明显比 MODIS 和 CYCLOPES LAI 的精度更高。

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