Quality control and quality assessment of photosynthetically active radiation remote sensing products

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Abstract: Quality control and quality assessment are important tasks in developing quantitative remote sensing products. Product quality can provide detailed information for users. However, quality control and assessment of remote sensing products may be d ifficult to achieve, particularly for products with complicated algorithms that require the verification and assessment of numerous inputs, which is time-consuming. This paper describes a proposed method of quality control and quality assessment for Photosynthetically Active Radiation (PAR) products. Within the design of the overall technology framework, the detailed input data, the quality control system for the products, and the method of quality control and quality assessment are clearly demonstrated. Multisource remote sensing data and other geographical data for PAR estimates can result in numerous uncertainties. Thus, the quality control scheme was established using algorithm uncertainty analysis, quality system design and multiple levels of the products, and each possible uncertainty/error was recorded in the overall assessment of the products. The quality assessment method is briefly d escribed using the ground measured data and quality designation of products.

Key words: quantitative remote sensing products, quality control, quality assessment, Photosynthetically Active Radiation (PAR)

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1 INTRODUCTION

Many international organizations and research teams have been drawing support from the development of remote sensing models and surface parameter retrieval methods, to generate d ifferent levels and types of quantitative remote sensing products with the development of remote sensing and space technology. As a result, many scientific research data are provided in the fields of the atmospheric science, oceanography, ecology, agriculture, and forestry. These products contain the common surface albedo products (Schaaf, et al., 2002), vegetation index products (Baret, et al., 2007), and photosynthetically active radiation (PAR) products. Research on the theory and technology of quantitative remote sensing has become a current focus in the aforementioned research fields (Li, 2005). Quantitative remote sensing products play an important role in the study of global change and regional environmental monitoring. Directly evaluating data validation and accuracy is difficult because of generally little quality information for most remote sensing products, which limits further analysis and application.

Quality control is the key point in the process of producing remote sensing products. Quality control aims to provide detailed reference information of data quality for users and for further r esearch. The current research on data quality is generally focused on the ground observation and metadata of the images (China Meteorological Administration, 2010; Xie, et al., 2011). The quality control of Moderate-resolution Imaging Spectroradiometer (MODIS) land-atmosphere-ocean products is performed using a data quality control system (Huete, et al., 1999; Solano, et al., 2010). However, few studies focus on the quality control of remote sensing, with most studies focusing instead on uncertainty analysis. Uncertainty analysis is used to analyze the uncertainty factors and eliminate or reduce their impact on the remote sensing products (Zhou, et al., 2009; Ge, et al., 2004). For a standard remote sensing product, the evaluation of the product is an essential procedure, and a long-term and continuous quality e valuation is usually performed through quality control and a ccuracy assessment. Studies of quality control and quality a ssessment for satellite-derived products for application should be performed (Shi & Liu, 2004).

PAR is the part of solar radiation between 400 nm and 7 00 nm that is the important energy source for photosynthesis and

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is the basic energy that forms biomass. Consequently, PAR has a direct impact on plant growth, development, yield and product quality (Zuo, et al., 1991). PAR is not only an important parameter for vegetation growth models, ecological processing models and other studies, but also affects the exchange of matter and energy between the surface and the atmosphere (Li, et al., 1997), such as in the carbon, nutrient, water, and thermal cycles. However, much research on current PAR products has focused on the retrieval algorithm and product validation, while few studies have focused on error analysis, quality control methods, and product quality designation. This paper describes a quality control system for PAR products and its quality assessment.

2 METHODOLOGY

The overall quality control and quality assessment of PAR products was performed below. First, the uncertainty of PAR products was analyzed based on the algorithms and the production processes, and the possible sources of algorithms´e rrors and the major impact factors were identified. Afterward, on the basis of an uncertainty analysis to build a reliable product quality control system, by means of the product quality designation system, the quality of the products could be controlled effectively, with the aim to screen and analyze the final production and quality assessment of the products. Finally, the generated quality designation files and the ground measured data are used to analyze and compare the PAR products.

2.1 Algorithm principles of PAR inversion

Huang, et al. (2011) used a method of combining data from the MODIS and the Multifunctional Transport Satellite (MTSAT) to estimate the national solar radiation. Li, et al. (2010) and Zhang, et al. (2013) performed further research on solar radiation estimation using remote sensing. The principle of their methods was based on the lookup table, which consisted of various atmospheric and surface parameters. The input data to their model is derived from polar-orbiting and geostationary satellites. The algorithms for the estimation of PAR take into account the physical process by which solar radiation passes through the atmosphere to reach the surface, especially with regard to cloud attenuation. These algorithms have a clear physical mechanism. Various input parameters of the algorithms are derived from quantitative remote sensing products; these products have a good portability because they can reduce the process in the parametric algorithm, so that the parameters do not need to be calibrated several times to achieve the adaptation station. From the view of the structure of the algorithms, adding new parameters is easy, which will be important in improving and expanding the algorithms in the future. By means of the data from MODIS and MTSAT, these algorithms could produce the national PAR products, with a spatial resolution of 0.05°; the temporal resolution has three types of scales: instantaneous, hourly and daily. The aerosol optical thickness data can be obtained from the formula for conversion between aerosol optical thickness and visibility (Berk, et al., 1999).

The PAR algorithm process is shown in Fig. 1, and the d etails of the algorithms are below.

(1) The lookup table was created using the Santa Barbara DISTORT Atmospheric Radiative Transfer (SBDART) model, which consists of different scattering geometries (solar zenith a ngle, satellite zenith angle, and relative azimuth), different surface albedos and different cloud optical thicknesses.

(2) The surface albedo was derived from the MODIS land products, the different observation times under the apparent radiance (solar zenith angle) were derived from the visible channel data of MTSAT, and the cloud optical thickness was retrieved from the lookup table interpolation.

(3) The cloud detection method of the cloud optical thickness is combined with the MODIS ice/snow cover product data to distinguish the snow, cloudy, and cloudless areas.

(4) For the clear-sky condition, the PAR lookup table was created using the model of the Second Simulation of the Satellite Signal in the Solar Spectrum (6S). For the cloudy-sky condition, the downward PAR lookup table was built by SBDART and could retrieve the cloudy-sky PAR. Based on the downward PAR lookup table, the horizontal surface PAR could be estimated in the entire region for any weather condition.

(5) Using the surface elevation data to correct the terrain effects on PAR, the value of instantaneous PAR of the undulating surface would be determined.

(6) On the basis of the cumulative value of instantaneous PAR, the hourly and daily total PAR could be obtained.

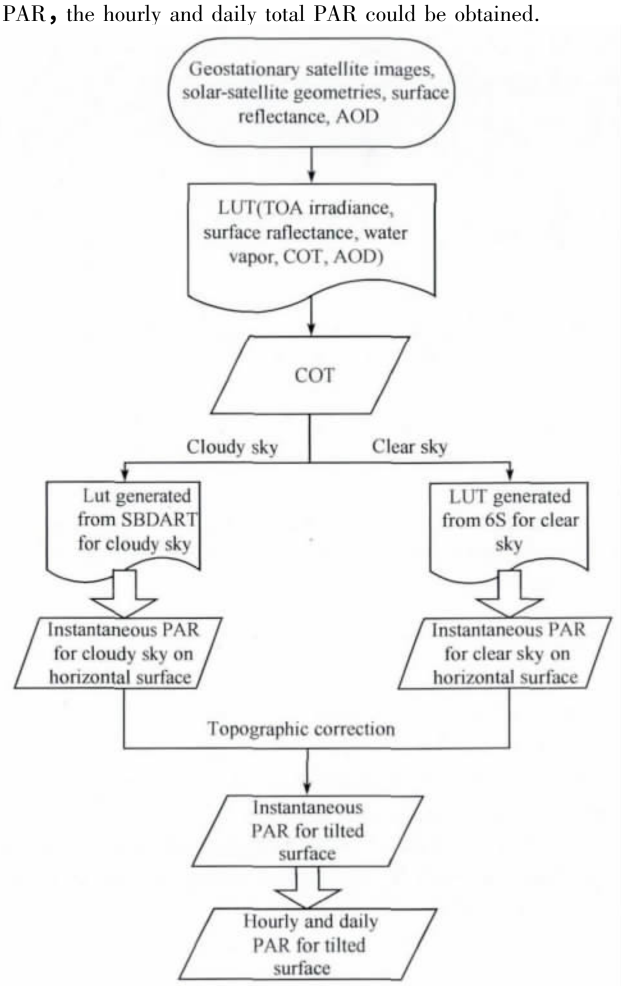

Fig. 1 The flowchart of the PAR retrieval algorithm

2.2 Uncertainty analysis of the PAR products

2.2.1 *Uncertainty analysis of the input data*

The required input data of PAR production are: geostationary satellite data, surface albedo, water vapor content, total ozone content, ice/snow covered area, visibility, and Digital Elevation Model (DEM). The input data are listed in Table 1.

Table 1 The input data of the PAR products

Input data	Source	Temporal resolution	Spatial resolution	Parameters
MTSAT-visible band	MTSAT-1R	1 h	0.05°	Cloud optical thickness
MCD43C2	MODIS	1 time/8 days	0.05°	Surface albedo
MOD05/MYD05	MODIS	2 times/day	1 km	Water vapor content
MOD07	MODIS	1 time/day	1 km	Ozone content
MOD10	MODIS	1 time/day	5 km	Ice/snow cover
Horizontal visibility	China Meteorological Administration	8 times/day	—	Aerosol Optical Depth
DEM	Shuttle Radar Topography Mission	—	30″	Surface elevation

The primary factors that affect PAR were determined by the sensitivity analysis method with the radiative transfer model. Li, et al. analyzed the sensitivity of the aerosol optical depth, water vapor, ozone and surface albedo to the PAR, and found that PAR is sensitive to the aerosol optical depth and the surface albedo, whereas PAR is not sensitive to water and ozone. In our proposed method, aerosol optical thickness was converted from the visibility data. The visibility and surface albedo were determined in detail, while the values of water vapor and ozone were simply determined as being valid or not.

Cloud optical thickness is an important parameter of PAR retrieval; the effect of cloud optical thickness at a solar zenith of 30°and a surface albedo of 0.3 on the PAR is shown in Fig.2.

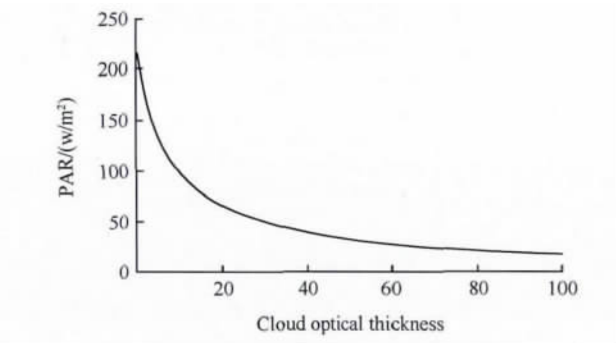

Fig.2 The relationship between cloud optical thickness and downward PAR

For cloudy sky, cloud is the primary factor affecting the surface downward PAR, which is determined in detail in our p roposed method.

2.2.2 *Uncertainty analysis of the algorithm*

The instantaneous downward PAR was estimated separately for the clear sky and the cloudy sky, and the method for cloud detection was based on the threshold of the cloud optical thickness. The cloud optical thickness was derived from the visible channel of the geostationary images along with other auxiliary input data. The accuracy of the inversed cloud optical thickness was mainly affected by the surface reflectivity and the solar s atellite geometries.

Given the high reflectivity of ice/snow and cloud, ice/snow was often detected as cloud, resulting in a high value for cloud optical thickness in ice/snow-covered areas. The ice/snow-covered areas were first detected, and the cloud was detected only for ice/snow-free pixels. Note that some pixels are masked by cloud; hence, only the clear ones are designated. The uncertainty of ice/snow and cloud detection algorithm will affect the accuracy of the PAR products, and the ice/snow covered pixels were also designated in our proposed model.

2.2.3 *Uncertainty analysis of the production process*

Primary algorithms and backup algorithms for many a dvanced remote sensing products have been developed. These products will use different algorithms depending on the different inputs and demands. The primary algorithms are usually the first choice, while the backup algorithms will be used when the input data are limited. Given the simplicity of the backup algorithms and the lack of input data, the accuracy of these backup algorithms is lower than that of the primary algorithms. Thus, backup algorithms should be designated by two or more optional methods. In our proposed method, only one algorithm for the PAR estimation is used and is not designated.

The proposed model for PAR estimation uses geostationary satellite (MTSAT) and polar-orbiting satellite (MODIS) data, and the accuracy of their geometric registration will result in uncertainty in the process of PAR production; their impact on quality control has not yet been considered.

In the production process, some uncertainties for missing data or filled values should be designated for the missing data and the filled values. Some missing values of surface albedo in southeast China are observed because the cloud is masked over a long time period. In PAR production processing, the missing surface albedo values were filled using the long term averaged values and designated.

2.3 Quality control and quality assessment method for PAR products

Quality control of the PAR products is represented by quality designation. The quality designation system presented here is based on the quality designation system of the MODIS products to be performed. Furthermore, based on the uncertainty analysis of the method, product quality control is designated in terms of the validation check, the quality designation of input data and the levels of classification. The quality information of the products was stored in the quality designation files. The product quality was evaluated using the ground observation data and the quality designation files. The overall flowchart is shown in Fig. 3.

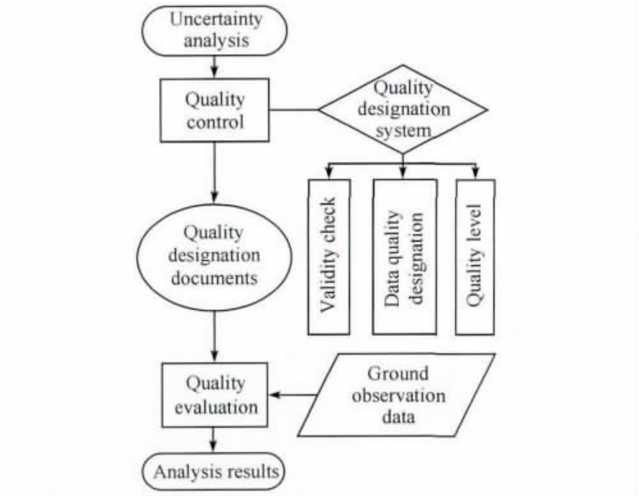

Fig. 3 The overall flowchart of quality control and quality assessment

3 PRODUCT QUALITY DESIGNATION SYSTEM DESIGN

Quality control is designed in terms of the quality designation system, and the quality designation files were automatically generated and stored in binary as metadata with the PAR products.

3.1 Validation check

The valid range of the input parameters must be validated for each pixel. The surface albedo is within 0 to 1, the water vapor content is within 0.01 g/cm^2 to 5.0 g/cm^2, the ozone content is 0.258—0.430 cm-atm, the horizontal visibility is within 0 to 50 km, the snow-covered area is within 0 to 1, and the cloud optical thickness is within 0 to 100. If all the input values were valid, then the overall quality of products will be designated as 0. If the values of water vapor and ozone content were invalid, then the values will be filled with the default values that confirm their insensitivity to the effects of PAR and the overall product quality will be designated as 1. If the values of ice/snow-covered areas were invalid, then the overall product quality will be designated as 2. The values will be filled by the default values if the surface albedo was invalid, and the overall product quality will be designated as 3. If the values of the cloud optical thickness or the horizontal visibility were invalid, then the PAR will not be retrieved because the primary input data are missing, and then the overall product quality is designated as 4.

3.2 The quality designation of the input data

(1) Ozone and water vapor: given that the influence of ozone and water vapor on the PAR is weak and the validation check is an important procedure, the valid data will be designated as 0 to indicate a valid value, and the invalid data will be designated as 1 to indicate a filled value.

(2) Visibility: the aerosol optical thickness was derived from the interpolation of the visibility data of approximately 700 meteorological stations. Quality information of visibility will be referenced first, and then the information records of the quality of the visibility data will be represented as below: 0—the correct data; 1—the suspicious data; 2—the wrong data; 3—the data with corrected value; 4—the modified data; 8—data missing; 9—data without quality control operation. In the process of quality designation, the stations with corrected data are designated as 0, the stations with wrong data or null data are designated as 2, and the stations with other data situations are designated as 1. Then, the quality at the station will be regarded as the quality of the same station, which is the center of a region of 21 × 21 pixels, and the poor value will be replaced by the quality value of the pixel if there is an overlapping portion between the pixels. The unmarked pixels can indicate that the observation stations are sparse in this region, as such, the interpolated data of visibility is questionable; thus, their quality will be designated as 1.

(3) Surface albedo: the surface albedo of the MODIS products has quality control documents, and the quality of the data is classified into six levels, as listed in Table 2. After the quality control documents are read and the quality is designated, the quality values of the pixels of 0 and 1 will be set to 0 to indicate that the quality is good, the quality value of the pixels of 2 and 3 will be set to 1 to indicate that the quality is ordinary, and the quality value of the pixels of 4 and 255 will be set to 2 to indicate that the value is filled or that the data are missing.

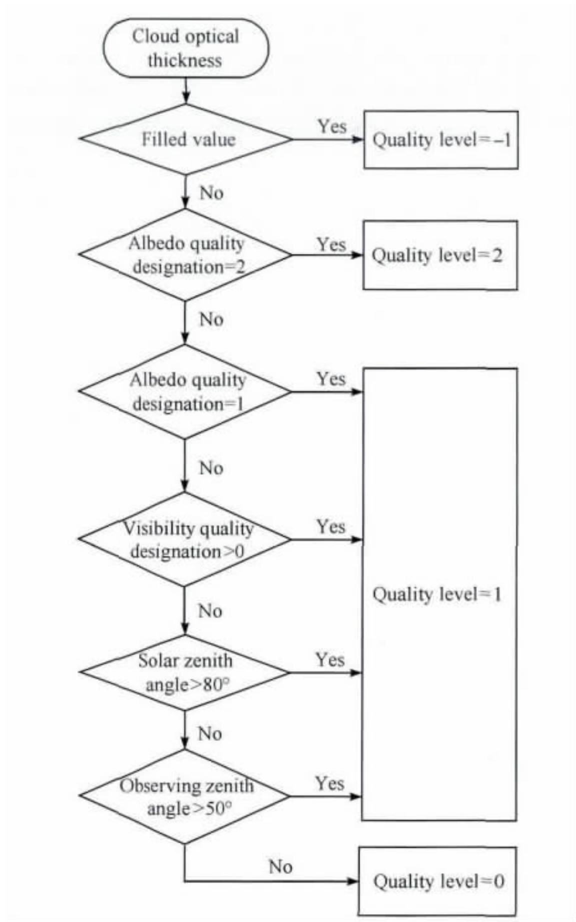

Fig. 4 The flowchart to classify the quality level of the cloud optical thickness

(4) Cloud optical thickness: within the design of the algorithm, the retrieved cloud optical thickness is influenced by the surface albedo, visibility, solar zenith angle, view zenith angle, and other parameters, and the quality designation information of the data will be regarded as the quality information for surface albedo and visibility. The detailed quality classification process contains four levels, as shown in Fig.4, where 0 represents high quality, 1 denotes normal quality, 2 indicates low quality, and −1 indicates that the cloud optical thickness is the filled value.

Table 2 Quality control documents of the surface albedo

Parameters	Value	Data quality description
Surface albedo	0	Best quality (more than 75% are retrieved prefect)
	1	High quality (more than 75% are retrieved completely)
	2	<75% are retrieved completely or <25% are filled values
	3	Using the backup algorithms or <50% are filled values
	4	>50% are filled values
	255	Values are filled or missing

(5) Ice/snow-covered areas: the areas will be checked to determine whether they are covered by ice/snow or not; if not, the areas will be designated as 0; otherwise, the areas will be designated as 1.

The detailed quality designation information of the binary of the input data is listed in Table 3.

3.3 Product quality classification design

The quality level of the products was classified by the u ncertainty analysis, the validation check and the quality designation of the input data, and the daily total PAR was obtained from the integration of the instantaneous value. Thus, the quality of the daily total PAR must be considered again.

Table 3 Quality designation information of each binary value

Bit	Parameters	Value	Description
0—2	Overall product quality	0	Produced
		1	Produced, water vapor or ozone content are filled values
		2	Produced, ice/snow-covered pixels are missing
		3	Produced, surface albedo is a filled value
		4	Not produced, cloud optical thickness or visibility is missing
		5	Produced but invalid for other reasons
3	Ozone content	0	Valid value
		1	Filled value
4	Water vapor content	0	Valid value
		1	Filled value
5,6	Horizontal visibility	0	Data are corrected
		1	Data are suspicious, and some are revised or modified
		2	Incorrect data or data missing
7,8	Surface albedo	0	High quality
		1	Moderate quality
		2	Data are filled or missing
9—11	Cloud optical thickness	0	High quality
		1	Moderate quality
		2	Low quality
12	Ice/snow cover	0	No
		1	Yes

3.3.1 The instantaneous/hourly PAR product quality classification design

Fig. 5 shows the overall flowchart of the classification process. By means of the validation check and the results of the quality designation of the input data, the quality of instantaneous/hourly PAR products can be classified, and the classification is listed in Table 4.

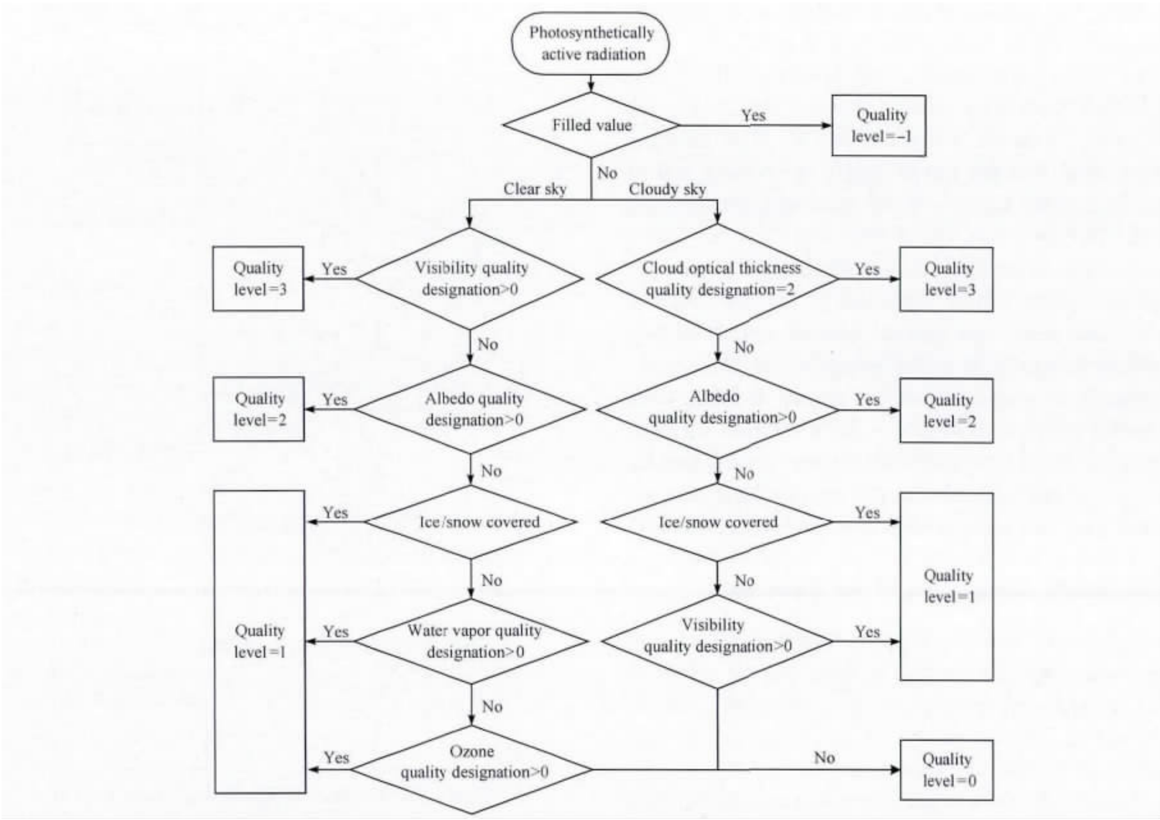

Fig. 5 The flowchart of the instantaneous/hourly PAR product levels classification

Table 4 Quality level description

Quality level	Quality condition	Description
−1	Filled value	Not produced or invalid for other reasons
0	High quality	Data with best quality
1	Moderate quality	Useable, see details in quality identification files
2	Low quality	Useable, surface albedo quality is not satisfactory
3	Lower quality	Useable, visibility/cloud optical thickness quality is not satisfactory

3.3.2 The daily total PAR product quality classification design

From sunrise to sunset, the number of hours of the daily total PAR can be calculated, and the quality of the daily total PAR can be obtained through the quality of the instantaneous PAR. Eq. (1) can be used to calculate the number of hours of daily total PAR n:

$$n = \mathrm{int}(t_2 - t_1) \tag{1}$$

where t_1 is the sunrise time, t_2 is the sunset time, and int represents the rounding-up function. Based on the flowchart in Fig. 6, the classification of the quality of the daily total PAR can be d escribed clearly. Q_i represents the quality of the instantaneous PAR of the i^{th} hour, and i is in the range 1 to n. N_Q represents the number of Q_i when Q_i satisfies the certain conditions, for e xample, $N_{Q=3}$ means that Q_i satisfies three certain conditions. Similar to the instantaneous PAR quality level, the quality level values of the daily total PAR of −1, 0, 1, 2, and 3 represent filled value, high quality, normal quality, low quality and lower quality, respectively.

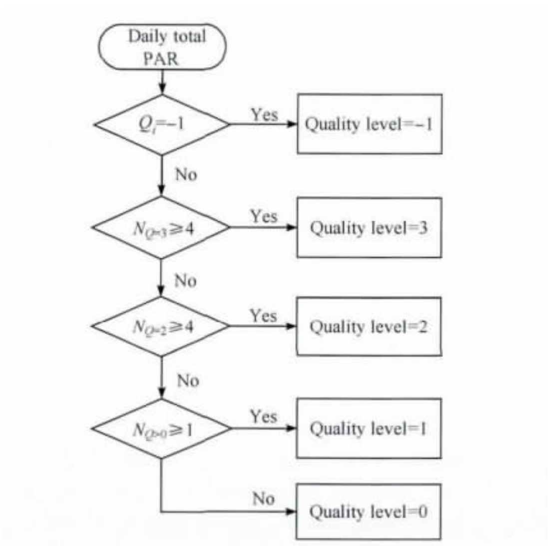

Fig. 6 The flowchart of the daily total PAR quality levels classification

4 THE QUALITY EVALUATION OF THE PAR PRODUCTS

Using the solar radiation data in the Beijing station as an example, we can use the quality of the daily total PAR products to evaluate and analyze the quality control methods of this paper. The data of the 6 months from January to June in 2010 had been verified (because the partial data of the MTSAT image are missing, and a total of 95 days of data are valid), and the ratio b etween the PAR and total radiation around the world is relatively stable (in the seasonal or interannual scales); as a result, some scientists have taken this conversion factor to be constant (Bai, 2009). The conversion factor is 0.47 in this paper, and the comparison results are shown in Fig. 7 and Table 5.

Table 5 The results of the product quality classification

Quality level	R^2	MBE/(MJ/m^2)	RMBE/%	RMSE/(MJ/m^2)	RRMSE/%	Number	Impact factors
0	—	—	—	—	—	0	—
1	0.92	0.52	5.03	1.06	10.21	26	Ice/snow, water vapor, and ozone
2	0.88	0.97	15.18	1.76	27.64	47	Surface albedo
3	0.82	1.17	23.24	1.65	32.86	22	Cloud optical thickness
−1	—	—	—	—	—	86	Filled value

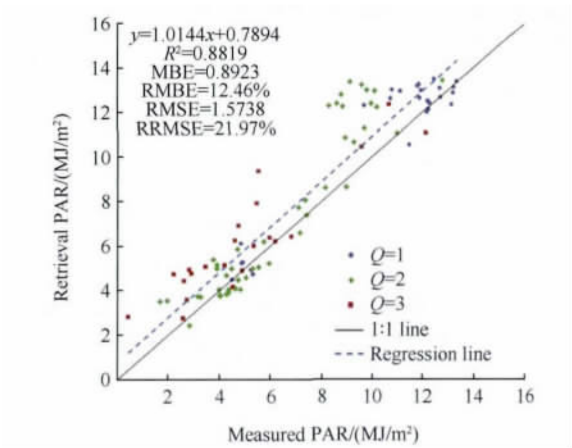

Fig. 7 The scatter plots of the measured and retrieved PAR

The correlation coefficient R^2 between the retrieved PAR and the measured PAR is 0.88 for the Beijing station, with an a verage deviation of 0.89 MJ/m^2 (12.46%) and a RMSE of 1 .57 MJ/m^2 (21.97%). The overall product was obviously overestimated. Detailed evaluation and accuracy results regarding the quality of the products can be obtained using the quality designation documents and the product quality level. As listed in Table 5, the precision of the products of quality level 1 is the highest, t he precision of the products of quality level 2 is low, and the precision of the products of quality level 3 is worst. Based on the quality designation documents of the Beijing station and the a nalysis of the impact factors of product quality, cloud optical thickness has the worst quality, but visibility and other parameters have good quality. Thus, cloud optical thickness and surface albedo can be considered to be the primary factors determining the quality of the PAR at the Beijing station. For the first 6 months of 2010, the quality of the surface albedo data of B eijing station is not good; thus, the quality of the overall products was reduced. However, the quality control system is relatively reasonable and can reflect the quality information of the products objectively.

5 CONCLUSION

Some methods of quality control for the remote sensing products were presented in this paper; for example, the quality of the complicated PAR products can be controlled through the quality designation system, and a preliminary evaluation of the PAR can be obtained, depending on the data of the meteorological radiation station. The evaluation results indicate that the product quality evaluation system could classify the level of product quality reasonably and has the ability to assist in identifying product data and analyzing the error sources in products, thus making it more convenient for users and researchers to use the product.

Uncertainty in quantitative remote sensing products has many sources, and many imperfections or unconsidered factors may be discovered. Nevertheless, considerable research remains devoted to continuously developing and improving the methods of quality control. The problem of geometric registration between the different remote sensing images will generate errors in the f inal results; however, but the present study did not analyze the reasons for these errors. A further analysis will be implemented in the later study. A detailed quality assessment will be performed in this later study; in addition, complete inspection of the quality control system and analysis of the accuracy of products will be more convenient. This paper only used the data from the Beijing station to evaluate the quality of the PAR, and many imperfections in the quality evaluation and the quality c ontrol methods for PAR products remain.

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摘　要: 定量遥感产品的质量控制和质量评价是产品生产过程的重要环节,生成的产品质量信息对用户具有重要的参考价值。对于算法较为复杂,涉及诸多输入数据和计算环节的遥感数据产品,质量控制和质量评价是一个难点。本文以一个极轨卫星与静止卫星结合的光合有效辐射(PAR)产品算法为例,分析了定量遥感产品质量控制和质量评价的方法。在确定总体技术框架的基础上,详细描述了数据输入及产品输出质量控制标识体系的建立、质量控制方法实施以及产品质量评价具体方案。光合有效辐射估算需要多源遥感数据和较多空间数据,导致最终产品不确定性的来源较多。本研究通过算法解析、产品的不确定性分析以及建立质量标识体系等方法来确定质量控制方案,从而可以利用质量控制标识追溯到输入数据和每一个中间处理过程的质量或者误差,并最终生成产品的总体质量等级。最后简要介绍了利用地面实测数据和产品质量标识对产品进行质量评价的方法。

关键词: 定量遥感产品,质量控制,质量评价,光合有效辐射(PAR)

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1　引　言

随着遥感和航天技术的发展,众多国际组织及科学研究团队通过发展遥感模型和地表参数的提取方法,生成了不同等级和不同类型的定量遥感数据产品,为大气、海洋、生态、农业、林业及矿产等研究领域提供了合适的遥感影像数据,例如常见的地表反照率产品(Schaaf 等,2002)、植被指数产品(Baret 等,2007)以及本文研究的光合有效辐射PAR(Photosynthetically Active Radiation)产品等,定量遥感理论及技术方法研究已成为当前遥感研究与应用的前沿领域(李小文,2005)。定量遥感产品在全球变化,区域环境监测研究中发挥了重要作用,但由于产品生产者在发布产品的同时未能提供充足有效的产品质量信息,使得用户和研究人员在使用和对数据进行进一步分析时难以对数据的有效性和精度做出评判,从而限制了定量遥感产品应用的科学性以及进一步应用。

遥感产品质量控制是遥感产品生产过程中的关键环节,其目的是为数据使用人员提供详尽的质量参考信息,以便更好地使用数据及进行研究。目前对数据的质量控制多集中在对地面观测数据以及影像元数据质量控制的研究(中国气象局,2010;谢振红 等,2011)。较为成熟的遥感产品,如MODIS的大气、陆地以及海洋产品等有相关的质量控制信息,其产品质量控制主要通过质量保障体系实现(Huete 等,1999; Solano 等,2010)。但多数定量遥感产品的质量控制研究较少,多集中在对遥感信息的不确定性分析上,遥感信息不确定性分析的目的是分析不确定性因子,消除或削弱它们对遥感影像

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或产品的影响(周冠华 等,2009; 葛咏 等,2004)。对于一个标准的遥感产品,产品的质量评价是必不可少的一部分,主要通过产品的质量检查及精度评价实现其长期、连续的质量评价。开展卫星产品质量控制和质量评价研究对于卫星反演产品的应用和在国民经济中发挥作用是非常必要的(师春香和刘玉洁,2004)。

光合有效辐射是太阳辐射中 400—700 nm 部分,它是植物进行光合作用的重要能量来源,是形成生物量的基本能源,直接影响着植物的生长、发育、产量与产品质量(左大康 等,1991),在植被生长模型、生态过程模型等研究中具有非常重要的意义,也影响着地表与大气的物质与能量交换(Li 等,1997),如碳循环、营养物质循环、水循环以及热循环等。目前,对于 PAR 产品的研究多集中于反演算法以及产品验证等方面,而对产品生产中的误差分析、质量控制方法和产品的最终质量标识则较少涉及,基于此,本文以 PAR 产品生产为例,提出了一种针对遥感数据的卫星产品质量控制体系流程,并对产品进行质量评价。

2 研究方法

对 PAR 产品进行质量控制及评价的具体方法为:首先根据算法原理及生产流程,对光合有效辐射产品进行不确定性分析,分析算法可能的误差来源及主要影响因子,从而对相关参数的质量进行控制,在此基础上构建了一套可靠的产品质量控制体系,利用产品质量标识体系完成对产品的质量控制,以便在最终产品生产与质量评价中加以甄别、分析。最后对生产的 PAR 产品进行质量评价,参考生成的质量标识文件,利用地面站点实测数据对 PAR 产品进行比较分析。

2.1 PAR 遥感反演算法原理

Huang 等人(2011)利用 MODIS 和 MTSAT 数据相结合的方法对全国的太阳辐射进行了估算,Li 等人(2010)和 Zhang 等人(2013)对太阳辐射的遥感估算进行了深入的研究,通过构建基于大气辐射传输模型的光合有效辐射与大气/地表参数的查找表,结合极轨卫星与静止卫星提供和反演得到模型所需的各种输入参数,能够反演全球的光合有效辐射。算法对于光合有效辐射的估计考虑了太阳辐射在穿过大气到达地表的真实物理过程,尤其是在云对光合有效辐射的消减方面,因此本算法具有明确的物理机制。算法中的各种输入参数为定量遥感反演产品,减少了参数化算法中需要对各参数进行多次率定以达到适应的过程,具有良好的可移植性。从算法的结构上看,可以方便地增加新参数,利于今后对算法进行改进和扩充。通过此算法,利用 MODIS 和 MTSAT 数据,生产了全国的 PAR 产品,其空间分辨率为 0.05°,时间分辨率为瞬时、小时以及日累计 3 种尺度。其中,气溶胶光学厚度数据采用气溶胶光学厚度和能见度的转换公式(Berk 等,1999)得到。

PAR 算法的流程如图 1 所示,具体流程包括:

(1)利用大气辐射传输模型 SBDART(Santa Barbara DISTORT Atmospheric Radiative transfer),建立不同散射几何(太阳天顶角、卫星天顶角和相对方位角)、不同地表反照率和高程条件下的云光学厚度与卫星入瞳辐照度的查找表。

(2)利用 MODIS 陆地产品获取地表反照率,利用 MTSAT 可见光通道数据获取不同观测时间(太阳天顶角)下的入瞳辐照度,通过查找表的插值得到云光学厚度。

(3)利用云光学厚度进行云检测,结合 MODIS 雪盖产品数据,区分冰雪、有云及无云区域。

(4)针对晴空条件,利用 6S(the Second Simulation of the Satellite Signal in the Solar Spectrum)构建的光合有效辐射查找表,估算晴空条件下光合有效辐射;针对有云区域,则利用 SBDART 构建的下行 PAR 查找表,实现云天 PAR 的反演,从而得到整个区域任意天气状况下的水平地表光合有效辐射。

(5)利用地表高程数据对水平地表光合有效辐射进行地形校正,得到起伏地表的瞬时光合有效辐射值。

(6)对瞬时光合有效辐射进行积分,得到每小时的光合有效辐射累积值,进而得到全天总光合有效辐射值。

2.2 PAR 产品不确定性分析

2.2.1 输入数据的不确定性分析

PAR 产品生产所需要的输入数据包括静止卫星数据可见光影像、地表反照率、大气水汽含量、大气臭氧含量、冰雪覆盖、水平能见度以及 DEM 等,输入数据信息,如表 1 所示。

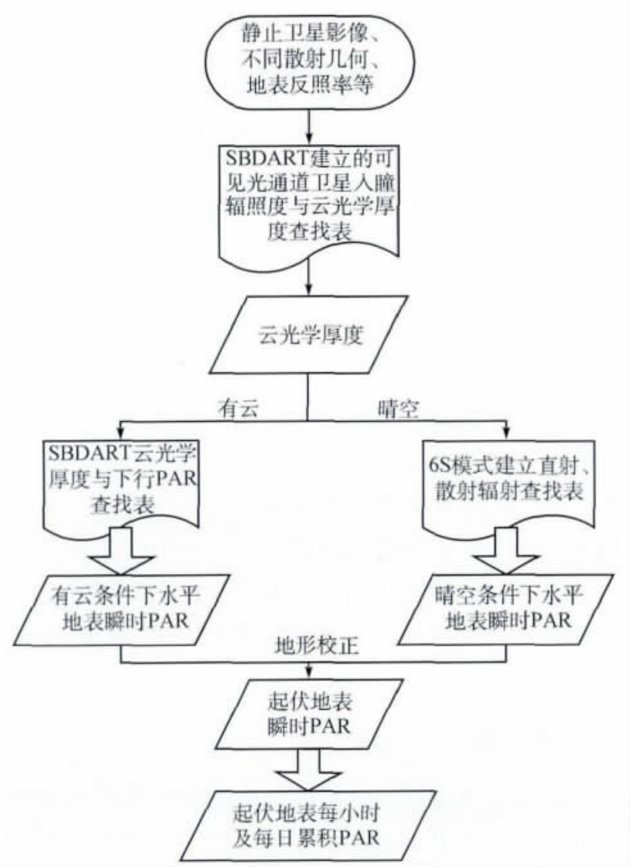

图 1 PAR 反演算法流程图

表 1 PAR 产品所需的输入数据

输入数据	来源	时间分辨率	空间分辨率	参数
MTSAT-可见光波段	MTSAT-1R	1 h	0.05°	反演云光学厚度
MCD43C2	MODIS	1 次/8 d	0.05°	地表反照率
MOD05/MYD05	MODIS	2 次/d	1 km	水汽含量
MOD07	MODIS	1 次/d	1 km	臭氧含量
MOD10	MODIS	1 次/d	5 km	冰雪覆盖
水平能见度	国家气象局	8 次/d	观测点	用于生成气溶胶光学厚度
DEM	SRTM	—	30″	地表高程

首先对输入数据进行敏感性分析,以确定估算 PAR 产品的主要影响因子。Li 等人(2010) 对气溶胶光学厚度、水汽、臭氧以及地表反照率等参数进行了敏感性分析,发现光合有效辐射对气溶胶光学厚度很敏感,由于气溶胶光学厚度是由能见度转换得到,所以需要对能见度进行详细的质量控制; 光合有效辐射对地表反照率较为敏感; 水汽和臭氧对光合有效辐射的影响比较微弱,所以只对其进行简单的质量控制,通过有效性检查来标记是否为有效值。

由于云光学厚度是反演 PAR 的关键参数,对云光学厚度进行了敏感性分析,将太阳天顶角设为 30°,地表反照率为 0.3,光合有效辐射通量随云光学厚度的变化情形如图 2 所示。

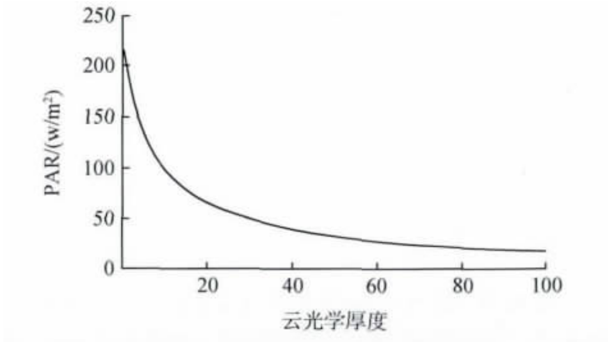

图 2 光合有效辐射随云光学厚度变化

从图 2 可以看出,有云天气下,云是影响地表下行 PAR 的关键因子,所以需要对云光学厚度的质量进行控制。

2.2.2 算法的不确定性分析

根据 2.2.1 节算法原理可知,算法主要分为晴天和云天两种情况,利用云光学厚度进行云检测,从而区分云与非云。云光学厚度是通过反演得到的,受地表反照率、散射几何等输入数据质量的影响。

反演云光学厚度时,由于冰雪的高反射率,常常会被误判成云,造成冰雪区域的云光学厚度也很高,这就容易造成晴空冰雪区域被误判成云,使估算精度降低,所以在云检测之前先进行冰雪识别,只对非冰雪区域进行云检测。这会导致冰雪区域有云但未检测到的情况,这是算法的不确定性,会影响反演精度,所以需要对冰雪覆盖进行标记,检查地表是否为冰雪覆盖。

2.2.3 生产流程的不确定性分析

很多成熟的遥感产品有主算法与备用算法两种算法,生产过程中会根据具体情况采用不同的算法,通常主算法是首要算法,在受到输入数据等条件限制时,会采用备用算法进行计算,备用算法通常比主算法原理简单,考虑的因素较少,所以反演的精度较差,需要分别进行标记。本文研究的产品生产流程中只有一种算法,所以未进行标记。

本文使用了静止卫星(MTSAT) 与极轨卫星(MODIS) 数据,其几何配准精度会在生产过程中产生不确定性,但在具体质量控制过程中未考虑其不确定性的影响。

在生产过程中,由于数据缺失等原因,经常会使用填充值来进行计算,这会导致不确定性,需要在生产过程中加以标记。地表反照率在中国东南地区大部分区域为空值,因而在实际计算中,对无值区采用多年的平均反照率来对空值进行填补,所以需要对填充区域进行标记。

2.3 PAR 遥感产品质量控制和评价方法

对 PAR 产品进行质量控制主要通过质量标识实现。本文的质量标识体系参考了 MODIS 产品的质量保证体系,通过对产品的不确定性分析,采用有效性检查、输入数据质量标记以及产品等级划分等方法,完成对产品的质量控制,生成产品的质量标识文件,确定产品的质量等级,从而为用户提供高质量、可靠的产品。之后对产品进行质量评价,利用地面观测数据与反演的 PAR 进行比较验证,并参考质量标识信息对产品进行精度评价,其总体流程如图 3 所示。

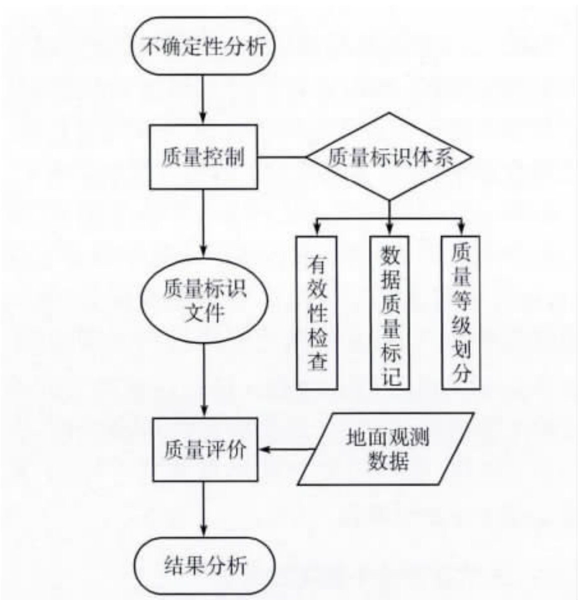

图 3 PAR 产品质量控制与质量评价总体流程图

3 产品质量标识体系研究

质量控制通过质量标识体系完成,生成产品的质量标识文件,质量标识由计算机自动生成,结果以比特位方式存储,并作为产品数据文件的元数据,与 PAR 产品一起输出。

3.1 有效性检查

对输入参数的有效范围进行逐像元的检查,其中地表反照率的值域为 0—1,大气水汽含量的值域为 0.01—5.0 g/cm^2,大气臭氧含量的值域为 0.258—0.430 cm-atm,水平能见度的值域为 0—50 km,冰雪覆盖的值域为 0—1,云光学厚度的值域为 0—100。如果输入数据全部通过有效性检查,则将产品整体质量标记为 0;如果大气水汽或臭氧含量未通过有效性检查,说明输入数据缺失,而水汽和臭氧对 PAR 反演影响微弱,算法会采用默认值填补,将产品整体质量标记为 1;如果冰雪覆盖参数未通过有效性检查,可能会导致云检测错误,将产品整体质量标记为 2;如果地表反照率未通过有效性检查,算法采用默认值填补,会影响 PAR 反演精度,将产品整体质量标记为 3;如果云光学厚度或水平能见度未通过有效性检查,则算法缺少关键输入参数,无法反演 PAR,将产品整体质量标记为 4。

3.2 输入数据质量标记

(1)臭氧和水汽:由于大气臭氧和水汽对光合有效辐射的影响比较微弱,只需通过有效性检查,将有效范围内的数据标记为 0,表示有效值,不满足有效性检查的标记为 1,表示填充值。

(2)能见度:气溶胶光学厚度是由全国 700 多个气象站点的能见度数据插值得到的,首先参考站点的能见度质检码信息,该信息记录了站点观测的能见度数据的质量状况,其质量控制码含义包括:0 表示数据正确;1 表示数据可疑;2 表示数据错误;3 表示数据有订正值;4 表示数据已修改;8 表示数据缺测;9 表示数据未作质量控制。质量标记过程中将数据正确的站点质量标记为 0,数据错误或缺测的站点质量标记为 2,其他情况标记为 1。然后将站点的质量标识作为以该站点为中心的 21×21 个像元的质量,如果像元间有重合部分,则取质量较差值作为该像元的质量标识,对于未标记到的像元,说明周围站点稀疏,插值后的能见度数据较为可疑,将其质量标记为 1。

(3)地表反照率:MODIS 地表反照率产品有质量控制文件,其数据质量分为 6 个级别,如表 2 所示。读取其质量控制文件,然后对其进行质量标记,将质量控制文件中值为 0 和 1 的像元质量标记为 0,表示高质量,将值为 2 和 3 的像元质量标记为 1,表示一般质量,将值为 4 和 255 的像元标记为2,表示填充值或数据缺失。

表 2 地表反照率质量控制文件

参数	值	数据质量描述
地表反照率	0	最佳质量,75% 以上最佳完全反演
	1	高质量,75% 以上完全反演
	2	75% 以下完全反演或者有 25% 以下的填充值
	3	采用备用算法或者有 50% 以下的填充值
	4	50% 以上的填充值
	255	填充值或数据缺失

(4) 云光学厚度: 根据算法原理,反演得到的云光学厚度受地表反照率、能见度、太阳天顶角以及观测天顶角等参数的影响,对于地表反照率和能见度,采用数据质量标识信息作为其质量信息,详细的质量划分过程如图 4 所示,共分为 4 个等级,其中 0 表示高质量,1 表示一般质量,2 表示低质量,－1 表示云光学厚度为填充值。

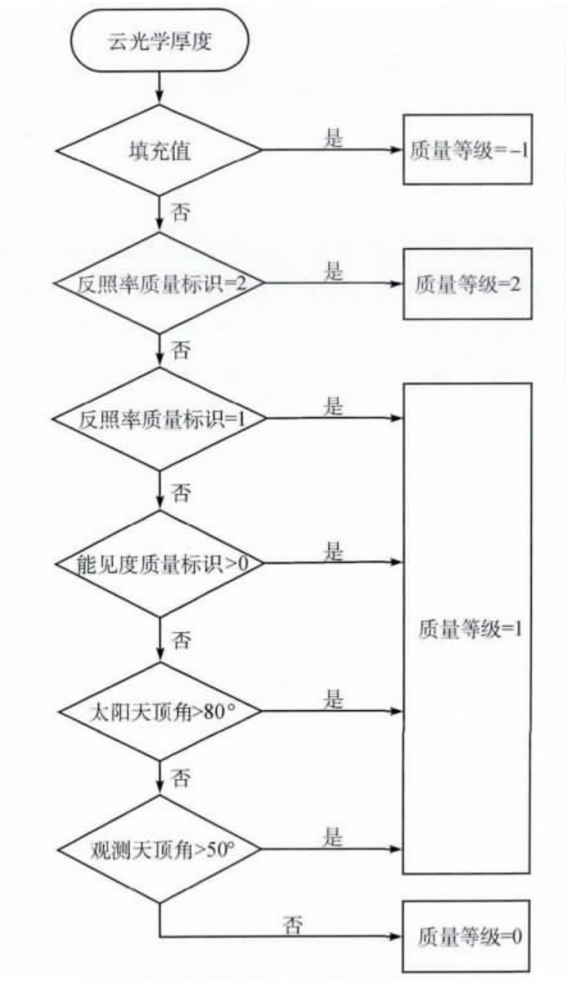

图 4 云光学厚度质量等级划分流程图

(5) 冰雪覆盖: 检查地表是否为冰雪覆盖,如果不是,则该像元标记为 0,如果是,则标记为 1。输入数据各 bit 位详细的质量标识信息如表 3 所示。

表 3 各 bit 位质量标识信息

bit 位	参数	值	描述
0—2	产品整体质量	0	已生产
		1	已生产,水汽或臭氧含量为填充值
		2	已生产,MODIS 冰雪覆盖缺失
		3	已生产,地表反照率为填充值
		4	未生产,云光学厚度或能见度缺失
		5	已生产,由于其他原因无法使用
3	大气臭氧含量	0	有效值
		1	填充值
4	大气水汽含量	0	有效值
		1	填充值
5,6	水平能见度	0	数据正确
		1	数据可疑、有订正值或已修改
		2	数据错误或缺测
7,8	地表反照率	0	高质量
		1	一般质量
		2	填充值或数据缺失
9—11	云光学厚度	0	高质量
		1	一般质量
		2	低质量
12	冰雪覆盖	0	否
		1	是

3.3 产品质量等级划分

根据产品的不确定性分析、有效性检查以及输入数据的质量标识,划分产品的质量等级,由于日总 PAR 是由瞬时值积分并累加得到的,所以对于日总 PAR 的质量需重新考虑。

3.3.1 瞬时/小时 PAR 产品质量等级划分

划分的流程如图 5 所示,利用有效性检查以及输入数据质量标记的结果对瞬时和小时 PAR 的质量进行划分,质量的等级说明如表 4 所示。

表 4 质量等级划分说明

质量等级	质量情况	描述
－1	填充值	未生产或由于其他原因无法使用
0	高质量	放心使用
1	一般质量	可用,需查看质量标记
2	较低质量	可用,地表反照率数据质量较差
3	低质量	可用,能见度/云光学厚度质量较差

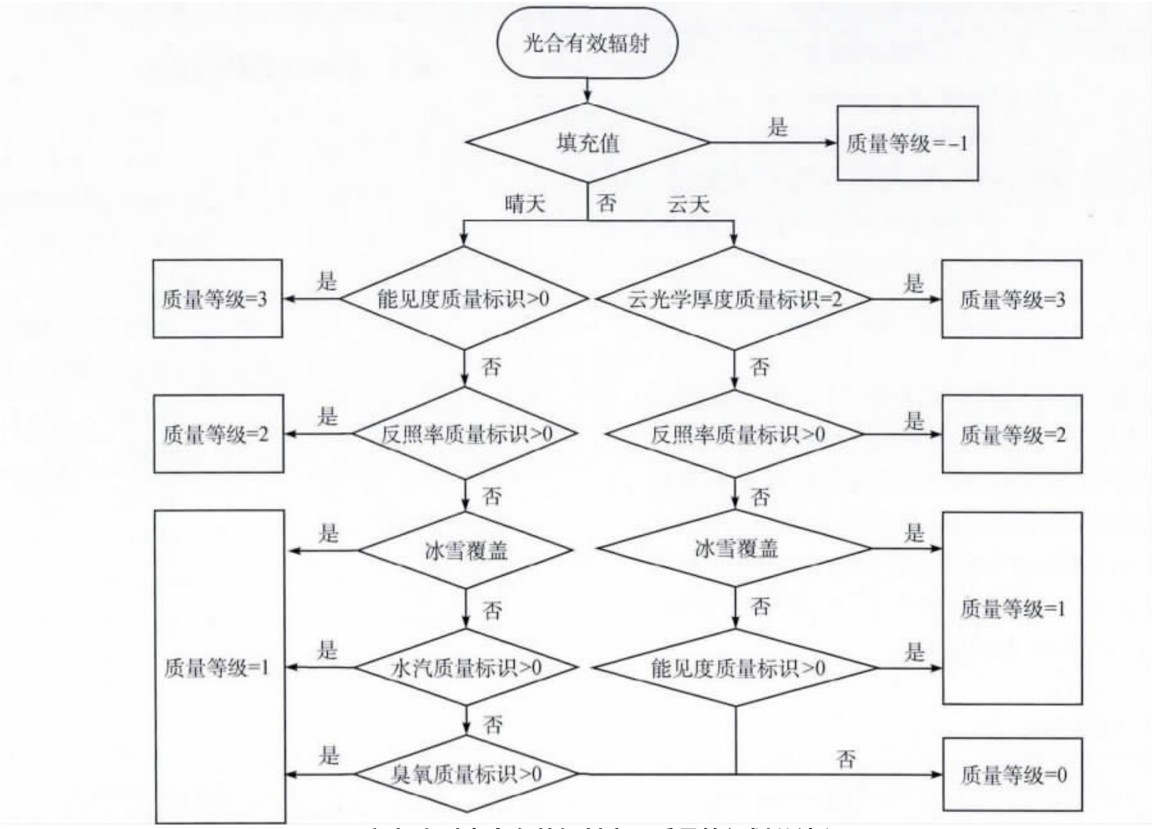

图5 瞬时/小时光合有效辐射产品质量等级划分流程图

3.3.2 日总PAR产品质量等级划分

首先根据日出日落时间确定用于计算日总PAR的小时数,通过这些瞬时PAR的质量得到日总PAR的质量。利用式(1)得到用于计算日总PAR的小时数n:

$$n = \mathrm{int}(t_2 - t_1) \tag{1}$$

式中,t_1为日出时间,t_2为日落时间,int表示向上取整。利用如图6所示的流程对日总PAR的质量进行划分,其中Q_i表示i从1到n时,第i个小时的瞬时PAR的质量,N_Q表示i从1到n时Q_i满足一定条件的个数,如$N_{Q=3}$表示i从1到n时满足$Q_i=3$的个数。与瞬时PAR的质量等级相似,日总PAR的质量等级从-1到3分别表示填充值、高质量、一般质量、较低质量和低质量共5个级别。

4 PAR遥感产品质量评价

以全国太阳辐射观测站的北京站为例,对日总PAR产品进行质量评价,并据此对本文的质量控制方法进行评估分析。本文验证了2010年1—6月共半年的产品(由于MTSAT影像数据缺失,半年产品共有95天有效值),由于PAR与总辐射的比例在世界各地相对稳定(季节或年际尺度上),因而有学者将此转换系数取为常数(白建辉,2009),本文中站点观测数据的日总辐射转换为光合有效辐射采用的转换系数为0.47,比较结果如图7及表5所示。

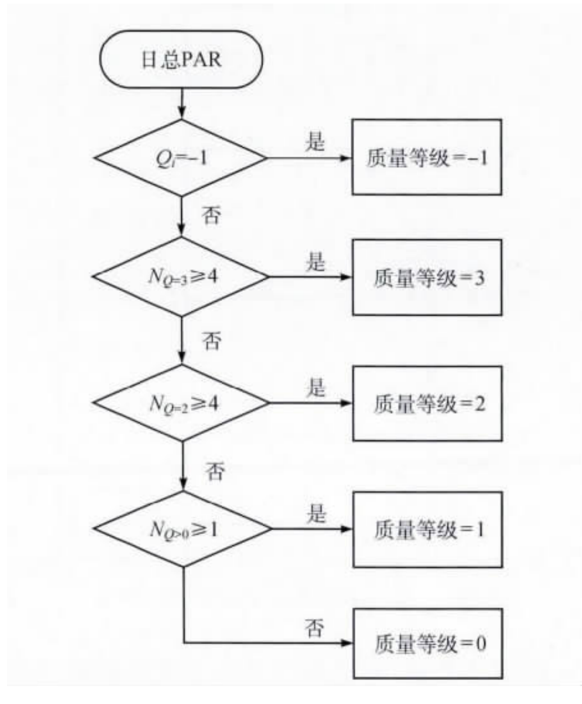

图6 日总光合有效辐射质量等级划分流程图

表 5 产品质量分级验证结果

产品质量等级	R^2	平均偏差/(MJ/m^2)	相对平均偏差/%	均方根误差/(MJ/m^2)	相对均方根误差/%	数量	质量影响因子
0	—	—	—	—	—	0	—
1	0.92	0.52	5.03	1.06	10.21	26	冰雪、水汽和臭氧
2	0.88	0.97	15.18	1.76	27.64	47	地表反照率
3	0.82	1.17	23.24	1.65	32.86	22	云光学厚度
-1	—	—	—	—	—	86	填充值

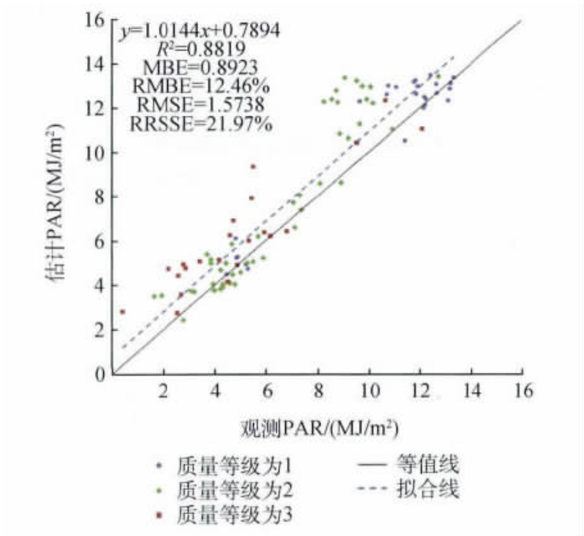

图 7 估计 PAR 与观测 PAR 比较的散点图(北京站)

北京站的估计 PAR 与观测 PAR 间的相关系数 R^2 为 0.88,平均偏差为 0.89 MJ/m^2(12.46%),均方根误差 RMSE 为 1.57 MJ/m^2(21.97%),产品整体高估。然后参考质量标识文件,根据产品质量等级,对产品进行详细的评价,得到了不同等级产品的精度结果,如表 5 所示,发现质量控制后质量等级划分为 1 的产品精度最高,而产品质量等级为 2 的精度较低,产品质量等级为 3 的精度最差,通过参考北京站的质量标识文件,分析影响产品质量的因子,发现云光学厚度和地表反照率的质量较差,而能见度等其他参数的质量较好,从而可以推测在北京站 PAR 产品的质量主要受云光学厚度和地表反照率的影响,由于 2010 年上半年北京站点的地表反照率等数据质量较差,所以导致整体产品没有等级为 0 的质量。该质量控制体系相对合理,能客观地反映出产品的质量信息。

5 结 论

对算法较为复杂的遥感产品的质量控制方法进行研究,以光合有效辐射遥感产品为例,研究了算法较为复杂的遥感产品的质量控制方法,通过质量标识体系完成对遥感产品的质量控制,并利用气象辐射站点北京站对产品进行了初步的评价,评价结果显示该质量评价体系对产品的质量划分较为合理,能够帮助产品使用人员甄别数据,分析产品的误差来源,更方便地使用该产品。

对于定量遥感产品,由于其不确定性来源较多,在质量控制过程中可能会有很多不完善的地方或者没有考虑到的因素,需要不断的研究来发展完善质量控制方法,如不同遥感影像的几何配准问题,会对结果引入误差,文中并未对其引起的误差进行分析,需要在之后的研究中进一步分析。本文只采用了北京站点进行质量评价,对于 PAR 产品的质量评价及对质量控制方法的检验还不够完善,详细的质量评价将会在之后开展,以便全面的检验产品质量控制体系以及分析产品的精度。

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