TERRA/AQUAデータによるクロロフィル評価画像のアーカイブ

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Introduction

これまで、本プロジェクトの一環として、Landsat/TMおよびTerra/ASTERなどの高分解能衛星データによる局地的な内水評価を行うためのchlorophyll-a推定アルゴリズムの構築を行い、成果を上げてきた。平成19年度の達成目標であるハイパー低解像度衛星Terra/Aquaデータへの「複合ラジオメトリック補正法」の適用について再度ハーパースペクトル現地計測を基本に行ってきた。**2007年**11月から2008年3月まで米国カリフォルニア大学サンタバーバラ校との共同で数回行った､「汚濁水塊を対象としたハーパースペクトル」の現地(SantaMonica Bay & Long Beach Port)計測においてSS混在の植物プランクトンがスペクトルノイズに影響を与えていることがわかった。

本年度は，最終目標の一つである「MODISデータによる水質定量評価を最終ゴールとした沿岸域をモニタリング」の実用化にむけて、これまで高解像度衛星を利用しながらアルゴリズムのMODIS解析結果のアーカイブシステムの構築を行った。

1.はじめに

MODISデータを受信・処理するシステムは，NASA[2]をはじめ国内の研究機関[3),4),5)]でも構築されており，FTPを通じて一般のユーザでも利用できるようなってきたが、これらのデータは直接受信した生データではなく，低次もしくは高次処理を施した補正済みデータであり，導入済みのアルゴリズムの更新や独自に開発したアルゴリズムをMODISデータへ反映させるためには，生データを受信するシステムを自前で用意しなければならない。また，MODISデータを高次処理したchlorophyll-aデータからの任意の地域における実利用に供せる水質環境GISを構築するためには，時系列のchlorophyll-aデータをアーカイブしておくシステムも必要になる。これらを統合したシステムを構築することができれば，衛星データをこれまで適用されてこなかった分野へ導入することも可能であり，萌芽性・発展性のある研究を実施することができると思われる。

そこで本研究では，日本近海(北緯50度～25度，東経125度～155度）を観測したMODISの生データをリアルタイムで受信し，高次処理したchlorophyll-aデータをアーカイブできる解析システムを構築することを目的とした。本論では，本研究で構築した解析システムの概要およびシステムに導入したアルゴリズムについて述べる。そして，実際に受信したMODISデータから高次処理したデータについてその妥当性を検討し，今後の運用方法や他分野と連携した利用方法について述べる。

2. 研究の方法

2.1 解析システムの構成

本解析システムは、米国SeaSpace社のTeraScanシステムを基に構成されており、認証サーバーを介して自動的に1日6～8パスのTerra/MODISおよびAqua/MODISの生データをリアルタイムで受信し，全ての生データと高次処理済みのデータをアーカイブしている。さらに，初期受信が良好に行えなかったデータに対しては,時間を遡ってデータを再受信し，同様な処理を行えるシステムとした。また，生データおよび高次処理済みのデータは2TBのファイルサーバーに一定期間格納し，生データに関しては解析が終了し次第オフライン上の媒体に保存する運用形態とした。ファイルサーバーに格納しているデータは,解析システム内部に配置されたPCのみからアクセスできるようにし,PC上から高次処理済みのデータを利用して様々な解析が実行できる環境とした。

2.2 解析システムに導入した複合ラジオメオリック補正アルゴリズム

Fig. 1は，解析システムに導入したアルゴリズムの処理フローである。本システムでは，上方から順に処理が始まり，生データを処理する低次処理からchlorophyll-aデータを生成する高次処理までを実行する。図中のLevel 0 fileが生データにあたり，まず生データから表1に示したバンドを含みこれ以降の処理に必要なバンドを選定してLevel 1A fileが生成される。Level 1A fileからは衛星の軌道情報を加えて，データの位置情報を格納しているGEO fileとそれらのデータから幾何学的な補正を施したLevel 1B fileが生成される。Level 1B fileからは衛星の軌道情報と観測時の大気の状態および風向・風速などのアンシラリデータを加えて大気補正を施し，最終的な成果物であるchlorophyll-aデータが生成される。次節では,Level 1B fileからLevel 2 fileが生成されるまでに用いており，解析システムに導入したアルゴリズムのコアについて述べる。

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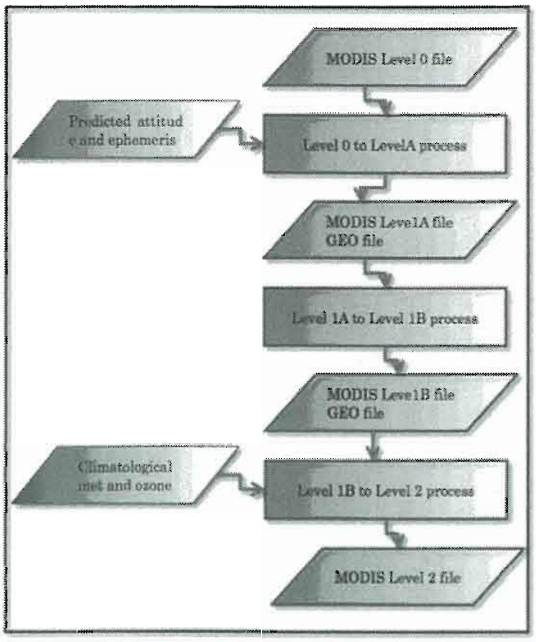

Fig. 1 導入したアルゴリズムの処理フロー

2.3 解析システムに導入した複合ラジオメオリック補正アルゴリズム

NASA では，1997 年から SeaBAM（SeaWiFS Bio-optical Algorithm Mini-Workshop）と呼ばれるプロジェクトにおいて，全世界に設置した観測点における海面からの射出放射輝度と chlorophyll-a データセットを収集し，Ocean Color4(以降、OC)と呼ばれる経験的アルゴリズムを構築している。OC4 の最新バージョンは 4.0 であり，2,853 の観測地点で得られてデータセットからアルゴリズムを構築し，その決定係数は R2=0.892 であることが報告されている。ここでこれらを基礎として，本プロジェクトの一つの目的である「OC4 を MODIS センサ用に改良ならびにアップグレード」を行い、構築してきた複合らジオメトリック補正アルゴリズム Filamen-Shaped 法を考慮した『OceanColor3Modis』を同解析システムに導入した。以降更に，SeaBAM によるアルゴリズムの改良は進める予定であるが，現段階では OC3M が最良のアルゴリズムと考えられるため，本研究では，これにより chlorophyll-a 濃度を推定することにした。

3. 結果と考察

2007 年 8 月 24 日 04 時 44 分(UTC)に Aqua/MODIS が観測したデータから生成した 443nm，488nm，551nm 波長帯域の正規化射出放射輝度データを利用して生成した chlorophyll-a 濃度推定画像を Fig. 2 に示した。画像の黒い部分は被雲がある部分か，この時間帯では観測できない領域である。本解析システムでは，これらのデータを準リアルタイムで生成し，ファイルサーバーにアーカイブしている。

本研究では 2007 年度（2007 年 4 月～2008 年 3 月）に本解析システムで受信・処理した MODIS データを合成した chlorophyll-a 濃度の平均値画像を作成した。 Fig. 3 は、2007 年 8 月における Chl-a 濃度の平均値画像である。MODIS データは光学センサのため，画像中に被雲があるとデータは欠損値として扱われるが，本研究で構築した手法により任意の期間ごとにデータを合成することでマクロ的な chlorophyll-a の時系列の流動を判読することができる。なお，カラースケールは，chlorophyll-a 濃度 0.01～100.0mg/m^3 までを対数で分割したものを当てはめている。

Fig. 2 Chlorophyll-a imagery by MODIS (Through a year)

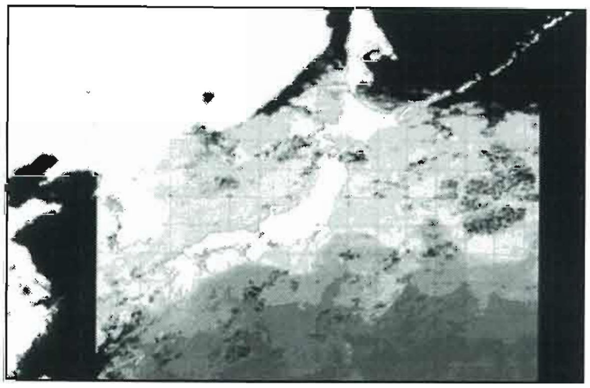

Fig. 3 Chlorophyll-a imagery by MODIS (monthly mean of Aug.)

東京都環境局によると，東京湾における赤潮の発生基準は，次のとおりである

- 海水が、茶褐、黄褐、緑色などの色を呈している
- 透明度が、おおむね 1.5m 以下に低下していること
- 顕微鏡下で赤潮プランクトンが多量に存在している
- クロロフィル濃度が 50.0mg/m3 以上あること

そこで、東京湾付近を 2007 年 8 月中に本解析システムで受信・処理した MODIS データを利用し，解析した結果、chlorophyll-a 濃度が 50mg/m3 すなわち高濃度と判読された地点は最も多いところで 12 回と判読された(Fig. 3)。行政側の平成 19 年度調査速報から 8 月の赤潮観測は 7 回と報告されており，赤潮の兆候と分布を，この海域では概ね正確に推定できていると考えられる

このように，MODIS はマクロ的な観測に優位であ

るだけでなく，高い時間分解能を有していることから，ほぼリアルタイムで特定の海域における水質環境を判読することができる。よって，本解析システムからは日本近海の水質環境モニタリングに有用なデータを得ることができ，時系列のアーカイブデータから様々な海域における水質環境 GIS を構築するための基礎ができたといえる。しかしながら，本研究で適用した chlorophyll-a 濃度を推定するアルゴリズムは，100.0(mg/m3)以上の海域では精度の低下が報告されていることから，内湾や沿岸域など赤潮が多発する水域における　RVI 法を基調としたアルゴリズムについても更に検討する必要がある。

Conclusions

A MODIS semi-analytical algorithm for chlorophyll *a* was tested using a total of 976 global data points from regions where the pigments were typically unpackaged, packaged, or transitional with appropriate algorithm parameters applied for each data type. This resulted in "Version 1" of the semi-analytic algorithm, which did not address the high-latitude regions with extremely packaged pigments which are included in "Version 2" of the semi-analytic algorithm. The algorithm has thus evolved to better represent the entire global data set.

The "unpackaged" type consisted of data sets that were generally consistent with the case 1 CZCS algorithm and contained mostly tropical, subtropical, and summer temperate data. This algorithm type was parameterized using Gulf of Mexico and Arabian Sea data, and it continues to remain the same in both Version 1 and Version 2 of the algorithm. The Version 1 "packaged" type of pigment-absorption parameterization was consistent with pigments found in eastern-boundary upwelling data sets containing somewhat more packaged pigments, but not consistent with the fully packaged pigments found in high-latitude data. Note that at times for upwelling centers, some of the phytoplankton have pigments that are as highly packaged as found in high-latitude data sets, but that is not true for the general region. The packaged data sets studied with Version 1 were processed with the algorithm modified for phytoplankton-absorption parameters consistent with the Southern California Bight area. This resulted in two fairly equally divided data sets totaling 604 points. That left 372 data points that were not well enough characterized to classify.

The Version 1, semi-analytical (SA) algorithm for chlorophyll *a* performed well on each of the data sets after classification, resulting in RMS1 errors of 0.099 and 0.111 (e.g., 0.10 log unit) for the unpackaged and packaged data classes, respectively, with little bias and with slopes near 1.0. RMS2 linearized errors for the algorithms were 23% and 27% for the two classes, respectively. The SA algorithm for phytoplankton absorption provided data accurate to about 30%.

While these numbers are excellent, one must bear in mind what misclassification does to the chlorophyll results. Using parameters for an average or transitional domain in the semi-analytical MODIS algorithm with the global data set (n=976) yielded an RMS2 error of 44.6%, while applying the unpackaged parameters on the global evaluation data set yielded an RMS2 error of 92%. So, without classification, the algorithm performs better globally using the average parameters than it does if misclassification occurs.

For the difficult transition period between spring and summer or the regions between upwelling centers and the warmer offshore waters, a data set was tested that included the eastern boundary region of the North Atlantic. Nitrogen-depletion temperatures were used with AVHRR-derived sea-surface temperatures to sort stations into packaged, unpackaged, and transitional domains. Comparing sea-surface temperature (SST) to the nitrate-depletion temperature (NDT) provides a means of estimating how packaged were the pigments for a given pixel. Cold SST values relative to NDTs suggest convective overturning or upwelling has brought cold, nutrient-rich water to the surface. Phytoplankton in these waters are typically large, contain high ratios of chlorophyll pigment per cell because they have recently experienced very low light levels, and exhibit low chlorophyll specific absorption coefficients. Solar heating warms this water, reduces the cell requirement for light-harvesting pigments including chlorophyll *a* while increasing the cell requirement for photo-protective pigments, decreases the size of cells that can remain neutrally buoyant, and results in an increase in the chlorophyll specific absorption coefficient.

RMS2 errors dropped from 50% to 38% as a result of this data-sorting exercise. Since large regions of the subtropical and tropical Atlantic, Pacific, and Indian Oceans remain in the unpackaged bio-optical domain during all seasons and provide stable data accuracies from 24% to 28%, it is reasonable to expect that use of an NDT-based sorting algorithm with MODIS sea-surface temperatures to separate data into appropriate bio-optical domains will result in accuracies for the MODIS semi-analytical chlorophyll *a* algorithm that are significantly lower than our target value of 35%.

This completed the evaluation of mid- to low-latitude data sets considered for Version 1 of the algorithm and used in Collections 1 through 3 for ocean data found in the MODIS Data Active Archive Computer (DAAC) at NASA Goddard. Version 2 of the algorithm is discussed below and is used in Collection 4 of the ocean data found in the DAAC. Version 2 is summarized below.

In Version 2, "fully packaged" pigment parameters were derived from high latitude polar and temperate upwelling data sets to replace the previously designated "packaged" parameter set. In addition, a smoother strategy for transitioning from the unpackaged to the fully packaged pigment domain was introduced using sea surface temperatures and nitrate depletion temperatures. These transitions can be thought of as transitions between fall and winter (fall overturn) and spring and summer (spring bloom) or as transitions between upwelling and offshore waters.

The 5℃ range between unpackaged-pigment conditions (warm waters) and conditions of fully packaged pigments, provides a means of transitioning algorithm parameterization between the two extremes using the weighted average of chlorophyll retrievals from the two based upon SST-NDT values from -1℃ to 4℃. Tests in the Southern California Bight transition region between upwelled and offshore waters indicate that errors are reduced from 39 to 31% using this method for transitioning between packaging domains.

Compared to the SeaWiFS OC4 empirical algorithm, application of the MODIS Chlor_a_3 semi-analytical algorithm to Southern Ocean field data reduced the error in deriving chlorophyll concentration by almost a factor of two. Accuracy tests using MODIS satellite data for November 2000 show that Chlor_a_3 retrievals of global mean chlorophyll *a* concentration are within 8% of the historical seasonal mean, while OC4-like empirical retrievals using Chlor_a_2 are but 2/3 of the seasonal mean. This suggests that Chlor_a_3 semi-analytical algorithm retrievals of chlorophyll *a* concentrations will lead to larger, more accurate pigment and subsequent global primary production numbers than are presently being retrieved using SeaWiFS and Coastal Zone Color Scanner data sets.

Both the Chlor_a_3 and Chlor_a_2 algorithms used with MODIS Terra (Collection 4) data provide nearly identical modal chlorophyll values for the northern (0.087 mg m^{-3}) and southern (0.078 mg m^{-3}) central gyres in December 2000. However, the global mean value for Chlor_a_3 is higher (0.294 mg m^{-3}) than for Chlor_a_2 (0.231 mg m^{-3}). This difference can be explained by the Southern Ocean where Chlor_a_2 values are on average about half of field and Chlor_a_3 values due to lower chlorophyll-specific absorption coefficients typical of this region. MODIS Terra retrievals of chlorophyll *a* using reprocessed Collection 4 data are accurate to better than 41%. Removing data points from continental shelves improves Chlor_a_3 accuracies to 21%, while promoting shelf data using more appropriate nitrate-depletion temperatures can improve accuracies to about 20%. The higher accuracies do exceed our expectations, and only when data from more regions (e.g. southern central gyres, the southern ocean) and seasons (northern summer and fall) are included will a better idea of the actual range of accuracies be known. Then, an area-weighted global mean accuracy for each algorithm can be assessed for MODIS Terra. For MODIS Aqua performance evaluation awaits reprocessing with vicariously calibrated data.

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