Comparison of seasonal and interannual variations of leaf area index from satellite data and a dynamic vegetation model

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Abstract—Using Moderate Resolution Imaging Spectrometer (MODIS) and Global Inventory Monitoring and Modeling Studies (GIMMS) data, leaf area index (LAI) has been compared with the simulated results by a recently developed dynamic vegetation model, Interactive Canopy Model (ICM), which includes the carbon and nitrogen cycling processes of the ecosystem. Results show that ICM has the capability of reproducing the seasonal and interannual variations of the global vegetation. However, LAI was generally overestimated in the high and low latitudes but underestimated in the middle latitudes. The underestimations in mid-latitude are always followed by the vegetation sprout for the reason that modeled growth period lag behind the observed. The significant interannual variabilities and the spatial distributions of LAI are well captured by the model. But the simulated LAI exhibits larger variabilities than the observations in most areas except for some tropical regions. The temporal and spatial evolutions of the observed LAI are well simulated in low-latitudes. The bimodal distributions in seasonal variations of the tropical evergreen broadleaf trees and crops have not been well simulated. In addition, the model gives better results in the interannual variations of the boreal shrubs, savanna and deciduous needleleaf trees than other types of vegetation. And the simulated LAI in natural vegetation cases is better than that of crop in both seasonal and interannual time scales, which suggests that it is very important to incorporate the human interferences into the dynamic vegetation model.

Keywords—satellite data, dynamic vegetation model, ICM, model assessment

I. INTRODUCTION

Terrestrial vegetation has a significant impact on land-atmosphere interaction though not only the biophysical but also the biochemical pathway. Changes of vegetation structure and biogeography because of the climate variation alter land surface albedo, surface roughness, stomatal resistance, etc., and thus influence the exchanges of mass, energy and momentum fluxes between land and atmosphere.

Empirical canopy conductance calculation and arbitrary prescription of vegetation phenology have been included in the BATS [1] and SIB [2], controlling the surface energy and moisture balance. And then, a photosynthesis-conductance submodel [3, 4] is incorporated in the Land Surface Models [5-7], describing the simultaneous transfers of CO2 and water vapor into and out of the leaf. Additionally, a one-layered, two-big-leaf submodel has been developed [8].

LAI, defined as half the total leaf area per unit ground surface area [9], is a key morphology and functional parameter that has functional relationships with many physical and biological processes associated with vegetation, and is a required input to many LSMs and climate models. Dickinson et al. [10, 11] has developed a dynamic vegetation model, ICM, which includes the ecosystem carbon and nitrogen cycling processes that occur on time scales of weeks to seasons. Unlike previous LSMs that using satellite data or other observations to derive time-series fields of LAI, ICM simulates LAI according to the leaf carbon in the carbon cycling process. Ji [12] and Huang et al. [13] have proposed a similar approach, but there are some differences especially in their descriptions of nitrogen cycle.

In this paper, ICM will be assessed by comparing the LAI that from the model to the satellite products on its performance of simulating the global vegetation variations.

II. DATA AND MODEL

A. LAI form MODIS and GIMMS

The LAI products that derived from MODIS onboard the National Aeronautics and Space Administration’s (NASA’s) Terra satellite at 0.25° resolution through February 2002 to December 2006 was used in this paper to give the observed seasonal vegetation variation. And the data with time series of January 1982 to December 2002 produced by the GIMMS group was employed to analyze the interannual vegetation variations.

The MODIS LAI algorithm is based on the three-dimensional radiative transfer theory [14], and developed for inversion using a look-up table (LUT) approach [15, 16]. The products include quality control (QC) information regarding data processing conditions and cloud. Nevertheless, it is greatly worth revealing the actual seasonal vegetation variations. GIMMS data has a similar dynamic range with the MODIS [17].

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B. Model

The ICM has already been taken in the National Center for Atmospheric Research (NCAR) Community Land Model, version 3.0 (CLM3.0) [18]. It has one vegetation layer, 10 unevenly spaced vertical soil layers, and up to 5 snow layers. Spatial land heterogeneity in ICM is presented as a nested subgrid hierarchy without lateral interactions between each grid cell. Surface pressure, air temperature, precipitation, solar radiation, longwave radiation, wind velocity and air specific humidity are used to force the model. The ICM consists of the biophysical-physiological module (BPM) and the ecosystem module (EM). The surface physical parameters including the energy, water and momentum balances and the biophysical parameters such as stomatal resistance and photosynthesis rate are simulated in the BPM. The carbon and nitrogen cycling processes are depicted in the EM, influenced by the physical attributes such as leaf and soil temperature, soil moisture and light-limited rate of the carbon assimilation. Synchronously, the simulated LAI and the content of Rubisco nitrogen outputs from the EM provide the biophysical and biochemical features of the vegetation need for the energy and water balances computation in the BPM.

We drive the ICM with the dataset of a global meteorological forcings [19] at 1° × 1° resolution, and 30 minutes timestep from January 1970 through December 2006 while the first 12-yr was used as a spinup.

III. Results

A. LAI seasonal variations

1) Seasonal patterns in global scale

The ICM has the capability of simulating the global vegetation seasonal variations (Fig. omitted), with the LAI high in the summer and low in the winter. However, the modeled results are not consistent exactly with the observed ones. In January, the ICM values are higher than the MODIS over most regions south of 25°N, especially in Amazon and central Africa, and lower in most areas between 25°N and 50°N (Fig. 1a). In April, the areas with negative anomalies expand to the north and the differences become lager in southeastern North America, Europe and southeastern China (Fig. 1b). The underestimated areas north of 30°N are the most obvious in July except a few regions. Besides, the negative anomalies also appear in some regions in the southeast part of Australia. The tropics are still overestimated (Fig. 1c). In October, the areas with lower LAI shrink, and the anomalies in southern China become positive (Fig. 1d).

To better illustrate the spatial distributions of the seasonal LAI differences, the monthly means of differences of ICM and MODIS data are calculated (Fig. 2). The simulated LAI are higher than the MODIS throughout the whole year in areas south of 20°N, with the largest positive anomalies near 10°S in the first half of the year and near 10°N in the second half of the year. The negative anomalies present over mid-latitudes of Northern Hemisphere from April to August, with its magnitude large in May to July. Most areas in high-latitudes of NH are occupied by the positive anomalies, especially before April and after August, when most vegetation is not in their growth period. The differences are small nearby 30°N mainly because of the scarceness of vegetation in this area.

Figure 1. Spatial pattern of differences (ICM-MODIS) in (a) January, (b) April, (c) July, (d) October LAI

Figure 2. Spatiotemporal variations of differences (ICM-MODIS) in LAI
2) Seasonal patterns for various types of vegetation

The MODIS product incorporates 17 classes of primary land cover scheme defined by the IGBP, including 12 vegetation classes among them. ICM expand the 7 primary classes, that is needleleaf evergreen or deciduous trees, broadleaf evergreen or deciduous trees, shrubs, grasses and crops, to 15 physiological variants based on climate rules to distinguish arctic, boreal, temperate, and tropical types, C3 and C4 grasses, and evergreen and deciduous shrubs [20]. The vegetated types in this classification scheme were named as plant function types (PFTs). Up to 4 of 15 PFTs plus bare ground comprise the vegetated surfaces in each grid cell.

We select 7 regions according to the vegetation types in both MODIS and ICM, to analyze the vegetation seasonal variations of the 7 primary vegetation types.

Northeastern USA (50-55°N, 90-95°W) was occupied mainly by evergreen needleleaf trees. The simulated LAI are higher than the observed ones except in May to July. The highest value presents in August from ICM rather in July from MODIS, showing that the trees growth period lags behind the real time (Fig. 3a). Evergreen broadleaf trees mostly distributed in the tropics, and Amazon was chosen (0°-10°S, 60-75°W) for comparing. LAI simulated in ICM are higher than the observed throughout the year (Fig. 3b). Seasonal pattern of evergreen broadleaf trees changes a little all the year round probably because of the sufficient solar radiation and rainfall in this area. Nevertheless, the MODIS data have two peak points, which are not exist in the ICM results, implying us that solar radiation is not the only climate element that influence the vegetation growth. The simulations for the deciduous needleleaf trees in Siberia (57-62°N, 120-135°E) have their max value in August, while the maximum of observations appearing in July. The simulations are higher than the observations except May and June (Fig. 3c). The modeled LAI of deciduous broadleaf trees in southeastern North America (35-40°N, 75-85°W) are lower than the observed and the peak point presents in September which lags behind the real situation for several months (Fig. 3d). Northern Eurasia (65-75°N, 70-170°E) was selected to compare the simulated LAI of shrubs to those from MODIS. The modeled LAI reaches its summit in August but the observed maximum occurs in July, with the similar problem of growth period lag presenting (Fig. 3e). North Africa (5-15°N, 0°-40°E) is mostly distributed with Savanna (Fig. 3f). The simulated values are higher than the observed and have a larger magnitude, but their maximums appear in the same month. Northern China is a main region for agricultural products. The observations have two peak points in May and August respectively, while the simulations have only one in September (Fig. 3g). The seasonal pattern of crop may attribute its bimodal distribution to human influences such as seed sowing and harvest.

![Figure 3](image)

The ICM is able to simulate the LAI seasonal variations that manifest the vegetation’s growth and fade. But the simulations are higher than the observations in low and high latitudes and lower in middle latitudes. Positive anomalies exist for most types of vegetation except for deciduous broadleaf trees. Besides, there is another common problem that the growth periods from ICM lag behind those from the MODIS, which explain the area expansion and shrink of NH where the negative anomalies distribute. Considering the quality control problem of the MODIS data, the phase differences between the simulations and observations existing in the model should be more essential than the amplitude differences.

B. LAI interannual variations

Variances of LAI interannual variabilities can show the intensities of vegetation variations. The global distribution of LAI variances from ICM and GIMMS and their differences are given in Fig. 4. In January, regions with large variances are located in areas south of 25°N except in Amazon, Congo Basin, northeastern Africa, and central and western Australia. Besides, some regions in Siberia near 60°N have intense
variabilities, too (Fig. 4a). Variances from GIMMS distributed similarly (Fig. 4c), but the anomalies are less than the simulated ones in most areas except in some parts of North America and Eurasia near 50°N and some parts in Amazon and central Africa (Fig. 4e). In July, areas with large variances expand to the north in NH both in simulations and observations (Fig. 4b, d). Most patches with large interannual variabilities in the observations are presented in the simulations except for some parts in Congo Basin. But the variances are still lower in the ICM than in the GIMMS (Fig. 4f).

EOF analysis was performed on data from ICM and GIMMS in January and July respectively, in order to better investigate the temporal evolution of LAI interannual variations. The analysis was taken on separately in low latitudes (30°S-30°N) and high latitudes of NH (40°N-90°N) because regions that with large variances of interannual variabilities are mainly distributed in these two zones, and their vegetation-atmosphere interactive processes may be dissimilar. The leading patterns were given in Fig. 5 and Fig. 6.

Figure 4. Distributions of LAI variance simulated by ICM in (a) January and (b) July, and observed by GIMMS in (c) January and (b) July, and their difference (ICM-GIMMS) in (e) January and (f) July.
In January, the first EOF accounts for 10.3% of the covariance matrix variance on average in simulations, and the increasing trend is found in northeastern and eastern South America, Sub-Saharan Africa, South Africa, northern Australia and southern China from 1989 to 1990 and after 1995. The opposite trend occurs in plateau south to Amazon and eastern Africa (Fig. 5a, b). The first EOF in observations accounts for 15.6% variance and the similar trend is found in principle variable regions as in Fig. 5a (Fig. 5c, d). Increasing tendency is presented in most areas of boreal high latitudes except in some parts of central Siberia for simulated results (Fig. 5e, f). However, oscillation is displayed in the observations, with large variabilities occurring in 1985, 1988 and 1994 (Fig. 5g, h). The GIMMS data may have quality problems that cause the discontinuouness near 50°N. The first EOF accounts for 33.2% and 30.1% variance in simulations and observations respectively in boreal high latitudes.
In July, evident increasing tendency is found in northern South America and some parts of southern Africa, while decreasing tendencies appear near 20°S in South America (Fig. 6a, b). But large variances of interannual variabilities are displayed in most areas of tropics especially in central Africa. Conspicuous decrease occurred in 1994 (Fig. 6c, d). Most part of high latitudes in NH is displayed by increasing trend in simulations (Fig. 6e, f) while a periodic oscillation is found for GIMMS values (Fig. 6g, h).

The spatial distributions of large variance have been well captured and the relevant time series are presented as continuous increase or decrease in simulated results. However, the GIMMS data are found to have oscillation patterns in principle variable areas. Besides, the obvious LAI variations happened in mid-90s of the 20th century are not apparent in the simulations.

The same 7 regions as in Fig. 3 were selected in comparing the differences of interannual variations between simulations and observations. All the 7 regions are situated in NH and almost all types of boreal vegetation flourish in boreal summer, so that LAI averages of June to August every year were chosen from ICM and GIMMS to compute their LAI interannual variabilities and the related regression tendencies. The modeled values of evergreen needleleaf trees have an obvious increase though 1982 to 2002 that inconsistent with the observed ones. The decreases in 1994 and 1999 have not shown in simulations (Fig. 7a). The modeled LAI for evergreen broadleaf trees in Amazon increases more than the observed and there exist opposite tendencies in the former 80s and later 90s of 20th century (Fig. 7b). The obvious decreases in 1991 and 1994 have not been presented in the simulations. The ICM and GIMMS values have the same increase tendencies for deciduous needleleaf trees in Siberia (Fig. 7c), although the phases in ICM seems to ahead of that in GIMMS for 1 year. LAI for deciduous broadleaf trees in southeastern North America decreases in observations but increases in simulations (Fig. 7d). Interannual variations for Shrubs in northern Eurasia (Fig. 7e) and Savanna in North Africa (Fig. 7f) are modeled better than other types, with the correlations of ICM and GIMMS data at 0.73 and 0.53, passing 0.01 and 0.02 significance levels respectively. The simulated LAI of crop in eastern China has an obvious biennial oscillation, which does not agree with the real situation (Fig. 7g).

Overall, the ICM also has the capability of simulating the global vegetation interannual variations. Areas with large variance have been well captured in the modeled results. Simulations for Shrubs and Savanna which have sparse vegetation coverage perform better than other types.

IV. CONCLUSION AND DISCUSSION

Unlike many other dynamic vegetation models in which LAI change in a long time scale or are predicted by satellite data or empirical values, ICM computes LAI in an interactive processes with climate, approaching the realities more than before, and the output occurring on time scales of hours to seasons. Results show that the model is able to simulate the seasonal and interannual variations of global vegetation.

Carbon and nitrogen cycles in land surface ecosystem is included in this model, describing the processes of carbon assimilation, partition and loss in vegetation. LAI is determined by the leaf carbon multiplied by the Specific Leaf Area (SLA). SLA is the ratio of leaf area to leaf mass and is a constant for each type of vegetation. The changeable leaf carbon because of organic gain and loss is the direct reason that LAI changes. The inaccuracies of simulated results imply
that there should be some uncertainties in the parameterization of the carbon partition or loss processes. Besides, parameterizations of nitrogen controls of photosynthesis and carbon partition may be another limitation that exists in this model.

Growth of vegetation in different regions are affected by different climate attributes, with temperature considered to be the main factor in middle and high latitudes [21] while moisture and solar radiation playing more important roles in low latitudes[22, 23]. However, the climate controls of vegetation interannual variations are more complicated than those of seasonal variations, causing that the interannual correlations of simulations and observations worse than the seasonal ones in some part.

Besides, simulated results of crop land are worse than the natural vegetation not only in seasonal but also in interannual time scales, suggesting that human interferences should be considered in the crop modeling.

ICM is superior to proceeding land surface models in its depiction of ecosystem carbon and nitrogen cycles, although many shortcomings still exist. The model’s parameterization scheme and parameters should be improved in the future.

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REFERENCES


