A Correlation Analysis of Satellite Chlorophyll and Iron Dust Flux to Ocean

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Table of Contents

Abstract	1
Introduction	2
Two Approaches	2
Results	3
Conclusion	5
Reference	6
Acknowledgements	6
Appendix	7

Abstract

According to the "iron theory", iron from the atmosphere is an important source of a required nutrient for oceanic phytoplankton. In the presence of iron the phytoplankton produce biomass at enhanced rates compared to iron depleted regions resulting in higher concentrations of chlorophyll. Using data for the year 2000 from two sources, the GOCART model (atmospheric dust composition – iron model) and SEAWIFS satellite sensor (ocean color – chlorophyll-a), correlation analysis of iron and chlorophyll are made using two approaches. The data are processed into yearly averages and monthly anomalies which are then used to produce correlation coefficients between ocean Fe flux and ocean color. The first approach utilizes GRADS programming to plot global maps of the annual average, monthly anomalies, and correlation coefficients. The second approach uses the singular value decomposition to expose spatial patterns from a mathematical standpoint. Correlation coefficients demonstrate some connection between iron and chlorophyll but advanced analysis are needed to fully quantify their relationship.

Introduction

The "iron theory" is a proposal that relates the supply of iron to ocean productivity, thus influencing the Carbon Dioxide (CO_2) in the atmosphere, one of the top three green house gases in the atmosphere. According to John Martin, there is an iron deficiency in certain ocean regions and increasing their iron content will stimulate phytoplankton growth [2]. Further more, enriching the ocean will reduce atmospheric CO_2 by the process of photosynthesis. A little less than half of the photosynthesis on earth is processed through phytoplankton. Phytoplankton is the primary engine for the biological pump, transporting carbon from the atmosphere and storing in the deep ocean [2]. Proposals to lower atmospheric CO_2 levels by modifying the biological pump should be based on a clear understanding of the processes at work and their interactions and feedbacks with the climate system. The local and regional responses need to be understood along with the global patterns.

The objective of this project is to analyze iron dust and chlorophyll anomalies derived from satellite data to gain some insight of their interactions. Iron is one of the limiting nutrients in the southern ocean and north Pacific because there is high nitrate low chlorophyll responses [1]. Dessert sand is a main source of open-ocean iron; approximately one forth of the iron in the ocean is a result of dessert dust storms [5]. Prevailing winds cause these storms to deposit iron dust upon the ocean surface. As the iron dust settles in the water, it interacts with the chlorophyll a, the pigmentation of phytoplankton. The pigment alters the ocean color depending on the chlorophyll levels and the SeaWif satellite records the changes in color. When the ocean reflects high levels of chlorophyll, it implies a greater source of phytoplankton; the growth rate is observed through the chlorophyll data. The GOCART model of dust deposition simulates the iron data. After obtaining satellite data, anomalies are constructed to acknowledge the different monthly flux in iron and chlorophyll levels. The data clearly uncover seasonal patterns and origin factors that will be described in the result analysis.

Two Approaches to Solving Problem

The first approach to finding the relationship between the iron flux and the chlorophyll is the statistical method of correlation. This approach was followed in Erickson [3] using monthly averages over an eight month time period. This is refined here using a full years data and by computing the correlations of the monthly anomalies.

Adjusting an existing FORTRAN code developed by Jose Hernandez, the monthly dust flux and chlorophyll data were read and averages computed. From these averages the monthly anomalies (1) were computed as the difference of the variable at a particular grid point from the annual average. The correlation coefficient (2) expresses the linear the relationship between iron dust (X) and chlorophyll (Y). The computed quantities were formatted for GRADS graphic tools to produce global data maps of the correlations of anomalies. Direct comparison to work of Erickson is then possible.

(1) Anomaly

$A_{ij} = \hat{A} + a_{ij}$

$i =$ month 1,12 $\quad j =$ variable 1,2

$\hat{A}_j =$ annual average $\quad a_{ij} =$ anomaly

(2) Correlation Coefficient

$$cc = \frac{\sum (xy - n\hat{x}\hat{y})}{\sqrt{\sum (x - n(\hat{x})^2)\sum (y - n(\hat{y})^2)}}$$

$\hat{x} =$ iron dust sample mean

$\hat{y} =$ chlorophyll sample mean

The second approach to the analysis of the data seeks to identify the coherent spatial patterns present in the data using mathematical methods that represent the data as matrices that can be decomposed into components. The singular value decomposition (SVD) is used to analyze the "spatial variability" in monthly anomaly data. The data are reformatted and imported in matrix form to MatLab 6.0. The SVD of a matrix $A=USV^T$ decomposes the matrix into two orthogonal matrices U and V whose columns consist of the left and right singular vectors. The singular values are also present in the decomposition as elements of a diagonal matrix. The U and V are two orthogonal bases and S is the diagonal of the transformed matrix. Each monthly anomaly is represented by an m by n matrix, where m is the number of latitude lines and n is number of lines of longitude. Using the graphic techniques of MatLab, images were plotted of the monthly anomalies and used to further explain the ocean iron and chlorophyll connection.

(3) Singular Value Decomposition

$A = USV^T$

$= \sum \sigma_i u_i v_i^T$

such that $\sigma_1 > \sigma_2 > \sigma_3 >$

Analysis Results

In this project, the monthly anomalies of dust flux and chlorophyll concentration for the year 2000 are analyzed. The correlation coefficient of the monthly anomalies is shown in figure 1. Positive CC implies iron dust and chlorophyll react on one accord, while negative CC implies iron dust and chlorophyll are strongly anti-correlated. High correlation appears in the ocean regions bordering desert lands as a result of the supply of the greatest iron source. Upper level winds carry the iron dust thousands of kilometers across the ocean. Dust storms are frequent in North Africa, the Gobi and Taklamakan desert, Loess Plateau of China and the arid regions of Australia, India, Israel, and Central Asia.

There is a strong source of iron and also high correlation between dust and chlorophyll along the Atlantic shores of Western Africa because of the Sahara Desert, the largest dust source to the ocean. As shown in the peak of the dust annual average of figure 2, the only site that reflected extremely high averages is in northwestern Africa. Because the monthly anomalies are calculated by taking out the annual average factor, they feature the deviations from the average. The chlorophyll anomalies do not show much deviation from the annual average because Western Africa is very close to the warm equator. However, chlorophyll increasingly responds, at a slower rate, as dust levels increases. The dust anomalies reveal levels much above average during winter months December (figure 5d), January (figure 3a), and February (figure 3b), and dust flux much below average in the summer months such as June (figure 4b), July (figure 4c), and August (figure 4d). Winter months have higher wind speeds in the north hemisphere, causing more sand to blow off of the Sahara Desert. As the season changes to the Summer, the current send the iron dust away from the Africa southwest towards east South America.

The currents move the African iron dust from the Atlantic to the Pacific. As the season in the southern hemisphere changes to winter, the February (figure 3b), March (figure 3c), and April (figure 3d) anomalies clearly show iron dust movement and the slight chlorophyll response. Figure 1 illustrates some correlation east of South America but there is a much higher correlation west of South America and east Australia where the annual average for dust and chlorophyll remains very low. Both chlorophyll and dust monthly anomalies show the same pattern, slightly above the annual average in south hemisphere winter months January (figure 3a), February (figure 3b) and December (figure 4d) and slightly above average as evident in June (figure 4b), July (figure 4c), August (figure 4d). March (figure 3c), April (figure 3d), and May (figure 4a) anomalies show the transition period where this area has patches of both high and low. That constant region is between 25S to 50S and known as the southern band. This demonstrates a significant characteristic of the correlation coefficient analysis because it registers a high correlation when iron and chlorophyll do not have high absolute concentrations. This relationship is consistent with the small variation from the annual average shown in the anomaly fields. High correlation does not imply high concentration.

Other areas of positive correlation are west of North America and East of Asia. Asian dust blows toward the western North Pacific. Large pressure gradients in the mountain areas of California cause dust storms carried by the Santa Ana winds. Ocean upwelling is another source of plankton nutrients taking iron from the bottom of the ocean bringing it on cool currents towards the northern California coast. In regions where other sources of nutrients are available, the phytoplankton growth may not be iron limited and additional flux from the atmosphere will not stimulate growth. In this way, there will not be high correlation between dust flux and chlorophyll even when concentrations of chlorophyll are high.

Another factor evident from the anomaly data for chlorophyll is a dependence on temperature. A strong seasonal cycle of plankton growth can be seen in the high latitudes of both hemispheres. This may indicate that plankton growth is not iron limited by temperature limited in these regions. The present analysis does not consider temperature fields and the extent to which other variables are correlated with the ocean color. But complex dependencies are evident because the dust is not strongly correlated in these areas where there is a large change shown in the anomalies.

The linear algebra approach allows each monthly anomaly to be linearly transformed by the using the singular value decomposition. The diagonal matrix S of the SVD is very important because it tells a lot about the relative weight of different components. The principle component of the data, corresponding to the largest singular value of S, is the matrix $\mathbf{u}_1\mathbf{v}_1^T$. This is computed for each monthly anomaly. The first vector of the U and V transposed gives the most information and the remaining vectors add a more detail. It is very similar to the first term in a mathematical series.

The principal component of the dust anomalies show the spatial patterns associated with the Sahara and mid-Atlantic regions. The principle components of the chlorophyll anomalies show three spatial patterns of response, the southern band, and the high latitude regions. An EOF analysis is planned to identify the spatial pattern of the variation over the year.

Conclusion

In conclusion, based on the satellite iron dust flux and chlorophyll data, it is evident that some ocean areas bordering desert areas have very high correlation between dust input and remotely sensed chlorophyll. There is an overall positive correlation in the southern ocean that does not suggest high levels of iron and chlorophyll. But there is significant positive connection due to the iron-limited nature of the ocean biological ensembles and the fact that they react strongly to whatever (even if it is small) input of iron to the system.

The findings of this project were quit similar to those of Erickson [3] but there were some variations. Both correlation coefficient maps show basically the same response, but deep in the southern ocean, between 55S – 75S this analysis showed less negative variance. This may be due to Erickson's analysis only being over a period of eight months.

Other factors that were not mentioned in this project are iron sources from local rives that drain its nutrients into the ocean. Upwelling ocean currents are also good iron sources, bringing nutrients from the depths of the ocean to the top. Upwelling can also have a negative effect of bringing stored carbon dioxide back to the atmosphere.

The possibility that many other feedbacks exist that have not yet been identified p precludes the serious consideration of massive iron addition to the ocean. Scientists have not yet fully grasped how other biological and chemical processes would respond to such an intervention. Not only should this be studied statistically but by other means of applied mathematics. I hope to continue studying the spatial variability through singlular value decomposition and introduce empirical orthogonal functions for future analysis.

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Appendix

Figure 1: Anomaly Correlation Coefficient

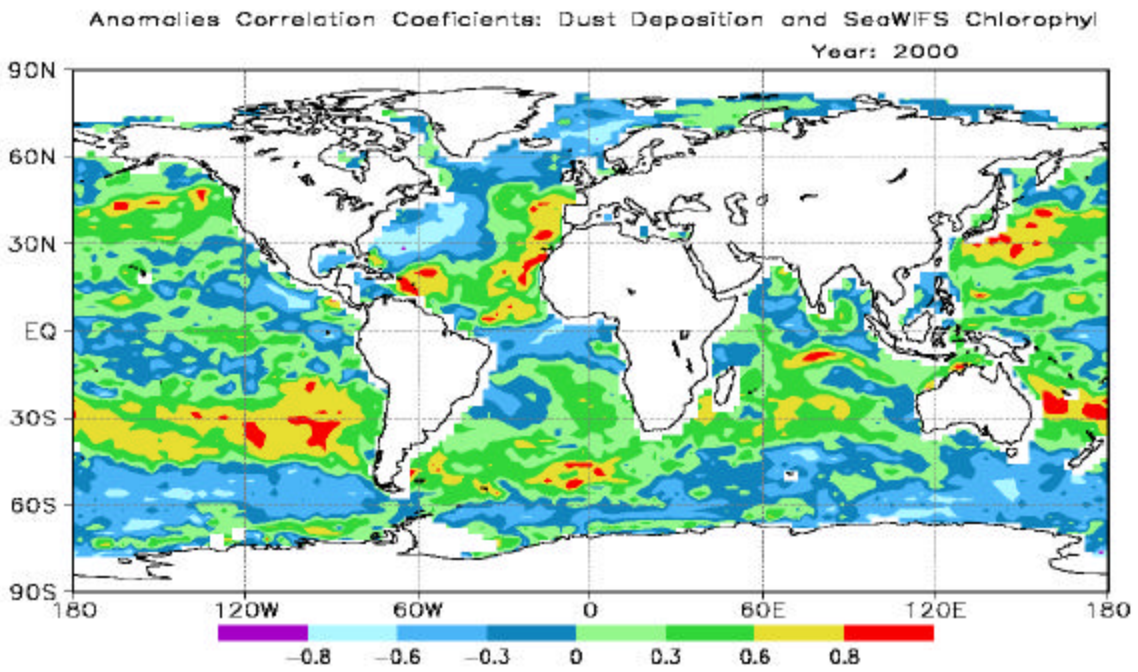
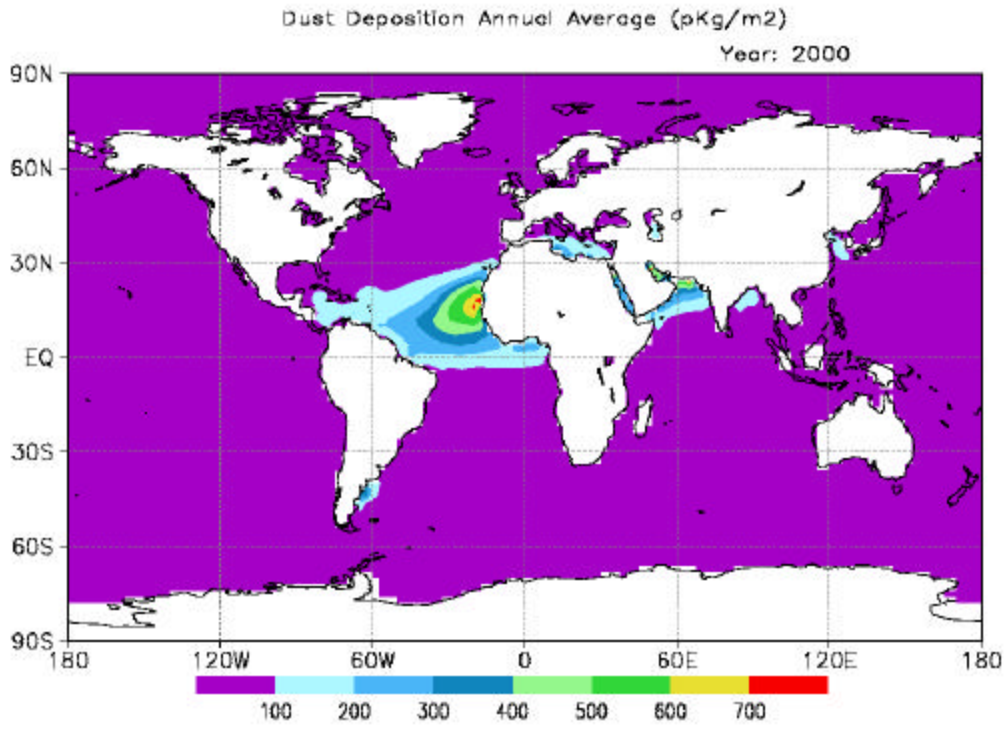


Figure 2a-b: Annual Average 20001



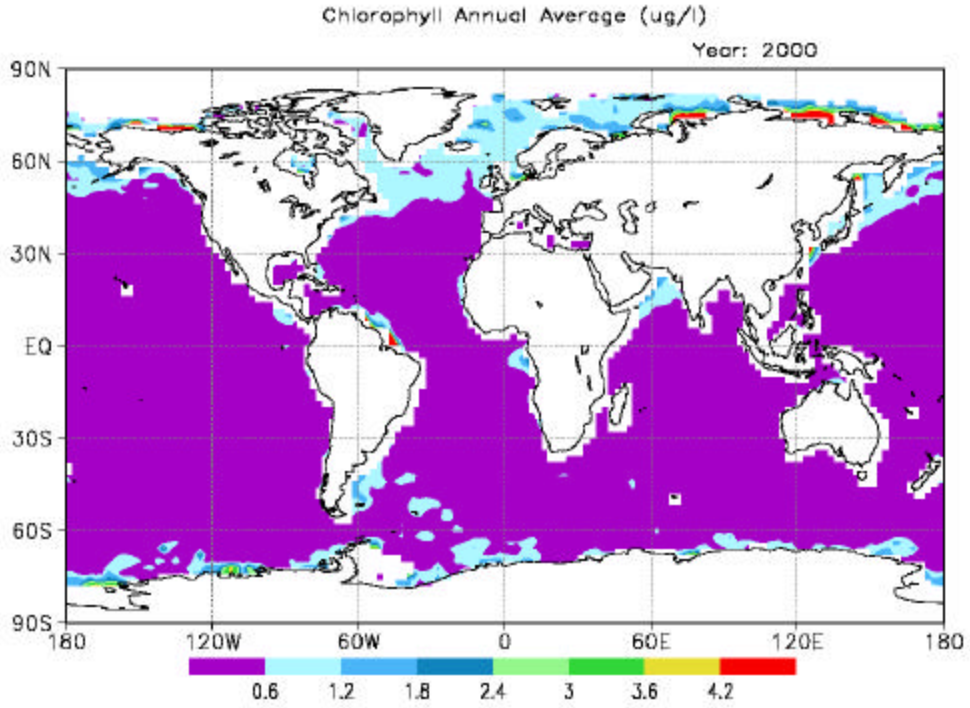


Figure 3a-d: Anomalies January-April 2001

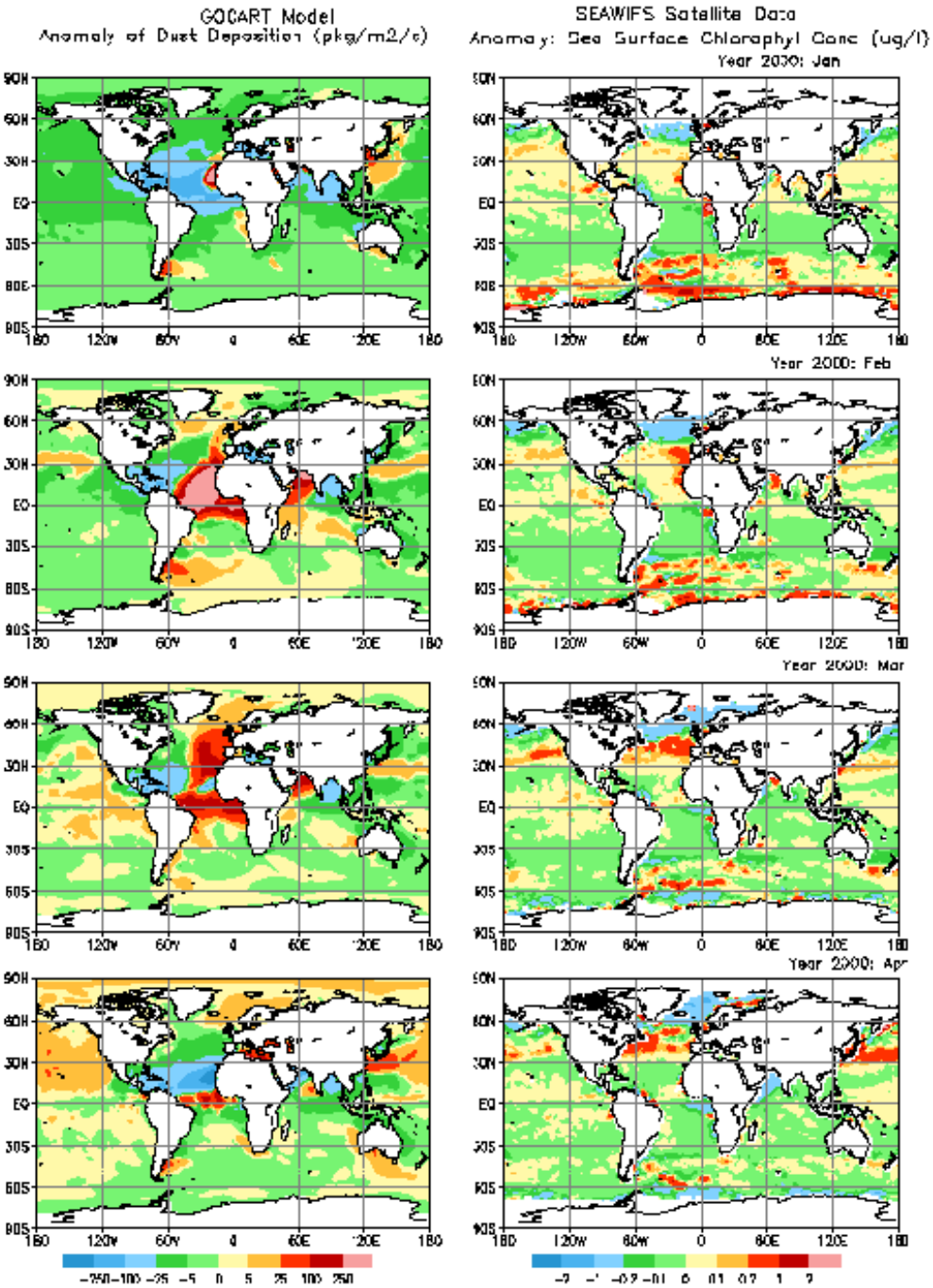


Figure 4a-d: Anomalies May-August 2000

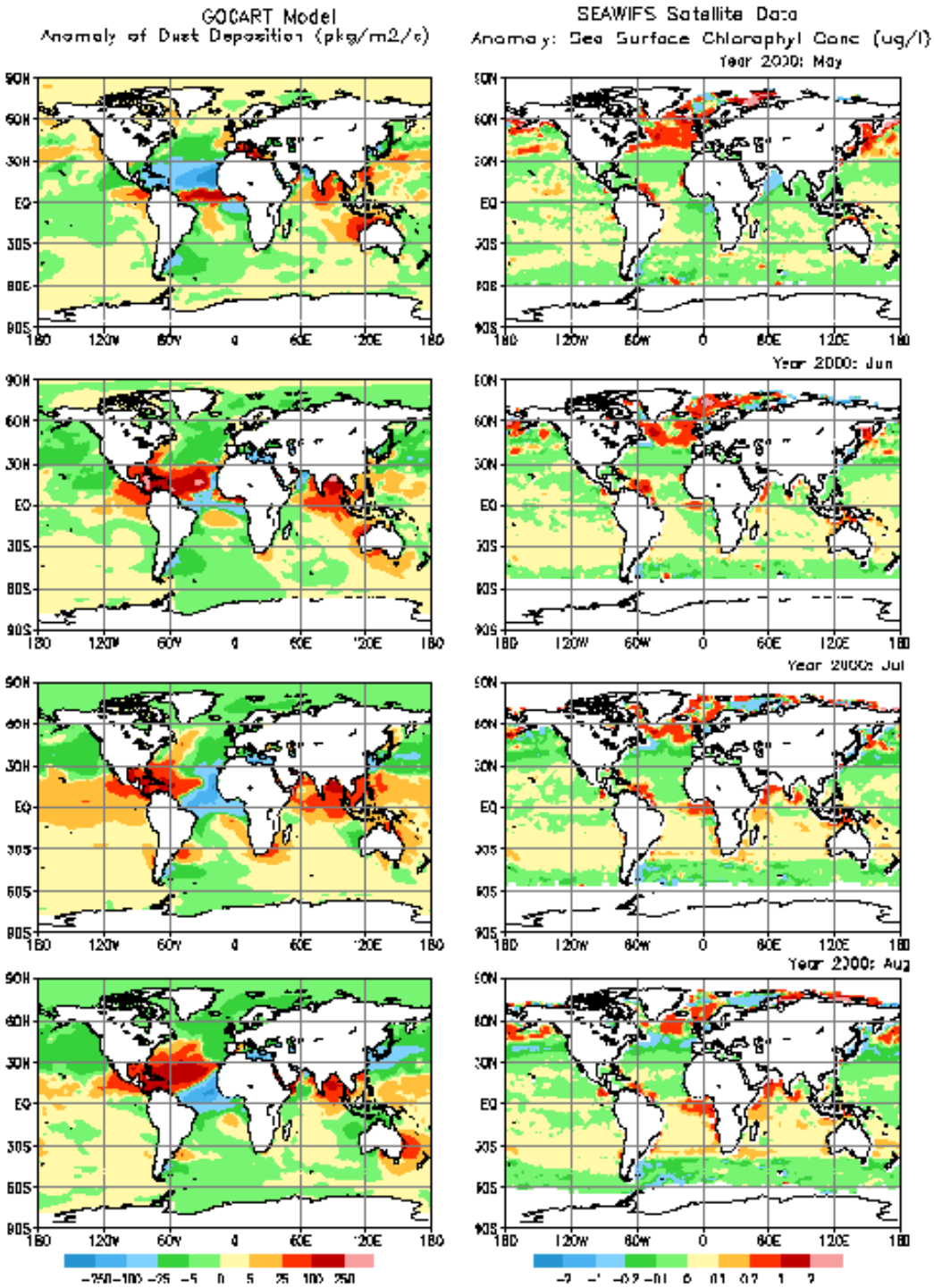
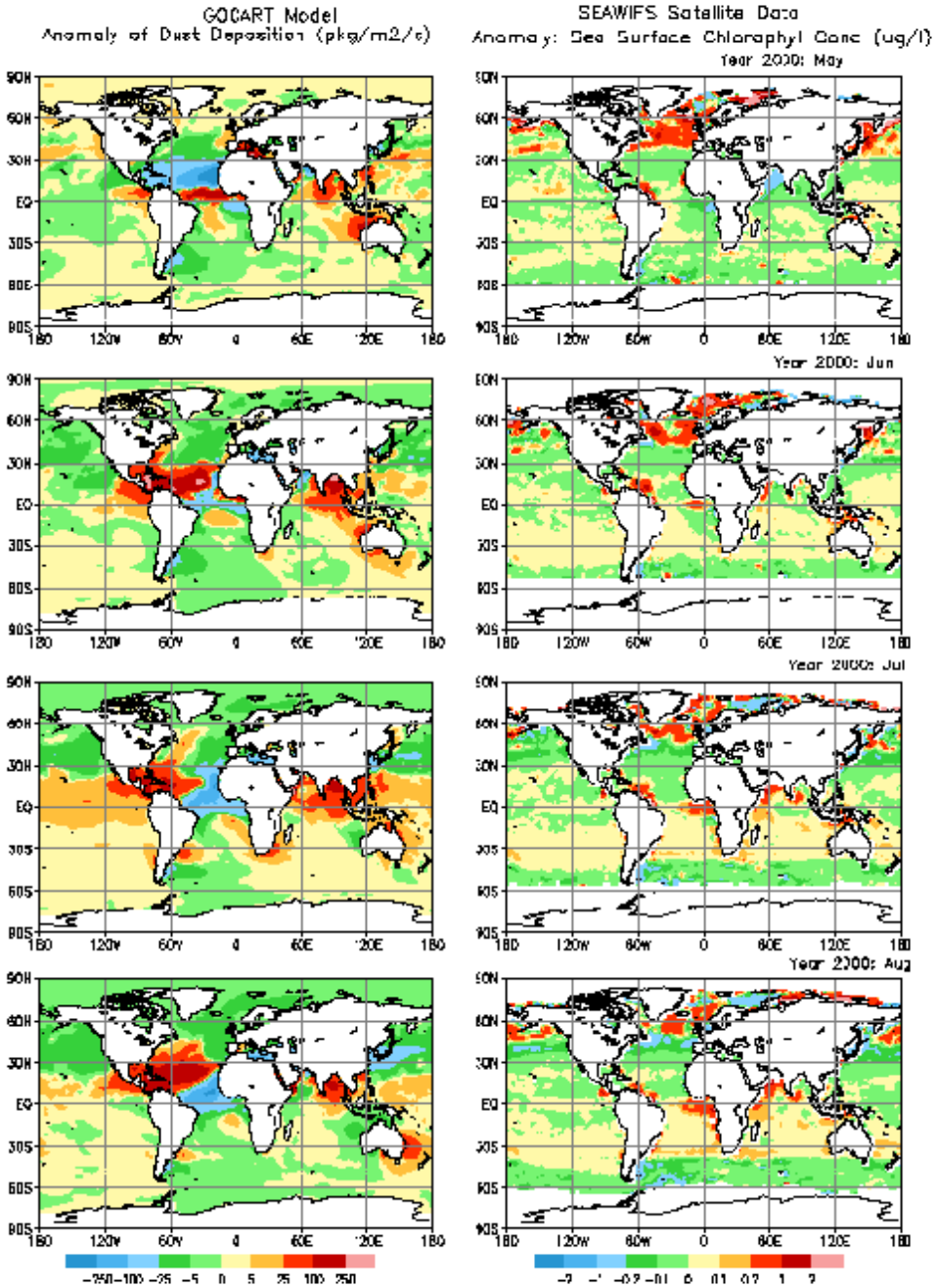



Figure 5a-d: Anomalies September-December 2000