ALGORITHM

THEORETICAL BASIS DOCUMENT

FOR MODIS PRODUCT MOD-27

OCEAN PRIMARY PRODUCTIVITY

(ATBD-MOD-24)

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1. Introduction

A primary objective of this algorithm is to advance understanding of the magnitude and inter-annual variability (seasonal-interannual-decadal trends) in oceanic primary productivity and phytoplankton carbon fixation. The annual productivity product will be used for global and regional scale studies of interannual variability of ocean productivity, for comparisons with annual summations of daily analytic algorithms, and for comparison with global biogeochemical models. It will be useful in the study of interactions and coupling between physical and biological processes, and fisheries productivity. The short-term product is designed to be an index to daily productivity. It will be used for local and regional studies on the dynamic scales relevant to field studies, pending the development of a consensus algorithm developed within the NASA Primary Productivity Working Group.

The annual algorithm has been described in earlier versions of this ATBD. The approach is updated here to describe an objective global classification which is used to delineate the ocean areas to which it is directly applicable. These regions are responsible of the particulate carbon exported from the euphotic zone. At each grid point the depth-integrated values of Annual Carbon Production (P_C), Annual New Nitrogen Production (P_{NN}), and Export Carbon Production (P_{XC}) and associated statistics are computed. The derivation of these equations is treated more extensively in Iverson & Esaias (submitted) and is discussed briefly.

The annual product is based on level 3 chlorophyll *a* fields at 4 km resolution (modified ISSCP grid used for AVHRR SST pathfinder and SeaWiFS) initially at 8 day resolution (MOD 21). Every eight days these are average fields are used to generate an annual running mean, from which the annual production terms are computed.

A short-term algorithm is derived from the work of Howard (1955) and J. Yoder, and will be implemented in Version 2 Code for at-launch operation at the request of the NPPWG. It returns an estimate of Total Carbon in units of milligrams per square meter per day, over 8 day periods.

The short term algorithm will be computed at 8 day and 4 km resolution. In addition to MODIS chlorophyll a, it requires sea surface temperature, ocean mixed layer depth, and daily integrated surface photosynthetically active radiance (PAR). Eight day averages are chosen to provide maximal opportunity for sampling around clouds with nearly uniform sampling of a given pixel as a function of scan angle (8 days is one half orbital repeat period), while still giving a reasonable number for annual averaging and not overly weighting clear periods. An eight day average is about equal to the spatial decorrelation time for coastal waters (Denman and Abbott, 1988). These scales are also more consistent with the resolution of the ancillary fields. Merging of multiple sensors will likely be required to achieve adequate cloud-free ocean sampling on shorter time scales, and will be addressed by the NASA SIMBIOS program which is in the selection process.

The modified ISSC grid scale will enable relatively simple binning or averaging of multiple grid points to provide gridded products at convenient resolutions such as 1/4 degree, etc. for comparison with various large scale model resolutions.

1.1 Background

The following definitions are used here.

Net Photosynthesis = Photosynthesis rate - Respiration (light) rate

- Instantaneous rate of organic carbon production via photosynthesis.
- Potential new techniques for rapid measurements.
- MODIS fluorescence research.

Net Productivity = Gross Productivity - Respiration - Loss (consumption).

- Daily integration period implied.
- Summed over longer periods.
- Severe operational constraints to in-situ measurements.
- Units grams C/m2/time.

New Production = Productivity resulting from use of new nutrients.

- Typically nitrate from seasonal overturn, or upwelling.

Export Production = Rate of carbon leaving the euphotic zone (150 m).

- A key component for ocean carbon sequestration issue.

For the purposes of this discussion, ocean primary productivity algorithms fall into two general classes, termed empirical and analytic algorithms. Both are based upon a) a strong, but not invariant, correlation between chlorophyll a concentration and phytoplankton biomass (estimated either by cell concentration, cell volume, or phytoplankton carbon, and b) the primary role that cellular chlorophyll a plays in photosynthesis. Both relate “standing stock” biomass to the rate of carbon fixed.

1.2 Empirical Algorithms

The empirical approach is based on direct correlation between in-situ estimates of productivity (historically performed in-site with the radiocarbon technique) and satellite derived estimates of surface chlorophyll concentration (C_{sat}). This approach was first addressed by Eppley, et. al. (1985) and refined using additional data and on an annual basis by Iverson and Esaias, 1994). G. Mitchell and co-workers are examining a daily, empirical algorithm which uses C_{sat} and sea surface temperature (SST). Balch et. al. (1991) have examined other daily, empirical algorithms. The annual empirical approach used here provides estimates (on annual scales only) for important parameters including total water column production, total new production, and export production.

1.3 Analytic Algorithms

The second general class, the analytic approach, is based on models of the general photosynthetic response of the algal biomass (chlorophyll a concentration) as a function major environmental variables such as light, temperature, nutrient concentration, and the like. These generally require computation within a depth profile of chlorophyll, and are then integrated over the euphotic zone. Several different approaches have been investigated. The approach of Morel and co-workers, (e.g. Morel, 1991; Antoine and Morel, 1995) is based on environmental photosynthetic yield (Y*); the approaches of Platt and co-workers (e.g. Platt et al, 1991, Longhurst et al., 1995) are based on the parameters of photosynthesis-light response (alpha and Pmax) together with profiles of available light. Keifer's approach is based on the photosynthetic quantum yield estimate obtained with laboratory cultures with extrapolation from in-situ observations (e. g. Keifer and Reynolds,1992). Kolber and Falkowski (1994) suggest an approach based on the determination of the absorptance cross section for photosynthesis, determined from observations of fluorescence kinetics.

A more complex approach toward ocean primary productivity is taken through the development of coupled physical ocean and biological food web simulation models, in which satellite data is assimilated and analyzed, simulated output is derived (e. g. Sarmiento, 1994, and W. Gregg, unpublished). These will not be discussed further, as they properly belong in the application model arena.

While the analytic approaches share common photo-physiological mechanisms and assumptions, each depends upon knowledge of the spatial and temporal distribution of one or more physiological parameters which describe the efficiency of light utilization at various light (depth) levels for the phytoplankton population as estimated by chlorophyll a concentration. These must be estimated *a priori*, or inferred from other geophysical fields or relationships to them. The parameters within the above approaches are thought to be very consistent for a given set of environmental conditions, but are dependent upon population history, season, temperature, and composition. The overall methodologies differ significantly in the way various parameters are estimated and in the way they are assigned spatially and temporally across ocean basins. A example is in the manner in which depth and light dependency on the photosynthetic parameters is estimated between the analytic models. A recent attempt (Brown and Esaias, 1995) to distinguish major taxonomic groups (diatoms, dinoflagellates, etc.) based upon euphotic zone depth and stratification met with very limited success.

Resolving the differences in the approaches for estimating parameters (for which there are no current independent, direct remotely sensed surrogate) is likely to take some time. It will depend upon availability of both satellite chlorophyll data which more uniformly samples the ocean (not CZCS) and in-situ estimates. To date, only limited and very non-synoptic data from ship stations exist on the spatial and temporal variability of the parameters. Depending upon choice of technique, only a few to a few tens of estimates are possible per ship per day and there are considerable uncertainties in how to relate short term and/or simulated light measurements to natural daily numbers. A climatology of parameters could be developed over the next decade, but will be very limited on any but regional and annual scales. It is hoped that observations of satellite solar stimulated chlorophyll fluorescence can be useful in assigning values in the post-launch period.

Present data are inadequate to describe the spatial and temporal variations independently from biomass using visible remotely sensed data, and therefore there is little basis to judge the accuracy of different approaches to assigning values on daily, regional bases, let alone ocean basin and global scales.

A series of comparisons of analytic models using common data sets using first CZCS and SeaWiFS data is underway. Several members of the SeaWiFS Science Team are embarked on development of algorithms for daily productivity on regional to ocean basin scales. A joint MODIS/SeaWiFS Primary Productivity Group has been formed with these members under the direction of Paul Falkowski and Wayne Esaias. The group met January 23-24, 1994 at Brookhaven National Laboratory, with additional participation by non-team members. A short synopsis is attached, and full report of the meeting is available as a draft and will shortly be made available over the Primary Productivity home page. Paul Falkowski of Brookhaven National Laboratory has developed an open data base of relevant parameter determined throughout the oceans to aid in application and assessment of the analytic models. Progress toward intercomparison of analytic algorithms was made at the second meeting at Goddard. Using their own, independent algorithms, thirteen participants have calculated primary productivity from surface chlorophyll and other parameters, as measured at a small set of ship stations. Initial results of this “Round-Robin”, which has been administered by Janet Campbell, are in preparation, and will provide important insight into similarities and differences between the algorithms.

A new technique based on fluorescence yield kinetics (Kolber and Falkowski, 1994) promises to enable rapid underway determination of the fluorescence cross section, from which the absorbance cross section may be estimated. Experience with the new techniques, and several years of application of analytic approaches with SeaWiFS data, can be expected to resolve many of the differences among approaches. This may very well occur before the launch of MODIS AM.

The above analytic model calculations provide estimates of depth resolved photosynthesis, total water column production on a daily basis, which can be integrated or summed to provide global production on various larger time scales. The integrated annual production from the models for time series stations provides the best comparison between the empirical and annual algorithms, but global and ocean basin estimates from both are possible. Experience by Esaias and Iverson, Berthod and Morel (1995) and others have shown that application of the annual algorithms to monthly and seasonal periods is inappropriate, as assimilation numbers (carbon fixed per mg chlorophyll) change significantly at these scales. The comparisons can clearly extend to regional scales for seasonal periods, but again the spatial scaling needs further examination in light of local conditions, especially in those regions where the annual variability is not the dominate one.

The approach taken here is to begin implementation of the annual, global, empirical algorithm for at-launch product generation, while pursuing a vigorous research program within the SeaWiFS / MODIS Primary Productivity Working Group to develop a consensus algorithm for daily or short -term productivity. In preparation, and due to the lateness of SeaStar, a simple candidate algorithm which requires common key ancillary data inputs, will be implemented in the at-launch code.

2. The Empirical Annual Ocean Productivity

2.1 Algorithm Description

Primary productivity is the time rate of change of phytoplankton biomass, and with allowance for excreted soluble carbon compounds, sinking, and grazing, reflects the daily integrated photosynthesis within the water column. The integral of daily values over the year is the annual primary productivity. The annual empirical algorithm is based on a linear empirical relationship between remotely sensed chlorophyll concentration, averaged annually, and annual averaged daily productivity measured with in-situ techniques.

Using relationships between carbon and nitrogen production observations and sediment trap estimates of export production, a linear relationship between total and new production, and a linear relationship between annual production and export production was also demonstrated on annual scales for waters with seasonally varying production. The analysis indicates that nitrogen tends to be conserved in the biomass, while carbon has a higher turn-over and its flux reflects energy flow. Over annual periods the major local environmental variables, including light, temperature, and nutrient concentration, experience a complete range of variability. Loss terms due to grazing and sinking also experience their annual cycle. These processes are result in a standing biomass, which integrates the ocean biosphere response. The linear relationships developed on these scales are not valid on shorter temporal scales.

The annual relationships were demonstrated by analysis of in-situ primary production and chlorophyll concentration (weighted according to depth to simulate the remotely sensed parameter) at a number of locations where times series are available with sufficient sample density to enable a reliable annual mean to be computed. Relationships between total and new production, and total and export production on annual time scales was demonstrated by re-analysis of radio carbon and nitrogen uptake studies, and sediment trap studies, respectively. These empirical fits are illustrated in Figure 4.

The plots between annual production and annual satellite chlorophyll concentration show two distinct regions. Annual production is highly variable at very low chlorophyll concentrations. Above about 0.3 mg/m3, however, a very significant linear relation exists. Relationships between new production and chlorophyll, and export production and chlorophyll production show similar behavior. This demonstrates that meaningful estimates of annual production terms based solely on annual chlorophyll concentration are possible for regions of the oceans above about 0.3 mg/m3. At lower concentrations, there appears to be no direct relationship.

2.1.1 Global Classification Approach

We have developed a classification approach to delineate those regions of the ocean where the linear estimate of annual production is appropriate. It is based on non-supervised classification techniques using the mean and variance of monthly composited chlorophyll values.

The mean chlorophyll pigment concentration and the maximum monthly standard deviation from CZCS for the period 1978-1981 are shown in Figure 2 and 3. Numbered points on Figure 3 refer to locations of in-situ observations used in the development of the regression relationships shown in Figure 1. Each composite consists of a 2048x1024 array of equal-angle gridcells with equatorial resolution of 18.5 kilometers. The monthly sample mean and standard deviation are available for each gridcell, where the sample consists of all pigment values within that gridcell for that month. Southern Ocean monthly data south of 30° S were corrected here for a regional bias (Arrigo et al. 1994) using a multiplier for the mean and a scaled variance.

Long-term mean pigment, μ, was calculated over the first three years of monthly composites. A corresponding map of Max(σ) (Figure3) was created by finding the maximum monthly standard deviation, σ, for each gridcell over the 36 month time-series. The central gyres are characterized by low variance at these spatial and monthly temporal scales, while coastal and high latitude waters exhibit high variance. The extremely low variance regions found in the Arctic are probably artifacts from errors in the CZCS algorithm. Note that coverage is also very poor around Antarctica. We have observed a correspondance between low sampling frequency and low variance in the CZCS data.

Ranges of either pigment mean or variance can be used to classify ocean regions. However, both parameters applied together provide a better classification tool when the relationship between them is not simple. A log-log bivariate histogram of maximum σ and μ contains a complete distribution of all global ocean gridcells (Figure 4). The maximum σ is not a simple function of μ, but is divided into three major clusters based on count density. The lower end of the distribution is truncated as a result of CZCS sensor sensitivity (> 0.04 mg/m^3). The root-mean -square of σ was also calculated for each gridcell through 36 months of composited data. The patterns in that histogram was similar to the pattern shown, however the distribution did not resolve Southern Ocean data as well. These patterns do not change drastically if the histogram is developed with only well sampled bins.

The three gridcell clusters appear to represent separable classes of oceanic environments. Phytoplankton distribution structure differs among the environments as a result of variations in physical forcing dynamics that transport nutrients into the euphotic zone and that control plankton patchiness (Steele, 1979). Cluster A, which contains highest variance, is populated mainly by high latitude and coastal environment data that experience large annual variability in euphotic zone nutrient input. The phytoplankton community in these areas is typically dominated by diatoms that account for most of the global new production (Goldman, 1993). Cluster B is dominated by the Southern Ocean, but also includes regions of the northern Central North Pacific. This oceanic cluster is characterized by strong wind forcing with only moderate seasonality. The configuration of Cluster B may be related to low sample density, and may therefore show lower mean and variance as a result. However, the cluster appears in histograms of only northern hemisphere data, and is not a result of the bias removal applied to the Southern Ocean. The cluster with lowest variance, C, is populated by data from the ocean central gyres. Food webs in this group are based on nanno and picophytoplankton that use nutrients mainly recycled by microzooplankton (Vinogradov, A.V. and Shushina, 1978).

Since gridcells in the same mean-variance clusters appear to have similar ecological association, statistical properties of gridcells may be useful in classifying ocean regions. Therefore, μ and Max σ were taken from 5x5 arrays of gridcells centered on the in-situ location. Parameter pairs were plotted over the bivariate histogram. For each site, the mean plot position was used to center an ellipse of the set of 25 plotted points. The semi-major axes of the ellipse were defined by the standard deviation of the plot positions. Thus the ellipse bounds a small region about the majority of plotted points and represents the combined effects of temporal and spatial pigment. Grid points from the global distribution that fall within these ellipses served as criteria for classifying gridcells

The set of in-situ points within the high variance region of Figure 4 are those which fall on the linear portions of the regression plots in Figure 1. The points in the low standard deviation, lower mean regions of the figure 4. are not described by the linear region of the production equations. We conclude that the annual linear estimator can be applied to all locations throughout the ocean that fall within the high mean, high standard deviation portion of the annual histogram. About 28% of the ocean falls into this category, and is shown in Figure 5. While this is a relatively small areal extent, it has great significance to the global carbon cycle. Based on this approach and the CZCS composite data, 75% of the global export production occurs in this region. This represents the major fraction of carbon transport of the biological pump. Furthermore, this presents an objective approach to begin to study interannual changes in the area of the ocean in which the biological pump is a significant player in the ocean carbon cycle.

This classification approach is consistent with the functionality of marine food webs with respect to the production components. In regions of extreme nutrient limitation, the community tends to conserve the nutrients by recycling them within the euphotic zone. Little nitrogen is lost, and little carbon is exported. The food web, and especially the coupling between producers, consumers, and recyclers is highly efficient. Physical dynamics introducing nutrients tend to have long spatial and temporal scales, which preserves, or does not disrupt, the temporal and spatial coupling of the community. Components tend to have small generation times. At the other extreme, in physically dynamic regions such as coastal upwelling regions and the N. Atlantic, nutrients are much less limiting, and coupling between components of the food web is less efficient and is also limited by physical processes. In these regions, rapid growth, rather than nutrient conservation, is a key attribute of populations. Recycling of particulate carbon and nutrients is less important to the organisms. Loss of carbon due to sinking (export production) can represent a significant fraction of total carbon produced. These regions are characterized by the more classical food chain of primary producers, herbivores, and carnivores representative of the major fisheries of the world. The annual scale is important in nutrient recycling, often involving the benthos and deep winter mixing.

To illustrate the relevance of this classification to climate and oceanic change issues, consider a population at a point near the intercept of the regression line in fig 1a. The chlorophyll concentration is low, and annual productivity is near the minimum found in the oceans. The food web is tightly coupled conserving nitrogen or perhaps iron. Now, if the rate of limiting nutrient supply is increased incrementally, primary productivity will increase. This can lead either to an increase in primary producer biomass (the linear portion of Fig 1a), or, it can exhibit little change in biomass of primary producers and little increase in export production of carbon characteristic of highly coupled food webs. Based on the correspondence of high spatial and temporal variability with exporting food webs shown in bivariate histogram, we postulate that the temporal and spatial scales of the physical processes responsible for the nutrient increases are a significant factor in determining how the ecosystem will respond to the change.

We can hypothesize that two regions of equal rates of primary productivity may either show very low, or significant carbon export, depending primarily on physical dynamics affecting the coupling of nutrient supply and food web structure. If nutrient inputs are pulsed, the food web may not have the capacity to respond in time, leading to uncoupling of producers and herbivores. The system will change from the left portion of Fig 1a to the linear portion. It will export more carbon than a system with an equal but constant average supply rate which retains a highly coupled food web. Both systems might be considered “steady state” with respect to heat and salt budgets. The recent IRONEX II study (Behrenfeld et al. 1996) showed clearly that artificial pulsed addition of trace amounts of iron led to such uncoupling, and increased carbon export.   We postulate that the variance on <100 km and monthly scales will be useful for discriminating these conditions. Therefore, changes in the global ocean area having characteristics of high chlorophyll variance is a useful feature to determine changes in ocean the structure of the carbon system.

With additional long term research, it may be possible to develop more robust coupled physical and biological models which can be describe such differences in food webs, based on readily available, recent, global observations. When fully developed, these models presumably would assimilate data such as altimetric topographic variability and wind velocity information in addition to improved temperature and visible reflectance, and describe vertical mixing and advection at scales that are important for descriptions of the biological implications. Some of the approaches look promising, but many of the important relationships with biological systems are unknown, unconstrained, and therefore not easily adaptable to modeling.

Model complexity is also an issue. Gaining insight into how biological systems function in the upper ocean is a prime goal of the JGOFS program, and we look to that effort and other (NASA) research efforts for progress over the next decade. Climatological values (e.g. mixed layer depth, ocean province) are useful in many models (Longhurst et al., 1995, Antoine and Morel, 1996) to proscribe structure, but this approach is limited if changes in food web structure are important to the global carbon export budget. Gross phytoplankton population assemblage does not appear to be predictable from mixed layer depth (Brown & Esaias, 1995). The selected classification approach is a simple, objective procedure, dependent only on contemporaneous data.

2.1.2 Treatment for other regions

The linear relations between average annual chlorophyll and new production discussed above do not extend to high latitudes (>60°) where light is strongly limiting in the winter, and to regions in low to mid latitudes which do not have a strongly seasonal variation. The prime case of the latter are the high nutrient low chlorophyll regions. Here, distinctly different relationships are observed.

The difficulties at high latitudes is overcome by using a logarithmic relationship on a seasonal time period, with an implicit dependence on day length. While the uncertainty of this approach is somewhat larger than for the cases described by linear relationships, it appears reasonably satisfactory for arriving at global estimates since these regions have relatively small contribution to the global total.

Further work is required for the HNLC environments, but if they are not adequately characterized by the classifier, the alternate approach will be to delineate these regions and apply a separate relationship within them. As a default, Pnn and Pxc are set to the mean for the points within the clusters in Figure 1c and 1d. Sensitivity analysis will be performed to assess the impacts, on the uncertainty of global totals, of both the particular relationships and variations in the size and configuration of the area to which they are applied.

Using either SeaWiFS and/or OCTS level 3 data, we will try to confirm the basic shape of the bivariate histogram. This is important to address whether the rather poor sampling of CZCS has a major effect on the shape, and whether the Southern Ocean is a distinct class. This study will benefit from improved validation and accuracy assessment of the chlorophyll and atmospheric correction algorithms from those missions. The earliest that such studies can begin is in spring 1997. If successful, these comparisons will provide a useful measure of decadal change in ocean carbon export terms.

It is not inconceivable that the Southern Ocean will exhibit a distinct relationship different from that shown in Fig 1, since we presently have very little annual primary productivity station data from the southern ocean between 30 and 60 degrees South. The JGOFS and SIMBIOS programs may provide some information along these lines, we will continue to search for useful historical data, and to encourage international participation along these lines. We have no plans for funding a S. O. productivity time series station from MODIS.

We want to see if the classification is improved with the addition of other globally available observations, such as SST and surface variability.

The eastern equatorial regions of the Pacific and Atlantic show relatively high variability with little export production. These areas will be defined by a simple geographic mask and treated separately. Further studies will be directed toward developing a more satisfying and objective approach. A serial approach adding a classifier based on temperature will be examined. We still need to determine the impact of assuming constant spatial export values for the central gyres.

The present spatial and temporal intervals (monthly and 19 km) result from computational convenience. We would like to investigate the sensitivity of classifier to these values with SeaWiFS and/or OCTS data. This has significant demands on computational resources and approach. This question is closely related to the optimal spatial interval useful in computing and reporting annual production terms.

Data taken from the near shore and estuarine regions which we have examined (Chesapeake Bay, Appalachicola Bay, and nearshore S. Cal. upwelling) do not fall on the same linear relationship, and are therefore we do not perform the calculations in these regions. In many of these regions productivity appears unrelated to annual chlorophyll concentration. The discriminator in the present approach is depth (30 m). Further studies are needed to improve understanding as to where the inshore boundary should be drawn, and to develop objective approach for implementing an improved mask based on MODIS data.

2.2 Mathematical Description

The chlorophyll a concentration derived from satellite ocean color measurements is averaged over a 365 day period at the level 3 pixel resolution. An arithmetic average is required. Masks are applied to exclude the low variance, eastern equatorial, and coastal regions. Using the relationships in Table 1, the annual integrated total, annual new nitrogen production, and annual carbon production exported past 150 meters (assumed maximum depth of the euphotic zone) is calculated. Values are then summed over the region of interest, or globally. The total ocean area values are adjusted for less than 100% coverage by a simple ratio. The units for Pc and P_{XC} are grams Carbon per square meter per year, and for P_{NN} are grams nitrogen per square meter per year.

Relationships poleward of 60 degrees appear to be significantly different and it is more appropriate to apply a seasonal algorithm for Pc to these regions. Alternatively, the latitude limits for the annual regression will vary as a function of solar elevation. Presently, the relationships used is based on a reparameterization of the Eppley relationship (Eppley, et al., 1985).

These high latitude areas experience high areal production during the summer, which is important for both global and local ocean biogeochemical processes. However, the global fractional area is low and higher uncertainty in the relationship there does not contribute significantly to overall errors in the global total. Differences between applying equation 1 to the entire ocean mean chlorophyll, and extrapolating from the area between 60 N and S to the entire ocean based on area, are only a few percent.

2.3 Variance or uncertainty estimates.

In the empirical approach the data used to formulate the regression is considered validation data, and therefore the uncertainty estimates are provided by Type I analysis. However, a more complete error budget also should include errors induced by sampling (cloud and glint obscuration), errors in the level 2 chlorophyll fields and binning procedures, errors in performing the in-situ estimates of daily production including spatial variability at the sub-pixel level, and extrapolating incomplete time series to global annual scales.

A significant problem is the accuracy of the standard in-situ technique for measuring primary productivity. There is no recognized standard protocol for this measurement. Use of ultra clean sampling and incubation techniques (Fitzwater et al., 1982) enjoy a consensus of investigators, but there are still unresolved issues for sample collection, incubation methodology and procedures for extrapolating to daily values. Comparisons to in-vivo oxygen techniques and other radioisotope techniques is also difficult. Treatment of these issues is beyond the scope of this ATBD, but is under discussion by the Primary Productivity Group. It is essential that differences between various techniques be documented, and accounted for in discussions of errors. If possible, a standard protocol should be adopted.

An approach for assessing errors in the CZCS data was developed to account for the highly skewed sampling. The regression equations 1, 2. and 3 show very high correlation coefficients, indicating that the precision is on the order of a few percent if one assumes that the literature values for annual production and annual average satellite chlorophyll concentration are perfect.

However, propagation of errors in both values, accounting for spatial variability, uncertainty in the daily estimate, and temporal averaging is not straight-forward. Our initial approach is discussed in Appendix A, and is expected to undergo some change in the next month to account for the classification approach.

2.4 Merged data from multiple satellite sensors

Data from various ocean color sensors can be used in order to improve sampling coverage, and to provide annual means of chlorophyll a concentration during the first year of EOS-AM-1. However, we have no plans to do this other than in a research mode.

Cloudiness prevents deriving chlorophyll a concentrations over about 60 percent of the ocean on a daily basis, excluding that already lost (about 30%) due to high sun glint, resulting in about 12% global coverage on a daily basis. Merging chlorophyll a concentrations derived from multiple sensors in complementary orbit is the primary means to increase sampling frequency to obtain information at times shorter than the spatial decorrelation times in the coastal zones and other dynamic areas (3-5 days, Denman and Abbott, 1988). The principal rationale for EOS Color Mission was to obtain multiple sensor data to combine with MODIS AM before the flight of MODIS PM, to enable adequate coverage. Assuming that SeaWiFS is launched in early 1996 and operates for 5 years, and that MODIS AM and PM are launched on time, there should be fairly complete coverage from US sensors until 2004. With proper accounting for errors (expected to be greater than for MODIS and SeaWiFS), other candidates are MISR, the Japanese OCTS on ADEOS, and ESA's MERIS on ENVISAT, and SeaWiFS. The task of assessing errors in these combined and merged data, taken with different designs, bands, swaths, and times of day, is discussed within the proposed plan for Sensor Intercomparison and Merger for Biological and Interdisciplinary Ocean Studies (SIMBIOS), which is available via the MODIS and SeaWiFS home pages. The new investigators for the SIMBIOS team is in the selection process

The procedures to merge chlorophyll a concentration is relatively straightforward, and in fact is performed in principle within the time binning step for daily level 3 SeaWiFS data at high latitudes. However, the merged data from multiple sensors will include errors which are additional to those for single sensor data due to the different acquisition times, and may include effects of advection (water motion) due to mean flows and tidal currents, diel variations in cell chlorophyll concentration and in-vivo chlorophyll absorbance, and time dependent changes in chlorophyll depth profiles caused by changes in vertical mixing intensity due to winds, currents, and tides, and motility and buoyancy of the phytoplankton.

For these reasons relationships between water leaving radiance and chlorophyll a determined for noon sampling sensors may be somewhat different than for morning or afternoon sensors. Likewise, due to diel variations in chlorophyll a per cell and photosynthetic efficiency, there may be some differences in the slope of the annual regression equations due to sampling time. These effects may have to be examined at the level 2 product (chlorophyll a at highest resolution, but our assumption is that the bulk of the error analysis of the chlorophyll fields will be performed to a satisfactory level by the mission specific investigators as a result of the peer-review process.

A reasonable approach will be to simply combine the variance which is determined for the accuracy of chlorophyll a derived from each sensor. Differences in mean properties can be used to determine whether sensor, spatial and / or temporal biases exist. In regions where currents induce motion, and in regions of strong frontal systems, such as the shelf-slope fronts, estuarine plumes, and edges of western boundary currents like the Gulf Stream, averaging procedures must be considered carefully (Campbell, 1994). For the annual estimate, a simple average is preferred, and the algorithm should prove relatively insensitive to such effects.

2.5 Instrument characteristics

The MODIS instrument characteristics required for the early primary productivity algorithms are the same as those for chlorophyll a for combined Case 1 and Case 2 waters. Special attention must be paid to cloud flagging, and sampling at high latitudes as close to the terminator as possible in order to obtain maximum global sampling without decreasing accuracy. With development of an overall error budget, inaccuracies in chlorophyll concentration derived at low sun angles can be assessed and compared with errors in global productivity.

Measurements of spatial and temporal variance will be used to classify regions of high carbon export. Impacts of instrument scattering, especially in the region of the shoulders present in the point spread function, are a potential concern. High PSF values will tend to decrease observed variance in total radiance, but may have non-linear effects when propagated through level 2 algorithms.

Since rapid sampling of the global ocean biosphere is required at time scales consistent with the spatial decorrellation times, merging of chlorophyll a data from multiple sensors is potentially very beneficial. Merging data is treated separately, and the empirical algorithm can be used to evaluate performance of merger programs. Attention must be paid to errors induced by sensor performance calibration, and characterization before routinely merging data.

Variance or uncertainty estimates have been discussed above in general. The standard deviation of the running annual average will be computed using the number of 8 day averages included. It is very important that the binned chlorophyll field selected be uniform, rather than making abrupt switches between different algorithms from Case 1 to Case 2 waters.

2.6 Practical Considerations

2.6.1 -Programming and procedural considerations

The empirical calculations are relatively simple. A flow chart is given in Figure 5.. Computation of the running annual average chlorophyll concentration is by standard techniques. Use of 8 day average composites will require access to only 45 9 km global level 3 chlorophyll a fields. The computations are carried out only for oceanic pixels according to the ocean/land flag which will have been applied at level 2 on a pixel level. The mask will exclude estuaries, inland seas and lakes as well, since the relationships developed do not apply in those regions. Computation of coastal level 3 pixel areas will be performed once to account for irregular coastline. Within coastal regions, application of a conservative set of land/ocean, land brightness recovery, and similar sensor and algorithm effects will be necessary, but it is expected that these will be used routinely during production of the chlorophyll a product. A fixed delineation of HNLC areas for computation of new production will be provided.

A running annual average file is computed along with the sums of squares and sample sizes. The contribution from the first 8 day period (a year earlier) is subtracted from the running average, and the current 8 day period is added to it.

2.6.2 -Calibration, validation, initialization

The relationships discussed in Iverson and Esaias (1995a) utilize data from various independent field programs. The major factor limiting the accuracy of the regression is the relatively small number of annual time series which permit reasonable annual estimates of the three parameters to be computed. This requires concurrent measurements of carbon production using clean radiocarbon techniques, nitrogen new production using nitrogen isotopes, and/or measurement of sinking flux. The relationships are used as predictions, and like any empirical approach, will require constant reexamination using contemporaneous data. This will rely heavily upon established programs within the international ocean community, such as JGOFS, and LTER sites. The LTER site in Antarctic waters is especially important as one of the few high latititude time series sites. It is expected that additional sites will be added through the SIMBIOS program and its international analogues.

The validation period will be continual, and will depend on numbers of stations available, unlikely to total more than a few tens of stations per year. The empirical relationships must be continually verified in order to distinguish change in magnitude of production from potential changes in the productivity vs chlorophyll a relationship. Such changes could potentially be brought about through variations in ocean mixing processes, phytoplankton population structure, patterns in iron enrichment, and food web transitions. The empirical relationships depend upon having included data which fully represents the global environment. That few stations are available is a major concern.

Augmentation of the JGOFS time series stations with a high latitude, high productivity time series station is recommended, and additional stations in transition regions should be considered.

Initialization of the annual productivity will occur with the generation of the first MODIS weekly/8 day chlorophyll average, which is expected to occur some two months after the sensor is turned on. The full annual average chlorophyll field will be generated by substituting currently available ocean color data from either SeaWiFS or other current ocean color sensor data as substitutes for MOD 21 input data to produce the running annual average chlorophyll a and statistics files. Delivery schedule of these data sets is not expected to pose a problem. The running statistics files will be produced in the SCF in the appropriate format for use by the PGS. The potential biases during this first year arising from the different sampling times, sensors, and algorithms will be estimated in the second year, by comparisons of the chlorophyll a products between the missions.

2.6.3 - Quality control and diagnostics

Quality control of the empirical productivity estimate is based heavily upon good quality control of the chlorophyll a fields, and the number of available weekly images to compute an annual mean. The valid range of chlorophyll a values will determine the range of annual productivity values on the pixel level. Values above the equivalent of 10 gC/m2 day will be flagged as questionable. In addition to the run-time QA which is performed as part of product generation, we intend to manually examine every product.

2.6.4 - Exception handling

The algorithm is very robust in this area. Provided that the chlorophyll field contains data and a quality flag, there should be few exceptions. Exceptions would be expected when cloudiness or heavy aerosol preclude derivation of a chlorophyll field on a frequent basis. This will decrease the accuracy of the annual average, especially if there is a pronounced seasonal effect, because of the few number of data values. Provided spurious data has been flagged at the level 2 chlorophyll product level, most of the problems should already have been identified. With a running annual average, a value should be available for virtually every level 3 grid. With the CZCS data set missing values at the monthly level were filled with the grand mission average. The number of 8 day averages included in the final value is saved.

2.6.5 - Data dependencies (error propagation from ancillary data)

The empirical annual estimate is a linear function of annual average chlorophyll, which contains errors as described for the chlorophyll product. The annual product also contains errors described by the confidence in the empirical chlorophyll to productivity relationship. The propagation of these errors to the annual estimate is under investigation and is discussed in Appendix A. The approach for the launch version is to combine the confidence limits of the regression errors with the uncertainties in the mean chlorophyll field assuming equivalent weighting.

2.6.6 -Output products

The output products are gridded level-3 fields at 9 km of the three major products, (total carbon production, new nitrogen production, and export production), together with the running annual mean of 8 day chlorophyll a (Figure 6). The variance of the estimate, and the number and sequence (42 bit flag) of 8 day composites and the total number of 1 km pixels included in the average are saved. An overview of the product structure is shown in Table 4 and Figure 7.

3. The Daily Productivity Algorithm

3.1 INTRODUCTION

Estimates of primary production on short time scales are essential for understanding marine phytoplankton dynamics on scales which contain the interactions of physical forcings and biological systems, and on annual scales for low-variance regions. The short term estimates are required for eventual assimilation into marine ecosystem models and coupled climate and ocean carbon models. The objective of understanding the role of ocean biota within climate change, and impacts of climate change on marine food web processes can only proceed with a firm understanding of responses on local and regional scales.

This section outlines a two phase, parallel approach for a standard annual global algorithm and a research daily productivity algorithm. Research leading to selection of a short time period algorithm (or set of algorithms) is conducted by NASA SeaWiFS and international investigators, with the NASA Primary Productivity Working Group (PPWG) serving as a coordinating body. The Working Group was organized as a joint activity between the SeaWiFS Science Team Investigations and the MODIS Instrument Team investigations. This group set as a goal to have a selected algorithm within two years following a successful launch of SeaStar, since validation and other consistency checks was deemed crucial for making any decision among the several theoretical approaches available at the time. The SeaWiFS Project would then implement the selected product in conjunction with planned annual reprocessing of SeaWiFS data.

The path for implementation within EOS is via the MODIS Instrument Team and the EOS Product Generation System (PGS). Development of a long term (annual) empirical algorithm was selected in the Execution Phase process. Development of this algorithm has maintained delivery schedules for software required by EOSDIS in order to meet AM-1 launch readiness. Implementation of a short term chlorophyll concentration based algorithm was deferred to research product status consistent with the PPWG process. As initially envisioned, given the SeaWiFS launch schedule, comparisons of candidate algorithms within the PPWG would be accomplished in sufficient time to incorporate the selected short term algorithm for MODIS as an immediate post-launch product. This would ensure that the data products would be consistent, and the long time series would thus begin with SeaWiFS data.

For MODIS EOS, this approach was thus dependent upon the SeaStar launch and experience with real data, as well as the planned approach for EOSDIS and its capacity to support research products and to absorb post-launch implementation loads. Neither of these requirements have stood the test of time. SeaStar is now planned for launch in May, 1997. Budget austerity forces us to assume that EOSDIS will have no capacity for routine research products for AM-1 and little capacity to implement new post-launch standard products except as required for the PM mission. Research product development and generation is viewed by EOSDIS as within the purview of Science Team Member Computing Facilities (SCF's), but these are insufficiently supported or scoped to provide routine generation and distribution.

As a related activity, Abbott is preparing a research algorithm based on solar stimulated chlorophyll fluorescence as a MODIS research product. This is based on the standard at-launch MODIS Fluorescence Line Height product (MOD 26), and the Instantaneous PAR (IPAR) from MODIS. The fluorescence based productivity is constrained to sensors with fluorescence bands, including MODIS, GLI, and MERIS. It will be produced in a research mode at the OSU MODIS SCF for evaluation by Abbott and the larger community.

In June, 1996, the PPWG reaffirmed its goal of selecting a consensus short term algorithm two years following SeaWiFS launch. A reasonable SeaStar schedule makes this selection in February 1999. Experience with OCTS data may enable a selection by fall, 1998. In relation to EOSDIS code delivery schedules, these dates are not inconsistent with implementing a short term algorithm for MODIS -PM 1 launch in December 2000, as well as a post launch product for MODIS-AM at that time.

In the June 1996 meeting the PPWG also recommended that NASA begin development of a simple primary productivity index for short time periods for implementation soon after launch. This would be a research product available to the community to aid in evaluating analytic algorithms. The group was unable to make a recommendation among several choices for the same reasons that selection of a consensus global algorithm is dependent upon development of protocols, comparison criteria, and experience with real data.

3.2 Algorithm Description

As implemented by Howard (1995), the algorithm assumes that surface observations of temperature and chlorophyll are uniform throughout the mixed layer, and that the maximum potential primary productivity is a function of temperature only. The algorithm assumes that nutrient limitation is expressed through the standing stock (chlorophyll concentration) as does the annual algorithm. The model assumes a constant carbon:chlorophyll ratio of 60 (mass units) globally, and a constant initial slope (a=2.64 mg C(mg Chl)$^{-1}$ W m^{-2} d^{-1}). for the light dependency of photosynthesis. These values are the averages of large assemblages of data.. The calculations are thus performed on upper mixed layer averages of light and biomass, and integrated over the mixed layer by multiplication by the mixed layer depth. As developed by Howard, the vertical light extinction coefficient is estimated for case 1 conditions from the pigment concentration. The equations used in the algorithm are given in Table X (from Table 3 in Howard, 1995 with some minor corrections). Preliminary results of the round-robin exercise indicate that this algorithm compares very favorably with others (J. Campbell, per. comm).

In Howard's implementation, Levitus's climatological data sets were used for the mixed layer depths. Bishop and Rossow's (1991) insolation data were used for the retrospective study. In this implementation we will use current estimates for these properties.

3.3 Mathematical Description

The algorithm is based on 5 equations, given here with minor corrections to those in Howard, 1995, as Table 3. These are implemented sequentually.

3.4 Variance or uncertainty estimates

Howard (1995) has performed some uncertainty estimation, but does not develop a full error analysis. Assessing the variance and uncertainties on daily scales will proceed along several lines. These include comparisons at the integrated annual scale with the empirical algorithm, which is already underway as part of this investigation using CZCS test data sets. More importantly, comparisons with other algorithms and primary productivity models, and comparisons with short term observations at sea will continue to be the focus of several key investigators supported by other NASA programs as well as this investigation. The NASA Primary Productivity Working Group is the focus of this interaction. The Primary Productivity Round Robin activity sponsored by the PPWG is currently undertaking aspects of this activity, and the selected algorithm is one of the algorithms being evaluated within the round-robin. The PPWG is also preparing protocols and attempting to set standard criteria for assessing accuracy and uncertainties with respect to field observations. Intra-pixel variability, sampling biases of in situ data, extrapolation from relatively few in-situ data to large oceanic scales, and high variance are concerns.

This activity will also have to assess the uncertainties propagated from the ancillary data fields. This will begin with a sensitivity tests of the algorithm to these values in a test mode. It is beyond the scope of this investigation to perform completely independent assessment of the accuracy of the Mixed Layer Depth and daily short-wave radiation fields, although we are extremely interested in reducing such errors to a minimum.

3.5 Data from multiple satellite sensors.

As described in the implementation plan, initial testing of this algorithm and data products will begin with data from OCTS and/or SeaWiFS, when it becomes available, in the pre AM era. Such data will not be required post-launch for a MODIS product. We look forward to adapting to the use of merged chlorophyll fields which may be developed by SIMBIOS investigators when this is appropriate at some future point.

3.6 Ancillary data required

The algorithm requires measurements of daily integrated Photosynthetically Available Radiation, and the depth of the ocean mixed layer. The sources are specified in the Implementation approach. For PAR, the products produced by W. Bishop and W. Rossow (1991) are very high quality, but unfortunately there is a considerable delay in their availability of several months. The daily PAR needed is identical to that needed for LAI/FPAR of Running, except this algorithm requires the ocean data. We will use a simple factor of 0.45 applied to the surface incident short-wave radiation to convert it to PAR. The accuracy of this is on order of 15%, and results will be compared to the Bishop data set to see if this uncertainty can be reduced efficiently. Kuring and Lewis (1990) found that a simple cloud fraction applied to TOA PAR gave reasonable results. The planned back-up to the DAO or NMC product will be a weekly climatology.

Mixed layer depths are available from the Navy's FNOC and are available electronically. The accuracy of the mixed layer calculation is of concern, and this will be researched in the literature. Lack of adequate test data limits validation efforts, especially in the southern ocean. Based on preliminary sensitivity tests, errors in MLD propagate directly through the algorithm. The backup to lack of availability with be a weekly climatology.

3.7 Instrument characteristics

There requirements are the same as for the annual algorithm, with the addition of a direct need for the MODIS SST. The accuracy of the SST field should be very adequate.

3.8 Practical Considerations

3.8.1 Programming and procedural considerations

As discussed in the Implementation Plan, the algorithm inputs are level 3 chlorophyll a fields and SST from MODIS, binned over an 8 day period. This choice minimizes procedural impacts on the Level 2 code and data storage. The algorithm will run following generation of the level 3 products, similar to the annual algorithm. It will be necessary to develop a procedure for averaging FNOC MLD and PAR fields and interpolating them to the MOD-27 grid.

For generation of the PAR field, it may be worthwhile to consider a modification to the code used for MOD- XX FPAR to some extent. The ocean portion of daily average incident short wave radiation could be saved to an intermediate product separate from the land product. The ocean intermediate product would then be used as an input to form an 8 day average, interpolated to the required spatial resolution.

3.8.2 Calibration, validation and initialization

These aspects have been discussed in other sections which describe the relationship with the NPPWG and expected relationship with SIMBIOS.

3.8.3 Quality control and diagnostics

The flags used for the annual product form a convenient base for departure. The acceptance limits will be adjusted and augmented to account for exceptions in ancillary data fields. The products will also undergo manual inspection at the SCF. Criteria for this subjective component will be developed in consultation with the NPPWG

3.8.4 Exception handling

The major modifications to the annual algorithm required here will involve adjusting limits, and substitution of climatological values for missing ancillary data.

3.8.5 Data dependencies (error propagation from ancillary data).

The ancillary data will require automated QC screening which will be performed as part of the routines necessary to interpolate them to the MODIS bin level. Approaches used by SeaWiFS form the basis for this activity.

3.8.6 Inputs and Output products

The inputs are as follows:

8 day chlorophyll a (arithmetic average).
kpar (from 8 day average of MODIS chlorophyll or k490)
SST (first choice from MODIS).
MLD (first choice, from FNMOC; alternate - climatology).
Daily integrated PAR - 1 deg. resolution
first choice DAO or NMC daily short-wave flux * 0.45, avail 1/day.

The low resolution fields would be interpolated as done for SeaWiFS processing.

The outputs are scoped as follows:

1. 8 day average productivity mC/m2/day 8 day ("week") at 9.5 km resolution.
for all waters of acceptable chlorophyll values,
regions <30m, inland waters will be flagged.
pixels also flagged according to source (& quality) of ancillary data.

Sum, Sum of squares, N, n
Quality flags

The global integral of the above will be carried in the summary information. It may also be possible to carry integrated values over fixed geographic regions, such as is done with SeaWiFS browse regions, in the summary information.

2. Running, annual integration of above.

4. Implementation Schedule

A suggested approach (Figure 7) is that the MODIS group perform the coding (Esaias), MODIS handle the ancillary fields (Esaias and SDST) and MODIS run the code with SeaWiFS level 3 converted to MODIS format as input. Data could be made available through the Productivity SCF to interested researchers, but not the world. Once the SeaWiFS processing system becomes routine, they would assume routine operations as a new, post-launch, SeaWiFS data product. This is expected one year from launch of SeaStar. Data would then be available through the DAAC along with other SeaWiFS products. The MODIS Product Generation System would implement the non-linear algorithm at launch, using MODIS data, and the MODIS productivity data would be available through the DAAC as a MODIS product.

Upon selection of a consensus algorithm, the SeaWiFS Project and MODIS PGS would convert to the new product as soon as acceptable code could be produced and tested. This product would replace the non-linear algorithm, unless the PPWG believed the data to be non-redundant and important.

This dual stream of processing (SeaWiFS and MODIS) would continue until and unless appropriate methods for combining chlorophyll inputs is developed by SIMBIOS.

As proposed above, the Daily Product would be produced on a weekly basis, at 9.5 km spatial resolution. Alternatives were a daily product could be produced at the same spatial resolution from level 3 chlorophyll. A third alternative is to perform the calculation at the resolution of level 2 data, and also bin the data at daily, weekly, and annual periods. The volumes of data increase by roughly one and two orders of magnitude for the second and third alternative. The third approach would necessitate a significantly different processing approach.

5. List of Tables

Table 1. MOD 27 Productivity Calculation f(Latitude, μ,σ)

		Ppc	Pnn	Pxc
$<60^\circ$	High Var.	$P=ax+b$ $\varepsilon=((a\varepsilon x)^2+(\varepsilon ax)^2+\varepsilon b^2)^{1/2}$ $x=\mu$ $\varepsilon_x=\sigma/n^{1/2}$ $a=51.9$ $\varepsilon_a=1.2$ $b=125.6$ $\varepsilon_b=2.0$	$P=ax+b$ $\varepsilon=((\varepsilon ax)^2+(\varepsilon ax)^2+\varepsilon b^2)^{1/2}$ $x=\mu$ $\varepsilon_x=\sigma/n^{1/2}$ $a=8.58$ $\varepsilon_a=0.50$ $b=4.24$ $\varepsilon_b=0.34$	$P=ax+b$ $\varepsilon=((\varepsilon ax)^2+(\varepsilon ax)^2+\varepsilon b^2)^{1/2}$ $x=\mu$ $\varepsilon_x=\varepsilon Ppc$ $a=.63$ $\varepsilon_a=0.03$ $b=-32.2$ $\varepsilon_b=4.7$
	Low Var.	P=Howard Algorithm Table 4 ε=TBD	$P=15.391$ $\varepsilon=13.733$	$P=4.433$ $\varepsilon=3.444$
$>60^\circ$	High Var.	$P=bx^a$ $\varepsilon=\mu((\varepsilon_b \ln 10)^2+(\varepsilon_a \ln x)^2+(a\varepsilon_x/\mu)^2)^{1/2}$ $x=\mu$ $\varepsilon_x=\sigma/n^{1/2}$ $a=0.299$ $\varepsilon_a=0.081$ $b=10^{(-0.084)}$ $\varepsilon_b=0.059$	$P=ax+b$ $\varepsilon=((\varepsilon ax)^2+(\varepsilon ax)^2+\varepsilon b^2)^{1/2}$ $x=\mu$ $\varepsilon_x=\sigma/n^{1/2}$ $a=8.58$ $\varepsilon_a=0.50$ $b=4.24$ $\varepsilon_b=0.34$	$P=ax+b$ $\varepsilon=((\varepsilon ax)^2+(\varepsilon ax)^2+\varepsilon b^2)^{1/2}$ $x=\varepsilon Ppc$ $\varepsilon_x=\varepsilon Ppc$ $a=.63$ $\varepsilon_a=0.03$ $b=-32.2$ $\varepsilon_b=4.7$
	Low Var.	$P=bx^a$ $\varepsilon=\mu((\varepsilon b \ln_{10})^2+(\varepsilon a \ln x)^2+(a\varepsilon x/\mu)^2)^{1/2}$ $x=\mu$ $\varepsilon_x=\sigma/n^{1/2}$ $a=.299$ $\varepsilon_a=0.081$ $b=10^{(-0.084)}$ $\varepsilon_b=0.059$	$P=15.391$ $\varepsilon=13.733$	$P=4.433$ $\varepsilon=3.444$

Table 2. Esaias-Iverson Annual Production Estimates

Region	% Ocean Area	Total Prod	New Prod	Export Prod
High Var.	28	16.6	22.7	7.7
Low Var.	72	33.6*	3.9	2.5
Total	100	50.2	26.6	10.2
% in High Var.		33*	86	75

Productivity units are Gigatons Carbon / year
New, export numbers assume constant values in low variance regions:
New Production = 2 gN / m2 / yr
Export Production = 10 gC / m2 / yr
Total Prod. in Low variance regions is an underestimate, made by assuming the linear relationship extends to all regions.

Other Recent Total Production Estimates

Antoine and Morel (1996)	46
Longhurst et al. (1996)	45-50
Behrenfeld and Falkowski (1996)	44
Howard (1995) with mixed layer corr.	48

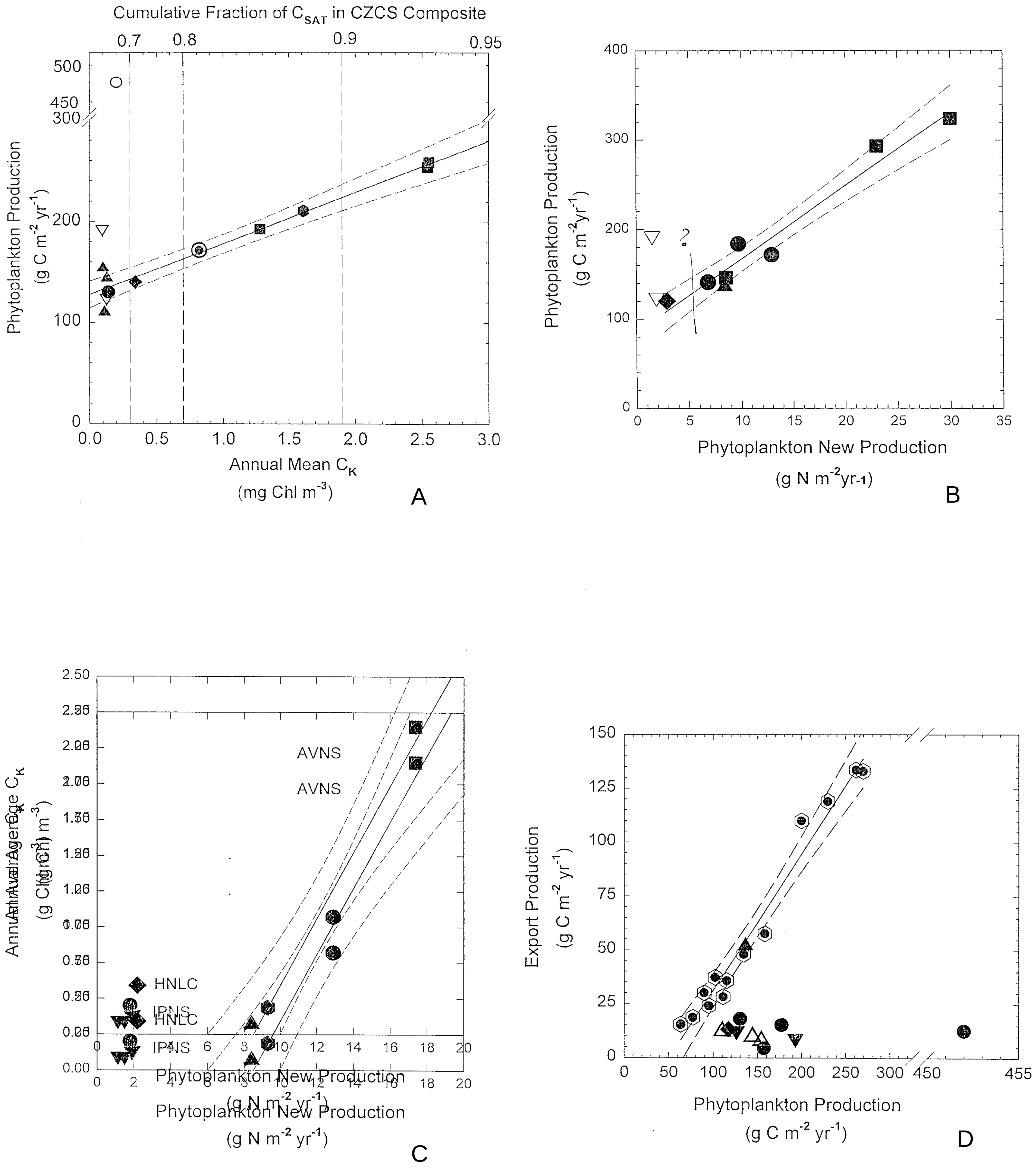
TABLE 3. Equations and Constants	Source
Constants:	
$\alpha = 1.1*24 = 2.64$ mgC / mgChla W / m2 day-1	Platt et al., 1991 (Table 4)
C:Chl a = 60	Eppley, 1972 (Fig. 9)
Equation 1: $P_{max} = 24e^{0.09*sst}$ $(mgC(mgChl)^{-1} d^{-1}$	Eppley, 1972 (Fig. 9)
Equation 2: $K_{par} = 0.04+(0.0088*chl)+(0.054*chl^{0.66})$ (m^{-1})	Nelson and Smith, 1991
Equation3: $E_{bar} = [E_0(1-e^{K_{par}*MLD})] / -K_{par} * MLD$ (watts m^{-2})	Walsh, 1975; Riley, 1957
Equation 4: $Ps_Z = (P_{max} * E_{bar}) / [(P_{max} / \alpha) + E_{bar}] * chl$ $(mgCm^{-3}d^{-1})$	Platt and Jassby, 1976
Equation 5: $PP = Ps_Z * -MLD$ $(mgCm^{-2}d^{-1})$	

Chl a FLAGS:	# bits	position
Chlorophyll *a* Field Id (0-5)	4	0-3
Chlorophyll *a* Quality Index (0=Good,15=Bad,1-14=Ugly)	4	4-7
High-Variance Class	1	8
Low-Sampling Rate (n < ____)	1	9
Open Ocean Flag (1=ocean, 0=inland waters)	1	10
Coastline in Bin	1	11
Depth < 30 meters	1	12
High Average Aerosol	1	13
Low Average Radiance	1	14
High Cloud Frequency	1	15
No Chlorophyll *a*	1	16
No Chlorophyll *a* Uncertainty	1	17
No Sea Surface Temperature	1	18
No Sea Surface Temperature Uncertainty	1	19
No Mixed-Layer Depth	1	20
No Mixed-Layer Depth Uncertainty	1	21
No Average Daily PAR	1	22
No Average Daily PAR Uncertainty	1	23

Product Gridcell Flags:	# bits	position
Function Id (0-15)	4	0-3
Quality Index (0=Good,15=Bad,1-14=Ugly)	4	4-7

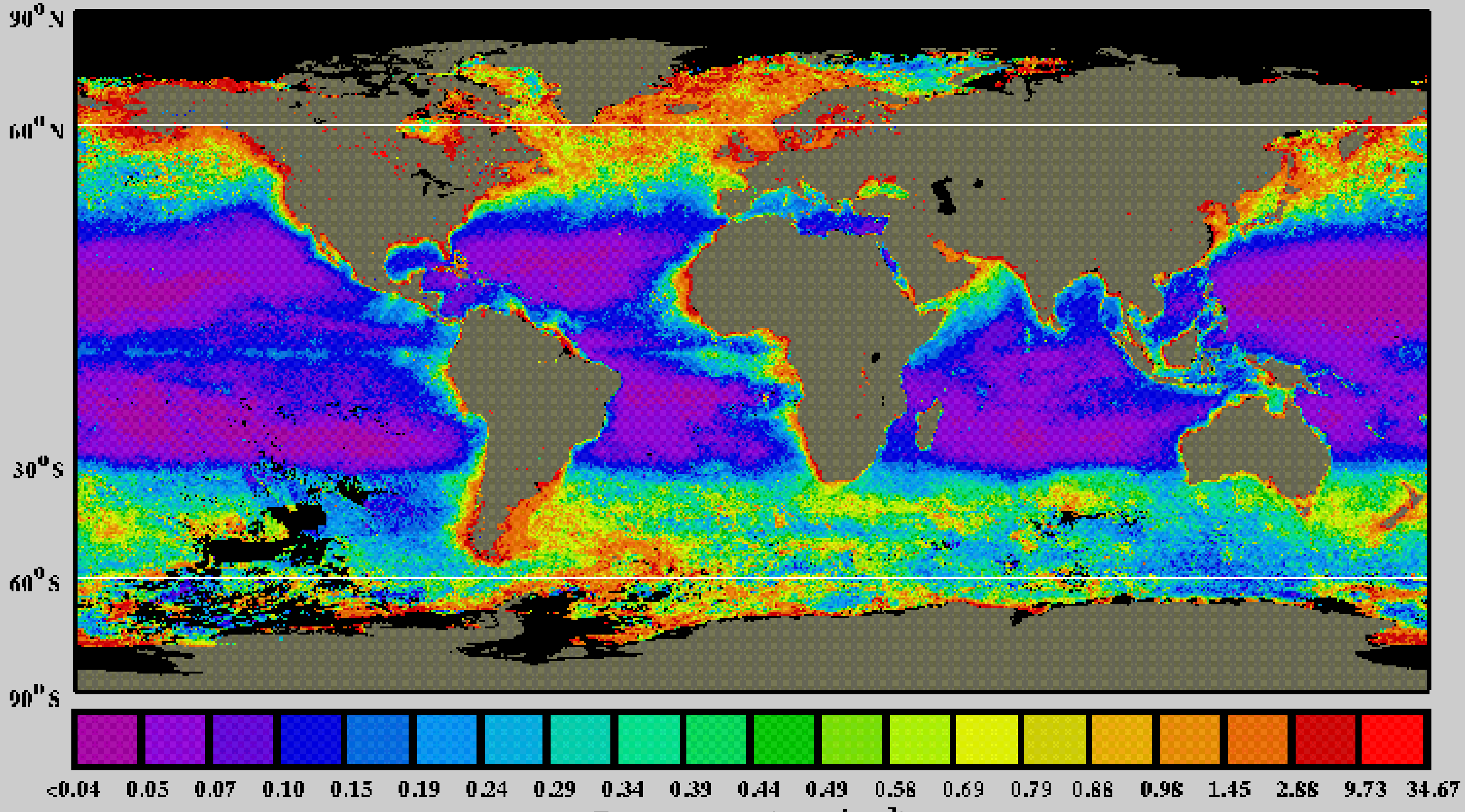
Table 4

6. List of Figures

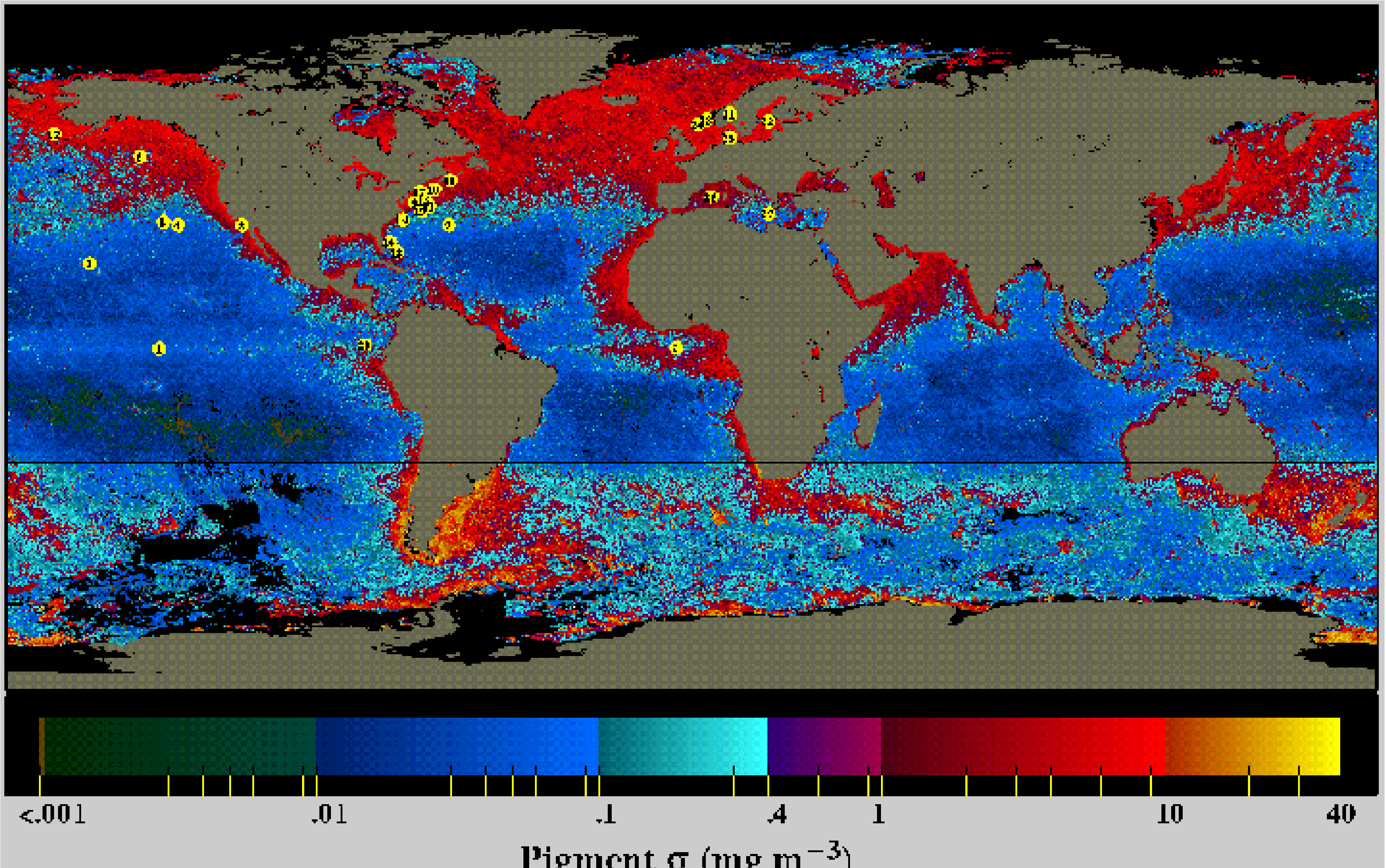


Cumulative Fraction of C_SAT in CZCS Composite
0.7
0.8
0.9
0.95
Phytoplankton Production
(g C m-2 yr-1)
Annual Mean C_K
(mg Chl m-3)
A
Phytoplankton Production
(g C m-2yr-1)
Phytoplankton New Production
(g N m-2yr-1)
B
Annual Average C_K
(g Chl m-3)
AVNS
HNLC
IPNS
Phytoplankton New Production
(g N m-2 yr-1)
C
Export Production
(g C m-2 yr-1)
Phytoplankton Production
(g C m-2 yr-1)
D

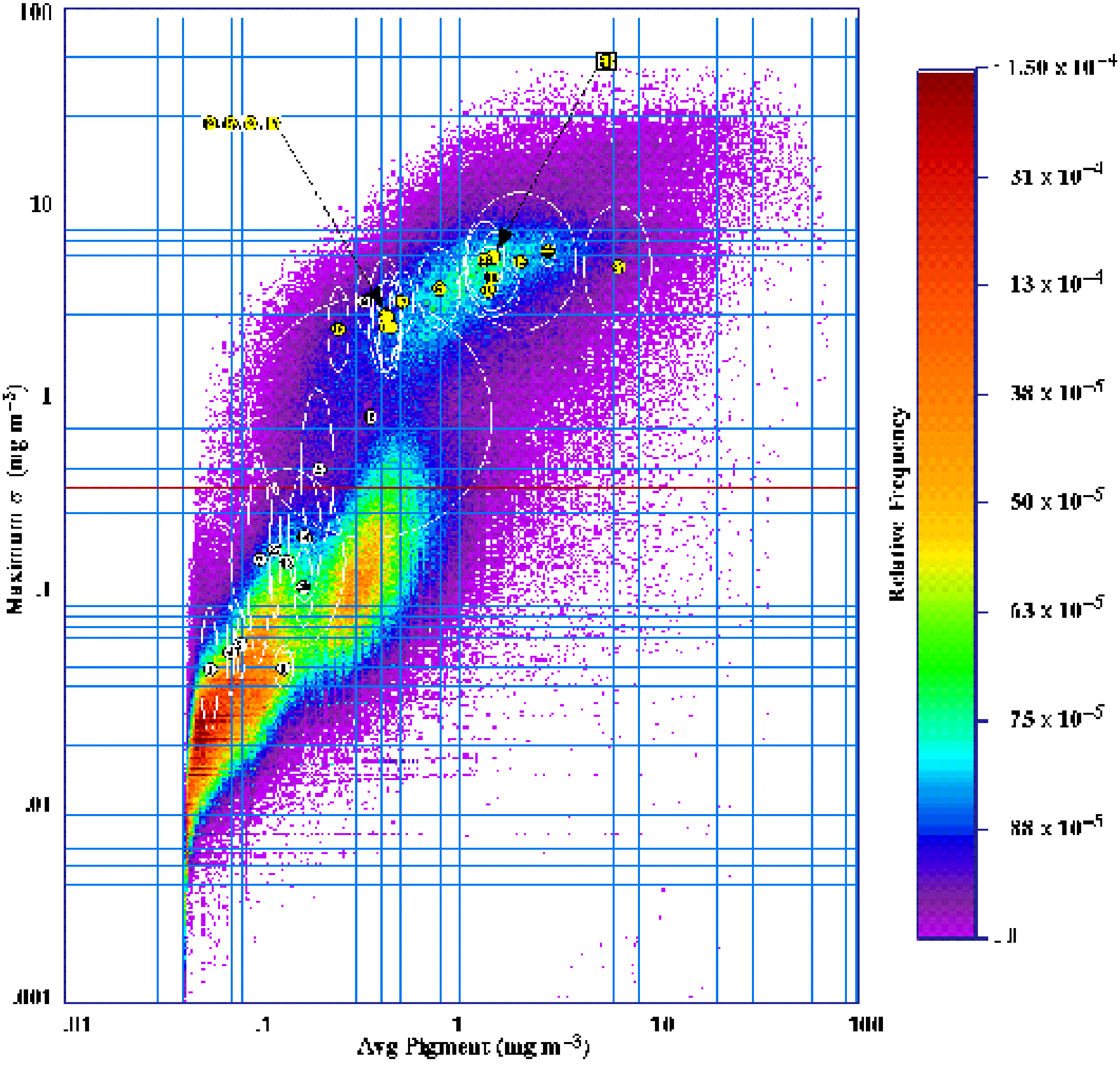
Figure 1



Monthly μ for 36 CZCS monthly composites (11/78 to 10/81)

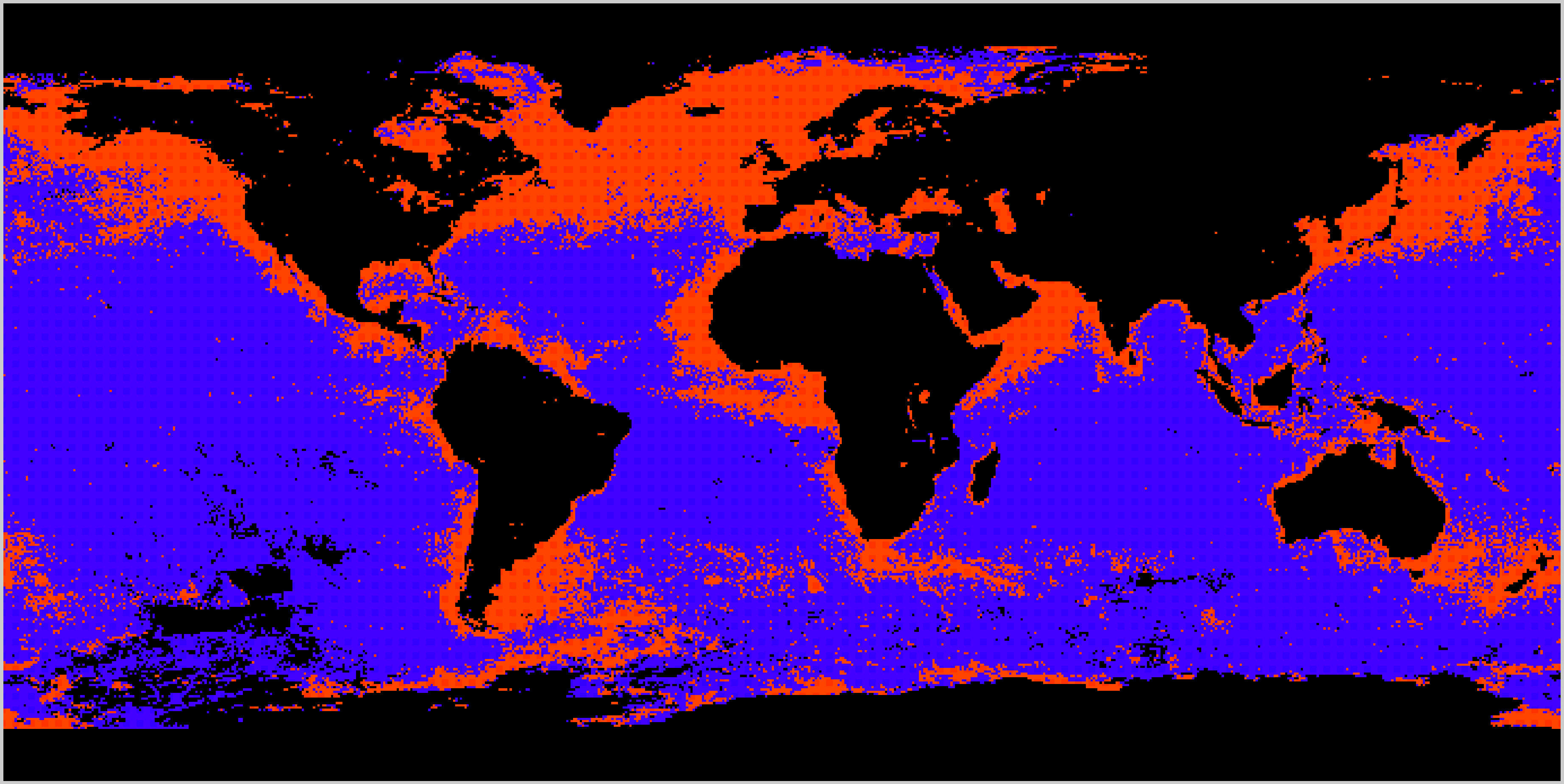


Maximum Monthly σ for 36 CZCS monthly composites (11/78 to 10/81)



100
10
1
.1
.01
.001
.01
.1
1
10
100
Avg Pigment (mg m^{-3})
Maximum σ (mg m^{-3})
Relative Frequency
1.50 x 10^{-4}
31 x 10^{-4}
13 x 10^{-4}
38 x 10^{-5}
50 x 10^{-5}
63 x 10^{-5}
75 x 10^{-5}
88 x 10^{-5}
0

CZCS Maximum Standard Deviation



≤ .04 (mg m^{-3})

> .04 (mg m^{-3})

11/78 – 10/81

MOD 27 Logical Flow

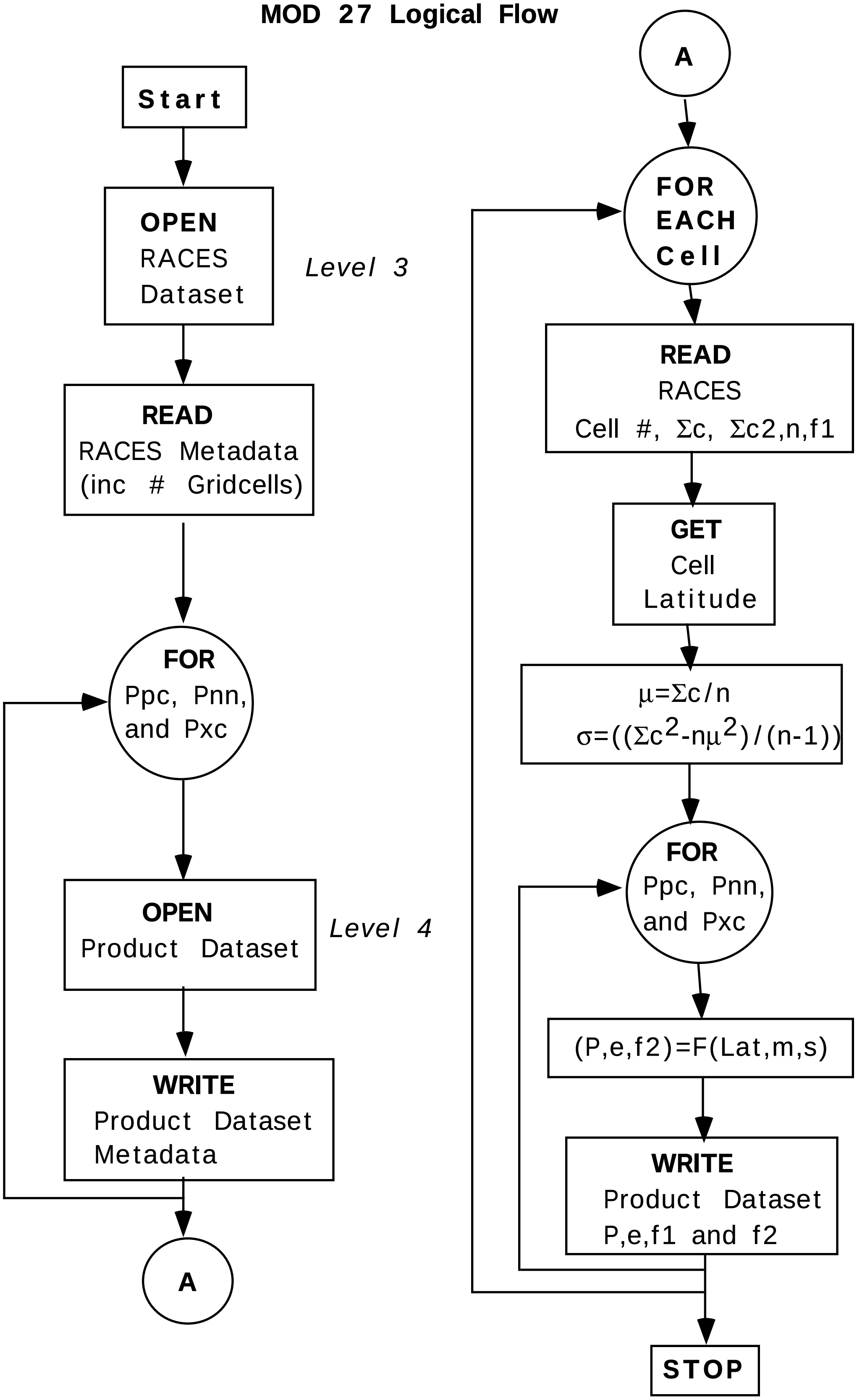
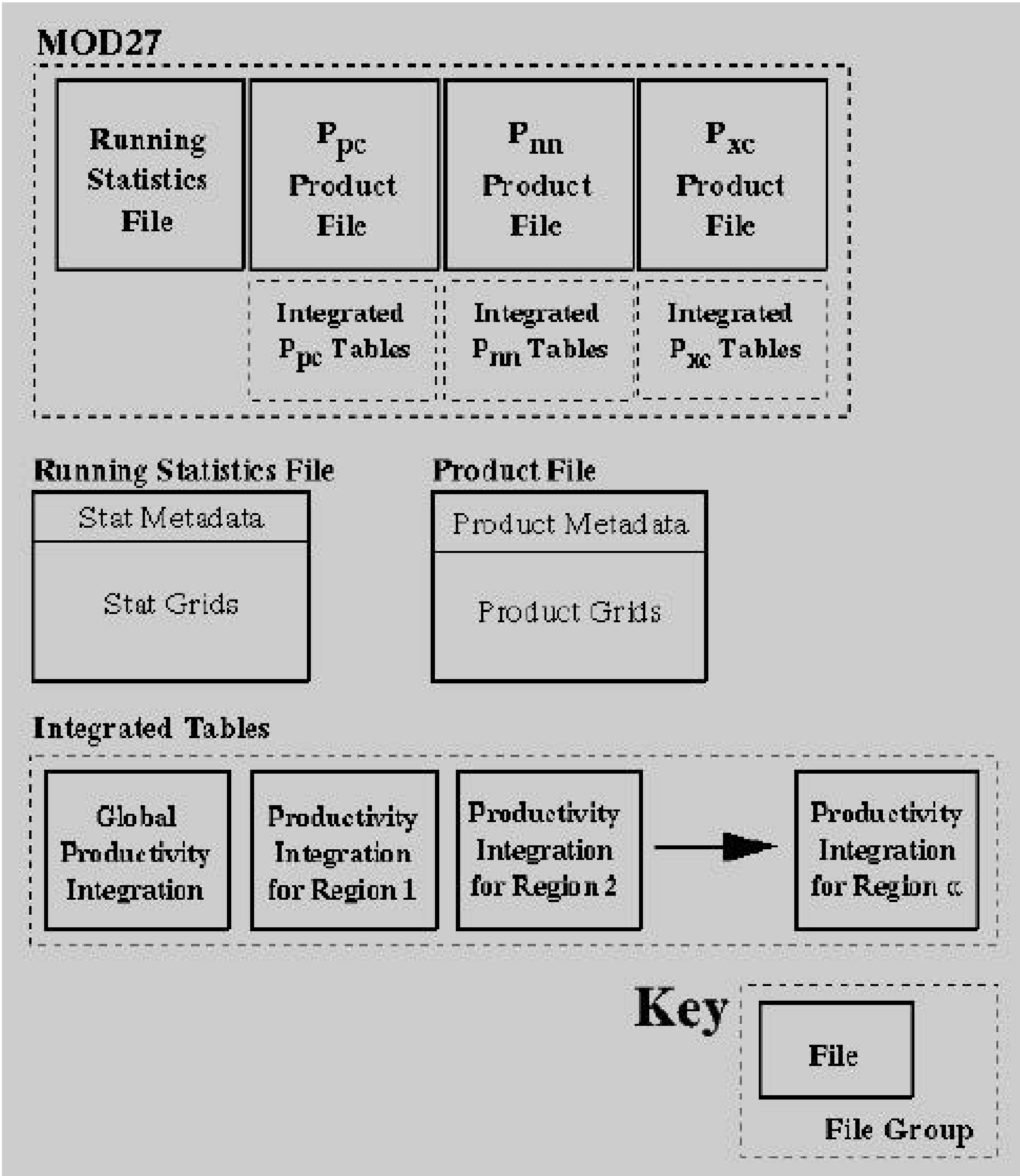


Figure 6


MOD27
Running Statistics File
Ppc Product File
Pnn Product File
Pxc Product File
Integrated Ppc Tables
Integrated Pnn Tables
Integrated Pxc Tables
Running Statistics File
Stat Metadata
Stat Grids
Product File
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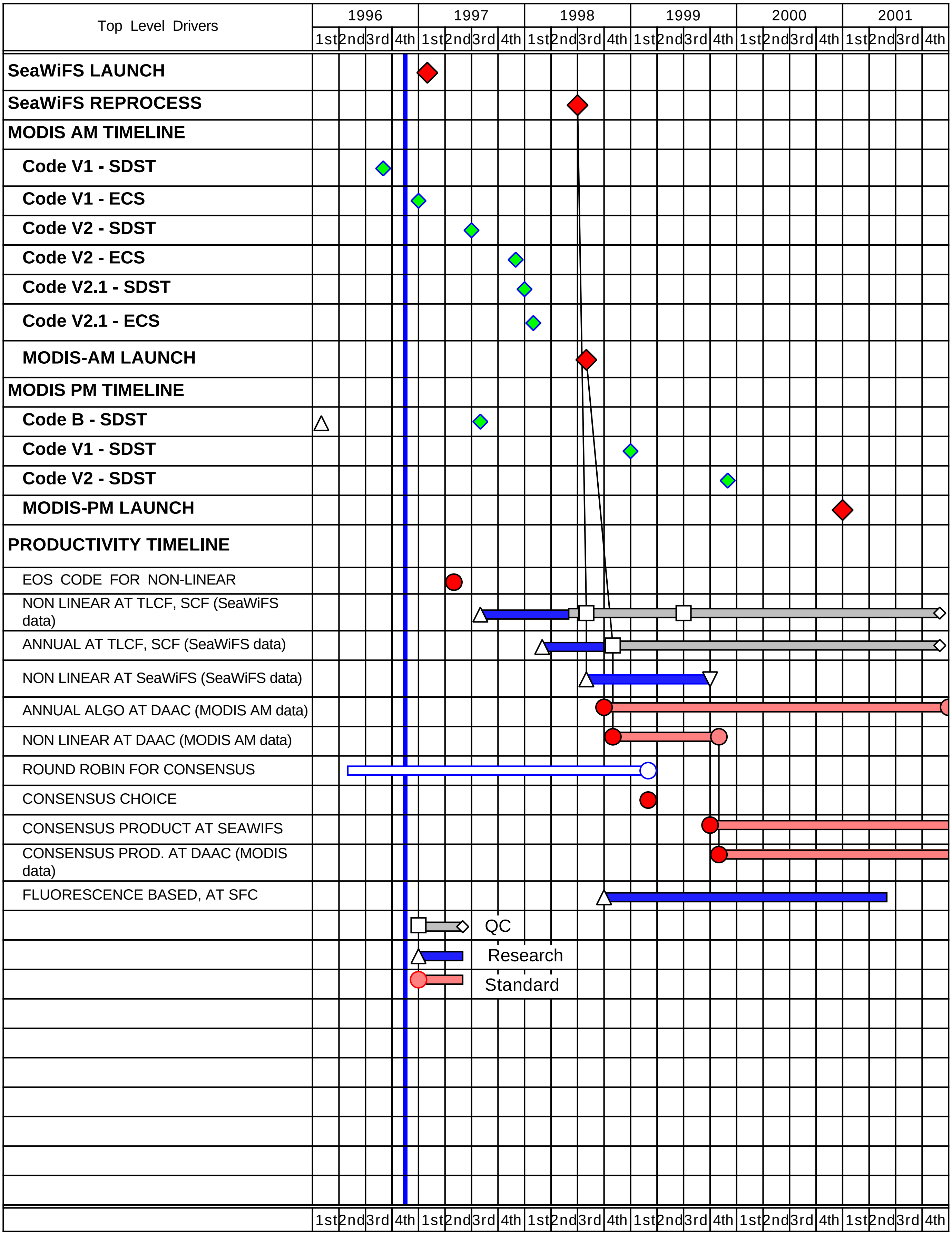
Productivity Integration for Region α
Key
File
File Group


Top Level Drivers
1996
1997
1998
1999
2000
2001
1st 2nd 3rd 4th 1st 2nd 3rd 4th 1st 2nd 3rd 4th 1st 2nd 3rd 4th 1st 2nd 3rd 4th 1st 2nd 3rd 4th
SeaWiFS LAUNCH
SeaWiFS REPROCESS
MODIS AM TIMELINE
Code V1 - SDST
Code V1 - ECS
Code V2 - SDST
Code V2 - ECS
Code V2.1 - SDST
Code V2.1 - ECS
MODIS-AM LAUNCH
MODIS PM TIMELINE
Code B - SDST
Code V1 - SDST
Code V2 - SDST
MODIS-PM LAUNCH
PRODUCTIVITY TIMELINE
EOS CODE FOR NON-LINEAR
NON LINEAR AT TLCF, SCF (SeaWiFS data)
ANNUAL AT TLCF, SCF (SeaWiFS data)
NON LINEAR AT SeaWiFS (SeaWiFS data)
ANNUAL ALGO AT DAAC (MODIS AM data)
NON LINEAR AT DAAC (MODIS AM data)
ROUND ROBIN FOR CONSENSUS
CONSENSUS CHOICE
CONSENSUS PRODUCT AT SEAWIFS
CONSENSUS PROD. AT DAAC (MODIS data)
FLUORESCENCE BASED, AT SFC
QC
Research
Standard
1st 2nd 3rd 4th 1st 2nd 3rd 4th 1st 2nd 3rd 4th 1st 2nd 3rd 4th 1st 2nd 3rd 4th 1st 2nd 3rd 4th

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