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TITLE: Geographic variation in the relationships of temperature, salinity or  $\sigma_t$  versus plant nutrient concentrations in the world ocean.

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THE RELATIONSHIPS OF TEMPERATURE, SALINITY  
OR SIGMA SUB t VERSUS PLANT NUTRIENT  
CONCENTRATIONS IN THE WORLD OCEAN Final  
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## ABSTRACT

A NCDC data set comprised of 230,202 oceanographic stations representing all regions of the world ocean was statistically analyzed for temperature and sigma-t relationships with nitrate, phosphate or silicic acid. Six cubic regressions were computed for each ten degree square of latitude and longitude containing adequate data. World maps display the locations that allow the prediction of plant nutrient concentrations from temperature or sigma-t within the limits of selected subjective and objective criteria. Geographic coverage improves along the sequence: nitrate, phosphate and silicic acid and is better for sigma-t than for temperature. Contour maps of the approximate temperature or sigma-t at which nitrate, phosphate or silicic acid are no longer measurable in a parcel of water are generated based on a percentile analysis of the temperature or sigma-t at which less than a selected amount of plant nutrient occurs. These regression and percentile results are stored on magnetic tape in tabular form. The analyses summarizes into the global potential to predict plant nutrient concentrations from remotely sensed temperature or sigma-t and emphasize the latitudinally and longitudinally changing phytoplankton growth environment in present and past oceans.

## INTRODUCTION

Temperature versus salinity (T-S) plots have long been used to characterize the different water masses in the world ocean. Mamayev (1975) has traced the history of the technique to Forch et al. (1902) who proposed an equation of state of sea water and Helland-Hansen (1912) who constructed a T-S diagram on which he plotted the real T-S relations of the waters of the oceans. Plant nutrients (PN) including nitrate (N), phosphate (P) and silicic acid (Si) have been applied to water mass studies relatively recently.

Aston (1980) has provided a review of plant nutrient relationships with salinity (S-PN) in estuaries. The scatter plots are primarily used to determine whether plant nutrients act conservatively as river water mixes with seawater. The exact pattern observed depends on the environmental conditions in each estuary. These studies suggest that salinity may be a useful predictor of plant nutrients that enter coastal water from rivers. In ocean regions beyond the influence of rivers, salinity does not usually exhibit sufficient variability over adequate spatial and temporal scales to serve as a good predictor of plant nutrient concentrations. Temperature and sigma-t are the conservative physical factors of choice under normal oceanic conditions.

According to Stefansson & Atkinson (1971a), Cooper (1952) was probably the first to suggest the use of silicic acid in identifying certain deep-water masses which are difficult to distinguish by means of their T-S characteristics. The temperature-silicic acid (T-Si) or the sigma-t-silicic acid ( $\sigma$ -Si) relationships have been used to identify water masses in the Antilles Arc region (Richards, 1958), the North Atlantic and Western Equatorial Atlantic (Metcalf, 1969), the Western Mid-Atlantic (Stefansson and Atkinson 1971a; 1971b) and several other regions including the Gulf of Mexico and the Southern Ocean (W. Nowlin, personal communication). Several GEOSECS

Program (Craig and Turekian, 1980) investigators have used various plant nutrient or derived plant nutrient parameters (i.e. "NO") as conservative markers of different water masses (Broecker, 1974) and have inferred the contribution of different water masses to a given parcel through water mass end-member interpolations (Broecker and Takahashi, 1980; Chung, 1980; Broecker et al. 1980; Broecker and Peng 1982).

Oceanographers interested in water mass identity and propagation routinely avoid the upper 200 m of the water column because of the complexities inherent in the ocean layer affected by the atmosphere and by the enhanced biological activity. Strickland et al. (1970) were probably the first to point out the surprisingly conservative nature of the temperature-plant nutrient (T-PN) relationship in near-surface water and to discuss the dynamic dependencies of the correlation. Nearly all of the data collected during the early weeks (May to mid-July) of their program in La Jolla Bight lay near a single curve from which one could predict plant nutrient concentration almost to within experimental accuracy, irrespective of how deep in the water column a given temperature was encountered. Data from later weeks deviated somewhat from the initial curve. Strickland et al. (1970) have stated that the relationship between plant nutrient depletion and the heating of the water column cannot be expected to be exact and must depend upon the amount and activity of plankton in the water.

In recent years other oceanographers have used T-PN, sigma-t versus plant nutrient ( $\sigma$ -PN) or other plant nutrient correlations that include the upper 200 m of the water column for various purposes in several locations off the California coast. Kamykowski (1973) has provided a temperature versus nitrate (T-N) scatter plot that is composed of 12 months of data collected from a 40 m water column at a station in La Jolla Bight. The range of nitrate

at any temperature below the temperature at which nitrate depletes ( $\sim 14^{\circ}$  C) is generally less than  $8 \mu\text{M}$ . Lower nitrate concentrations occur at a given temperature in January-June than in July-December. Eppley et al. (1979) have used the range of nitrate concentrations at a given sigma-t in  $\sigma$ -N plots to estimate the possible role of horizontal eddy diffusion in contributing to nitrate flux in the Southern California Bight. Station differences in the  $\sigma$ -N relationships increased as the distances between stations increased over the greater than  $1^{\circ}$  square grid of stations. As earlier suggested by Zentara and Kamykowski (1977), Traganza et al. (1983) have used T-PN relationships to predict plant nutrient distribution patterns off Northern California based on temperature determined from satellite infrared images and has applied these plant nutrient patterns to the interpretations of ocean color images of chlorophyll from CZCS imagery.

Off the Atlantic coasts of Canada and the United States, Smith (1978), Lee et al. (1981) and Atkinson et al. (1982) have used various plots of more easily measured physical or chemical factors versus plant nutrients to predict plant nutrient concentration. Long term mooring records of temperature, salinity, or oxygen combined with current meter velocities were used in conjunction with plant nutrient regressions to compute a time-series of probable plant nutrient flux on the Scotian, the Georgia and the North Carolina shelves.

In upwelling areas off South America and Africa, Friederich and Codispoti (1979) and Treguer and LeCorre (1979) have discussed the enrichment effects of local plant nutrient regeneration on the concentrations of nitrate, phosphate and silicic acid at the inshore end of a cross-shelf transect. Codispoti (1982) has stated that T-N and/or S-N plots show that the source waters of upwelling have concentrations that are higher than offshore waters with

similar temperatures and salinities. Friederich and Codispoti (1981) have shown a similar enrichment occurring along the longshore path of the poleward undercurrent that is the source of the upwelling waters off Peru. The  $\sigma$ -PN relationships can exhibit complex patterns in this area. During July to October 1976, the 26.0 sigma-t surface below 40 m was characterized by a nitrate range from 11 to 22  $\mu$ M and by a silicic acid range from 7 to 18  $\mu$ M. During March to May 1977 the ranges were 16 to 32  $\mu$ M for nitrate and 6 to 36  $\mu$ M for silicic acid. A times-series station at midshelf occupied during May 1976 showed a fluctuation of 9  $\mu$ M in nitrate and 8  $\mu$ M in silicic acid on the 26 sigma-t surface during a 24 hr period. This Peruvian coastal area is influenced by unusually strong denitrification and by a complex intermingling of water masses (equatorial and subantarctic) with very different hydrographic and plant nutrient characteristics. The observed plant nutrient variability may be extreme but it does emphasize the caution that must be exercised in the interpretation of plant nutrient relationships with temperature, salinity or sigma-t. In contrast, Voituriez and Herbland (1984) have suggested that the seasonal stability in the nitrate/temperature linear relationship observed in the nitracline of the Gulf of Guinea indicates an equilibrium between physical and biological processes in the region.

Zentara and Kamykowski (1977) have compiled a data set along the west coast of North and South America that allowed the generation of temperature versus nitrate, phosphate and silicic acid plots. Several trends were evident: 1) the plant nutrient concentration generally increased linearly with decreasing temperature for each block within the depth limits of the data set (ocean bottom or the depth below which nitrate remained constant); 2) the predicted plant nutrient depletion temperature decreased with increasing latitude from the equator; and, 3) actual nitrate depletion temperatures

occurred throughout the northern hemisphere, but were less likely to occur south of 45° S; silicic acid depletion temperatures occurred south of 45° S. This larger data set verified the coherent latitudinal applicability of T-PN relationships. The area studied, however, was chosen for its relatively simple physics and geology and did not consider the complexities of large river outflow, broad continental shelves, and large scale fronts. The latter areas may offer special problems due to altered plant nutrient ratios and the physical and chemical effects caused by the proximate sediment interface and by complex water mass structure.

The present paper provides T-PN and  $\sigma$ -PN analyses of a global data set obtained from NODC. This analysis provides a global view of the present capability to predict plant nutrient concentration or plant nutrient depletion from temperature or sigma-t using a slightly modified NODC data set.

#### METHODS

Twenty magnetic tapes in Station Data II format containing 230,202 oceanographic stations with at least one plant nutrient (nitrate, phosphate or silicic acid) represented were obtained from the National Oceanographic Data Center (NODC). Each ocean area was successively processed through the sequence of programs listed in Table 1 in which JCL refers to Job Control Language, SAS refers to the Statistical Analysis System and CAMIVA refers to the Cartographic Automatic Mapping System (Version IV-A). The reduced data sets created by OCEAN were limited by depth (<1000 m), temperature (-5 to 35° C), salinity (28 to 38 ppt), and appropriate plant nutrient concentration (nitrate -0 to 40  $\mu$ M; phosphate -0 to 3.5  $\mu$ M, or silicic acid -0 to 200  $\mu$ M). Scatter plots of temperature or sigma-t versus nitrate, phosphate or silicic acid were used to assign subjective values of overall data quality. The possible data quality symbols were: 'X' -data generally fell along a main



line trend that was consistent with that expected from surrounding TENSQs (10°Lat x 10°Lon); 'M' -a relatively large number of data points compared to the number in a TENSQ deviated from the expected main line trend apparently as a result of decimal point errors; and 'B' -no expected main line trend was discernible. Only TENSQs designated 'X' were considered for this paper. No attempt was made to correct suspect data. The statistical analyses performed using the SAS procedures (SAS Institute Inc., 1982) included cubic regression calculations with associated statistics including the variance-covariance table, estimates of means and ranges for the variables used in the cubic regressions and percentile determinations of the temperature or sigma-t values associated with plant nutrient levels below a selected level ( $N < 5$ ;  $P < 1$ ;  $Si < 10$ ). The levels were chosen as a compromise based on a survey of the data and they certainly work better in some regions (i.e. lower latitudes) than in others. These percentiles provide a mechanism for estimating the temperature or sigma-t at which the different plant nutrients tend to unmeasurable concentrations. The 50th percentile approximates this ideal within the range of the main contour intervals of 5°C for temperature or 1 unit for sigma-t. This amount of error is considered acceptable for the global comparisons in this paper but must be refined for actual application to a given region.

## RESULTS

Table 2 provides a listing of the factors recorded in the six final tables for the temperature or sigma-t versus nitrate, phosphate or silicic acid relationships that are considered in this paper. In addition, the variance-covariance tables are also available to allow the calculation of confidence limits for predicted plant nutrients concentrations at a selected temperature or sigma-t in a given TENSQ. These data sets are stored on magnetic tape at North Carolina State University. Figure 1 provides examples

of the range of scatter plots chosen as suitable for predicting plant nutrient concentration based on four criteria: 1) data point number (i.e., TNNC) > 10; 2) subjective data quality (i.e. TNQUAL) = 'X'; 3) adjusted  $r^2$  (i.e. TNARC) > 0.5; and, 4) root mean square error (i.e. TNEC) < 6 (N), 0.4 (P) or 20 (Si). The last criteria was chosen as the mid-range of error in each plant nutrient data set. The cubic regression fits are superimposed over the data. The entries for these scatter plots in the final tables are respectively listed in Table 2 (except for variance-covariance matrix).

Figures 2-4 provide map summaries of the TENSQs with adequate data to allow prediction of nitrate, phosphate or silicic acid, respectively, from temperature (upper) or sigma-t (lower) within the criteria mentioned above. For temperature or sigma-t, the geographic coverage is least for nitrate, intermediate for phosphate and most for silicic acid. The region bracketed between 40° N and 60° S is most suitable for plant nutrient predictions based on temperature. Plant nutrient predictions based on sigma-t are useful into higher latitudes. Several poorly represented regions (i.e. the U.S. east coast) may require reduced spatial groupings of data (i.e. 1° Lat x 1° Lon or smaller) to survive the selected criteria because of juxtapositioned water masses with different temperature or sigma-t versus plant nutrient signatures.

Figures 5-7 provide contour maps of the approximate temperature (upper) or sigma-t (lower) at which nitrate, phosphate or silicic acid respectively decline to unmeasurable concentrations using classical nutrient analysis techniques (Strickland and Parsons, 1968). These data represent only the TENSQs that are characterized by the subjective criteria 'X' and that contain more than 10 data points below the selected low plant nutrient criterion. The contours represent the 50th percentile of temperature (upper) or sigma-t

(lower) below these plant nutrient criteria within the acceptable TENSQs for each plant nutrient.

Figure 8 compares the latitudinally changing temperatures along the west coasts of North and South America for nitrate (Figure 5) and silicic acid (Figure 7) with those given in Zentara and Kamykowski (1977). The overall patterns are quite similar, although specific latitudes exhibit significant temperature differences. This can be attributed to the interaction between the TENSQ boundaries relative to the longitude of the coast line; the large TENSQ area can incorporate more or less offshore water compared to the data in Zentara and Kamykowski (1980).

Since the temperature and sigma-t contours in Figures 5-7 represent plant nutrient depletion, they are generally symmetrical around the equator and depict the late growth season condition in both hemispheres. The contours tend to be compressed toward the equator in the eastern parts of each ocean and toward the poles in the western part of each ocean. The warmest temperatures of plant nutrient depletion occur in the eastern Indian and western Pacific Oceans. This region is also characterized by the lowest sigma-t values of plant nutrient depletion as a result of the abundant rainfall and river runoff. The North Atlantic generally has warmer but denser contour values than the North Pacific. The Southern Ocean exhibits generally symmetrical contours around Antarctica that are occasionally distorted by blocking land masses. The silicic acid contours tend to be colder and denser than those of nitrate or phosphate at the same high southern latitudes.

#### DISCUSSION

The NODC data set is an oceanographic resource that has the potential to provide global views of different factors and their interactions. Unfortunately, the data set is compromised by several sources of error that

limit this potential. The results presented in this paper use both subjective and objective criteria to circumvent the obvious errors. Alternate criteria can be applied to the refined data set derived from the statistical analysis to yield maps either more or less stringently controlled. The present criteria demonstrate that useful information can be extracted from the NODC data set and the potential utility of the NODC data set for examining plant nutrient relationships with temperature and sigma-t.

The cubic regressions of temperature or sigma-t versus nitrate, phosphate or silicic acid for each TENSQ in Figures 2-4 can be used to predict plant nutrient concentrations. The required estimates of temperature or sigma-t can come from various sources including buoy, airplane or satellite mounted sensors. Traganza et al. (1983) have demonstrated this application for satellites and have used the added insight to more completely interpret CZCS ocean color determinations of chlorophyll. The cubic equations derived in the present analysis can be similarly applied to data such as that provided by Shannon et al. (1984). These investigators presented contours of remotely sensed surface temperature and chlorophyll collected off southwestern South Africa during February 1980. This location occurs in TENSQ 500 which is characterized by the following temperature-dependent cubic regressions:

$$N = 37.15 - 0.21T - 0.24T^2 + 0.008T^3 \quad r^2 = 0.92 \quad RMSE = 3.42$$

$$P = 1.48 + 0.35T - 0.05T^2 + 0.001T^3 \quad r^2 = 0.58 \quad RMSE = 0.42$$

$$Si = 41.46 - 4.56T - 0.17T^2 - 0.002T^3 \quad r^2 = 0.39 \quad RMSE = 9.13$$

Since all relationships are subjectively rated 'X', the error term (>0.40) prevents the appearance of this phosphate relationship in Figure 3 and the adjusted  $r^2$  term (<0.5) eliminates this silicic acid relationship in Figure 4. The nitrate relationship is well within the criteria used in this paper.



Depending on the standards selected by the investigator, the nitrate or all of these equations could be used to supplement the published temperature contours with derived plant nutrient contours that would help specify the future growth potential of the measured chlorophyll.

The present analysis of the NODC data set is not the best choice to predict plant nutrients from temperature in a given local study except if concurrent plant nutrient measurements are unavailable or impossible. Based on the present analysis, however, plant nutrient concentrations can be uniquely predicted from temperature over broad geographic regions. The extent of these regions for the different plant nutrients is reasonably delineated in Figures 2-4. Each matrix of regression equations provides a potential capability to generate global or ocean basin maps of plant nutrient concentrations based on routine surveillance of surface temperature from satellites. This capability can eventually contribute to the routine surveillance of chlorophyll as primary production in the world ocean (Perry, 1982). Eppley et al. (1985) have stated that plant nutrients are one of the factors that control photosynthesis per chlorophyll and that the variation in the relationship between primary production and chlorophyll that is explained by temperature may be partly based on plant nutrient relationships with temperature.

The plant nutrient predictions based on  $\sigma_t$  are generally more reliable and apply over a broader geographic area than those based on temperature. The  $\sigma_t$  based relationships may eventually be compatible with satellite-sensed determinations if salinity can be remotely determined. Alternately, these  $\sigma_t$  based relationships provide a mechanism for interpreting past or future mooring data as demonstrated by Atkinson et al. (1982). For the latter purpose, however, local concurrent calibration will

usually be better than the NODC relationships alone. The NODC data can be used to place local calibration in a spatial context.

Figures 5-7 provide approximate contours of the temperatures and sigma-t values at which nitrate, phosphate and silicic acid are no longer measurable in the world ocean. These contours supplement the cubic regressions represented in Figures 2-4 and demonstrate the dependence of the plant nutrient relationships with temperature or sigma-t on the large scale oceanographic processes. These processes must include the global seasonal cycle of incident solar radiation and its effect on evaporation-precipitation and on wind, the major currents associated with surface and deep circulation, and the location of the continental land masses and their associated river systems. More local effects include the average environmental conditions that determine the seasonal upper mixed layer stratification sequence and the conditions that affect phytoplankton growth. These contours attest to the ability of organisms to maintain a high level of biological activity over a broad range of temperature and sigma-t conditions determined according to physical laws. This biological activity is adequate to drive near-surface plant nutrient concentrations to unmeasurable levels over broad geographic expanses of the world ocean.

These contours also emphasize the spatial and temporal application of these relationships as factors in phytoplankton competition and community succession (Tilman et al., 1981). This temperature, sigma-t and plant nutrient interaction combined with latitudinal patterns of other biologically significant factors like day length, light intensity, and mixed layer depth advances the conceptual view of the coordinated environmental factors affecting planktonic phytogeography (Smayda, 1980). Recall, however, that several investigators (i.e. Strickland et al. 1970) have emphasized that seasonal adjustments between physical and biological processes can alter the

local expression of these relationships within confined but measurable limits.

Finally, these contours initiate paleoceanographic speculation concerning variability of the planktonic growth environment during various stages of the earth's history. CLIMAP (1981) has provided a seasonal representation of the sea-surface temperatures during a glacial period based on a factor analysis of the abundance of organism remains in the underlying sediment. Although the average temperature difference from the present condition is small ( $\sim 1.5^{\circ}$  C), the glacial temperature can range  $10^{\circ}$  C lower at certain geographic locations. The plant nutrient relationships with temperature and sigma-t provide an added dimension to the causal factors that allow organism abundances to yield temperature information. This is especially true when interpreted in light of the complex interactive effects that these factors have on phytoplankton growth (Goldman, 1977), nutrient uptake (Goldman, 1979) and behavior (Walsby and Reynolds, 1980; Bienfang and Harrison, 1984; Cullen and Horrigan, 1981; Kamykowski, 1981).

#### CONCLUSIONS

The statistical analysis of temperature and sigma-t relationships with nitrate, phosphate and silicic acid using the NODC data base demonstrates the existence of a global prediction capability and of a diverse global texture of temperature, sigma-t and plant nutrient patterns acting on phytoplankton processes. Plant nutrient concentrations can be predicted based on temperature or sigma-t with varying amounts of certainty depending on the complexity of water masses in the region and on the quality of the existing data. These predictions can contribute to the interpretation of the satellite chlorophyll data as primary production. Latitudinal and longitudinal variations in these relationships as exemplified by the approximate temperature or sigma-t values

at which plant nutrients deplete can be related to the matrix of global environmental processes and to the ability of phytoplankton to adapt to the resulting range of environmental conditions. These contour maps of the temperature or sigma-t at which nitrate, phosphate or silicic acid deplete provide insight into present and paleoceanographic phytogeography.

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TABLE 1 - List of the program sequence applied to each ocean area

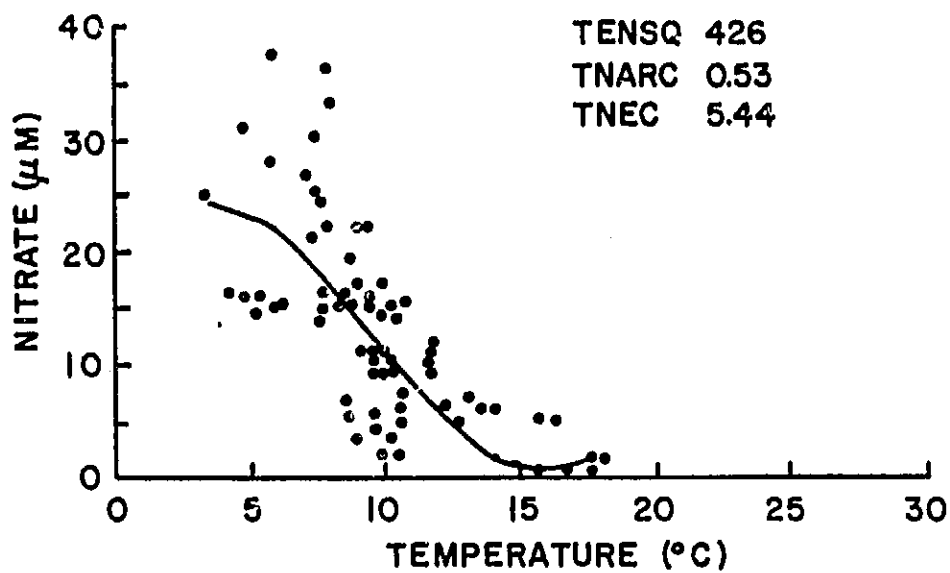
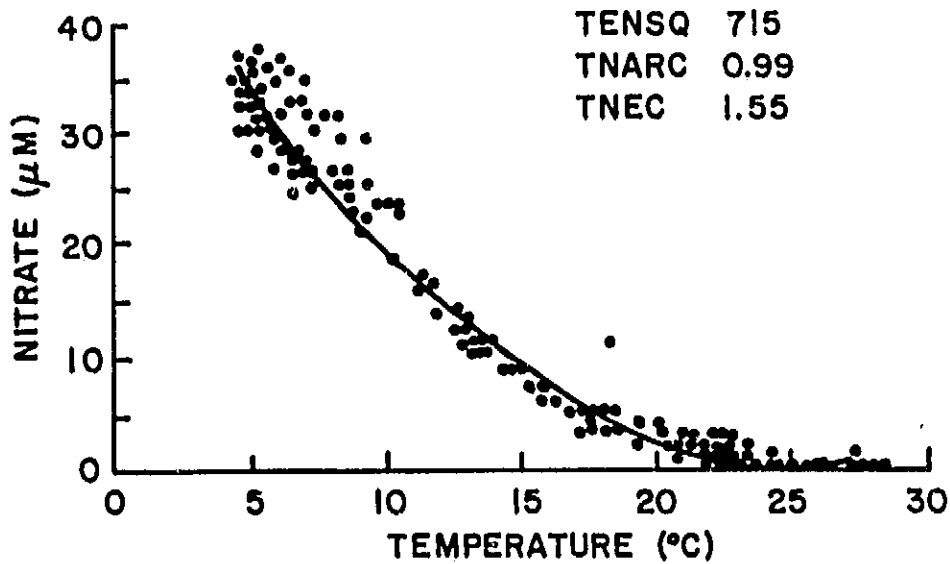
PROGRAM	SOURCE	FUNCTION
COPYDCTP	JCL	Copies the NODC data set for a given ocean area to a private disk (AREA).
OCEAN	SAS	Creates two modified SAS data sets; one contains the general information about each station (LOG); the other contains the depth profile information from each station (WATER).
SCATTER	SAS	Sorts the WATER data set according to 10° Canadian Square designation and provides plots of temperature or sigma-t <u>versus</u> nitrate, phosphate or silicic acid.
REGRESC	SAS	Computes cubic regressions for temperature or sigma-t <u>versus</u> nitrate, phosphate or silicic acid; Calculates means and percentiles for selected data subsets. Six versions - one for each relationship.
TABLE	SAS	Corrects errors in the preliminary Table from COMBINE. Six versions-one for each relationship.
WMSYM	SAS	Creates a Fortran compatible data set for selected variables. Several versions depending on variable.
WORLDMAP	CAMIVA	Superimposes specific variables from WMSYM on a world map.

TABLE 2 - Representative list of the output terms in the final table resulting from the statistical analysis of temperature versus nitrate data.

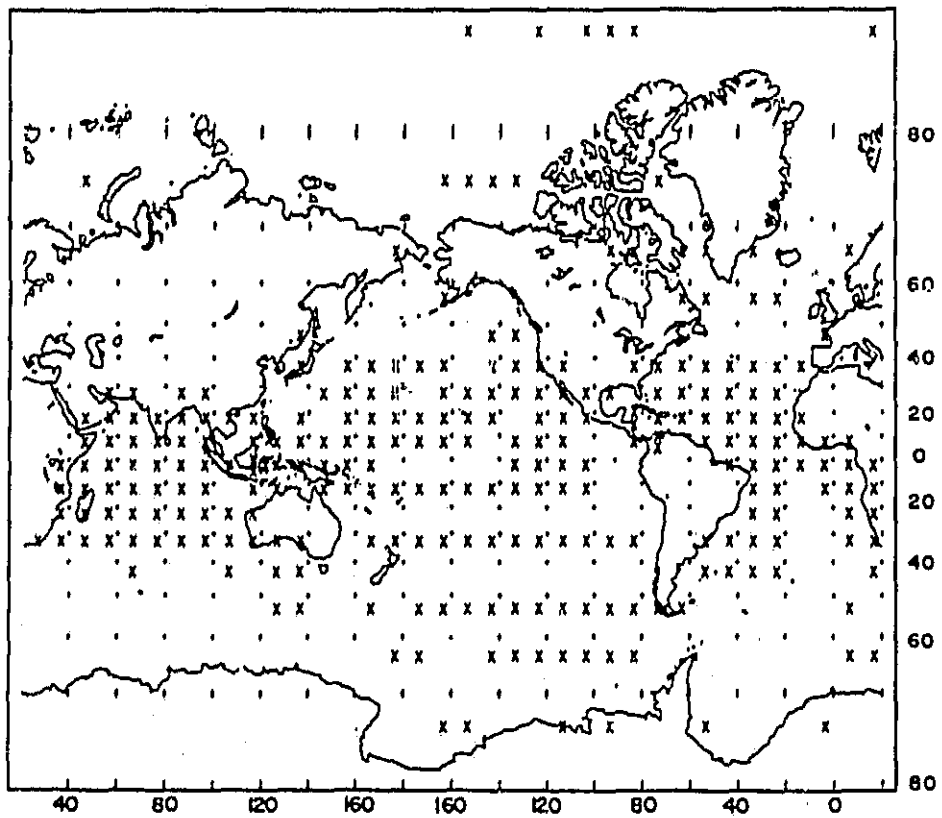
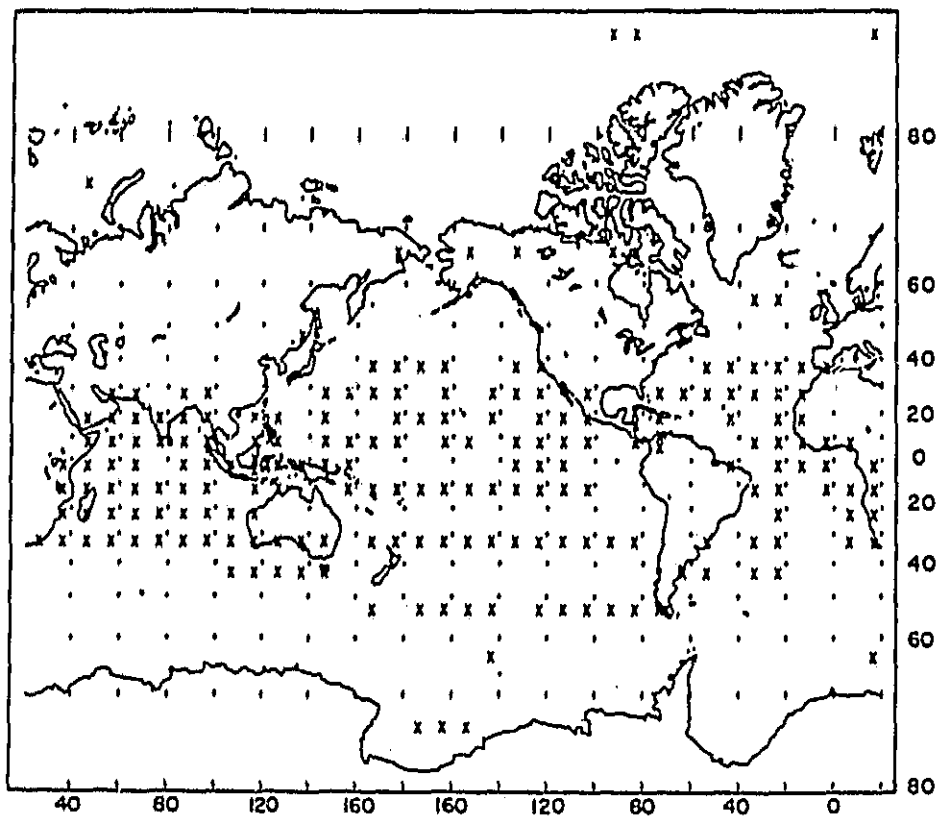
<u>VARIABLE</u>		<u>SAMPLE SETS</u>	
AREA	- NODC ocean area designation	4	3
TENSQ	- Canadian square number for 10° longitude by 10° latitude	426	715
LAT	- mid-latitude of the TENSQ; south is negative	-45	-15
LON	- mid-longitude of the TENSQ, east is negative	-115	135
TNNC	- number of nitrate data points in the TENSQ and the number of points used to compute the cubic regression	105	356
TNTL	- lowest nitrate temperature in the TENSQ	2.9	4.4
TNTM	- mean nitrate temperature in the TENSQ	9.7	17.9
TNTH	- highest nitrate temperature in the TENSQ	17.6	28.1
TNIC	- nitrate intercept of the cubic regression	18.15	49.74
TN1SC	- first order slope coefficient of cubic regression	3.69	-3.53
TN2SC	- second order slope coefficient of cubic regression	-0.67	0.04
TN3SC	- third order slope coefficient of cubic regression	0.02	0.0007
TNEC	- root mean square error of the cubic regression	5.44	1.55
TNARC	- adjusted $r^2$ for cubic regression	0.53	0.99
TNQUAL	- a subjective value of overall data quality	x	x
TNNL	- lowest nitrate in TENSQ	0.2	0.0
TNNM	- mean nitrate in TENSQ	12.2	10.2
TNNH	- highest nitrate in TENSQ	37.4	36.9
TLNTC	- low nitrate criterion for temperature of nitrate depletion	5	5
TLNTN	- number of temperatures with nitrate levels below criterion	20	214
TLNT25	- 25th percentile temperature with nitrate levels below criterion	9.4	22.4
TLNTM	- 50th percentile temperature with nitrate levels below criterion	11.6	25.2
TLNT75	- 75th percentile temperature with nitrate levels below criterion	17.0	26.2

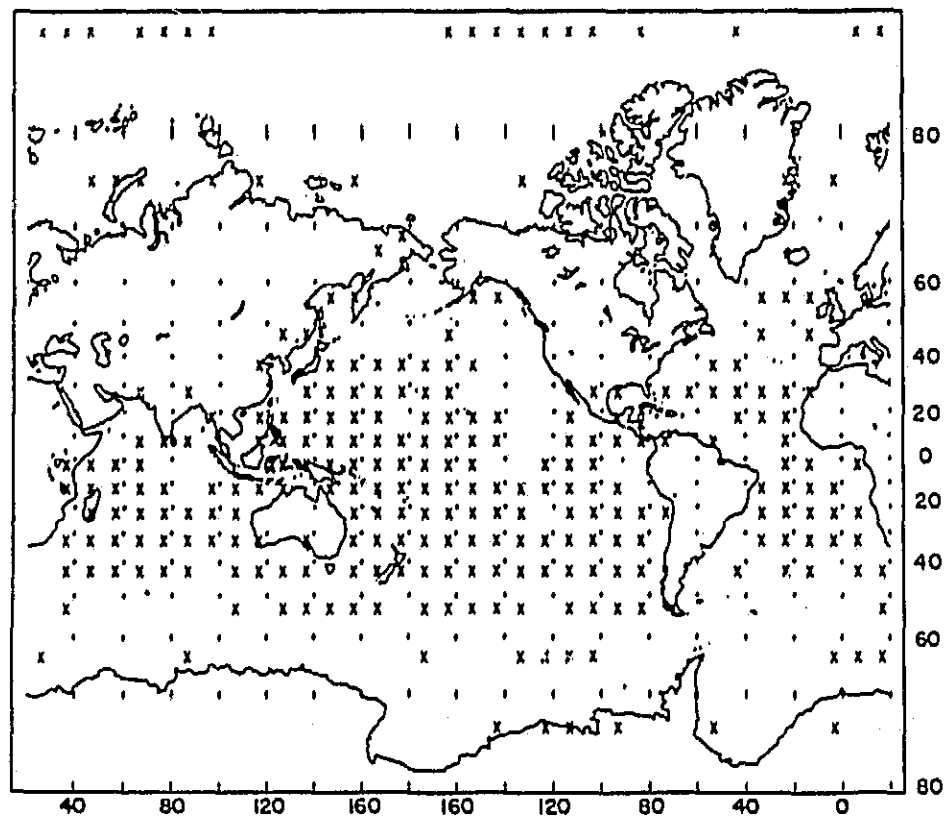
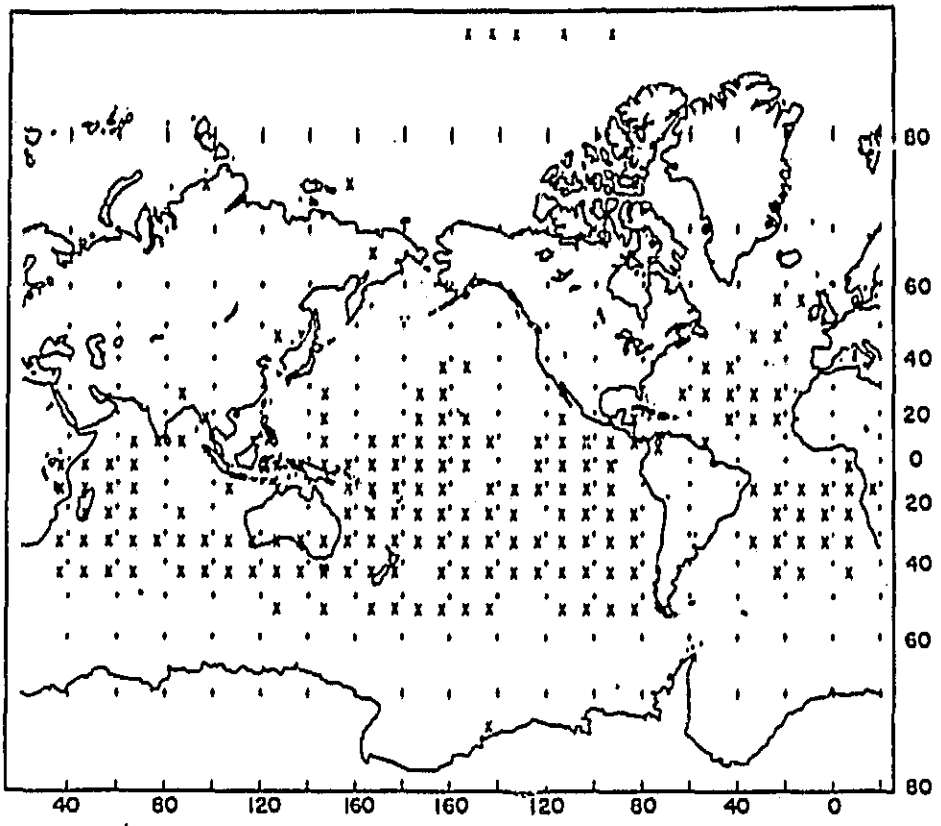
## FIGURE CAPTIONS

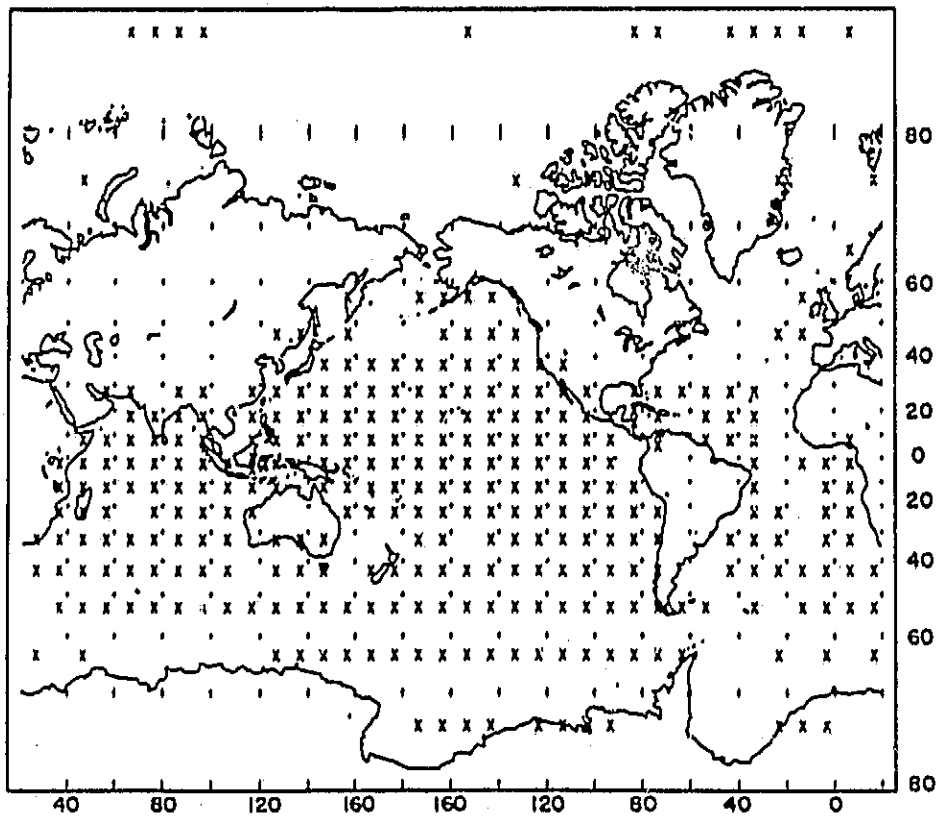
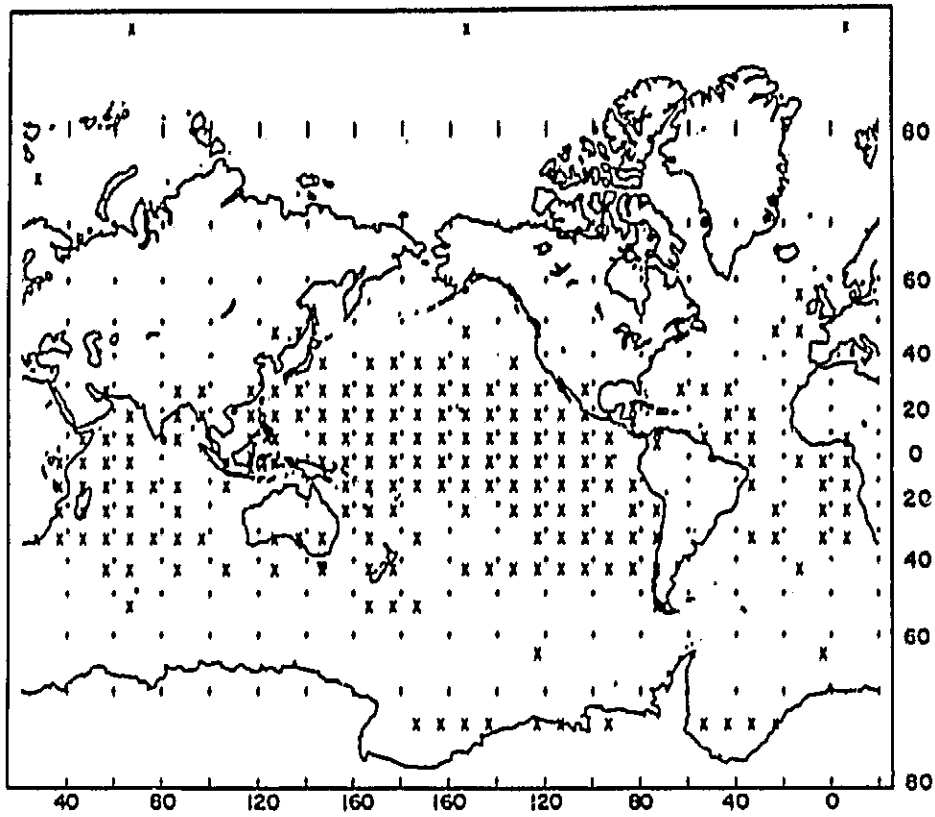
- Figure 1: Sample scatter plots demonstrating the range of acceptable data (top: best, bottom: worst) and cubic regression fits included in the present analysis.
- Figure 2: World maps of the  $10^\circ$  squares of latitude and longitude that contain acceptable data and cubic regression fits for temperature versus nitrate (top) and sigma-t versus nitrate (bottom) based on specified selection criteria. The 'X' marks over continental areas represent coastal regions within the bounds of the  $10^\circ$  square.
- Figure 3: Same as Figure 2 for temperature versus phosphate (top) and sigma-t versus phosphate (bottom).
- Figure 4: Same as Figure 2 for temperature versus silicic acid (top) and sigma-t versus silicic acid (bottom).
- Figure 5: Contour maps of the approximate temperature (top) or sigma-t (bottom) at which nitrate approaches unmeasurable concentrations in the world ocean. The cross hatched area in the temperature plot marks the  $27^\circ\text{C}$  contour.
- Figure 6: Same as Figure 5 for phosphate.
- Figure 7: Same as Figure 5 for silicic acid.
- Figure 8: A comparison of the temperatures at which nitrate or silicic acid approach unmeasurable concentrations along the west coasts of North and South America from Figure 5 (top) and Figure 7 (top), respectively, and from the data in Zentara and Kamykowski (1977).

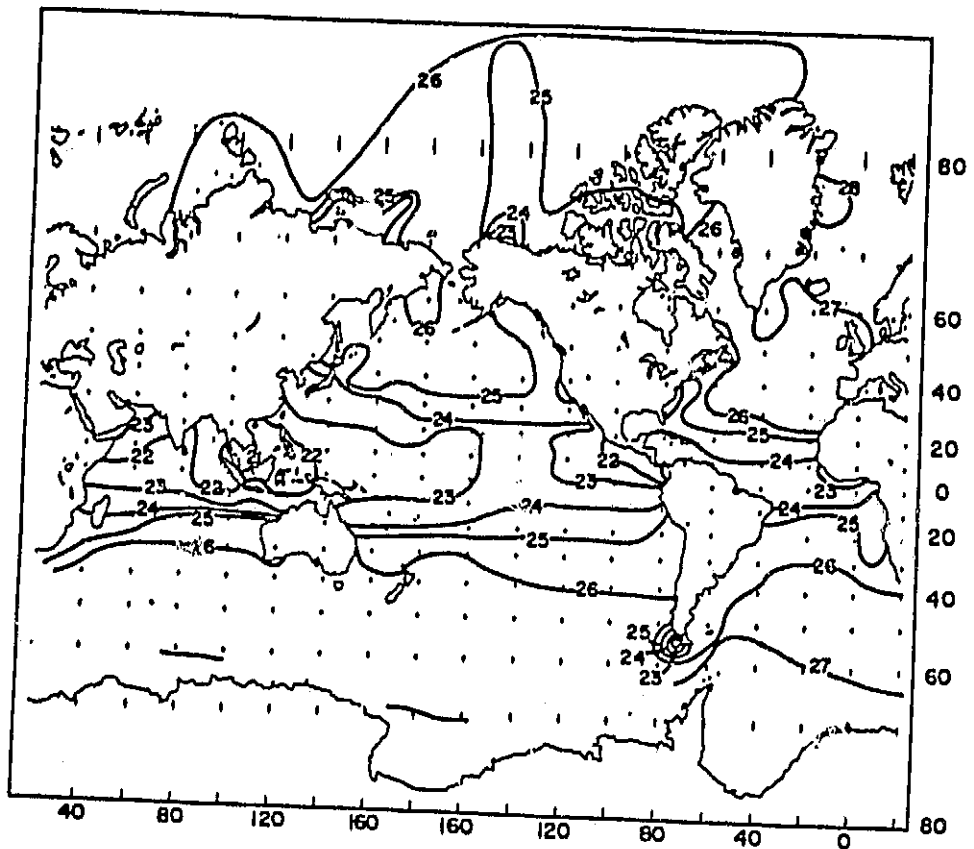
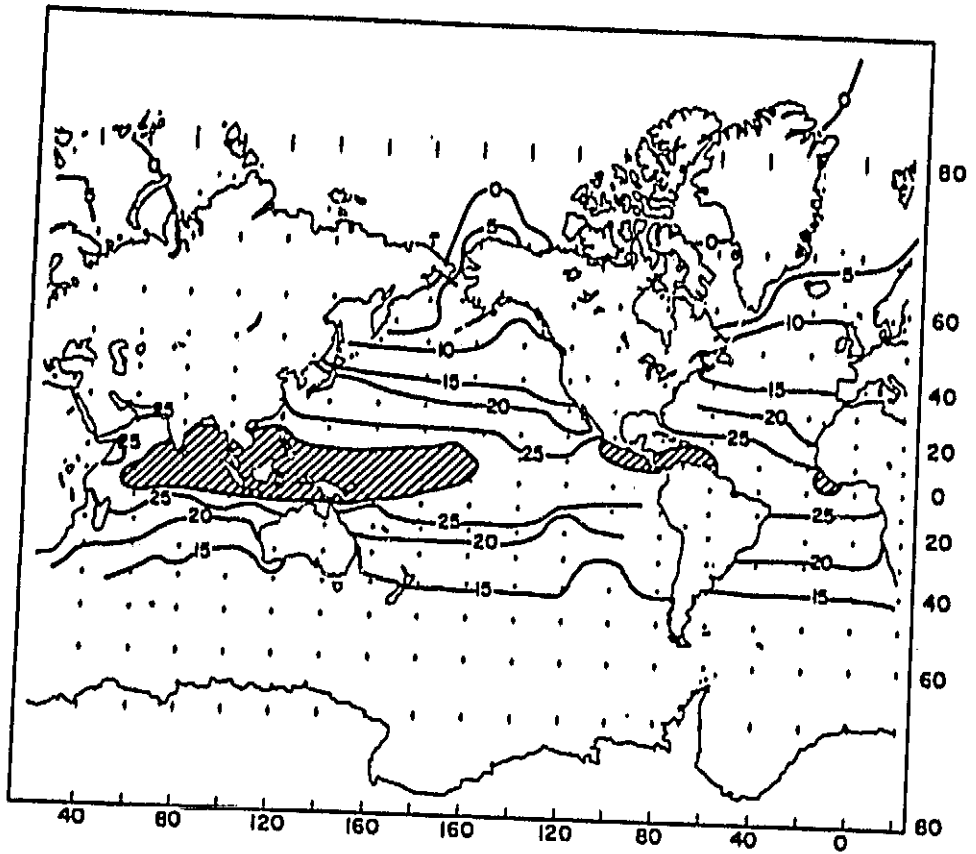


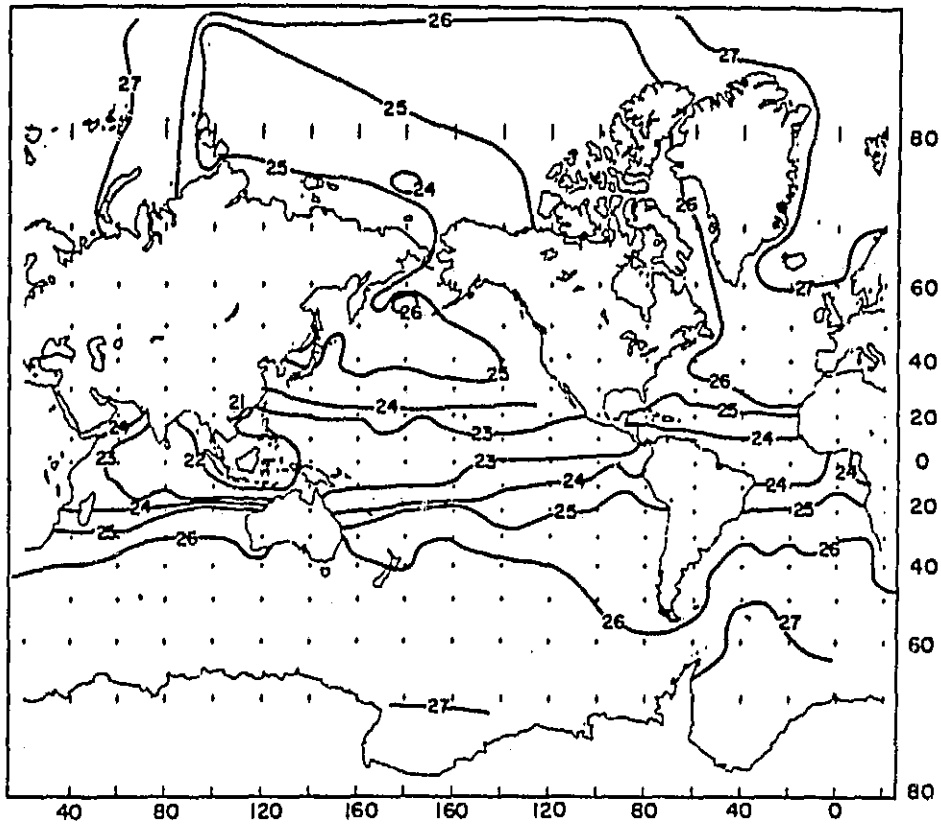
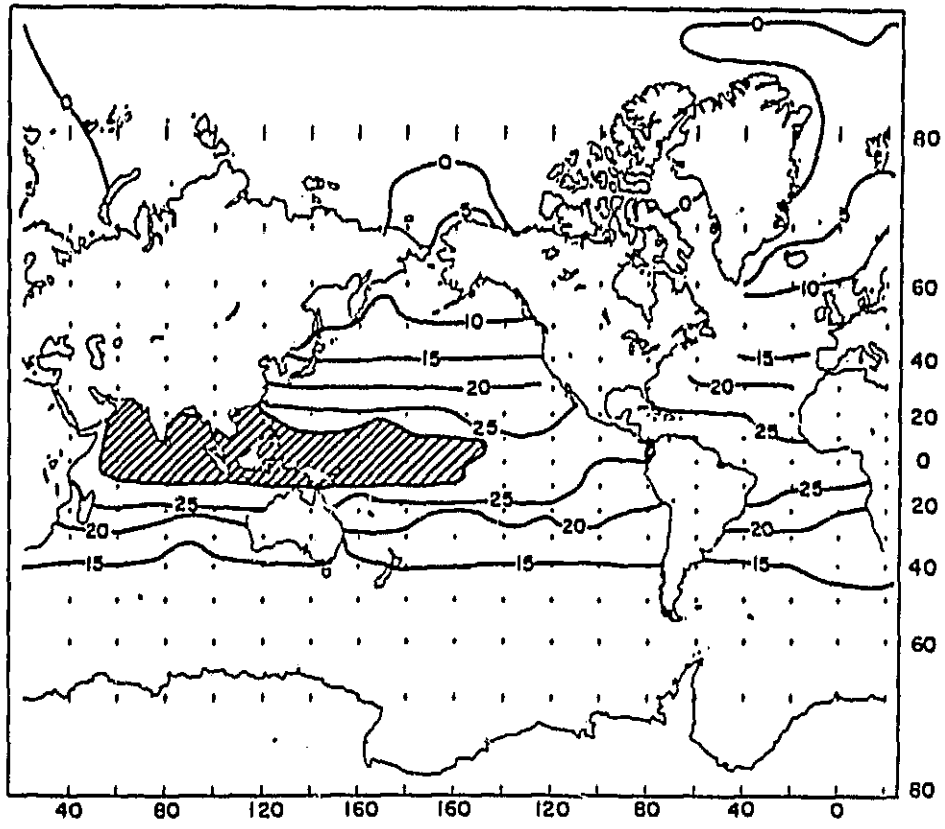


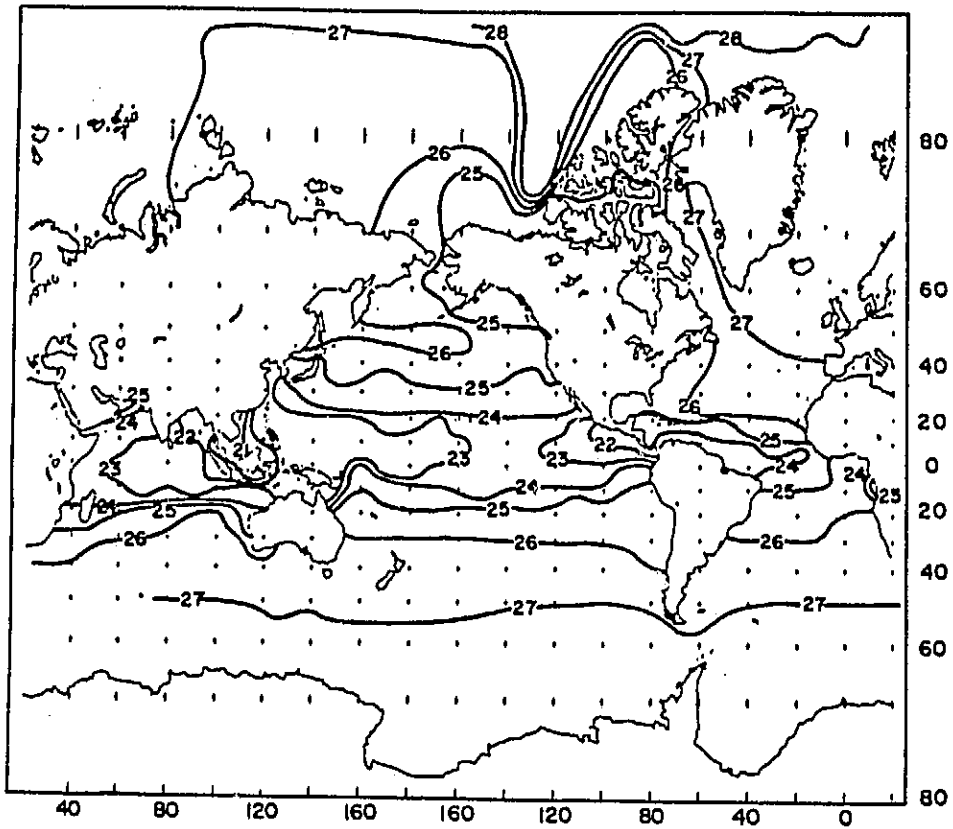
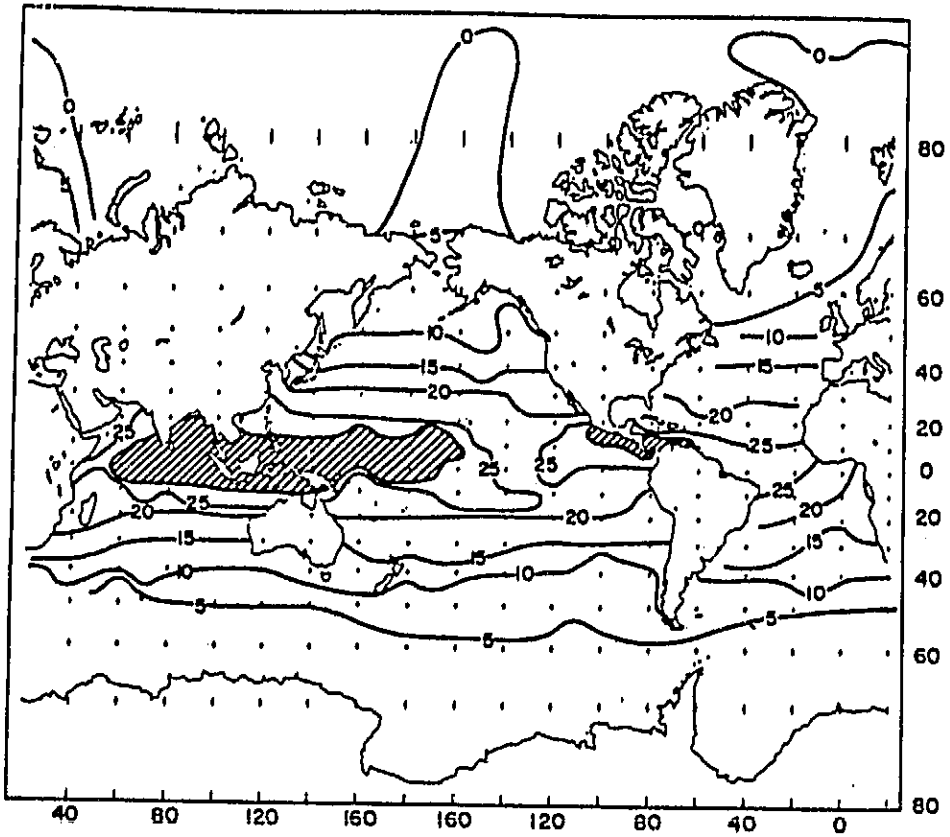


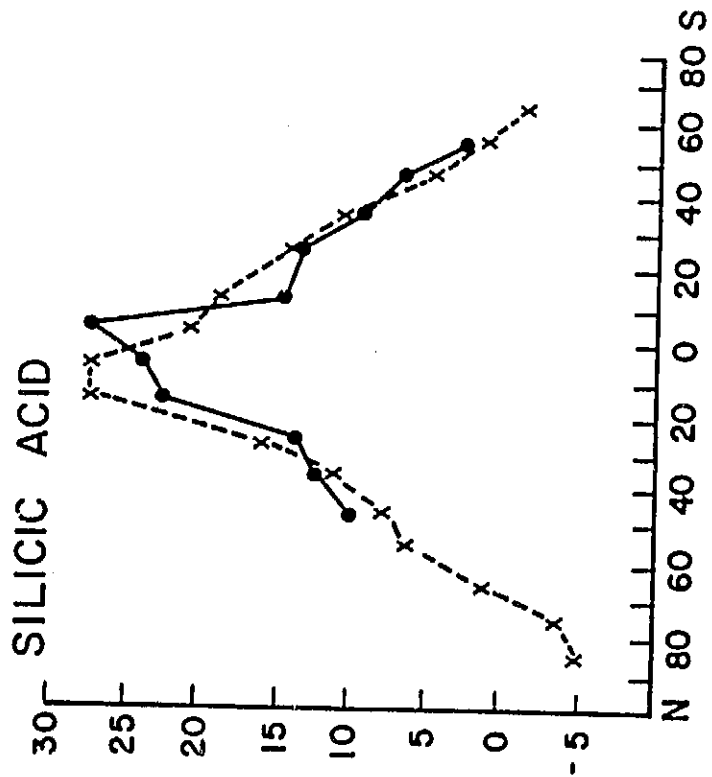
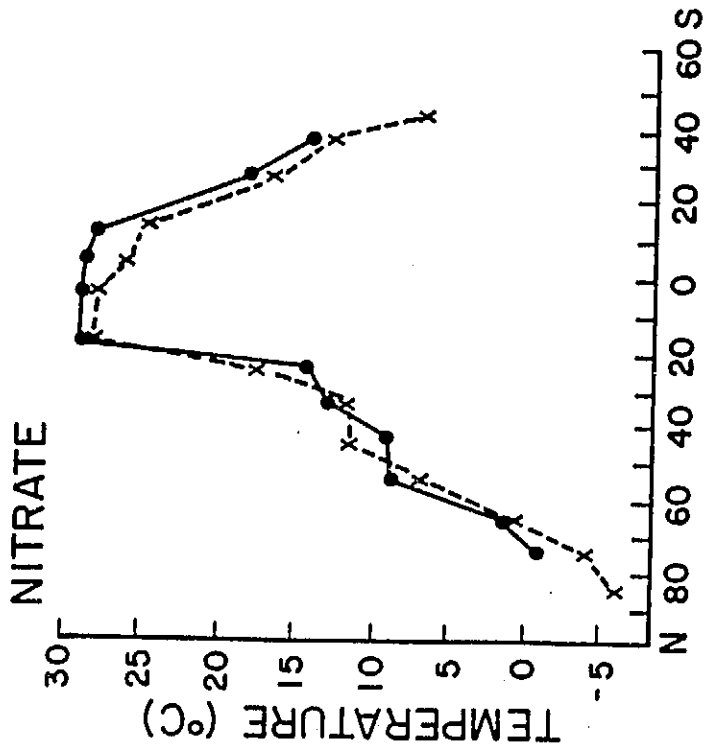












LATITUDE

## APPENDIX I

The attached set of tables provide a record of the:

1. Temperature vs. nitrate cubic regression coefficients
2. Temperature vs. nitrate variance-covariance matrix
3. Temperature vs. nitrate means, ranges and percentiles

for each 10° square of latitude and longitude for which data exists in the analyzed NODC data set. The labels are identified in Table 2 of the accompanying manuscript entitled 'Predicting plant nutrient concentrations from temperature and sigma-t in the world ocean'. Five additional sets of tables for temperature vs. phosphate, temperature vs. silicic acid, sigma-t vs. nitrate, sigma-t vs. phosphate and sigma-t vs. silicic acid are also available on the Triangle Universities Computer System in North Carolina. Some specific aspects of the three tables within the attached set are discussed in the following sections.

### 1. Temperature vs. nitrate cubic regression coefficients.

- The regression coefficients in this table are substituted into the equation

$$N = a + b_1T + b_2T^2 + b_3T^3$$

or

$$N = TNIC + TNISC(T) + TN2SC(T)^2 + TN3SC(T)^3.$$

- The lowest (TNL), mean (TNM) and highest (TNH) temperatures mark the range of best application of the cubic regression equation. TNNC gives the number of data points considered.

### 2. Temperature vs. nitrate variance-covariance matrix

- The 4x4 matrix (TNIC, TNISC, TN2SC, TN3SC) associated with each TENSQ corresponds to the labels

$$\begin{bmatrix} aa & ab_1 & ab_2 & ab_3 \\ ab_1 & b_1b_1 & b_1b_2 & b_1b_3 \\ ab_2 & b_1b_2 & b_2b_2 & b_2b_3 \\ ab_3 & b_1b_3 & b_2b_3 & b_3b_3 \end{bmatrix}$$



The variance of a predicted nitrate (N) concentration at a chosen temperature ( $T=\hat{T}$ ) given by

$$\hat{\text{Var}}(\hat{N}) = \left. \frac{\partial N}{\partial T} \right|_{T=\hat{T}}^2 \hat{\text{V}}(\hat{T}) \left. \frac{\partial N}{\partial T} \right|_{T=\hat{T}}$$

3. Temperature vs. nitrate means, ranges and percentiles

- The lowest (TNNL; TNL), mean (TNNM; TNM) and highest (TNNH; TNH) nitrate concentrations and temperatures are given.
- The 25th (TLNT25), 50th (TLNTM) and 75th (TLNT75) percentiles of the temperature at which nitrate is less than 5  $\mu\text{M}$  are given. TLNTC gives the number of data points considered.





























































































OBS  
 AREA  
 TENSO  
 IAT  
 LOH  
 THINL  
 TNNH  
 THINK  
 THTL  
 TNYH  
 TNYH  
 TINTH  
 TLNTC  
 TLNTH  
 TLNT25  
 TLNTH  
 TLNT75



UBS  
AREA  
TERM  
CAT  
LON  
TRINL  
TRINH  
TRINH  
TRINL  
TNTL  
TNTH  
TNTH  
TLNTC  
TLNTN  
TLNTS  
TLNT#  
TLNTS





TLNT75  
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TLNTM  
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TLNT25  
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TLNTH  
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TLNTC  
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