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Seasonal cycle of phosphate in the open ocean

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Abstract

The seasonal cycle of phosphate in the world ocean is described using all historical data (over 170,000 profiles) held at the U.S. National Oceanographic Data Center and World Data Center-A for Oceanography. Generally, phosphate concentrations are depressed in the season of highest primary production, in conformance with phosphate's role as a major nutrient. Mean phosphate concentration in the North Pacific are twice those in the North Atlantic. The largest seasonal differences occur in the sub-polar North Atlantic and Pacific, where changes in concentration are as large as a factor of two. Temperate and equatorial regions exhibit less seasonal variability. High latitudes, upwelling areas, and river mouths exhibit a notable seasonal signal in phosphate. Enrichment of phosphate from the Amazon and Orinoco rivers appears to dominate the seasonal signal in the tropical Atlantic. In fact, the extent of the rivers' effects extend so far north into the North Atlantic gyre that it obscures the normal pattern of summer depletion occurring elsewhere in the basin. The seasonal signal in the tropical Pacific Ocean is a function of seasonal variability in the winds, which affect the strength of coastal upwelling. Published by Elsevier Science Ltd.

1. Introduction

An understanding of the distribution of nutrients in the ocean is of primary concern if we are to describe ocean biogeochemical processes. Changes in the ocean carbon pool are influenced by the availability of nutrients, which are essential for phytoplankton growth. Phosphate, along with nitrate and silicate, are the critical micronutrients (Raymont et al., 1980).

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Phosphate is generally not considered to be limiting for primary production in oceanic ecosystems, a distinction that is usually accorded to nitrate (e.g., Perry and Eppley, 1981; Ryther and Dunstan, 1971; Dugdale and Goering, 1967). However, there are suggestions that phosphate can be limiting in certain situations, such as in the North Pacific central gyre during the 1991–1992 El Niño event (Karl et al., 1995), at times in the North Atlantic and North Pacific central gyres (DeBaar, 1994; Fanning, 1989), and in the lower photic zone off the Hawaiian Islands (Bienfang et al., 1984).

Because of its role as a major nutrient in oceanic primary production, phosphate has historically been frequently sampled. The U.S. National Oceanographic Data Center (NODC) and World Data Center-A for Oceanography station data archive contains more than 170,000 stations with phosphate profiles. This extensive phosphate archive enables us to go beyond analysis of all-data annual distributions (Conkright et al., 1994a; Levitus et al., 1993). In this paper we describe the seasonal distribution of phosphate based on objectively analyzed fields of historical phosphate data held at the NODC, as of the first quarter of 1993.

2. Methods

The seasonal cycle of sea surface phosphate is described by examining the difference between the winter and summer mean fields. In order to describe basin-wide features, it is necessary to use all available data, regardless of the year of observation, due to the sparseness of data. The seasonal variability of phosphate concentrations, as a function of depth, will be described using basin zonal averages (for the upper 400 m) of the winter minus summer mean phosphate fields for each major ocean basin. Computation of basin zonal averages and the boundaries of the individual ocean basins are described by Conkright et al. (1994a) and Levitus and Boyer (1994). Coastal regions, defined as any area where the bottom depth is less than 200 m, will be ignored in this discussion.

For this study, all historical data were composited into four seasons regardless of year of observation. The seasons are defined according to Northern Hemisphere convention as: Winter (January–March), Spring (April–June), Summer (July–September), and Fall (October–December). Fig. 1 shows the distribution of phosphate observations as a function of season and year of collection. Most data were collected between 1950 and 1980, mostly during the 1960s (over 50,000 profiles) and the 1970s (over 55,000 profiles). Even though the information is not available in the digital archive, we assume these data were obtained by manual methods (automated methods were non-existent during the earlier years or not extensively used during the later time period). Phosphate has historically been sampled more frequently in Northern Hemisphere summer (50,257 profiles) and spring (46,858 profiles) than winter (39,696 profiles) and fall (33,520 profiles).

Fig. 2 shows the distribution of phosphate observations at the sea surface for the winter and summer seasons. These maps are useful in identifying possible bias in the analyses due to data sparseness. Boundary current and coastal regions worldwide have been sampled more frequently than deep-sea regions. Most of the Arctic Ocean

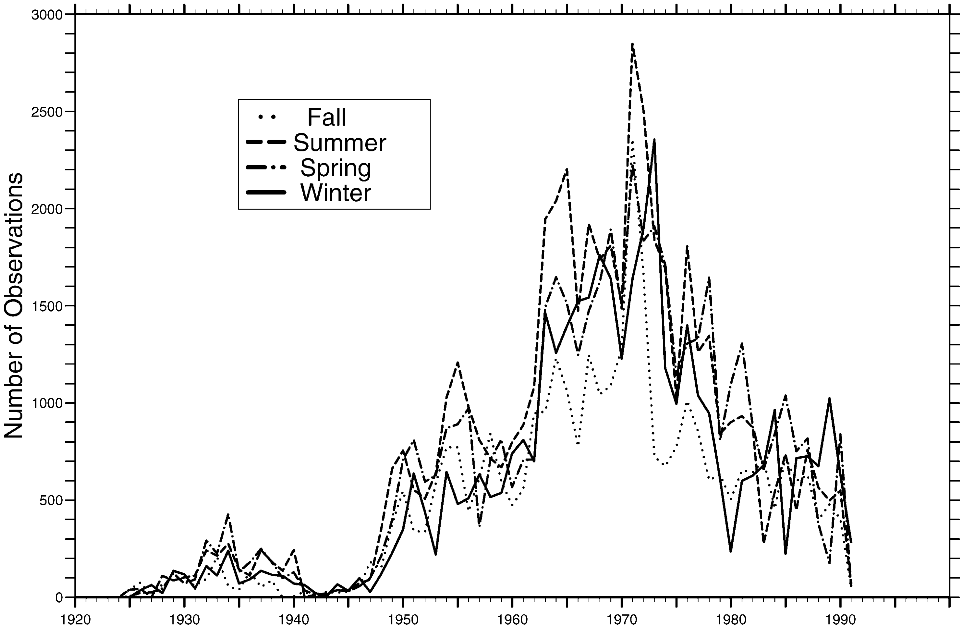

Fig. 1. Phosphate observations as a function of year and season.

and Southern Hemisphere contain large areas where insufficient data are available to produce representative fields. As more data become available, we will be able to prepare more representative fields for these regions and also extend the seasonal analyses below 400 m depth.

Our objective analyses are meant to represent large-scale permanent or semi-permanent features. Data were objectively analyzed at standard levels for the upper 400 m of the water column. All historical phosphate data were used in this study regardless of year of observation. The analyses were prepared on surfaces of constant depth as opposed to isopycnal surfaces, since it is not feasible to prepare objectively analyzed fields for the sea surface on isopycnal surfaces.

2.1. Quality control of historical phosphate data

Quality control procedures (used for all data regardless of the date of collection) are described by Conkright et al. (1994b), but a brief overview here will aid understanding. The data were initially screened for extreme values prior to a statistical check to eliminate erroneous or unrepresentative data. Phosphate data were averaged by five-degree squares, at each standard level, to produce a record of the number of observations, mean, and standard deviation in each square. Data were flagged if they were outside an envelope three to five standard deviations from the mean. The weaker criteria were used in the coastal and near-coastal regions due to the high variability in these areas. The data are produced on a standard Earth grid using objective analysis

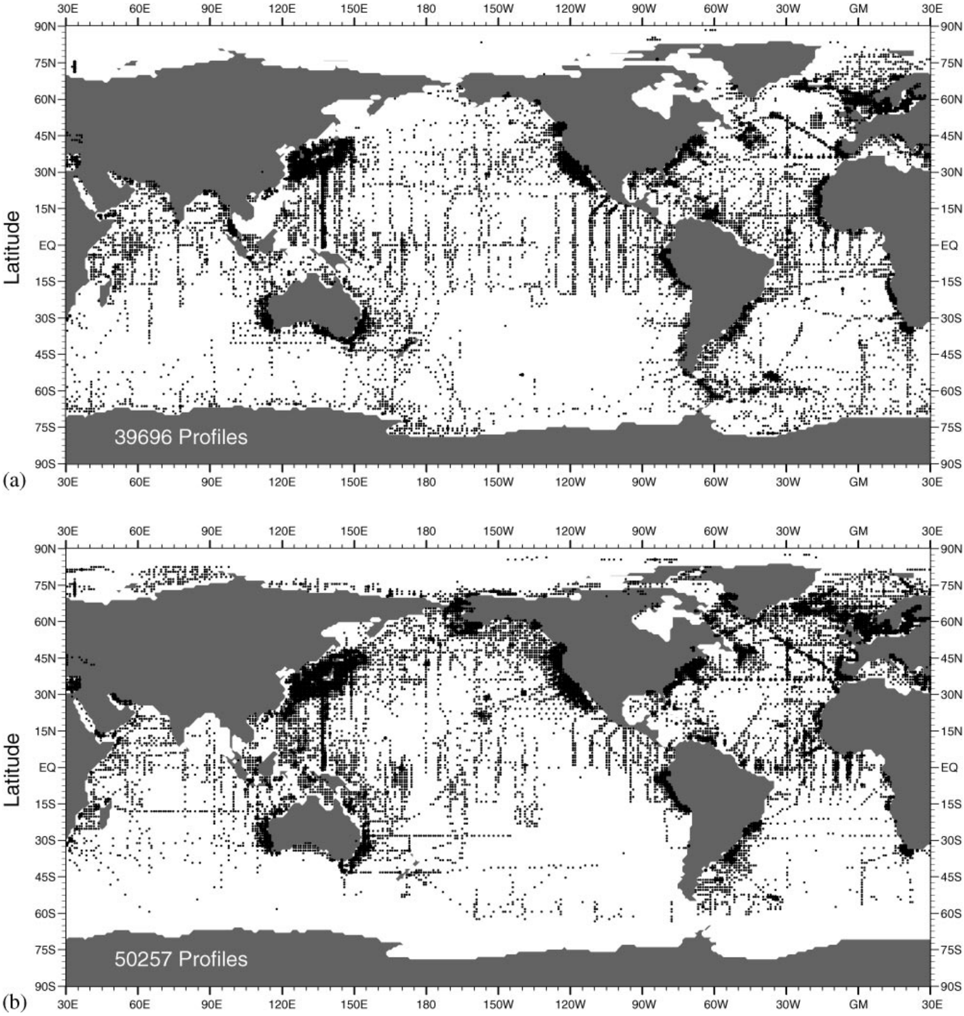

Fig. 2. (a) Winter (Jan.–Mar.) distribution of phosphate observations at the sea surface. (b) Summer (Jul.–Sep.) distribution of phosphate observations at the sea surface.

methods (Levitus and Boyer, 1994). Briefly, all data at a standard level are first zonally averaged in each one-degree latitude belt by individual ocean basin to provide the first-guess field for the annual analysis at the standard depth levels. The annual analysis at each level is then used as the first-guess field for a seasonal analysis at that level. The annual analysis is then recomputed from the four seasonal analyses and used as the first guess for the final seasonal analyses. In areas where the data coverage is sparse, the analyzed field is the first-guess field (e.g. the all-data annual mean value). This procedure results in smoother seasonal means and reduces the amount of bias due to lack of geographic or seasonal coverage, since these areas will not contribute to the statistical signal of the annual phosphate cycle (Levitus, 1984). A gridpoint for which less than four one-degree square observations contributed to the analyzed value at the gridpoint is indicated by an "x" in all figures. Zonal averages are then computed for the winter minus the summer period in the upper 400 m. Phosphate concentrations are expressed as μM, since most historical nutrient data are reported in this unit.

2.2. Biases in the analyses of historical data

Biases may be introduced into the analysis of historical data due to differences in measurement techniques used over time, lack of representative spatial and temporal coverage of available data, and biases introduced by the choice of analysis.

Historically, nutrients have been measured manually using spectrophotometric methods such as those described by Strickland and Parsons (1972). These methods have generally been replaced by automated methods such as the Technicon Autoanalyzer (Technicon Industrial Methods, 1969). A major concern is whether data collected using manual versus automated methods can be combined into one coherent data set as is the case in this data set. Comparison studies between automated and manual methods show that results from both methods are within experimental deviations (Airey and Sandars, 1987; Berberian and Barcelona, 1979), except at low concentrations (<0.5 μM), where there is a loss of sensitivity in the automated methods. Berberian and Barcelona (1979) conclude the advantage of the Auto-Analyzer methods (economy and speed of sample) make up for the loss of sensitivity in low concentration areas.

3. Results and discussion

3.1. Basin-scale seasonal distribution of phosphate

A general overview of the seasonal distribution of phosphate is provided by examining area-weighted basin mean concentrations in winter and summer in the major ocean basins excluding the Arctic and Southern Oceans (Fig. 3). Means and standard deviations are shown for winter and summer.

Generally, phosphate concentrations are depressed in the season of highest primary production: winter (Jan.–Mar.) in the Southern Hemisphere and summer (Jul.–Sep.) in the Northern Hemisphere (Fig. 3), in conformance with phosphate's role as a critical nutrient. The differences from winter to summer can be very large: about twice as much phosphate is found in the sub-polar North Atlantic and North Pacific in winter than in summer. Temperate and equatorial regions typically exhibit much less seasonal variability on basin scales than the sub-polar regions. These observations generally conform to conclusions reached in past studies (Takahashi et al., 1993; Vaccaro, 1963; Armstrong and Butler, 1962; Ketchum et al., 1958).

In the sub-polar North Pacific Ocean, surface phosphate mean concentrations range from a maximum winter value of 1.44 μM to a minimum of 0.76 μM in the

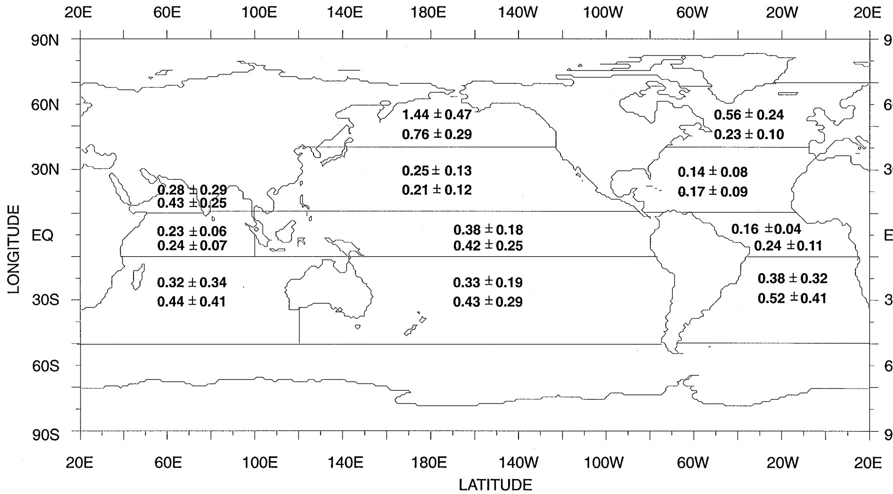

Fig. 3. Surface phosphate winter and summer means and standard deviations. Top numbers are mean values and standard deviations for winter, bottom numbers for summer. Coastal regions are excluded.

summer (Fig. 3). Summer phosphate values are reduced almost by half as primary production reaches its peak with prevalent solar energy and with the formation of the seasonal thermocline, which reduces the upward supply of nutrients to surface waters. The availability of phosphate in winter is due to light limitation of phytoplankton and mixed layer deepening resulting from increased vertical mixing.

Phosphate concentrations are also highest in the sub-polar North Atlantic Ocean during the winter months, 0.56 μM (Fig. 3), with a minimum occurring in summer (0.23 μM), for similar reasons as for the sub-polar North Pacific. However, maximum and minimum values for the sub-polar North Atlantic are two to more than three times lower than those for the sub-polar North Pacific. The general circulation of the world ocean leads to a surface depletion of nutrients in the North Atlantic due to export of nutrients via deep water, and a surface enrichment of nutrients in the North Pacific, due to input of nutrient-rich deep waters (Broecker and Li, 1970).

In the temperate North Pacific, phosphate distributions generally follow the same seasonal cycle as the sub-polar North Pacific, with higher values in winter than summer. In contrast, the North Atlantic central gyre has a maximum phosphate mean during the summer (0.17 μM). These results are puzzling since, if any seasonal differences were to be present, a summer minimum would be expected. Statistical analysis of the data (z-test, or student's t-test for large samples) shows that for most of the North Atlantic, or even the entire Northern Hemisphere, the seasonal differences are significant (Fig. 4). We suggest an explanation for the North Atlantic variability in Section 3.2. Summer phosphate levels are about the same in the temperate North Pacific and Atlantic, but the North Pacific mean is nearly twice the level of the North Atlantic in winter.

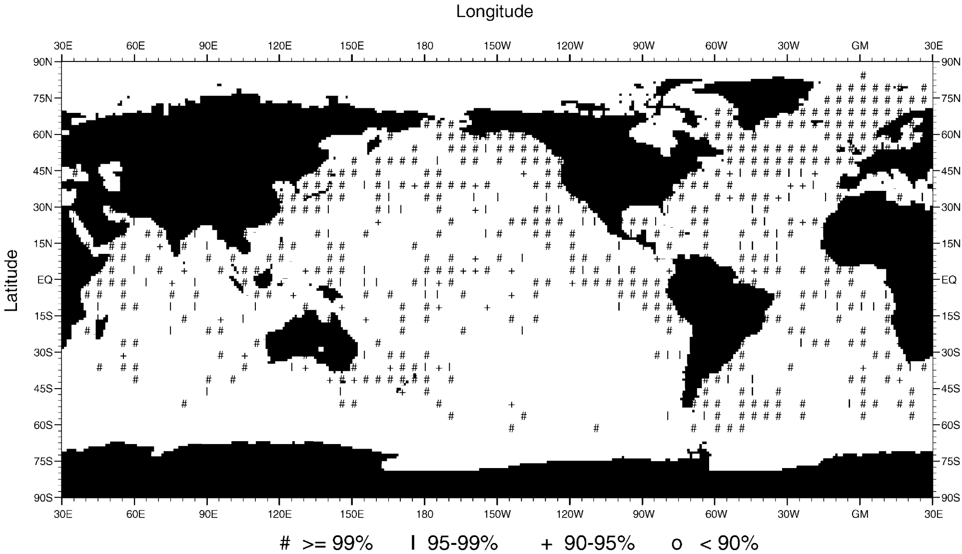

Fig. 4. Statistical significance of winter minus summer phosphate differences by five-degree squares at the sea surface. Levels of confidence are denoted by the symbols shown.

The seasonal distribution of phosphate in the North Indian Ocean shows much higher values in the summer than the winter (Fig. 3). This is probably a result of the circulation change during the summer monsoon season. In the North Indian Ocean, phosphate basin mean values increase from 0.28 μM in the winter to 0.43 μM in the summer (Fig. 3). Increased concentrations of chlorophyll have been observed along the western Arabian Sea and Somali coast during the summer (Brock et al., 1991; Banse and McClain, 1986; Smith and Codispoti, 1979). The increase in phosphate, observed during the summer months, marks the beginning of the southwest Monsoon, which causes upwelling in the Arabian Sea and along the eastern coast of India (Pant, 1992). A high rate of phosphate supply to surface waters by upwelling supports the enhanced productivity during the southwest monsoon (Yentsch and Phinney, 1992). By the fall, concentrations decrease to 0.71 μM (Conkright et al., 1994c). In addition, maximum freshwater discharge from the Ganges and Brahmaputra Rivers into the Bay of Bengal occurs during the monsoon period (Rao, 1975), and increased nutrients such as phosphate and nitrate are added to the region (Kumar et al., 1992).

Except in the Atlantic Ocean, the seasonal signal in the tropical oceans is small (Fig. 3), as observed with the present database. The classic spring bloom, summer stratification, fall bloom, winter mixed-layer deepening pattern, which drives the seasonal variability of phosphate in temperate and high latitude regions, does not apply to the tropical ocean. Instead, circulation patterns associated with Earth rotation and consequent equatorial upwelling, and coastal upwelling resulting from persistent winds, dominate. In addition, the ecliptic plane is centered about this region, resulting in reduced seasonal variability in the solar energy necessary for photosynthesis and nutrient uptake. Factors affecting seasonal variability in these regions may be associated largely with the Inter-Tropical Convergence Zone (ITCZ), which affects cloud cover and precipitation patterns (Mann and Lazier, 1991). A shift of the ITCZ northward (to about 5°N) from August to October leads to a wet season over much of the region (Etter et al., 1987). In fact, this process most likely determines the substantial seasonal signal observed in the tropical Atlantic, which varies from 0.16 μM phosphate in the winter to 0.24 μM in the summer (Fig. 3). Summer in this analysis corresponds to the wet season in the Amazon rain forest, which produces increased outflow from the Amazon and Orinoco rivers. Low salinity water, from the Amazon river, is transported northwest into the Caribbean (Muller-Karger et al., 1988; Frolic et al., 1978) as it is entrained in the Guinea Current system (Metcalfe, 1968). As it travels from east to west there is additional input from the Orinoco River. Riverine outflow into the Caribbean would account for the higher summer phosphate concentrations observed in the temperate region of the North Atlantic (Fig. 3). During the summer, the North Equatorial Counter Current is formed, which diverts some of the Amazon River outflow eastward (Lent, 1995; Muller-Karger et al., 1989). The effect of the ITCZ is not evident in the tropical Pacific due to the absence of major rivers in this area.

All three temperate Southern Hemisphere basins follow the typical pattern of maximum phosphate concentrations in the Northern summer (Jul.–Sep.) and minima in the winter (Jan.–Mar.) (Fig. 3). The variability is somewhat larger than observed in the temperate basins in the Northern Hemisphere, however, except for the Indian Ocean. It is more difficult to ascertain actual seasonal variability in the Southern Hemisphere, for which there are substantially less data in the NODC/WDC-A archives. Standard deviations and statistical analysis are indicative of the paucity of data in these regions (Fig. 4). Whereas most of the Northern Hemisphere and tropical regions exhibit statistically significant differences between winter and summer concentrations, less confidence exists in the Southern Hemisphere, due to relatively poor sampling.

3.2. General features of the seasonal distribution of phosphate

Winter and summer distributions of phosphate (Fig. 5) generally show agreement with the distribution of oceanic primary production. Large concentrations are present at high latitudes, upwelling regions, and river mouths, whereas low concentrations dominate the mid-latitudes. These general distribution patterns agree with annual distributions (Conkright et al., 1994a; Levitus et al., 1993) and with other observations of phosphate (Takahashi et al., 1993; Kamykowski and Zentara, 1977; Anderson et al., 1969; Reid, 1962). The large concentrations in upwelling areas and river mouths are due to physical processes that inject phosphate into the surface waters. Large concentrations in the high latitudes are due to the seasonal cycle involving light limitation of photosynthesis, warm season stratification, and changes in vertical mixing. The low concentrations at mid-latitudes are associated with the subtropical anticyclonic gyre systems, where semi-permanent stratification and downwelling exist, restricting input of new nutrients into the euphotic zone. This produces regions that are the least

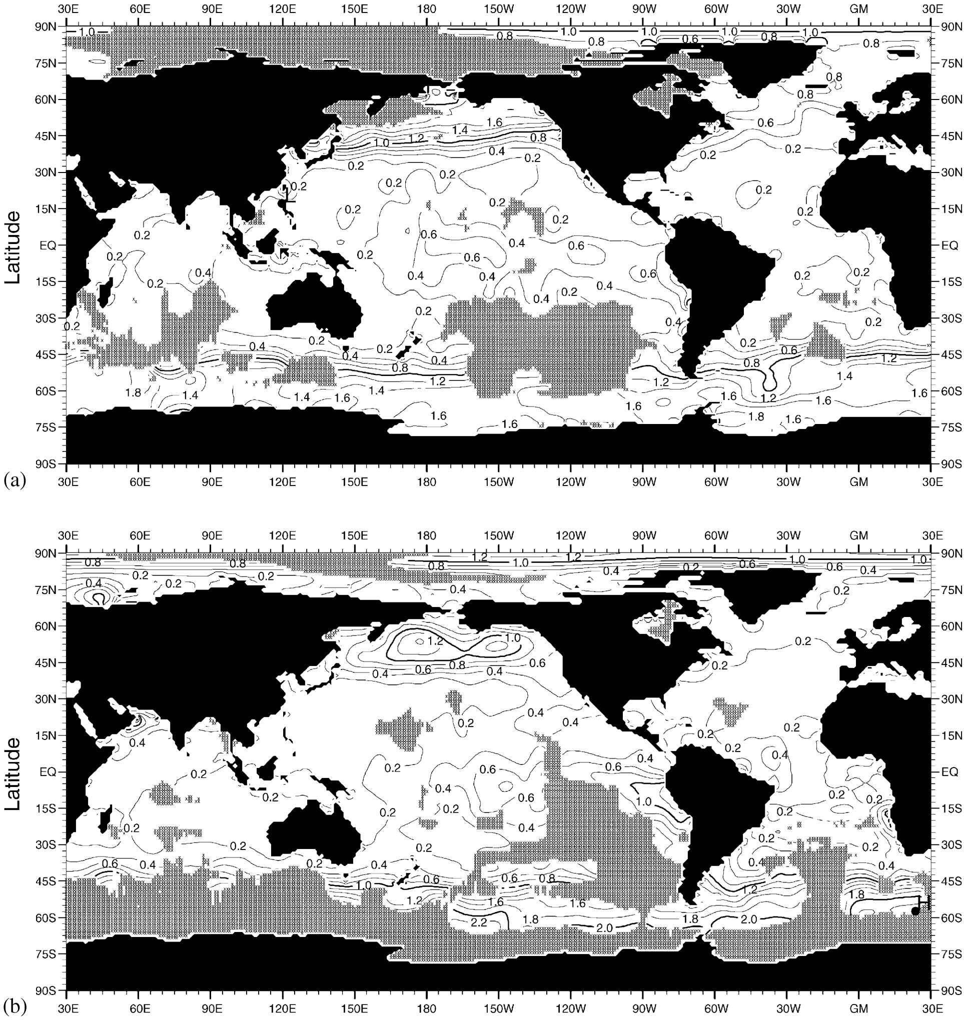

Fig. 5. Surface seasonal mean phosphate (μM) fields are shown in Fig. 5a for Winter (Jan.–Mar.) and Fig. 5b for Summer (Jul.–Sep.).

productive waters in the world (Blackburn, 1981). An exception is the large tongue of 0.4 μM phosphate that extends from the Baja California coast well out into the central North Pacific, to nearly 150°W longitude in the summer. This feature is found in sub-surface analyses as well and appears to correspond to the return of flow from the California current into the North Equatorial Current, simultaneous with the convergence of a northward extension of the Equatorial Counter-Current in the summer (Neumann and Pierson, 1966; Sverdrup et al., 1942). This suggests the cause of this feature is related to the summer ocean circulation, producing input of phosphate into the surface layer. The feature has no correlation with previously observed Coastal

Zone Color Scanner (CZCS) pigment (e.g., Feldman et al., 1989), suggesting that primary production here is limited by other variables.

Seasonal variability in phosphate also corresponds with seasonal changes in primary production and is clearly depicted in Fig. 5. High concentrations in the North Atlantic and Pacific in the winter result from light limitation of phytoplankton growth and mixed layer deepening. Reduced concentrations occur in summer due to utilization by primary producers. Similar, but seasonally reversed, patterns exist in the Antarctic.

Not only the magnitude of phosphate concentrations, but also the pattern of concentration exhibit a seasonal change in the sub-polar North Pacific as reflected by the pattern of the isolines. Isolines run mainly east to west during the winter months. In the summer there are two sets of well defined closed contours bounded in the north by the Alaska current and Aleutian islands. The change in isoline pattern may be related to circulation changes. The North Pacific is dominated by cyclonic circulation in the Gulf of Alaska, Bering Sea and Sea of Okhotsk (Tchernia, 1980). Such zones are characteristically high in nutrients (Anderson et al., 1969; Reid, 1962).

Upwelling areas, such as offshore regions of Peru, California, and Cape Blanc (northwest Africa) and the Benguela system off southwest Africa also show variability between winter and summer phosphate values (Fig. 5). Intensification of the trade winds during the summer months (May–October) (Tchernia, 1980) can influence the magnitude of upwelling and therefore the surface phosphate concentrations. In the Peru region, strong upwelling during the northern summer (Jul.–Sep.) is illustrated by a broader, more distinct, zonal extent of the tongue of high phosphate concentrations. Stronger upwelling in the summer (Jul.–Sep.) is associated with the southern extension of the Equatorial Undercurrent and increased winds (Zuta et al., 1978). Intensification of upwelling leads to an increase in productivity reaching a peak in late summer (Vinogradov, 1981). The difference between winter and summer phosphate values in this region is as high as 0.4 μM. Phosphate concentrations in the upwelled waters in the Benguela system are also greater during the summer months (the season of reduced production) (Fig. 5).

The seasonal influence of the Amazon and Orinoco Rivers is clearly apparent. A large plume of 0.2 μM phosphate concentrations extends from the river mouths northward to 15°N and 30°W (Fig. 5) in summer but is nearly absent in winter. The reason for the summer enhancement of phosphate in the temperate North Atlantic could be that normal summer drawdown of phosphate in the center of the gyre is compensated by the Amazon/Orinoco river plume, which extends well into the domain of the North Atlantic gyre region. Surface winter and summer salinities for this region (presented in Fig. 6) show a freshening of the waters during the summer due to an increase in the outflow from these rivers. Fig. 6 shows lower salinities extending past 15°N into the North Atlantic basin. Mixed layer depths (based on sigma-*t* criterion) for this region show a shoaling during the summer months extending to about 15°N (Monterey and Levitus, 1997). Thus, the temperate North Atlantic is in fact operating according to expected seasonal cycles of primary production, but the influence of large amounts of phosphate from the South American rivers is obscuring the effect. The extent of the influence of the riverine input of phosphate is large in both

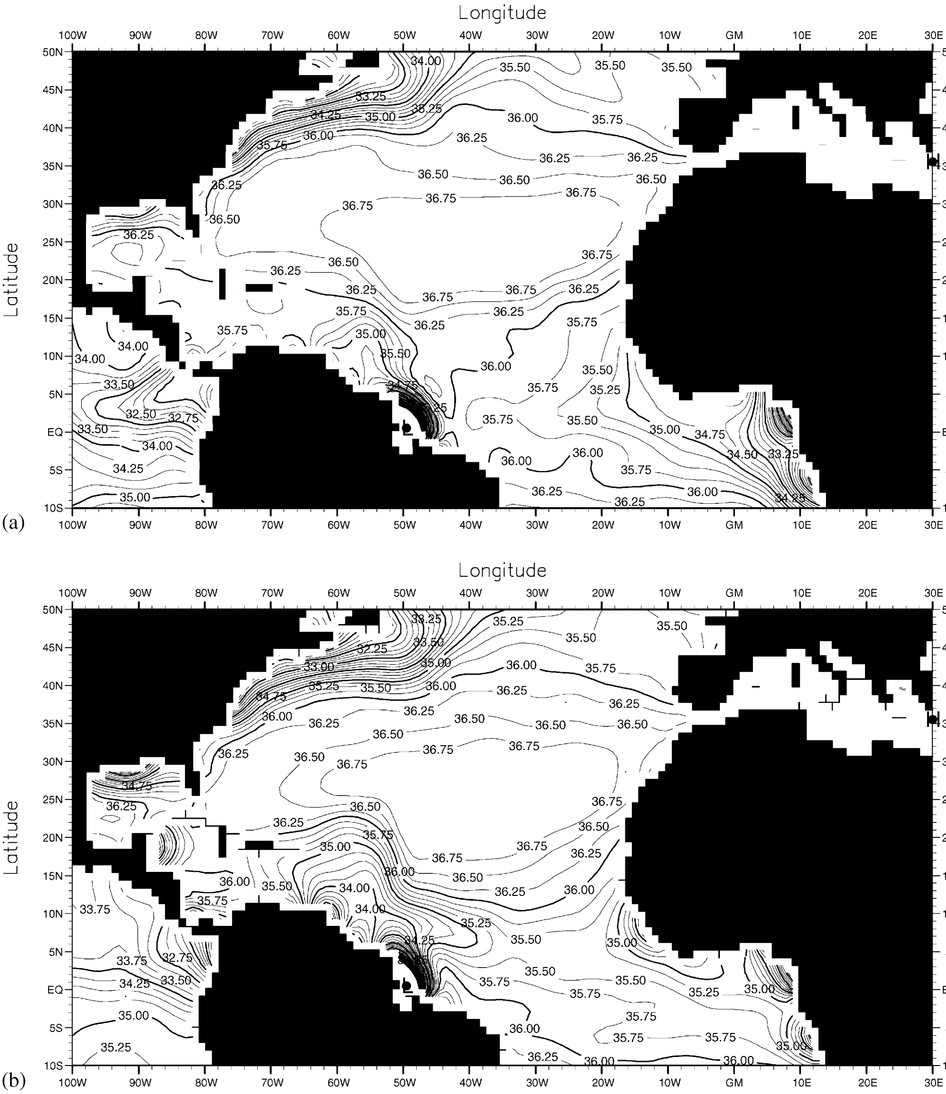

Fig. 6. Surface seasonal mean salinity fields are shown in Fig. 6a for Winter (Jan.–Mar.) and Fig. 6b for Summer (Jul.–Sep.) in the North Atlantic Ocean.

magnitude and domain, serving to obscure the normal seasonal cycle of the central Atlantic gyre, at least with the areal definitions customarily used. These results do not support previous findings by Ryther et al. (1967), who found the outflow from the Amazon River to be rich in silicate but low in nitrate and phosphate. The input of Orinoco River outflow into the Caribbean was used to explain seasonal variability observed in remotely sensed phytoplankton populations (Muller-Karger et al., 1989).

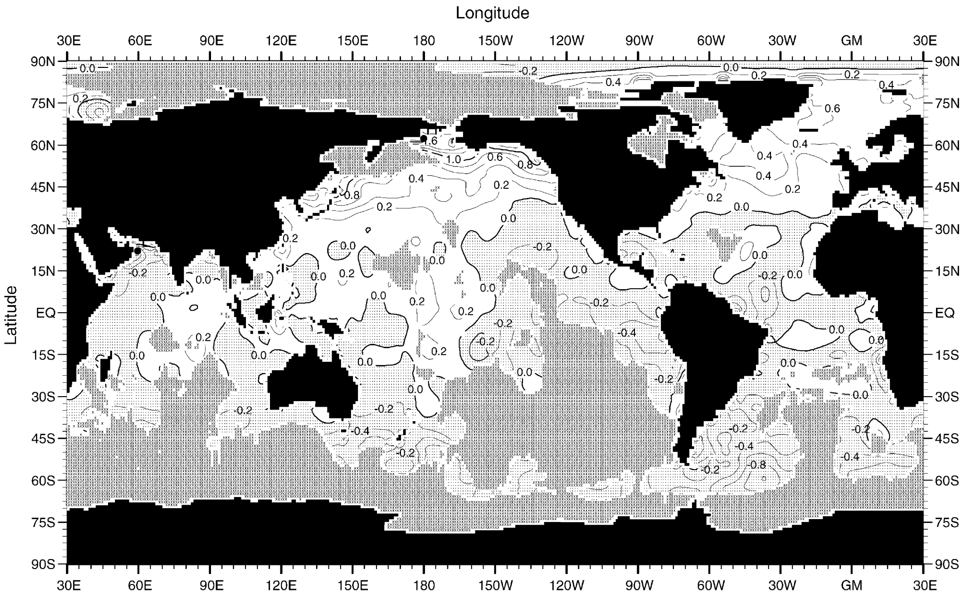

Fig. 7. Winter (Jan.–Mar.) minus Summer (Jul.–Sep.) differences in phosphate. Stippled areas represent negative values (e.g. summer values are greater than the winter mean values).

Seasonal distributions are emphasized by subtracting winter and summer mean concentrations from each other (Fig. 7). Positive seasonal phosphate differences (e.g., higher concentrations in winter than summer) are observed primarily in the temperate and high latitudes of the North Pacific and North Atlantic basins. The reverse is observed through most of the Southern Hemisphere. The greatest concentration difference is observed in the sub-polar North Pacific. Around 35°N is the transition from waters with low phosphate content (associated with the central gyres) to waters with high phosphate content in the northern North Pacific. It is north of this latitude where the largest winter minus summer differences occur on basin scales. Upwelling regions along eastern boundary currents in the Northern Hemisphere have positive phosphate differences (i.e. Cape Blanc in Africa and the California coast); upwelling areas in the Southern Hemisphere (i.e. Peru and SW Africa) have negative phosphate differences. Negative differences are also found in high southern latitudes and in the western Indian Ocean. In general, the eastern basin of the Pacific Ocean contains higher phosphate concentrations during both the winter and summer seasons.

Fig. 7 also shows that subtropical and temperate Pacific and Atlantic phosphate values do not deviate much throughout the year (with the exception of coastal upwelling areas). Typical mean values are $\leqslant 0.2$ μM (Fig. 5) for both basins. These regions are dominated by anticyclonic gyres, which characteristically are low in nutrients (Reid et al., 1978). In the North Pacific central gyre, the absence of deep winter mixing, and therefore reduced upward transport of nutrients, leads to uniform plankton biomass and productivity throughout the year (Hayward et al., 1983;

McGowan and Hayward, 1978) and a lack of a marked seasonal signal in pigment concentrations as observed from CZCS satellite images (Banse and English, 1994).

3.3. Seasonal cycle of zonal mean phosphate

3.3.1. Pacific Ocean

The seasonal cycle of zonal mean phosphate, as a function of depth, is described by examining difference plots of winter minus summer (Fig. 8). The largest range of surface phosphate concentrations is found in the Pacific Ocean north of 35°N. There is an enrichment of phosphate in the winter relative to summer values in the entire upper 400 m north of 45°N. A distinct sub-surface plume of negative difference (higher values in the summer) can be seen between 15°N and 45°N. Generally, phosphate is depleted in the upper 50 m in the Northern Hemisphere in summer as phosphate is utilized by phytoplankton. Concentrations increase below 50 m depth as phosphate is regenerated, but there is little seasonal variability apparent except north of about 45°N. Summer enrichment occurs in the surface layers south of 45°S as a result of similar dynamics.

3.3.2. Atlantic Ocean

In the North Atlantic, there is winter enrichment of phosphate north of 40°N, but the difference is not as large as in the North Pacific (Fig. 8b). A subsurface winter minimum is also observed below 75 m depth and between 65°N and 75°N. As in the Pacific, summer enrichment occurs in the South Atlantic, but the seasonal difference is larger and more widespread. Note especially the winter/summer difference between the equator and 15°N. Sub-surface seasonal variability in the Atlantic is overall much more complex than in the Pacific at nearly all latitudes (Fig. 8).

3.3.3. Indian Ocean

The maximum range of phosphate values in the Indian Ocean is north of 15°N. Fig. 8c shows depletion of phosphate is typical during the winter months north of the Equator from the surface to 400 m depth. Sub-surface winter enrichment occurs in the Indian Ocean centered at about 12°S. This is about 5° further south than a similar feature in the South Atlantic. Southern Indian Ocean patterns are generally similar to the Southern Ocean patterns of the Pacific and Atlantic Oceans.

3.3.4. Depth of penetration of the seasonal cycle

The zonal seasonal-difference plots can also indicate the depth at which the seasonal signal extends. In the Pacific Ocean, phosphate winter and summer values converge at about 50–75 m depth in the North Pacific south of 45°N but extend to 400 m depth north of this latitude. In the Atlantic Ocean, winter and summer mean values converge at a shallower depth in the North Atlantic (50–75 m depth), compared to 125–150 m or deeper in the South Atlantic. Significant sub-surface summer enrichment of phosphate occurs as deep as 400 m between 45°S and 65°S. Below 75 m depth in the North Atlantic, summer concentrations are higher than winter values. This reversal in the magnitude of the phosphate signal is not observed in the South

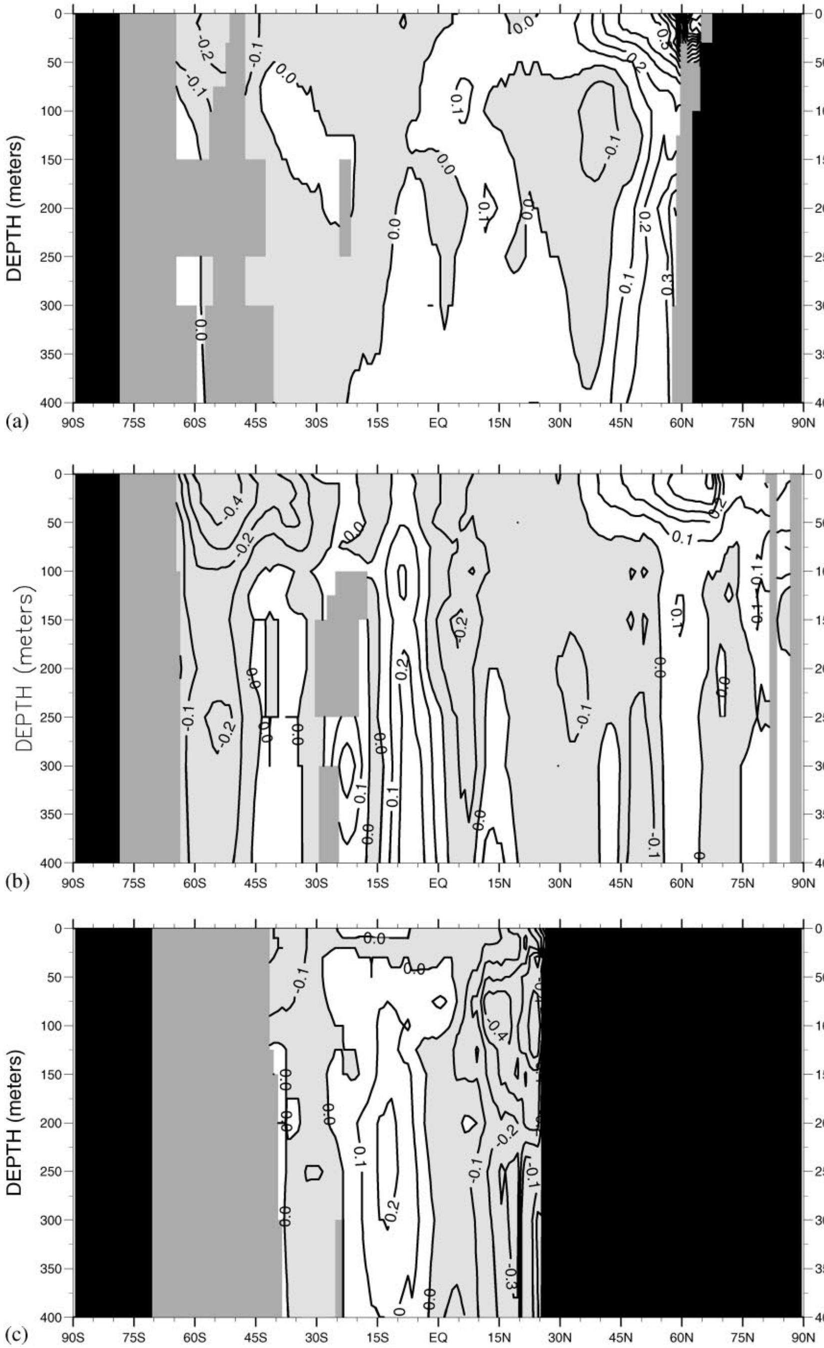

Fig. 8. Zonal mean phosphate distributions as a function of depth, expressed as Winter minus Summer for the Pacific Ocean (8a), Atlantic Ocean (8b), and Indian Ocean (8c).

Atlantic. The seasonal signal in the Indian Ocean extends from the surface to 400 m (Fig. 8c). The surface waters of the Indian Ocean appear to have little seasonal variability between 15°N and 30°S, but there is a considerable seasonal signal in the sub-surface waters.

4. Conclusions

The seasonal cycle of phosphate in the extra-tropics generally follows the expected pattern of high concentration during the winter, due to light limitation of phytoplankton growth and a deepening of the mixed layer. Lower values occur during the summer as phosphate is utilized by primary producers. This pattern in distribution is evident in the temperate and sub-polar oceans. Surface waters in the North Pacific subpolar latitudes are about twice those observed in the summer. Winter surface values at these latitudes in the North Atlantic are also about twice the summer phosphate values but are half the values at similar latitudes in the North Pacific. The depletion of phosphate during the summer extends to 50 m depth in both basins.

Seasonal variability is also observed in the North Indian Ocean and can be related to the onset of the monsoons and the generation of coastal upwelling during the summer months. Also, as a result of increased precipitation, greater outflow from the Ganges and Brahmaputra Rivers pumps additional phosphate into the Bay of Bengal. A similar situation is observed in the tropical Atlantic Ocean, where increased outflow from the Amazon and Orinoco rivers during the summer months results in higher phosphate concentrations during the summer than winter in this region. The effects of the outflow from these two rivers extends into the western North Atlantic gyre.

The distribution of phosphate in the oceanic central gyres remains relatively constant throughout the year. Variations in the seasonal phosphate concentrations occur in upwelling regions, such as off the coast of Peru and the Benguela, where the zonal extent of the upwelling area is broader in summer and fall.

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