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**Seasonal Patterns and Long-term Trends in an Estuarine Upwelling Ecosystem
(Ría de Vigo, NW Spain)**

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Thermohaline properties, nutrient salts, chlorophyll *a* and meteorological variables have been intensively monitored since February 1987 in the Ría de Vigo (NW Spain), in order to examine the temporal variability and the relationships between these variables over different time scales. In this paper, the seasonal and the long-term components of the 1987–92 time series are analysed. The seasonal changes in thermohaline properties are forced by meteorological factors, but whereas temperature shows a well-defined annual cycle, salinity presents a higher frequency variation pattern due to the influence of upwelling–downwelling events and runoff. Nutrient concentrations change in a regular way through the seasons, so that characteristic and well-defined cycles are observed, but they are different for each nutrient and, for a given nutrient, exhibit a marked contrast between surface and bottom layers. The seasonal changes of nutrients are not explainable by advection and water column processes alone; fractionation of nutrients during recycling and, presumably, sedimentary processes should also play an important role. The annual cycle of chlorophyll *a* shows a bimodal pattern, which corresponds with the development of the spring and autumn blooms; even though the seasonal cycle accounts for an important amount of the observed temporal variability, variation at lower time scales is also important. Long-term trends, as a change in the mean level of the analysed time series, have been observed for most of the variables. Salinity increased and temperature decreased both for surface and bottom series. The largest trend, in terms of the percentage to the observed variability it represents, was an increase in bottom salinity. In relation to nutrient salts, there was no evidence of increasing eutrophication, although surface dissolved inorganic nitrogen, and surface and bottom phosphate increased slightly. Chlorophyll *a* concentration showed a decreasing trend, especially at the surface. The observed long-term trends could be attributed to changes of the meteorological factors that operate through an increase in the estuarine residual circulation.

Keywords: seasonal cycles; long-term trends; remineralization; Ría de Vigo; NW Spain

Introduction

Estuaries are complex and very dynamic systems; their physical, chemical and biological properties show a sharp distributional gradient and large temporal variability (Lewis & Platt, 1982; Nixon & Pilson, 1983; Taylor & Howes, 1994). The cycle is the basic element of temporal organization in such systems (Platt & Denman, 1975).

Two broad types of periodic or organized behaviour can be distinguished. One of the classes depends on the non-linear properties of the system itself; the modes of behaviour are independent of the external conditions—free oscillations (Prigogine & Nicolis, 1971). A second type of periodic behaviour may result from periodicities in the supply of external energy, i.e. from periodic forcing, e.g. seasonal cycles.

Time series analysis allows the description of the temporal variability in an ecosystem. A complete description of the system would include a list of frequencies of all its dominant cycles and an estimation of their relative importance or magnitude (Platt & Denman, 1975). It is also necessary to find out those elements that can be considered as *deterministic* (Chatfield, 1992; Peña, 1992), which generally includes the seasonal cycle and the long-term variation.

The Galician Rías Baixas are four coastal embayments in the NW Iberian Peninsula. Hydrodynamically, they behave as partially mixed estuaries (Bowden, 1975; Beer, 1983). In the Galician rías, in addition to the boundary conditions that usually determine the patterns of circulation in estuarine systems, an additional factor must be taken into account; the coastal upwelling, as a consequence of the wind regime over the adjacent shelf, induces the inflow of subsurface oceanic Eastern North Atlantic Central Water (ENAW) into the rías, having a major influence on their hydrography (Blanton *et al.*, 1987; Prego & Fraga, 1992; Álvarez-Salgado *et al.*, 1993).

During upwelling events and as a consequence of the circulation pattern, part of the biomass which is produced inside the rías is transported offshore by the surface outgoing current. Part of this exported organic matter is remineralized either in the

water column or on the bottom of the continental shelf (Fraga, 1981), and therefore the incoming bottom current supplies the rías with not only new nutrients but also with remineralized nutrients through a feedback mechanism (Figueiras *et al.*, 1986; Álvarez-Salgado *et al.*, 1993). Consequently, nutrient trapping is enhanced in the rías due to the combined effect of coastal upwelling and of the two-layered positive residual circulation pattern.

This fertilizing process causes the Rías Baixas to be highly productive ecosystems; for the Ría de Vigo, mean annual values of net primary production are about $800 \text{ mg Cm}^{-2} \text{ day}^{-1}$ (Prego, 1994), and the maxima values, from spring to autumn, lie between 700 and $1800 \text{ mg Cm}^{-2} \text{ day}^{-1}$ (Vives & Fraga, 1961). When contrasted with those from other estuarine systems (Boynton *et al.*, 1982), these values exceed those given for different coastal embayments; if compared with river dominant systems, they are intermediate.

Since 1987, and following the UNESCO advice in order to maintain time series observations (Tabata, 1984), the Instituto de Investigaciones Mariñas keeps a fixed station in the Ría de Vigo (Stn. E3, Figure 1), sampled twice a week. The resulting hydrographic database (thermohaline properties, inorganic nutrients and chlorophyll *a* concentrations) is enlarged with a meteorological database (runoff in the drainage basin, components of the Ekman transport derived from geostrophic wind and incoming solar radiation).

This study aimed to: (1) estimate the level of variability associated to different time scales, i.e. the relative magnitude of the dominant modes of time variation; (2) establish the average seasonal cycle and the relationships between variables at this time scale; and (3) analyse the long-term trends and the possible mechanisms that link the inter-annual variability of the hydrographic variables to that observed for the meteorological ones.

Methods

Survey area

The Ría de Vigo (Figure 1) is located between 42°09' and 42°21'N, 8°36' and 8°54'W; it is the most meridional of the Rías Baixas. Its orientation follows approximately an axis, from head to mouth, ENE–WSW (~20° anticlockwise with the parallel). It can be divided into three zones according to the degree of continental or oceanic influence. The innermost zone includes San Simón bay and shows the characteristics of a typical estuary, due to the effects of tides (~3 m of averaged tidal range) and to the influence of the Verdugo river mouth (Pérez *et al.*, 1992). This river is the main tributary of freshwater, with a mean annual flow of $13 \text{ m}^3 \text{ s}^{-1}$ (Ríos *et al.*, 1992a). The middle zone, which spreads from the Estreito de Rande to Cabo de Mar, is under the influence of both continental and oceanic contributions. Finally, the outer zone, which is under dominant oceanic influence, includes the area lying between Cabo de Mar and the Cíes islands. The Ría de Vigo is connected with the ocean by means of two mouths; the Northern mouth, about 2.5 km wide and 23 m deep, and the Southern mouth, 5 km wide and 52 m of maximum depth.

The surface:volume ratio is 0.05, typical of v-shaped basin systems that gradually deepen and widen towards the mouth, thus favouring export (Odum *et al.*, 1979). In the innermost zone, this ratio is 0.40, more like in a typical estuarine system.

Sampling and analysis

The fixed station (Stn. E3, Figure 1) is located in the main channel (45 m depth in low water) in the middle zone of the ría, 42°14.5'N, 8°45.8'W. Its position makes it suitable for evaluating and averaging the main processes that take place in the system due to changes in the external forcing factors (Ríos, 1992; Figueiras *et al.*, 1994).

Samples were taken twice weekly at depths of 1 and 40 m, with 5 l PVC Niskin bottles provided with Watanabe rotating thermometer frames for temperature and depth control. The data set shown here comes from a 6-year period, from February 1987 to January 1993. Since the sampling interval is 3–4 days, the sampling-frequency-induced errors in computed seasonal cycles begin to approach the limit of the analytical methods (Taylor & Howes, 1994).

Salinity was calculated from conductivity measurements with an Autosal 8400A (UNESCO, 1983). Nutrient salt concentrations were determined with a Technicon AutoAnalyser AAII, according to Grasshoff *et al.* (1983), with some modifications (Mouriño & Fraga, 1985; Álvarez-Salgado *et al.*, 1992). Chlorophyll *a* concentrations were estimated from fluorescence determinations with a Turner Designs 10 000 R fluorometer; the maximum *in vivo* fluorescence was measured after the addition of a saturated solution of DCMU [3-(3,4-Dichlorophenyl)-1,1-dimethylurea] to the sample, which had previously been kept in darkness for 20 min at room temperature (Falkowski & Kiefer, 1985).

The components of the Ekman's transport were supplied for the Instituto Español de Oceanografía (Vigo); they were obtained from geostrophic wind calculations (Bakun, 1973) for a point located at 43°N, 11°W. The cross-shore, q_x , and the along-shore, q_y , components have been rotated 20° anti-clockwise here, so that they result, respectively, parallel and perpendicular to the main axis of the Ría de Vigo.

The runoff in the drainage basin up to Stn. E3 (~480 km²), Q_r , was estimated as a function of precipitation by using the equation given by Ríos *et al.* (1992a). The precipitation values monitored by the Instituto Nacional de Meteorología at the meteorological station in Peinador airport, located approximately 10 km away from the Stn. E3, 200 m above sea level, in the middle of the catchment area, were used in the present study. The incoming solar radiation, Q_s , was estimated by Mosby's formula (Dietrich *et al.*, 1980).

Data management

In order to analyse the temporal variability, the time series were subjected to a smoothing procedure (Chatfield, 1992), carried out in several stages and represented in Figure 2. The rough time series (S_0 in Figure 2) were first checked and purged; those data with a stationary residual, i.e. deseasonalized and detrended residual (R in Figure 2), out of the range $\pm 3s_R$ (where s_R is the standard deviation of the correspondent stationary residual time series) were removed. By following this procedure, approximately 1% of the rough data was eliminated. Besides, the rough time series contain some gaps, 12% on average for each variable, due to bad weather conditions.

The gaps were filled using linear interpolation. Table 1 shows some basic statistics for the purged and filled time series (S_0' in Figure 2). Spectral analysis and the smoothing procedure were applied to the S_0 -time series. The percentage of variability of each variable at different time scales (Table 2) is also referred to the S_0' time series and mentioned in the text as the percentage of the observed variability.

Spectral analysis allows recognition of the fundamental modes of the ecosystem behaviour (Platt & Denman, 1975). The filters that must be applied to the time series to produce an output with emphasis on variation at particular frequencies can be derived from the spectrum (Chatfield, 1992). An example of the resulting spectrum applied to the S_0' time series is given in Figure 3, showing that the annual period and the long-term component are significant frequency modes of variation of the analysed time series.

Each filtering stage provides an output series which, following differentiation from the input series, results in a residual (R with different subscripts in Figure 2) containing the variability in correspondence to the window of the applied filter (Chatfield, 1992). In the present case, the variation below approximately 2 weeks from the S_0' time series has been removed by means of a symmetric nine-term moving average (9-MA) filter (Chatfield, 1992). This first stage of the smoothing procedure renders the S_1 time series. In the second stage, the S_1 time series of the previous stage was averaged fortnightly, and then the symmetric 9-MA filter was applied again, thus smoothing the fluctuations between 15 days and approximately 2 months (S_2 series). Finally, by simply averaging the S_2 time series for each fortnight, a smooth seasonal cycle (SSC) and its magnitude related to the S_0' time series was obtained. Figure 4, for example, shows the effect of the in-series filtering process applied to the bottom nitrate time series.

Long-term trends (T in Figure 2), as defined by Granger (1966), were tested with the non-parametric, seasonal Kendall's τ , which tests for long-term trends and differences in trends among different fortnights of the year (van Belle & Hughes, 1984). The method of Hirsch *et al.* (1982) was used to calculate the median rates that were statistically significant.

Results and discussion

Seasonal cycles

The relative magnitude of the SSC for each variable is given as a percentage in relation to the total variance of the purged and filled (S_0') time series (Table 1), and is shown in Table 2 in the SSC column.

Meteorological variables

The SSC of the incoming solar radiation (Q_s) [Figure 5(a)] accounts for *c.* 80% of the observed variability (Table 2). It is typical of middle latitudes; maximum and minimum values occur during the summer and winter solstices, with mean values of incoming solar radiation *c.* 650 and 200 cal cm⁻² day⁻¹, respectively.

The SSC of the other meteorological variables did not account for a high percentage of the observed variability. Thus, the annual runoff cycle (Q_r) [Figure 5(a)] accounts for about 15% of the observed variability. It is typical of a small catchment area (~589 km²), lying not very high above sea level (~200 m mean height) and under the influence of a maritime Mediterranean rain regime, with strong precipitations from autumn to spring (mean annual values of ~2500 mm year⁻¹) (Pérez *et al.*, 1992; Río Barja & Rodríguez, 1992). Since the end of October, when southerly winds are dominant, and for approximately 3 months, more than 30 m³ s⁻¹ flows into the ría by means of runoff. Maximum averaged values, over 35 m³ s⁻¹, occur during November. From February onwards, the runoff decreases; annual averaged minima, *c.* 5–10 m³ s⁻¹, occur during summertime.

The SSCs for the Ekman's transport components, q_x and q_y [Figure 5(b)], show a strong correlation ($r = -0.96$, $P < 0.001$); both the SSC of q_x and q_y account for about 10% of total variability. The cross-shore component, q_x , ranges, on average, from -0.50 to 0.50 m² s⁻¹. Two contrasting periods were observed throughout the year; from November to February, this component is directed towards the coast (positive values), thus causing downwelling which is extreme during December and January. For the rest of the year, the opposite situation occurs, causing upwelling (negative values) (Fraga, 1981; Blanton *et al.*, 1987; Álvarez-Salgado *et al.*, 1993). Seaward transport intensifies from April to

September; the absolute averaged values exceed $0.25 \text{ m}^2 \text{ s}^{-1}$, and extreme values occur from July to September.

The along-shore component, qy , shows a wider range of variation, *c.* -1.00 – $0.25 \text{ m}^2 \text{ s}^{-1}$. Negative values indicate a southward transport of the Ekman layer. Most of the year, from May to October, this situation predominates. Northward transport increases from the end of November to February (more than $0.50 \text{ m}^2 \text{ s}^{-1}$). The averaged maximum, *c.* $1.00 \text{ m}^2 \text{ s}^{-1}$, occurs during December and January. From May to the end of September, it is directed southwards, with the mean extreme values, *c.* $-0.3 \text{ m}^2 \text{ s}^{-1}$, being recorded from July to September.

The annual wind regime can be inferred from the seasonal cycles of the Ekman's transport components. Three different situations could be distinguished: (1) from October to February, when the wind is mostly S–SW; (2) from March to April, with W–NW winds; and (3) from May to September, with N–NE and N–NW winds predominating. According to the orientation of the Ría de Vigo, the last regime of winds, with its characteristic north component, is the most favourable for the coastal upwelling into the ría.

The seasonal cycles for each meteorological variable show a marked relationship, resulting in high values of the determination coefficients; all values between $r^2=0.76$ for Qr vs. qx and $r^2=0.96$ for Qs vs. qx . This seasonal coupling is mainly due to the seasonality in the relative position of the Greenland low pressure centre and the Azores high (McClain *et al.*, 1986; Blanton *et al.*, 1987), and also to the seasonal development of thermal lows over the Iberian peninsula (Fraga, 1991).

Thermohaline properties

The SSC for surface and bottom salinity accounts for a low percentage of the observed variability; 14 and 12%, respectively. The mean annual evolution is similar at both depths ($r=0.97$, $P<0.001$), but the range of variation at the surface is greater than in the bottom layer [Figure 6(a)]. The lowest averaged salinity values occur from November to April, *c.* 33.30 for the surface and *c.* 35.45 for the bottom layer. From June to the end of September, averaged surface salinity is over 35.00, with maximum averaged values, *c.*

35.50, in August. For this period, the averaged bottom salinity is higher than 35.65; the maximum averaged value, 35.73 PSS, is also recorded in August.

The averaged values of surface temperature [Figure 6(b)] range between 13°C, from January to early May, and 18°C, during July and August. The SSC accounts for an important percentage (71%) of the observed thermal variability. The annual evolution of temperature at 40 m differs from that at surface temperature, accounting for 38% of the observed variability. The bottom temperature ranges, on average, between 13°C, from the end of May to August, and *c.* 14°C, from the end of September to January. The highest averaged values, *c.* 15°C, occur in November.

Such a different evolution determines the characteristic thermal structure of the water column. From November to early March, thermal inversion takes place, and the difference between surface and bottom temperature is *c.* -1°C on average during January and early February. The thermal inversion is maintained by a sharp halocline [Figure 6(a)]. From May onwards and after a short period of thermal homogeneity, thermocline develops, lasting until early October. The thermal gradient is maximum, *c.* 4°C, from June to September. Fluctuations in river discharge and wind mixing episodes, especially by means of upwelling–downwelling events, may impose an important source of short-term variability (Table 2) over the basic mixing–stability cycle (Simpson *et al.*, 1991). The short-term variability imposed by upwelling–downwelling cycles (Table 2) is of the order of 5–14 days (Blanton *et al.*, 1987; Álvarez-Salgado *et al.*, 1993).

There is a 1 month time lag between the SSC for surface temperature in relation to that for incoming solar radiation. The correlation between these cycles increased from $r=0.82$ ($P<0.001$) when they are in phase, to $r=0.98$ when the SSC of surface temperature is 1 month lagged. In the open ocean, at the same latitudes, this phase out is larger, over 2 months, and the averaged maximum of surface temperature is greater, *c.* 20°C (Pickard & Emery, 1990). The different phase out and amplitude are caused by increasing vertical velocities derived from strengthening coastal upwelling and the estuarine circulation pattern. The annually averaged velocity of net water ascent is in the Ría de Vigo on the order of 10^{-3} cm s⁻¹ (Prego *et al.*, 1990).

The TS diagrams summarize the annual evolution of the thermohaline properties. It can be seen that runoff ($r=-0.75$, $P<0.001$, for S_{sfc} vs. Qr) and incoming solar radiation are the main factors that control the annual evolution of thermohaline properties at the surface [Figure 6(c)]. By contrast, at the bottom layer [Figure 6(d)], the thermohaline properties are controlled mainly by the advection of subsurface oceanic water into the ría, due to the coastal upwelling which occurs from the end of February to September (Fraga, 1981). The average percentage of ENAW in the bottom samples can be calculated by the mixing triangle procedure. By taking the segment of ENAW that corresponds with ENAW_t (for subtropical origin), which is the water mass that upwells in the area (Ríos *et al.*, 1992b; Álvarez-Salgado *et al.*, 1993), the averaged percentage of ENAW_t during the upwelling season is about 88%, the rest being water from the surface. The highest average percentage of ENAW_t occurs during summer months, about 90%, and the lowest average percentage occurs at the beginning of winter, about 75%.

Nutrient salts and chlorophyll a

The SSCs for the inorganic forms of nitrogen at the surface are similar [Figure 7(a–c)], and explain 40–50% of the observed variability (Table 2). The correlation coefficient between nitrate and nitrite is $r=0.92$; slightly lower, $r=0.89$, between ammonium and nitrite, and even lower, $r=0.78$, between ammonium and nitrate ($P<0.001$). The ranges of variation are about 4, 0.6 and 7 $\mu\text{mol kg}^{-1}$ for ammonium, nitrite and nitrate, respectively. Maximum averaged values occur from the end of autumn to the beginning of spring; minimum averaged values take place, approximately, from May to September. Despite the similarities, some salient differences may be pointed out: (1) from January to the end of May, the normalized decreasing rates (fortnightly change normalized to the mean of the respective S_0 time series; Table 1) are -0.11, -0.17 and -0.23 fortnight^{-1} for ammonium, nitrite and nitrate, respectively; and (2) from May to the end of August, the averaged nitrate concentration tends to be exhausted, while that of ammonium and nitrite remain nearly constant, about 0.7 and 0.2 $\mu\text{mmol kg}^{-1}$, respectively. Since the averaged values in the SSCs of nutrient salt concentrations reveal the balance between sources and sinks of nutrients, e.g. net averaged values, and given that phytoplankton shows a preferent uptake of ammonium vs. nitrate (Dortch, 1990), the observed differences between ammonium and nitrate are likely to be due to

the shorter turnover time of the former, that has been estimated to be around 5 days (Wada & Hattori, 1991). The differences between the surface SSCs of the inorganic nitrogen forms become apparent from September onwards; the maximum nitrite level is lagged 1 month behind that of ammonium, and the maximum nitrate level is 2 months lagged. Although the nitrate phase out may be exaggerated by runoff, which has a $\text{NO}_3^-:\text{NH}_4^+$ ratio about 2.5 (Pérez *et al.*, 1992), this succession of maxima is due to the remineralization sequence: ammonium \rightarrow nitrite \rightarrow nitrate. This remineralization sequence has been observed in different marine environments (Spencer, 1975; Millero & Sohn, 1992). The percentage of each of the inorganic nitrogen species is related to the total dissolved inorganic nitrogen ($\text{DIN}=\text{NH}_4^++\text{NO}_2^-+\text{NO}_3^-$), strengthening the fact that the observed differences in the surface SSCs of the inorganic nitrogen forms are due to their fractionation during recycling. From January to August, the percentage of ammonium increases from 25 to 65% DIN, while that for nitrate decreases from 70 to 20% of DIN, showing that during this period, the recycling of nitrogen at the oxidation level of ammonium prevails. From September onwards, the situation changes; the percentage of ammonium decreases while that for nitrate increases, due to the nitrate contribution by runoff. The percentage of nitrite remains nearly constant, about 10% of DIN, as could be expected as it is in an intermediate state of oxidation.

The SSC for surface silicate [Figure 7(d)] accounts for approximately 30% of the observed variability. The averaged maximum concentration occurs during January. As for surface nitrate, the concentration decreases sharply from January onwards; from about $8 \mu\text{mol kg}^{-1}$ in February to nearly $2 \mu\text{mol kg}^{-1}$ 2 months later. From April to September, the mean concentration is about $2 \mu\text{mol kg}^{-1}$. For nitrate and silicate, the correlation between surface SSCs is high ($r=0.93$, $P<0.001$). From January to the end of May, when the first peak of biomass occurs, the normalized decreasing rate for surface silicate is the same as that for DIN, i.e. $-0.18 \text{ fortnight}^{-1}$, which is in accordance with the Redfield uptake ratio for diatoms, the dominating group of the phytoplankton community in spring. From late spring until late August, the averaged surface silicate concentration remained nearly constant, while that for nitrate still decreased. This different pattern is probably due to the shift in the phytoplankton community from diatoms towards dinoflagellates and small flagellates during summer and early autumn (Margalef *et al.*, 1955; Figueiras & Ríos, 1993).

At the surface, the mean annual evolution of phosphate concentration [Figure 7(e)] differs from those of the inorganic nitrogen species and silicate described above. From the end of October to January, the mean concentration changes from 0.75 to 0.60 $\mu\text{mol kg}^{-1}$. From January onwards, it decreases until May at a fortnightly medium rate of $-0.05 \mu\text{mol kg}^{-1}$, which is the lowest normalized decreasing rate for this period ($-0.07 \text{ fortnight}^{-1}$), thus suggesting the shortest turnover time of phosphate. From May onwards, and differing from the other nutrient salts, phosphate levels increase; the fortnightly medium rate is $0.03 \mu\text{mol kg}^{-1}$ until September, and about $0.10 \mu\text{mol kg}^{-1}$ during autumn. The averaged maximum concentration occurs at the end of October.

From spring to autumn, when phytoplankton biomass is higher (Figure 8), low DIN:phosphate ratios are typical of marine environments where nitrogen rather than phosphorus is more likely to limit production (Boynton *et al.*, 1982; Howarth, 1988). In the Ría de Vigo, when the concentration of DIN is nearly exhausted, the concentration of phosphate is, on average, over $0.35 \mu\text{mol kg}^{-1}$ [Figure 7(g)]. At the surface, the differences between nitrogen forms (and silicate) and phosphate concentrations sharpen during summer and autumn (DIN:phosphate ratio is *c.* 8 from late March to May, and *c.* 3 during summer, when it reaches its minimum value). The main biochemical mechanisms regulating nutrient limitation (Howarth, 1988; Vitousek & Howarth, 1991) are, for the Ría de Vigo, the ratios of nutrient inputs and the fractionation of nutrients during recycling. In summer, when the DIN:phosphate imbalance is more severe, the bulk of nutrient inputs to the ría is supplied by the subsurface oceanic water and by means of remineralization processes inside the ría, *c.* 70 and 25%, respectively (Prego, 1994). The DIN:phosphate ratio of the ENAW is between 15 and 17. When this subsurface water crosses the shelf and enters the ría, it is further enriched with remineralized nutrients (Fraga, 1981), and its DIN:phosphate ratio decreases, because both sedimentary and water column processes tend to reduce this ratio (Howarth, 1988). Besides, the averaged phosphate concentration in the sewage from the city of Vigo is about $130 \mu\text{mol kg}^{-1}$. (Pérez *et al.*, 1986), thus resulting in a very low DIN:phosphate ratio, around 0.6. The sewage flux into the ría is nearly constant, about $0.5 \text{ m}^3 \text{ s}^{-1}$ (Ríos, 1992). During the dry season, it represents a non-rejectable percentage of the freshwater contribution, and although during this period the nutrient inputs by means of freshwater supplies are scarce, *c.* 5% of the total nutrient inputs, this fact may partially explain the observed decrease in the DIN:phosphate ratio.

Phosphate, nitrate and ammonium enlarged the organic pool through the photosynthetic process [Figure 7(f)]. Inorganic nitrogen is diverted mainly towards the dissolved organic fraction (DON), *c.* 80% of the total organic nitrogen pool (Fraga, 1967). Assuming that during summer, the nutrient supply to the photic zone is through the upward flux of water from the bottom layer and that phytoplankton uptake follows Redfield's ratio, the average percentage of inorganic nitrogen which is diverted towards the organic nitrogen pool can be derived. The averaged bottom DIN and phosphate concentrations are, during summer, *c.* 9.5 and 0.8 $\mu\text{mol kg}^{-1}$, respectively. Considering that the averaged DIN:phosphate ratio for the phytoplankton of the Ría de Vigo is *c.* 17 (Ríos & Fraga, 1987), when all inorganic nitrogen is consumed, there would be *c.* 0.2 $\mu\text{mol kg}^{-1}$ of phosphate at the surface; since the averaged surface phosphate concentration is 0.4 $\mu\text{mol kg}^{-1}$, the phosphate surplus due to the hydrolysis of organic phosphorus is 0.2 $\mu\text{mol kg}^{-1}$. If remineralization of the organic nitrogen fraction took place following Redfield's ratio, the expected averaged DIN concentration at the surface would be *c.* 2.9 $\mu\text{mol kg}^{-1}$. Therefore, as the averaged DIN concentration at the surface is *c.* 1.3 $\mu\text{mol kg}^{-1}$, the averaged percentage of DIN diverted towards the organic fraction, mainly as DON, would be *c.* 55%, which means that the hydrolysed turnover rate for organic phosphorus is twice than that for remineralized DON. When the averaged surface nitrate concentration, *c.* 0.5 $\mu\text{mol kg}^{-1}$, alone is considered in the above calculations, the averaged percentage of DIN which is diverted towards DON reaches 80%; in this case, the time required for DON to be remineralized is five-fold that for hydrolysed organic phosphorus.

Since the turnover time of 50% of DON is around 11–16 days (Fraga & Vives, 1961), the organic nitrogen fraction [Figure 7(f)] is a substantial proportion of the total nitrogen (organic+inorganic). By contrast, the organic fraction of phosphorus is a low percentage of the total phosphorus [Figure 7(f)], as 30–66% of this pool is hydrolysed with a turnover time of 3–6 days (Garber, 1984). The different residence times of nitrogen and phosphorus in their respective organic compartments is the main factor that causes the distinct seasonal evolution pattern at the surface and thus the observed imbalance of the DIN: phosphate ratio [Figure 7(g)].

At the bottom, the SSCs of nutrient salts are very different from those at the surface. A common feature is that during winter and early spring, due to runoff inputs, averaged values are higher in the surface than in the bottom layer.

The mean annual evolution of ammonium at the bottom shows a bimodal pattern [Figure 7(a)]. The first peak occurs in June, *c.* $3 \mu\text{mol kg}^{-1}$; the second peak, 4 months later, is slightly higher. The mean lowest values, *c.* $1.5 \mu\text{mol kg}^{-1}$, are reached during February and March. During winter, the averaged surface concentration is *c.* $1 \mu\text{mol kg}^{-1}$ higher than in the bottom. When the SSC for bottom ammonium is lagged 1 month behind that for surface chlorophyll *a* (Figure 8), both variables show a high correlation ($r=0.93$, $P<0.001$, lag=2 weeks). This fact is related to phytoplankton sedimentation and its subsequent remineralization inside the ría, since ammonium is the first inorganic nitrogen form delivered from organic matter remineralization.

The SSC of nitrite in the bottom [Figure 7(b)] peaks firstly in August, *c.* $0.8 \mu\text{mol kg}^{-1}$. From the first peak onwards, the mean concentration decreases until October, and then peaks again. In December, its mean value is over $0.6 \mu\text{mol kg}^{-1}$; the mean lowest concentration is reached at the end of April.

From November to the end of May, the mean concentration of bottom nitrate [Figure 7(c)] remains *c.* $4 \mu\text{mol kg}^{-1}$. During these months, surface concentration is higher, *c.* $3 \mu\text{mol kg}^{-1}$ on average, than that at the bottom. By means of upwelling, hence forth for 2 months, the average bottom concentration increases at a fortnightly rate over $1 \mu\text{mol kg}^{-1}$. Mean values reach maximum as *c.* $7 \mu\text{mol kg}^{-1}$, from the end of June to the end of August, when upwelling is more intense [Figure 5(b)]. As for silicate and phosphate [Figure 7(d,e)], the mean concentrations reach maximal values during September, when upwelling is still strong, over $-0.3 \text{ m}^2 \text{ s}^{-1}$ on average, and net remineralisation rates are the highest of the year (Álvarez-Salgado *et al.*, 1993; Rosón *et al.*, in press). From this month until November, the mean concentration decreases fortnightly at a rate of *c.* $-0.8 \mu\text{mol kg}^{-1}$.

The SSCs of both silicate and phosphate at the bottom [Figure 7(d,e)] account for nearly 40% of the observed variability, and show a similar pattern ($r=0.93$, $P<0.001$). The maxima mean values, from August to October, are *c.* $0.8 \mu\text{mol kg}^{-1}$ for phosphate and 8

$\mu\text{mol kg}^{-1}$ for silicate. For both nutrients, the mean concentration decreases slightly from October onwards. Phosphate concentration at the bottom shows the lowest mean values, *c.* $0.5 \mu\text{mol kg}^{-1}$, in February and March; then, mean concentration increases at a fortnight mean rate of $+0.05 \mu\text{mol kg}^{-1}$. The mean silicate concentration in the bottom is the lowest, *c.* $4 \mu\text{mol kg}^{-1}$, during March and April. From late April onwards, the increasing rate is high, *c.* $1 \mu\text{mol kg}^{-1}$ fortnightly, and it is due to upwelling and remineralization.

The SSCs of nutrients at the bottom show marked differences in the percentage of explained variability (Table 2); the SSCs of inorganic nitrogen species accounted for 15% of the observed variability, while those from DIN, silicate and phosphate accounted for 40%. The main factor which controls average bottom concentration of nitrite and nitrate seems to be upwelling, a variable with a high frequency variation pattern; therefore, the low percentage of variability explained by the SSCs for these variables is not surprising. In the case of silicate and phosphate, whose inputs to the system are also controlled by upwelling, a mechanism should be acting through the sediment, tending to diminish the expected high frequency variation. In relation to phosphate, the 'buffered' phosphate phenomenon has been reported for several estuarine systems (Sharp *et al.*, 1982). Further investigations are needed since the biogeochemical consequences of processes acting through the sediment are poorly understood in the Ría de Vigo.

The SSC for chlorophyll *a* (Figure 8) shows a bimodal pattern, and accounts for 20 and 15% of the observed variability for surface and bottom series, respectively. In Figure 3, this bimodal pattern is reflected by a secondary peak of the power spectrum at the 6-month period. During December, the mean lowest values, *c.* $1 \mu\text{g l}^{-1}$, are reached for both surface and bottom cycles. From January onwards, the mean concentration increases: at the surface, the fortnight averaged increasing rate is *c.* $1 \mu\text{g l}^{-1}$; so the first peak occurs in May (spring bloom), with mean values $>8 \mu\text{g l}^{-1}$; at the bottom, the fortnight averaged increasing rate is *c.* $0.5 \mu\text{g l}^{-1}$, and the first peak, *c.* $3 \mu\text{g l}^{-1}$, also occurs in May. In July, the mean concentration in the surface descends below $6 \mu\text{g l}^{-1}$; from this month onwards, it increases again and reaches the second peak in September (autumn bloom), with a value similar to the first one. From September onwards, the mean concentration decreases abruptly, at a fortnight averaged rate of *c.* $-2 \mu\text{g l}^{-1}$. In the

bottom, the SSC of this variable also shows a second peak, but it is less important than the first one, being 2 weeks lagged in comparison to that of the surface.

Long-term trends

This work follows Granger (1966), who defines ‘trend in mean’ as ‘comprising all cyclic components whose wavelength exceeds the length of the observed time series’ (Chatfield, 1992). Trends in mean were tested with the non-parametric, seasonal Kendall’s, τ , which examines the level of significance of the trend and possible seasonal differences (van Belle & Hughes, 1984). The mean rates of the trend were estimated according to Hirsch *et al.* (1982).

The results for trend in mean (Table 3) are expressed as the rate of yearly change, and as the percentage of yearly change relative to the mean value of the S_0 , time series (Table 1) (Jordan *et al.*, 1991). The percentage of variability associated with the trend in mean related to the observed variability (S_0) is also given. Aiming to establish when a possible change in the trend in mean could be produced, the analysis was applied to both the complete time series (6 years) and to the last 4 years (values in parentheses in Table 3).

Thermohaline properties show a significant trend, both for surface and bottom time series. In the surface, salinity increases and temperature decreases at a percentage of yearly change relative to the mean, of *c.* 0.6 and -0.6%, respectively. At the bottom, both variables show a similar trend, and the percentage of yearly change relative to the mean is *c.* 0.1% for salinity and -0.9% for temperature. The contribution of the trend to the total observed variability is greater in the bottom series; at the surface, the estimated trend accounted for 2.7 and 0.4% of the observed variability for salinity and temperature, respectively; for the bottom layer, the contribution is *c.* 8.5% for salinity and 3.4% for temperature.

At the surface, the ammonium, nitrite and phosphate time series show an increasing trend; the percentages of yearly change relative to the mean are *c.* 3.3, 4.7 and 7.0%, respectively. These nutrients show an increasing trend at the bottom too; the percentages of yearly change relative to the mean are *c.* 2.3% for nitrite; 4.4% for nitrate

and phosphate; and 3.6% for ammonium. In relation to the percentage of the observed variability which is due to trend, the trend in mean estimated phosphate clearly stands out; both for surface and bottom layers, this accounts for *c.* 5% of the observed variability, whereas for the other nutrients, it accounts for *c.* 1% of the observed variability at both layers.

By contrast, silicate shows a decreasing trend; the percentage of yearly change relative to the mean is *c.* -3%, both in the surface and in the bottom time series. This estimated value involves a percentage of variability due to trends of *c.* 0.4 and 2% for the surface and bottom silicate time series, respectively.

Both for the surface and bottom observed time series, the higher percentages of yearly change relative to the mean are those estimated for chlorophyll *a*; *c.* -12%.

Nevertheless, this rate of annual change implies that the contribution of the trend to the observed variability is *c.* 4 and 2% for the surface and bottom chlorophyll *a* time series, respectively.

When testing for trends in the last 4 years time series (1989–92), some differences arise (Table 3). Salinity does not show a significant trend for the 1989–92 time series, neither at the surface nor the bottom; thus, the salinity increases abruptly in the 1988–90 period. This fact agrees with the high surface salinity observed at some coastal zones in the Northeast Atlantic during 1989 and 1990 (Heath *et al.*, 1991; Ellet & Turrell, 1992). By contrast, temperature shows a higher percentage of yearly decrease, *c.* -2%, both for surface and bottom time series.

The percentages of yearly change for the nutrient salts are the same as those estimated for the 6 years time series, except for nitrate and silicate. Nitrate, both for surface and bottom 1989–92 time series, shows a significant increasing trend in the last 4 years; the percentage of yearly change is *c.* 4.4 and 16.0% for surface and bottom, respectively. Silicate, during 1989–92, maintains the decreasing trend in the surface, but it is more acute; by contrast, in the bottom, the trend is opposite to that of the 6 years time series.

Chlorophyll *a* corresponding to the period 1989–92 maintains the same sign of trend as that estimated for the 6-year period, but it is more intense; the percentage of yearly change is *c.* -16.8 and -20.4% for surface and bottom, respectively.

Meteorological variables did not show significant trends when tested with the non-parametric seasonal Kendall's τ . Nevertheless, Ekman transport components and, to a lesser degree, runoff are variables that present high variability at high frequencies (Table 2); this high frequency variability being much greater than that associated with longwaves (i.e. long-term trends). For example, the high frequency oscillations for the Ekman transport components may be several orders of magnitude greater than the possible interannual variation (Codispoti, 1983). This is an important error source when aiming to estimate long-term variability of variables with high frequency variability. In this case, the trend can be assessed using seasonal or annual averaged values (Fedorov & Ostrovskii, 1986). The mean annual values (Table 4) for the cross-shore Ekman transport component (qx) show a decreasing trend, particularly in the 1989–92 period, thus involving a yearly increasing seaward transport of the Ekman layer (yearly upwelling increasing). By least square fitting, the derived annual decreasing rate is *c.* $-18.3 \pm 4.4 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-1}$ of coast ($r=0.90$, $P<0.01$). The runoff also shows an annual decreasing trend (Table 4), but non-monotonic due to the high runoff values recorded in 1991, of *c.* $-0.9 \pm 0.4 \text{ m}^3 \text{ s}^{-1}$ ($r=0.73$, $P<0.05$).

When taking into account the quarter averaged values of the cross-shore component of the Ekman transport [Figure 9(a)], it is worth noting that: (1) a clear increasing pattern of upwelling (negative values) was not evident, although a slight trend can be observed for the second averaged quarter (except for 1992) and also for the second plus the third quarters (except for 1990 and 1992, that, however, showed a predominance of the north wind component); and (2) when the along-shore component of the Ekman transport is also considered, northerly and easterly winds become increased in the last 3 years. For runoff [Figure 9(b)], no clear quarterly pattern can be observed, although a soft decreasing trend can be inferred from the fourth quarter evolution.

An increasing trend of equatorward winds, and thus advection of deep waters, has been reported for some upwelling areas (Bakun, 1990). For a point located at 43°N 11°W, an increasing annual trend for the wind stress of the north wind component, in the 1987–92

period, of $c. +160 \cdot 10^{-5} \text{ Nw m}^{-2}$ has been estimated. This agrees with that given by Bakun (1990) for the same point. He used 35 years of data for the upwelling season, giving an increasing rate of $c. +33 \cdot 10^{-5} \text{ Nw m}^{-2}$. By contrast, other authors (Lavín *et al.*, 1991), using 1966–89 period data for the same location, have deduced a general decreasing trend of the wind stress of the north wind component ($c. -42 \cdot 10^{-5} \text{ Nw m}^{-2}$), although this decreasing trend appears to change its sign from the 1980s onwards.

The present authors' estimations for the 1989–92 period suggest an increase in the north wind component, with a notorious domain of the NE winds in the last 3 years of the study period, and also a general decrease of precipitation on an annual basis.

The present paper proposes a mechanism which links the estimated trends in mean for the hydrological variables with those estimated for the cross-shore component of the Ekman transport and runoff. An increase of upwelling may explain the trend in mean observed for salinity and temperature, because of the entrance of greater volumes of cooler and saltier subsurface water into the ría; besides, as a consequence of the observed upwelling trend, an increase in the residual flow of the ría is also expected (Blanton *et al.*, 1987; Prego & Fraga, 1992). The present authors have applied the box model proposed by Pritchard (1969) to estimate residual flows, assuming that surface and bottom salinities may stand for the mean salinity of the upper and lower layer, respectively. The estimated fortnightly averaged time series for the residual outflow (Figure 10) shows a significant annual trend, tested with the seasonal Kendall τ , of $c. +89 \text{ m}^3 \text{ s}^{-1}$.

As recently pointed out by Rosón *et al.* (in press), coastal upwelling is the main factor which controls the residual circulation in the Galician Rías Baixas. Thus, the increasing annual trend observed for the crossshore Ekman transport must agree with the increasing annual trend estimated for the residual outflow. In the analysed period, the observed annual trend for the wind stress of the north wind component, $160 \cdot 10^{-5} \text{ Nw m}^{-2}$, is equivalent to an annual increasing trend for the cross-shore Ekman transport of $16 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-1}$ of coast, which, once the width of the Ría at the mouth has been considered ($\sim 7 \text{ km}$), gives a flow of the Ekman layer of $c. 112 \text{ m}^3 \text{ s}^{-1}$, which agrees quite well with the estimated annual trend for the residual outflow. The higher the residual outflow, the lower the renewal time, which implies an increase of the washout effect and of the

exporting rates of phytoplankton towards the shelf (Codispoti, 1983). This washout effect explains the decreasing trend observed for chlorophyll *a*. The concentration of nutrient salts in the ría increases during the study period due to enhanced residual circulation and the associated decreasing in phytoplankton biomass. The decreasing trend estimated for silicate may be a consequence of the decreasing trend of runoff, as this nutrient is mainly supplied to the ría (50% of silicate inputs) during autumn and winter by means of runoff (Pérez *et al.*, 1986, 1992), when the decreasing trend in precipitation was more severe.

It is not clear whether the observed trends are part of a longer-term trend, or of a longer-term cycle (UNESCO, 1992; Pérez *et al.*, 1995), or simply represent a coincidental sequence of inter-annual variations. Further investigation, involving the maintenance of long-term monitoring, is desirable.

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Table 1. Mean coefficient of variation (CV), maxima and minima values of the purged and filled time series (S_0' in Figure 2). The number of data (n) for the rough time series (S_0 in Figure 2) is also given

	Variable	Mean	CV (%)	Max.	Min.	n	
Meteo	qx	-0.06	1400	6.98	-3.25	626	
	qy	-0.21	-770	4.05	-8.17	626	
	Qr	20.50	160	170.00	3.7	626	
	Qs	415.90	40	781.30	221.6	626	
Sfc	S	34.35	6	35.78	12.89	545	
	t	15.33	15	21.76	11.24	542	
	NO_2^-	0.29	89	1.59	0.00	539	
	NO_3^-	2.75	126	30.40	0.00	538	
	NH_4^+	1.82	96	13.48	0.00	538	
	DIN	4.99	101	34.81	0.01	537	
	SiO_2	4.24	97	42.76	0.13	537	
	HPO_4^{2-}	0.51	56	2.58	0.00	536	
	Chl. a	5.03	103	34.16	0.02	536	
	Btm	S	35.57	1	36.03	33.84	540
		t	13.62	8	18.04	11.66	540
		NO_2^-	0.53	56	2.14	0.00	533
		NO_3^-	5.68	52	15.33	0.02	532
NH_4^+		2.36	67	9.69	0.03	531	
DIN		8.36	37	22.40	0.80	529	
SiO_2		6.38	14	18.44	0.00	533	
HPO_4^{2-}		0.67	36	1.40	0.17	530	
Chl. a		1.63	48	17.01	0.00	525	

qx and qy , cross-shore and along-shore components of the Ekman's transport, $m^2 s^{-1}$; Qr , runoff in the drainage basin up to Stn. E3 ($\sim 480 km^2$), $m^3 s^{-1}$; Qs , incoming solar radiation, $cal cm^{-2} day^{-1}$; S, salinity practical salinity scale; t, temperature, $^{\circ}C$; nutrient salts and dissolved inorganic nitrogen (DIN) ($NO_2^- + NO_3^- + NH_4^+$), $\mu mol kg^{-1}$; Chlorophyll a concentration, $\mu g l^{-1}$; Meteo, meteorological data; Sfc, surface data; Btm, bottom data.

Table 2. Percentage of variability associated with each of the series, and residuals resulting from the smoothing procedure applied to the rough time series (Figure 2). The percentage is related to the observed variability (S_0' time series)

	Variable	SD	S1	R1	S2	R2	SSC	R3	R	T
Meteo	qx	0.84	41	49	16	23	10	6	90	0
	qy	1.62	45	46	18	25	9	9	91	0
	Qr	32.8	71	20	31	35	16	15	82	0

	Q_s	166.0	87	11	80	6	79	1	21	0
Sfc	S	2.06	75	19	38	30	14	24	81	3
	t	2.30	93	5	81	9	71	10	28	0
	NO_2^-	0.26	83	12	61	16	49	12	50	1
	NO_3^-	3.47	87	8	59	21	40	19	56	0
	NH_4^+	1.75	73	21	45	21	36	9	61	0
	DIN	5.04	86	17	60	19	47	14	49	0
	SiO_2	4.11	83	11	48	27	33	15	63	0
	HPO_4^{2-}	0.29	74	20	50	20	25	24	70	5
	Chl. <i>a</i>	5.18	66	25	39	23	20	19	75	4
Btm	S	0.36	67	23	34	28	12	23	80	9
	t	1.09	92	5	72	13	38	34	57	3
	NO_2^-	0.30	75	19	35	34	16	19	83	1
	NO_3^-	2.95	82	12	48	28	19	30	77	2
	NH_4^+	1.58	67	23	24	36	15	10	82	1
	DIN	3.09	82	21	63	16	37	26	59	4
	SiO_2	0.89	77	17	54	17	38	17	60	2
	HPO_4^{2-}	0.24	79	17	61	14	39	22	54	5
	Chl. <i>a</i>	0.78	68	23	30	33	15	16	82	2

Meteo, meteorological data; Sfc, surface data; Btm, bottom data; S_x , output series; R_x , residuals; T, trend; S, salinity; t, temperature; DIN, dissolved inorganic nitrogen.

Table 3. Long-term trends (T). Only data with significant trend ($P < 0.05$, seasonal Kendall τ) are given. Annual change is based on the median annual rate of change (Hirsch *et al.*, 1991). The percentage of annual change relative to the mean (Table 1) and the percentage of the observed variability which is due to the trend, are also given

Variable	Change (year^{-1})				% Change (year^{-1})				Variance (trend)	
	Sfc		Btm		Sfc		Btm		Sfc	Btm
S	0.20		0.05		0.59		0.13		2.58	8.50
t	-0.08	(-0.36)	-0.12	(-0.30)	-0.55	(-2.33)	-0.87	(-2.17)	0.42	3.40
NO_2^-	0.01		0.01		4.65		2.25		0.83	0.49
NO_3^-		(0.13)	0.24	(0.88)		(4.42)	4.33	(16.01)		2.10
NH_4^+	0.06		0.08		3.29		3.62		0.36	0.89
DIN			0.38	(0.96)			4.45	(11.24)		4.49
SiO_2^-	0.16	(-0.40)	-0.19	(0.11)	-3.54	(-9.21)	-3.07	(1.68)	0.40	1.91
HPO_4^{2-}	0.04	(0.03)	0.03	(0.03)	6.97	(6.82)	4.39	(4.55)	4.73	4.55
Chl. <i>a</i> -	0.61	(-0.83)	-0.20	(-0.34)	-12.32	(-16.78)	-12.06	(-20.44)	4.11	1.99

S, salinity; t, temperature; DIN, dissolved inorganic nitrogen; Sfc, surface; Btm, bottom

Table 4. Annual mean and monthly maxima and minima values of runoff (Qr) and of the cross-shore component (qx) of the Ekman's transport ($\text{m}^3 \text{s}^{-1} \text{km}^{-1}$ of coast)

	1987	1988	1989	1990	1991	1992
Runoff (Qr)						
Mean	24.2	20.8	19.9	18.6	22.6	17.3
Monthly max.	81.6	67.6	69.8	61.4	84.8	51.7
Monthly min.	4.5	3.9	3.8	4.6	3.9	4.2
Cross-shore transport (qx)						
Mean	-47	-41	-30	-47	-107	-144
Monthly max.	1058	1299	1387	647	961	439
Monthly min.	-776	-615	-571	-650	-683	-979