

The volume of water filtered by a Continuous Plankton Recorder sample: the effect of ship speed

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The Continuous Plankton Recorder (CPR) survey is one of the largest plankton-monitoring programmes in the world. Since 1931, the CPR has collected ~380 000 samples, each representing 10 miles of tow. It has been assumed that the volume of seawater filtered by each sample remained constant and close to 3 m³. In this study, the volume filtered for each CPR sample was measured on two routes (SA and IN), monitored by the CPR survey, between 1995 and 2000. Although the filtered volume was near the theoretical value of 3 m³ on the SA route (3.2 m³), it was significantly higher on the IN route (3.8 m³). A significant negative relationship was found between the volume filtered and the speed of the ships. This relationship indicates that the faster the speed of the ship, the lower the volume filtered. This could have implications for the CPR survey as the speed of the ships has increased continuously since the end of the 1950s. However, no significant correlation was found between the long-term changes in the speed of the ships and two commonly used indicators of plankton variability: the Phytoplankton Colour and the Total Copepods indices. This absence of relationship may indicate that the effect found is small in comparison with the influence of hydroclimatic forcing, although a more extensive study is needed to confirm these findings.

INTRODUCTION

The Continuous Plankton Recorder (CPR) survey provides a unique long-term record of >450 plankton taxonomic groups or species in the North Atlantic Ocean and adjacent seas (Reid *et al.*, 2003). Results from the CPR survey have been used to investigate many ecological issues. Biogeographic studies have been conducted, showing spatial distribution throughout the North Atlantic Ocean and shelf seas of >250 species or taxonomic groups (Colebrook *et al.*, 1961a,b). A number of investigations have allowed a better characterization of seasonal cycles and spatial changes for many taxa (Glover, 1957; Colebrook-1969, 1984, 1991). Other works have examined long-term changes in phytoplankton and zooplankton (Colebrook, 1981, 1982; Reid *et al.*, 1998; Beaugrand *et al.*, 2002). Studies on diel vertical migration of some calanoid copepods (Hays *et al.*, 1995, 1996; Hays, 1996; Hirst and Batten, 1998), spatial and temporal changes in the diversity of decapod crustacean larvae (Lindley, 1998), the monitoring of non-indigenous

species (Edwards *et al.*, 2001a) and unusual events (Lindley *et al.*, 1990, 1993; Edwards *et al.*, 1999, 2001b) have been undertaken and have led to a better understanding of the ecology and of the functioning of North Atlantic ecosystems.

Since the beginning of the CPR survey, it has been assumed that with 100% efficiency each sample filtered 3 m³ of water (Robinson and Hiby, 1978). Hardy (Hardy, 1939) was, however, aware that flow might vary because of clogging by plankton of the silk mesh used to filter the organisms within the CPR and also with ship speed. He designed the CPR with a small entrance aperture leading to a tunnel that gradually widens to a filtration area of ratio 1:29. The enlarged filtration area lessens the water-flow speed and, together with the continual advance of the silk, decreases clogging by plankton. By experimentation, Hardy (Hardy, 1939) found that zooplankton numbers would have to be greatly in excess of the usual summer maximum to cause a 25% reduction in flow. He considered

that dense phytoplankton would cause a more serious clogging. John *et al.* (John *et al.*, 2002) also studied the effects of clogging of the CPR mesh by plankton and found that with the highest plankton densities recorded the flow rate decreased by only ~20%.

While the design of the CPR and plankton analysis methods have remained virtually the same since 1958, there has been a change, outside of the control of the agencies managing the survey (Batten *et al.*, 2003). The average speed of the towing ships has increased from ~11 knots in the early years to ~14.5 knots today. Hays and Warner (Hays and Warner, 1993) established that changes in ship speed did not result in significant variations in the towing depth of the CPR; however, the effect of ship speed on the volume of seawater filtered by the CPR silk has never been investigated. It is possible that the filtered volume per sample may be affected by the towing speed of the ship, and this could have implications for the zooplankton abundance recorded by the CPR survey. In this study, the relationship between ship speed and volume of water filtered by CPR samples is investigated and possible consequences for the CPR survey are discussed.

METHOD

The CPR survey

The CPR survey is a plankton-monitoring programme that uses a high-speed plankton recorder to sample the epipelagic environment. Water enters the recorder through a square aperture of 1.62 cm² and passes towards an area with a cross sectional dimension of 5 × 10.2 cm. There, plankton is filtered by a slowly moving band of silk

with an average mesh size of 270 µm (Hays, 1994). Then, a second band of silk covers the organisms to form a sandwich that is reeled into a tank containing 4% formalin. The speed of silk movement is adjusted to the speed of the ship by means of a propeller and a gearbox located above the internal mechanism (Fig. 1).

The CPR is towed behind voluntary merchant ships at a depth of ~10 m. The times and locations of deployment, alterations in course and retrieval of the CPR for each tow are recorded in a log maintained by officers of the towing ships. The silk roll was cut into sections (~10 cm), representing 10 nautical miles of tow, for analysis taking in consideration the above information (Colebrook, 1960; Warner and Hays, 1994).

Relationships between the volume filtered by a CPR and the speed of the ships

To test the hypothesis of a relationship between the volume of seawater filtered by a CPR sample and ship speed, an experiment was conducted on a monthly basis between 1995 and 2000, on the routes SA and IN monitored by the CPR survey (Fig. 2). These routes were mainly chosen for logistical reasons (e.g. frequency of voyages). A CPR was assigned to each route, although occasionally other CPRs were substituted for tows because of repairs.

To measure the water filtered, electromagnetic flowmeters (Walne *et al.*, 1998) were attached to CPRs (Fig. 1). Flowmeters were dedicated to individual CPRs and calibrated approximately every 6 months. When a CPR was deployed, a seawater switch turned the flowmeter on and burst-sampled, averaging the results every 30 s until hauled. On return to the laboratory, the data were downloaded from the flowmeter and the

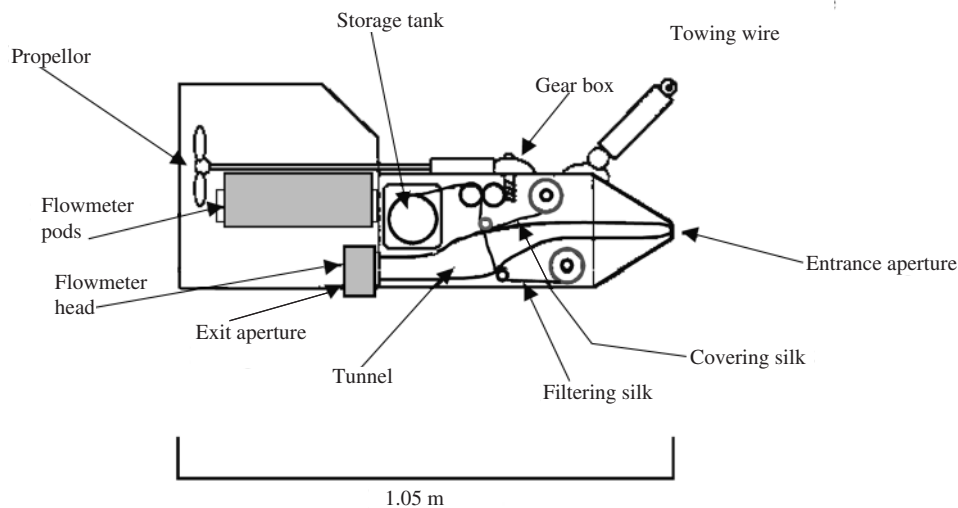


Fig. 1. Schematic diagram of Continuous Plankton Recorder (CPR) showing location of the flowmeter.

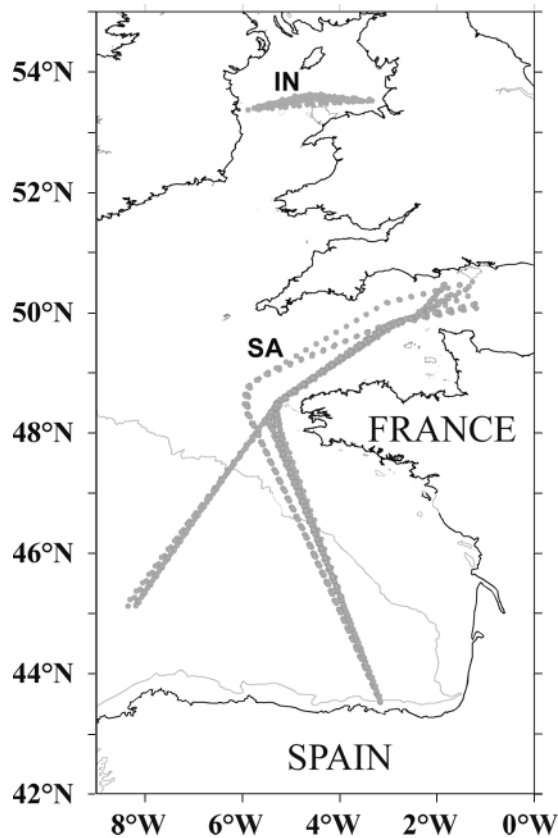


Fig. 2. Position of the Continuous Plankton Recorder (CPR) samples collected along the IN and SA routes between April 1995 and March 2000.

calibration was applied to calculate flow in $L \text{ min}^{-1}$ (Walne *et al.*, 1998). Filtered volumes were calculated for every sample from 69 successful tows. The mean volume of water filtered per sample (m^3) was obtained from the mean filtering rate ($L \text{ min}^{-1}$) and the start and finish times for each sample.

From the log information, the speed of the ship was calculated for each leg (i.e. a section between two alterations in course) of the tow. When a leg contained more than one CPR sample, an average flow for the samples was calculated.

Spearman's coefficient of rank correlation (Sokal and Rohlf, 1995) was applied to examine the relationship between the volume of seawater filtered by a CPR sample and the speed of the ship. A Monte Carlo test was used to estimate the significance of each correlation coefficient. A total of 5000 simulations were performed to assess the probability.

Relationships between the speed of the ships and plankton

To investigate the relationship between long-term changes in ship speed and plankton, the Phytoplankton

Colour index and the Total Copepods index were used. Phytoplankton Colour is an index of the concentration of chlorophyll on the CPR silk (Reid *et al.*, 1998). This index has been shown to have increased substantially in the North Sea and in an area west of the British Isles after the mid-1980s (Reid *et al.*, 1998). The category Total Copepods has often been used as a measure of zooplankton abundance (secondary production) and also to investigate relationships between copepods and the Gulf Stream North Wall (Taylor and Stephens, 1980; Hays *et al.*, 1993). The index Total Copepods increased in the North Sea after a regime shift (Reid *et al.*, 2001; Beaugrand and Reid, 2003). Both Phytoplankton Colour and Total Copepods anomalies for the North Atlantic and North Sea were derived by principal component analysis using data from Beaugrand and Reid (2003).

Potential relationships between long-term changes in the speed of the ships and plankton were investigated using the Pearson correlation coefficient. Probabilities were adjusted to take into consideration temporal autocorrelation (Beaugrand, 2003). The Box-Jenkins (Box and Jenkins, 1976) autocorrelation function, modified by Chatfield (Chatfield, 1996), with the correction formula of Chelton (Chelton, 1984) was applied.

RESULTS

During the period between April 1995 and March 2000, CPR and flowmeter deployments were successful for 35 and 34 tows on the IN and SA routes, respectively. A summary of results for the successful tows for the two routes is shown in Table I. The speed of the ships and the volume filtered on the IN route were significantly higher than those on the SA route (speed of the ships: Kruskal-Wallis test = 116.11, $P < 0.001$; volume filtered: Kruskal-Wallis test = 77.96, $P < 0.001$; Table I).

A significant and negative relationship was found between ship speed and the volume filtered for both routes, although clearer on the SA route (Fig. 3). The relationship between the two variables was similar on both routes, the

Table I: Summary of results for the IN and SA routes

	IN route	SA route
Tows	35	34
Samples	272	1451
Mean volume filtered sample m^{-3} (standard deviation)	3.84 (0.87)	3.16 (0.67)
Mean speed per sample (knots) (standard deviation)	16.5 (1.58)	13.9 (1.63)

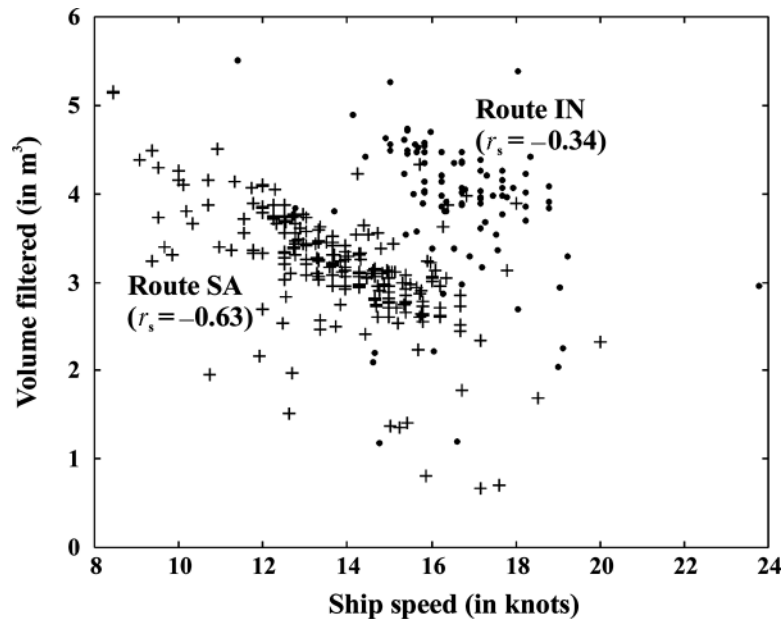


Fig. 3. Scatter plot of volume filtered (in m^3) and the speed of the ships (in knots; 1 knot = 1 nautical mile h^{-1}) for the routes IN (93 degrees of freedom) and SA (228 degrees of freedom). Spearman correlation coefficients between the two variables are indicated for both routes. Both coefficients were highly significant ($P < 0.002$). The plus denotes the data for the SA route, and the dot represents data for the IN route.

volume filtered being on average higher on the IN route. This result could be related to the different ships used to tow the CPR on the routes. Therefore, we examined the relationship between flow and speed for each ship. For the IN route, the relationship between flow and speed was only significant for one ship (Fig. 4a and b). For the SA route, the relationship was significant for all ships, although the scatter plot indicates that some assessments of the flow/speed were outside the cloud of points for the first two ships.

The negative relationships detected between flow and ship speed indicate that an increase in the average speed of the ships may decrease the concentration or abundance of plankton on the silk. However, despite the continued increase in the ship speed observed since 1948, no significant relationship was found between changes in either Phytoplankton Colour or Total Copepods and ship speeds (Fig. 5). Furthermore, the high positive (but non-significant) correlation found between Phytoplankton Colour and speed changes should in fact be negative if there is any effect of ship speed. Indeed, an increase of the speed decreases the volume of water filtered and hence the concentration of phytoplankton on the silk.

DISCUSSION

The mean volume of water filtered by the CPRs, in this study, was higher than the theoretical 3 m^3 (Robinson and Hiby, 1978). An aspiration effect, which can occur in

samplers with a small inlet aperture, may partly account for the higher-than-expected results (Tranter and Smith, 1968; Le Fèvre, 1973). Although the mean volume filtered per sample was near to 3 m^3 for the SA route, it was substantially higher for the IN route. The differences detected between the SA and IN routes could be explained by a number of factors. Firstly, this could be related to the different CPRs. All the CPRs used in this study were of the same design (type II Mark III) with a 'box-tail' (Warner and Hays, 1994; Reid *et al.*, 2003) and were in good condition. However, the CPRs inevitably develop individual sampling characteristics and the condition or construction of each machine may affect filtration efficiency. Hays (1994) recorded that a well-sealed CPR filtered, on average, 1.19 times the amount of water of a poorly sealed recorder.

Secondly, certain technical characteristics of the ships could explain the differences in the filtered volume between the SA and IN route. Altogether, eight ships were used during this study, five ships on the SA and three on the IN route (Table II). For example, ships on the SA route generally towed at speeds of <15 knots and used a wire length of 70 m, while those on the IN route towed at >15 knots and used a wire length of 100 m (Table II). The size and displacement of the ships and the configuration of their propellers affect water turbulence and possibly the measurement of flow rate through the CPR (P. Pritchard, Sir Alister Hardy Foundation for Ocean Science, Plymouth, personal communication). The

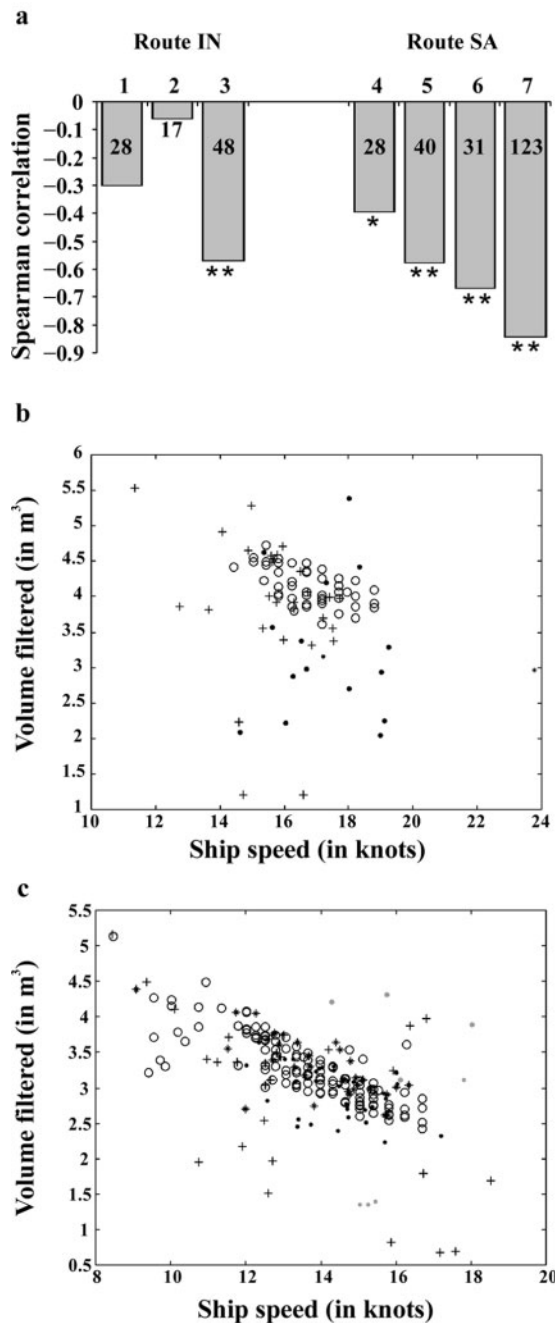


Fig. 4 (a) Spearman correlation coefficient between the volume filtered (in m³) and the speed of the ship (in knots) for each ship. IN route: 1, *Buffalo*; 2, *Puma*; 3, *European Leader*. SA route: 4, *Nyk Porto*; 5, *Churruca*; 6, *Pacheco*; 7, *Pelayo*; insufficient data for *Republica di Amalfi*. The degree of freedom is indicated within the grey bar. * $P < 0.05$; ** $P < 0.001$. No asterisk, a non-significant correlation. (b) Scatter plot of volume filtered (in m³) and the speed of the ships (in knots) for the IN route. The plus and the dot and the circle denote data from the ships *Buffalo*, *Puma* and *European Leader* respectively. (c) Scatter plot of volume filtered (in m³) and the speed of the ships (in knots) for the SA route. The plus (in black), the grey dot, the black dot, the asterisk (in black) and the circle (in black) denote data from the ships *Nyk Porto*, *Republica di Amalfi*, *Churruca*, *Pacheco* and *Pelayo* respectively.

pitch and roll motion of the ship is not predictable; hence, variations in the tension of the towing wire are inevitable and can affect the stability of the CPR and its flow rate. Table II identifies some other parameters that may also explain the difference between the two routes.

Thirdly, plankton composition and abundance may also play a role. John *et al.* (John *et al.*, 2002) have recently investigated the impact of plankton on the volume filtered by the CPR for a number of routes including the IN and SA. Turbidity (sand and detritus) and plankton (e.g. Cnidaria and *Phaeocystis* spp.) that are not recorded quantitatively were seen to increase the clogging of the mesh and decrease flow. However, it is unlikely that this explains the difference between the routes IN and SA. The latter route crosses the English Channel and the oceanic area of the Bay of Biscay, different hydrodynamic regions (Beaugrand *et al.*, 2000), from the IN route, but results found for the SA route were less variable than those for the IN route.

A number of factors were not considered in the present study. First, the flowmeters were designed not to impede the flow of water through the CPR but had the disadvantage of being quite large and heavy (17.3 kg). It is not known whether the flight pattern of the CPR would be altered by the attachment of the flowmeter or whether the flow would be different with or without this instrument. Earlier studies indicate that if the pitch of the CPR is altered, the flow may change (Reid *et al.*, 2003). Second, more accurate recording of ship speed could be provided if the ship log form was more detailed. A Global Positioning System (GPS) would also provide frequent recording of time and position. Given the differences found between the results for the IN and SA routes, it is not currently possible to extrapolate to other routes, but the study gives an indication of where further investigation or information may be useful.

Although mechanical records of each CPR and the specification of the ships are available, it is not possible to relate this information quantitatively to the plankton time series. Comparisons of the CPRs with respect to flow rates and flight patterns, using test tanks, are being considered. In controlled conditions, it should be possible to ascertain whether CPRs indeed filter the much higher volumes than expected or whether other variables are at play. Ideally, different types of flowmeters should be tested and ultimately the most appropriate should be fitted to every CPR.

The data from the CPR survey are spatially and temporally extensive and therefore a valuable resource. As plankton abundance is recorded in log₁₀ units, alterations in flow as reported in this study would have little influence on the overall trend in abundance. The design of the CPRs and methods of plankton analysis have changed as little as possible over the years so as to maintain the integrity of the

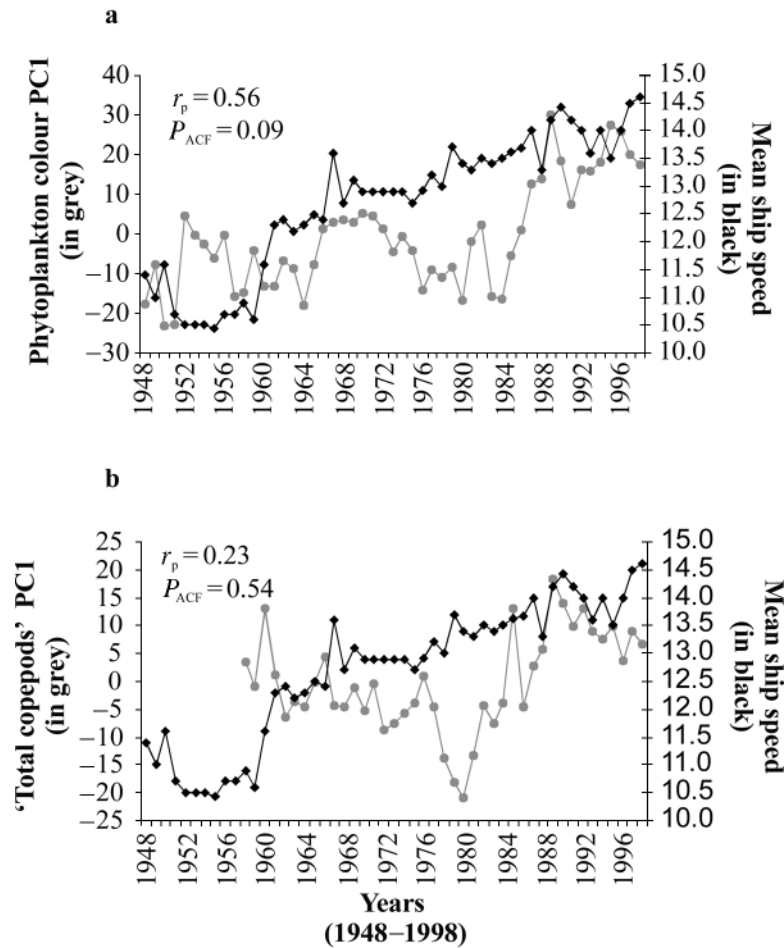


Fig. 5. (a) Long-term changes in the mean annual towing speed (in black) of all ships and all routes used by the Continuous Plankton Recorder (CPR) survey and long-term changes in the Phytoplankton Colour in the northeast Atlantic and the North Sea [as a principal component (Beaugrand and Reid, 2003)]. (b) Long-term changes in the mean annual towing speed (in black) of all ships and all routes used by the CPR survey and long-term changes in the CPR index ‘Total Copepods’ in the northeast Atlantic and the North Sea [as a principal component (Beaugrand and Reid, 2003)]. The Pearson correlation coefficient and its probability are superimposed on both graphs. Each probability was corrected to account for temporal autocorrelation.

Table II: Technical characteristics of the ships used to tow the Continuous Plankton Recorder (CPR) on the IN and SA route

Ship name	Routes	Ship size	Propeller type	Position of the aft towing point	Height of the aft towing point (m)	Length of towing wire (m)	Ship speed (knots)
<i>Puma</i>	IN	1	Twin	Starboard	13	100	17.8
<i>Buffalo</i>	IN	1	Twin	Starboard	13	100	15.8
<i>European Leader</i>	IN	2	Twin	Starboard	13	100	16.7
<i>Churruca</i>	SA	3	Single	Port	9	70	14.1
<i>Pacheco</i>	SA	3	Single	Port	9	70	13.5
<i>Pelayo</i>	SA	3	Single	Port	7	70	13.6
<i>Nyk Porto</i>	SA	4	Single	Central	12	70	12.2
<i>Republica di Amalfi</i>	SA	5	Single	Central	22	100	16.6

1, ROPAX ship (~130 m); 2, ROPAX ship (~150 m); 3, container ship (~110 m); 4, container ship (~170 m); 5, RoRo (~180 m). Length of towing wire is adjusted for ship speed.

time series (Batten *et al.*, 2003). However, the speed of the towed CPR depends on the operational speed of each ship of opportunity. The negative relationship between flow and speed has important implications for the CPR survey. Because of this effect, the use of a limited number of samples to assess the value of a CPR-derived biological indicator (i.e. abundance of a species) may prevent the detection of any relationship with the environmental factors (Beaugrand *et al.*, 2000; Beaugrand and Edwards, 2001). However, the absence of a significant relationship between changes in the average speed of the ships and both the Phytoplankton Colour and the Total Copepods indices suggests that the influence of ship speed is small relative to hydroclimatic variability. Beaugrand and Reid (2003) have shown that long-term changes in these plankton indicators are highly related to fluctuations in hydrometeorological forcing.

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