PHOSPHATE IN THE ENGLISH CHANNEL, 1933–8, WITH A COMPARISON WITH EARLIER YEARS, 1916 AND 1923–32

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(Text-fig. 1)

Continued observations of dissolved inorganic phosphate at International Hydrographic Station E 1, 22 miles S. 37° W. from Plymouth, started by Atkins in 1923, support the accepted picture of the seasonal cycle (Matthews, 1917; Atkins, 1923–30; Harvey, 1928, 1934; Cooper, 1933*a*, *c*; Harvey *et al.*, 1935), but fresh points of interest have emerged, their significance lying in the contrast they offer to earlier years. Difficulties due to the uncertainty as to the salt error have now been overcome (Cooper, 1938).

Numerical records for phosphate have not been published for 1930, 1931, 1933 and 1937 whilst the results for January to April 9 1934, given in the *Bulletin Hydrographique*, have been corrected by too low a factor. Those for April 20–December 1934 and for 1935 and 1936 in that *Bulletin* are correct.

There is a strong case for publishing nutrient salt results in terms of the milligram-atom of the element concerned (Cooper, 1933*d*; Carter, Moberg, Skogsberg & Thompson, 1933), and this has been endorsed by a subcommittee of the International Council. The milligram-atom of phosphorus per cubic metre corrected for salt error has therefore been adopted as the unit of measurement for this paper and for future work here. To facilitate comparison all my results since 1930 for Station E 1 expressed in this unit are brought together in Table I. Each is corrected by the salt error factor appropriate to the conditions of analysis (Cooper, 1938). In 1938 and sometimes in earlier years, the factor has been accurately determined at the time of analysis. There must always be a little uncertainty unless the factors are so determined since they are not true constants. Records for Station E 2 are similarly presented in Table II.

The salt error correction factor for all Atkins' (1923, 1925, 1926, 1928, 1930) phosphate results is 1·35 so that, to convert these to mg.-atoms P per cubic metre corrected for salt error, it is necessary to multiply by 1·35/71 = 0·0190.

To compare production of phytoplankton for different years, as deduced from phosphate records, Table III has been prepared to show the average content of the water column down to 20 m. (including the region of active photo-synthesis) and down to the bottom at 70 m. for every cruise to E 1 between March 1923 and August 1938. Furthermore, to establish whether

Table I. Complete Phosphate Records at Station E 1 August 1930 to August 1938; mg.-atom/m.^{3} P

All corrected for salt error.

Depth	1930					1931								
m.	12/8	10/9	9/10	11/11	4/12	13/1	4/2	19/2	23/3	7/4	22/4	18/5	10/7	26/8
0	0·10	0·00	0·33	0·50	0·53	0·53	0·58	0·46	0·25	0·42	0·23	0·11	0·07	0·03
5	0·06	0·00	...	...	...	...	...	...	0·21	0·28	0·17	0·11	0·07	0·04
10	0·05	0·05	...	...	...	...	...	...	0·26	0·24	0·18	0·14	0·08	0·08
15	...	0·18	...	...	...	...	...	...	...	...	0·20	...	0·09	0·04
20	0·13	0·18	...	...	...	...	...	...	...	...	...	...	0·12	...
25	0·24	0·20	0·27	0·51	0·48	0·48	0·49	0·49	0·25	0·25	0·19	0·13	0·15	0·04*
50	...	...	...	0·52	0·51	0·48	0·38	0·39	0·23	0·24	0·17	0·11	0·14	0·07
70†	0·23	0·20	0·33	0·48	0·60	0·49	0·40	0·47	0·26	0·25	0·16	0·10	0·17	0·07

Depth	1931					1932‡							1933	
m.	8/9	25/9	20/10	30/11	31/12	28/1	15/6	16/8	12/9	27/10	15/11	20/12	11/1	14/2
0	0·16	0·19	0·19	0·31	0·39	0·46	0·24	0·00	0·00	0·46	0·41	0·42	0·54	0·46
5	0·17	0·19	0·19	0·44	0·43	0·45	0·02	0·00	0·08	...	0·42	0·44	0·55	0·46
10	...	...	...	...	...	...	...	...	...	...	...	...	...	...
15	0·17	0·19	...	...	...	...	0·10	0·00	0·09	...	...	...	...	...
20	...	...	...	...	...	...	...	...	...	...	...	...	...	...
25	0·18	0·17	0·20	0·44	0·43	0·47	0·10	0·05	0·22	...	0·42	0·47	0·55	0·46
50	0·19	0·16	0·20	0·47	0·43	0·48	...	0·03	0·22	...	0·40	0·50	0·51	0·48
70†	0·26	0·20	0·18	0·45	0·43	0·46	0·24	...	0·28	...	0·42	0·57	0·51	0·48

Depth	1933									1934				
m.	13/3	4/4	11/5	18/7§	9/8	19/9	23/10	15/11	15/12	22/1	12/2	20/3	1/5	30/5‖
0	0·31	0·31	0·02	0·00	0·00	0·16	0·17	0·28	0·48	0·36	0·32	0·39	0·09	0·13
5	...	0·30	0·08	0·02	0·02	0·32	0·18	0·26	0·48	0·36	0·36	0·38	0·08	0·05
10	0·40	0·29	...	0·02	...	0·21	...	...	...	...	...	...	...	...
15	...	0·33	0·14	0·03	0·04	0·17	...	...	...	...	...	...	0·20	...
20	...	...	...	0·02	...	...	...	...	...	...	...	...	...	...
25	0·42	0·33	0·19	0·03	0·05	0·21	0·18	0·28	0·48	0·36	0·35	0·39	0·21	0·20
50	0·44	0·38	...	0·14	0·04	0·34	0·17	0·27	0·48	0·38	0·35	0·41	0·20	...
70†	0·48	0·35	0·22	0·15	0·06	0·33	0·23	0·27	0·48	0·38	0·35	0·39	0·21	0·20

Depth	1934						1935							
m.	9/7	15/8	21/9	18/10	14/11	20/12	15/1	26/2	22/3	2/5	4/7	8/8	16/10	21/11
0	0·00	0·00	0·09	0·21	0·23	0·35	0·41	0·44	0·54	...	0·07	0·02	0·20	0·43
5	0·03	0·00	0·09	0·21	0·26	0·33	0·41	0·44	0·39	0·11	0·06	0·03	...	...
10	...	...	...	...	...	...	...	...	...	...	...	...	...	...
15	0·14	0·00	...	...	...	...	...	...	...	...	0·07	0·12	0·25	0·41
20	...	...	...	...	...	...	...	...	...	...	...	...	...	...
25	0·13	0·19	0·10	0·22	0·24	0·33	0·43	0·42	0·42	0·24	0·13	0·15	0·25	0·41
50	0·16	0·19	0·24	0·19	0·24	0·33	0·42	0·42	0·37	0·25	0·23	0·16	0·25	0·41
70†	0·25	0·21	0·27	0·18	0·24	0·33	0·42	0·41	0·37	0·25	0·25	0·16	0·25	0·41

Depth	1935	1936							1937					
m.	13/12	23/1	10/3	28/4	12/5	18/6	22/7¶	30/9	14/1	18/2	19/5	17/6	22/7	21/9
0	0·45	0·58	0·24	0·10	0·29	0·07	0·06	0·13	0·48	0·47	0·05	0·03	0·05	0·10
5	0·45	0·44	0·22	0·10	0·05	0·01	0·06	0·14	0·49	0·48	0·00	0·04	0·05	0·10
10	...	...	...	...	...	...	0·07	...	...	...	...	...	...	...
15	...	0·46	0·22	0·13	0·18	0·05	...	...	...	...	0·06	0·05	0·06	0·10
20	...	...	...	...	...	...	...	...	...	...	...	...	...	...
25	0·46	0·47	0·31	0·19	0·22	0·10	0·24	0·25	0·47	0·49	0·10	0·22	0·30	0·13
50	0·46	0·47	0·41	0·24	0·27	0·26	0·24	0·34	0·49	0·49	0·26	0·28	0·33	0·26
70†	0·46	0·48	0·43	0·20	0·27	0·26	0·24	0·34	0·48	0·49	0·28	0·28	0·35	0·26

Depth	1937		1938								
m.	14/10	8/12	24/1	22/2	29/3	14/4	18/4	13/5	8/6	24/7	12/8
0	0·21	0·39	0·52	0·46	0·35	0·25	0·17	††	0·22	0·05	0·00
5	0·24	0·38	(0·66?)	0·46	0·30	0·26	0·15	0·22	0·06	0·04	0·00
10	...	...	...	...	...	...	...	...	...	0·06	...
15	0·21	...	...	0·46	...	0·26	...	0·19	0·09	0·04	0·01
20	...	...	...	...	...	...	...	0·19	...	0·09	...
25	0·21	0·38	0·45	0·49	0·41	0·28	0·17	0·29	0·11	0·12	0·04
50	0·21	0·39	0·45	0·48	0·42	0·32	0·18	0·24	0·20	0·26	0·18
70†	0·21	0·37	0·47	0·44	0·45	0·30	0·18	0·24	0·20	0·26	0·18

* 35 m., 0·04.
† Samples from 2–4 m. above the bottom.
‡ Interval February–May due to illness.
§ Station L 6.
‖ Station L 6, bottom sample at 55 m.
¶ Near E 1, 11 miles S.W. × W. of Eddystone.
†† See Table X.

any particular year was early or late, the maximum, minimum and average values that have been found for each of the twelve calendar months between March 1923 and February 1938 have been set out in Table IV. The differences between the averages for any two spring months gives the average monthly consumption at that time. It will be seen that by April, on an average, half of the year's supply of phosphate has been used up.

TABLE II. COMPLETE PHOSPHATE RECORDS AT STATION E 2, 1930 TO 1936. MG.-ATOM/M.^{3} P

All corrected for salt error.

Depth	1930	1931				1932	1933			1934				1935				1936
m.	9/10	4/2	22/4	26/8	30/11	15/11	14/2	9/8	13/11	12/2*	1/5	15/8	14/11	26/2*	2/5	4/7	21/11	12/5
0	0·42	0·42	0·58	0·01	0·27	0·50	0·36	0·00	0·52	0·52	0·22	0·00	0·25	0·39	...	0·00	0·37	0·11
5	...	...	0·34	0·02	0·38	0·50	0·36	0·00	0·53	...	0·27	0·00	0·27	0·40	0·32	0·02	...	0·10
10	...	...	0·33	0·04	...	...	...	...	...	...	...	...	...	...	...	...	...	...
15	...	...	0·29	0·04	...	...	...	0·00	...	...	0·27	0·00	...	...	...	...	0·37	0·12
25	...	0·40	0·30	0·05†	0·50	0·51	0·37	0·27	0·52	0·45	0·27	0·37	0·27	0·41	0·35	0·29	0·37	0·13
50	...	0·46	0·34	0·13	0·48	...	0·37	0·27	0·48	0·43	0·26	0·33	0·30	0·43	0·36	0·31	0·37	0·17
70–75	...	0·60	...	0·16	...	0·51	...	0·29	...	...	...	...	...	...	...	...	...	...
80–90	0·44	0·52	0·34	0·18	0·50	0·50	0·40	0·29	0·52	0·40	0·28	0·37	0·31	0·42	0·37	0·31	0·37	0·17

* Midway E 1–E 2; 33 miles S.W. of Eddystone. † 35 m., 0·05; 40 m., 0·07; 45 m., 0·13.

The consumption of phosphate as a measurement of plant production is affected by the length of time elapsing between two cruises. A more useful criterion of the intensity of an outburst is the consumption of phosphate per day (Fig. 1). Even here it should be recognized that the highest consumption may appear when cruises are very frequent (e.g. April 1938). Since a high intensity of production is unlikely to persist for a month or more, within that time a period of intense production may be partially masked by a preceding or following quiescent one. This comment applies with especial force in the years 1932 and 1937.

THE WINTER MAXIMUM OF PHOSPHATE

The maximum amount of phosphate is usually found at E 1 towards the end of December or beginning of January. This winter maximum is a measure of the amount of phosphate available for the following season's crop of phytoplankton and indirectly may control the survival of the larval planktonic stages of many marine animals.

Organically combined phosphorus, after allowing for the presence of arsenic, may amount to about 0·25 mg.-atom/m.^{3} (Cooper, 1937). There is evidence that organic phosphorus may become available fairly quickly (Cooper, 1935; Redfield, Smith & Ketchum, 1937; Seiwell & Seiwell, 1938). Since organic phosphorus is formed by the breakdown of living matter, at midwinter it is likely to be proportional to the inorganic phosphate available in a given area for plant growth. Deductions from records of the winter maximum of inorganic phosphate are therefore unlikely to be invalidated by vagaries of organic phosphorus.

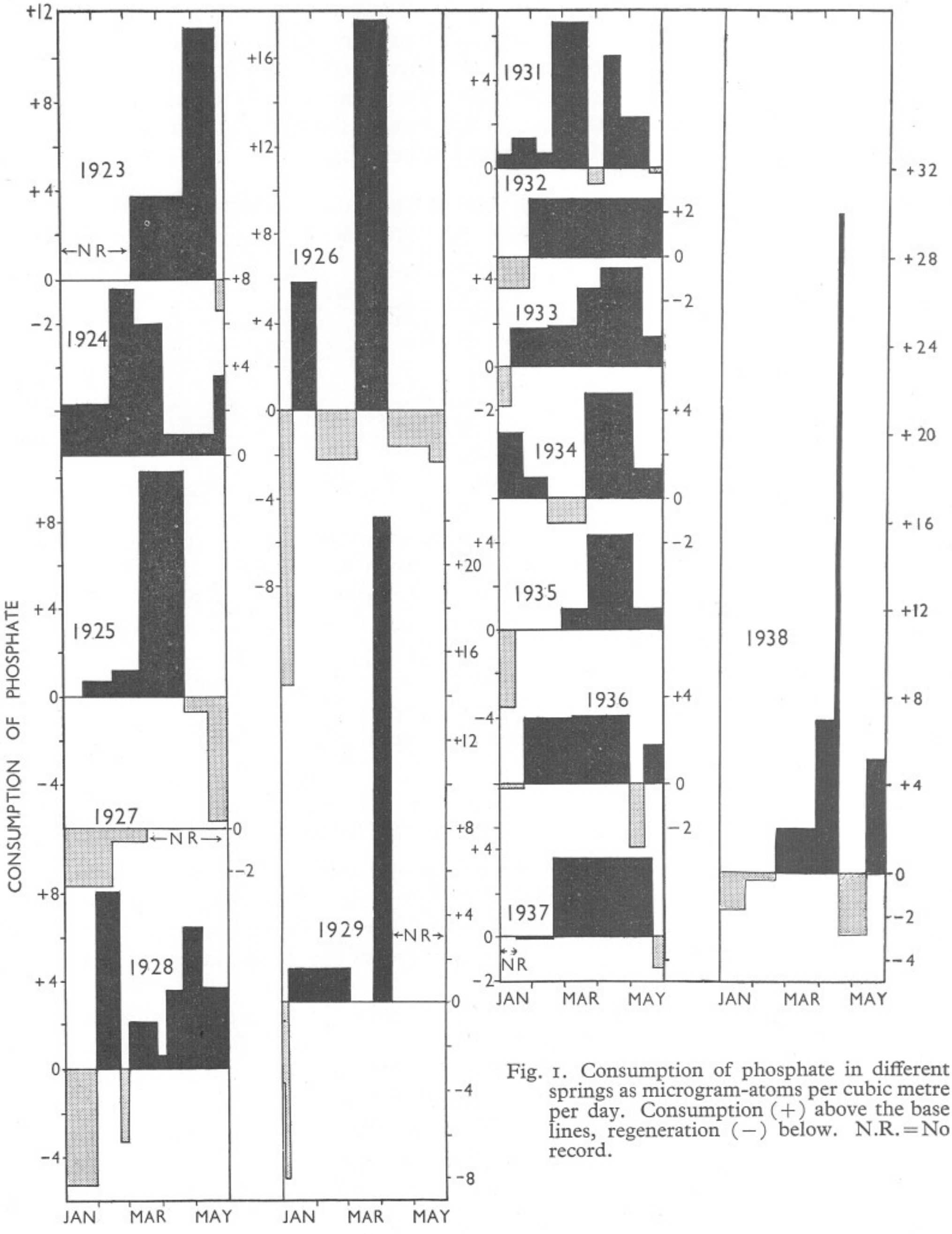

Fig. 1. Consumption of phosphate in different springs as microgram-atoms per cubic metre per day. Consumption (+) above the base lines, regeneration (−) below. N.R. = No record.

TABLE III. AVERAGE PHOSPHATE CONTENT BETWEEN THE SURFACE AND 20 M. AND BETWEEN THE SURFACE AND BOTTOM AT STATION E 1

All corrected for salt error; mg.-atom/m.³ P.

	January			February			March			April			May			June		
	Day of month	0–20 m.	0–70 m.	Day of month	0–20 m.	0–70 m.	Day of month	0–20 m.	0–70 m.	Day of month	0–20 m.	0–70 m.	Day of month	0–20 m.	0–70 m.	Day of month	0–20 m.	0–70 m.
1923	...	...	...	...	...	...	7	0·70	0·71	24	0·49	0·53	22	0·14	0·21	19	0·09	0·25
1924	2	0·73	0·715	15	0·615	0·615	10	0·37	0·44	4	0·28	0·29	20	0·19	0·25	17	0·08	0·17
1925	19	0·59	0·61	17	0·59	0·59	14	0·56	0·56	22	0·05	0·16	13	0·09	0·175	3	0·13	0·30
1926	12*	0·76	0·76	3	0·63	0·63	11†	0·68	0·71	10†	0·19	0·18	17†	0·21	0·24	24	0·18	0·33
1927	...	...	...	15	0·53	0·53	21	0·53	0·55	...	...	...	...	...	...	...	...	...
1928	31	0·71	0·69	21	0·52	0·52	1	0·55	0·55	5	0·47	0·49	7	0·26	0·325	4	0·175	0·210
							27	0·49	0·495	19	0·44	0·44				13	0·09	0·17
1929	2	0·68	0·66	...	...	...	4	0·61	0·61	11	0·24	0·27	...	...	...	...	...	...
	7	0·715	0·70				26	0·51	0·61									
1930	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
1931	13	0·50	0·49	4	0·53	0·46	23	0·25	0·24	7	0·26	0·25	18	0·125	0·12	...	...	...
				19	0·475	0·45				22	0·19	0·18						
1932	28	0·46	0·47	...	...	...	...	...	...	...	...	...	...	...	...	15	0·09	0·135
1933	11	0·55	0·53	14	0·46	0·47	13	0·38	0·42	4	0·31	0·34	11	0·11	0·175	...	...	...
1934	22	0·36	0·37	12	0·35	0·35	20	0·385	0·39	...	...	...	1	0·14	0·19	...	...	...
1935	15	0·42	0·42	26	0·43	0·42	22	0·42	0·395	...	...	...	2	0·18	0·22	...	...	...
1936	23	0·47	0·47	...	...	...	10	0·23	0·23	28	0·12	0·18	12	0·15	0·22	18	0·04	0·155
1937	14	0·48	0·48	18	0·48	0·48	...	...	...	...	...	...	19	0·04	0·16	17	0·05	0·20
1938	24	0·48	0·46	22	0·46	0·47	29	0·34	0·40	14	0·26	0·29	13	c. 0·20	0·24	8	0·10	0·14
										18	0·16	0·17						

	July			August			September			October			November			December		
	Day of month	0–20 m.	0–70 m.	Day of month	0–20 m.	0–70 m.	Day of month	0–20 m.	0–70 m.	Day of month	0–20 m.	0–70 m.	Day of month	0–20 m.	0–70 m.	Day of month	0–20 m.	0–70 m.
1923	12	0·07	0·16	15	0·185	0·32	13	0·10	0·27	15	0·36	0·31	8	0·38	0·38	10	0·65	0·65
1924	9	0·09	0·19	7	0·06	0·20	3	0·28	0·34	1	0·25	0·28	12	0·37	0·38	9	0·615	0·615
1925	8	0·08	0·13	5	0·165	0·37	...	...	...	1	0·23	0·325	11	0·50	0·50	11	0·33	0·36
				31	0·05	0·09												
1926	8	0·115	0·20	16	0·03	0·195	22	0·06	0·16	19	0·35	0·35	24	0·495	0·49	14	0·52	0·54
																31	0·425	0·41
1927	...	...	...	...	...	...	...	...	...	...	...	...	4	0·38	0·44	9	0·59	0·59
1928	4	0·10	0·265	9	0·01	0·18	18	0·115	0·37	2	0·24	0·25	30	0·52	0·54	...	...	...
	11	0·06	0·27	16	0·12	0·23												
	23	0·03	0·20	29	0·20	0·30												
1929	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
1930	...	...	...	12	0·08	0·185	10	0·08	0·165	9	0·30	0·30	11	0·51	0·51	4	0·50	0·515
1931	10	0·075	0·13	26	0·05	0·06	8	0·17	0·19	20	0·195	0·195	30	0·43	0·445	31	0·425	0·43
							25	0·19	0·18									
1932	...	...	...	16	0·01	0·03	12	0·09	0·19	27	0·46	0·46	15	0·42	0·41	20	0·45	0·49
1933	18*	0·02	0·08	9	0·03	0·04	19	0·22	0·27	23	0·18	0·18	13	0·27	0·27	15	0·475	0·475
1934	9	0·08	0·14	15	0·00	0·14	21	0·09	0·18	18	0·21	0·20	14	0·25	0·24	20	0·33	0·33
1935	4	0·07	0·16	8	0·08	0·12	...	...	...	16	0·23	0·245	21	0·42	0·41	13	0·455	0·46
1936	22	0·09	0·20	...	...	...	30	0·17	0·27	...	...	...	...	...	...	...	...	...
1937	27	0·07	0·25	...	...	...	21	0·10	0·18	14	0·22	0·21	...	...	...	8	0·38	0·38
1938	24	0·05	0·17	12	0·02	0·09	...	...	...	...	...	...	...	...	...	...	...	...

* Station L 6. † All values in March, April and May 1926 may be high as the standard had deteriorated and the correction applied was only an approximation.

A fall in the winter maximum, from the level of earlier years of about 0·7 mg.-atom/m.^{3}, was noticed in 1930–1 and 1931–2. Since then it has remained within narrow limits—around 0·47 mg.-atom/m.^{3} (Table V).

The influx of warm saline Atlantic water into the English Channel in the autumn of 1921 and its marked effect on the climate of the south-west of England is well attested (Harvey, 1925). It is quite possible that this influx brought with it the relatively rich supply of nutrient salts which was found when the routine determinations of phosphate started in 1923. Atkins (1938)

TABLE IV. AVERAGE PHOSPHATE CONTENT OF WATER COLUMN

Showing the maximum, minimum and "normal" or mean values found between March 1923 and February 1938 at the International Hydrographic Station E 1; mg.-atom/m.^{3} P, corrected for salt error.

Month	No. of years for which data are available	Average content between 0 and 20 m.			Average content of whole water column (70 m.)		
		Max.	Min.	Normal	Max.	Min.	Normal
Winter max.	13	..	..	..	0·76	0·42	0·559
January	13	0·76	0·36	0·554	0·76	0·37	0·548
February	11	0·63	0·35	0·506	0·63	0·35	0·503
March	12	0·70	0·23	0·465	0·71	0·24	0·490
April	9	0·49	0·05	0·262	0·53	0·16	0·292
May	11	0·26	0·04	0·149	0·32	0·12	0·208
June	8	0·18	0·04	0·100	0·33	0·135	0·216
July	11	0·115	0·02	0·075	0·27	0·08	0·171
August	11	0·20	0·00	0·068	0·37	0·03	0·160
September	11	0·28	0·06	0·126	0·37	0·16	0·235
October	12	0·46	0·18	0·269	0·46	0·18	0·275
November	12	0·52	0·25	0·412	0·54	0·24	0·418
December	12	0·65	0·33	0·473	0·65	0·33	0·481

has suggested that the 1921 influx may be related to the remarkable maximum in the constant of solar radiation found by Abbot (1935) in the autumn of that year. Abbot has analysed his records of the solar constant and has found that the resulting periodicities, which are integral multiples or sub-multiples of 23 years, may be correlated with fluctuations in weather in different parts of the world. Such attempts to relate terrestrial weather to astronomical periodicities have occupied others, in particular, O. Pettersson (1914*a*, *b*). As to the shorter periods there is no general agreement but Pettersson has arrived at two long lunar periodicities of 92 and 111 years. Of these the first is an exact multiple of Abbot's 23-year period and the second is reasonably close to Abbot's period of $115 = 5 \times 23$ years. Since terrestrial weather appears to be the result of a large number of periodic astronomical functions closely interwoven, any speculative attempt to link up our results more closely with these would be premature. Meanwhile, it is essential that our routine determinations of phosphate shall be continued and that special attention be devoted to the autumn and winter of 1944–5 when a period of 23 years from the notable influx of 1921 will have elapsed.

Evidence in support of the view that the English Channel was enriched with phosphate during the 1921 influx of Atlantic water may be found in Matthews' pioneer phosphate determinations in 1916–17 (Matthews, 1917). His control experiments suggest that the method is free from salt error and the results appear to be accurate to within $\pm 0{\cdot}04$ mg.-atom P/m.³ Due to war-time restrictions his samples were taken at the Knap Buoy which lies outside Plymouth Breakwater between stations L 2 and L 3. Admixture of estuarine water is liable to increase the amount of phosphate so that only waters having

TABLE V. WINTER PHOSPHATE MAXIMA FOR WHOLE WATER COLUMN AT E 1

Calculated minimum production of phytoplankton and actual production of young fish.

Winter	Phosphate maximum, mg.-atom/m.³	Deviation from mean, mg.-atom/m.³	Percentage deviation from mean	Year	Minimum production of phytoplankton. Metric tons wet weight per sq. km. and depth of 72 m.		Young fish summer spawners (Russell)
					Between winter phosphate max. and May	Between winter phosphate max. and summer min.	
1921–22	>0·65*	>+0·09	>+16	1922	..	..	..
1922–23	>0·71†	>+0·15	>+27	1923	>1700	>1850	..
1923–24	0·71	+0·15	+27	1924	1600	1850	696
1924–25	0·61	+0·05	+ 9	1925	1500	1600	140
1925–26	0·76	+0·20	+36	1926	>1750	>2000	909
1926–27	0·55	−0·01	− 2	1927	..	..	170
1927–28	0·69	+0·13	+23	1928	1250	1750	..
1928–29	0·69	+0·13	+23	1929	>1400	..	321
1929–30	..	..	..	1930	..	..	403
1930–31	0·52	−0·04	− 7	1931	1450	1650	230
1931–32	0·47	−0·09	−16	1932	1150	1500	197
1932–33	0·53	−0·03	− 5	1933	1200	1650	117
1933–34	0·48	−0·08	−14	1934	1000	1150	79
1934–35	0·42	−0·14	−25	1935	700	1000	37
1935–36	0·47	−0·09	−16	1936	800	1050	115
1936–37	0·48	−0·08	−14	1937	1100	1100	174
1937–38	0·47	−0·09	−16	1938	1050	1350	..
Mean 1923–24–1937–38	0·56	..	..	..	..	..	..

* March 1922 by Matthews' method.
† March 15 1923, 0·71 mg.-atom; maximum probably higher.

salinities greater than about 33·4 ‰ may be legitimately compared with station E 1. In 1916 on January 14, 18 and 24, he found respectively 0·45, 0·48 and 0·52 mg.-atom phosphate-P/m.³ In 1917 on January 10 the amount was somewhat higher, 0·62 mg.-atom P. In 1922, on February 12, when the winter maximum had almost certainly been passed, the Government Chemist using the same method found as much as 0·72 mg.-atom P (Atkins, 1923), agreeing closely with Atkins' own corrected analyses at that time and season. Our more recent records show that at midwinter, the phosphate content at stations L 2 and L 3, in waters more saline than 33·4 ‰, lies on an average about 0·05 mg.-atom P/m.³ higher than at E 1.

Although these investigations were the first to give even the right order of magnitude of the phosphate content of sea water, we may place considerable confidence in them. They suggest, firstly, that the phosphate content of the English Channel in 1916 and 1917 was similar to that in the 1930's and, secondly, that the increase took place between January 1917 and February 1922.

Table V shows also that in the winters of 1923–4 to 1928–9, the phosphate maximum averaged 0·67 mg.-atom/m.^{3}, whereas for the winters 1930–1 to 1937–8 it averaged only 0·48 mg.-atom. The high catches of young fish in the summer of 1930 suggest that the winter of 1929–30 was also one of high phosphate. The winter 1930–1 was therefore probably the first of low phosphate. Our results show a correlation with the direction of the residual current at the Varne lightship in the Straits of Dover (Carruthers, 1935). I am greatly indebted to Dr Carruthers for providing unpublished records required to bring the comparison up to date (Table VI). The records are arranged in order

TABLE VI. COMPARISON BETWEEN WINTER PHOSPHATE MAXIMA AND REPRESENTATIVE DAILY WATER-FLOW PAST THE VARNE LIGHT VESSEL IN THE PRECEDING YEARS

Year Jan.–Dec.	Residual current at Varne; miles per lunar day towards a true direction	Winter	Phosphate maximum at E 1: mg.-atom/m.^{3}	Phosphate maximum at E 1: Deviation from mean (%)
1927	3·1 N 40° E	1927–28	0·69	+33
1930	3·8 N 33° E	1930–31	0·52	0
1928	3·3 N 26° E	1928–29	0·69	+33
1929	3·2 N 25° E	1929–30	..	..
1931	3·2 N 18° E	1931–32	0·47	−10
1935	4·2 N 10° E	1935–36	0·47	−12
1936	4·1 N 9° E	1936–37	0·48	− 8
1934	3·9 N 7° E	1934–35	0·42	−19
1932	3·5 N 6° E	1932–33	0·53	+ 2
1937	3·5 N 6° E	1937–38	0·47	−10
1933	2·9 N 8° W	1933–34	0·48	− 8
		Mean*	0·52	..

* Mean of winters 1927–8–1937–8, except 1929–30 for which no records are available. This mean is not the same as that in Table V.

of decreasing easting of the current. In the four calendar years 1927–30 the average set of the current always lay between 25° and 40° east of north. In 1932–7, years of low phosphate, the average set lay between 8° west and 10° east of north. This comparison suggests that water of higher phosphate content is unlikely to work into the western end of the English Channel until the average residual current at the Varne lightship shows greater easting.

THE RELATION BETWEEN THE WINTER PHOSPHATE MAXIMA AND ABUNDANCE AND COMPOSITION OF PLANKTON AND YOUNG FISH

Russell (1935, 1936) has found that fluctuations in the phosphate content at E 1 are closely correlated with fluctuations in numbers and changes in composition of the plankton population. Broadly speaking water poor in phosphate as judged by the winter maximum, is characterized by the presence of *Sagitta setosa*, scarcity of all other holoplanktonic organisms, and poor production of the young of summer spawning fish. Water rich in phosphate is associated with *S. elegans* and other indicators of "Atlantic" water, a rich and varied zooplankton population and successful production of young fish. For a more detailed account of this topic Russell's papers must be consulted.

In any study of the impoverished state of the fisheries in the western end of the English Channel, the question of overfishing must take pride of place. If the intensity of fishing exceeds the natural recovery rate of the stock, the chemical and biological conditions governing that recovery rate are of lesser importance. Even so the evidence is growing ever stronger that the impoverishment, at least in part, may work back to the depletion of inorganic phosphate available in the first place for the growth of phytoplankton and ultimately for that of all animals living in our waters. As yet we are unable to say whether the richer conditions of the 1920's or the poorer ones of the 1930's are the more normal or whether both form part of some cyclical process which will recur. Even so it would appear that any considerable improvement in the fisheries is likely to be preceded, not only by a lesser intensity of fishing, but by an increase in the available inorganic phosphate and with predominance of *Sagitta elegans* over *S. setosa* in the western end of the Channel.

More detailed Comparison of the Years 1923 to 1937

The interval between the time of the winter maximum for phosphate and mid-May (Table III) covers the vernal outburst of diatoms and the consumption of phosphate is an index of the quantity of phytoplankton produced. The years may be grouped in order of productivity:

*****	1923	1926		
****	1924	1925	1929	1931
***	1928	1933		
**	1932	1934	1937	1938
*	1935	1936		

In several of the earlier years much of the phosphate was used up in short periods of intensive plant production. Nevertheless 1932, 1934, 1937 and 1938 were probably poor survival years and 1935 and 1936 must have been exceptionally bad. In 1935 not only was the winter maximum the lowest on record but of this phosphate only 49 % was used between January and May, the lowest percentage utilization yet recorded. The entire consumption during these five months was considerably less than during several periods of a few weeks in earlier years. These conditions were mirrored in the exceedingly low production of young fish in that year, also the lowest recorded (see Table V).

Due no doubt to different degrees of vertical mixing in different years (cf. Atkins, 1930, p. 825), the percentage consumption of the total inorganic phosphate content of the water column fluctuates between 49 and 81 % for the spring period and between 63 and 93 % for the period between winter maximum and summer minimum. Although some phosphate may be regenerated and used more than once in one growing season, these fluctuations are probably highly significant. For example although the maximum in the winter 1930–1 was only 0·52 mg.-atom/m.^{3}, the efficiency of phosphate utilization in the following spring and early summer was so high that the year 1931 is placed in the "four star" class in the list on p. 189. If other periods be studied in Table III similar variations will be found between the different years which may be of significance for the survival of young fish.

In 1931 (Cooper, 1933*b*) calculations of minimum crop production were made on the basis of the fall in several nutrient salts between the winter maximum and summer minimum at station E 1 (Table VII). The figure for

TABLE VII

1931 Between	On basis of change in	Phytoplankton produced, wet weight. Metric tons per sq. km. of surface for a depth of 72 m.
4/12 and 26/8	Phosphorus	1650
19/2 and 10/7	CO_2	1730
23/3 and 10/7	Nitrate-N (incl. nitrite-N)	1270
23/3 and 18/5	Total inorganic N	1350
19/2 and 26/8	O_2 lost to atmosphere	1000

phosphorus has now been corrected for salt error. The oxygen calculation is almost certainly too low and the nitrate-nitrogen took no account of other available forms of nitrogen such as ammonia. Such a calculation based on total inorganic nitrogen has been added to Table VII. Even this is rather uncertain since we know nothing of the amounts of urea, amino-acids and other simple organic nitrogen compounds which may quickly become available. The agreement is good and a figure of about 1650 metric tons for a water column one sq. kilometre in area and 72 m. deep seems representative. This was associated with a consumption of 0·46 mg.-atom P/m.^{3} (corrected). On this basis crop figures have been calculated for all the years for which data are available (Table V). A summarized account of phytoplankton production follows:

PRODUCTION OF PHYTOPLANKTON 1923–38, AS DEDUCED SOLELY FROM NUTRIENT SALT DATA

(In this account "available phosphate" means the winter maximum available for the following year's production.)

1923 No data until March 7. Probably little production until then. Average consumption of phosphate during April. Very heavy consumption during May. A late year.

1924 Production started in January and continued steadily until June. Although definitely an early year, conditions were good throughout for the survival of young fish dependent on phytoplankton. The water was, however, very cold.

1925 Production was crowded into the 6 weeks between March 14 and April 22 when two-thirds of the available phosphate and also silica were consumed. Possibly a poor survival year for all organisms other than those able to use this concentrated production of diatoms. Much of this may have gone to waste.

1926 Three-quarters of the available phosphorus was used in the four weeks, March 11–April 10. In this period the consumption was greater than the total amounts available for use in the springs of 1932, 1934, 1935, 1936, 1937 and 1938 and equal to those of 1931 and 1933.

1927 A very late year. Regeneration of phosphate preponderated up to March 21 after which no phosphate data are available. Nitrate results show considerable production in April and May.

1928 "Early and late." Periods of strong production: January 31–February 21; March 27–April 5; April 19–May 5. The first two were periods of diatom production, the last one of *Phaeocystis* or other non-siliceous phytoplankton. The period February 21–March 27 was one of regeneration and conditions were then unfavourable.

1929 On the whole an average year. Although some production occurred between January 7 and March 4, the vernal outburst cannot be said to have got under way before March 26. In the fortnight following, one half of the available phosphate was consumed. Records cease on April 11. Such intense short period production as occurred in 1925, 1926 and 1929 is not likely to be of great value to the herbivores since these are thought to avoid dense growths of phytoplankton.

1930 No records.

1931 An early year. Production started in December and was well spread out. The month February 19–March 23 was the peak period during which 40 % of the available phosphate was used.

1932 Inadequate data.

1933 A late year but even so has much in common with 1931.

1934 "Early and late." Greatest production occurred in January and April. February and March were poor months.

1935 Very late and exceptionally poor. April was the only month with production of any consequence, consumption of phosphate being then about average. Not only was the initial stock of phosphate very low, but it was very inadequately used.

1936 A poor year. Some consumption of phosphate occurred throughout February, March and April.

1937 In mid-February no sign of any vernal outburst was apparent. No further records are available until mid-May when surface phosphate was nearly exhausted.

1938 A late year and poor; 25 % of the total phosphate was used up in four days, April 14–18, and 50 % during the first three weeks of April. This represented four-fifths of the spring minimum production.

N.B. All the years after 1930 are affected by the marked fall in the winter maximum for phosphate which took place about then.

Autumn Diatom Outbursts

In the late summer and autumn the chemical evidence is difficult to interpret owing to the uncertain balance between consumption by plants and regeneration from dead material. The evidence suggests that outbursts occurred as follows:

1923	August, September.	1931	August?
1924	September.	1932	None.
1925	August.	1933	End September–mid-October.
1926	None.	1934	None.
1927	(No records.)	1935	?
1928	September (1st fortnight).	1936	?
1929	(No records.)	1937	August?
1930	None.		

The Spring Outbursts at Stations E 1 and E 2

Attention has been drawn (Atkins, 1930; Cooper, 1933*a*) to the quite different behaviour of the water masses at these stations between the February and May cruises. Three further years' work has added more data which repay examination (Tables VIII and IX). In only one year has more phosphate been found in February at E 2 than at E 1 and in five out of nine years the amount has been much less. Either the spring outburst regularly starts earlier in the more southerly waters, or, equally regularly, Station E 2 is occupied by a body of water quite different from that at E 1. The salinities shed no light on this. However, when the February results are examined in conjunction with the next cruise in May, it is seen that for every year except 1934 production at E 1 has far outstripped that at E 2 (Table IX). For the nine years for which we have phosphate records, the mean production in the upper layers at E 1 was twice as great as that at E 2. It is difficult to allow for the different depths at the two stations but, if the calculations are based on the changes in the whole water column to the bottom, the same general picture emerges. There is probably

Table VIII. Average Content of Water Column between the Surface and 20 m. depth at Stations E 1 and E 2 in February; mg.-atom/m.³ P

Date	E 1	E 2
4/2/31	0·53	0·41
12/2/34	0·35	0·48*
14/2/33	0·46	0·365
15/2/27	0·53	0·51
15/2/24	0·615	0·59
17/2/25	0·59	0·37
21/2/28	0·52	0·42
26/2/35	0·43	0·40*
Mean	0·50	0·44
Also 11/3/26	0·68	0·47

* Station midway E 1–E 2.

Table IX. Fall in the Average Phosphate Content of the Water Column between the Surface and 20 m. depth at Stations E 1 and E 2 between the February and May Cruises; mg.-atom/m.³ P

Year	Between cruises of	Fall at E 1	Fall at E 2
1929	Jan. 7–Mar. 26	0·20	0·17
1931	Feb. 4–Apr. 22	0·34	0·06
1934	Feb. 12–May 1	0·21	0·21
1924	Feb. 15–May 20	0·42	0·32
1925	Feb. 17–May 13	0·50	0·18
1928	Feb. 21–May 7	0·26	0·20
1935	Feb. 26–May 2	0·25	0·07
1923	Mar. 7–14–May 22–25	0·56	0·28
1926	Mar. 11–May 17	0·47	0·05
	Mean for nine years	0·36	0·17

more vertical mixing of the water in mid-Channel, but while this may tend to keep down multiplication of the diatoms in stormy weather, it should also help to bring up the bottom store of phosphate into the optimum photosynthetic zone. Cruises to E 2 were discontinued in 1936.

Surface Regeneration of Phosphate

Atkins (1930) found large quantities of phosphate, up to 3 mg.-atom/m.^{3}, at the L series of stations on January 2 1929 and attributed them to regeneration of phosphorus from organic material at the surface. Supporting evidence for this view is set out in Table X which includes all occasions when the phosphate content of the surface water was at least 0·1 mg.-atom/m.^{3} greater than at 5 m.

Table X. Surface Regeneration of Phosphate at Station E 1

Depth (m.)	2/1/29	23/1/36	31/1/28	1/3/28	21/3/27	22/3/34	7/4/31	12/5/36	13/5/38
0	0·91	0·58	0·82	0·63	0·78	0·54	0·42	0·58	*
5	0·64	0·44	0·67	0·49	0·51	0·39	0·28	0·44	0·22
Average 5–25	0·64	0·46	0·68	0·53	0·52	0·41	0·25	0·46	0·22
Depth (m.)	8/6/38	15/6/32	4/7/28	11/7/28	16/8/28	29/8/28	23/9/26	19/10/26	24/11/26
0	0·22	0·24	0·23	0·16	0·65	0·46	0·29	0·49	0·78
5	0·06	0·02	0·09	0·03	0·02	0·07	0·10	0·32	0·46
Average 5–25	0·09	0·06	0·08	0·05	0·10	0·21	0·09	0·32	0·48

* Triplicate analyses on three samples taken in one routine haul, 1·10, 1·10, 1·13; analysis on sample collected half an hour later, 0·44.

Occasionally, as in the four cruises in June and July, this might be attributed to the light at the surface being too intense for active photosynthesis, depletion of phosphate occurring at the optimum depth around 5 or 10 m. This explanation cannot hold at other seasons. On May 13 1938, analyses showed a large change in surface phosphate whilst the ship was drifting freely at Station E 1. Since this type of irregularity is confined to surface samples, contamination only of these is highly unlikely. The phenomenon is not confined to any one season of the year and appears to be independent of weather conditions. High surface phosphate values have been found following calm and stormy weather and with winds from all points of the compass. It is true that winds from the southerly and westerly quadrants have predominated, but these are the prevailing winds of the district. Regeneration of phosphate from decomposing floating organic material, as suggested by Atkins, provides the only reasonable explanation.

I am indebted to Dr H. W. Harvey for collecting the greater part of the water samples used in this work, also to Mr C. F. Hickling and Mr P. G. Corbin for some in 1937 and 1938.

Summary

At Station E 1, 22 sea miles south-west from Plymouth, the winter maximum for phosphate, representing the stock available for plant growth in the following spring, averaged 0·67 mg.-atom/m.³ for the winters 1923–4 to 1928–9 and only 0·47 mg.-atom for 1930–1 to 1937–8. This fall in phosphate shows a close correlation with the abundance of summer-spawning young fish (Russell). Since water containing similar low phosphate appeared to occupy the English Channel in 1916 (Matthews), the inflow of warm Atlantic water in the autumn of 1921 may well have brought with it the relatively rich phosphate found in the 1920's.

The impoverishment of phosphate around 1930 runs parallel with a decrease in the easting of the residual current at the Varne lightship in the Straits of Dover (Carruthers).

On the basis of spring phosphate consumption, the years may be classified in order of productivity:

* * * * *	1923	1926		
* * * *	1924	1925	1929	1931
* * *	1928	1933		
* *	1932	1934	1937	1938
*	1935	1936		

The efficiency of utilization of the total stock of phosphate varies from year to year. In 1935 it was only 63 % whereas a much higher percentage, 93 %, placed 1931 in the four star class.

Between February and May, the phosphate consumption in the upper layers at E 1, averaged over nine years, is twice as great as that at E 2 in mid-Channel.

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