

Atmospheric wet deposition of soluble macro-nutrients in the Cilician Basin, north-eastern Mediterranean sea

Türkan Özsoy

Mersin University, Science and Literature Faculty, Department of Chemistry, Çiftlikköy, 33342 Mersin, Turkey. E-mail: tozsoy@mersin.edu.tr; Fax: +90 324 361 00 46; Tel: +90 324 361 00 01 (10 lines)/124

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In order to estimate wet deposition atmospheric fluxes of macro-nutrients into the eastern Mediterranean coastal waters, soluble inorganic phosphate (PO_4^{3-}), nitrate (NO_3^-) and nitrite (NO_2^-) concentrations in precipitation (from February 1996 to June 1997) have been measured at a coastal sampling site, Erdemli, Turkey. Water-soluble inorganic PO_4^{3-} -P, a reactive, bioavailable, limiting macro-nutrient in the oligotrophic waters of the eastern Mediterranean was studied with respect to its contribution to biological productivity. Reactive PO_4^{3-} -P and $\text{NO}_2^- + \text{NO}_3^-$ -N concentrations were found to be highly variable in rainwater samples. One of the aims of the study was to determine the contribution of dust transport to the soluble macro-nutrient budget of the eastern Mediterranean. No differences were found between the mean reactive P and $\text{NO}_2^- + \text{NO}_3^-$ -N concentrations of "red rain" and normal rain events. Most likely as a result of low solubility of crustal phosphorus, dust episodes were not found to be important sources of reactive P, in terms of wet deposition. The annual wet deposition fluxes of reactive PO_4^{3-} -P and $\text{NO}_2^- + \text{NO}_3^-$ -N into the Cilician Basin were respectively estimated to be 0.010 g P m^{-2} per year and 0.23 g N m^{-2} per year, which are comparable to the fluxes from land-based sources in the north-eastern Mediterranean. The incorporation of water soluble bioavailable PO_4^{3-} -P and $\text{NO}_2^- + \text{NO}_3^-$ -N delivered via atmospheric wet deposition could be responsible for approximately 3.3% (0.40 g C m^{-2} per year) and 11.0% (1.31 g C m^{-2} per year) respectively, of the mean annual new production in the north-eastern Mediterranean.

1 Introduction

The atmosphere has been recognized as one of the main transport pathways for nutrients and trace elements to the sea surface.¹⁻⁴ Wet and/or dry deposition mechanisms play important roles particularly for oligotrophic oceanic areas⁵ and semi-enclosed seas such as the Mediterranean.^{6,7} Among the atmospherically transported materials, pulses of mineral dust from North Africa into the Mediterranean region could deposit micro- (e.g. Fe, Zn, Mn, Co, Ni)^{8,9} and macro-nutrients (e.g. PO_4^{3-} and NO_3^-)^{6,10,11} at the sea surface, and possibly contribute to marine biological production.¹² Among these nutrients, PO_4^{3-} is generally known to be the limiting nutrient for phytoplankton production in the eastern Mediterranean, typically having a high N:P ratio (>20:1) near the sea surface.^{13,14}

Most studies in the western^{6,10,15-17} and the eastern^{11,18} Mediterranean regions have been directed at the determination of macro-nutrient contents of wet deposition. Particular attention has been given to inorganic nitrogen for its major role in anthropogenic air pollution related to industrial/agricultural activities or traffic emissions,¹⁹ which are partly responsible for increased acidity of rainwater²⁰ and contribute to eutrophication in coastal²¹⁻²³ and/or terrestrial ecosystems.^{24,25} The data for macro-nutrient contents of dry deposition are very scarce and as in the case of wet deposition, they are mostly based on flux estimates derived from inorganic nitrogen concentrations of atmospheric aerosols.^{26,27} Although the experiments applied to loess material showed the process of phosphate removal by aeolian loess particles exists, due to higher release of P, the input of such aeolian loess particles to the Levantine waters results in a net addition of atmospherically derived dissolved inorganic phosphate.¹¹

This study aims to quantify soluble macro-nutrient contents

in wet atmospheric deposition, in particular, the supply of macro-nutrients when dust exists in the local atmosphere. We evaluate the annual nitrogen and phosphorus supply by wet deposition and estimate their contribution to primary production in the north-eastern Mediterranean coastal waters.

2 Materials and methods

2.1 Sampling station

The sampling site is located at the Institute of Marine Sciences-Middle East Technical University (IMS-METU) ($36^\circ 33' 54'' \text{ N}$, $34^\circ 15' 18'' \text{ E}$) on the south-eastern Mediterranean coast of Turkey, which can be accepted as a rural area. The station is not under the direct influence of industrial sources since activities such as petroleum refining, soda production, non-ferrous metal industry (e.g. chromium), thermal power and fertilizer plants and pulp and paper production take place along the coast at distances of more than 50 km to the east and west of the sampling tower. Erdemli (a small town with a population of 25 000) and Mersin (a big and industrialized city with more than 1 000 000 inhabitants) are the two nearest urban centres located 7 and 45 km east of the sampling site, respectively. Intensive agricultural and limited touristic activity can be found in the close vicinity.

2.2 Sampling procedure

A total of 87 precipitation samples were collected on an event basis between 5 February 1996 and 13 June 1997 by a Wet/Dry Sampler Analyzer, Model ARS 1000, MTX Italy, S.p.A., installed on a tower at a height of 22 m above sea level. For a detailed procedure readers are referred to Özsoy and Saydam.²⁸ Precipitation samples collected for each event were brought to

the laboratory immediately following the cessation of rain. Monthly field blanks were prepared by pouring 200 mL of double-distilled, de-ionized water into the sampling bucket. A total of 14 field blanks were submitted to the same procedure as the precipitation samples. Precipitation samples and field blanks were filtered through a 0.45 µm pore size membrane filter (MFS, cellulose acetate, 47 mm diameter) by applying gentle negative pressure immediately after collection to avoid possible exchange between solid and liquid phases. Precipitation samples were divided into aliquots to be used in different analyses, and subsamples reserved for nutrient analysis were kept frozen at -18 °C in HDPE bottles for a few weeks until analysis. Some events could not be sampled for macro-nutrient analysis due to insufficient quantities of precipitation (rainfall <1.0 mm). Sixty-one precipitation samples of sufficient volume were collected for macro-nutrient analysis during the 16 month sampling period. Because the labile ammonia fraction might often constitute a major part of the N deposition, samples should be analyzed as soon as possible. Because of insufficient means, such as availability of laboratory facilities and the quantity of collected samples, we were not able to carry out prompt analyses for this ion.

The pH in rainwater was measured by a Microprocessor pH-meter (WTW-Model pH537, accuracy of 0.01 pH unit). Conductivity measurements were performed with a Model 4070 Conductivity-Meter (Cole Palmer). The amount of precipitation was recorded at a sampling rate of 0.5 h by a rain-gauge of Anderrea Meteorological Station-installed at the roof of the Institute.

Soluble macro-nutrient analyses were performed using a Technicon Model two-channel Autoanalyzer. The applied colorimetric methods were similar to those described by Strickland and Parsons²⁹ and Grasshoff *et al.*³⁰ The subtracted blanks were less than 1% of the mean sample concentration for NO₂⁻ + NO₃⁻-N and below the detection limit for ortho-phosphate (o-PO₄³⁻-P) for the precipitation samples. The accuracy of the analytical results were tested against QUASIMEME (Quality Assurance of Information for Marine Environmental Monitoring in Europe Laboratory Performance Studies) intercalibration program samples. The analytical precision was found to be approximately 7% for PO₄³⁻ and 8% for both NO₃⁻ and NO₂⁻ anions. The detection limits for NO₃⁻ and PO₄³⁻ were 0.05 µM and 0.02 µM, respectively.

Since the concentration of the dissolved Al in precipitation was below the detection limit of the method (7.5 µM), only particulate Al concentrations, remaining on the 0.45 µm filter have been measured as an indicator of dust in the particulate fraction of the precipitation samples. Membrane filters were digested according to the procedure given by UNEP,⁴⁹ using a microwave digestion oven (Questron Corporation, Q45 EnviroPrep Model). Particulate Al concentrations were determined directly with an Atomic Absorption Spectrophotometer equipped with a deuterium (D2) lamp for background correction (GBC model 906 unit with a FS3000 flame attachment) using a N₂O/acetylene flame. KNO₃, at a final concentration of 2000 mg L⁻¹ K⁺, was added to samples and standards to suppress ionization. The mean Al concentration

of 14 field blanks submitted to the same treatment as the precipitation samples was found to be below the detection limit of 7.5 µM, defined as three times the standard deviation of the blank value. The accuracy of the analytical procedure was tested by analyzing standard reference material light sandy soil (CRM 112) of Community Bureau of Reference Brussels (BCR). The overall analytical precision was approximately 6% for Al.²⁸

2.3 Air mass back trajectories

Three dimensional, 3-day backward trajectories for air masses arriving at the sampling point on 12 00 UT of the sampling day at levels of 900 and 850 hPa within the boundary layer and 700 and 500 hPa within the free troposphere were calculated for each aerosol and precipitation sampling day. The trajectory model of the European Center for Medium-Range Weather Forecasts (ECMWF) in Reading, England was applied to 3D analyzed wind fields available from the MARS archive of ECMWF. The method is similar to the method developed by Martin *et al.*,³¹ and does not give any information about precipitation events during the excursion of the air masses.

3 Results and discussion

3.1 Macro-nutrient content of precipitation samples

Minimum and maximum rainfall values for the sampling period of 5 February 1996–13 June 1997 were, respectively, 0.2 and 87.6 mm. The cumulative precipitation during this same period was 710 mm. The climatological mean annual precipitation in the sampling region was 581 mm,³² compared with 540 mm during the 5 February 1996–5 February 1997 period. The measurements of pH, conductivity and particulate Al obtained during the same sampling period have been described elsewhere.²⁸ The overall statistics of the measured parameters in Erdemli precipitation are presented in Table 1. Due to variability in atmospheric transport, particulate Al, as well as other measured constituents in precipitation showed large variations, with standard deviations typically larger than the arithmetic mean of each constituent (Table 1).

Particulate Al measurements of filtered precipitation samples, including 18 "red rain" samples, supported by air mass back trajectory analyses revealed a total of 12 outstanding dust transport episodes during the entire sampling period. Tropospheric air mass trajectories arriving at 500 hPa pressure level in Fig. 1 indicate all of these episodes either to have originated or passed over North Africa with an ascending motion that is typical of frontal systems,^{33,34} reinforcing dust transport.³⁵

Statistical results for the measured parameters in red rain samples collected during the 12 outstanding dust transport episodes and normal rain samples not containing mineral dust are compared in Table 2. Although the volume weighted mean NO₂⁻ + NO₃⁻-N concentration of red rain (38.6 µM) is approximately 50% greater than the mean of the normal rain samples (25.2 µM), the difference between arithmetic means of NO₂⁻ + NO₃⁻-N concentration of red rain and normal rain is not statistically significant (*p* < 0.05). Since concentration of soluble species is a function of precipitation volume³⁶ this type

Table 1 Statistical results of the measured parameters: pH, conductivity (µS cm⁻¹), particulate Al (Al_{par}), PO₄³⁻-P and NO₂⁻ + NO₃⁻-N concentrations (µM) in the precipitation samples for the whole sampling period at Erdemli. The number of the samples are given in parenthesis.

Parameter	Arithmetic mean	Geometric mean	VWM ^a	Minimum–maximum
pH (87)	5.6 ± 0.9	5.5	4.95	3.5–7.6
Conductivity (41)	74.6 ± 79.6	51.4	—	12.9–391.0
Al _{par} (84)	88.77 ± 247.50	15.28	56.31	0.37–1843.0
PO ₄ ³⁻ -P (61)	1.09 ± 2.94	0.19	0.51	BDL ^b –16.09
NO ₂ ⁻ + NO ₃ ⁻ -N (61)	45.09 ± 50.31	28.13	26.50	BDL ^b –247.40

^aVWM: volume weighted mean ^bBDL: below detection limit

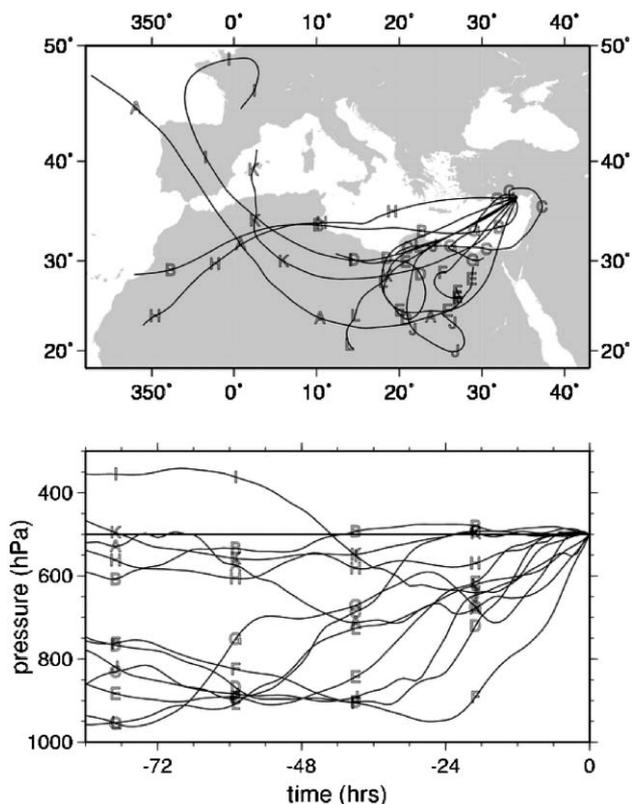


Fig. 1 The air mass-back trajectories of 12 outstanding dust transport episodes at 500 hPa, associated with 18 “red rain” events during the entire precipitation sampling period in Erdemli. Letters A–L respectively were assigned to trajectories ending at Erdemli, on each dust transportation date. The assigned letters establish horizontal and vertical components of three-dimensional motions for 3.5 days preceding an event recorded in precipitation measurements.

of comparison should in fact be based on volume weighted means. The difference between the volume weighted mean $\text{NO}_2^- + \text{NO}_3^-$ -N concentrations of two different data sets is larger and seems to support the suggestion that mineral dust surface might act as a receptor for the accumulation of atmospheric oxidation products,³⁷ indicating the highly soluble character of nitrite and nitrate ions during wet scavenging processes. However, the same is not true for atmospheric soluble phosphorus, most probably due to the low solubility of the crustal fraction. The mean PO_4^{3-} -P concentration ($0.47 \mu\text{M}$) of red rain samples (Table 2) is almost the same as the mean of normal rain samples ($0.52 \mu\text{M}$) (Table 2). The maximum solubility of crustal phosphorus in Saharan material was found to be 8%³⁸ and this poor solubility has been confirmed by several other authors.^{5,10} The positive correlation we find between $\text{NO}_2^- + \text{NO}_3^-$ -N and reactive PO_4^{3-} -P in precipitation ($r = 0.51$ for a sample size of $n = 61$) suggests that the source of soluble phosphorus is mostly anthropogenic, since

atmospheric nitrogen is exclusively of anthropogenic origin. One common source for these elements might be nitrate and phosphate fertilizers extensively used in the region, especially during the spring and early summer months, dominated by rainfall. Most likely, part of the applied fertilizers appear to have become airborne through wind action, contributing to the atmospheric budget of these elements by forming aerosols. Positive correlation between $\text{NO}_2^- + \text{NO}_3^-$ -N and PO_4^{3-} -P concentrations of the data set of 18 red rain events ($r = 0.70$ for a sample size of $n = 9$) also supports the suggestion that mineral dust most likely acts as the host accumulating anthropogenic phosphorus fractions (from biomass burning, incinerators, fertilizers, etc.).

The pH in precipitation samples had a range of 3.5–7.6. Although nitric acid has been indicated to be an important contributor to the acidity of precipitation,³⁹ with a 50% relative contribution at Antalya, Turkey,⁴⁰ we found no correlation between H^+ (calculated from pH values) and the corresponding $\text{NO}_2^- + \text{NO}_3^-$ -N concentrations in our samples.

3.2 Wet deposition fluxes

The amounts of precipitation measured during each event have been converted into daily quantities in order to calculate wet deposition fluxes. On an event basis, the minimum and the maximum wet deposition fluxes of macro-nutrients were highly variable ($0.1\text{--}36.6 \text{ mg NO}_2^- + \text{NO}_3^-$ -N m^{-2} and $0.001\text{--}6.7 \text{ mg PO}_4^{3-}$ -P m^{-2}). The annual fluxes were calculated as the sum of the daily fluxes measured during February 1996–February 1997. The alternative method of estimation based on a product of the volume-weighted mean concentrations with the annual mean precipitation was not used because it would create greater uncertainties in the wet deposition flux estimates. The calculated annual wet deposition flux of particulate Al, 942 mg m^{-2} per year was found to be the highest value among reported values from various stations around the world.²⁸ A total of 65 rain events occurred within the one year period, while 22 events could not be sampled for nutrient analysis due to insufficient amount of precipitation ($< 1.0 \text{ mm}$). The comparison of the annual wet deposition fluxes of $\text{NO}_2^- + \text{NO}_3^-$ -N and reactive PO_4^{3-} -P with those reported from various coastal locations around the Mediterranean are summarized in Table 3. The values presented in this table are not directly comparable with each other since the sampling periods and the precipitation of the corresponding hydrological years change from one station to another. In addition, most studies are based on dissolved inorganic nitrogen (DIN) measurements, corresponding to the sum of NO_3^- -N and NH_4^+ -N. The wet deposition fluxes reported for Israeli stations¹¹ are consistent with our results, despite the fact they were calculated from annual precipitation and volume-weighted mean concentrations. The annual NO_3^- -N flux value reported for Antalya,⁴⁰ approximately 500 km to the west of Erdemli, is low compared to our values at Erdemli.

Time series of wet deposition fluxes of $\text{NO}_2^- + \text{NO}_3^-$ -N and reactive PO_4^{3-} -P plotted alongside with Al concentrations,

Table 2 Statistical results of the pH, conductivity ($\mu\text{S cm}^{-1}$), particulate Al (Al_{par}), PO_4^{3-} -P and $\text{NO}_2^- + \text{NO}_3^-$ -N concentrations (μM) measured in the red rain samples, collected during 12 outstanding dust transport episodes and the normal rain samples not containing mineral dust. *N* refers to the number of the samples.

Parameter	<i>N</i>		Arithmetic mean		Geometric mean		VWM		Minimum–maximum	
	Red	Normal	Red	Normal	Red	Normal	Red	Normal	Red	Normal
pH	18	69	6.7 ± 0.6	5.4 ± 0.8	6.7	5.3	6.56	4.90	5.3–7.6	3.5–7.3
Conductivity	7	34	180.4 ± 134.8	52.8 ± 38.9	133.0	42.3	—	—	38.6–391.0	12.9–189.8
Al_{par}	17	67	360.3 ± 466.0	19.9 ± 24.1	152.4	8.5	433.8	11.0	4.9–1843	0.4–112
PO_4^{3-} -P	9	52	0.80 ± 0.95	1.13 ± 3.16	0.35	0.17	0.47	0.52	BDL–3.03	BDL–16.1
$\text{NO}_2^- + \text{NO}_3^-$ -N	9	52	57.5 ± 39.1	43.0 ± 52.0	45.6	25.9	38.6	25.2	15.9–126.1	1.1–247.4

Table 3 Comparison of the annual wet deposition fluxes of $\text{NO}_2^- + \text{NO}_3^-$ -N and reactive PO_4^{3-} -P (mg m^{-2} per year) with the data reported from various locations around the Mediterranean. The number of the samples are given in parenthesis.

Location	$\text{NO}_2^- + \text{NO}_3^-$ -N	PO_4^{3-} -P
Erdemli ^a (43)	230.9	9.7
Ashdod (Israel) ^b (57)	101.0	9.0
Tel Shikmona (Israel) ^b (179)	287.0	9.0
Haifa (Israel) ^c (84)	334.0*	7.4
South-eastern Mediterranean ^c (6)	301.0*	6.7
Antalya (Turkey) ^d (120)	174**	—
Cap Ferrat (France) ^e (25)	—	2.0
Capo Cavallo (Corsica) ^f (57)	—	13.1
Bavella (Corsica) ^g (164)	730*	—
Cap Ferrat (France) ^h	608–726*	15.8
C. Carbonare (Sardinia) ⁱ	240*	—
La Castanya (Spain) ^j (344)	252.5***	—

^aPresent work ^bHerut *et al.*,¹¹ ^cHerut and Krom,¹⁸ *DIN ($\text{NO}_3^- + \text{NH}_3$) flux ^dAl-Momani *et al.*,⁴⁰ **soluble wet deposition flux of NO_3^- -N ^eMigon and Sandroni,¹⁰ ^fBergametti *et al.*,⁶ ^gLoye-Pilot *et al.*,¹⁶ ^hMigon *et al.*,⁴⁶ after Guerzoni *et al.*,⁷ ⁱGuerzoni *et al.*,⁴⁷ ^jAvila,⁴⁸ ***calculated from reported volume weighted mean concentration of dissolved NO_3^- in bulk precipitation and the mean amount of precipitation.

respectively in Fig. 2a and b, do not seem to indicate any correlation of these macro-nutrients with mineral dust represented by Al. In Fig. 2a two outstanding cases of increased $\text{NO}_2^- + \text{NO}_3^-$ -N flux are indicated on 22 March 1996 and 4 December 1996. In the first case, a very high $\text{NO}_2^- + \text{NO}_3^-$ -N concentration of 224.2 μM in precipitation was responsible for a flux of 32.2 mg m^{-2} , while in the second case, high precipitation of 87.6 mm was responsible for the highest measured flux of 36.6 mg m^{-2} . In Figure 2b, only one peak occurred in the reactive PO_4^{3-} -P flux, reaching 6.66 mg m^{-2} on 15 December 1996, corresponding to an extremely high concentration of 14.4 μM . This phosphorus is most probably anthropogenic, since the particulate Al flux of this particular sample is quite low (0.63 mg m^{-2}). The same situation is also valid for the sample collected on 18 May 1997, with maximum reactive P concentration of 16.09 μM and a corresponding flux value of 0.7 mg m^{-2} . Since particulate Al flux of this sample was low (1.35 mg m^{-2}) we can safely conclude that phosphorus is mainly of anthropogenic origin in this case. Air mass back trajectories arriving at 900 and 850 hPa levels on 18 May 1997 are presented in Fig. 3. The almost isobaric air flows within the boundary layer appear to have spent most of their travel time over the Anatolian mainland. The short trajectory suggests that the air masses have been affected mainly by land based anthropogenic sources.

3.3 Wet-deposition of macro-nutrients to the north-eastern Mediterranean and its possible impact on primary production

Atmospheric wet deposition fluxes of $\text{NO}_2^- + \text{NO}_3^-$ -N and reactive PO_4^{3-} -P into the Cilician Basin were respectively estimated to be 0.23 g N m^{-2} per year and 0.010 g P m^{-2} per year. When these fluxes are uniformly distributed to the surface area of the Cilician Basin (approximately 34 000 km^2), the total wet atmospheric inputs of macro-nutrients, are found to be 7.85×10^3 tons N per year and 3.3×10^2 tons P per year. These inputs amount to approximately 14 and 4% of the total inputs respectively, of N and P from land-based sources in the north-eastern Mediterranean (57.2×10^3 ton $\text{NO}_2^- + \text{NO}_3^-$ -N per year and 9.6×10^3 ton PO_4^{3-} -P per year⁴¹). Therefore, the contribution of macro-nutrients from the atmosphere must be significant for the surface waters of the north-eastern Mediterranean, and particularly for the eastern Mediterranean, which is known to be one of the world's most oligotrophic seas with limited supply of nutrients to sustain production.⁴²

The total new production rate of 12 g C m^{-2} per year was estimated for the year 1992 in the Cilician Basin.⁴³ By using the Redfield C:N molar ratio of (106:16), we calculate that the estimated atmospheric wet deposition $\text{NO}_2^- + \text{NO}_3^-$ -N flux of 0.23 g m^{-2} per year could support a new production rate of 1.31 g C m^{-2} per year in the north-eastern Mediterranean and this value approximately accounts for 11% of the total new production rate of the Cilician Basin of the mean annual new production in the north-eastern Mediterranean. In fact, the contribution of atmospheric N deposition to the primary production rate of the north-eastern Mediterranean surface waters must be much higher than this value, since our N measurements did not include the NH_4^+ -N content of the wet atmospheric samples. As we have already stated in Section 3.2, our N and P flux estimates are consistent with the values reported for Israeli Stations.¹¹ The atmospheric DIN contribution to the primary production rate of the south-eastern Mediterranean was estimated to be 8% by Herut *et al.*¹¹ Even though, our N flux doesn't take into account inorganic N from atmospheric NH_4^+ , the atmospheric contribution to the primary productivity of the north-eastern Mediterranean (11%) is greater than the value reported for the south-eastern Mediterranean, most likely due to the calculation based on higher total new production rate of 16.7–19.2 g C m^{-2} per year reported for the eastern Mediterranean.⁴⁴ Our percentage is closer to values reported for the western Mediterranean (10–50% by Martin *et al.*¹⁵). Likewise, by using the C:P molar ratio of Redfield (106:1) we find that a total reactive PO_4^{3-} -P flux of 0.010 g m^{-2} per year could support a new production rate of 0.40 g C m^{-2} per year, which approximately corresponds to 3.3% of the total new production in this region. This value is within the range of 4–11% estimated by Herut *et al.*¹¹ for the south-eastern Mediterranean.

4 Conclusions

Reactive PO_4^{3-} -P and $\text{NO}_2^- + \text{NO}_3^-$ -N concentrations in precipitation (from February 1996 to June 1997) were measured at a coastal sampling site, Erdemli, Turkey. The concentrations of soluble macro-nutrients were found to be highly variable in rainwater samples. No difference was found between the mean reactive PO_4^{3-} -P concentration of red rain and normal rain events. Most likely as a result of low solubility of crustal phosphorus, dust episodes were not found to be important sources of reactive P, in terms of wet deposition. On the basis of volume weighted mean concentrations, red rain events were found to contain higher concentrations (approximately 50%) of $\text{NO}_2^- + \text{NO}_3^-$ -N, than the normal rain events. Therefore, dust episodes, particularly, associated with red rain events could be accepted as an important inorganic nitrogen source to the sea surface in the north-eastern Mediterranean.

The annual wet deposition fluxes of reactive PO_4^{3-} -P and $\text{NO}_2^- + \text{NO}_3^-$ -N into the Cilician Basin were respectively estimated to be 0.010 g P m^{-2} per year and 0.23 g N m^{-2} per year, which are comparable to the fluxes from land-based sources in the north-eastern Mediterranean. The incorporation of water soluble bioavailable PO_4^{3-} -P and $\text{NO}_2^- + \text{NO}_3^-$ -N delivered *via* atmospheric wet deposition could be responsible for approximately 3.3% (0.40 g C m^{-2} per year) and 11.0% (1.31 g C m^{-2} per year) respectively, of the mean annual new production in the north-eastern Mediterranean.

The N:P molar ratio of the wet atmospheric deposition (52.5) was found to be much higher than the mean N:P ratio (23.6) reported for the upper 1000 m water column of the Northern Levantine Basin.⁴⁵ The same ratio has been reported as ~ 28 for the deep waters of the Levantine Basin by the same authors. By considering the existence of the additional NH_4^+ -N contribution to the atmospheric inorganic nitrogen pool, we can safely estimate a much higher N:P ratio for the atmospheric

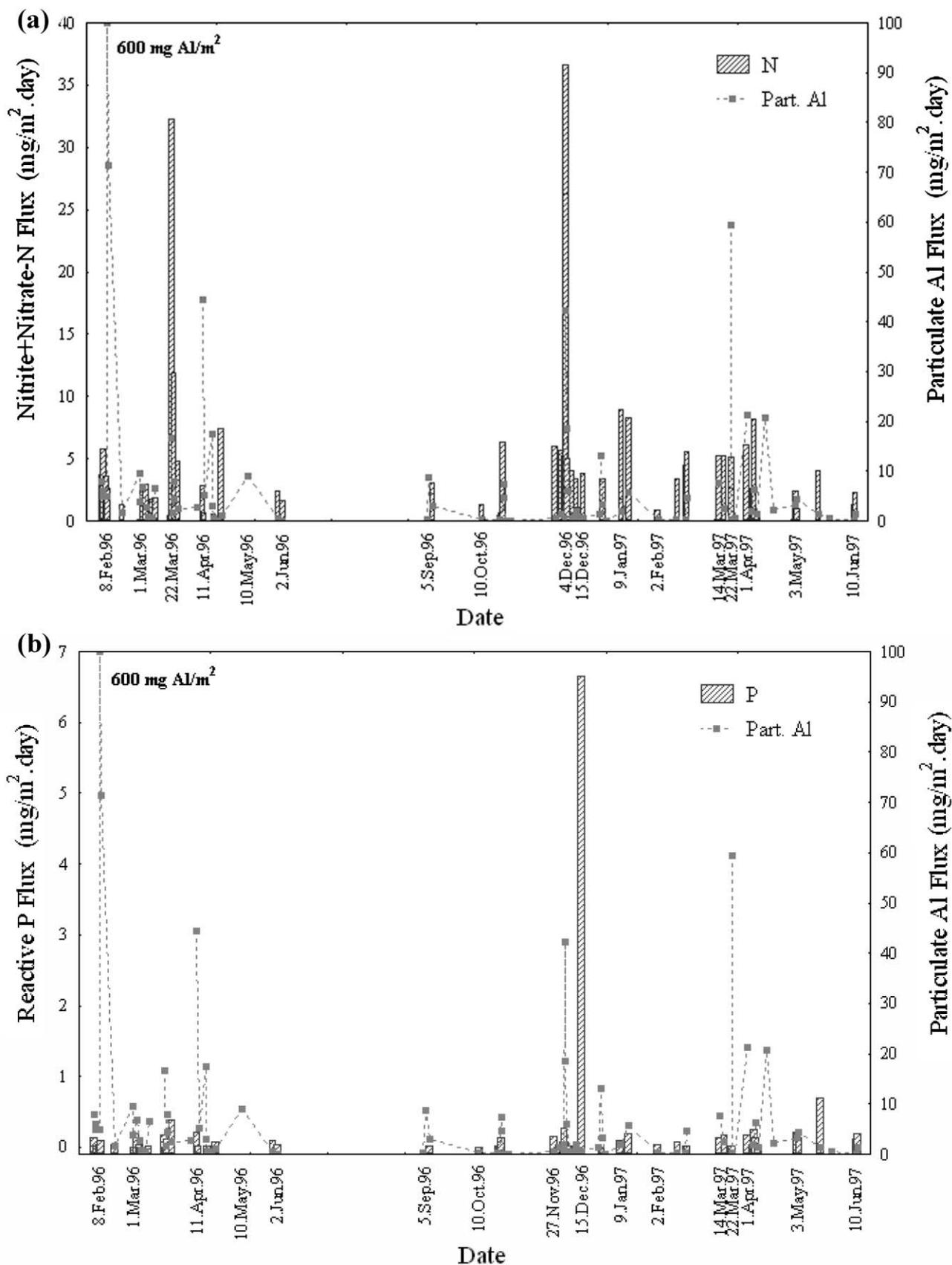


Fig. 2 (a) The time series of the wet deposition flux of $\text{NO}_2^- + \text{NO}_3^-$ -N and of particulate Al (mineral dust) in the north-eastern Mediterranean. (b) Time series of the wet deposition flux of reactive PO_4^{3-} -P and of particulate Al (mineral dust) in the north-eastern Mediterranean.

deposition over the north-eastern Mediterranean. Therefore, our atmospheric N:P molar ratio is much higher than the molar DIN:BIP (bioavailable, reactive IP) ratio reported for the Israeli Mediterranean coast (33) and the south-eastern Mediterranean (30).¹¹ This higher ratio of atmospheric N:P

is most probably due to the higher influence of anthropogenic nitrogen sources over the region compared with the south-eastern Mediterranean, and suggests a stronger reinforcement for arguments concerning the P-limited nature of the north-eastern Basin.

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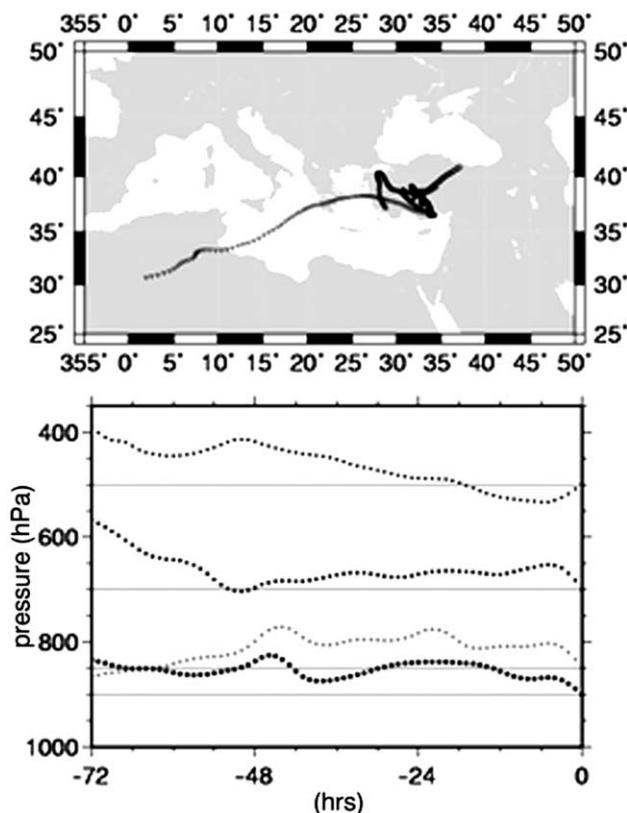


Fig. 3 Back trajectories arriving at Erdemli on 18 May 1997.

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