Biogeosciences Discuss., 9, 8307–8336, 2012
www.biogeosciences-discuss.net/9/8307/2012/
doi:10.5194/bgd-9-8307-2012

Biogeosciences
Discussions

Contribution of dust inputs to dissolved organic carbon and water transparency in Mediterranean reservoirs

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Received: 19 May 2012 – Accepted: 1 June 2012 – Published: 11 July 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Mediterranean reservoirs receive frequent Saharan dust inputs with soil-derived organic compounds mostly during stratification periods, when run-off inputs are particularly limited. Here, we quantified and optically characterized the water-soluble organic carbon (WSOC) of the (dry and wet) atmospheric deposition in collectors located near three reservoirs from the Western Mediterranean Basin. In addition, we determined, during the stratification period, the WSOC contribution to the pool of dissolved organic carbon (DOC) and the influence of the chromophoric organic compounds from the dust on water transparency.

We found synchrony both in the WSOC atmospheric inputs among collectors and in the DOC dynamics among the three reservoirs. DOC concentrations and WSOC atmospheric inputs were positive and significantly correlated in the two reservoirs more sensitive to atmospheric inputs: the most oligotrophic reservoir (Quentar) and the reservoir with the highest ratio of surface area to mixing water depth (Cubillas). Nevertheless, WSOC atmospheric inputs, during the stratification period, represented less than 10 % of the total DOC pool, suggesting that indirect effects of dust inputs such as primary productivity stimulation may also induce these synchronic patterns. Chromophoric compounds from dust inputs can significantly reduce water transparency to ultraviolet radiation (UVR). The depths where UVR at $\lambda = 320$ nm is reduced to ten percent of surface intensity (Z10 %) decreased 15 cm (about 24 %) in Beznar, 17 cm (about 27 %) in Cubillas, and 43 cm (about 39 %) in Quéntar due to dust inputs.

1 Introduction

Dissolved organic carbon (DOC) in lakes and reservoirs play a significant role in the context of global carbon cycle, since they are active sites for transport, transformation and storage of considerable amounts of organic C (Cole et al., 2007; Tranvik et al., 2009). A portion of this dissolved organic matter, termed chromophoric dissolved organic matter (CDOM), also absorbs ultraviolet and visible radiations regulating the intensity and spectral quality of light attenuation into the water column (Morris et al., 1995).

DOC dynamics in an aquatic ecosystem is determined by the balance between inputs vs. outputs, within-system production vs. loss, and concentration vs. dilution from exchange of water directly with the atmosphere (evaporation vs. precipitation). Then, DOC and CDOM depend on the relative influence of inherent ecosystem properties (i.e. morphometry, photosynthetic production, microbial processing, etc.) and external factors such as the catchment area, soil type and environmental conditions (Tipping et al., 1988; Curtis, 1998; Pace and Cole, 2002; Reche and Pace, 2002; Mladenov et al., 2008). Although external controlling factors of DOC in lakes are well documented across diverse geographical regions (Xenopoulos et al., 2003; Sobek et al., 2007), scarce information exists for reservoirs assuming a major role of run-off inputs in northern temperate regions. This lack of information is surprising in view of the increasing area occupied by reservoirs worldwide, particularly in arid and semiarid regions. In fact, Downing et al. (2006) recognized that the volume of water in impoundments increased by an order of magnitude between the 1950s and the present.

The geographic proximity of Mediterranean basin to the Sahara Desert, the world's major source of soil dust to the atmosphere (≈ 50 % of the global dust production) (Schutz et al., 1981), and the increase in dust exports as a consequence of Africa desertification (Prospero and Lamb, 2003; Mulitza et al., 2010), makes Mediterranean aquatic ecosystems particularly exposed to atmospheric inputs of Saharan dust (Löye-Pilot et al., 1986; Bergametti et al., 1992; Mladenov et al., 2011). These massive airborne plumes from Sahara Desert travelling toward the Mediterranean region are particularly frequent during spring and summer (Moulin et al., 1997). Previous studies in this region showed that Saharan dust contains substantial inorganic nutrients as soluble phosphorus that stimulates both phytoplankton (Bonnet et al., 2005; Morales-Baquero et al., 2006; Pulido-Villena et al., 2008a) and bacteria (Pulido-Villena et al., 2008b; Reche et al., 2009). However, scarce information exists about the direct contribution of atmospheric organic carbon associated with dust to DOC pool (Mladenov et al., 2009). These last authors have shown that a fraction of this water-soluble organic carbon (WSOC) contains chromophoric groups that affect significantly the optical properties of alpine lakes.

We selected three reservoirs ca. 40 km distant between them and located in an area submitted to intense dust deposition in the Southern Spain (Mladenov et al., 2011). They are within 1000 km of the Sahara Desert and it is known that about 70 % of dust exports are deposited within the first 2000 km from the mentioned desert (Schutz et al., 1981). These reservoirs differ in their trophy, morphometry and watershed characteristics (Perez-Martínez et al., 1991; Morales-Baquero et al., 1994; de Vicente et al., 2008) allowing us to explore the relative importance of reservoir-specific properties versus climatic external forcings.

In addition, during the stratification period in these Mediterranean reservoir (March–September), the typical reduction in rainfall (i.e. the decrease of runoff inputs), the concurrent higher frequency of Sahara dust events, and the conformation of an isolated upper layer (epilimnion); makes this period as the most convenient for evaluating the maximum contribution of atmospheric organic carbon inputs into these reservoirs. Here, we quantified and optically characterized water-soluble organic C (WSOC) from atmospheric (dry and wet) deposition and assessed its contribution to DOC pool and its influence on water UVR transparency in three contrasting reservoirs.

2 Material and methods

2.1 Study sites

The study reservoirs present contrasting characteristics, particularly with respect to nutrient limitation and morphometric and catchment properties (Table 1). Quentar is an oligotrophic, extremely P-limited (N:P molar ratio = 381) reservoir. It is located on the headwaters of the Genil River, a tributary of the Guadalquivir River, the largest river in Southern Spain. Its oligotrophic status is mainly a consequence of its location on sparsely populated and mountainous area, across closed-valley areas that render a low surface: depth ratio (Fig. 1). Cubillas reservoir is also located in the headwaters of the Genil River but its catchment area is much higher and affected by anthropogenic activity. Beznar reservoir is located at the Izbor River discharging directly into the Mediterranean Sea. Beznar and Cubillas, contrarily to Quentar reservoir, are located in densely populated and open-valley areas, which is lastly responsible for their higher trophic state (Perez-Martinez et al., 1991; Morales-Baquero et al., 1994). The catchment area in Cubillas is more than 6 fold higher than in Quentar and ≈ 1.8 fold higher than in Beznar (Table 1). In addition, the reservoir area to maximum depth ratio is much higher in Cubillas (109 m) than in Quentar (5 m) and Beznar (16 m) reservoirs. More details on these reservoirs can be found elsewhere (Rueda et al., 2007; de Vicente et al., 2008).

2.2 Atmospheric deposition sampling

Separate dry and wet atmospheric deposition samples were collected weekly using three MTX ARS 1010 automatic deposition samplers, located near to each one of the study reservoirs. Dry deposition was collected by rinsing the bucket with 1000 ml of Milli-Q ultrapure water, which was later used for all analysis. The volume of rain in the wet deposition bucket was recorded, and a 1000 ml aliquot was analyzed. If the rain volume was <1000 ml, it was brought up to that volume with Milli-Q ultrapure water. Detailed procedures for chemical analyses and for calculation of atmospheric deposition rates can be found elsewhere (Morales-Baquero et al., 2006).

Water-soluble organic carbon (WSOC) refers to the organic carbon from atmospheric deposition that is soluble in water and is measured as DOC (Yang et al., 2003; Mladenov et al., 2008). Samples for WSOC were analyzed by filtering collector samples through precombusted Whatman GF/F glass-fiber filters into pre-combusted 20 ml glass ampoules, acidified with phosphoric acid (final pH < 2), sealed and stored at 4 °C until analysis. DOC was analyzed by High-Temperature Catalytic Oxidation using a Shimadzu TOC-V CSH. WSOC absorbance of the filtrate was also measured during the 2004 samplings. UV-vis absorbance scans (220–750 nm) were performed in a 10 cm path length quartz cuvettes using a Perkin Elmer Lambda 40 spectrophotometer connected to a computer equipped with UV-Winlab software. The average value at the range 700–750 nm was used to correct UV absorbance values for scattering. Absorbances at 250, 320 and 440 nm were expressed as Neperian absorption coefficients (a_λ, m^{-1}) and molar absorption coefficients (ε_λ, $\mathrm{m}^2\,\mathrm{mol}^{-1}$) were calculated by dividing a_λ by the corresponding DOC concentration in mmol^{-1}.

Finally, to quantify the relevance of the inputs of chromophoric compounds on the diffuse attenuation coefficients for solar UV radiation in the reservoirs, we scaled-up the absorption coefficients at $\lambda = 320$ nm of WSOC inputs considering the collector area vs. lake area and water extraction volume vs. epilimnetic volume. Then, using the equations for attenuation coefficients at $\lambda = 320$ nm proposed by Morris et al. (1995), we estimated the depths where light intensity at 320 nm is reduced to ten percent of that at the surface ($z_{10\,\%}$) in the reservoirs and adding the absorbance of the chromophoric compounds linked to dust.

2.3 Monitoring of the water column

Water samples were collected on a weekly basis from March to September of 2004 and 2005. We merged epilimnetic water evenly distributed from three depths over the thermocline. Thermocline was determined each sampling day by using vertical temperature profiles at the deepest site of Quentar, Beznar and Cubillas reservoirs. All chemical and biological analysis were performed by duplicates.

Samples for dissolved organic carbon (DOC) analyses were collected after filtration through pre-combusted Whatman GF/F filters into pre-combusted 20 ml glass ampoules, acidified with phosphoric acid (final pH < 2), sealed and stored at 4 °C until analysis. DOC was analyzed following the same procedure described for WSOC. UV-vis absorbance scans (220–750 nm) of filtered samples were also performed following the same procedure described above for the atmospheric samples.

2.4 Statistical analysis

Statistical analyses were performed using Statistica 6.0 Software (StatSoft Inc, 1997) and Excel. For Student *t*-tests, unless otherwise stated, the significance level was set at $p < 0.05$. Since synchronous dynamics of variables among neighbour ecosystems is considered as a sign of climatic forcing at regional scale (Baines et al., 2000), we first performed correlation analyses among the WSOC and DOC dynamics and its optical properties to evaluate if there was any significant reservoir-external forcing. To link the atmospheric deposition of WSOC and DOC in the reservoir waters, we performed correlation analyses.

3 Results

3.1 Water-soluble organic carbon and chromophoric content in dust inputs

The average dry and wet deposition of WSOC during 2004 was 0.231 and 0.260 $\mathrm{mmol\,m^{-2}\,d^{-1}}$ in Quentar; 0.333 and 0.226 $\mathrm{mmol\,m^{-2}\,d^{-1}}$ in Cubillas; and 0.393 and 0.182 $\mathrm{mmol\,m^{-2}\,d^{-1}}$ in Beznar (Table 2). During 2005, the average dry and wet deposition of WSOC was 0.358 and 0.419 $\mathrm{mmol\,m^{-2}\,d^{-1}}$ in Quentar; 0.363 and 0.303 $\mathrm{mmol\,m^{-2}\,d^{-1}}$ in Cubillas; and 0.396 and 0.288 $\mathrm{mmol\,m^{-2}\,d^{-1}}$ in Beznar (Table 2). Significant synchrony of atmospheric WSOC inputs among collectors was found when all (2004 + 2005) data were merged and also between the collectors of Cubillas and Quentar for each year independently (Fig. 2; Table 3).

In 2004, the average absorption coefficients at 320 nm (a_{320}) of dry and wet deposition of WSOC were 2.28 and 2.30 $\mathrm{m^{-1}\,m^{-2}\,d^{-1}}$ in Quentar; and 3.09 and 1.80 $\mathrm{m^{-1}\,m^{-2}\,d^{-1}}$ in Cubillas; and 2.41 and 1.07 $\mathrm{m^{-1}\,m^{-2}\,d^{-1}}$ in Beznar (Table 2). The absorption coefficients at 250 nm (a_{250}) and 440 nm (a_{440}) of the dry and wet deposition of the WSOC are also reported in Table 2. We also observed synchronous dynamics in the absorption coefficients at 320 nm (a_{320}) between the collectors located in Quentar and in Cubillas reservoirs (Fig. 2, Table 3).

This synchrony among the collectors suggests a strong climatic forcing for the WSOC inputs and chromophoric contents superimposed on local sources of dust. In fact, the most prominent peaks of WSOC inputs (Fig. 2, black arrows) can be related to Saharan dust intrusions over the Southern Spain as reflected by aerosol index global maps and the data provided by the Spanish Ministry of Agriculture, Food, and Environment (www.calima.ws) (Fig. 3).

3.2 Dissolved organic matter and absorption coefficients in the reservoirs

During the stratification period of 2004, average DOC concentration was 0.163 mM in Quentar, 0.357 mM in Cubillas and 0.236 mM in Beznar and average DOC concentration during stratificaion of 2005 was 0.120 mM in Quentar, 0.336 mM in Cubillas and 0.235 mM in Beznar (Fig. 4, Table 4). DOC concentrations in the three study reservoirs showed synchronous dynamics during 2004 and 2005, except between Quentar and Beznar during 2004 and when all data were merged (Table 5). The absorption coefficients a_{250}, a_{320} and a_{440} were significantly higher in Cubillas and Beznar reservoirs than in Quentar during 2004 and 2005 (Fig. 4, Table 4). Synchronous dynamics of the absorption coefficients at 320 nm were found only between Quentar and Cubillas during 2005 (Table 5). The molar absorption coefficients (i.e. the absorption per mol of organic C) were slightly lower in Cubillas than in Quentar and Beznar (Fig. 4, Table 4).

3.3 WSOC contribution to dissolved organic matter and water transparency in the reservoirs

We explored if DOC synchrony among the reservoirs could be related to the climate-driven atmospheric inputs of WSOC. We found positive and significant correlations between DOC concentrations and WSOC inputs in Cubillas ($n = 38$; $r = 0.42$; $p < 0.05$; slope $= 0.14 \pm 0.05$) and in Quentar ($n = 44$; $r = 0.39$; $p < 0.05$; slope $= 0.08 \pm 0.03$)

when 2004 and 2005 data were merged (Fig. 5). Cubillas is the reservoir with the highest ratio surface area to mixing water depth and Quentar is the most oligotrophic reservoir (Table 1).

To evaluate whether atmospheric deposition provide substantial WSOC mass to directly influence DOC pool in each reservoir, we calculated the mass of WSOC loaded to the reservoirs during the stratification periods (Table 6). The mass of WSOC loaded during the whole stratification in 2004 and 2005 in the Quentar reservoir was 11 562 mol and 10 622 mol; in the Cubillas reservoir was 80 934 mol and 70 218 mol and in the Beznar reservoir 65 236 mol and 47 094 mol, respectively. Accordingly, WSOC loadings during the stratification periods of 2004 and 2005 accounted for 3.8 % and 3.6 % in Quentar; 5.6 % and 6.3 % in Cubillas; and 2.7 % and 2.5 % in Beznar of the epilimnetic DOC mass.

To explore the direct influence of the chromophoric compounds of WSOC on the UVR attenuation, we compared the depths where light intensity at 320 nm is reduced to ten percent of that at the surface ($z_{10\%}$) for each reservoir and considering also the extra absorption provided by the chromophoric compounds of WSOC (+ dust). Our results show that a highly significant ($p < 0.0001$) reduction in $z_{10\%}$ occurred in all of the study reservoirs by inputs of chromophoric compounds with the dust (Fig. 6). Average $z_{10\%}$ at 320 nm decreased from 0.62 m to 0.45 m in Cubillas (ca. 27 %), from 0.59 m to 0.45 m in Beznar (ca. 24 %) and from 1.10 to 0.67 m in Quentar (ca. 39 %).

4 Discussion

In general, we found synchronic DOC dynamics among the three study reservoirs (Table 5). Synchrony among spatially distant aquatic ecosystems is considered indicative of a significant climatic control in the region (Baines et al., 2000; Pace and Cole, 2002). In the study region, Saharan dust intrusions are frequent climatic events (Loye-Pilot et al., 1986; Bergametti et al., 1992) with a definite seasonal pattern with maximum dust exports during spring and summer (Moulin et al., 1997). In fact, we also found synchrony in WSOC inputs among all the atmospheric collectors (Table 3) underlining a minor contribution of local sources of dust. This synchrony among the DOC in reservoirs and among the WSOC in the collectors established significant links between DOC concentrations and atmospheric WSOC inputs in Quentar and Cubillas. The low DOC concentration in Quentar and the high ratio of reservoir area to mixing depth in Cubillas make these two reservoirs especially responsive to atmospheric dust inputs. Similarly, Mladenov et al. (2008) found that the relationship between lake DOC and dry atmospheric WSOC loading was only significant in the most oligotrophic high mountain lake. Despite the differences observed in the background DOC concentrations among the study reservoirs, the relationships between DOC and atmospheric loading of WSOC (Fig. 5) showed similar slopes between them (from 0.08 ± 0.03 in Quentar to 0.14 ± 0.05 in Cubillas) and with previous ones reported by Mladenov et al. (2008).

Despite these synchronies, the direct, quantitative contribution of WSOC to the DOC pool in the reservoirs was moderate (lower than 10 %), and hardly could explain the relationships between WSOC inputs and DOC concentrations in Quentar and Cubillas reservoirs. These apparently contradictory results could be explained by the indirect influence of dust inputs into the reservoirs. It is well acknowledged that dust is a vector of mineral nutrients such as P, Fe, Ca, Mg and K (Jickells et al., 2005; Pulido-Villena et al., 2006; Mahowald et al., 2008; Ballatyne et al., 2011). In the study region, previous studies by Morales-Baquero et al. (2006) reported that dry deposition was P-enriched and caused a significant increase of chlorophyll *a* in two alpine lakes. Therefore, an expected stimulus of the primary producers by dust inputs can indirectly increase DOC pool due to the exudation of dissolved organic carbon by phytoplankton (Baines and Pace, 1991). Hence, the additive effects of the direct WSOC inputs and the indirect DOC inputs derived from phytoplankton activity could explain the synchronic patterns between WSOC inputs and DOC dynamics in two out of three studied reservoirs. In fact, the only reservoir where we did not find a significant relationship between WSOC inputs and DOC concentrations was in Beznar. This reservoir has the lowest N:P ratio (Table 1) being the less P-limited.

We compared the contribution of WSOC to DOC pool with the estimated inputs of the dissolved organic carbon provided by phytoplankton (exudation inputs) (Table 6). We estimated primary productivity for each reservoir from chlorophyll *a* data (Smith, 1979) and we assumed an exudation rate of 13 % of primary productivity (Baines and Pace, 1991). Whereas estimations of DOC derived from phytoplankton for the whole stratification period could be between 31 % (Quentar) and 147 % (Cubillas) of the DOC pool, the WSOC inputs ranged from 2.5 % (Beznar) to 11 % (Quentar). This comparison suggests a low to moderate contribution of atmospheric inputs to DOC pool. In the more oligotrophic reservoir (i.e. the lower chlorophyll *a*) was detected the more relevant direct contribution of atmospheric inputs of organic carbon to DOC pool. The importance of the degree of oligotrophy to detect the dust effects has been also reported for marine ecosystems (Marañon et al., 2010).

DOC concentrations in the study reservoirs, similar to other Mediterranean reservoirs (Marcé et al., 2008), were in the upper range of those previously reported in the literature for Asian temperate reservoirs (Kim et al., 2000; Wei et al., 2008) but they were much lower than those reported for several European temperate reservoirs (Goslan et al., 2004; Pierson-Wickmann et al., 2010). DOC concentrations in the study reservoirs were always higher in Cubillas than in Beznar and Quentar which are likely reflecting its more extensive catchment area (>6 fold bigger than Quentar and ≈ 1.8 fold bigger than Beznar). Most of the catchment area in Cubillas is occupied by agricultural land, then the amount of microbially derived dissolved organic matter may likely be more significant as was observed by Wilson and Xenopoulos (2009). In addition, catchment to reservoir area ratio is higher in Cubillas (313) than in Quentar (240) and in Beznar (207). For north temperate lakes, it has been also observed a significant and positive relationship between DOC concentration and catchment to reservoir area ratio (Xenopoulos et al., 2003).

The comparatively lower chromophoric organic matter per C mole (i.e. ε_{320} values) in Cubillas reservoir could be related to the uneven effects of solar radiation on CDOM dynamics. For instance, photomineralization (the loss of DOC) is a process slower than photobleaching (the loss of CDOM) (Reche and Pace, 2002). Indeed, our hypothesis is that CDOM pool is much more exposed to photobleaching in Cubillas than in the other two reservoirs as it is reflected by the higher ratio between reservoir area to mixing depth (Table 1). By contrast, reservoir morphometry makes CDOM less exposed to solar effects in Quentar and Beznar. Indeed, the morphometry of aquatic ecosystems can have significant effects on the total losses of CDOM (Reche et al., 2000). These authors estimated, using a model, that increases of the mean depth of the lake from c.a. 0.4 m to 9.4 m resulted in 5 or 15-fold slower rates of total CDOM photobleaching for DOC concentrations of 1 or 10 $\mathrm{mg\,l^{-1}}$, respectively. Additionally, the high water retention time in Cubillas (2.94 yr) may also favor higher CDOM photobleaching effects.

Finally, we tried to get some insights about the impact of dust deposition on the UVR (at 320 nm) attenuation in the epilimnion. Saharan dust contains chromophoric and fluorescent organic compounds (Mladenov et al., 2009). Indeed, our results have shown that dust inputs can cause a significant reduction in the water UVR transparency ($z_{10\%}$ at 320 nm) in all the study reservoirs. The higher effect of inputs of chromophoric compounds on light attenuation were observed, as expected, in the reservoir characterized by the most oligotrophic conditions (Quentar reservoir) and in the reservoir with the smallest epilimnetic volume in relation to its surface area (Cubillas reservoir), which ultimately caused a lower dilution of the chromophoric compounds linked to dust inputs. These substantial direct effects of dust on water transparency could be boosted considering that bacterial activity is significantly stimulated by dust inputs (Reche et al., 2009) and they also produce significant quantities of chromophoric compounds (Ortega-Retuerta et al., 2009; Romera-Castillo et al., 2011). Indeed, Mladenov et al. (2008, 2011) found a key role of bacteria controlling the optical properties of dissolved organic matter in oligotrophic, high mountain lakes.

5 Conclusions

We obtained a low-moderate contribution of atmospheric water-soluble organic carbon (WSOC) to DOC pool in the reservoirs even during the stratification periods, but an important reduction in water transparency to ultraviolet radiation was observed. The DOC synchrony among reservoirs and the significant relationships between WSOC inputs and DOC concentrations in two out three reservoirs could be explained by a higher indirect contribution of phytoplankton exudates to DOC pool than by a direct atmospheric WSOC inputs. The trophic status and the reservoir morphometry were key properties to detect the effects of dust inputs. The more oligotrophic and the more extensive and shallow reservoir, the more sensitive was to dust inputs.

Acknowledgements. We thank O. Romera for valuable help in the field. This work was funded by the Spanish Ministry of Science and Technology (DISPAR, CGL2005-00076 to IR and CGL2008-06101/BOS to IdV) and by the Spanish Ministry of Education and Science (CICYT grant REN2003-03038 to RM-B).

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Table 1. General physical, chemical and biological features of the study reservoirs. Z_{mix} is the mixing water depth (6 m in Cubillas and 15 m in Quentar and Beznar). Modified from de Vicente et al. (2008).

Reservoirs	Quéntar	Cubillas	Beznar
Year of improundment	1973	1958	1986
Altitude a.s.l. (m)	1030	650	485
Total volume (V; 10^6 m^3)	13.6	21	54
Reservoir area (A_{R}; km^2)	0.42	2	1.7
Catchment area (A_{C}; km^2)	101	626	352
A_{C}:A_{R}	240	313	207
Water retention time (y)	3.85	2.94	1.00
A_{R}:z_{mix} (10^3 m)	28	333	113
Total phosphorus (µmol l^{-1})[1]	0.12 (0.03–0.28)	0.84 (0.26–1.47)	1.05 (0.38–1.70)
Total nitrogen (µmol l^{-1})[1]	40.0 (12.9–94.3)	185.0 (18.6–350.0)	82.9 (27.1–305.7)
N:P molar ratio[1]	333	220	79
Chlorophyll a (µg l^{-1})	2.4 (0.9–6.9)	33.1 (10.3–88.5)[2]	40.4 (22.6–73.6)

[1] Data from Reche et al. (2009), [2] data from Pérez-Martínez et al. (1991).

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9, 8307–8336, 2012

Atmospheric organic carbon inputs in reservoirs

I. de Vicente et al.

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Table 2. Values (average and range) of water-soluble organic carbon (WSOC), absorption coefficients at 250 nm (a_{250}), 320 nm (a_{320}) and 440 nm (a_{440}), and molar absorption coefficients at 250 nm (ε_{250}), 320 nm (ε_{320}) and 440 nm (ε_{440}) in the dry and wet atmospheric collectors in 2004.

Collectors	WSOC (mmol $m^{-2} d^{-1}$) 2004	2005	a_{250} ($m^{-1} m^{-2} d^{-1}$)	a_{320} ($m^{-1} m^{-2} d^{-1}$)	a_{440} ($m^{-1} m^{-2} d^{-1}$)	ε_{250} ($m^2 mol^{-1}$)	ε_{320} ($m^2 mol^{-1}$)	ε_{440} ($m^2 mol^{-1}$)
Dry Quentar	0.231 (0.036–0.715)	0.358 (0.173–0.660)	7.24 (3.29–14.16)	2.28 (0.55–5.79)	0.76 (0.12–1.81)	35.01 (14.08–72.04)	10.30 (3.70–25.75)	3.42 (1.08–6.15)
Dry Cubillas	0.333 (0.111–0.675)	0.363 (0.099–0.907)	9.7 (5.88–18.98)	3.09 (0.73–7.20)	0.95 (0.55–2.33)	32.61 (13.41–69.83)	10.27 (2.76–19.77)	3.98 (1.05–9.51)
Dry Beznar	0.393 (0.204–0.709)	0.396 (0.168–0.682)	9.31 (6.82–14.71)	2.41 (0.24–4.03)	0.69 (0.20–1.41)	31.45 (12.84–64.98)	7.99 (0.91–19.09)	2.32 (0.58–6.45)
Wet Quentar	0.260 (0.055–0.669)	0.419 (0.171–1.084)	8.13 (2.39–13.09)	2.30 (1.03–4.06)	0.59 (0.26–1.37)	–	–	–
Wet Cubillas	0.226 (0.010–0.508)	0.303 (0.156–0.403)	6.51 (3.26–11.47)	1.80 (1.44–3.76)	0.57 (0.50–1.07)	–	–	–
Wet Beznar	0.182 (0.060–0.304)	0.288 (0.085–0.489)	4.63 (2.42–6.57)	1.07 (0.30–2.39)	0.38 (0.10–0.91)	–	–	–

Table 3. Correlation coefficients between the different atmospheric collectors for total deposition of water-soluble organic carbon (WSOC) and its absorption coefficients at 320 nm (a_{320}).

		Collectors at	Quéntar	Cubillas
WSOC	2004	Cubillas	0.76^{**}	
		Béznar	0.44^{NS}	0.59^{*}
	2005	Cubillas	0.66^{**}	
		Béznar	0.72^{**}	0.36^{NS}
	All data	Cubillas	0.68^{***}	
		Béznar	0.60^{**}	0.45^{*}
a_{320}	2004	Cubillas	0.72^{*}	
		Béznar	0.52^{NS}	0.45^{NS}

Correlations were significant at the * $p < 0.05$; ** $p < 0.001$ and *** $p < 0.0001$ levels. NS, not significant.

Table 4. Values (average and range) of dissolved organic carbon (DOC), absorption coefficients at 250 nm (a_{250}), 320 nm (a_{320}), and 440 nm (a_{440}) in the study reservoirs during the stratification periods of 2004 and 2005.

Year	Reservoirs	DOC (mM)	a_{250} (m^{-1})	a_{320} (m^{-1})	a_{440} (m^{-1})	ε_{250} ($m^2\,mol^{-1}$)	ε_{320} ($m^2\,mol^{-1}$)	ε_{440} ($m^2\,mol^{-1}$)
2004	Quentar	0.163 (0.057–0.345)	5.80 (3.10–8.04)	1.69 (0.56–2.29)	0.42 (0.01–0.85)	41.0 (18.0–93.8)	12.0 (3.6–24.0)	2.9 (0.1–5.6)
	Cubillas	0.357 (0.198–0.573)	10.39 (7.75–13.23)	2.69 (1.60–3.84)	0.53 (0.22–0.77)	31.92 (20.82–50.49)	8.49 (3.72–16.26)	1.68 (0.53–3.71)
	Beznar	0.236 (0.094–0.444)	9.02 (8.16–10.44)	2.69 (2.04–3.07)	0.60 (0.29–0.76)	50.59 (18.90–90.60)	15.16 (5.43–28.93)	3.32 (1.08–6.15)
2005	Quentar	0.120 (0.065–0.217)	4.42 (1.69–5.87)	1.17 (0.27–2.11)	0.44 (0.03–0.97)	42.67 (11.92–82.66)	11.88 (3.84–29.76)	4.35 (0.41–13.67)
	Cubillas	0.336 (0.220–0.506)	9.40 (6.41–11.64)	2.59 (0.77–4.01)	0.83 (0.25–1.80)	29.37 (14.37–47.59)	7.81 (1.74–12.19)	2.38 (0.64–4.53)
	Beznar	0.235 (0.140–0.320)	8.79 (2.76–11.73)	2.65 (0.10–4.36)	0.80 (0.28–1.72)	38.72 (8.73–51.95)	11.71 (0.30–16.66)	3.59 (1.72–5.78)

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Table 5. Correlation coefficients between the different reservoirs for dissolved organic carbon (DOC) concentrations and absorption coefficients at 320 nm (a_{320}).

			Quéntar	Cubillas
DOC	2004	Cubillas	0.60^{**}	
		Béznar	0.22^{NS}	0.54^{*}
	2005	Cubillas	0.75^{***}	
		Béznar	0.47^{*}	0.53^{*}
	All data	Cubillas	0.64^{***}	
		Béznar	0.268^{NS}	0.50^{*}
a_{320}	2004	Cubillas	0.04^{NS}	
		Béznar	-0.36^{NS}	-0.03^{NS}
	2005	Cubillas	0.80^{**}	
		Béznar	-0.05^{NS}	-0.14^{NS}
	All data	Cubillas	0.38^{*}	
		Béznar	-0.07^{NS}	0.05^{NS}

Correlations were significant at the * $p < 0.05$; ** $p < 0.001$ and *** $p < 0.0001$ levels. NS, not significant.

Table 6. Contributions of water-soluble organic carbon (WSOC) inputs to mean dissolved organic carbon (DOC) pool into the epilimnion of the three study reservoirs and to the total DOC inputs (atmospheric + phytoplankton exudation) during the stratification period.

Reservoir	Quentar		Cubillas		Beznar	
Year	2004	2005	2004	2005	2004	2005
Epilimnetic DOC pool (mol)	301 979	296 787	1 434 127	110 7836	2 423 874	1 902 893
Atmospheric WSOC inputs (mol)	11 562	10 622	80 934	70 218	65 236	47 094
Contribution of WSOC to DOC pool (%)	3.8	3.6	5.6	6.3	2.7	2.5
Estimations of DOC inputs from phytoplankton exudation (mol)	93 549		2 108 444		2 500 606	
Contribution of WSOC to DOC inputs during stratification (%)	11		3.7		2.5	

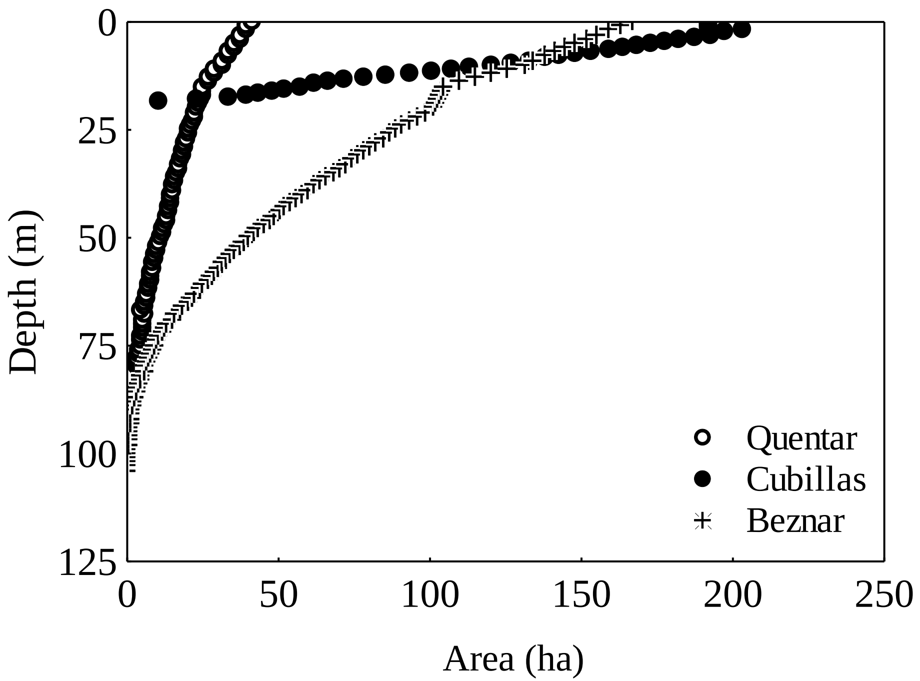

Fig. 1. Absolute hypsographic curves of area versus depth for the three study reservoirs.

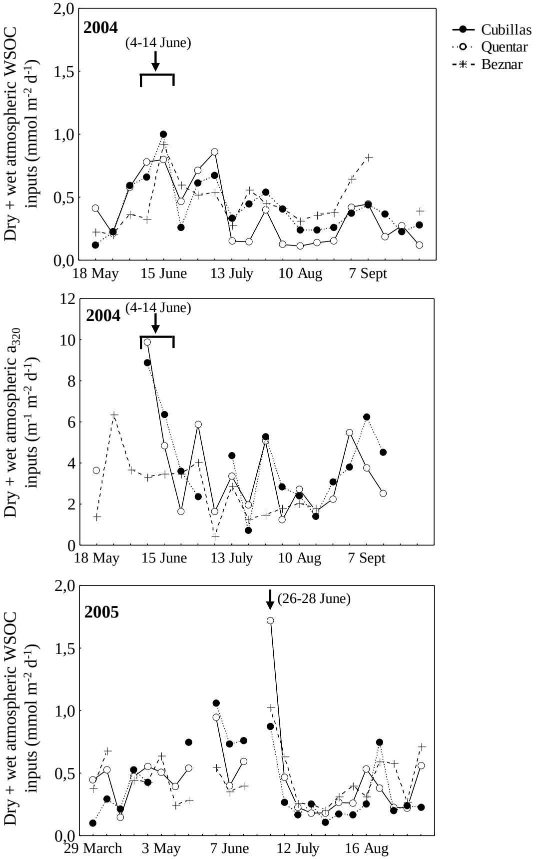

Fig. 2. Synchronous dynamics of water-soluble organic C (WSOC, mmol m^{-2} d^{-1}) and its absorption coefficient at 320 nm (a_{320} m^{-1} m^{-2} d^{-1}) in the three collectors during the study periods of 2004 and 2005. Arrows point relevant Saharan dust intrusions (see also Fig. 3).

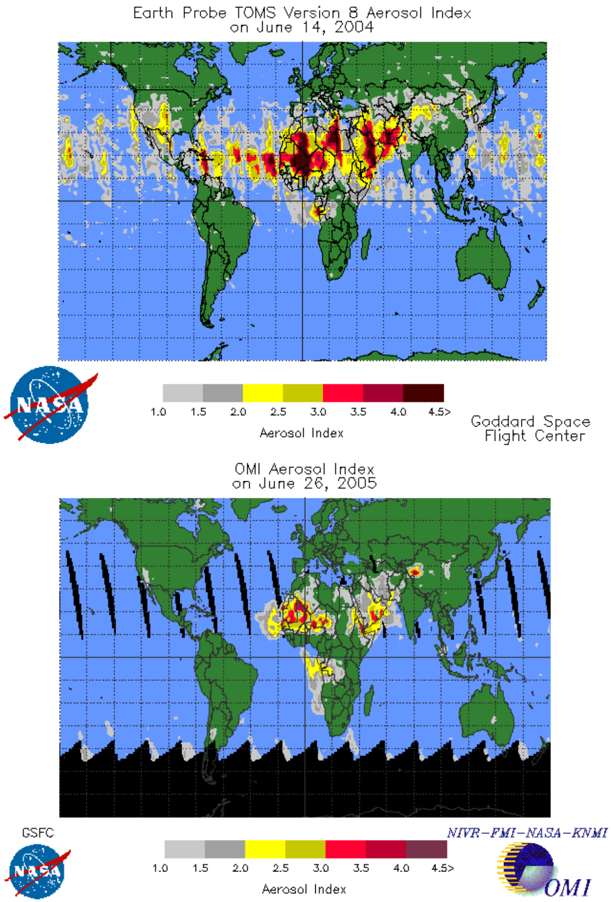

Fig. 3. Global maps of aerosol index provided by the spacecraft Earth Probe-Total Ozone Mapping Spectrometer (TOMS) for 14 June 2004 and Ozone Monitoring Instrument (OMI) for 26 June 2005 (http://toms.gsfc.nasa.gov/aerosols/).

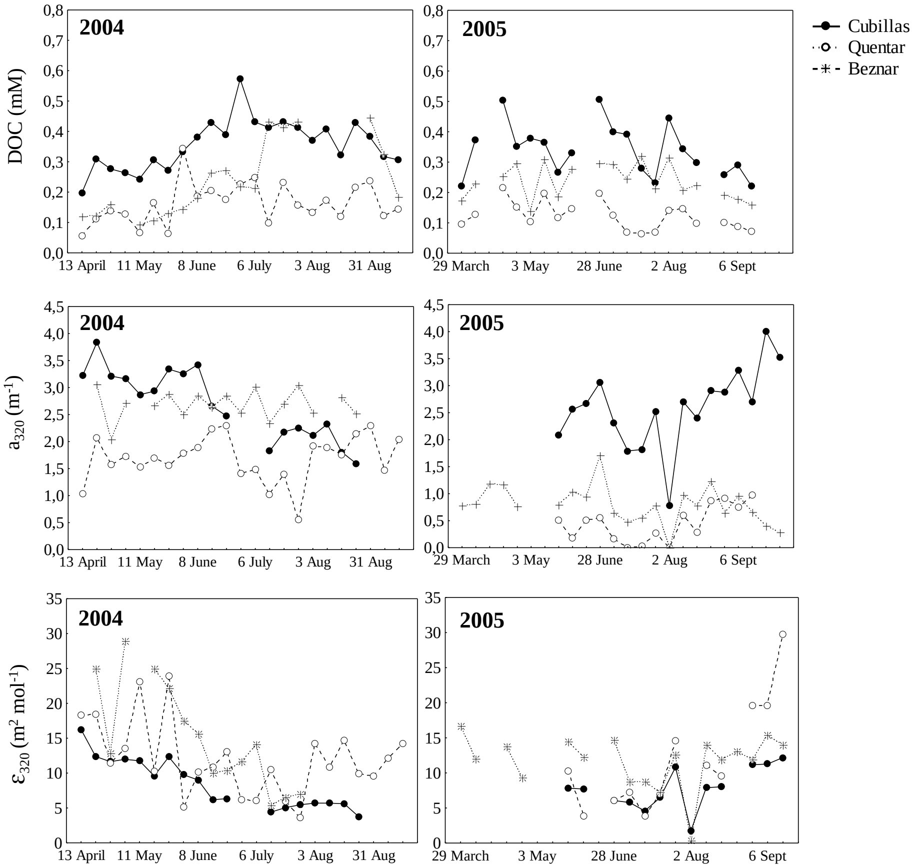

Fig. 4. Dynamics of dissolved organic carbon (DOC), absorption coefficients at 320 nm (a_{320}) and molar absorption coefficients at 320 nm (ε_{320}) during the stratifications periods of 2004 and 2005 in the three study reservoirs.

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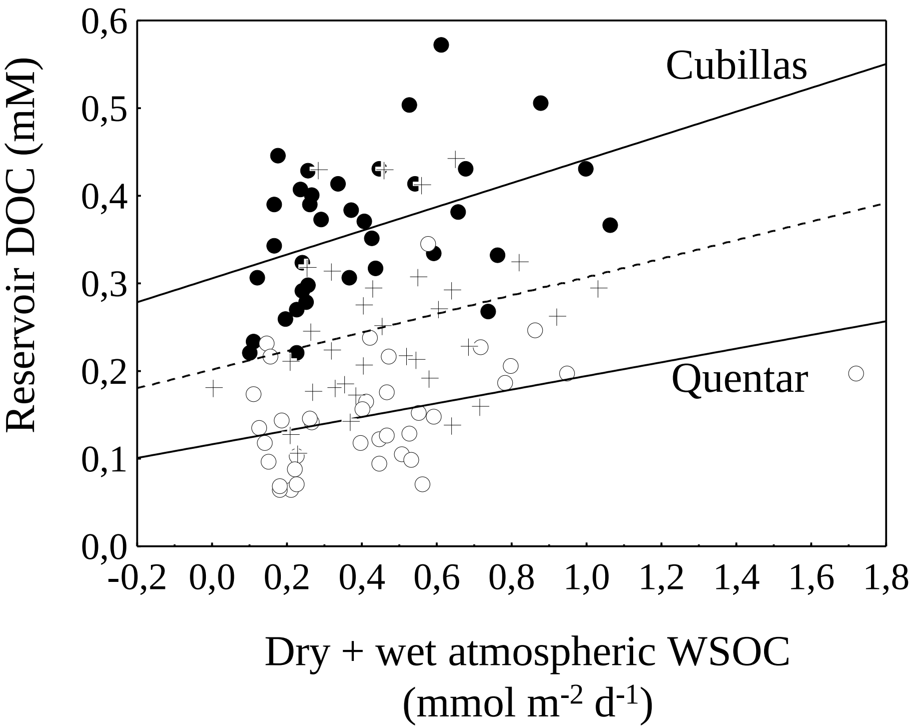

Fig. 5. Relationships between total (dry+wet) atmospheric WSOC inputs ($\text{mmol}\,\text{m}^{-2}\,\text{d}^{-1}$) and DOC concentrations (mM) in the reservoirs merging data for both study years. Solid lines are shown for significant relationships ($p < 0.05$) in Cubillas and in Quentar.

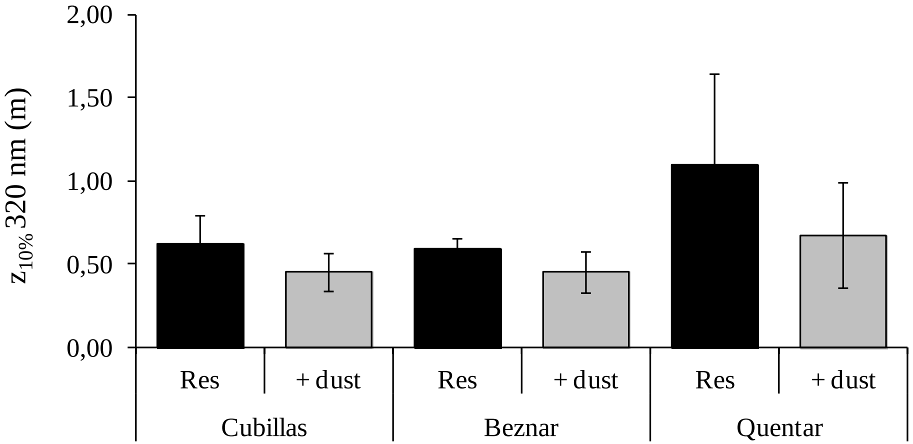

Fig. 6. Means (bars) and standard deviations (error bars) of the depth at which reach 10 % of the surface incident irradiance at 320 nm in the reservoir (Res) and considering the extra absorption due to inputs of chromophoric compounds (+ dust).