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岷江上游水体中 DOM 光谱特征的季节变化

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摘要: 川西北高原湿地和高山峡谷区是岷江等河流重要集水区, 地表水体中溶解性有机质 (DOM) 更多受环境背景影响, DOM 来源与结构特征对认识流域有机碳输出通量及模式有重要意义. 本文对岷江上游在 4 月 (枯水期末) 和 10 月 (丰水期末) 分别进行沿程地表水采样并测定了 DOM 三维荧光光谱 (EEM), 结合平行因子模型 (PARAFAC) 分析岷江上游水体 DOM 沿程和季节变化特征. 结果表明, DOM 荧光峰 (类腐殖峰 A、C 和类蛋白峰 B、T) 沿程波动趋势和程度不同; 枯水期末 (4 月) A、C 峰强而丰水期末 (10 月) B、T 峰强. PARAFAC 识别出 3 个荧光组分, 即 C1 (250 ~ 260/380 ~ 480 nm, 类腐殖质, 占比 48.68% ~ 65.02%), C2 (300 ~ 330/380 ~ 480 nm, 类腐殖质, 占比 23.17% ~ 29.83%) 和 C3 (270 ~ 280/300 ~ 350 nm, 类蛋白质, 占比 11.83% ~ 21.53%); 枯水期末 (4 月) 组分沿程波动更明显, 其中 C1 沿程波动最显著. 荧光指数 (FI) 均值在 1.4 ~ 1.9 之间, 说明不同季节 DOM 均有内外源混合特征; 枯水期末 (4 月) DOM 腐殖化、芳香性和疏水性高, 表明 DOM 陆源贡献更大, 而丰水期末 (10 月) DOM 自生源贡献比枯水期更高. CDOM 浓度 [$a(355)$] 与类腐殖质浓度 [$F_n(355)$] 极显著正相关, 这也证实岷江上游水体中 DOM 的陆源输入. C1、C2 在枯水期末 (4 月) 相关性极显著而丰水期末 (10 月) 相关性未达到显著性水平, 进一步表明岷江上游水体中 DOM 的外源性及其季节性差异.

关键词: 三维荧光及平行因子法; 溶解性有机质; 高海拔河流; 季节变化; 岷江上游

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Seasonal Variations of DOM Spectral Characteristics in the Surface Water of the Upstream Minjiang River

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Abstract: Alpine wetlands and valleys of northwestern Sichuan are the main catchment areas of Minjiang River, where dissolved organic matter (DOM) in surface waters comes mainly from the natural background environment. Sources and structure parameters of DOM are important for calibrating the flux and pattern of organic carbon exports from plateau wetlands and alpine rivers. In this study, surface water samples along the upstream Minjiang River were collected at the end of dry season (April) and rainy season (October). Excitation emission matrix (EEM) fluorescence spectroscopy coupled with parallel factor analysis (PARAFAC) was used to characterize seasonal variations of DOM along Minjiang River. Results showed fluorescence peaks (humic-like peaks A and C, protein-like peaks B and T) were different along the river. Peak A and peak C were more obvious at the end of dry season, while peak B and peak T were more obvious at the end of rainy season. PARAFAC produced a three-component model including two humic-like components [C1 (250-260/380-480 nm) and C2 (300-330/380-480 nm)] and one protein-like component [C3 (270-280/300-350 nm)], accounting relative intensity 48.68% - 65.02% for C1, 23.17% - 29.83% for C2, and 11.83% - 21.53% for C3. Fluorescence components showed variations along the river more prominently in April than October, in which the most significant one was C1. Average fluorescence index (FI) values ranged from 1.4 to 1.9, indicating that DOM consisted of both autochthonous and allochthonous components. Moreover, higher degrees of humification, aromaticity and hydrophobicity were found in April than those in October, suggesting more terrigenous sources at the end of dry season and more biological sources at the end of rainy season. Additionally, chromophoric dissolved organic matter (CDOM) [$a(355)$] correlated significantly with humic-like substance [$F_n(355)$], which also indicated that DOM components originated from terrigenous input in the upstream Minjiang River. The results also showed significant positive correlation between C1 and C2 in April, with no significant correlation in October, which further proved that exogenous input and seasonal variations characterized DOM sources in the upstream Minjiang River.

Key words: EEM-PARAFAC; dissolved organic matter (DOM); alpine river; seasonal variation; the upstream of Minjiang River

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水体有机质以溶解态、胶体或颗粒等形式存在, 其中溶解性有机质 (dissolved organic matter, DOM) 是指能通过 $0.45 \mu\text{m}$ 滤膜的复杂混合有机物^[1]. DOM 不仅作为碳的生物地化循环的重要组成部分^[2], 对全球碳循环有重要影响^[3]; 也作为污染物重要载体, 影响污染物的迁移和转化^[4]. 水体 DOM 可能来源于外源 (如土壤和凋落物等) 输入, 也可能由微生物活动等内源生成^[5], 二者共同形成水体中 DOM 化学结构和组成特征; 同时人类活动输入越来越多有机污染使水体 DOM 结构和转化过程更加复杂, 影响到流域地表水环境质量.

三维荧光光谱 (three dimension excitation-emission matrix, 3D-EEM) 近年来被广泛用于 DOM 来源及特征变化、地表水环境质量评价与管理等领域, 在指标灵敏度、选择性、信息量、可操作性和监测连续性等方面比其他方法有独特优势^[6,7], 其研究和应用日益受到重视, 尤其是在水体与土壤环境、沉积物、污水与堆肥处理等领域. 3D-EEM 结合相关数理统计方法已经用于研究海洋中不同来源 DOM 特征^[8]、湖泊 DOM 活性及气候变化对外源 DOM 输入的影响^[9]、海底热液中 DOM 转化和生物有效性^[10]、近岸水体 DOM 组分变化机制^[11]、降雨中 DOM 来源季节性特征^[12]及地下水 DOM 季节变化与垂直分布^[13,14]等水环境中 DOM 特征及动态, 河流 DOM 催化及臭氧化转化^[15]、工业废水 DOM 特征与环境效应^[16], 及热蚀变土^[17]、湖泊沉积物^[18]等多孔介质中 DOM 组成和分布等方面.

川西北高寒湿地是岷江等长江支流重要集水区, 也是全球重要高原湿地及低温土壤有机碳沉积重要地区, 近年来全球环境变化特别是暖冬等, 可能影响到该区域土壤环境变化, 使河流外源有机碳输入和转化及水生微生物活动特征改变, 从而导致水体 DOM 时空特征和动态发生变化. 本研究通过对岷江上游水体中 DOM 的沿程和季节特征分析, 对于认识高海拔河流中自然水体的 DOM 时空变化特征具有重要意义.

1 材料与方法

1.1 研究区域概况

岷江发源于岷山南麓松潘县郎架岭, 是长江上游最重要支流之一. 岷江源至都江堰以上部分为岷江上游, 流经青藏高原和四川盆地之间的地形陡变地带, 河流落差大; 该地区每年 5~10 月由于受东南季风和西南季风的共同影响形成了大量的降水,

旱季则为 11 月至次年 4 月, 干湿季节分明.

1.2 样品采集和处理

于 2016 年 10 月 (丰水期末) 和 2017 年 4 月 (枯水期末), 分别从岷江源向下经松潘县和茂县进行岷江上游干流河段地表水采样, 均采集 12 个点 (从源头向下编号为 S1~S12, 如图 1 所示). 依次用自来水、超纯水清洗特氟龙采样瓶, 并烘干备用; 采样前, 先用待测水样润洗采样瓶 3 次; 每个点取 3~5 个重复样; 取样后, 水样置于保温箱中 4°C 避光保存, 并尽快送回实验室. 将水样用 $0.45 \mu\text{m}$ 滤膜 (PVDF, Millipore, USA) 过滤后, 测定三维荧光光谱.

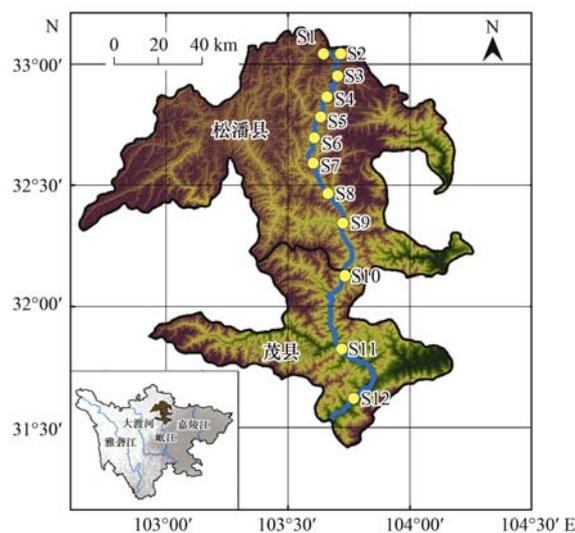


图 1 岷江上游沿程 DOM 采样点分布示意

Fig. 1 Location for DOM sampling along the upstream Minjiang River

1.3 测定方法

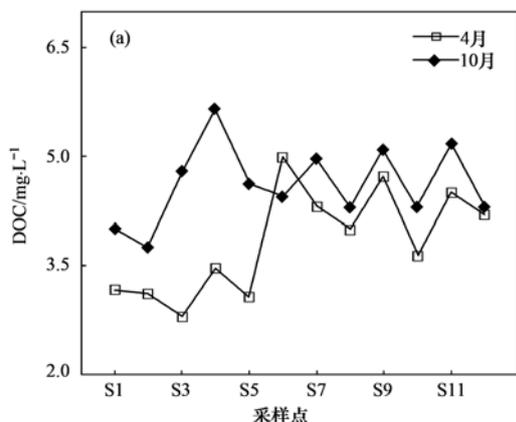
采用 Horiba 公司 Aqualog 荧光光谱仪同时测定样品三维荧光光谱和紫外-可见光吸收光谱. 荧光光谱扫描具体操作步骤是: 光源为 150 W 无臭氧氙弧灯, 以 Millipore 纯水作空白, 激发波长 (E_x) 范围 $240 \sim 550 \text{ nm}$, 增量 3 nm ; 发射波长 (E_m) 范围为 $210 \sim 620 \text{ nm}$; 积分信号时间 0.5 s , 系统自动校正瑞利散射和拉曼散射^[19].

另外, 水样中溶解性有机碳 (dissolved organic carbon, DOC) 和溶解性总氮 (total dissolved nitrogen, TDN) 采用总有机碳总氮分析仪 (Milti N/C 2100s, 德国 Jena) 测定, 用 Millipore 超纯水作空白 (丰水期末和枯水期末水样中水溶性碳氮沿程特征如图 2 所示).

1.4 光谱参数选取

选取常用的 3D-EEM 光谱参数和 UV-vis 吸收

光谱参数分析岷江上游水体 DOM 内外源贡献率、腐殖化程度、芳香化和疏水性等信息(见表 1)。



利用 OriginPro 9.0、Matlab 2016、Excel 2016、ArcMap10.1 软件进行数据处理、图形绘制和相关

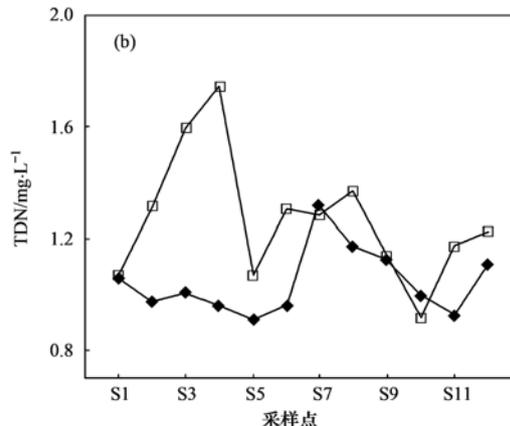


图 2 枯水期末(4月)和丰水期末(10月)岷江上游水体沿程水溶性碳氮特征

Fig. 2 Dissolved organic carbon (DOC) and total dissolved nitrogen(TDN) along the upstream Minjiang River at the end of dry season (April) and rainy season (October)

表 1 三维荧光光谱和紫外-可见吸收光谱的 DOM 特征参数

Table 1 Indices selected as characteristic parameters for the DOM 3D fluorescence and ultraviolet-visible absorption spectrum

光谱参数	计算方法	表征特征
荧光指数 (fluorescence intensity, FI)	激发波长 370 nm, 发射波长 450 nm 与 500 nm 处荧光强度的比值	衡量有机质来源: 小于 1.4 代表陆地或土壤源输入; 大于 1.9 代表微生物活动引起自生来源 ^[20]
自生源指数 (biological index, BIX)	激发波长 370 nm, 发射波长 380 nm 与 430 nm 处荧光强度的比值	衡量自生源贡献: 大于 1 为生物或细菌引起自生来源; 介于 0.6 ~ 0.7 受陆地源输入或人类影响较大 ^[21]
腐殖化指数 (humification index, HIX)	激发波长 254 nm, 发射波长 435 ~ 480 nm 与 300 ~ 345 nm 荧光强度平均值的比值	衡量腐殖化程度: 小于 4 说明 DOM 腐殖化程度较弱; 大于 10 说明 DOM 有显著腐殖质特征 ^[18]
F _n (355)	激发波长 355 nm, 发射波长 440 ~ 470 nm 间荧光强度最大值	代表类腐殖物质浓度水平: 值越大, 类腐殖物质含量越高 ^[12]
$a(355)$	吸收系数 $a(\lambda) = 2.303 \times A(\lambda) / l$, 式中, $A(\lambda)$ 为波长 λ 处的吸光度, l 为光程路径(m)	表示有色溶解性有机物 (CDOM) 浓度: 值越大, CDOM 浓度越高 ^[22]
SUVA(254)	254 nm 处吸收系数 $a(254)$ 与 DOC 质量浓度 ($\text{mg} \cdot \text{L}^{-1}$) 之比	表征芳香性: 值越大, 芳香化程度越高 ^[23]
SUVA(260)	260 nm 处吸收系数 $a(260)$ 与 DOC 质量浓度 ($\text{mg} \cdot \text{L}^{-1}$) 之比	表征疏水性: 值越大, 疏水组分比例越高 ^[24]

性分析。

2 结果与讨论

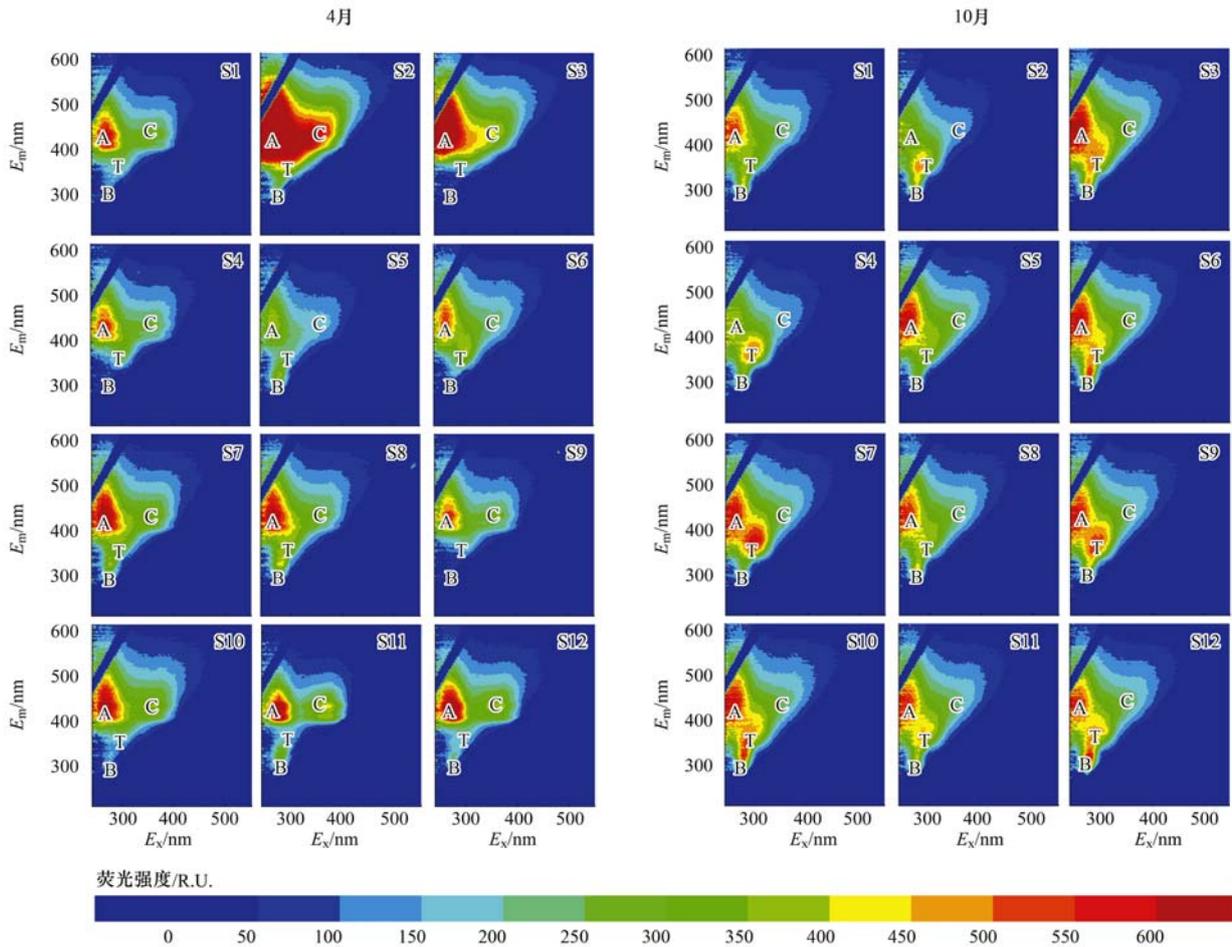
2.1 荧光峰特征

水体 DOM 根据 3D-EEM 中荧光位置分为 A 峰(紫外区类腐殖质, 低分子量而荧光特性强, 主要由陆源有机质产生^[25])、C 峰(可见光区类腐殖质, 分子量高于 A 峰, 具有相对稳定的芳香性和疏水性结构^[5])、B 峰(类络氨酸, 主要由微生物活动产生^[26])和 T 峰(类色氨酸, 指示比 B 峰更不易降解的蛋白类物质^[27]); 此外还有海洋类腐殖质 M 峰, 其相对淡水的腐殖质峰蓝移(激发波长变短)^[28]。不同来源 DOM 及光谱校正前后荧光峰的光谱位置有所差异^[29]。

DOM 荧光峰沿程变化显示(图 3), A 峰总体呈

沿程增加趋势(除 S2 ~ S3), 在枯水期末(4月)和丰水期末(10月)沿程波动都较大, 应该是沿程陆源输入引起 A 峰强度变化; C 峰强度沿程变化小, 与其具有相对稳定的结构有关^[5]; B 峰和 T 峰总体呈现沿程增加趋势, 因为沿程微生物活动等自生源输入增加; T 峰强度大于 B 峰, 因为其比 B 峰更不易降解^[27]。

类腐殖质峰(A 峰、C 峰)强度大于类蛋白峰(B 峰、T 峰), 说明岷江上游水体 DOM 陆源贡献更明显。其中 A 峰和 C 峰在枯水期末(4月)强度大于丰水期末(10月), 而 T 峰和 B 峰丰水期末(10月)强度增大, 说明水体 DOM 枯水期末(4月)更多来自于陆源腐殖质输入, 而丰水期末(10月)自生源贡献增强, 生物有效性高。



E_x 为激发波长, E_m 为发射波长; A 为紫外区类腐殖峰, C 为可见光区类腐殖峰, B 为类络氨酸峰, T 为类色氨酸峰

图 3 枯水期末(4月)和丰水期末(10月)岷江上游水体 DOM 荧光峰沿程变化趋势

Fig. 3 Comparison of DOM 3D fluorescence spectra measured at different Minjiang River sampling sites at the end of dry season (April) and rainy season (October)

此外, S2 处枯水期末(4月)A 峰显著增大, 而丰水期末(10月)A 峰很小, 可能因为枯水期末(4月)该处有显著外源输入, 丰水期末(10月)时该外源输入减小或因冰川融化和支流汇入等对 DOM 稀释使荧光峰减小. S3、S4 和 S9 在枯水期末(4月)B 峰几乎消失, 说明这些地点 DOM 自生源贡献很低.

2.2 荧光组分特征

本文用 PARAFAC 模型识别出 DOM 的 3 个组分^[30,31], 其中组分 C1 (250 ~ 260/380 ~ 480 nm) 为吸收 UVC 的类腐殖质, 分子量小且有抗光解性^[25]; 组分 C2 (300 ~ 330/380 ~ 480 nm) 为类腐殖质, 可吸收 UVC、UCB 和 UVA 降解, 分子量大于 C1 且具有一定疏水性^[25]; 组分 C3 (270 ~ 280/300 ~ 350 nm) 为微生物降解产生的类蛋白质^[27].

组分的沿程变化显示(图 4), 组分 C1 枯水期末(4月)沿程波动大于丰水期末(10月), 尤其是采样点 S1 ~ S4 组分 C1 波动很大, 说明 4 月时在 S1

~ S4 河段间应有外源类腐殖质输入, 与前文荧光峰的分析结论一致. 组分 C3 丰水期末(10月)含量高于枯水期末(4月)且沿程波动较大, 说明丰水期末(10月)河流 DOM 有更多的自生源贡献, 该来源也有明显沿程变化特征.

组分贡献率 C1 为 $65.02\% \pm 2.82\%$ (4月)、 $48.68\% \pm 3.64\%$ (10月); C2 为 $23.17\% \pm 2.77\%$ (4月)、 $29.83\% \pm 3.57\%$ (10月); C3 为 $11.83\% \pm 1.99\%$ (4月)、 $21.53\% \pm 2.52\%$ (10月). C1、C2 贡献率枯水期末(4月)显著高于丰水期末(10月) ($P < 0.05$), C3 贡献率枯水期末(4月)显著低于丰水期末(10月) ($P < 0.01$), 表明 DOM 组成有显著的季节差异. 有研究表明岷江上游季节性冻融的土壤促进了凋落物中木质素和纤维素降解^[32], 可能是枯水期末(4月)处于土壤冻融期(10月到次年 4月)结束时, 陆源土壤有机贡献使水体 DOM 类腐殖质增加.

综上,岷江上游 DOM 以类腐殖物质为主,类蛋白质物质贡献率低,河流生物有效性较低.有研究表明,自然水体 DOM 以类腐殖荧光为主,受人类活动影响类蛋白荧光峰增强^[5],说明人类活动对该流域地表水环境影响处于较低水平.

2.3 光谱参数分析

枯水期末(4月)荧光光谱特征参数沿程波动大

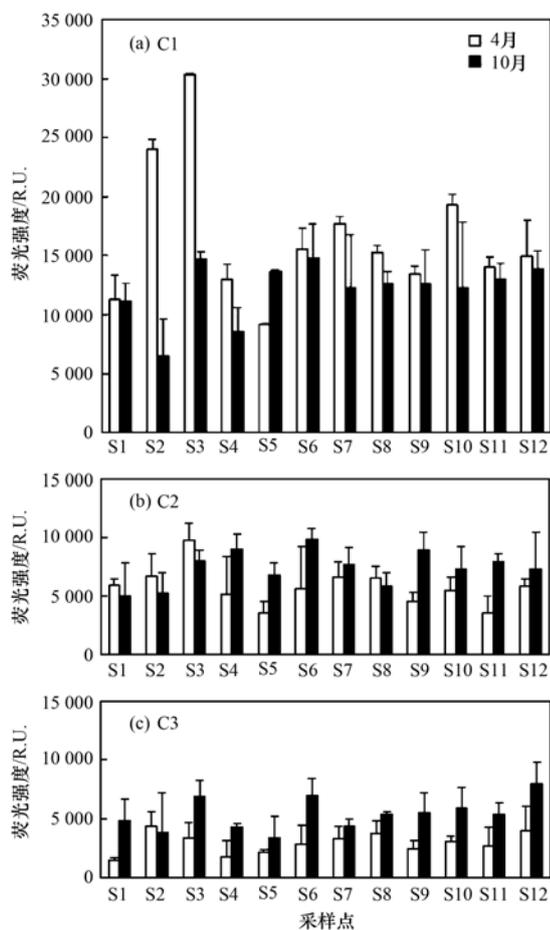


图4 枯水期末(4月)和丰水期末(10月)岷江上游水体 DOM 荧光组分沿程变化

Fig. 4 Changes in intensity of three components identified by PARAFAC application along the upstream Minjiang River at the end of dry season (April) and rainy season (October)

于丰水期末(10月)(如图5),且沿程变化趋势有明显季节差异,枯水期末(4月)DOM的来源更不稳定.枯水期末(4月)HIX普遍高于丰水期末(10月),说明DOM腐殖质化程度高;丰水期末(10月)BIX更高,说明DOM自生源贡献大,生物有效性高.

枯水期末(4月)S1~S4间的吸收光谱特征参数沿程波动大(图6),说明水体DOM动态变化明显.DOM的芳香性[SUVA(254)]和疏水性[SUVA(260)]有极相似的变化趋势,可能因为DOM芳香性结构主要存在于疏水性成分之中^[12].通常情况下,认为陆源比自生源DOM有更多芳环结构^[11],S1~S4枯水期末(4月)芳香性和疏水性高也说明该河段有陆源有机质输入,与前文荧光组分分析结论一致.

两次采样FI均值都在1.4~1.9之间(见表2),说明水体DOM为陆源与自生源贡献结合;枯水期末(4月)BIX<1,丰水期末(10月)BIX>1,说明丰水期末(10月)时DOM自生源贡献大,生物可利用性高;枯水期末(4月)HIX在4~10之间,丰水期末(10月)HIX<4,且Fn(355)在枯水期末(4月)显著大于丰水期末(10月)($P<0.01$),说明枯水期末(4月)DOM腐殖化特征明显,丰水期末(10月)DOM腐殖化程度低;枯水期末(4月)时河流中DOM的芳香性[SUVA(254)]更高,疏水性[SUVA(260)]也更高.

有色溶解性有机质(chromophoric dissolved organic matter, CDOM)是DOM重要组成部分,CDOM浓度[$a(355)$]的沿程波动可能由陆源输入或人为活动影响所致,同时降雨也是河流CDOM变化的重要来源^[12].两次采样时 $a(355)$ 无显著性差异($P>0.05$),说明虽然枯水期末(4月)S1~S4间水体CDOM波动大(图6),但岷江上游CDOM输入无显著季节差异.

表2 枯水期末(4月)和丰水期末(10月)岷江上游水体DOM三维荧光和紫外-可见光谱参数

Table 2 DOM characteristic parameters for 3D fluorescence and ultraviolet-visible absorption spectra of the upstream Minjiang River at the end of dry season (April) and rainy season (October)

光谱参数	4月		10月	
	均值	变异系数/%	均值	变异系数/%
荧光指数(FI)	1.88 ± 0.09	6.42	1.56 ± 0.04	3.69
自生源指数(BIX)	0.94 ± 0.13	18.04	1.21 ± 0.08	9.45
腐殖化指数(HIX)	8.21 ± 1.73	28.47	3.70 ± 0.49	17.80
Fn(355)/R. U.	336.04 ± 80.50	32.34	223.33 ± 31.10	18.80
$a(355)/m^{-1}$	8.21 ± 1.73	28.47	1.95 ± 0.30	20.76
SUVA(254)/L·(mg·m) ⁻¹	2.58 ± 0.88	45.87	1.80 ± 0.28	20.66
SUVA(260)/L·(mg·m) ⁻¹	2.64 ± 0.83	45.47	1.73 ± 0.27	20.88

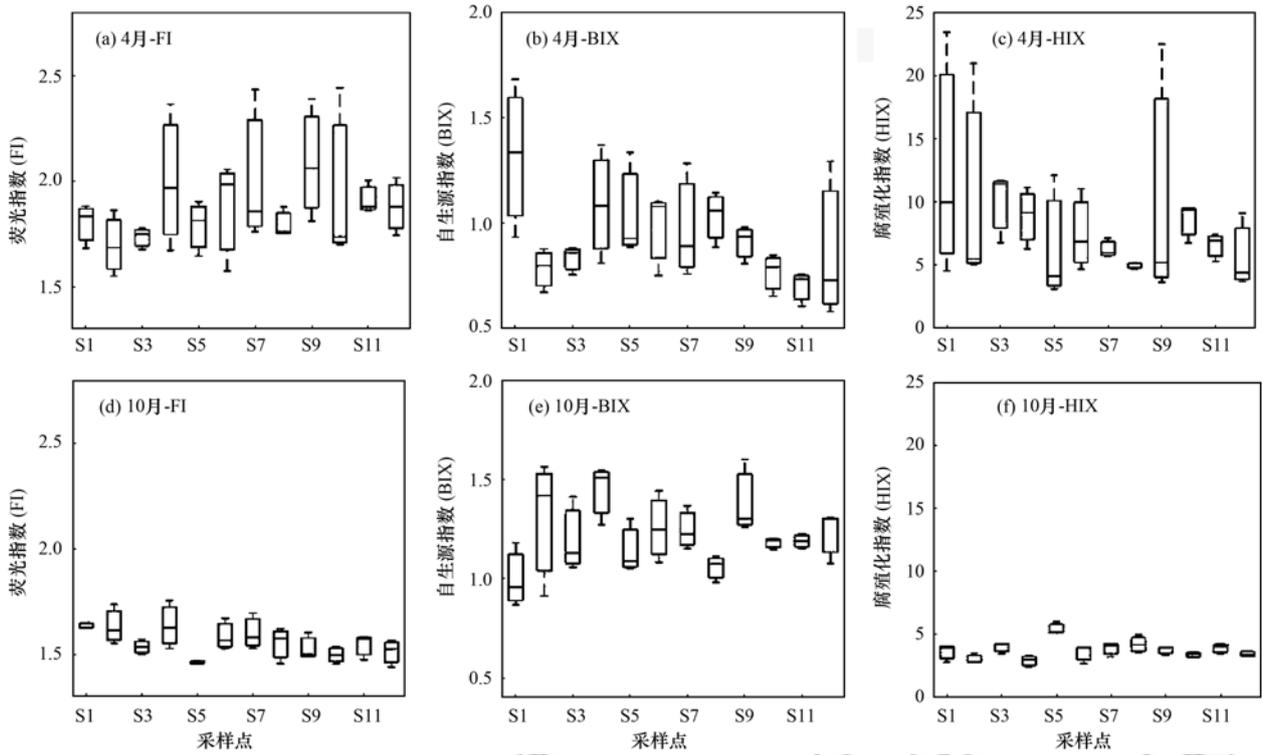


图 5 枯水期末(4月)和丰水期末(10月)岷江上游水体沿程 DOM 三维荧光光谱特征参数
 Fig. 5 Comparison of DOM characteristic parameters for 3D fluorescence spectra at different sampling sites along the upstream Minjiang River at the end of dry season (April) and rainy season (October)

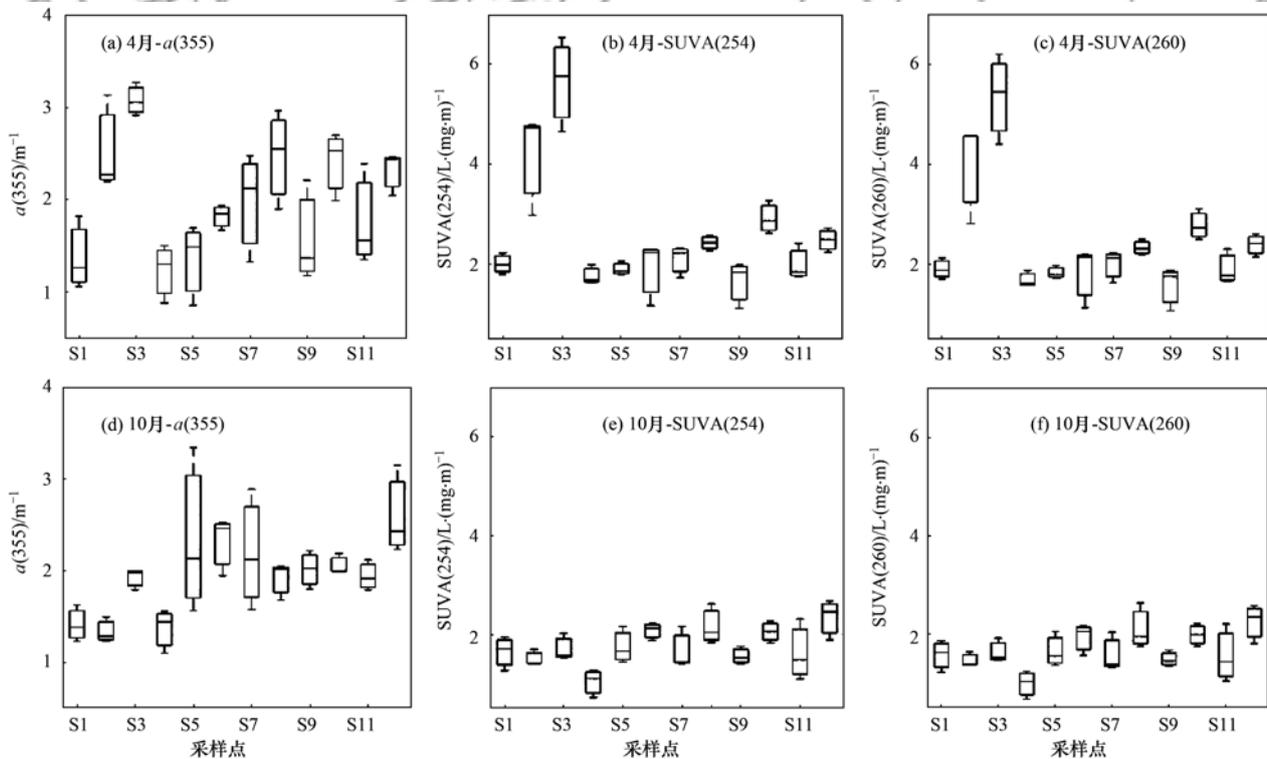


图 6 枯水期末(4月)和丰水期末(10月)岷江上游水体沿程 DOM 紫外-可见光谱特征参数
 Fig. 6 Comparison of DOM characteristic parameters for UV-vis absorption spectra at different sampling sites along the upstream Minjiang River at the end of dry season (April) and rainy season (October)

综上,岷江上游河流 DOM 为内外源贡献结合,但丰水期末(10月)DOM 的自生源贡献更大,而枯水期末(4月)DOM 更多来自陆源,腐殖化、芳香性和疏水性更高.此外,枯水期末(4月)光谱参数的变异系数均大于丰水期末(10月),说明枯水期末时河流 DOM 来源更不稳定.

2.4 荧光组分与光谱参数和水溶性碳氮的相关性

岷江上游水体 DOM 呈现出时空变化特征,DOM 组成和结构参数(如荧光组分、腐殖化、芳香性和疏水性参数)的相关性结果揭示 DOM 内外源输入机制与变化.

DOC 与 C2 在丰水期末(10月)极显著正相关($P < 0.01$)(表3),说明 C2 对 DOC 转化与降解有重要影响;DOC 与其他荧光组分相关性不显著,可能由于 DOM 中非生色组分所占比例不同,也说明

仅用 DOC 指标不能全面描述 DOM 的地化特征^[12,33].TDN 与荧光组分无显著相关性,可能因为水体溶解性碳氮的行为特征比较复杂,也说明 TDN 不是限制高海拔河流 DOM 迁移转化的因素^[19].

C1 和 C2 丰水期末(10月)无显著相关,枯水期末(4月)却极显著($P < 0.01$)正相关,说明 C1、C2 在枯水期末(4月)来源更相似.C2 与 SUVA(254)、SUVA(260)枯水期末(4月)相关性极显著($P < 0.01$),丰水期末(10月)却无显著相关,说明 C2 结构特征(芳香性和疏水性)有季节差异.C2 和 C3 与 $\alpha(355)$ 仅在枯水期末(4月)极显著相关($P < 0.01$),说明枯水期末(4月)C2、C3 影响 CDOM 的动态变化.此外, $\alpha(355)$ 与 Fn(355)极显著正相关($P < 0.01$),说明水体中类腐殖质浓度水平[Fn(355)]对 CDOM 含量[$\alpha(355)$]有重要影响.

表3 岷江上游水体 DOM 荧光组分、光谱参数与水溶性碳氮之间相关性¹⁾

Table 3 Correlations between DOM fluorescent components, spectral parameters, dissolved organic carbon and nitrogen in the upstream Minjiang River

月份	项目	DOC	TDN	C1	C2	C3	Fn(355)	荧光指数 (FI)	自生源指数 (BIX)	腐殖化指数 (HIX)	$\alpha(355)$	SUVA(254)
4	TDN	-0.179										
	C1	-0.336	0.359									
	C2	-0.389	0.483	0.834 **								
	C3	0.062	0.094	0.613 *	0.467							
	Fn(355)	-0.264	0.333	0.992 **	0.822 **	0.609 *						
	荧光指数 (FI)	0.620 *	-0.098	-0.382	-0.431	-0.338	-0.271					
	自生源指数 (BIX)	-0.198	0.082	-0.530	-0.038	-0.611 *	-0.549	-0.043				
	腐殖化指数 (HIX)	-0.408	-0.010	0.223	0.236	-0.377	0.209	-0.113	0.249			
	$\alpha(355)$	-0.205	0.154	0.869 **	0.761 **	0.825 **	0.857 **	-0.449	-0.570	-0.103		
	SUVA(254)	-0.581 *	0.319	0.937 **	0.814 **	0.543	0.893 **	-0.612 *	-0.421	0.270	0.842 **	
SUVA(260)	-0.581 *	0.317	0.936 **	0.811 **	0.549	0.891 **	-0.616 *	-0.423	0.265	0.844 **	1.000 **	
10	TDN	-0.003										
	C1	0.122	0.089									
	C2	0.711 **	-0.116	0.405								
	C3	-0.098	0.082	0.613 *	0.376							
	Fn(355)	0.131	0.103	0.973 **	0.466	0.573						
	荧光指数 (FI)	-0.010	0.178	-0.660 *	-0.103	-0.273	-0.593 *					
	自生源指数 (BIX)	0.534	-0.149	-0.372	0.620 *	-0.046	-0.327	0.278				
	腐殖化指数 (HIX)	-0.003	-0.016	0.441	-0.177	-0.347	0.464	-0.602 *	-0.501			
	$\alpha(355)$	0.030	0.193	0.810 **	0.368	0.512	0.834 **	-0.731 **	-0.115	0.467		
	SUVA(254)	-0.503	0.088	0.663 *	-0.128	0.469	0.672 *	-0.687 *	-0.531	0.497	0.785 **	
SUVA(260)	-0.522	0.083	0.646 *	-0.139	0.477	0.655 *	-0.672 *	-0.534	0.473	0.765 **	0.999 **	

1) **表示在0.01显著性水平上(双侧)相关; *表示在0.05显著性水平上(双侧)相关

3 结论

(1)岷江上游水体 DOM 荧光峰(包括类腐殖峰 A、C 与类蛋白峰 B、T)的沿程波动趋势和范围不同;A、C 峰在枯水期末(4月)强度大于丰水期末

(10月),而 B、T 峰丰水期末(10月)强度大于枯水期末(4月).

(2)平行因子识别出 DOM 的3个组分:类腐殖质 C1(250~260/380~480 nm)、类腐殖质 C2(300~330/380~480 nm)和类蛋白质 C3(270~280/300

~350 nm), C1 贡献率 4 月 > 10 月, C3 贡献率 10 月 > 4 月; 枯水期末(4 月)组分沿程波动大, 来源更不稳定。

(3) 光谱参数表明水体 DOM 为内外源结合: 枯水期末(4 月)陆源贡献大, 腐殖化程度、芳香性、疏水性高; 丰水期末(10 月)有更多自生源贡献, 生物有效性高。

(4) DOC 与 C2 在丰水期末(10 月)极显著正相关; TDN 与荧光组分相关性不显著; C1 与 C2 枯水期末(4 月)极显著正相关; C2 与 DOM 芳香性 [SUVA(254)]、疏水性 [SUVA(260)] 在枯水期末(4 月)极显著正相关; 组分与光谱参数间的相关性表明枯水期末(4 月)DOM 组分来源更相似。

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