

方知库
Eco-Environmental
Knowledge Web

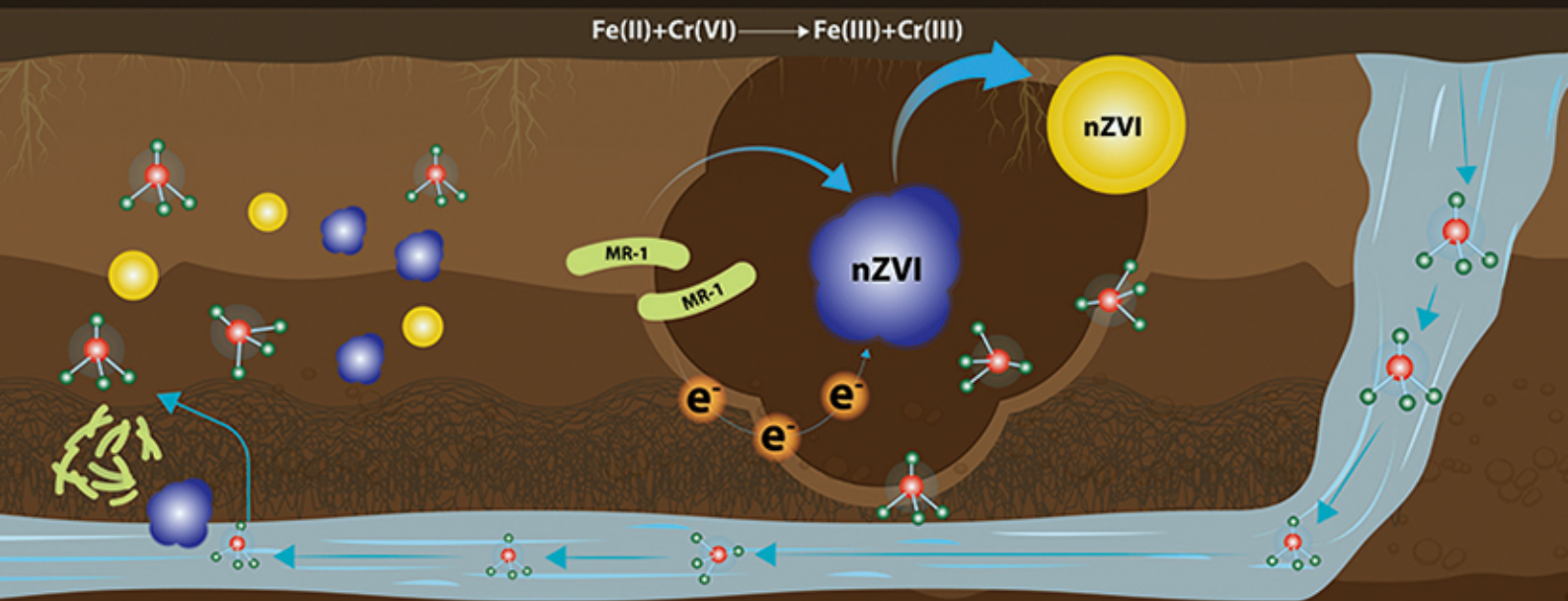
环境科学

ENVIRONMENTAL SCIENCE

ISSN 0250-3301 CODEN HCKHDV
HUANJING KEXUE

电活性微生物激活生物质炭/零价铁协同钝化Cr(VI)及机制

廖聪坚, 赵晓蕾, 刘凯, 钟松雄, 李芳柏, 方利平, 叶挺进, 石虎砚



■ 主办 中国科学院生态环境研究中心

■ 出版 科学出版社



2021年9月

第42卷 第9期
Vol.42 No.9

目次

北京市 2014~2020 年 PM _{2.5} 和 O ₃ 时空分布与健康效应评估	陈菁, 彭金龙, 徐彦森 (4071)
京津冀地区高分辨率 PM _{2.5} 浓度时空变化模拟与分析	杨晓辉, 宋春杰, 范丽行, 张凌云, 魏强, 李夫星, 王丽艳, 王卫 (4083)
京津冀典型城市冬季人为源减排与气象条件对 PM _{2.5} 污染影响	邵玄逸, 王晓琦, 钟巍盛, 王瑞鹏 (4095)
太行山两侧污染物传输对横谷城市气溶胶的影响分析	王雁, 郭伟, 闫世明, 裴坤宁, 李明明, 陈二萍 (4104)
嘉善冬季碳质气溶胶变化特征及其来源解析	张颖龙, 李莉, 吴伟超, 吕升, 秦阳, 祝新明, 高晋徽, 唐倩, 夏峰 (4116)
基于机器学习算法的新冠疫情管控对河南省空气质量影响的模拟分析	魏煜, 徐起翔, 赵金帅, 张瑞芹 (4126)
新乡市大气 PM _{2.5} 载带金属元素季节分布、来源特征与健康风险	刘恒嘉, 贾梦珂, 刘永丽, 赵艺洁, 郑爱华, 刘恒志, 徐肃阳, 肖晴晴, 苏晓燕, 任言 (4140)
黄渤海气溶胶中砷的分布特征和季节变化	袁帅, 王艳, 刘汝海, 种习习, 刘晓雨, 邵龙 (4151)
天津市 2020 年冬季重污染过程气溶胶消光特性及其来源	李立伟, 肖致美, 杨宁, 蔡子颖, 闫斌峰, 元洁, 白宇, 郑乃源, 唐邈 (4158)
中国暖季近地面臭氧浓度空间格局演变及主要气象驱动因素	何超, 慕航, 杨璐, 王丹璐, 邱彦峰, 叶志祥, 易嘉慧, 柯碧钦, 田雅, 洪松 (4168)
乌海市夏季臭氧污染特征及基于过程分析的成因探究	张瑞欣, 陈强, 夏佳琦, 刘晓, 郭文凯, 李光耀, 陈梅 (4180)
珠江三角洲海岸背景区大气 VOCs 污染特征与来源	云龙, 李成柳, 张明棣, 何龙, 郭键锋 (4191)
永定河上游地表水-地下水水化学特征及其成因分析	孔晓乐, 杨永辉, 曹博, 王艺璇, 裴宏伟, 沈彦军 (4202)
汉江中下游水质时空变异与驱动因素识别	程兵芬, 张远, 夏瑞, 张楠, 张新飞 (4211)
环境持久性药物在江苏省地表水中的污染水平、分布特征及生态风险评估	赵美美, 范德玲, 古文, 汪贞, 梁梦园, 刘济宁, 张志 (4222)
柳江流域河流溶解态重金属时空分布及污染评价	张婉军, 辛存林, 于爽, 刘齐, 曾鹏 (4234)
雷州半岛地下水重金属来源解析及健康风险评价	师环环, 潘羽杰, 曾敏, 黄长生, 侯清芹, 皮鹏程, 彭红霞 (4246)
龙子祠泉域地下水金属元素分布特征及健康风险评价	谢浩, 梁永平, 李军, 邹胜章, 申豪勇, 赵春红, 王志恒 (4257)
硫氧同位素解析典型岩溶地下河流域硫酸盐季节变化特征和来源	任坤, 潘晓东, 兰干江, 彭聪, 梁嘉鹏, 曾洁 (4267)
包头南海湿地磷形态及污染源定量识别	拜亚红, 钱晨歌, 袁思静, 谢子嫣, 来凌子, 张敏, 刘颖, 苗春林 (4275)
城市新城区公园沟塘沉积物磷释放风险及影响因素分析	李如忠, 宋敏, 杨继伟 (4287)
水力停留时间对潜流湿地净化效果影响及脱氮途径解析	齐冉, 张灵, 杨帆, 颜昌宙 (4296)
锰砂人工湿地对污染物的强化去除	马权, 王东麟, 林慧, 柏耀辉 (4304)
4 种典型沉水植物对去除磷污染底泥的应用效果	陶理, 王沛芳, 袁秋生, 王洵, 胡斌 (4311)
输水情景下白洋淀好氧反硝化菌群落对溶解性有机物的响应	周石磊, 张甜娜, 陈召莹, 张紫薇, 于明会, 姚波, 崔建升, 罗晓 (4319)
木屑生物炭在雨水径流中的氮磷淋出和吸附特性	孟依柯, 王媛, 汪传跃 (4332)
海州湾潮间带沙蚕对沉积物微塑料的指示作用	王嘉旋, 宋可心, 孙一鑫, 方涛, 李瑾祯, 张涛, 冯志华 (4341)
纳米二氧化钛与镉对斜生栅藻 (<i>Scenedesmus obliquus</i>) 生长的拮抗效应及其作用机制	王璞, 赵丽红, 朱小山 (4350)
螺旋霉素废水处理过程中菌群结构、水质特征及抗性基因之间关系分析	武彩云, 李慧莉, 覃彩霞, 佟娟, 魏源送 (4358)
整合铁对厌氧铁氨氧化脱氮效能及微生物群落的影响	廖宏燕, 宋诚, 万柳杨, 时绍鹏, 王兴祖 (4366)
溶解氧对低碳源城市污水处理系统脱氮性能与微生物群落的影响	池玉蕾, 石炬, 任童, 王晓昌, 金鹏康 (4374)
间歇梯度曝气下缩短 SRT 强化短程 SNEDPR 系统脱氮除磷	张玉君, 李冬, 王歆鑫, 张杰 (4383)
生物膜系统中部分反硝化实现特性	于莉芳, 张兴秀, 张琼, 王晓玉, 彭党聪, 张日霞 (4390)
厌氧推流进水对反硝化除磷好氧颗粒污泥系统的影响	李冬, 曹思雨, 王琪, 张杰 (4399)
不同好氧/缺氧时长联合分区排泥优化生活污水短程硝化反硝化除磷颗粒系统运行	王文琪, 李冬, 高鑫, 张杰 (4406)
中国西南地区金属矿开采对矿区土壤重金属影响的 Meta 分析	张健琳, 瞿明凯, 陈剑, 杨兰芳, 赵永存, 黄标 (4414)
青藏高原典型流域土壤重金属分布特征及其生态风险评价	杜昊霖, 王莺, 王劲松, 姚玉璧, 周悦, 刘晓云, 芦亚玲 (4422)
电子垃圾拆解区土壤-农作物系统中镉元素的空间分布特征及其风险评价	张璐瑶, 赵科理, 傅伟军 (4432)
改性生物炭特性表征及对冶炼厂周边农田土壤铜镉形态的影响	王鑫宇, 孟海波, 沈玉君, 王佳锐, 张曦, 丁京涛, 周海宾, 李春燕, 程琼仪 (4441)
组配改良剂联合锌肥对土壤-水稻系统镉迁移转运的影响	周坤华, 周航, 王子钰, 刘雅, 刘佳伟, 辜娇峰, 曾鹏, 廖柏寒 (4452)
不同结构改良剂对铜镉污染土壤水稻生长和重金属吸收的影响	魏玮, 李平, 郎漫 (4462)
1 株草螺属植物内生菌 R-13 的分离鉴定及对龙葵吸收土壤镉的影响	鹿杰, 刘月敏, 黄永春, 王常荣, 刘斌, 刘仲齐, 黄益宗, 黄雁飞, 张长波 (4471)
不同地区土壤古菌群落对重金属污染响应	李雨桐, 杨杉, 张艺, 范例, 刘坤, 张晟 (4481)
高通量测序分析黄土高原退耕还林区土壤细菌群落特征	刘晓华, 魏天兴 (4489)
餐厨垃圾生物发酵液对黄土丘陵区土壤质量的影响试验	邵立明, 任俊达, 吕凡, 章骅, 何晶晶 (4500)
秦岭不同海拔土壤团聚体稳定性及其与土壤酶活性的耦合关系	马震菲, 胡汗, 李益, 郭鑫鑫, 任成杰, 赵发珠 (4510)
电活性微生物激活生物炭/零价铁协同钝化 Cr(VI) 及机制	廖聪坚, 赵晓蕾, 刘凯, 钟松雄, 李芳柏, 方利平, 叶挺进, 石虎砚 (4520)
降水变化对荒漠草原土壤呼吸的影响	蒿康伊, 张丽华, 谢忠奎, 赵锐锋, 王军锋, 郭亚飞, 高江平 (4527)
氮肥分施次数及硝化抑制剂对盆栽玉米 N ₂ O 排放的影响	符佩娇, 吉恒宽, 何秋香, 汤水荣, 王鸿浩, 伍延正, 孟磊 (4538)
负载 NH ₄ ⁺ -N 生物炭对土壤 N ₂ O-N 排放和 NH ₃ -N 挥发的影响	马晓刚, 何建桥, 陈玉蓝, 李德天, 刘川, 董建新, 郑学博 (4548)
微塑料添加对橘园土壤有机碳矿化的影响	张秀玲, 鄢紫薇, 王峰, 王玺, 徐晗, 胡荣桂, 严昶, 林杉 (4558)
1985~2019 年中国全氟辛酸磺酰基化合物的动态物质流分析	王佳钰, 陈景文, 唐伟豪, 崔蕴晗, 王中钰, 宋国宝, 陈伟强 (4566)
《环境科学》征订启事(4201) 《环境科学》征稿简则(4340) 信息(4382, 4537, 4565)	

黄渤海气溶胶中砷的分布特征和季节变化

袁帅^{1,2}, 王艳^{1,2}, 刘汝海^{1,2*}, 种习习^{1,2}, 刘晓雨^{1,2}, 邵龙^{1,2}

(1. 中国海洋大学环境科学与工程学院, 青岛 266100; 2. 中国海洋大学海洋环境与生态教育部重点实验室, 青岛 266100)

摘要: 于2017~2018年冬、春和夏季,在黄渤海海域走航采样,采集总悬浮颗粒物(TSP)样品,分析总砷(As)、As(V)、As(III)以及水溶性离子,讨论了As在黄渤海气溶胶中浓度、空间分布以及季节变化,估算了As的干沉降通量。气溶胶中As含量冬季($6.6 \text{ ng} \cdot \text{m}^{-3}$) > 夏季($5.5 \text{ ng} \cdot \text{m}^{-3}$) > 春季($4.4 \text{ ng} \cdot \text{m}^{-3}$),渤海和北黄海远大于南黄海。冬、夏季As(III)/As(V)比值分别为0.41和0.21。冬、春和夏季As/TSP平均值分别为95.4、83.9和81.4 $\mu\text{g} \cdot \text{g}^{-1}$,冬季明显高于春季和夏季。冬季在冬季风主导下,携带了环渤海地区排放的污染物导致砷含量最高,夏季受东南季风携带的东部沿海地区污染物的影响也较大,而春季受西伯利亚陆地气团和东南远海海洋性气团的共同影响,浓度最小。冬季 K^+/TSP 与As/TSP存在显著正相关($r = 0.78, P < 0.05$),说明受陆地生物质燃烧排放的As的影响明显,而夏季两者相关性不显著,说明来源不同。冬、春和夏季黄渤海大气气溶胶As的干沉降通量分别为1.15、0.77和0.97 $\mu\text{g} \cdot (\text{m}^2 \cdot \text{d})^{-1}$,年平均为0.95 $\mu\text{g} \cdot (\text{m}^2 \cdot \text{d})^{-1}$ 。

关键词: 黄渤海; 总砷; 季节变化; 后向轨迹; 干沉降通量

中图分类号: X513 文献标识码: A 文章编号: 0250-3301(2021)09-4151-07 DOI: 10.13227/j.hjxx.202102106

Distribution Characteristics and Seasonal Variations of Arsenic in Atmospheric Aerosols over the Yellow Sea and Bohai Sea

YUAN Shuai^{1,2}, WANG Yan^{1,2}, LIU Ru-hai^{1,2*}, CHONG Xi-xi^{1,2}, LIU Xiao-yu^{1,2}, SHAO Long^{1,2}

(1. College of Environmental Science and Engineering, Ocean University of China, Qingdao 266100, China; 2. Key Laboratory of Marine Environment and Ecology, Ministry of Education, Ocean University of China, Qingdao 266100, China)

Abstract: Marine aerosol samples of total suspended particulates (TSP) were collected in winter (2017) and spring and summer (2018) over the Yellow Sea and Bohai Sea. These samples were analyzed for total arsenic (As), As(V) and As(III), and water soluble ions to investigate the distribution and seasonal variation of As in atmospheric aerosols, as well as the dry deposition flux. Results showed that As concentrations in winter, spring, and summer were 6.6, 5.5, and 4.4 $\text{ng} \cdot \text{m}^{-3}$, respectively. The highest As concentrations occurred in the winter. Obvious differences in the spatial distribution of As were observed in different seasons. The highest concentrations of As were observed over the Bohai Sea in winter and the northern Yellow Sea in spring, with an average of 8.8 and 11.3 $\text{ng} \cdot \text{m}^{-3}$, respectively. As concentrations exhibited a relatively uniform spatial pattern in summer over the Yellow Sea and Bohai Sea, which may have been affected by the different sources of As. As(V) was the main species of As, while As(V)/As(III) ratios were 0.41 in winter and 0.21 in summer, respectively. Average As/TSP ratios in the winter, spring, and autumn were 95.4, 83.9, and 81.4 $\mu\text{g} \cdot \text{g}^{-1}$, respectively. Obviously higher As/TSP ratios, indicating higher intensity, occurred in winter. Air masses carry pollutants released over the Bohai Rim Region by the winter monsoon, resulting in higher As concentrations in winter. In summer, As concentrations are also higher, because air masses bring pollutants to the southeast coastal economic zone via the northeast monsoon. In spring, most air masses arriving in this region originate from Siberia and the southeast ocean with high rate, resulting in lower As concentrations. The significant correlation between K^+/TSP and As/TSP ($r = 0.78, P < 0.05$) in winter indicates that As is affected by the combustion of land biomass. No significant correlation in summer reveals the difference in As sources between winter and summer. The dry deposition flux of As over the Yellow Sea and Bohai Sea was 1.15 $\mu\text{g} \cdot (\text{m}^2 \cdot \text{d})^{-1}$ in winter, 0.77 $\mu\text{g} \cdot (\text{m}^2 \cdot \text{d})^{-1}$ in spring, and 0.97 $\mu\text{g} \cdot (\text{m}^2 \cdot \text{d})^{-1}$ in summer, with an annual mean value of 0.95 $\mu\text{g} \cdot (\text{m}^2 \cdot \text{d})^{-1}$.

Key words: Yellow Sea and Bohai Sea; total arsenic; seasonal variations; backward trajectory; dry deposition flux

As是自然界中对人体有害的元素,人类活动排放占大气As排放量的57%^[1]。大气中的As主要来自金属的冶炼、化石燃料燃烧以及农药使用等^[2]。As在大气介质中主要以颗粒物形式存在,是潜在的有毒环境污染物。大气颗粒物中的As超过一定浓度可增加人类肺癌的风险^[3]。利用[GEOS]-Chem模型模拟结果表明,中国东部是大气As浓度最高值区之一,存在较高癌症健康风险^[4]。对中国7个省份和地区的TSP中As研究发现,不同地区气溶胶中As的季节变化存在显著差异,不同的季节模式受气候和

供暖排放的影响^[5]。中国台湾台南市^[6]和青岛市^[7]的研究表明,As在细粒子中的浓度高于粗粒子,主要受人为源影响。气溶胶中As的干湿沉降是近海海水中As的重要来源,约占海水As来源的10%,对近岸海水以及沉积物中As的积累有重要贡献^[8]。

黄渤海是中国近海海域,被东亚主要经济区所

收稿日期: 2021-02-16; 修订日期: 2021-03-08

基金项目: 国家自然科学基金项目(41506128); 山东省自然科学基金项目(ZR2020MD118, ZR2018MD004)

作者简介: 袁帅(1994~),男,硕士研究生,主要研究方向为城市大气气溶胶, E-mail: 540178718@qq.com

* 通信作者, E-mail: ruhail@ouc.edu.cn

环绕,是人为影响最严重的海域之一.冬季,中国北方供暖期间,霾天频发,燃煤供暖和生物质燃烧会加重大气 As 污染^[9],在冬季风的影响下可输送至黄渤海.长江三角洲等东部沿海地区污染物也可经南向气团输送至黄渤海.黄渤海气溶胶中 As 的输送路径、As 空间分布以及季节变化等还少见报道.因此,本文采集 2017 ~ 2018 年冬、春和夏季黄渤海走航 TSP 样品,分析了 As、As(V) 和 As(III) 浓度,结合 HYSPLIT 后向轨迹模型以及水溶性离子浓度,讨论黄渤海气溶胶中 As 的空间分布、季节变化、来源和沉降通量.

1 材料与方法

1.1 采样地点

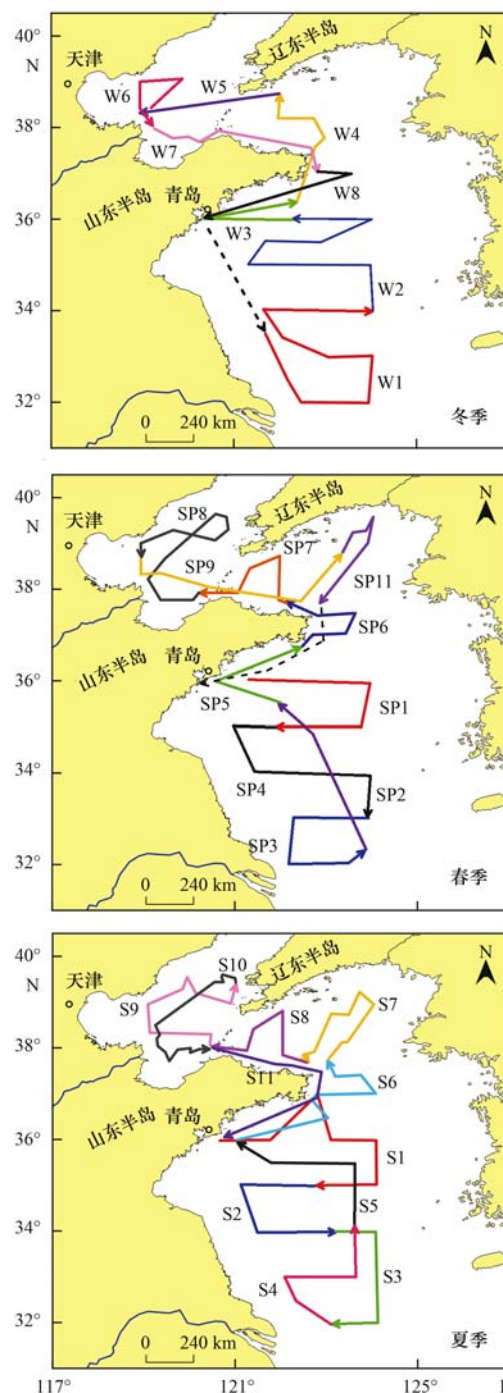
2017 年冬季(2017 年 12 月 19 日至 2018 年 1 月 9 日)与 2018 年春季(2018 年 3 月 18 日至 2018 年 4 月 16 日)和 2018 年夏季(2018 年 7 月 24 日至 2018 年 8 月 10 日),乘“东方红 2 号”在黄渤海海域进行走航采样(图 1). TSP 样品用 KC-1000(崂山电子)大流量采样器采集,采样膜为 500℃ 高温处理的石英纤维膜(Whatman 41),采样流量为 $1.05 \text{ m}^3 \cdot \text{min}^{-1}$,采样器位于船舶顶层甲板,距离海面约 15 m. 为了避免船舶尾气的影响,仅在开船时采样,每个样品累积采样时间 24 h. 采样完毕后,将采样膜对折后放入聚乙烯封口袋中,置于 -20°C 条件下保存,空白膜与样品膜用相同方法处理. 风速、风向、气温和相对湿度等气象参数由船舶携带的自动观测仪器测定.

1.2 样品的分析

裁取 40 cm^2 采样膜,加入体积比为 3:1 硝酸和盐酸混合溶液进行微波消解(EPA 3051A),过 $0.45 \mu\text{m}$ 微孔滤膜,取 5 mL 过滤后样品,加入 2 mL 5% 硫脲-抗坏血酸溶液,采用原子荧光光谱仪(AFS-920)测定总 As; 裁取 40 cm^2 采样膜,用 $1 \text{ mol} \cdot \text{L}^{-1}$ 磷酸超声提取 1 h,用 $0.45 \mu\text{m}$ 微孔滤膜过滤,取 5 mL 过滤液加硫脲-抗坏血酸测定总无机 As,取 5 mL 过滤液直接测定 As(III),As(V) 含量为总无机 As 和 As(III) 的差值. 同步分析空白膜和近海沉积物(GBW07314)标准样品,As 的回收率为 95%. 取 40 cm^2 采样膜,水浴超声萃取 45 min, $0.45 \mu\text{m}$ 微孔滤膜过滤,用离子色谱仪(ICS-3000)测定主要水溶性离子. 采用水溶性离子标准储备液作为标准物质,8 种水溶性离子的回收率为 94% ~ 107%.

1.3 后向轨迹分析

利用美国国家海洋与大气局(NOAA)的后向轨迹模型(HYSPLIT4)^[10],以各航段采样站点为起



W、SP 和 S 分别代表冬、春和夏季采样航段编号;
彩色线条代表走航路径,箭头代表航向

图 1 大气气溶胶采样区域和走航示意

Fig. 1 Study area and aerosol sampling sites along the cruise track in three seasons

点,模拟了 500 m 高度 72 h 后向轨迹图,用于气溶胶 As 的来源及输送路径的分析.

1.4 As 干沉降通量通过模型估算

As 的干沉降按照以下公式计算:

$$F = \sum c_i V_i \quad (1)$$

式中, F 为干沉降通量 [$\text{ng} \cdot (\text{m}^2 \cdot \text{s})^{-1}$]; c_i 是大气颗粒物中 As 的浓度 ($\text{ng} \cdot \text{m}^{-3}$), V_i 是干沉积速度

($\text{cm}\cdot\text{s}^{-1}$). 气象参数(风速、温度等)、颗粒物粒径和采样方式等均影响颗粒物沉降速度^[11],难以准确地确定. Qin 等^[12]将细颗粒($<2.5\ \mu\text{m}$)和粗颗粒($>2.5\ \mu\text{m}$)沉降速率分别设为 $0.1\ \text{cm}\cdot\text{s}^{-1}$ 和 $0.5\ \text{cm}\cdot\text{s}^{-1}$,估算了中国近海(黄海、渤海和东海)TPM的干沉降通量,经计算 V_i 为 $0.2\ \text{cm}\cdot\text{s}^{-1}$.因此,本文选用 $V_i=0.2\ \text{cm}\cdot\text{s}^{-1}$ 估算As干沉降通量.

2 结果与讨论

2.1 黄渤海气溶胶中As浓度空间分布和季节变化

渤海春、夏季气溶胶中As浓度分别为 6.0

$\text{ng}\cdot\text{m}^{-3}$ 和 $4.4\ \text{ng}\cdot\text{m}^{-3}$,均低于冬季结果 $8.8\ \text{ng}\cdot\text{m}^{-3}$.北黄海春季气溶胶中As含量分别为 $11.3\ \text{ng}\cdot\text{m}^{-3}$,都远大于其他季节(冬季: $6.8\ \text{ng}\cdot\text{m}^{-3}$;夏季: $5.6\ \text{ng}\cdot\text{m}^{-3}$).夏季北、南黄海As浓度分别为 $5.6\ \text{ng}\cdot\text{m}^{-3}$ 和 $6.0\ \text{ng}\cdot\text{m}^{-3}$,高于渤海 $4.4\ \text{ng}\cdot\text{m}^{-3}$,且各海域差异较小(图2).冬、春、夏季气溶胶中As浓度的最高值分别出现在区域采样站点W5($10.3\ \text{ng}\cdot\text{m}^{-3}$)、SP7($14.0\ \text{ng}\cdot\text{m}^{-3}$)和S6($16.8\ \text{ng}\cdot\text{m}^{-3}$)(图3).渤海属于内海,北黄海是半封闭海域,被山东、辽宁、河北、天津、北京以及韩国等经济区包围,受人为活动排放污染物的影响大于南黄海.

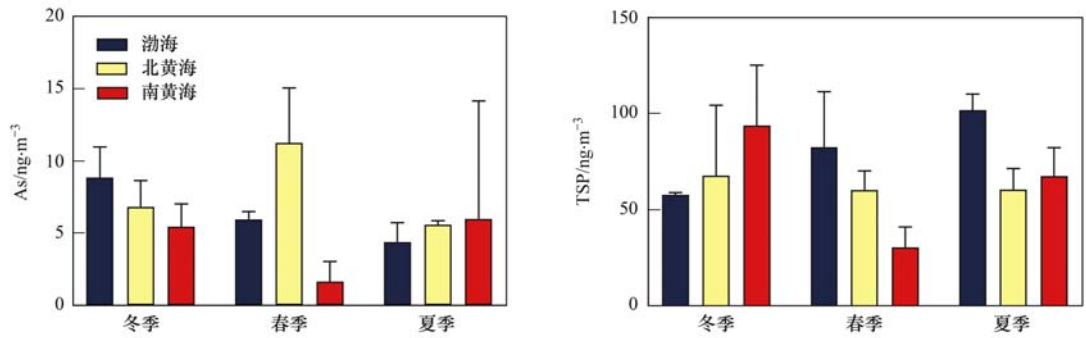


图2 黄渤海各季节气溶胶中As和TSP浓度

Fig. 2 Average concentrations of As and TSP in the Bohai Sea and Yellow Sea in three seasons

从季节变化来看,黄渤海海域2017年冬季航次气溶胶中As浓度($6.6\ \text{ng}\cdot\text{m}^{-3}$)高于2018年夏季($5.5\ \text{ng}\cdot\text{m}^{-3}$),明显高于2018年春季($4.4\ \text{ng}\cdot\text{m}^{-3}$)(图2),这可能与气溶胶中As的来源的季节差异有关.与国内部分城市对比发现,黄渤海气溶胶的As含量小于保定^[9]($131\sim233\ \text{ng}\cdot\text{m}^{-3}$)、郑

州^[13]($28.7\ \text{ng}\cdot\text{m}^{-3}$)、延吉市^[14]($11.9\ \text{ng}\cdot\text{m}^{-3}$)和中国7地区 $\text{PM}_{2.5}$ 中As平均浓度(湖南、河北、湖北、山西、云南和上海等)^[15]($11.3\ \text{ng}\cdot\text{m}^{-3}$).本研究的浓度与青岛市^[7]($6.0\ \text{ng}\cdot\text{m}^{-3}$)、兰州^[14]($6.68\ \text{ng}\cdot\text{m}^{-3}$)和上海^[18]($6.6\pm4.7\ \text{ng}\cdot\text{m}^{-3}$)的浓度相近(表1).

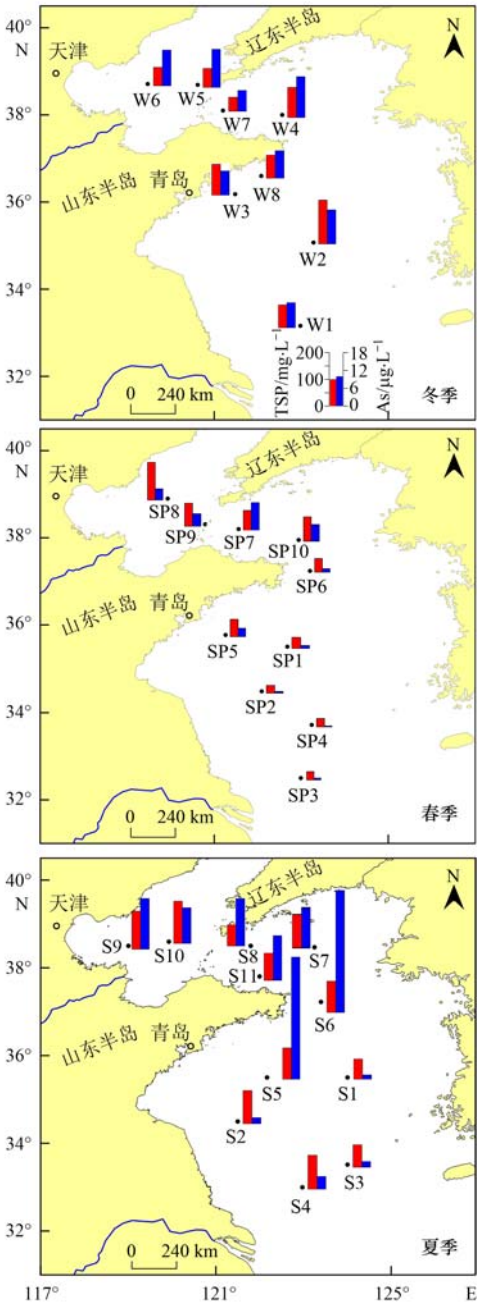
表1 黄渤海及其他地区气溶胶中As浓度比较

Table 1 Concentrations of As over the Bohai Sea and Yellow Sea compared with other sites around the world				
地区	类型	时间(年·月)	As/ $\text{ng}\cdot\text{m}^{-3}$	文献
黄渤海	海洋(TSP)	2017-12~2018-01	$6.6\pm2.0(4.2\sim10.4)$	本研究
	海洋(TSP)	2018-03~2018-04	$4.4\pm4.1(0.5\sim14.0)$	
	海洋(TSP)	2018-07~2018-08	$5.5\pm5.6(0.4\sim16.8)$	
青岛	城市(TSP)	2016-06~2016-07	6.0	[7]
保定	城市(TSP)	2016~2017	131~233	[9]
延吉市	城市(TSP)	2015~2017	11.9	[14]
中国7省	城市和乡村(TSP)	2013-10~2015-08	11.3	[15]
兰州	城市($\text{PM}_{2.5}$)	2015~2018	6.68	[16]
郑州	城市($\text{PM}_{2.5}$)	2016冬	28.7	[13]
上海	城市($\text{PM}_{2.5}$)	2015-12~2016-05	6.6 ± 4.7	[17]

2.2 As的形态

冬季,黄渤海海域As(V)和As(III)的浓度分别为 $4.9\ \text{ng}\cdot\text{m}^{-3}$ 和 $1.7\ \text{ng}\cdot\text{m}^{-3}$,均高于夏季测定值 $4.5\ \text{ng}\cdot\text{m}^{-3}$ 和 $1.0\ \text{ng}\cdot\text{m}^{-3}$,表现为冬季>夏季,As(V)和As(III)浓度的季节差异与As分布一致.气溶胶中As主要以As(V)的形式存在,这与之前在北京^[5]和Wuelva^[19]气溶胶中As的形态分布相

同.相较于As(V),As(III)具有更强的生物毒性.冬、夏季海洋气溶胶中As(III)/As(V)比值分别为0.41和0.21,这可能与陆源大气污染排放组成和大气氧化性差异有关.石绍萱等^[18]对北京 $\text{PM}_{2.5}$ 中砷污染特征研究发现,夏季As(III)/As(V)比值远低于其他季节.夏季高温强辐射促进 O_3 等氧化基团生成,海洋大气环境氧化性增强,有利于颗粒物



W、SP 和 S 分别代表冬、春和夏季采样航段编号
图 3 黄渤海各季节气溶胶中 TSP 和 As 的浓度空间分布
Fig. 3 Distributions of As and TSP in the Bohai Sea and Yellow Sea in three seasons

中 As(Ⅲ)向 As(Ⅴ)的转化,导致 As(Ⅲ)/As(Ⅴ) 比值较小.

2.3 气溶胶中 As 和 As/TSP 的含量及其与其它参数的关系

黄渤海气溶胶中 TSP 浓度为 20.26 ~ 137.84 $\mu\text{g}\cdot\text{m}^{-3}$, 季节变化较为明显, 呈现冬季 (78.2 $\mu\text{g}\cdot\text{m}^{-3}$) 与夏季 (73.0 $\mu\text{g}\cdot\text{m}^{-3}$) 相近, 大于春季 (46.7 $\mu\text{g}\cdot\text{m}^{-3}$) 的季节变化趋势.

黄渤海气溶胶中 As、As(Ⅴ) 和 As(Ⅲ) 和 TSP 含量不存在显著的相关关系 ($P > 0.05$). 相反, 北京大气气溶胶 As 形态中, As 及 As(Ⅲ) 和 As(Ⅴ) 均与 TSP 呈现显著的正相关性^[5]. As 的含量与风速呈显著负相关 ($P < 0.01$), 表明气象扩散条件较好时 As 污染不易累积. 其他研究也表明, 气象因素如风速、温度、湿度和太阳辐射等, 均是影响 As 在气溶胶中分布的重要因素^[20].

相较于质量浓度, As 在 TSP 中的质量分数 (As/TSP) 能更好地反映 As 在颗粒物上的富集程度. As/TSP 平均数和范围分别为 ($\mu\text{g}\cdot\text{g}^{-1}$): 冬季 95.5 (44.0 ~ 176.6)、春季 83.9 (35.1 ~ 262.2) 和夏季 81.4 (6.7 ~ 279.7), 季节差异可能是由于陆地污染物排放的季节差异和气象因素不同造成的. 在保定的研究表明, 冬季 As 在 TSP 中粒径分布主要集中在粗模态 ($\text{PM}_{2.5-10}$), 陆地向海洋传输过程中, 粗颗粒逐渐沉降, 细颗粒物占比增加, 使冬季 As/TSP 与 TSP 存在显著负相关 ($r = 0.69$, $P < 0.05$). 春季则呈现显著的正相关 ($r = 0.94$, $P < 0.01$), 这可能与春季受陆地和海洋气团的混合影响, 大气颗粒物来源不同和粒径差异有关. 夏季相关性不明显 (图 4).

整体上来看, 气溶胶中 As 与水溶性离子之间均不存在显著相关性 (表 2). 但冬季 As/TSP 与 K^+/TSP 存在显著的相关性 (表 3), K^+ 可以作为生物质燃烧的示踪剂, 表征海洋气溶胶受到陆地生物质燃烧的影响^[21], 表明冬季陆地生物质燃烧是气溶胶中 As 的重要来源, 而在夏季生物质燃烧较少, 这种相

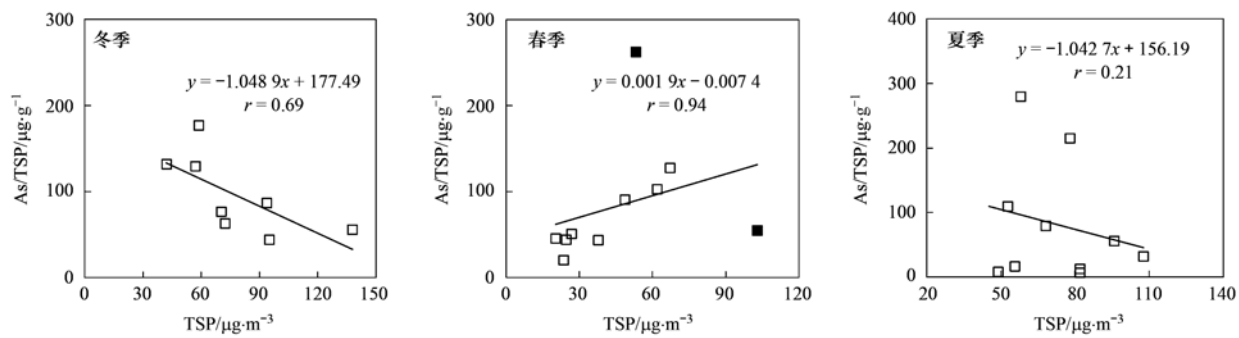
表 2 As 与水溶性离子的相关性

Table 2 Correlations between As and water-soluble ions in two seasons								
季节	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	NO_3^-
冬季	-0.350	-0.563	0.201	0.078	-0.401	-0.375	-0.375	-0.100
夏季	-0.092	-0.231	0.068	0.031	0.119	-0.080	-0.331	-0.013

表 3 As/TSP 与水溶性离子质量浓度的相关性¹⁾

Table 3 Correlations between As/TSP and mass concentration of water-soluble ions in two seasons								
季节	Na^+/TSP	NH_4^+/TSP	K^+/TSP	$\text{Mg}^{2+}/\text{TSP}$	$\text{Ca}^{2+}/\text{TSP}$	Cl^-/TSP	$\text{SO}_4^{2-}/\text{TSP}$	NO_3^-/TSP
冬季	-0.062	-0.089	0.780 *	0.502	0.269	0.141	-0.203	-0.542
夏季	0.189	-0.459	-0.165	0.075	0.112	0.012	-0.228	0.027

1) * 表示 $P < 0.05$



春季中黑色方块表示异常值不参与方程拟合

图 4 黄渤海各季节气溶胶 As/TSP 随 TSP 变化

Fig. 4 Correlations between As/TSP and TSP in the Bohai Sea and Yellow Sea in three seasons

关性不明显.

域后向轨迹分析可以看到(图 5),黄渤海海域气团来源季节差异明显.

2.4 后向轨迹分析

从 2017 年冬季、2018 年春季和夏季黄渤海海

冬季北方供暖排放较多大气污染物,黄渤海位

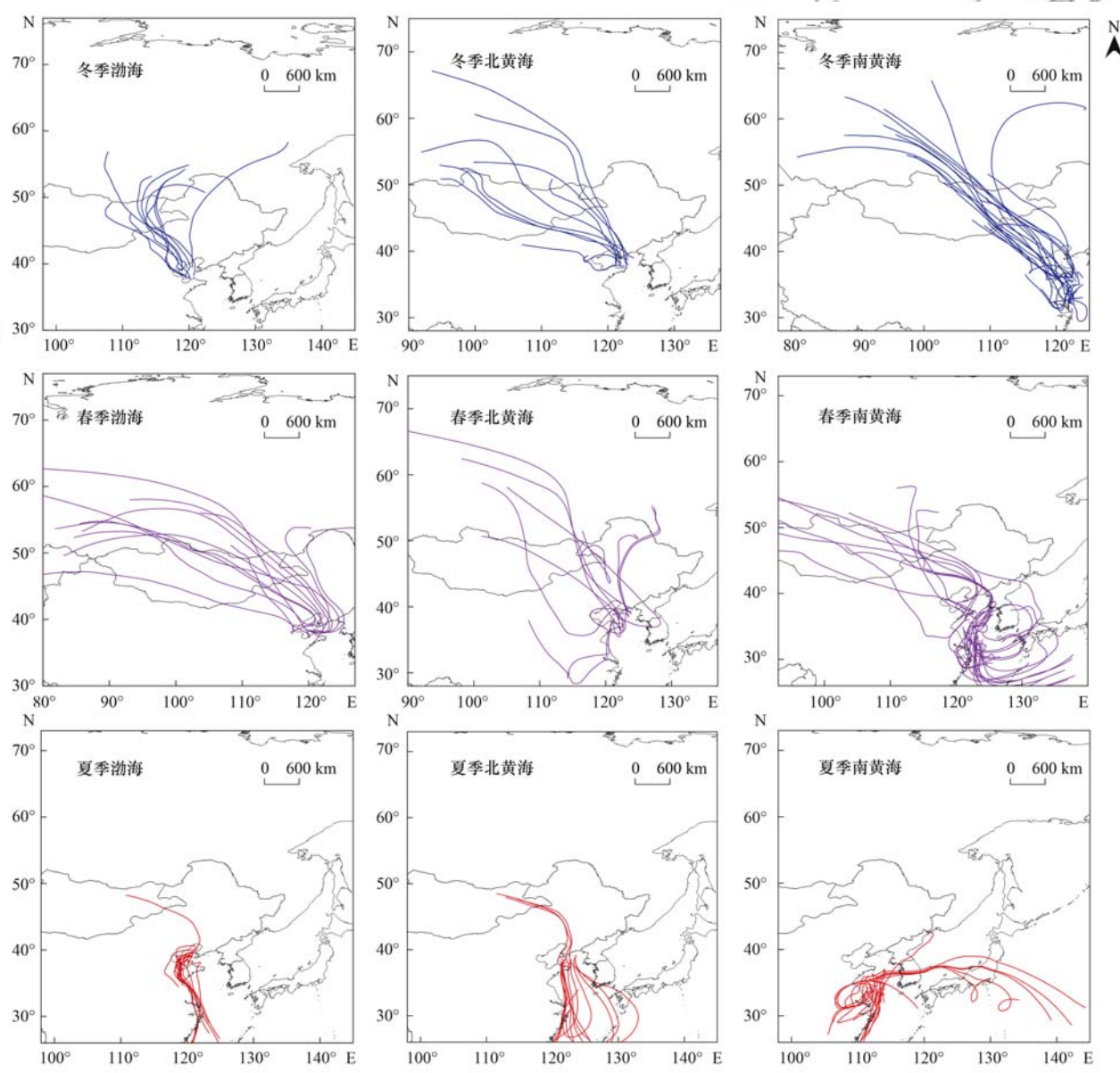


图 5 2017 年冬季、2018 年春季和夏季黄渤海海域后向轨迹分析

Fig. 5 Distribution of backward trajectories over the Bohai Sea and Yellow Sea in winter 2017, spring and summer 2018

于中国大陆的下风向,易受陆地排放污染的影响导致 As 浓度升高;而夏季受东南季风的影响,东部沿海经济区污染气团导致夏季气溶胶 As 浓度增高.

冬季,研究海域主要受来自西北高压冷气团的影响,气团来自蒙古和西伯利亚地区,经过京津冀、山东半岛和辽东半岛等大气污染较重的区域.有研究表明,As 与燃料燃烧排放密切相关^[22].影响渤海气团轨迹较短,移动速度较慢,携带了京津冀近地面的污染物,导致渤海气溶胶中 As 浓度最高为 $8.8 \text{ ng}\cdot\text{m}^{-3}$.与渤海和北黄海不同,南黄海部分航段受南向沿岸气团影响,As 浓度偏低,为 $5.4 \text{ ng}\cdot\text{m}^{-3}$,而且气团在近海海面有较长时间的停留,受相对清洁的海洋大气稀释.

春季,气团主要来自西伯利亚和东南远海两个方向.渤海和北黄海受西北长距离气团的控制.与冬季不同的是,北黄海气溶胶中 As 浓度 ($11.3 \text{ ng}\cdot\text{m}^{-3}$) 高于渤海 ($6.0 \text{ ng}\cdot\text{m}^{-3}$),这可能是由于到达北黄海的气团移动缓慢,携带了山东半岛和辽东半岛之间近地面大气污染物有关.而到渤海的气团为高空输送,携带污染物较少.南黄海,在来自西北太平洋气团影响下气溶胶中 As 浓度偏低.春季,采样期间风速较高,高空气团较多,陆地排放污染物影响偏小.

夏季,影响研究海域的气团主要来自海洋,大部分气团来自东海,途经福建、浙江和江苏沿海以及山东半岛,少部分来自北方蒙古和西太平洋以及日本海.气团来源的变化,可能是夏季气溶胶中 As 浓度相较于春季较高的原因.从模拟 2015 年全球大气 As 分布发现,长江三角洲地区和山东中部是 As 的重要污染源区^[4].夏季,东部沿海地区是气溶胶中 As 的主要来源.但渤海和北黄海气溶胶中 As 浓度仍然较高.值得注意的是, S5 和 S6 采样点 As 浓度显著升高,分别为 $16.3 \text{ ng}\cdot\text{m}^{-3}$ 和 $16.8 \text{ ng}\cdot\text{m}^{-3}$,是夏季气溶胶中 As 平均浓度的 3 倍左右.影响 S5 和 S6 气团路径为:西太平洋→日本南部→日本海→韩国→黄海,因此日本和韩国是该点气溶胶中高浓度 As 的主要原因.

2.5 沉降通量

气溶胶干沉降是海水中重金属的重要来源^[23,24].本研究估算了黄渤海走航采样期间气溶胶中 As 的干沉积通量.冬、春和夏季,As 干沉降通量分别为 1.15 、 0.77 和 $0.97 \mu\text{g}\cdot(\text{m}^2\cdot\text{d})^{-1}$,冬、夏季高于春季.黄渤海气溶胶 As 干沉降通量平均为 $0.95 \mu\text{g}\cdot(\text{m}^2\cdot\text{d})^{-1}$,低于沿海城市和郊区 As 的沉降通量^[7,25,26,27],明显低于在徐州北郊的观测结果^[28](表 4).

表 4 黄渤海与各地区 As 沉降通量对比

Table 4 Atmospheric dry deposition fluxes of As in this study and comparison with other regions

采样区域	地区类型	沉降类型	时间(年·月)	沉降通量/ $\mu\text{g}\cdot(\text{m}^2\cdot\text{d})^{-1}$	文献
黄渤海	海洋	干沉降	2017~2018	0.95	本研究
青岛	沿海城市	干沉降	2016-06~2016-07	1.9 ± 1.4	[7]
渤海湾	沿海城市	混合沉降	2016-11~2017-10	1.75	[25]
大亚湾	沿海郊区	干沉降	2015-10~2017-05	1.21	[26]
加勒比海	沿海郊区	混合沉降	2014-03~2016-11	1.2	[27]
徐州北郊	城市郊区	混合沉降	2017-07~2017-12	8.1	[28]

3 结论

(1) 黄渤海海域气溶胶中 As 浓度冬、夏季高于春季,存在明显的季节变化特征.春、夏季渤海和北黄海远大于南黄海;冬季渤海高于北黄海和南黄海,南北黄海差异较小.冬、夏季海洋气溶胶中 As(Ⅲ)/As(Ⅴ)比值分别为 0.41 和 0.21.冬、春和夏季 As/TSP 平均值分别为 95.5、83.9 和 $81.4 \mu\text{g}\cdot\text{g}^{-1}$,冬季高于春季和夏季.

(2) 后向轨迹分析表明,冬季气团受京津冀、山东半岛和辽东半岛地区大气污染物输送的影响明显;夏季以东海沿岸气团为主,受中国东部和东南沿海城市排放的影响明显,来自日、韩的气团具有最高的 As 浓度;春季影响气团主要为西北内陆和东南远海,As 浓度偏低.

(3) 冬季气溶胶中 As/TSP 与 K^+/TSP 显著相关,表明其受陆地生物质燃烧影响较大.黄渤海气溶胶中 As 的沉降通量为 $0.95 \mu\text{g}\cdot(\text{m}^2\cdot\text{d})^{-1}$,冬季 > 夏季 > 春季.

参考文献:

[1] Wang S L, Mulligan C N. Occurrence of arsenic contamination in Canada: sources, behavior and distribution[J]. Science of the Total Environment, 2006, **366**(2-3): 701-721.

[2] Hedberg E, Gidhagen L, Johansson C. Source contributions to PM_{10} and arsenic concentrations in central Chile using positive matrix factorization[J]. Atmospheric Environment, 2005, **39**(3): 549-561.

[3] Yoshikawa M, Aoki K, Ebine N, et al. Correlation between the arsenic concentrations in the air and the SMR of lung cancer[J]. Environmental Health and Preventive Medicine, 2008, **13**(4): 207-218.

[4] Zhang L, Gao Y, Wu S L, et al. Global impact of atmospheric arsenic on health risk: 2005 to 2015[J]. Proceedings of the

- National Academy of Sciences of the United States of America, 2020, **117**(25): 13975-13982.
- [5] Yang G S, Ma L L, Xu D D, *et al.* Levels and speciation of arsenic in the atmosphere in Beijing, China[J]. *Chemosphere*, 2012, **87**(8): 845-850.
- [6] Tsai Y I, Kuo S C, Lin Y H. Temporal characteristics of inhalable mercury and arsenic aerosols in the urban atmosphere in southern Taiwan [J]. *Atmospheric Environment*, 2003, **37**(24): 3401-3411.
- [7] 李鹏志, 李茜, 石金辉, 等. 夏季青岛大气粗细粒子中微量元素浓度、溶解度及干沉降通量[J]. *环境科学*, 2018, **39**(7): 3067-3074.
- Li Z P, Li Q, Shi J H, *et al.* Concentration, solubility, and dry deposition flux of trace elements in fine and coarse particles in Qingdao during summer[J]. *Environmental Science*, 2018, **39**(7): 3067-3074.
- [8] Liang X X, Tian C G, Zong Z, *et al.* Flux and source-sink relationship of heavy metals and arsenic in the Bohai Sea, China [J]. *Environmental Pollution*, 2018, **242**: 1353-1361.
- [9] Xie J J, Yuan C G, Xie J, *et al.* Fraction distribution of arsenic in different-sized atmospheric particulate matters [J]. *Environmental Science and Pollution Research*, 2019, **26**(30): 30826-30835.
- [10] Draxler R R, Hess G D. An overview of the HYSPLIT_4 modelling system for trajectories, dispersion and deposition[J]. *Australian Meteorological Magazine*, 1998, **47**(4): 295-308.
- [11] Zhu L, Chen Y, Guo L, *et al.* Estimate of dry deposition fluxes of nutrients over the East China Sea: the implication of aerosol ammonium to non-sea-salt sulfate ratio to nutrient deposition of coastal oceans[J]. *Atmospheric Environment*, 2013, **69**: 131-138.
- [12] Qin X F, Wang F W, Deng C R, *et al.* Seasonal variation of atmospheric particulate mercury over the East China Sea, an outflow region of anthropogenic pollutants to the open Pacific Ocean[J]. *Atmospheric Pollution Research*, 2016, **7**(5): 876-883.
- [13] 闫广轩, 张朴真, 黄海燕, 等. 郑州-新乡冬季 PM_{2.5} 中元素浓度特征及其源分析[J]. *环境科学*, 2019, **40**(5): 2027-2035.
- Yan G Z, Zhang P Z, Huang H Y, *et al.* Concentration characteristics and source analysis of PM_{2.5} during wintertime in Zhengzhou-Xinxiang[J]. *Environmental Science*, 2019, **40**(5): 2027-2035.
- [14] 扈孟楠, 金光洙, 王爽, 等. 延吉市大气颗粒物中重金属的分布特征和风险评价[J]. *延边大学农学学报*, 2020, **42**(4): 50-57.
- Hu M N, Jin G S, Wang S, *et al.* Distribution characteristics and risk assessment of heavy metals in air particulates in Yanji City[J]. *Journal of Agricultural Science Yanbian University*, 2020, **42**(4): 50-57.
- [15] Wang J W, Wan Y J, Cheng L, *et al.* Arsenic in outdoor air particulate matter in China: tiered study and implications for human exposure potential[J]. *Atmospheric Pollution Research*, 2020, **11**(4): 785-792.
- [16] 程妍, 刘小云, 夏智恒, 等. 2015—2018 年兰州市两区大气 PM_{2.5} 中 10 种金属和类金属元素浓度变化[J]. *卫生研究*, 2021, **50**(1): 79-85.
- Cheng Y, Liu X Y, Xia Z H, *et al.* Concentration changes of ten metal and metalloid elements in atmospheric PM_{2.5} in two districts of Lanzhou City from 2015 to 2018 [J]. *Journal of Hygiene Research*, 2021, **50**(1): 79-85.
- [17] 马瑾. 上海市大气细颗粒物中元素分析及来源解析[D]. 上海: 上海师范大学, 2018.
- [18] 石绍萱, 杨艳蓉, 秦娟娟, 等. 北京市 PM_{2.5} 中砷污染特征[J]. *环境科学*, 2020, **41**(1): 57-64.
- Shi S X, Yang Y R, Qin J J, *et al.* Chemical characteristics of arsenic in PM_{2.5} in Beijing[J]. *Environmental Science*, 2020, **41**(1): 57-64.
- [19] de la Campa A M S, de la Rosa J D, Sánchez-Rodas D, *et al.* Arsenic speciation study of PM_{2.5} in an urban area near a copper smelter[J]. *Atmospheric Environment*, 2008, **42**(26): 6487-6495.
- [20] Gao J J, Wang K, Wang Y, *et al.* Temporal-spatial characteristics and source apportionment of PM_{2.5} as well as its associated chemical species in the Beijing-Tianjin-Hebei region of China[J]. *Environmental Pollution*, 2018, **233**: 714-724.
- [21] Andreae M O, Merlet P. Emission of trace gases and aerosols from biomass burning[J]. *Global Biogeochemical Cycles*, 2001, **15**(4): 955-966.
- [22] Gao J J, Tian H Z, Cheng K, *et al.* Seasonal and spatial variation of trace elements in multi-size airborne particulate matters of Beijing, China: mass concentration, enrichment characteristics, source apportionment, chemical speciation and bioavailability[J]. *Atmospheric Environment*, 2014, **99**: 257-265.
- [23] Chen Y, Paytan A, Chase Z, *et al.* Sources and fluxes of atmospheric trace elements to the Gulf of Aqaba, Red Sea[J]. *Journal of Geophysical Research: Atmospheres*, 2008, **113**(D5), doi: 10.1029/2007JD009110.
- [24] Duan X Y, Li Y X. Distributions and sources of heavy metals in sediments of the Bohai Sea, China: a review[J]. *Environmental Science and Pollution Research*, 2017, **24**(32): 24753-24764.
- [25] 张国忠, 崔阳, 潘月鹏, 等. 渤海湾大气金属元素沉降和来源解析研究[J]. *环境科学学报*, 2019, **39**(8): 2708-2716.
- Zhang G Z, Cui Y, Pan Y P, *et al.* Deposition fluxes and source apportionment of atmospheric trace metals in the Bohai Bay[J]. *Acta Scientiae Circumstantiae*, 2019, **39**(8): 2708-2716.
- [26] Wu Y C, Zhang J P, Ni Z X, *et al.* Atmospheric deposition of trace elements to Daya Bay, South China Sea: fluxes and sources [J]. *Marine Pollution Bulletin*, 2018, **127**: 672-683.
- [27] Morera-Gómez Y, Santamaría J M, Elustondo D, *et al.* Determination and source apportionment of major and trace elements in atmospheric bulk deposition in a Caribbean rural area [J]. *Atmospheric Environment*, 2019, **202**: 93-104.
- [28] 栾慧君, 塞古, 徐蕾, 等. 徐州北郊大气降尘重金属污染特征与风险评价[J]. *中国环境科学*, 2020, **40**(11): 4679-4687.
- Luan H J, Mohamed-Conde S, Xu L, *et al.* Characteristics and risk assessment of heavy metals from atmospheric deposition in northern suburban of Xuzhou[J]. *China Environmental Science*, 2020, **40**(11): 4679-4687.

CONTENTS

Spatiotemporal Distribution and Health Impacts of PM _{2.5} and O ₃ in Beijing, from 2014 to 2020	CHEN Jing, PENG Jin-long, XU Yan-sen (4071)
High-resolution Estimation of Spatio-temporal Variation in PM _{2.5} Concentrations in the Beijing-Tianjin-Hebei Region	YANG Xiao-hui, SONG Chun-jie, FAN Li-hang, <i>et al.</i> (4083)
Impacts of Anthropogenic Emission Reduction and Meteorological Conditions on PM _{2.5} Pollution in Typical Cities of Beijing-Tianjin-Hebei in Winter	SHAO Xuan-yi, WANG Xiao-qi, ZHONG Yi-sheng, <i>et al.</i> (4095)
Influence of Pollutant Transport from Both Sides of the Taihang Mountains on Cross-Valley Urban Aerosols	WANG Yan, GUO Wei, YAN Shi-ming, <i>et al.</i> (4104)
Variation Characteristics and Source Analysis of Carbonaceous Aerosols in Winter in Jiashan	ZHANG Ying-long, LI Li, WU Wei-chao, <i>et al.</i> (4116)
Simulation Analysis of the Impact of COVID-19 Pandemic Control on Air Quality in Henan Province based on Machine Learning Algorithm	WEI Yu, XU Qi-xiang, ZHAO Jin-shuai, <i>et al.</i> (4126)
Seasonal Variation, Source Identification, and Health Risk of PM _{2.5} -bound Metals in Xinxiang	LIU Huan-jia, JIA Meng-ke, LIU Yong-li, <i>et al.</i> (4140)
Distribution Characteristics and Seasonal Variations of Arsenic in Atmospheric Aerosols over the Yellow Sea and Bohai Sea	YUAN Shuai, WANG Yan, LIU Ru-hai, <i>et al.</i> (4151)
Extinction Characteristics of Aerosols and the Contribution of Pollution Sources to Light Extinction During Three Heavy Pollution Episodes in the Winter of 2020 in Tianjin	LI Li-wei, XIAO Zhi-mei, YANG Ning, <i>et al.</i> (4158)
Spatial Variation of Surface Ozone Concentration During the Warm Season and Its Meteorological Driving Factors in China	HE Chao, MU Hang, YANG Lu, <i>et al.</i> (4168)
Exploring Characteristics and Causes of Summer Ozone Pollution Based on Process Analysis in Wuhai	ZHANG Rui-xin, CHEN Qiang, XIA Jia-qi, <i>et al.</i> (4180)
Pollution Characteristics and Source Analysis of Atmospheric VOCs in the Coastal Background of the Pearl River Delta	YUN Long, LI Cheng-liu, ZHANG Ming-di, <i>et al.</i> (4191)
Hydrochemical Characteristics and Factors of Surface Water and Groundwater in the Upper Yongding River Basin	KONG Xiao-le, YANG Yong-hui, CAO Bo, <i>et al.</i> (4202)
Temporal and Spatial Variations in Water Quality of Hanjiang River and Its Influencing Factors in Recent Years	CHENG Bing-fen, ZHANG Yuan, XIA Rui, <i>et al.</i> (4211)
Pollution Level, Distribution Characteristic, and Ecological Risk Assessment of Environmentally Persistent Pharmaceutical Pollutants in Surface Water of Jiangsu Province	ZHAO Mei-mei, FAN De-ling, GU Wen, <i>et al.</i> (4222)
Spatial and Temporal Distribution and Pollution Evaluation of Soluble Heavy Metals in Liujiang River Basin	ZHANG Wan-jun, XIN Cun-lin, YU Shi, <i>et al.</i> (4234)
Source Analysis and Health Risk Assessment of Heavy Metals in Groundwater of Leizhou Peninsula	SHI Huan-huan, PAN Yu-jie, ZENG Min, <i>et al.</i> (4246)
Distribution Characteristics and Health Risk Assessment of Metal Elements in Groundwater of Longzici Spring Area	XIE Hao, LIANG Yong-ping, LI Jun, <i>et al.</i> (4257)
Seasonal Variation and Sources Identification of Dissolved Sulfate in a Typical Karst Subterranean Stream Basin Using Sulfur and Oxygen Isotopes	REN Kun, PAN Xiao-dong, LAN Gan-jiang, <i>et al.</i> (4267)
Phosphorus Fractions and Quantitative Identification of Pollution Sources in Nanhai Wetland, Baotou	BAI Ya-hong, QIAN Chen-ge, YUAN Si-jing, <i>et al.</i> (4275)
Release Risk of Phosphorus by Sediments and Its Influencing Factors in Ponds and Ditches of a New Urban District Park	LI Ru-zhong, SONG Min, YANG Ji-wei (4287)
Effect of Hydraulic Residence Time on Removal Efficiency of Pollutants in Subsurface Flow Constructed Wetlands and Analysis of Denitrification Mechanism	QI Ran, ZHANG Ling, YANG Fan, <i>et al.</i> (4296)
Enhanced Removal of Pollutants in Constructed Wetlands with Manganese Sands	MA Quan, WANG Dong-lin, LIN Hui, <i>et al.</i> (4304)
Application Effect of Four Typical Submerged Macrophytes on Removing Cadmium from Polluted Sediment	TAO Li, WANG Pei-fang, YUAN Qiu-sheng, <i>et al.</i> (4311)
Structure of Aerobic Denitrification Bacterial Community in Response to Dissolved Organic Matter in Baiyangdian Lake During the Water Delivery Period	ZHOU Shi-lei, ZHANG Tian-na, CHEN Zhao-ying, <i>et al.</i> (4319)
Nitrogen and Phosphorus Leaching Characteristics and Adsorption Properties of Hardwood Biochar in Stormwater Runoff	MENG Yi-ke, WANG Yuan, WANG Chuan-yue (4332)
Indicator Function of Ragworm (<i>Nereididae</i>) on Sediment Microplastic in Haizhou Bay Intertidal Zone	WANG Jia-xuan, SONG Ke-xin, SUN Yi-xin, <i>et al.</i> (4341)
Antagonistic Effect and Mechanism of Nano Titanium Dioxide and Cadmium on the Growth of <i>Scenedesmus obliquus</i>	WANG Pu, ZHAO Li-hong, ZHU Xiao-shan (4350)
Mutual Influence Between Microbial Community, Wastewater Characteristics, and Antibiotic Resistance Genes During Spiramycin Production Wastewater Treatment	WU Cai-yun, LI Hui-li, QIN Cai-xia, <i>et al.</i> (4358)
Effect of Chelated Iron on Nitrogen Removal Efficiency and Microbial Community Structure in the Anaerobic Ferric Ammonium Oxidation	LIAO Hong-yan, SONG Cheng, WAN Liu-yang, <i>et al.</i> (4366)
Effects of Dissolved Oxygen on Nutrient Removal Performance and Microbial Community in Low Carbon/Nitrogen Municipal Wastewater Treatment Process	CHI Yu-lei, SHI Xuan, REN Tong, <i>et al.</i> (4374)
Shortening SRT of Intermittent Gradient Aeration to Realize Nitrogen and Phosphorus Removal in Short-range SNEDPR System	ZHANG Yu-jun, LI Dong, WANG Xin-xin, <i>et al.</i> (4383)
Characteristics of Partial Denitrification in Biofilm System	YU Li-fang, ZHANG Xing-xiu, ZHANG Qiong, <i>et al.</i> (4390)
Effect of Anaerobic Plug-flow on Nitrification Denitrifying Phosphorus Removal Aerobic Granular Sludge with Intermittent Aeration	LI Dong, CAO Si-yu, WANG Qi, <i>et al.</i> (4399)
Combining Different Aerobic/Anoxic Durations with Zoned Sludge Discharge to Optimize Short-cut Nitrification Denitrifying Phosphorus Removal Granules in Domestic Sewage	WANG Wen-qi, LI Dong, GAO Xin, <i>et al.</i> (4406)
Meta-analysis of the Effects of Metal Mining on Soil Heavy Metal Concentrations in Southwest China	ZHANG Jian-lin, QU Ming-kai, CHEN Jian, <i>et al.</i> (4414)
Distribution Characteristics and Ecological Risk Assessment of Soil Heavy Metals in Typical Watersheds of the Qinghai-Tibet Plateau	DU Hao-lin, WANG Ying, WANG Jin-song, <i>et al.</i> (4422)
Spatial Distribution Characteristics and Risk Assessment of Cadmium Pollution in Soil-crops system of an E-waste Dismantling Area	ZHANG Lu-yao, ZHAO Ke-li, FU Wei-jun (4432)
Characteristics of Modified Biochars and Their Immobilization Effect on Cu and Cd in Polluted Farmland Soil Around Smelter	WANG Xin-yu, MENG Hai-bo, SHEN Yu-jun, <i>et al.</i> (4441)
Combined Effects of Soil Amendment and Zinc Fertilizer on Accumulation and Transportation of Cadmium in Soil-Rice System	ZHOU Kun-hua, ZHOU Hang, WANG Zi-yu, <i>et al.</i> (4452)
Effects of Different Soil Conditioners on Rice Growth and Heavy Metal Uptake in Soil Contaminated with Copper and Cadmium	WEI Wei, LI Ping, LANG Man (4462)
Isolation and Identification of the Plant Endophyte R-13 and Its Effect on Cadmium Accumulation in <i>Solanum nigrum</i> L.	PANG Jie, LIU Yue-min, HUANG Yong-chun, <i>et al.</i> (4471)
Response of Soil Archaeal Community to Heavy Metal Pollution in Different Typical Regions	LI Yu-tong, YANG Shan, ZHANG Yi, <i>et al.</i> (4481)
High-throughput Sequencing Analysis of Soil Bacterial Community in the Grain for Green Project Areas of the Loess Plateau	LIU Xiao-hua, WEI Tian-xing (4489)
Experimental Influence of Food Waste Fermentation Broth on the Soil Quality in a Loess Hilly Area	SHAO Li-ming, REN Jun-da, LÜ Fan, <i>et al.</i> (4500)
Stability of Soil Aggregates at Different Altitudes in Qinling Mountains and Its Coupling Relationship with Soil Enzyme Activities	MA Huan-fei, HU Han, LI Yi, <i>et al.</i> (4510)
Reactivation of Passivated Biochar/Nanoscale Zero-Valent Iron by an Electroactive Microorganism for Cooperative Hexavalent Chromium Removal and Mechanisms	LIAO Cong-jian, ZHAO Xiao-lei, LIU Kai, <i>et al.</i> (4520)
Influence of Precipitation Change on Soil Respiration in Desert Grassland	HAO Lian-yi, ZHANG Li-hua, XIE Zhong-kui, <i>et al.</i> (4527)
Effects of Nitrogen Fertilizer Application Times and Nitrification Inhibitor on N ₂ O Emission from Potted Maize	FU Pei-jiao, JI Heng-kuan, HE Qiu-xiang, <i>et al.</i> (4538)
Gaseous Nitrogen Emission from Soil After Application of NH ₄ ⁺ -N Loaded Biochar	MA Xiao-gang, HE Jian-qiao, CHEN Yu-lan, <i>et al.</i> (4548)
Effects of Microplastics Addition on Soil Organic Carbon Mineralization in Citrus Orchard	ZHANG Xiu-ling, YAN Zi-wei, WANG Feng, <i>et al.</i> (4558)
Dynamic Material Flow Analysis of Perfluorooctane Sulfonate in China: 1985-2019	WANG Jia-yu, CHEN Jing-wen, TANG Wei-hao, <i>et al.</i> (4566)