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### Key Points:

- Meteorological conditions contributed significantly to atmospheric mercury seasonality across diverse temperate regions particularly Asia
- Typical monsoon climate in Asia led to differences in the crucial meteorological factors between Asia and other temperate regions
- Significant contributions of meteorological factors predicted further changes in atmospheric mercury seasonality under future global warming

### Supporting Information:

Supporting Information may be found in the online version of this article.

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## Meteorological Drivers of Atmospheric Mercury Seasonality in the Temperate Northern Hemisphere

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**Abstract** Mercury (Hg) is a neurotoxic pollutant that can be transported globally by atmospheric circulation and poses risks to wildlife and humans. Strong atmospheric Hg seasonality has been observed in the temperate Northern Hemisphere and explained by several hypothetical mechanisms. Here, we found that meteorological conditions were important drivers of the seasonality across diverse temperate regions particularly Asia through various indirect effects. Meteorological conditions can explain approximately 47%, 43%, and 67% of the seasonal amplitudes at the North American (NA) remote sites, European remote sites, and Asian monsoon sites, respectively. Surface air temperature, solar radiation, and surface wind collectively contributed significantly to the seasonality at the NA and European sites through vegetation resistance and oceanic evasion, while monsoon wind and precipitation promoted the summertime removal of Hg at the Asian sites through atmospheric transport and wet deposition, respectively. The findings predicted further changes in atmospheric Hg seasonality under future global warming.

**Plain Language Summary** Mercury is a neurotoxic pollutant that can be transported globally by atmospheric circulation before being removed from the atmosphere by deposition. Deposited mercury poses potential risks to ecosystems and human health owing to methylation and bioaccumulation. Strong seasonality of atmospheric mercury concentrations has been observed in the temperate Northern Hemisphere. Several hypotheses have been proposed to explain this strong seasonality, including vegetation uptake, chemical transformations, and anthropogenic emissions. In this study, we found that meteorological conditions were important drivers of the seasonality across diverse temperate regions particularly Asia through various indirect effects. Typical monsoon climate in Asia led to differences in the crucial meteorological factors between Asia and other temperate regions.

## 1. Introduction

Mercury (Hg) is a neurotoxic pollutant ubiquitously present in the environment (Obrist et al., 2021). Atmospheric Hg cycling is a crucial component of biogeochemical Hg cycling, owing to the extreme volatility of Hg (Sommar et al., 2020). Atmospheric Hg consists of a gaseous, elemental, and dominant type (Hg<sup>0</sup>; approximately 95%), and a gaseous or particulate divalent type (Hg<sup>II</sup>) (Lindberg & Stratton, 1998). Owing to its low chemical reactivity and water solubility, Hg<sup>0</sup> has a long lifespan in the troposphere (0.8–1.3 a) (Saiz-Lopez et al., 2018). It can be transported globally through atmospheric circulation before being adsorbed by vegetation and soils through dry deposition (Gustin et al., 2008; Wright et al., 2016) or transformed into Hg<sup>II</sup>, which is easily removed by wet deposition (Lyman et al., 2020). Deposited Hg potentially poses risks to wildlife and humans owing to its methylation and bioaccumulation characteristics (Roman et al., 2011; Zhang et al., 2010, 2021).

Seasonality of atmospheric Hg concentrations has been observed at multiple ground-based monitoring sites worldwide. In particular, the observed seasonality is stronger in the temperate Northern Hemisphere, which includes forest, coastal, and urban sites (Fu et al., 2019; Sprovieri et al., 2016; Weigelt et al., 2015). For instance, atmospheric Hg concentrations in summer accounted for 94% of those in winter at all sites from Canadian Atmospheric Mercury Network during 1995–2005 (Temme et al., 2007). The seasonal amplitudes of atmospheric Hg

concentrations at five temperate Northern Hemisphere sites averaged  $0.39 \text{ ng m}^{-3}$ , equaling 25% of the background concentrations in the hemisphere ( $1.5\text{--}1.7 \text{ ng m}^{-3}$ ) (Jiskra et al., 2018; Sprovieri et al., 2016).

Atmospheric Hg cycling is controlled by various atmospheric processes such as emissions, chemical transformations, atmospheric transport, dry deposition, and wet deposition. Accordingly, several hypothetical mechanisms based on these processes have been proposed to explain the strong seasonality in the temperate Northern Hemisphere, including vegetation uptake, chemical transformations, natural emissions, and anthropogenic emissions (Fu et al., 2015; Holmes et al., 2010; Horowitz et al., 2017; Jiskra et al., 2018). For instance, evidence of both Hg stable isotope signatures in litterfall (Liu et al., 2021; Wang, Bao, et al., 2016, 2020b) and the consistent seasonality between atmospheric Hg concentrations and vegetation activity (Jiskra et al., 2018) have confirmed the control of vegetation uptake on atmospheric Hg seasonality in the temperate Northern Hemisphere (MacSween, Edwards, & Beggs, 2020; Yu et al., 2018; Zhou et al., 2021). Additionally, high oxidant concentrations (e.g., Br,  $\text{NO}_2$ , and  $\text{HO}_2$  radicals) during warm months contribute to the high transformation rate of  $\text{Hg}^0$  to  $\text{Hg}^{\text{II}}$  and its subsequent removal via  $\text{Hg}^{\text{II}}$  deposition (Obrist et al., 2011; Pal & Ariya, 2004). Significant anthropogenic emissions from coal combustion occur during cold months owing to increased energy demands for heating, leading to elevated atmospheric Hg concentrations during this period (Liu et al., 2019; Wang et al., 2018; Weigelt et al., 2015).

Meteorological conditions have been recognized as key drivers that can induce seasonal variations of the atmospheric processes and subsequently induce atmospheric Hg seasonality indirectly. For instance, frequent rain and strong prevailing wind can contribute to the removal of atmospheric Hg through vertical wet deposition and horizontal atmospheric transport, respectively (Horowitz et al., 2017; Koenig et al., 2021; Sprovieri et al., 2017; Wang, Wang, & Zhang, 2020). Factors such as solar radiation, surface wind, and temperature can affect the natural emissions of Hg from the soil, snow, and ocean (Aspmo et al., 2006; Carbone et al., 2016; MacSween, Edwards, & Beggs, 2020). Although the role of meteorological conditions has previously been proposed (Fu et al., 2015; Liu et al., 2016; Tseng et al., 2012), their contributions to hemispherical seasonality have not been quantified, and the identification of crucial meteorological factors and the atmospheric processes of relevance have been poorly understood. This is in contrast to both the understanding of the driving forces of atmospheric Hg seasonality and projections of changes in biogeochemical Hg cycles under future climate change (Krabbenhoft & Sunderland, 2013). By reproducing the observed seasonality of atmospheric Hg during 2013–2017 at 44 Northern Hemisphere monitoring sites in model scenarios, the contributions of various meteorological factors to the seasonality were quantified.

## 2. Methods

### 2.1. Atmospheric Hg Observations

Atmospheric Hg observations were obtained from monitoring networks located in North America and Europe, including the Canadian Air and Precipitation Monitoring Network (CAPMoN), Atmospheric Mercury Network (AMNet), and European Monitoring and Evaluation Program (EMEP). Additionally, observations in tropical and Asian regions were collected from a literature survey. Observations conducted during 2013–2017 were included in our analysis, and the monthly means were archived for each monitoring site. The  $\text{Hg}^0$  species was only recorded at certain monitoring sites, whereas total gaseous mercury (TGM) was widely recorded. For consistency in the present study, TGM was used as a proxy for  $\text{Hg}^0$  because it is the dominant component in TGM.

A total of 44 ground-based monitoring sites were included in our analysis because of their multi-year seasonal TGM during 2013–2017. Observations without multi-year seasonal TGM were excluded, although they were collected from the above networks and a literature survey. The monitoring sites were divided into four groups based on their locations, including three temperate Northern Hemisphere groups: North American (NA) remote sites (20 sites), European remote sites (12 sites), Asian monsoon sites (8 sites), and one tropical group (4 sites). The details of the monitoring sites are provided in Table S1 in Supporting Information S1.

### 2.2. Atmospheric Hg Modeling

The GEOS-Chem chemical transport model ([www.geos-chem.org](http://www.geos-chem.org); version 12.5.0) was used to simulate atmospheric Hg cycling and reproduce the observed atmospheric Hg seasonality in the present study. The model is a

global 3-D atmospheric model that includes dynamic coupling between the atmosphere and surface reservoirs for Hg (Amos et al., 2012; Holmes et al., 2010; Horowitz et al., 2017; Selin et al., 2007; Shah et al., 2016). Both Hg<sup>0</sup> and Hg<sup>II</sup> are simulated in the model undergoing chemical transformations in the atmosphere and bidirectional transmission between the atmosphere and surface layers. Chemical transformations include the oxidation of Hg<sup>0</sup> to Hg<sup>II</sup> by Br and abundant atmospheric radicals (e.g., NO<sub>2</sub> and HO<sub>2</sub>), photoreduction of Hg<sup>II</sup> to Hg<sup>0</sup> in cloud droplets, and thermodynamic partitioning of Hg<sup>II</sup> between the gas and particle phases (Amos et al., 2012; Holmes et al., 2010; Horowitz et al., 2017; Shah et al., 2016). Dry deposition follows the standard resistance-in-series scheme (Wesely, 1989), and wet scavenging follows the scheme of Liu et al. (2001), including washout losses in convective updrafts and rainout losses in large-scale precipitation.

Model simulations were driven by assimilated meteorological fields from the NASA Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2) system (Gelaro et al., 2017). All simulations were conducted at 2° latitude × 2.5° longitude resolution and 47 vertical hybrid eta levels from the surface to 0.01 hPa. Four-year simulations were conducted for 2013–2016 with 2013–2014 for initialization and 2015–2016 for analysis. The global anthropogenic emission inventory was derived from Streets et al. (2019), indicating 2.4 Gg yr<sup>-1</sup> of Hg was released into the air by human activities in 2015. The model outputs were archived monthly for 2 years on average to reproduce the monthly observations at the monitoring sites.

### 2.3. Hypothetical Drivers and Model Scenarios

Based on the hypothetical mechanisms previously proposed (Fu et al., 2015; Holmes et al., 2010; Horowitz et al., 2017; Jiskra et al., 2018; Weigelt et al., 2015), both meteorological conditions and other potential drivers, such as vegetation activity, redox fields, biomass burning emissions, and anthropogenic emissions were included in the present study. These drivers would collectively affect atmospheric Hg processes and subsequent Hg seasonality (Figure S1 in Supporting Information S1). For example, vegetation uptake is controlled by vegetation activity, temperature, and solar radiation. It was difficult to enumerate all drivers, however, the representative drivers referenced from previous studies were investigated. These drivers remain relatively independent with meteorological conditions in regard to the direct effects on atmospheric Hg processes. A detailed description of the data sources and seasonal characteristics for these potential drivers, except for meteorological conditions, are provided in Text S1 in Supporting Information S1.

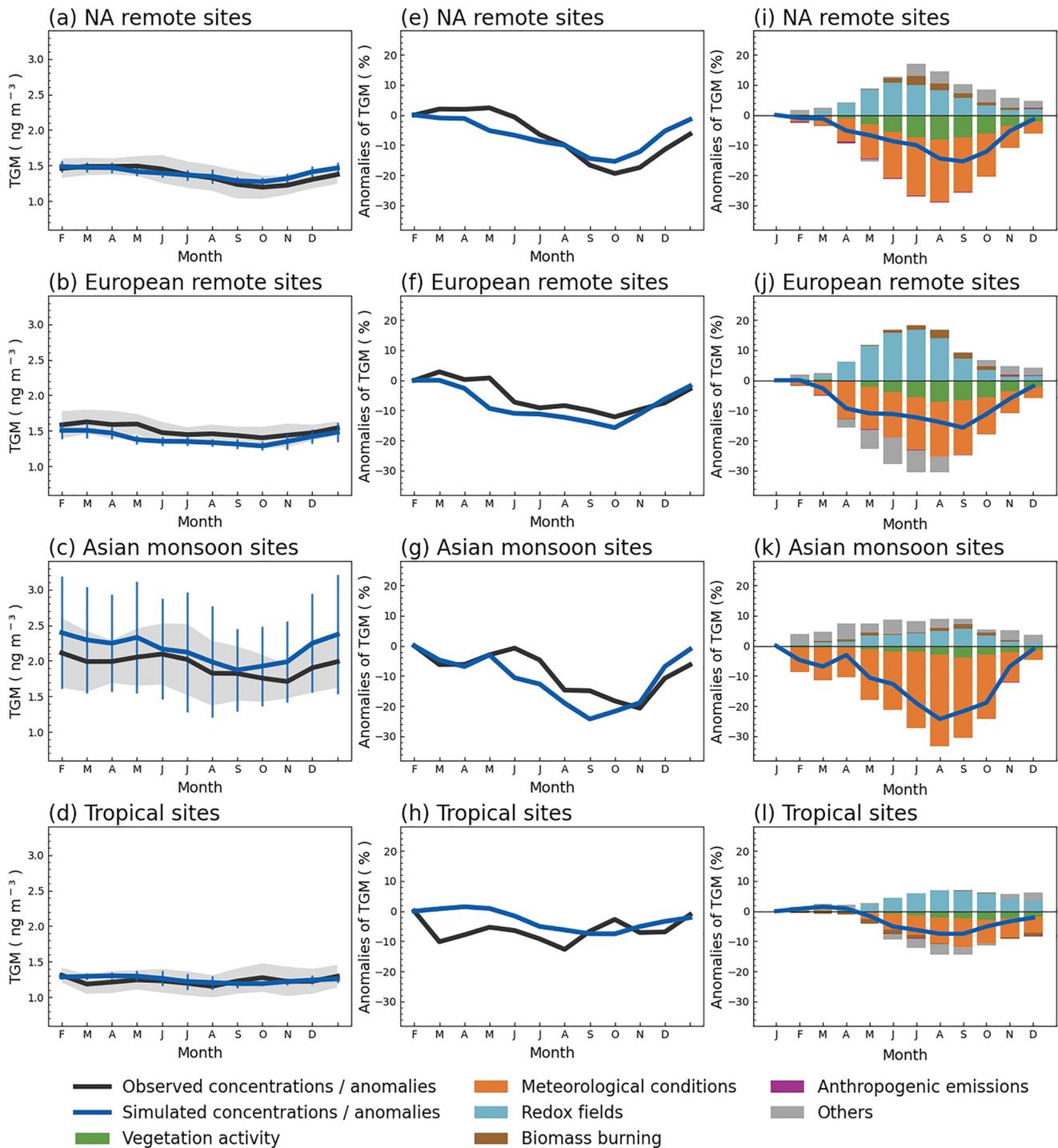
For meteorological conditions, assimilated fields for 2013–2016 were obtained from the NASA MERRA-2 system (Gelaro et al., 2017). The data collection of MERRA-2 has a native resolution of 0.5° latitude × 0.625° longitude with 72 vertical pressure levels and provides us with a complete gridded ensemble of meteorological variables. In addition to the entire meteorological field, seven meteorological factors that can significantly influence atmospheric Hg cycling were tested individually: the height of the planetary boundary layer (PBLH), temperature at 2 m above ground (T2M, namely surface temperature), temperature in the atmospheric vertical columns (T), surface wind at 10 m above ground (UV10M), wind in atmospheric vertical columns (UV), solar radiation, and precipitation. All meteorological factors, including these seven factors, were archived in a 1- or 3-hr time-averaged manner and stored as daily files for the model input. The seasonality of these seven factors in the Northern Hemisphere during 2015–2016 is shown in Figure S2 in Supporting Information S1.

First, a base scenario was run with default model inputs for 2013–2016. The results from the base scenario were used to reproduce the observed seasonality of the TGM concentrations at the monitoring sites. We then ran a model scenario for each driver to individually evaluate the contribution of the specific driver. For each model scenario, the seasonality of the corresponding driver during 2015–2016 was removed by repeating the data in January for the entire year. The contribution of each driver was quantified by comparing the model scenario with the base scenario.

## 3. Results and Discussion

### 3.1. Reproducing Observed Atmospheric Hg Seasonality in the Northern Hemisphere

Figures 1a–1h illustrates the distinct seasonality of TGM concentrations at the four studied groups of monitoring sites. The observed seasonality showed lower concentrations during warm months and higher concentrations



**Figure 1.** Observed and simulated seasonality of total gaseous mercury (TGM) concentrations (a–h) and contributions of various drivers to the seasonality (i–l) at the Northern Hemisphere sites. The shaded areas and error bars in panels (a–d) represent the standard deviations of observed and simulated concentrations, respectively. Anomalies of TGM concentrations (throughout the text) were calculated through subtracting the absolute value in January from the value in each month and then dividing annual mean.

during cold months at sites in the temperate regions. The anomalies reached negative minima of  $-19\%$  in September at the NA remote sites,  $-14\%$  in September at the European remote sites, and  $-22\%$  in October at the Asian monsoon sites. In contrast, the TGM concentrations at tropical sites showed no significant seasonal oscillations.

Scatter plots correlating the observed annual average TGM concentrations, wet deposition flux, and soil emission flux with the simulations illustrate a good track of the observations obtained by the model (Figures S3 and S4 in Supporting Information S1). The model reproduced TGM seasonality in all the studied groups of monitoring sites (Figures 1a–1h). Good performance was also observed at most of the individual monitoring sites (Figures S5–S8 in Supporting Information S1). Accordingly, the GEOS-Chem model with the latest input data, including meteorological fields and vegetation activity (see Methods), reproduced the observed TGM concentrations and seasonality, laying the foundation for quantifying the contributions of meteorological drivers.

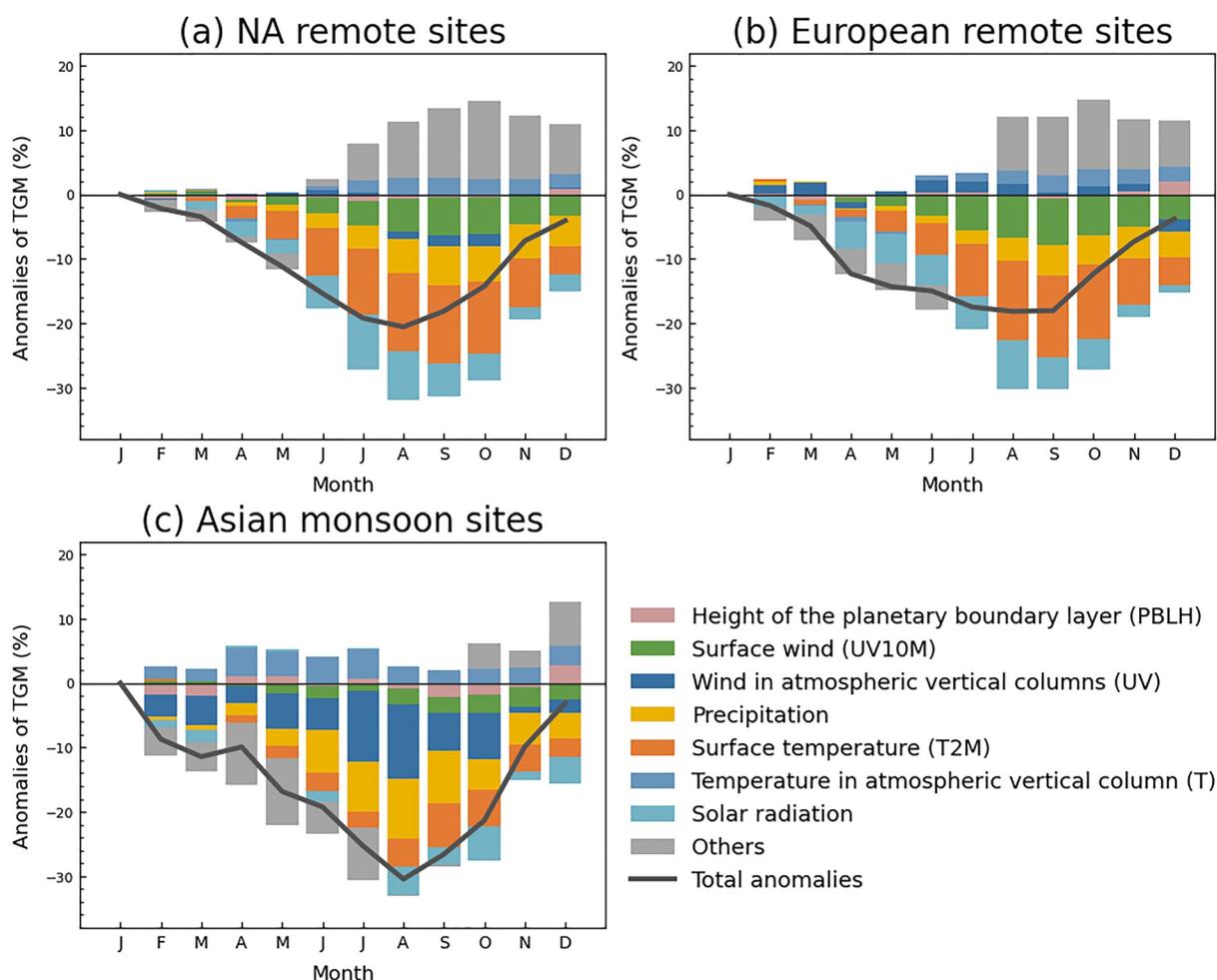
Figures 1i–1l illustrates the contributions of various potential drivers to the observed seasonal anomalies of the TGM concentrations. On average, the combination of these drivers explained approximately 87% of the observed seasonality at all the sites. Meteorological conditions served as the most important drivers of atmospheric Hg seasonality and promoted negative anomalies at all the sites (details in Section 3.2). The negative anomalies driven by meteorological conditions reached negative minima of  $-21\%$  and  $-19\%$  at the NA and European remote sites, respectively. On average, throughout the year, the contributions of meteorological conditions can explain approximately 47% and 43% of atmospheric Hg seasonality at the NA and European remote sites, respectively. In addition, high vegetation activity (Figure S9 in Supporting Information S1) contributed to an approximate decrease of  $-8\%$  during warm months in these two regions, which was attributed to the high stomatal resistance and cuticular resistance of vegetation (Wesely, 1989; Wright & Zhang, 2015). In contrast, the positive anomalies driven by redox fields peaked at 11% and 17% at the NA and European remote sites, respectively, indicating rapid photoreduction of  $\text{Hg}^{\text{II}}$  to  $\text{Hg}^0$  in very clean air during warm months in these regions.

Meteorological conditions at the Asian monsoon sites were more important than those at the NA and European remote sites, which contributed to a negative minimum of  $-32\%$  in August for the negative anomalies, and the contributions of vegetation activity and redox fields were not significant. On average, throughout the year, the contributions of meteorological conditions can explain approximately 67% of atmospheric Hg seasonality at Asian monsoon sites. These inconspicuous contributions were attributed to the profound influence of the typical monsoon climate. Strong monsoon circulation dominates the flow of the Hg-containing air mass, which can weaken the influence of other drivers. Additionally, the low contributions of various drivers were quantified at tropical sites. Weak seasonality of drivers, such as relatively stable meteorological conditions, evergreen forest vegetation, and relatively constant redox fields in the tropics, might account for the weak atmospheric Hg seasonality.

### 3.2. Evaluating the Indirect Effects of Meteorological Drivers

Based on the key role of meteorological conditions, the contributions of individual meteorological factors that influence atmospheric Hg cycling were evaluated. On average, the combination of seven meteorological factors explained approximately 78% of the total anomalies driven by entire meteorological field (Figure 2).

Similar patterns in the contribution of meteorological factors were observed at the NA and European remote sites. T2M, UV10M, solar radiation, and precipitation were crucial drivers at these sites. The negative anomalies driven by T2M and solar radiation reached negative minima of approximately  $-12\%$  and  $-8\%$  at these sites, respectively. High surface temperature and solar radiation can promote the opening of leaf stomata by changing the vapor pressure and photosynthesis-induced water potential of stomatal guard cells, respectively, subsequently increasing Hg assimilation by the leaf mesophyll (Taiz et al., 2014; Wesely, 1989; Wright & Zhang, 2015). Therefore, similar to vegetation activity, increased T2M and solar radiation during warm months (Figures S2b and S2d in Supporting Information S1) also led to a high dry deposition of Hg over the continents (Figures 3e and 3i). Increased solar radiation during warm months also amplifies the photoreduction of Hg compounds in soil and subsequently intensifies soil  $\text{Hg}^0$  emissions (Gustin et al., 2002; Lin et al., 2010). However, the potentially increased TGM concentrations driven by enhanced soil emissions were offset by the increased dry deposition, indicating net deposition driven by solar radiation (Figures 3i and 3l). The negative anomalies driven by UV10M reached a negative minimum of approximately  $-6\%$  at these sites. UV10M mainly participates in oceanic  $\text{Hg}^0$  evasion (Nightingale et al., 2000; Soerensen et al., 2010). Low UV10M during warm months (Figure S2e in Supporting Information S1) can reduce the turbulence of surface water and subsequently the frequency of mixing between surface and deep waters, which hinders the supply of Hg substances for reduction from deep water (Soerensen et al., 2013). Consequently, the efficiency of air-sea  $\text{Hg}^0$  exchange and related oceanic  $\text{Hg}^0$  evasion are reduced. Lower oceanic evasion (Figure 3o) can further decrease TGM concentrations in the marine

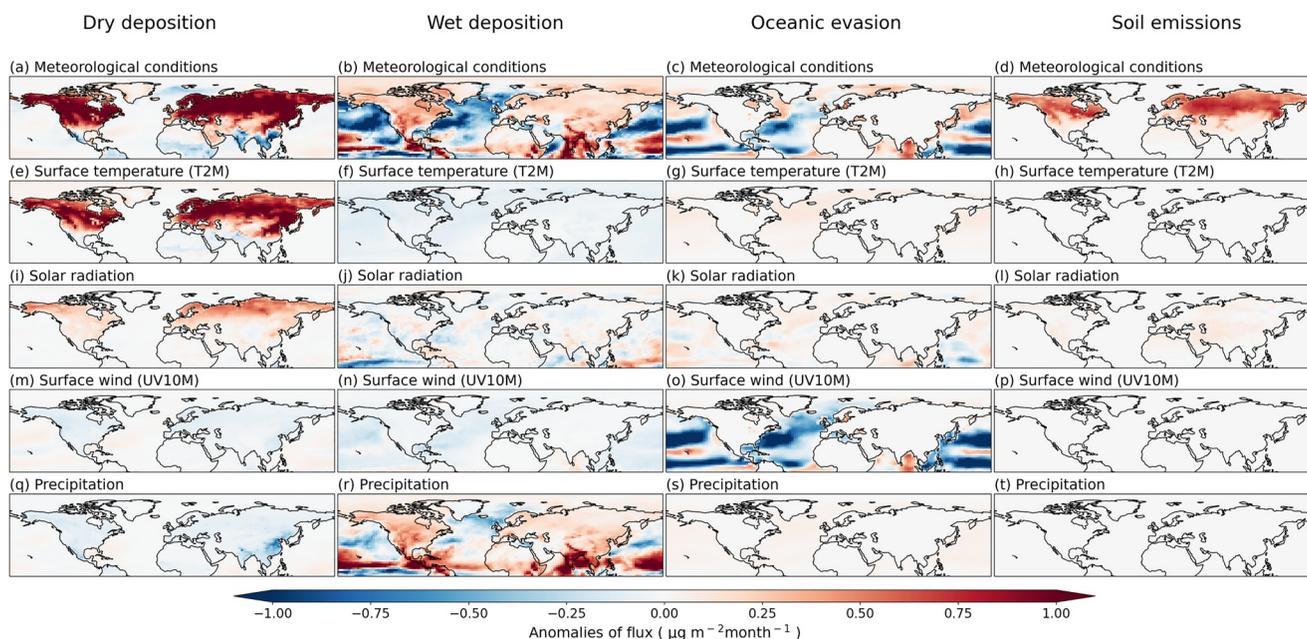


**Figure 2.** Decomposition of entire meteorological field to individual meteorological factors regarding the anomalies of total gaseous mercury concentrations at the Northern Hemisphere sites. Colored bars and gray line represent the anomalies driven by individual meteorological factors and entire meteorological field, respectively.

boundary layer (MBL) and downwind continents indirectly. Abundant precipitation during the warm months (Figure S2h in Supporting Information S1) enhanced the vertical removal of atmospheric Hg via wet scavenging (Figure 3r), resulting in a negative minimum of approximately  $-5\%$  at these sites. Other factors, such as PBLH, UV, and T, had relatively small influences on seasonality.

Unlike the NA and European remote sites, UV and precipitation were the dominant contributors at the Asian monsoon sites. The negative anomalies driven by UV and precipitation reached negative minima of approximately  $-15\%$  and  $-9\%$ , respectively. The Asian monsoon system is one of the most typical monsoon climate systems worldwide (An et al., 2015), and profoundly influences atmospheric pollutants in Asian monsoon regions (Chen et al., 2020). During warm months, the prevailing south-easterly monsoon wind carried clean air with lower Hg concentrations from the ocean, replacing air with higher Hg concentrations over continental regions (Figure S2g in Supporting Information S1). A significant quantity of water vapor comes from the ocean with the summer monsoon wind, resulting in more precipitation during warm months over the Asian monsoon regions, further enhancing the removal of atmospheric Hg (Liu et al., 2016; Tseng et al., 2012; Yu et al., 2015). Thus, more significant anomalies contributed by precipitation were observed at the Asian monsoon sites than at other temperate sites.

In summary, the typical monsoon climate in Asia leads to differences in the crucial meteorological drivers between the Asian monsoon sites and other monitoring sites in the temperate Northern Hemisphere. Meteorological factors such as UV and precipitation indirectly induced atmospheric Hg seasonality through atmospheric



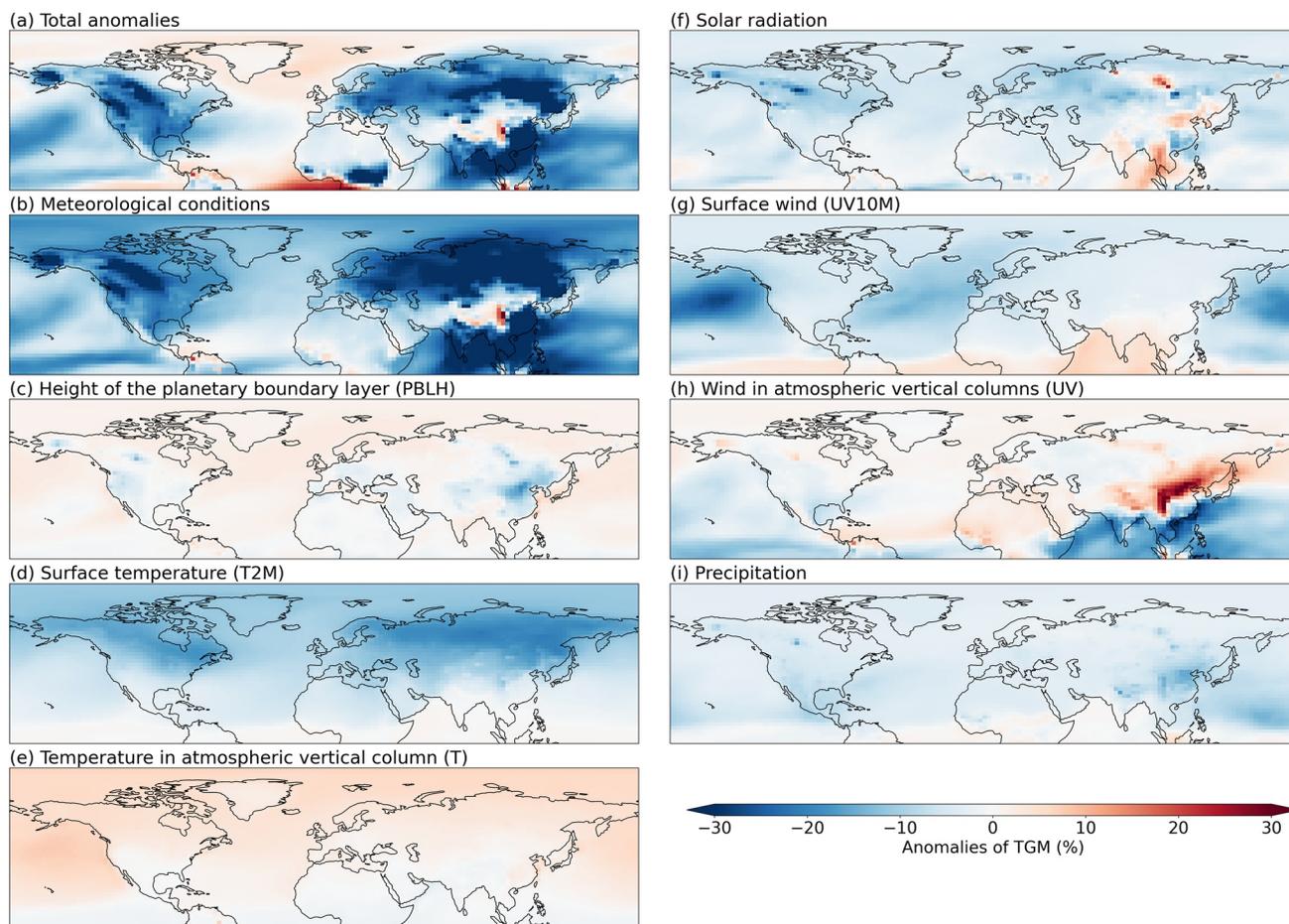
**Figure 3.** Anomalies of flux in typical atmospheric processes for warm months (July to October) in the Northern Hemisphere driven by entire meteorological field and specific meteorological factors. Panels in a column illustrate a type of atmospheric processes, and the average of anomalies during the 4 months was archived.

transport and wet deposition, and meteorological factors such as T2M, solar radiation, and UV10M indirectly induced atmospheric Hg seasonality through stomatal resistance, soil emissions, and oceanic evasion.

### 3.3. Mapping the Spatial Distribution of Atmospheric Hg Seasonality

Simulation of the global spatial distribution of surface TGM concentrations using the GEOS-Chem model enabled the presentation of atmospheric Hg seasonality from ground-based monitoring sites to the surface of the Earth, helping to illustrate atmospheric Hg seasonality over regions without Hg observations (Figure 4). Figure 4a shows that the seasonal hotspots of surface TGM concentrations during warm months were located in North America, Europe, North Asia, the Asian monsoon regions, and Central Africa. Meteorological conditions were important drivers of the observed negative anomalies during warm months (Figure 4b), with T2M, solar radiation, and UV10M promoting stomatal uptake and reducing oceanic Hg<sup>0</sup> evasion in the summer in the Northern Hemisphere, while the monsoon wind and precipitation promoted Hg removal via atmospheric transport and wet deposition in Asia. Owing to the vegetation-induced dry deposition mechanism (Wesely, 1989; Wright & Zhang, 2015), the seasonality of T2M and solar radiation mainly contributed to negative anomalies over the continents (Figures 4d and 4f). The hotspots of negative anomalies were concentrated in regions with dense vegetation, such as Canada, Russia, and Northern Europe. Positive anomalies for solar radiation were observed over certain Asian areas (Figure 4f), which was attributable to the predominant effects of soil emissions driven by solar radiation on land with sparse vegetation (Figures 3i and 3l).

UV mainly contributed to the decrease in surface TGM concentrations during warm months over the Asian monsoon regions, including Southeast Asia, South Asia, the Northwest Pacific, and the northern Indian Ocean (Figure 4h). Conversely, the surface TGM concentrations during warm months significantly increased over inland China and Mongolia. This increase was mainly attributed to the transport of an Hg-containing air mass from the industrialized regions in East China to the northwestern regions with south-easterly monsoon wind (Fu et al., 2015). UV10M mainly contributed to the decrease in surface TGM concentrations in the MBL and downwind continents, including hotspots over the North Pacific, North Atlantic, North America, and Western Europe (Figure 4g). Therefore, UV10M is a crucial driver of atmospheric Hg seasonality at the NA and European remote sites (Figure 2). Precipitation induced a decrease in surface TGM concentrations across the hemisphere, with hotspots in East Asia, South Asia, and the Northwest Pacific (Figure 4i). The hotspots were consistent with the



**Figure 4.** Anomalies of simulated surface total gaseous mercury concentrations for warm months (July to October) in the Northern Hemisphere and contributions of various meteorological factors.

Asian monsoon regions, indicating the important role of monsoon precipitation, which has significant seasonal variability.

#### 4. Implications and Conclusions

Meteorological conditions contributed significantly to atmospheric Hg seasonality, indicating the predictive changes in seasonality in the context of future climate change. Human influence has warmed the climate at an unprecedented rate over the past hundred years, and future greenhouse gas emissions will cause additional warming under various scenarios of Shared Socioeconomic Pathways (IPCC, 2021). The increase in air temperature, particularly surface temperature, will further intensify the stomatal resistance (i.e., stomatal uptake) of vegetation and subsequent dry deposition of Hg. Climate warming can also cause future forest fires and vegetation deaths (Duane et al., 2021; Goss et al., 2020; Ma et al., 2015), resulting in an opposite pattern of stomatal resistance and dry deposition of Hg. Accordingly, uncertainties in the impacts of climate warming have led to uncertainties in projections of future atmospheric Hg seasonality. Precipitation during warm months is projected to increase over high latitudes, the equatorial Pacific, and parts of the monsoon regions due to the increase in moisture flux convergence and local surface evaporation under global warming (IPCC, 2021). These regions coincide with regions where strong atmospheric Hg seasonality exists, indicating likely further strengthened amplitudes of atmospheric Hg seasonality via intensified wet deposition by precipitation.

Based on the above findings, changes in the Asian monsoon system under climate change are expected to significantly influence atmospheric Hg seasonality in the Asian monsoon regions. Land warming over the Eurasian continent is projected because of the increased CO<sub>2</sub> radiative forcing and decreased aerosol cooling effect during

the 21st century, intensifying the land-sea thermal contrast (Endo et al., 2018; Tian et al., 2019; Wang, Zhang, & Zhang, 2016). Consequently, the amplified land-sea thermal contrast can potentially strengthen the circulation and increase the precipitation of the Asian monsoon system. Climate models also project an increase in the length of the summer monsoon season owing to early onset and late retreat (Ha et al., 2020). Amplified monsoon circulation and precipitation and longer monsoon seasons are likely to strengthen future atmospheric Hg seasonality in the Asian monsoon regions. However, a weakening tendency of the Asian monsoon circulation is also projected in several climate models owing to pronounced warming in the mid-to-upper troposphere over the tropics with global warming (Kitoh et al., 2013; Ueda et al., 2006). Thus, significant uncertainties exist in the projections of climate systems such as the Asian monsoon system, resulting in uncertainties in the projections of atmospheric Hg seasonality under future climate change.

To be concluded, meteorological conditions can promote the variations of atmospheric processes which control global Hg cycling, and further indirectly induce atmospheric Hg seasonality across diverse temperate regions in the Northern Hemisphere. Typical monsoon climate in Asia led to differences in effects of meteorological factors from other regions. The findings help both the understanding of driving forces of atmospheric Hg seasonality and future projections of changes in biogeochemical Hg cycles.

### Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

### Data Availability Statement

Hg observations from the CAPMoN, AMNet, and EMEP are accessible at <https://donnees.ec.gc.ca/data/air/monitor/monitoring-of-atmospheric-gases/total-gaseous-mercury-tgm>, <http://nadp2.slh.wisc.edu/data/AMNet>, and <https://ebas-data.nilu.no>, respectively. Supporting data of the GEOS-Chem model can be obtained at <https://geos-chem.readthedocs.io/en/latest/gcc-guide/04-data/download-data.html>. MERRA-2 reanalysis data is accessible at [https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data\\_access](https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access). GFED4 data is accessible at <https://www.geo.vu.nl/~gwerf/GFED/GFED4>.

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