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Atmospheric cycling of gaseous selenium compounds: sources, transformations, and deposition

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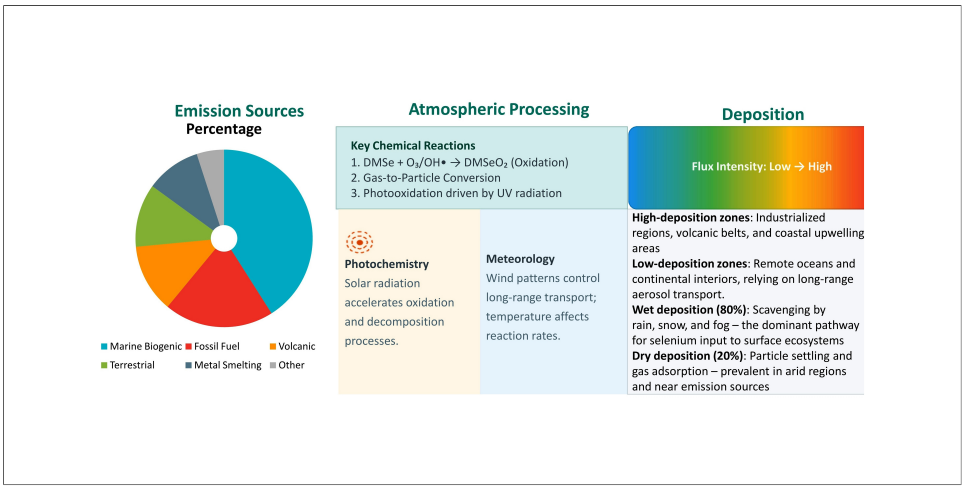

Abstract

Selenium (Se) is an essential trace nutrient for organisms, and its biogeochemical cycling plays pivotal roles in terrestrial ecosystem functioning and human health. Gaseous Se compounds, such as dimethyl selenide (DMSe) and dimethyl diselenide (DMDSe), are key carriers of selenium in the atmosphere. Their sources, transformation, and deposition processes profoundly influence the biogeochemical cycling of selenium. This review comprehensively summarizes the main natural and anthropogenic sources, atmospheric oxidation mechanisms (including reactions with O_3, OH, *etc.*), gas-particle conversion processes, and deposition processes of gaseous selenium compounds. It focuses on ozone oxidation kinetics, product formation, and the environmental fate of DMSe and DMDSe, and systematically summarizes the current research methods and future challenges. Studies have shown that oxidation products of gaseous selenium compounds (such as dimethyl selenoxide and methyl selenic acid) may deposit in the aerosol phase, thereby affecting the bioavailability of selenium. Future research should combine high-resolution observations and model simulations to more accurately predict the global cycling of selenium in the context of climate change.

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INTRODUCTION

Selenium (Se) is an essential trace element for both humans and animals, playing an indispensable role in living organisms[1,2]. It participates in the synthesis of various antioxidant enzymes, such as glutathione peroxidase, which has selenium at its active center and plays a crucial role in maintaining intracellular redox balance[3]. Appropriate selenium intake is vital for health[4,5], yet the window between deficiency and toxicity is narrow[4]. Normal adults need to consume approximately 55 micrograms of selenium per day[6]. Keshan disease, a type of endemic cardiomyopathy closely linked to selenium deficiency, may cause myocardial damage, cardiac enlargement, and heart failure[4,6-10]. Additionally, selenium deficiency is associated with Kashin-Beck disease, which primarily affects the bone development of children and adolescents, causing joint pain, deformities, and impairing normal growth and activity capabilities[11]. In terms of the immune system, selenium deficiency can weaken the body's immune function, reducing its resistance to pathogens and increasing the risk of infectious diseases[12]. Studies have also found that selenium deficiency may be linked to the occurrence and development of certain cancers, and appropriate supplementation of selenium may reduce the risk of cancer to a certain extent[1,3,12]. Conversely, excessive intake (> 400 μg·day^{-1}) can cause selenosis, manifesting as acute or chronic poisoning, with symptoms ranging from nausea and hair loss to neurological disorders and organ damage[13-16].

Atmospheric deposition is an important pathway through which terrestrial ecosystems obtain selenium in the natural selenium cycle[17,18]. Globally, an estimated 12.9 Gg of selenium enters terrestrial ecosystems annually via atmospheric deposition[19,20]. Gaseous selenium compounds, including dimethyl selenide (DMSe, CH_3-Se-CH_3) and dimethyl diselenide (DMDSe, CH_3-Se-Se-CH_3), as important forms of selenium in the atmosphere, are mainly emitted into the atmosphere by marine and terrestrial organisms[18,19]. They undergo complex oxidation processes in the atmospheric environment and gradually transform into particulate selenium, eventually returning to the surface through wet or dry deposition[18,21].

The global energy structure has recently shifted significantly, notably toward reduced coal usage[22,23]. This transition has decreased anthropogenic selenium emissions, a major atmospheric source[24-32]. Such changes may exacerbate selenium deficiency in some ecosystems that previously relied on anthropogenic selenium emissions for selenium supplementation[24-26]. In addition, recent advances in global Se cycling research since 2020 have refined atmospheric deposition models and introduced cutting-edge detection techniques. Feinberg *et al.* (2020) employed global sensitivity analysis to quantify uncertainty drivers in Se deposition, highlighting the interplay between emission sources, atmospheric chemistry, and precipitation dynamics[20]. Their work underscored the need for high-resolution data to constrain model variability. Building on this, Breuninger *et al.* (2024) integrated proton-transfer-reaction time-of-flight mass spectrometry (PTR-ToF-MS) and inductively coupled plasma mass spectrometry (ICP-MS) to achieve unprecedented speciation and quantification of atmospheric selenium[32]. Their study revealed how weather systems and anthropogenic emissions modulate Se deposition fluxes, emphasizing the role of volatile organic Se species. These studies demonstrate significant progress in resolving Se cycling complexities through advanced analytical techniques and refined modeling approaches, offering improved predictive capabilities for global biogeochemical cycles. Therefore, a thorough understanding of the sources, transformations, and deposition mechanisms of atmospheric gaseous selenium compounds is critical for accurately predicting their impact on ecosystems and human health. This paper synthesizes current knowledge on the sources, transformations, and deposition of atmospheric gaseous Se compounds, evaluates recent advances in online detection techniques, and identifies key uncertainties - particularly the roles of understudied oxidants and climate change - that must be addressed to improve predictive models.

SOURCES AND DISTRIBUTION OF GASEOUS SELENIUM COMPOUNDS

Marine organisms are significant contributors of gaseous selenium compounds and thus play a crucial role in its biogeochemical cycle[27]. Phytoplankton possess unique physiological mechanisms that enable them to methylate inorganic selenium in seawater into volatile DMSe and DMDSe[28]. This process makes the ocean a major natural source, with

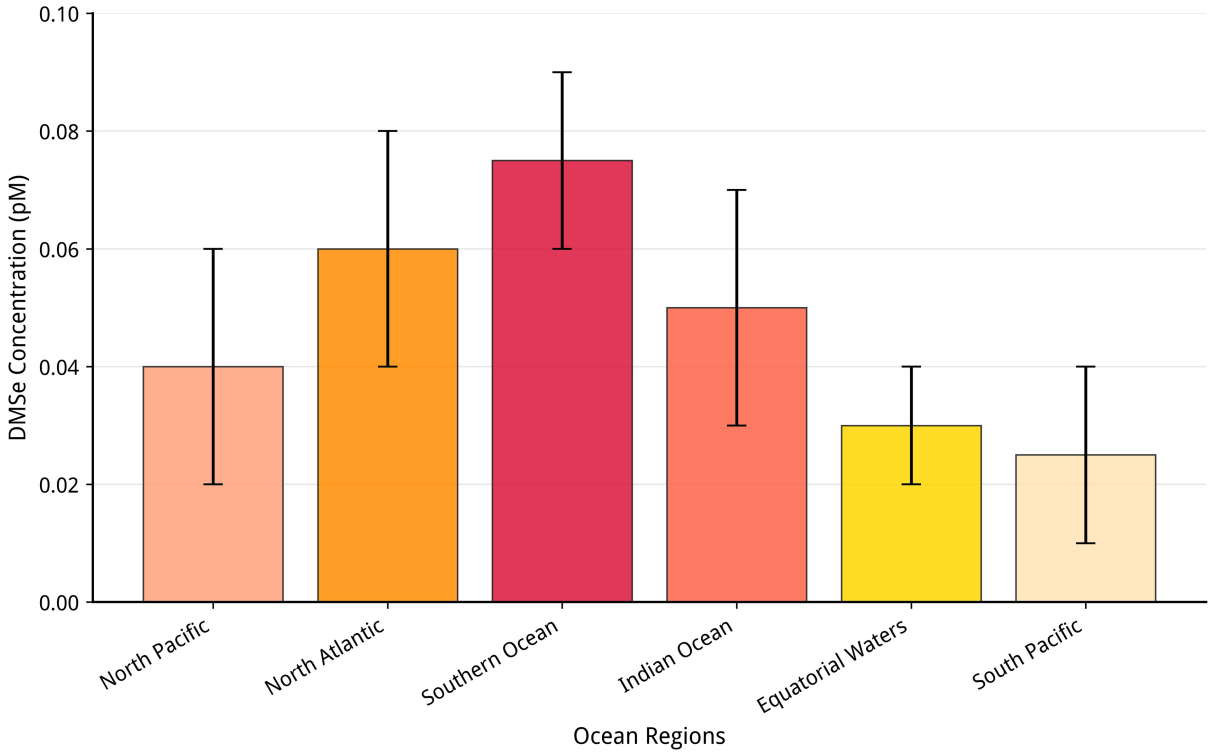

Figure 1. Bar chart showing the mean DMSe concentrations (pM) across different ocean regions based on data from reference[20], obtained using the SOCOL-AERv2 model. Vertical error bars represent the uncertainty range (standard deviation or min-max spread) derived from sensitivity analyses. DMSe: Dimethyl selenide.

estimated annual emissions of 29-36 Gg[20,29] [Figure 1]. Recent advances in environmental microbiology have elucidated the key enzymatic pathways governing selenium methylation in both marine and terrestrial organisms. In marine phytoplankton, selenium methylation occurs primarily via sulfur assimilation pathways, where enzymes evolved for sulfur metabolism inadvertently process selenium due to their chemical similarity[1]. This "promiscuous" methylation proceeds via S-adenosylmethionine (SAM)-dependent methyltransferases, which transfer methyl groups to selenide (Se^{2-}) or selenocysteine, yielding DMSe and DMDSe[3]. A study demonstrated that in *Pseudomonas tolaasii*, a model bacterium for studying Se methylation, methylation efficiency increases linearly with initial Se concentration at nanomolar levels (up to 80 nM), with 0.30% to 3.48% of atoms promiscuously methylated via sulfur methylation pathways[1,9]. At concentrations exceeding 640 nM, methylation increased steeply, suggesting induction of specific enzymes, possibly including SAM-dependent methyltransferases and selenocysteine lyases[5].

While marine organisms emit both Se and S compounds, organic sulfur compound emissions, including dimethyl sulfide (DMS) and dimethyl disulfide (DMDS), dominate, contributing ~60% of the sulfur flux to the marine boundary layer and driving sulfate aerosol formation in remote oceans[20]. In contrast, global Se emissions (e.g., DMSe) are orders of magnitude lower (~29-36 $Gg \cdot yr^{-1}$)[20], reflecting its trace biogeochemical role. This emission process is influenced not only by environmental factors (e.g., light, temperature, and nutrient concentrations) but also by phytoplankton species composition and abundance[27,30]. For instance, in areas with abundant light and nutrients, vigorous phytoplankton growth enhances inorganic selenium methylation, leading to greater DMSe and DMDSe emissions[31].

Figure 1 reveals distinct latitudinal gradients in DMSe concentrations, with elevated levels in equatorial and high-productivity zones. This pattern is driven by a combination of biological and physicochemical factors. First, phytoplankton abundance positively correlates with DMSe concentrations, with chlorophylla concentration often used as a proxy for

phytoplankton abundance. Evidence from the subtropical Pacific Ocean shows that the surface uptake of Se(VI) by blooming phytoplankton promotes methylation, which in turn results in greater DMSe emissions[2]. In Lake Kinneret, organic Se variations are directly associated with chlorophyll-a and primary production, attesting to the significant role of phytoplankton activity in the Se cycle[8]. Second, sea surface temperature (SST) modulates phytoplankton metabolic rates and the enzyme kinetics of Se methylation. Warmer equatorial waters (SST > 25 °C) promote higher phytoplankton growth rates and accelerate SAM-dependent methyltransferase activity, leading to enhanced DMSe production[2]. Third, nutrient availability, particularly the concentrations of nitrate, phosphate, and silicate, influences phytoplankton community composition and selenium uptake efficiency.In regions with upwelling-driven nutrient enrichment (e.g., equatorial Pacific), diatom-dominated phytoplankton assemblages exhibit high Se methylation capacities, contributing to elevated DMSe emissions[2,12]. Conversely, oligotrophic subtropical gyres with limited nutrients show lower DMSe concentrations, despite favorable temperatures, highlighting the co-limitation of Se methylation by both biological and physicochemical factors. Model simulations indicate that phytoplankton-mediated Se volatilization accounts for a significant fraction of marine Se output flux, with seasonal variations in primary productivity driving up to 10% of estimated Se input to the atmosphere[8,12].

Terrestrial organisms also contribute to atmospheric gaseous selenium compounds[19]. Wetlands are rich in selenium-methylating microorganisms[21]. These microorganisms convert inorganic selenium into volatile selenium compounds during their metabolic processes, with DMSe being one of the main emission products. In terrestrial environments, wetland microorganisms, particularly sulfate-reducing bacteria and methanogens, play a central role in selenium methylation. The process is closely linked to the sulfur cycle: selenium is taken up as selenate (SeO_4^{2-}) or selenite (SeO_3^{2-}), reduced to selenide (Se^{2-}), and subsequently methylated via the SAM-dependent pathway to form DMSe and DMDSe[1,5]. Notably, the sulfur amino acid status of microorganisms exerts hierarchical control over Se volatilization. When *Pseudomonas tolaasii* cells were supplemented with cystine, a major proportion of Se (~48%) was channeled to a novel non-volatile Se metabolite, 2-hydroxy-3-(methylselanyl)propanoic acid, at the expense of volatile DMSe and DMDSe production (< 4% of total Se)[5]. This finding suggests that environmental sulfur concentrations, which often exceed selenium by orders of magnitude, may be a major factor controlling selenium fluxes to the atmosphere[5]. For terrestrial plants, selenium methylation occurs primarily in roots and shoots via the sulfur assimilation pathway, where selenocysteine is methylated to methylselenocysteine and further converted to volatile DMSe. The efficiency of this process varies significantly among plant species, with Brassica and Allium genera showing particularly high selenium volatilization capacities due to their active sulfur metabolism. Understanding these enzymatic pathways and their regulation by sulfur availability is crucial for predicting selenium emissions under changing environmental conditions, as climate-induced alterations in sulfur cycling and microbial community composition may profoundly affect the magnitude and speciation of biogenic selenium emissions. Additionally, plants absorb selenium from the soil through their roots during growth and convert some of it into volatile forms that are released into the atmosphere[10]. Terrestrial organisms account for approximately 5%-18% of global selenium emissions[19,32-34].

Volcanic activity is an important pathway for the exchange of substances between the interior and exterior of the Earth, and it also plays a significant role in the natural release of selenium[35]. During volcanic eruptions, large amounts of substances are released, including selenium compounds such as SeO_2 and elemental selenium (Se^0)[35,36]. These selenium compounds are carried into the atmosphere by the powerful force of volcanic eruptions, becoming an important natural source of selenium in the atmosphere[35]. The intensity, frequency of volcanic eruptions, and the composition of volcanic magma all affect the amount and form of selenium released[36]. For instance, some volcanic eruptions are more intense, capable of ejecting large amounts of selenium compounds into the stratosphere, thereby influencing the distribution of atmospheric selenium over a wider area[36]. High-temperature magmatic degassing releases gaseous Se species, which may later condense onto ash particles or remain in the gas

phase, influencing long-range transport. Meanwhile, terrestrial environments, particularly wetlands, emit H_2Se and methylated Se compounds (e.g., DMSe) through microbial activity[21]. These biogenic emissions are climate-sensitive, with higher fluxes under warm, anoxic conditions. While volcanic SeO_2 dominates in geologically active zones, wetland-derived H_2Se contributes to regional Se cycling, particularly in tropical and temperate ecosystems[21]. Both sources require better quantification in global models to refine Se deposition estimates and assess ecological impacts.

Terrestrial ecosystems represent a significant yet seasonally variable source of atmospheric gaseous selenium. Wetlands, in particular, are rich in selenium-methylating microorganisms, such as sulfate-reducing bacteria and methanogens, which convert inorganic selenium into volatile compounds like DMSe and DMDSe. Plants also contribute by absorbing soil selenium and releasing volatile forms through their roots and shoots. These biogenic emissions are highly climate-sensitive. As illustrated in Figure 2, global terrestrial biogenic Se emissions exhibit a strong seasonal pattern that follows hemispheric trends. In the Northern Hemisphere, maximum fluxes occur during the boreal summer [June-July-August (JJA)], driven by higher temperatures and enhanced microbial and plant metabolic activities. Conversely, emissions in the Southern Hemisphere peak during the austral summer [December-January-February (DJF)], as observed in South American tropical regions. This seasonal asymmetry is consistent with temperature-dependent biological processes and underscores the importance of considering regional climate variability when predicting biogenic selenium fluxes to the atmosphere[32].

Minor sources include agricultural activities (e.g., fertilizer use) and waste treatment, though their contributions are poorly constrained and likely secondary to industrial and natural emissions[17,25,31,33]. The marine boundary layer, as a key area for the interaction between the ocean and the atmosphere, is representative of DMSe concentrations[38]. Studies have shown that the DMSe concentration in the marine boundary layer can reach 0.2 pptv[20,32,38]. This concentration may fluctuate in different sea areas and is influenced by various factors such as marine biological activities, ocean circulation, and atmospheric transport[17]. In industrial areas, owing to the extensive industrial activity, the concentration of aerosol selenium is relatively high, generally ranging from 0.1 to 2.1 $ng \cdot m^{-3}$[24]. The selenium emissions from these industrial zones not only affect the local air quality but may also influence the selenium distribution in surrounding areas through atmospheric transport[24,30,38-41].

The flux of selenium deposition varies significantly across different seasons[20]. Prior studies have found that the flux of selenium deposition in summer is typically higher than that in winter[18,19]. This is mainly due to the more complex meteorological conditions in summer, with higher frequency and intensity of precipitation and vigorous atmospheric convection activities, all of which are conducive to the deposition of selenium[17].

ATMOSPHERIC TRANSFORMATION MECHANISM OF GASEOUS SELENIUM COMPOUNDS

Ozone (O_3) oxidation

DMSe and DMDSe undergo chemical reactions with O_3 in the atmosphere, which plays a crucial role in their transformation and fate in the atmosphere[19,42]. The ozonolysis of DMSe proceeds through a mechanism analogous to that of DMS, with the initial formation of a primary ozonide (POZ) intermediate that subsequently decomposes via a Criegee-type pathway. The key steps are as follows:

$$DMSe + O_3 \rightarrow [DMSe \cdot O_3]^+ \text{ (primary ozonide)} \quad (1a)$$

$$[DMSe \cdot O_3]^+ \rightarrow CH_3SeO\bullet + \bullet OCH_3 \quad (1b)$$

$$CH_3SeO\bullet + O_2 \rightarrow CH_3SeOO\bullet \quad (1c)$$

$$CH_3SeOO\bullet + NO \rightarrow CH_3SeO\bullet + NO_2 \quad (1d)$$

The primary pathway yields $CH_3SeO\bullet$ and $CH_3SeOO\bullet$ radicals, which further react with NOx (NO/NO_2) to form stable products such as methylselenyl nitrate (CH_3SeONO_2) and dimethyl selenoxide (DMSeO, $CH_3Se(O)CH_3$)[42].

The overall reaction is:

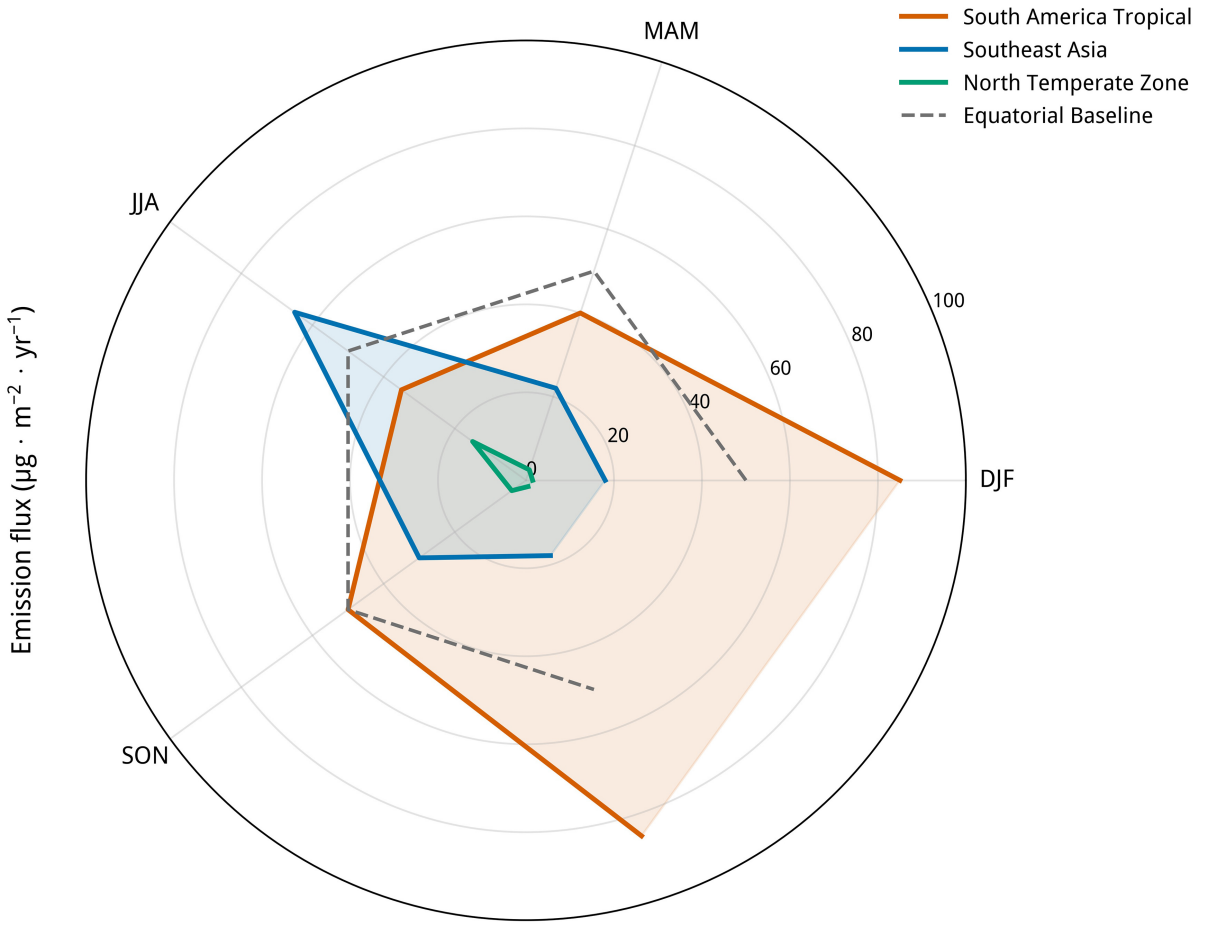

Figure 2. Seasonal distribution of global terrestrial biogenic Se emissions (μg Se·m^{-2}·yr^{-1}) estimated from the MEGAN-MACC inventory. The abbreviations denote the standard meteorological seasons: DJF (winter in the Northern Hemisphere), MAM (spring), JJA (summer), and SON (autumn). The emission maps are calculated by averaging monthly values over the available period (1980-2010) and are scaled so that total global emissions are 2.7 Gg Se·yr^{-1}. Data were obtained from reference[37]. Se: Selenium; DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November.

DMSe + O_3 → Dimethylselenoxide (DMSeO) (1)[42]

For DMDSe, the ozonolysis mechanism involves cleavage of the Se–Se bond, yielding methylseleninic acid (MSeA, CH_3SeO_2H) as the major product:

DMDSe + O_3 → CH_3SeO_2H (MSeA) + CH_3Se• (2)[42]

The reaction between DMSe and O_3 has a rate constant of 7.4 × 10^{-17} cm^3·molec^{-1}·s^{-1} at 25 °C under standard atmospheric conditions[42] [Figure 3A]. The rate is influenced by temperature, humidity, and light; higher temperatures increase the fraction of molecules that surpass the activation barrier, thereby accelerating the reaction. When the O_3 concentration in the atmosphere is 20 ppb, the atmospheric lifetime of DMSe is approximately 7.6 h based on reaction kinetics calculations[42]. This lifetime estimation considers only O_3 reactions and thus neglects other critical oxidation pathways [e.g., with OH and nitrate radicals (NO_3)], which can significantly shorten the atmospheric lifetime of DMSe. In real-world environments, background aerosols and varying humidity levels can significantly modulate these O_3-driven lifetimes. For instance, in marine boundary layers with high relative humidity (> 80%), the enhanced surface area of deliquescent sea-salt aerosols may facilitate heterogeneous uptake of DMSe, potentially shortening its effective atmospheric lifetime through surface-mediated reactions[42]. Conversely, in urban environments where aerosol acidity is elevated, the partitioning of oxidation products (e.g., dimethyl selenoxide) into the condensed phase may be accelerated, removing gaseous sele-

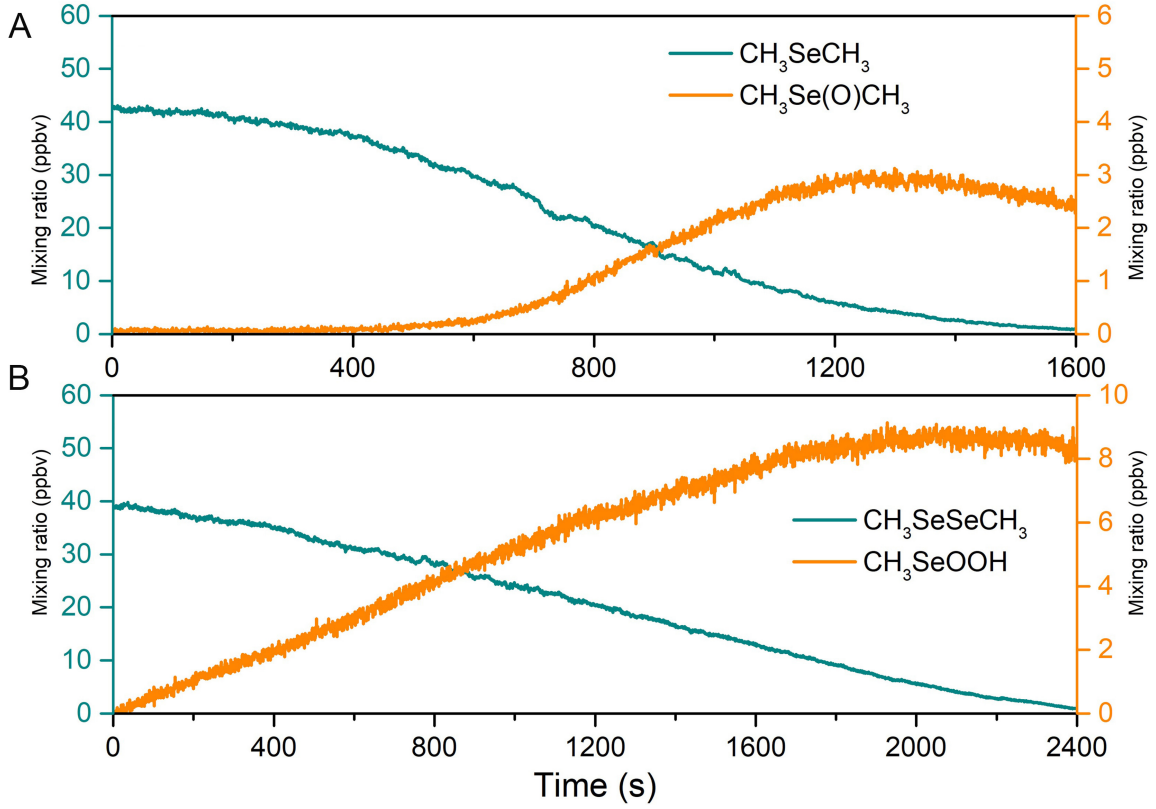

Figure 3. (A) Temporal trends in the ozonolysis of CH_3SeCH_3 reacting to dimethyl selenoxide as a multigeneration product (O_3 = 20 ppb, T = 25 °C); (B) Temporal trends in the ozonolysis of $CH_3SeSeCH_3$ forming the reaction product methylselenic acid (O_3 = 20 ppb, T = 25 °C)[42]. The reactions were carried out in a 48 inch × 72 inch (W × H) thick rectangular perfluoroalkoxy alkane pillow bag, which was pre-cleaned by continuous ozone exposure (> 20 L/min filtered compressed air purge) under ultraviolet irradiation for ≥ 10 h, followed by nitrogen purging (12 L·min^{-1}) before each experiment. Reaction products were monitored in real time using PTR-TOF-MS. (A) and (B) are redrawn using original data from Heine and Borduas-Dedekind[42]. This figure is reproduced with permission[42], Copyright 2023, American Chemical Society. PTR-TOF-MS: Proton-transfer-reaction time-of-flight mass spectrometry.

nium compounds from the gas phase more rapidly than predicted by homogeneous kinetics alone[19,20]. In contrast, under dry continental conditions, gas-phase oxidation remains the dominant loss pathway, and the O_3-driven lifetime estimates may better approximate actual atmospheric behavior. These geographical variations underscore the need for integrating heterogeneous chemistry into atmospheric models to refine selenium lifetime predictions across different environmental regimes.

Heine *et al.* (2023) has elucidated the ozonolysis pathways of DMSe and DMDSe, reporting rate constants of $(7.4 \pm 2.2) \times 10^{-17}$ cm^3·molec^{-1}·s^{-1} for DMSe and $(2.6 \pm 0.9) \times 10^{-17}$ cm^3·molec^{-1}·s^{-1} for DMDSe at 26 ± 1 and 27 ± 1 °C, respectively[42]. The activation energies were determined to be 50 ± 14 kJ·mol^{-1} for DMSe and 56 ± 5 kJ·mol^{-1} for DMDSe[42]. The primary oxidation product of DMSe was identified as dimethyl selenoxide ($CH_3Se(O)CH_3$), while the ozonolysis of DMDSe yielded methylselenic acid ($CH_3Se(O)OH$), likely formed via hydrolysis of the transient anhydride $CH_3Se(O)OSe(O)CH_3$. These findings demonstrate that DMSe reacts faster with O_3 than DMDSe, consistent with the higher electron density on the Se atom of monoselenides compared to diselenides.

Recent work by Heine *et al.* (2025) demonstrates the abiotic formation of dimethyl selenyl sulfide (DMSeS) through light-driven reactions in both liquid and gas phases, suggesting its potential role as an intermediate in atmospheric selenium transformations[36]. This finding highlights a previously overlooked pathway in selenium cycling, where mixed chalcogen species like DMSeS may form via photochemical processes involving DMSe and sulfur-containing

compounds. Given its reactivity, DMSeS could serve as a transient species influencing the speciation and fate of atmospheric selenium. This discovery expands our understanding of non-biological selenium chemistry in the environment. The study underscores the need to consider such mixed S-Se species in atmospheric models.

The chemical equation for the reaction between DMDSe and O_3 is:

$$DMDSe + O_3 \rightarrow MSeA \quad (2)[42]$$

This reaction is relatively slow, with a rate constant of 2.6×10^{-17} $cm^3 \cdot molec^{-1} \cdot s^{-1}$[42] [Figure 3B]. This results in a relatively long atmospheric lifetime for DMDSe, approximately 22 h[42]. The ozonolysis of DMDSe proceeds via a complex mechanism involving multiple intermediates and transition states[42]. Recent work by Breuninger *et al.* (2024) confirms that DMDSe can be detected in ambient air, but its atmospheric occurrence appears limited due to its relatively short lifetime of approximately 22 h[32]. This instability suggests DMDSe is likely a minor contributor compared to more stable selenium compounds like DMSe. The rapid degradation implies that any atmospheric DMDSe measurements would represent localized, recent emissions rather than accumulated background levels. This distinction is important for modeling selenium speciation and understanding its atmospheric cycling. DMSeO and MSeA likely dissolve in droplets because of their polar functional groups. O_3 cleaves the Se–Se bond in DMDSe, ultimately yielding methylseleninic acid through a series of oxidation steps[42]. Other gaseous species (e.g., NOx, SO_2) may influence this reaction by interacting with reactants or products, thereby altering the pathway and rate[19].

Hydroxyl radical (OH) oxidation

The hydroxyl radical (OH) is a highly reactive atmospheric oxidant[43,44]. The DMSe + OH reaction likely proceeds via H-abstraction from the $–CH_3$ group, forming $•CH_2SeCH_3$ and H_2O, followed by O_2 addition to yield peroxy radicals ($•O_2CH_2SeCH_3$)[45]:

$$DMSe + •OH \rightarrow •CH_2SeCH_3 + H_2O \quad (3a)$$

$$•CH_2SeCH_3 + O_2 \rightarrow •O_2CH_2SeCH_3 \text{ (peroxy radical)} \quad (3b)$$

$$•O_2CH_2SeCH_3 + NO \rightarrow •OCH_2SeCH_3 + NO_2 \quad (3c)$$

$$•OCH_2SeCH_3 + O_2 \rightarrow HCHO + CH_3SeO• \quad (3d)$$

The peroxy radical ($•O_2CH_2SeCH_3$) can also undergo isomerization or react with HO_2 to form organic hydroperoxides (CH_3SeCH_2OOH). The overall degradation pathway leads to the formation of formaldehyde (HCHO) and methylseleninic acid (CH_3SeOOH) as stable end products[45].

$$DMSe + OH \rightarrow CH_3SeOOH + HCHO \quad (3)[45]$$

Subsequent reactions may include RO_2 + NO or isomerization, analogous to DMS + OH pathways, forming stable intermediates such as formaldehyde (HCHO) and methylselenic acid (CH_3SeOOH)[45]. The reaction rate between DMSe and OH is relatively high[45]. Electron transfer is not a significant pathway; instead, radical-driven chain reactions dominate, as demonstrated for analogous sulfur compounds[43]. The OH-initiated oxidation of DMSe proceeds with a rate constant ($k = 6.8 \times 10^{-10}$ $cm^3 \cdot molec^{-1} \cdot s^{-1}$), ~30% faster than DMS ($k = 8.5 \times 10^{-12}$ $cm^3 \cdot molec^{-1} \cdot s^{-1}$), implying a shorter atmospheric lifetime (~5 h *vs.* ~1 day for DMS under typical [OH] = 1×10^6 $molec \cdot cm^{-3}$). This difference arises from weaker C–Se bonds and enhanced radical stabilization in selenium intermediates[45]. Under pseudo-first-order kinetics, the OH-dominated atmospheric lifetime of the compound is approximately 1.5 h (assuming [OH] = 1×10^6 $molec \cdot cm^{-3}$), while the O_3-dominated lifetime is 7.6 h. The combined effective lifetime is 1.3 h, indicating OH radicals dominate the degradation process[7,42,45]. Due to the relatively high concentration of OH in the atmosphere during the day, the reaction between DMSe and OH may dominate the atmospheric selenium transformation process during the daytime[19,45]. While OH and O_3 dominate daytime Se oxidation, NO_3 and Cl may play critical roles at night and in marine boundary layers. Additionally, the potential photolysis of DMDSe ($CH_3SeSeCH_3$) in the troposphere, due to weaker Se–Se bonds compared to S–S bonds, warrants further investigation as it could represent an alternative degradation pathway for DMDSe[42,45]. These future experimental studies may highlight key

advances in Se oxidation mechanisms while identifying critical gaps in NO_3/Cl chemistry.

During the daytime, a series of photochemical reactions occur in the atmosphere under sunlight, generating a large number of OH radicals[42]. These OH radicals can react rapidly with DMSe, and the reaction process involves steps such as hydrogen atom abstraction and electron transfer[42].

Gas-particle conversion

The adsorption of gaseous SeO_2 onto atmospheric aerosols represents a key pathway for selenium deposition. Experimental and modeling studies show that SeO_2 exhibits strong affinity for both mineral dust (e.g., Al_2O_3, Fe_2O_3) and sulfate aerosols, with partitioning coefficients increasing significantly at elevated relative humidity due to surface hydration effects[35]. While this adsorption enhances local deposition of Se(IV), it simultaneously limits the long-range transport of gaseous selenium. Notably, in the presence of acidic aerosols (pH < 4), adsorbed Se(IV) can be further oxidized to Se(VI), which exhibits different solubility and bioavailability patterns[20]. These processes create complex spatial gradients in selenium deposition, with implications for both atmospheric chemistry and ecological selenium cycling. The efficiency of this conversion depends on aerosol composition, atmospheric acidity, and meteorological conditions, requiring further constraints for global models.

The oxidation products generated by the reaction of DMSe and DMDSe with oxidants such as O_3 and OH, including DMSeO and MSeA, possess certain chemical reactivity and physical properties, making them prone to adsorption onto the surface of aerosols[19]. Aerosols, as a collection of solid and liquid particles in the atmosphere, provide a carrier for these oxidation products[45]. During the gas-particle conversion process, the oxidation products combine with aerosols through physical or chemical adsorption, gradually forming secondary organic aerosols (SOA)[24].

The formed SOA is transported in the atmosphere by atmospheric circulation and eventually removed through wet deposition[18]. During wet deposition, aerosol particles containing SOA fall to the ground with precipitation such as rain or snow, thereby transferring selenium from the atmosphere to the Earth's surface[21]. In this process, factors such as the intensity and duration of precipitation, as well as the properties of aerosols, will affect the efficiency of gas-particle conversion and the final deposition effect[19,29]. For instance, during heavy rainfall, many aerosol particles are rapidly washed to the ground, accelerating selenium deposition; particle size and aerosol surface properties also affect their atmospheric transport distance and the probability of being captured by precipitation[18].

ENVIRONMENTAL BEHAVIOR AND DEPOSITION PROCESS

Atmospheric lifetime and transport

DMSe has a short atmospheric lifetime of approximately 7.6 h, primarily due to its rapid reactions with O_3 and OH[41]. This short lifetime limits its atmospheric transport distance, hindering long-range transport[19,32]. Under the influence of atmospheric circulation, DMSe may undergo chemical reactions and transform into other substances or return to the surface through the deposition process within a short period[19,32].

In contrast, the reaction rate of DMDSe is relatively slow, which makes its lifetime in the atmosphere relatively long, approximately 22 h[42]. This longer lifetime provides the possibility for regional transport of DMDSe[42]. During atmospheric transport, DMDSe may react with other substances and be transformed into oxidation products such as MSeA[19,32]. These oxidation products also have certain volatility and chemical reactivity, and they may continue to be transported with the atmospheric circulation, participating in the regional-scale selenium cycle[19,32].

Weather systems, particularly thunderstorms, significantly influence the vertical transport and deposition flux of selenium[32]. During thunderstorms, intense convection forms strong updrafts and downdrafts. The updrafts can transport selenium-containing aerosols and gases near the ground to high altitudes, changing the distribution of selenium in the atmosphere, while the downdrafts can rapidly bring selenium compounds from high altitudes to the ground, increasing the flux of selenium deposition[18,32]. Additionally, the lightning activity accompanying thunderstorms may also affect the

transformation and transport of selenium[36]. Lightning generates high-temperature and high-pressure environments, promoting certain chemical reactions, which may alter the form and properties of selenium compounds, thereby affecting their transport and deposition in the atmosphere[36].

Deposition mechanism

Global selenium deposition is dominated by wet processes, accounting for ~80% of total fluxes, with dry deposition contributing the remaining 20%[20]. The speciation of deposited Se is strongly pH-dependent: under acidic conditions (pH < 5), Se(IV) (SeO_3^{2-}) dominates due to its higher stability, whereas in neutral to alkaline environments (pH > 6), Se(VI) (SeO_4^{2-}) becomes the predominant form due to enhanced oxidation kinetics[19]. This pH-mediated speciation critically influences Se bioavailability, as Se(VI) is more soluble and mobile in ecosystems. Model simulations indicate that regions with high anthropogenic emissions (e.g., industrial areas) exhibit elevated Se(IV) deposition, while marine and remote continental sites show higher Se(VI) fractions[20]. These findings highlight the need for pH-resolved deposition schemes in global Se cycling models to accurately assess ecological impacts[19].

Wet deposition is the main way of selenium deposition, accounting for approximately 80% of the total selenium deposition[19,20]. During wet deposition, selenium compounds in the atmosphere are carried to the ground with precipitation (e.g., rain, snow, fog)[46]. The pH of precipitation significantly affects the form and deposition process of selenium. Studies have shown that Se^{4+} is more stable under acidic conditions[19,20]. In acidic precipitation, Se^{4+} may exist in a relatively stable form and be deposited on the ground with the precipitation, while in alkaline precipitation, Se^{4+} may undergo chemical reactions and transform into other forms, such as Se^{6+}[19,20]. Moreover, the chemical composition of precipitation (e.g., the presence of other ions, acidic substances) can also affect the deposition efficiency and form of selenium[32]. Dry deposition is another way of selenium deposition, mainly referring to the process where aerosol selenium reaches the ground through gravitational settling or diffusion[19,20]. The rate of dry deposition is influenced by various factors, including the particle size, density, and shape of aerosols, as well as the properties of the ground (e.g., roughness and vegetation coverage)[29].

Recent SOCOL-AERv2 model simulations project significant shifts in global Se deposition patterns under a +2 °C warming scenario[32]. The model predicts a 10%-20% increase in wet deposition fluxes at high latitudes due to enhanced precipitation, while arid regions may experience reduced removal efficiency. Altered atmospheric circulation is expected to modify long-range transport, increasing Se deposition in some oceanic regions but decreasing continental inputs. The simulations highlight climate-sensitive processes, including changing oxidant levels (OH, O_3) and aerosol chemistry, which may perturb Se speciation (Se^{4+}/Se^{6+} ratios)[32]. These projections underscore the need for coupled climate-chemistry models to assess future selenium bioavailability in ecosystems.

DETECTIONS OF AMBIENT SELENIUM

Proton transfer reaction time-of-flight mass spectrometry

Online detection techniques, particularly PTR-ToF-MS and ICP-MS, play crucial roles in studying atmospheric gaseous selenium compounds[47,48]. PTR-ToF-MS is an advanced analytical instrument capable of real-time monitoring of gaseous selenium compounds[32,42]. It operates based on proton transfer reactions, using hydronium ions (H_3O^+) as reagent ions. When sample gas containing target analytes (e.g., DMSe, DMDSe) enters the reaction zone, H_3O^+ protonates them. These ions then enter the time-of-flight mass spectrometer, where they are analyzed and detected based on differences in flight time[47,49]. Because ions of different masses follow different trajectories in electric and magnetic fields and thus have different flight times, precisely measuring ion flight time determines the mass-to-charge ratio (m/z), enabling qualitative and quantitative analysis of gaseous selenium compounds[42,49].

PTR-ToF-MS offers significant advantages, including extremely high sensitivity for trace-level detection of gaseous selenium compounds[42,49]. For example, in the marine boundary layer, the concentration of DMSe is usually at an extremely low level, and PTR-ToF-MS can accurately capture its concentration changes[42,49]. In addition, it has excellent time resolution and can reflect the dynamic changes in gaseous selenium compound concentrations in real

time[41,49]. When studying the short-term fluctuations of selenium compounds in the atmosphere, such as the concentration changes affected by specific meteorological conditions or local sources, this real-time monitoring capability provides valuable data support for researchers[42,49]. During thunderstorm observations, PTR-ToF-MS can respond quickly and present the changing trends of DMSe and DMDSe concentrations in real time, helping researchers analyze the instantaneous impact of thunderstorms on the concentrations of gaseous selenium compounds[42,49]. PTR-ToF-MS offers exceptional sensitivity for real-time detection of volatile selenium compounds like DMSe, with typical limits of detection (LOD) ranging from 1 to 5 pptv[42,49]. This technique provides high temporal resolution and enables continuous monitoring of dynamic atmospheric processes involving organic Se species. However, PTR-ToF-MS is limited to volatile and semi-volatile compounds and cannot detect non-volatile Se forms such as particulate-bound selenium or inorganic species like SeO_2[42,49].

ICP-MS

ICP-MS plays a significant role in the quantitative analysis of selenium in aerosols[47,48]. The core principle of this technique is to ionize elements in the sample, and the resulting ion beam is separated and detected in the mass spectrometer based on the mass-to-charge ratio. When analyzing selenium in aerosols, the first step is to collect aerosol samples. Usually, devices such as filters are used to collect aerosol particles in the atmosphere, and then the collected samples are pre-treated[47,48]. The pre-treatment process may include digestion, dissolution, and other steps, aiming to convert selenium in the aerosols into an ionizable form[48]. The treated sample is then introduced into the ICP-MS instrument, where the selenium atoms are ionized in a high-temperature plasma environment[47,48]. The mass spectrometer separates and detects these ions under the influence of electric and magnetic fields based on their mass-to-charge ratios. By comparison with standard samples of known concentrations, the selenium content in the aerosols can be accurately determined[47,48]. ICP-MS has the advantages of low detection limits, fast analysis speed, and the ability to simultaneously determine multiple elements[47,48]. Its detection limit can be as low as nanograms per cubic meter or lower, meeting the requirements for precise determination of selenium content in atmospheric aerosols. In terms of analysis speed, ICP-MS can analyze a large number of samples in a short time, improving research efficiency[47,48]. Moreover, it can simultaneously detect multiple elements in aerosols, not only determining selenium content but also providing information on other related elements, which is helpful for studying the interrelationship between selenium and other elements as well as their synergistic effects in atmospheric processes[47,48]. When studying atmospheric pollution in industrial areas, ICP-MS can simultaneously analyze multiple elements such as selenium, sulfur, and nitrogen in aerosols, helping researchers understand the mutual influence and transport patterns of these elements in atmospheric pollution[19,24,47]. ICP-MS achieves ultra-low LODs (0.1-1 $pg \cdot m^{-3}$) for total selenium in aerosols, making it ideal for quantifying trace-level particulate Se[19,24,47]. While ICP-MS provides excellent sensitivity and multi-element capability, it requires offline filter sampling and laboratory analysis, which limits temporal resolution. Additionally, ICP-MS cannot distinguish between different Se species [e.g., Se(IV) *vs.* Se(VI)] or organic Se compounds without coupling with chromatography[19,24,47]. Thus, while PTR-ToF-MS excels in real-time organic Se detection, ICP-MS remains the gold standard for total Se quantification in aerosols[19,24,47]. The two techniques complement each other and provide a more complete understanding of atmospheric selenium cycling. In a typical field campaign, PTR-ToF-MS can be deployed for continuous, real-time monitoring of volatile organic selenium species (DMSe, DMDSe, and their oxidation products), capturing diurnal variability and pulse emissions during meteorological events such as thunderstorms[42,47]. Simultaneously, 24-h integrated filter samples can be collected for offline ICP-MS analysis to quantify total aerosol selenium concentrations, including particulate-bound Se(IV) and Se(VI) species. By combining real-time gas-phase data from PTR-ToF-MS with time-integrated aerosol-phase data from ICP-MS, researchers can construct a more complete atmospheric selenium budget that accounts for both volatile and particulate fractions. This synergistic approach enables closure of the selenium mass balance, allowing quantification of gas-to-particle conversion rates and assessment of deposition fluxes[19,24]. Such integrated measurements are essential for validating atmospheric chemistry models and improving our understanding of selenium's atmospheric fate.

FUTURE RESEARCH DIRECTIONS

Quantifying the contribution of other oxidants to selenium transformation

While the reactions of O_3 and OH with gaseous selenium compounds have been studied, the contributions of other atmospheric oxidants, such as NO_3[50,51] and chlorine atoms (Cl)[52,53], remain poorly quantified. Kinetic modeling and computational approaches have been instrumental in elucidating detailed reaction mechanisms between volatile selenium compounds and atmospheric radicals (OH, Cl, NO_3, and O_3)[54-56]. These studies play a pivotal role in accurately identifying reaction pathways and characterizing the formation of both primary and secondary products. Determining site-specific and overall rate coefficients is critical for calculating atmospheric lifetimes, providing insights into the environmental persistence of these species. These methods enable precise determination of site-specific rate coefficients (e.g., •OH attack at $–CH_3$ *vs.* –Se–) and secondary product yields[15]. Such insights are critical for refining atmospheric lifetime estimates and aerosol-formation potential[19]. Further experimental validation is needed to confirm the theoretical predictions and improve the reliability of these models[54-56]. Given the shared redox chemistry of the chalcogen group, the reactivity of Se compounds with NO_3 and Cl can be inferred from their S analogs (e.g., DMS/DMDS). However, because Se has lower bond dissociation energies and greater polarizability, Se compounds are expected to react faster, making the direct use of S-analog kinetics a potential source of uncertainty[54-56].

The NO_3 usually has a relatively high concentration in the atmospheric environment at night, especially in areas with severe pollution[50,51]. It can react with gaseous selenium compounds, but the reaction rate and products are not yet fully characterized. The NO_3 reacts with gaseous selenium compounds primarily via hydrogen abstraction or addition to the Se atom, analogous to its reactions with organic sulfides[50,51]. For example, NO_3 likely abstracts a hydrogen atom from DMSe, forming $•CH_2SeCH_3$ and HNO_3, or adds to the Se center, leading to intermediate adducts. These pathways are consistent with NO_3 chemistry observed in other chalcogen systems[44]. Gas-phase electron transfer from neutral NO_3 is unlikely; instead, reactions proceed through radical mechanisms. Studies have shown that the reaction mechanism of NO_3 with some organic compounds is rather complex, involving multiple intermediate steps and various products[50,51]. For gaseous selenium compounds, NO_3 may change their chemical structure and properties through electron transfer or addition reactions with selenium atoms. Future research should combine laboratory simulations and field observations to elucidate the kinetics and mechanisms of NO_3 reactions with DMSe and DMDSe, and accurately quantify their contribution to selenium transformation[50,51]. This will help provide a more comprehensive understanding of selenium transformation pathways in the atmosphere and improve atmospheric chemical models of selenium.

Chlorine atoms have relatively high concentrations in specific atmospheric environments, such as areas near the ocean or regions with industrial chlorine emissions[52,53]. Chlorine atoms are strong oxidizers and can rapidly react with various substances[52,53]. In marine environments, Cl radical reactions may compete with hydroxyl (OH) radicals in the atmospheric degradation of organic compounds due to the high abundance of Cl derived from sea salt aerosols[52,53]. This represents a specialized but significant oxidation pathway, particularly for sulfur and selenium species. Villanueva *et al.* (2009) demonstrated that Cl reactions with organic compounds (e.g., alkylfurans) proceed rapidly, often leading to distinct degradation products compared to OH-initiated pathways[52]. Similarly, Baptista *et al.* (2025) highlighted the role of Cl in the atmospheric oxidation of biofuel-related esters, showing both ring-retaining and ring-opening mechanisms[53]. Since Cl concentrations can be elevated in coastal and marine regions, its reactions with volatile selenium compounds (e.g., DMSe) may influence their atmospheric lifetimes and transformation products. This underscores the need to consider Cl-driven chemistry alongside OH reactions when modeling marine atmospheric processes. In reactions with gaseous selenium compounds, chlorine atoms may capture electrons from selenium compounds, triggering a series of chemical reactions. However, current research on reactions between chlorine atoms and gaseous selenium compounds is relatively scarce[52,53]. Future studies should focus on this area, employing advanced experimental techniques and analytical methods to deter-

mine the rate constants, activation energies, and reaction products, and to assess their impact on the transformation and migration of selenium in the atmosphere. It is also important to note that current global atmospheric chemistry models, such as SOCOL-AERv2 used in recent selenium deposition studies[32,37], either completely omit NO_3 and Cl oxidation pathways for selenium species or rely on sulfur analogs (e.g., DMS and DMDS reaction rates with NO_3 and Cl) as proxies for selenium compounds. While this approach provides a first-order approximation because of chemical similarities within the chalcogen group, it introduces significant uncertainties. As discussed earlier, selenium compounds exhibit higher reactivity with oxidants than their sulfur counterparts due to weaker C–Se bonds and greater polarizability[42,45]. Consequently, using sulfur analog kinetics may overestimate the atmospheric lifetimes of DMSe and DMDSe, particularly in regions where nocturnal NO_3 chemistry or coastal Cl chemistry is important. This oversimplification could bias predicted selenium deposition fluxes and spatial distributions. Therefore, integrating experimentally determined rate constants for Se-specific NO_3 and Cl reactions into global models represents a critical priority for improving the predictive capability of selenium biogeochemical cycling under both current and future climate scenarios.

Development of high-sensitivity selenium isotope analysis techniques

Selenium isotope analysis is a powerful tool for studying its sources, transformation, and cycling, but the sensitivity of current techniques remains a limitation[57-59]. Selenium has several stable isotopes, such as ^{74}Se, ^{76}Se, ^{77}Se, ^{78}Se, ^{80}Se, and ^{82}Se, which undergo fractionation in various geological and biological processes[56-58]. By analyzing selenium isotope composition, the source of selenium can be traced, and the transformation processes of selenium in different environmental media can be understood[57-59].

However, due to the low concentration of selenium in the atmosphere, existing selenium isotope analysis techniques have certain limitations in terms of sensitivity, making it difficult to accurately measure the isotope composition of trace selenium[57-59]. In the future, it is necessary to develop high-sensitivity selenium isotope analysis techniques, such as improving the detection methods of mass spectrometers to enhance their detection capabilities for trace selenium isotopes or exploring new analytical principles and technologies, such as selenium isotope analysis methods based on laser spectroscopy, to achieve accurate measurement of trace selenium isotopes in the atmosphere. This will provide more powerful technical support for in-depth research on the biogeochemical cycle of selenium.

Assessing the impact of climate change on the selenium cycle

The impact of climate change on atmospheric selenium cycling is a complex and important topic requiring further investigation[60]. Climate change will lead to a series of environmental changes, such as rising temperatures, altered precipitation patterns, and an increase in extreme weather events, all of which will affect the selenium cycle[22]. Rising temperatures may affect the metabolic activities of marine and terrestrial organisms, thereby changing biogenic selenium emissions[17,38]. A 2 °C increase may enhance biogenic Se emissions by 10%-20% due to accelerated microbial activity in wetlands and oceans[17,32]. In the ocean, increased water temperature may affect phytoplankton growth and metabolism, altering their ability to methylate inorganic selenium and thus influencing DMSe and DMDSe emissions[27]. Changes in precipitation patterns, such as variations in intensity and frequency, will affect selenium sedimentation[18,22]. Increased rainfall intensity could elevate wet deposition fluxes by 15%-30% in temperate regions, while arid areas may experience reduced deposition[18,20]. More frequent intense precipitation events may increase the wet deposition flux of selenium, but changes in the chemical composition of precipitation may also affect the form and sedimentation efficiency of selenium in precipitation[18]. The impacts of extreme weather events, such as thunderstorms and hurricanes, on the selenium cycle also cannot be ignored[17,37]. Thunderstorms may amplify vertical transport, increasing local deposition fluxes by up to 40% during events[32]. Model simulations suggest net increases in Se deposition at high latitudes but declines in subtropical zones under warming scenarios[32]. Strong convective activity in thunderstorms can rapidly transport selenium compounds to the ground, increasing selenium deposition flux, while large-scale storms like hurricanes may alter atmospheric circulation patterns, affecting selenium

transport pathways and distribution[27].

Quantitative assessments based on recent climate model projections provide initial estimates of how altered selenium deposition under warming and extreme precipitation may cascade through ecosystems. Under a +2 °C warming scenario, SOCOL-AERv2 model simulations project a 10%-20% increase in wet deposition fluxes at high latitudes due to enhanced precipitation, while arid regions may experience reduced removal efficiency[32]. These shifts in deposition translate into differential selenium inputs to terrestrial and marine food webs. For terrestrial ecosystems, model-based estimates project a 15%-30% increase in Se deposition in northern temperate regions by 2100 under RCP8.5. This could elevate soil Se(VI) by 0.05-0.15 mg·kg^{-1}, potentially alleviating deficiency in agricultural soils currently below the 0.2 mg·kg^{-1} threshold for plant health[20,32]. However, in regions where increased deposition raises soil selenium concentrations above the 2 to 5 mg·kg^{-1} toxicity threshold, especially in historically seleniferous areas, soil microbial communities may suffer from reduced diversity and activity. This occurs because selenate competes with sulfate for microbial uptake, thereby disrupting normal sulfur metabolism[33]. For small fauna (e.g., soil invertebrates and herbivorous mammals), a 0.1-0.3 mg·kg^{-1} increase in dietary Se intake could elevate tissue Se concentrations by 1.5-2.5-fold, potentially leading to chronic selenosis symptoms including reproductive impairment and growth inhibition[16]. In regions with reduced precipitation, such as Mediterranean and subtropical zones where deposition is projected to decline by 10 to 20 percent, soil selenium levels may fall by 0.05 to 0.1 mg·kg^{-1}. This decline exacerbates selenium deficiency and has cascading effects on livestock health, because dietary selenium below 0.05 mg·kg^{-1} is associated with increased incidence of white muscle disease and immune dysfunction[3].

For marine ecosystems, the impacts are more nuanced due to the long residence time of Se in the ocean. Model outputs suggest that climate-driven changes in ocean circulation and stratification may alter vertical Se transport, with potential 5%-15% reductions in phytoplankton-available Se(VI) in the euphotic zone under warming scenarios[2,12]. This could translate into a 10%-20% decrease in DMSe emissions from marine biogenic sources, as Se uptake by phytoplankton is directly linked to primary productivity[8]. Conversely, increased extreme precipitation events (projected 20%-30% increase in frequency in tropical regions) may enhance riverine Se inputs to coastal waters by 15%-25%, potentially shifting the Se(IV)/Se(VI) ratio in estuarine environments and affecting selenium bioavailability for marine microorganisms[18,20]. The net effect on marine food webs from phytoplankton to higher trophic levels remains uncertain and warrants integrated modeling approaches that couple atmospheric chemistry, ocean biogeochemistry, and ecosystem response functions. These quantitative projections underscore the need to refine climate--chemistry-ecology coupled models to better constrain the cascading ecological consequences of climate-driven alterations in selenium deposition and speciation. Future work should combine climate models, atmospheric chemistry models, and long-term observations to assess climate change impacts on the selenium cycle.

CONCLUSION AND OUTLOOK

The atmospheric cycling of gaseous selenium compounds (DMSe, DMDSe) is a complex process involving diverse sources, transformation mechanisms, and deposition pathways. They enter the atmosphere from marine and terrestrial biogenic sources, volcanic activity, and anthropogenic emissions. In the atmosphere, they react with O_3 and OH to form particulate selenium, which is eventually deposited onto surfaces via wet and dry deposition. The transformation rate and product distribution are controlled by the type and concentration of oxidants as well as environmental conditions such as temperature, humidity, and light. For example, DMSe reacts relatively rapidly with O_3 ($k = 7.4 \times 10^{-17}$ cm^3·molec^{-1}·s^{-1} at 25 °C, lifetime ~7.6 h at 20 ppb O_3), whereas DMDSe reacts more slowly ($k = 2.6 \times 10^{-17}$ cm^3·molec^{-1}·s^{-1}, lifetime ~22 h). Weather systems, such as thunderstorms, significantly affect the vertical transport of selenium, which can alter its distribution and deposition flux in the atmosphere. Current methods, particularly online detection techniques (e.g., PTR-ToF-MS and ICP-MS), have advanced our understanding of gaseous selenium cycling. However, many aspects still require further investigation. Future research should focus on (1) quantifying the role of understudied oxidants (NO_3, Cl); (2) developing high-sensitivity Se isotope analysis; and (3) assessing climate change impacts. These

efforts will improve predictions of global Se cycling and its ecological effects, informing environmental protection, resource management, and public health strategies.

DECLARATIONS

Authors' contributions

The author contributed solely to the article.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool Grammarly (version 1.2, released 2024-12) was used solely for language editing, grammar checking, and spelling correction. The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. The author takes full responsibility for the accuracy, integrity, and final content of the manuscript.

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