



Springtime regimes of lower tropospheric ozone distribution over East and Southeast Asia over 21 years (2004-2024)

Beatrice Biagi¹, Juan Cuesta¹, Hiroshi Tanimoto², Yugo Kanaya³, Benjamin Pohl⁴, Marco Gaetani⁵, Chang-Feng Ou-Yang⁶, Neng-Huei Lin⁷, Matthias Beekmann⁸ and Gaëlle Dufour⁸

5 ¹Univ Paris Est Creteil and Université Paris Cité, CNRS, LISA, Créteil, 94010, France

²National Institute for Environmental Studies (NIES), Tsukuba, Japan

³Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama, Kanagawa, Japan

⁴Centre de Recherches de Climatologie, UMR 6282 Biogéosciences, CNRS / Université Bourgogne Europe, Dijon, France

⁵Classe di Scienze Tecnologia e Società, Scuola Universitaria Superiore IUSS, 27100, Pavia, Italy

10 ⁶Department of Chemistry, National Central University, Taoyuan, Taiwan

⁷National Central University, Department of Atmospheric Sciences, Taoyuan, Taiwan

⁸Université Paris Cité and Univ Paris Est Creteil, CNRS, LISA, Paris, 75013, France

Correspondence to: Beatrice Biagi (beatrice.biagi@lisa.ipsl.fr)

Abstract. Lower-tropospheric ozone (O₃) pollution is a major environmental and societal concern in East and Southeast Asia (ESEA), where concentrations often exceed the thresholds recommended by the World Health Organization, causing hundreds of thousands of premature deaths each year. While lower-tropospheric O₃ plays a key role in air quality, its systematic spatial variability and the influence of synoptic and climatological drivers on its distribution over long periods have not yet been characterised. In this study, we describe the most commonly occurring spatial patterns of lower-tropospheric O₃ during spring (March and April), the season of its highest concentrations. These regional spatial patterns are called O₃ regimes, which are derived from chemical reanalyses during over 21 years (2004-2024) using a k-means clustering algorithm. This method allows us to identify four distinct regimes of O₃ regional distribution, which are validated with respect to multispectral IASI+GOME2 satellite observations.

Our results highlight the occurrence of a specific regime characterised by anticyclonic and high insolation conditions over ESEA, that favour the occurrence of biomass burning in Indochina and lead to positive O₃ anomalies (+4 to +13 ppb) extending from Southeast Asia towards the Pacific. Its occurrence is significantly correlated with El Niño conditions. Conversely, a contrasting regime is associated with La Niña, which enhance convection and cloudiness, while producing a negative anomaly of tropospheric O₃ over most of the region. These results highlight that lower-tropospheric O₃ in spring exhibits different distribution patterns, which can be strongly driven by synoptic conditions and large-scale climate variability.

1 Introduction

30 Tropospheric ozone (O₃) is a major air pollutant and a strong short-lived greenhouse gas (IPCC, 2023), playing a key role in regulating oxidizing capacity of the atmosphere and influencing climate. In the troposphere, O₃ is mainly produced through photochemical reactions involving the oxidation of precursors like volatile organic compounds (VOCs) and carbon monoxide



(CO), in the presence of nitrogen oxides ($\text{NO}_x = \text{NO} + \text{NO}_2$) and sunlight. Stratosphere to troposphere exchange (STE) also contributes to enhanced tropospheric ozone levels, particularly at high and mid-latitudes (Gaudel et al., 2018; Monks et al., 2015).

In this study, we focus on lower-tropospheric ozone, including ozone in the near-surface and lower free troposphere. Here, O_3 poses significant risks to human health, harms vegetation, and reduces crop yields (Monks et al., 2015). O_3 pollution over East and Southeast Asia (ESEA) is a serious social concern: 50% of the estimated cardiovascular premature mortality in this region is attributable to surface O_3 in 2019 (Sun et al., 2024). Consequently, WHO has introduced a new recommended standard for peak-season 8-hour mean ozone of $60 \mu\text{g}/\text{m}^3$ (World Health Organization, 2021). The measured peak-season O_3 level demonstrates that 98% of air quality stations in ESEA exceeded this WHO limit, indicating a widespread and critical risk of long-term exposure for the population (Li et al., 2025b). In this context, the research community has increasingly focused on characterizing the spatial and temporal variability of ozone in the lower troposphere across this region (Gaudel et al., 2018).

Despite recent important reductions of NO_x emissions in Asian countries, like China since 2013, surface ozone still shows positive trends across many parts of the region (Cao et al., 2024; Li et al., 2025b; Lu et al., 2025). This behaviour is driven by the complex, non-linear processes involved in ozone formation, which, depending on the chemical regime, make the response of ozone to NO_x either positive or negative (Sillman, 1999; Wang et al., 2021). In addition to regional photochemical production, O_3 levels also depend on atmospheric transport, and background levels, which are all influenced by meteorological and climatological variability (Lu et al., 2019; Monks et al., 2015). Previous studies that investigated precursor influences alone were often not conclusive, highlighting the importance of considering the role of meteorological and climatological variability (Dufour et al., 2021; Lu et al., 2019). In this context, the increasing availability of long-term satellite and ground-based measurements in recent years has allowed detailed analyses of regional ozone trends, spatial patterns, and temporal variability. Tropospheric ozone in ESEA is characterized by significant spatial and seasonal variations, with spring typically showing the highest ozone levels (Li et al., 2025b). This springtime ozone enhancement is driven by the combined influence of photochemistry and large-scale circulation, that defines the meteorological conditions favourable to high ozone levels and the presence of active sources. In this region, ozone pollution is intensified under persistent anticyclonic circulation, with enhanced solar radiation and reduced cloudiness and precipitation (Cao et al., 2024; Raktham et al., 2014). These conditions are often associated with the westward expansion of the Western Pacific Subtropical High (WPSH), associated with a large semi-permanent anticyclonic structure, which promotes dry and warm conditions over ESEA (Huang et al., 2024; Wei et al., 2023; Yen et al., 2013). These situations enhance photochemical ozone production and promote biomass burning activity in southern China and Indochina, thereby increasing precursors emissions and contributing to the springtime peak of tropospheric ozone in the subtropics (Jacob et al., 2003; Ogino et al., 2022). At mid- and high-latitudes, high level of tropospheric ozone is modulated by different dynamical processes. Frequent stratosphere-troposphere exchange events contribute to enhanced background ozone in the free troposphere, as demonstrated by satellite observations, ozone sondes and aircraft measurements (Kim et al., 2025; Li et al., 2025b). Episodic cold surge events are an efficient mechanism for uplifting pollutants emitted from



anthropogenic sources into the free troposphere, where they are then efficiently transported eastward (Brown-Steiner and Hess, 2011; Ikeda et al., 2021).

The El Niño-Southern Oscillation (ENSO) is a semi-periodic coupled ocean-atmosphere phenomenon defined by variations in sea surface temperatures and atmospheric circulation over the tropical Pacific, which can modify large-scale atmospheric circulation and climate patterns (Brassington, 1997). According to literature, it is a significant driver of the interannual variability of atmospheric circulation that influences lower tropospheric O₃ levels across ESEA and the subtropical North Pacific Ocean (Lin et al., 2014a; Liu et al., 2003; Okamoto et al., 2018; Xue et al., 2021). El Niño conditions enhance the subsident branch of the Walker circulation over Southeast Asia, enhancing solar radiation and suppressing rainfall (Li et al., 2025a). This condition intensifies fires, with biomass burning emission increasing up to 57% (Xue et al., 2021). The combination of enhanced emissions and large-scale circulation anomalies results in enhanced O₃ plumes of 15000 km across the subtropical North Pacific (Lin et al., 2014a; Xue et al., 2021). These plumes affect air quality in Hawaii, as observed at the Mauna Loa Observatory, which shows an almost 10% increase in O₃ during El Niño conditions, as well as other locations such as Taiwan (Raktham et al., 2014) and North America (Xue et al., 2021). La Niña anomalies tend to enhance deep convection and precipitations in Southeast Asia, suppressing fire activity, and may lead to lower ozone concentrations (Liu et al., 2003). As shown by Okamoto et al., (2018), long-range transport from East Asia is suppressed due to weaker westerly winds.

Given the increasing O₃ trends and the complex role of synoptic conditions, a complete characterization of the regional ozone distribution and variability over a multi-year period is required. The main gaps that remain concern 1) the lack of an objective multi-year climatology of tropospheric ozone spatial distributions including its variability in East Asia, with an emphasis on the spring season with enhanced surface ozone concentrations and 2) a better understanding of how synoptic circulation and large-scale modes, such as ENSO, modulate springtime ozone and its precursors.

The aim of this research is to investigate the synoptic and climatological influence on springtime tropospheric ozone variability in East Asia. This study provides an objective identification and classification of springtime tropospheric O₃ regimes over East Asia and identifies the synoptic variability of the atmospheric circulation controlling the production and the transport of ozone. Specifically, we present the first robust quantification of ozone regional distribution in terms of spatial regimes over a 21-year period and its links with synoptic conditions, precursor sources and ENSO variability. By integrating long-term in-situ and satellite observations and reanalysis data, this work aims to improve our understanding of processes that influence regional ozone formation and transport in East Asia.

The methodology and datasets are described in Section 2. Section 3 presents the main results describing: 1) the main identified ozone regimes and their evaluation with satellite and in-situ observations, 2) their key meteorological drivers over East Asia and the Pacific, and indicators of ozone precursor emissions and 3) the influence of ENSO on the spatial and temporal ozone variability. Finally, Section 4 summarizes the main conclusions of this study.



2 Method and data

2.1 Ozone regime classification

In this study, we conduct a classification of large-scale regimes of daily ozone spatial fields during spring (March-April), over a 21-year period (2004-2024). The methodology, summarized in Figure 1, follows the standard approach commonly used in the literature for identifying weather regimes, defined as persistent synoptic-scale circulation patterns e.g. (Michelangeli et al., 1995). To our knowledge, this is the first time that this framework is directly applied to ozone fields to derive ozone regional distribution regimes and investigate the typical spatial patterns of tropospheric ozone. The selected domain [10-40°N, 85-180°E] covers East Asia and the western Pacific Ocean, including the main regions where springtime ozone precursors are emitted (anthropogenic sources in highly industrialized areas and agricultural fires in the Indochinese Peninsula). Ozone fields are obtained from Copernicus Atmospheric Monitoring Service (CAMS) reanalysis for sake of full spatio-temporal coverage. We consider the 850 hPa pressure level (approximately 1.5 km above sea level) as reference for low-tropospheric ozone, which is roughly consistent with the altitude of maximum sensitivity of the IASI+GOME-2 product that is used for its validation (see section 2.3).

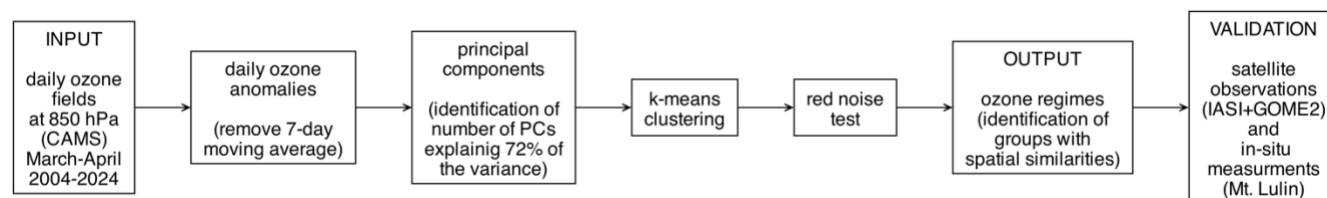


Figure 1: Scheme of the methodology used for ozone-regimes classification.

The first step of the method consists of deriving daily ozone anomalies to focus on their daily variability and equalizing contributions of each point of the spatial grid. This is done in two steps: first a 21-year climatology is calculated for each day of the year and at each grid point, and a 7-day moving window centred on the corresponding day is then applied. The 7-day window was used to obtain a robust estimate of the climatology and to avoid sensitivity to day-to-day fluctuations. The resulting day-of-year climatology was then removed from each daily ozone field to obtain the daily anomalies. Then, anomalies at each grid point are standardized by subtracting the long-term mean and dividing by the standard deviation, ensuring that all geographical locations contribute equally to the analysis. The dataset is then weighted by the square root of the cosine of latitude to account for the decreasing grid-cell area toward the poles, linked to the use of latitude/longitude as coordinates. As a second step, a principal component analysis (PCA) is applied to the ozone anomalies to identify the dominant spatial patterns of variability and their associated time series. We retain the first 40 largest empirical orthogonal functions (EOFs), which explain 72,2% of the total variance. This step is important to reduce the dimensionality of the dataset and to filter out some noise as the resulting principal components (PCs) are used as input for the clustering. The third step consists of clustering the 40 PCs into groups based on spatial similarities and differences, using the k-means clustering algorithm (as described in Michelangeli et al., 1995). Clustering is performed for each value of k classes from 2 to 10, with 100 independent runs with



different initializations for each k to assure the reproducibility of the results. The optimal number of regimes is assessed using the classifiability index, which evaluates the reproducibility of the clustering solution across independent runs. The statistical significance of the obtained classifiability was evaluated using a red-noise test (Supplementary Figure S1). Following this procedure, the ozone fields analysed can be partitioned into regimes according to spatial similarities (in our case, we identify 4 regimes, see section 3.1). Each ozone regime is obtained by grouping and averaging the input daily ozone anomalies belonging to its class (Supplementary Figure S2).

Additionally, we assess the robustness of the classification using two statistical tests (Gaetani et al., 2021). A T-test is applied at each geographical location to verify that the mean anomaly of each regime is significantly different from zero, meaning that each ozone regime is considered derived from different populations with the 95% confidence level according to the p -value. A one-way analysis of variance (ANOVA) is used to test if the distribution of each regime originates from populations with different mean values (Supplementary S3). Finally, the spatial and temporal variability of each ozone regime is validated using observational datasets from satellite ozone retrievals and in-situ observations.

2.2 Reanalysis data

Daily ozone and carbon monoxide (CO) fields at 850 hPa pressure level are obtained from CAMS global reanalyses (EAC4), produced by ECMWF (<https://www.ecmwf.int/en/research/climate-reanalysis/cams-reanalysis>) (Inness et al., 2019). Previous evaluations against independent ozone sonde observations over East Asia have shown that CAMS reanalysis reproduces the spatial distribution and seasonal cycle of lower-tropospheric ozone more realistically than several other reanalysis products, with statistically significant correlations at 850 hPa (Park et al., 2020). We use fields at 06:00 UTC, corresponding approximately to afternoon over the eastern Asia study region, regridded from the original 0.75° resolution to a uniform 1° horizontal grid to match the resolution of the satellite dataset used for validation. The targeted region is East Asia (10° – 40° N, 85° – 180° E) and the analysed period includes all days of the months of March and April over the 21-year period from 2004 to 2024 (considered for the ozone regime classification). The 850 hPa level is still sensitive to boundary layer photochemical ozone production, but is relevant for satellite observations (which can not directly detect surface ozone). The resulting ozone anomalies are used as inputs for the ozone-regime classification. The CO fields are used to identify combustion sources, such as biomass burning and industrial activities.

Additional analyses of the ozone regional distribution are conducted over an extended domain including the Pacific Ocean (5° – 55° N, 85° – 250° E) at 500 hPa for studying long-range transport that is more effective at this altitude, and over Taiwan at 700 hPa for comparing with in situ measurements at a mountain site.

To investigate the synoptic meteorological conditions influencing tropospheric ozone production and transport, we use geopotential height and zonal wind, at 850 hPa and 500 hPa (the latter only for the extended domain), and top-of-atmosphere net long-wave (thermal) radiation from the fifth-generation ECMWF reanalysis (ERA5) (Hersbach et al., 2020). The ERA5 data have an hourly temporal resolution and a spatial resolution of $0.25^\circ \times 0.25^\circ$. As for CAMS reanalysis, we use the fields at 06:00 UTC on a grid with a spatial resolution of $1^\circ \times 1^\circ$. For both reanalysis products, daily anomalies are computed at each



grid point by removing the corresponding 21-year day-of-year climatology over March–April. This step retains the day-to-day variability.

2.3 Satellite and in-situ observations

To validate and verify the consistency of the spatial distribution of ozone regimes derived from CAMS data, we use the lowermost tropospheric ozone observations (from the surface to 3 km of altitude above sea level - asl) from the multispectral satellite retrieval IASI+GOME2. This product combines thermal infrared atmospheric radiance observed by IASI and UV earth reflectance measured by GOME2, enhancing sensitivity to ozone in the lowermost troposphere compared with the individual retrievals (Cuesta et al., 2013). The retrieval has been validated against ozonesonde observations, showing good agreement in the 0–3 km layer, including over East Asia (Cuesta et al., 2018). In this study, we use a daily dataset of ozone mixing ratios at 09:30 local time, gridded on a regular grid of resolution of $1^\circ \times 1^\circ$. The CAMS fields used for the regime classification are sampled at 06:00 UTC. Although CAMS ozone at 850 hPa and IASI+GOME2 lowermost-tropospheric ozone represent different vertical quantities and the datasets are not sampled at the same time, both provide information on daytime ozone distributions and have been compared in previous studies (Okamoto et al., 2026). In this study, satellite observations are used mainly to assess the spatial consistency of the ozone regimes rather than their instantaneous absolute values. Additionally, we evaluate CAMS data with hourly in-situ O_3 observations from the Lulin Atmospheric Background Station (LABS), located on Mt. Lulin in central Taiwan ($23.47^\circ N$, $120.87^\circ E$) (Ou-Yang et al., 2022). This site is chosen because of its ideal location, corresponding to the transport pathways of airmasses from Southern China and the Pacific and at relatively high altitude. At an elevation of 2862 m, LABS is generally not affected by local sources, making it ideal for monitoring long-range transport of air pollutants from the continental East Asia. Moreover, the station is frequently located above the atmospheric boundary layer top. Previous studies use Mt. Lulin observations to characterize the long-range transport of biomass-burning emissions from Southeast Asia and Indonesia to the western North Pacific (Lin et al., 2014a; Ou Yang et al., 2012) and to link interannual variability of pollutants to ENSO (Pan et al., 2024).

To describe the locations and occurrences of fires over Indochina, we use the MODIS MCD14ML product from MODIS sensors on board both Terra and Aqua satellite (Giglio et al., 2016). Data are available from the University of Maryland fuoco SFTP server (fuoco.geog.umd.edu, last access: 22/11/2025).

2.4 ENSO Indices

We also investigate the relationship between ENSO and the obtained ozone regimes with NOAA $1/4^\circ$ Daily Optimum Interpolation Sea Surface Temperature (OISST) data, a long-term Climate Data Record of observations from several platforms (satellites, ships, buoys and Argo floats) merged into a regular global grid (Reynolds et al., 2007). In addition, several ENSO indices are also employed in our analysis (NOAA, 2025). The Southern Oscillation Index (SOI) quantifies ENSO by describing the bimodal variation in sea level barometric pressure between observations at Darwin, Australia and Tahiti (Ropelewski and Jones, 1987). Another ENSO index is derived from outgoing longwave radiation (OLR) anomalies at the top of the atmosphere,



observed by the Advanced Very High-Resolution Radiometer (AVHRR) aboard NOAA polar-orbiting satellites (Liebmann and Smith, 1996). We also use Niño 4, Niño 3.4, Niño 3 and Niño 1+2 indices, defined as sea surface temperature (SST) anomalies averaged over specific regions of the equatorial Pacific Ocean (Trenberth, 1997). Niño 1+2 and Niño 3 represent the eastern equatorial Pacific, Niño 3.4 and 4 represent the central and western equatorial Pacific, respectively. In addition, we use the Oceanic Niño Index (ONI), which is based on the 3-month running mean of SST anomalies in the Niño 3.4 region. To further characterize the Central Pacific flavour of ENSO, we use the El Niño Modoki Index (EMI), defined as a combination of SST anomalies over the central, eastern and western equatorial Pacific (Ashok et al., 2007). The Trans-Niño Index (TNI), computed as the normalized difference between Niño 1+2 and Niño 4 SST anomalies, is also included as it is designed to track the east–west gradient of SST anomalies along the equatorial Pacific and then to distinguish between different ENSO flavors (Trenberth et al., 2002). The Pacific Meridional Mode index (PMM) is used to account for the meridional, wind–evaporation–SST-driven mode of variability in the northeastern tropical Pacific, which has been shown to precede and influence ENSO development (Chiang and Vimont, 2004)

3 Results

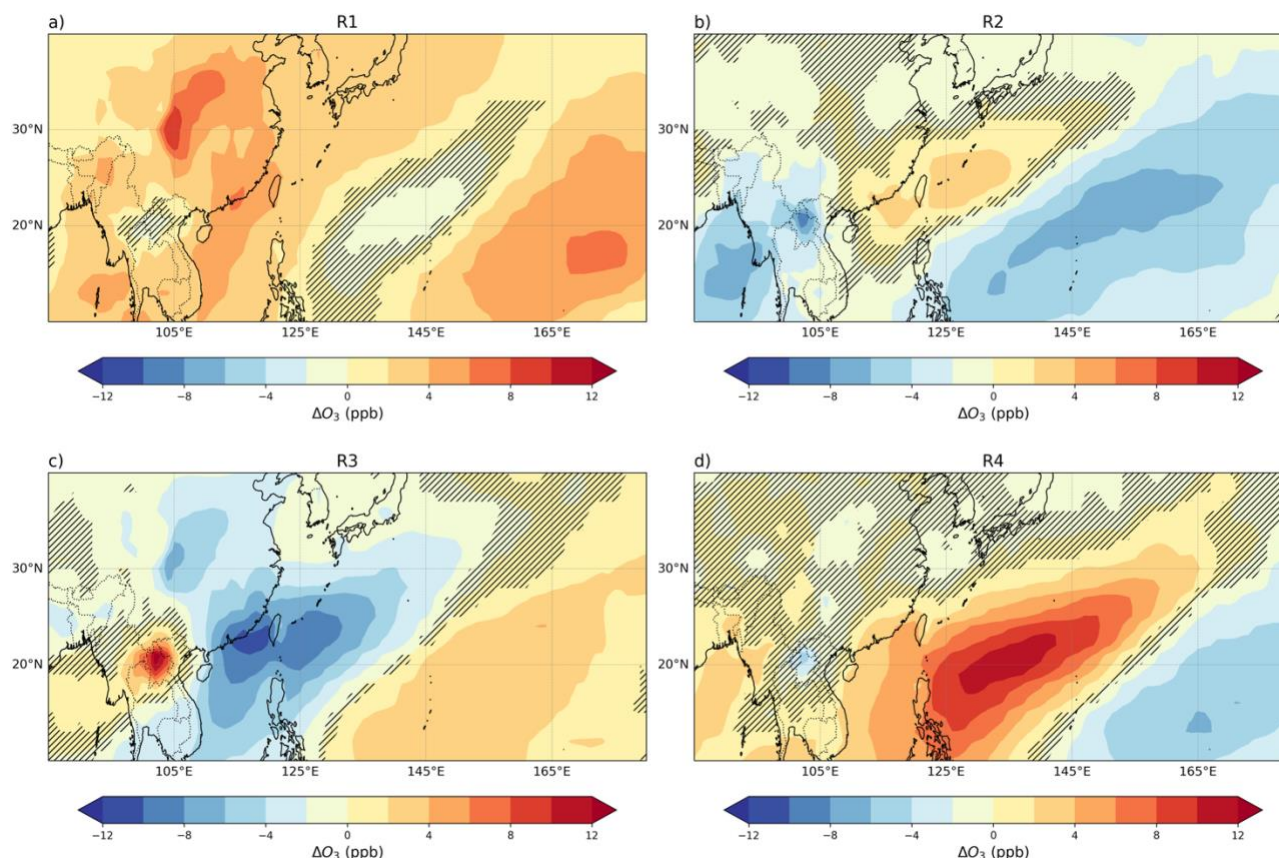
This section presents the recurrent springtime regimes characterizing the variability of lower-tropospheric ozone over East Asia during spring. We first describe their spatial structure and persistence characteristics (Section 3.1), then validate them using independent satellite and in-situ observations and investigate the synoptic-scale meteorological conditions and emission sources (Section 3.2). We study the physical link between the four ozone patterns and the associated meteorological conditions and CO emissions from biomass burning (Section 3.3). We then analyse the interannual modulation of the ozone regimes by ENSO, using multiple indices and independent in-situ observations (Section 3.4). Finally, we investigate how ENSO-related circulation anomalies affect the large-scale, trans-Pacific transport of ozone from East Asia toward North America (Section 3.5).

3.1 Regimes of lower tropospheric ozone regional distribution over East Asia

The k-clustering classification identifies four recurrent regimes of lower-tropospheric ozone variability (850 hPa) over East and South-East Asia during spring (March–April), representative of the 21-year period between 2004 and 2024 (Figure 2). A first regime (R1) is characterized by widespread positive ozone anomalies between +4 and +9 ppb throughout the region (Figure 2a). In contrast, a second regime (R2) produces negative ozone anomalies, between -8 ppb and -4 ppb, over the Indochinese Peninsula and the western Pacific Ocean, while weak positive anomalies (< +4 ppb) remain confined to the southeastern Chinese coast and Taiwan (Figure 2b). The third regime (R3) shows a localized ozone hotspot over northern Laos, where anomalies exceed +10 ppb, while negative ozone anomalies (< -4 ppb) affect northern and eastern China and the East China Sea. Moderate positive anomalies (< +5 ppb) also extend over the western Pacific Ocean (Figure 2c). Conversely, the fourth regime (R4) is associated with an elongated band of high positive ozone anomalies (+4 to +12 ppb) extending from



Indonesia to Taiwan and the western Pacific Ocean. An area of negative anomalies is localized over the central Pacific Ocean (Figure 2d).



- 225 **Figure 2: Regimes of ozone distribution in terms of ozone anomalies mixing ratio (ppb) from CAMS reanalyses at 850 hPa during the two-month periods of March-April over 21 years from 2004 to 2024. These regimes correspond to the overall conditions of (a) R1, (b) R2, (c) R3 and (d) R4. The non-shaded areas represent values significant at the 95% level of confidence after the T-test. Red colours represent positive anomalies in ppb and blue colours negative anomalies. The order of the ozone regimes provided in this figure does not reflect a specific occurrence frequency.**
- 230 These ozone regimes exhibit strong temporal persistence. Self-transition (i.e. that a regime remains the same from one day to another) probabilities range from 78% to 81%, while transitions between different regimes remain below 11% (Table 1). The resulting mean regime duration (consecutive days with the same regime) of approximately 4-5 days is consistent with a variability occurring at the synoptic scale. The persistence analysis further confirms the synoptic nature of the identified regimes (Figure 3). Median event durations range between 3 and 4 days for all classes. The regimes R3 and R4 (Fig. 2c, d)
- 235 tend to persist longer and display less variability. Whereas the other two regimes, R1 and R2, show generally shorter sequences, but occasionally produce unusually extremely long events, suggesting the modulation by low-frequency climate variability. Furthermore, all the four regimes show a clear interannual variability, as shown in Figure S4. The median occurrence frequencies are 21.3% for R1, 16.4% for R2, 26.2% for R3, and 19.7% for R4, respectively, with a wide interannual variability,



with annual frequencies ranging from 0–67.2%, 0–83.6%, 3.3–57.4%, and 0–42.6%, respectively. The Mann-Kendal test indicates a significant increasing trend in the occurrence frequency of R1 ($1.92\% \text{yr}^{-1}$, $p=0.042$) and a significant decreasing trend for R2 ($-1.48\% \text{yr}^{-1}$, $p = 0.046$).

Table 1. Transition rates of ozone regimes, expressed as the percentage of transitions from the regimes in the rows to those in the columns. Values on the diagonal represent the persistence of each regime.

Regimes	R1	R2	R3	R4
R1	78.8	3.2	10.9	7.1
R2	5.1	81.8	7.2	6.6
R3	7.9	9.3	80	2.8
R4	10.7	7.5	4	77.9

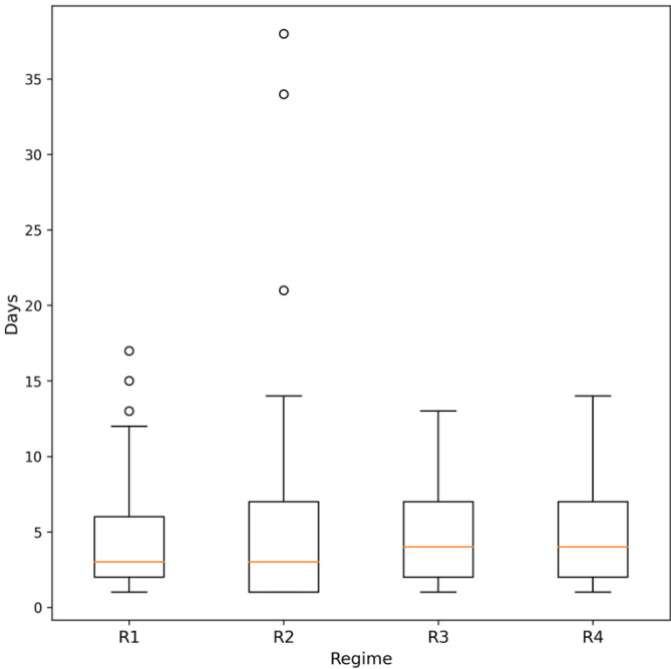


Figure 3: Ozone regimes persistence, displayed as the distribution of the regimes sequences in days. Orange lines represent the median, boxes represent the interquartile range, whiskers extend up to 1.5 times the interquartile range, and outliers are displayed as black circles.

3.2 Comparison of ozone regimes with satellite and in-situ observations

In this section, independent satellite and in-situ observations are used to assess if the ozone regimes identified from CAMS capture spatial and temporal features of lower-tropospheric ozone variability over East Asia. At the regional scale, the lower-tropospheric ozone columns (surface-3 km asl) retrieved from IASI+GOME2 (March-April, 2017-2024) reproduce the main



spatial structures associated with each regime (Figure 4). To reduce noise in the satellite data, IASI+GOME2 data are spatially
255 smoothed using a median filter with a $2^\circ \times 2^\circ$ kernel, conserving the resolution of 1° for comparing with CAMS data. Although
the satellite anomalies are weaker, likely because they represent ozone integrated over the surface-3 km layer rather than a
single pressure level, the spatial patterns remain clearly consistent in relative terms with the CAMS classification. R1 shows
widespread positive ozone anomalies ($> +3$ ppb) across East Asia, including Indochina, northern China, Japan and Pacific
Ocean (Figure 4a). R2 is associated with marked ozone reductions (< -5 ppb) over the Indochinese Peninsula and the Pacific
260 Ocean (Figure 4b). R3 in Figure 4c is characterized by enhanced ozone over Indochina and the western Pacific Ocean and
reduced ozone over northeastern China (< -4 ppb). Conversely, R4 enhances ozone concentration ($+2$ ppb) over Indonesia,
Taiwan, and the western Pacific Ocean, while reducing ozone over the central Pacific (> -3 ppb) (Figure 4d). The agreement
between CAMS and IASI+GOME2 demonstrates that the four regimes obtained from the reanalysis represent large-scale
ozone patterns independently observed from space. This consistency is more similarly observed when considering the same
265 period of 2017-2024 for averaging both CAMS and IASI+GOME2 ozone horizontal daily distributions (respectively 850 hPa
and surface-3km partial columns; see Figure S5 in the Supplementary Material). We also performed a spatial projection
analysis (Crétat et al., 2015) as reported in the Supplementary Material (Figure S6 and Table S1) to verify that the four regimes
identified from CAMS are robust and consistently reproduced in the independent IASI+GOME2 satellite observations, both
in space and in time.

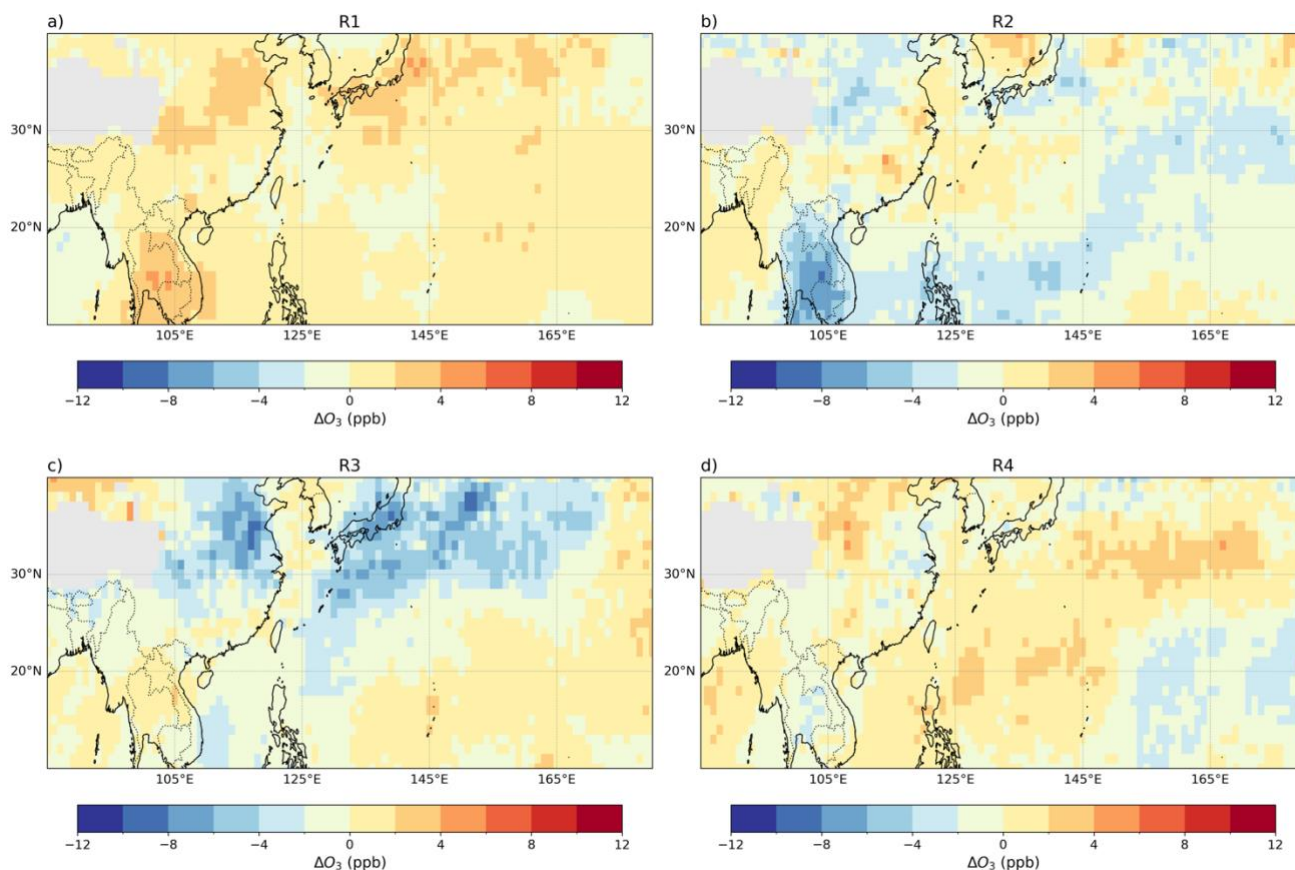


Figure 4: Column (0-3km) low-tropospheric ozone concentration patterns from IASI+GOME2 data associated with the ozone regimes classified from CAMS during March-April 2017–2024.

The temporal evolution of the tropospheric ozone concentrations derived by CAMS is also validated by long-term in-situ measurements from the LABS station at Mt. Lulin in Taiwan (2006–2024). For this comparison, CAMS ozone at 700 hPa is used to match the altitude of Mt. Lulin (2862 m.a.s.l.) over the grid point that includes its location.

In relative terms, the monthly ozone concentrations simulated by CAMS at 700 hPa clearly follow the observed interannual variability between 2006 and 2024 (Figure 5), capturing both the exceptionally low ozone minimum observed during spring 2022 and the major peaks recorded in 2007, 2009, 2016, 2021, 2023, and in 2024. Over the entire period, CAMS and observations exhibit a significant positive correlation ($r=+0.50$), indicating that the reanalysis captures part of the observed variability. In absolute terms, CAMS shows a moderate positive mean bias ($MB=+7$ ppb), suggesting a systematic overestimation of ozone concentrations with respect to the surface station measurements. It is worth noting that biases do not affect significantly the ozone regime classification done in this work, since the input ozone field (CAMS) are normalized and deseasonalized before the classification is done.



CAMS-derived tropospheric ozone concentrations associated to each ozone regime are consistent when evaluated against those from the in-situ observations (Figure 6). Both CAMS (Figure 6a) and in-situ observations (Figure 6b) identify R1 associated with the highest ozone levels, and the convection regime as the one associated with the lowest values. Ozone abundances observed at Mt. Lulin increase significantly with the occurrence of R1, whose monthly frequency correlates positively with the Mt. Lulin time series ($r = +0.48$, $p = 0.006$). This result confirms that this regime represents regional ozone outbreak conditions and it becomes more frequent during high ozone episodes. While CAMS generally overestimates ozone concentrations, the relative ranking of the regimes remains unchanged between datasets, indicating that the classification captures physically meaningful differences in ozone variability. The slightly larger spread observed for in-situ measurements reflects the higher temporal variability resolved by local observations compared with the gridded reanalysis. Taken together, these independent satellite and in-situ observations confirm that the ozone regimes identified from CAMS capture robust spatial and temporal features of lower-tropospheric ozone variability over East Asia.

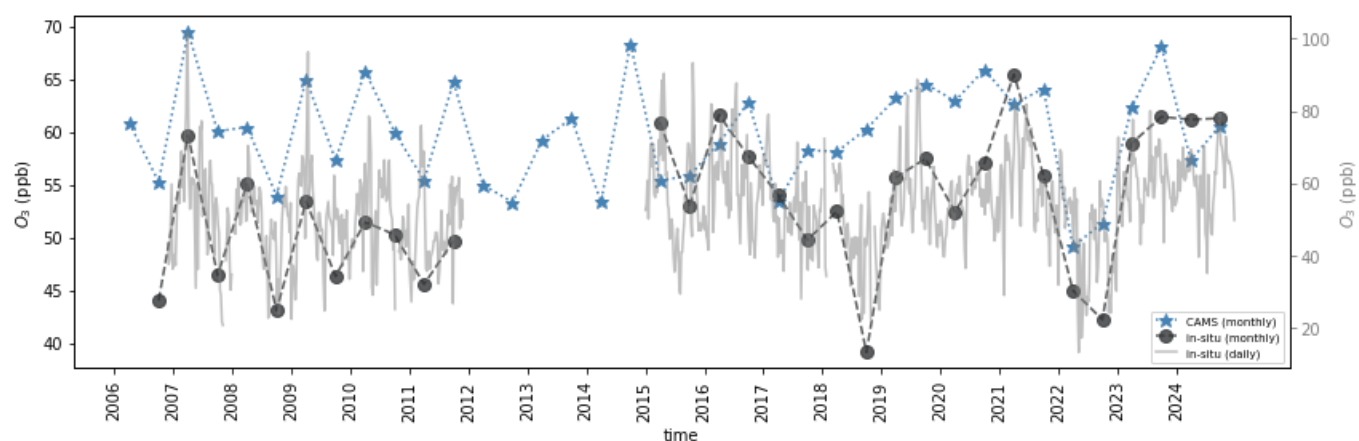
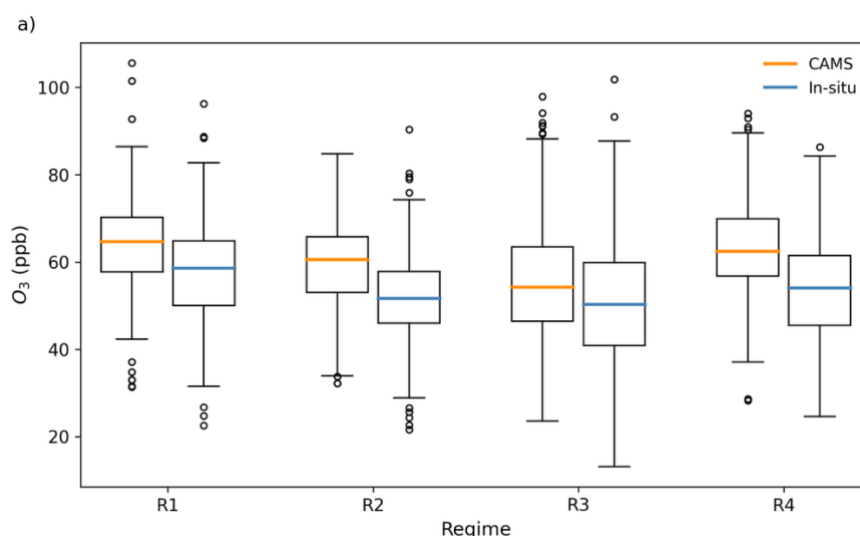


Figure 5: Springtime (March-April) O_3 concentrations from monthly CAMS data at 700 hPa (blue line) and from the in-situ LAB station at Mt. Lulin, Taiwan (2862 m.a.s.l.; grey line: daily data; black line: monthly averages).



300 **Figure 6: Boxplots of ozone concentrations (ppb) using CAMS data (orange) and in-situ observations at Mt. Lulin (blue), filtered according to the regime classification. The comparison is performed at the station location and the corresponding CAMS grid point.**

3.3 Ozone regimes: link with synoptic conditions and sources

In this section, we investigate the drivers of ozone variability over east Asia, linking ozone patterns to meteorological conditions, biomass-burning CO emissions and climate variability, and we show the physical framework associated with the
 305 four identified regimes.

3.3.1 Persistent high pressure over East Asia (R1)

R1 is characterized by widespread positive anomalies of ozone across most of East-Asia. The strongest enhancements exceeding +6 ppb occur in three key hotspots: 1) two important Chinese industrial hubs, the Sichuan Basin and the North China Plain, 2) the Southeastern Chinese coast, Taiwan and the South China Sea, and 3) the Pacific Ocean sector between
 310 160-180°E (Figure 7a). Positive CO anomalies over the Indochinese Peninsula (> 15 ppb) indicate that precursors emissions increase in this regime and contribute to the regional ozone enhancement (Figure 7b).

The dynamical circulation associated with this regime is influenced by a large-scale anticyclonic circulations and clear skies, which together promote O₃ photochemical production (Figure 7c and d). Given these characteristic circulation features, R1 can therefore be referred to as the “High Pressure” regime. Positive geopotential height anomalies at 850 hPa and higher
 315 outgoing longwave radiation reveal dry, cloud-free conditions over East Asia and the Western Pacific. Over the Indochinese Peninsula, subsiding dry air masses, increased solar radiation and warmer temperature promote biomass-burning and enhance the emission of O₃ precursors, such as CO. All these conditions accelerate photochemical ozone production. The circulation anomalies also promote the regional transport of pollutant. Specifically, emission originating from Indochina and Eastern

China are transported eastward and partially recirculated around the anticyclonic system (Figure S7a), contributing to the
 320 ozone enhancement across the continent and the western Pacific Ocean.

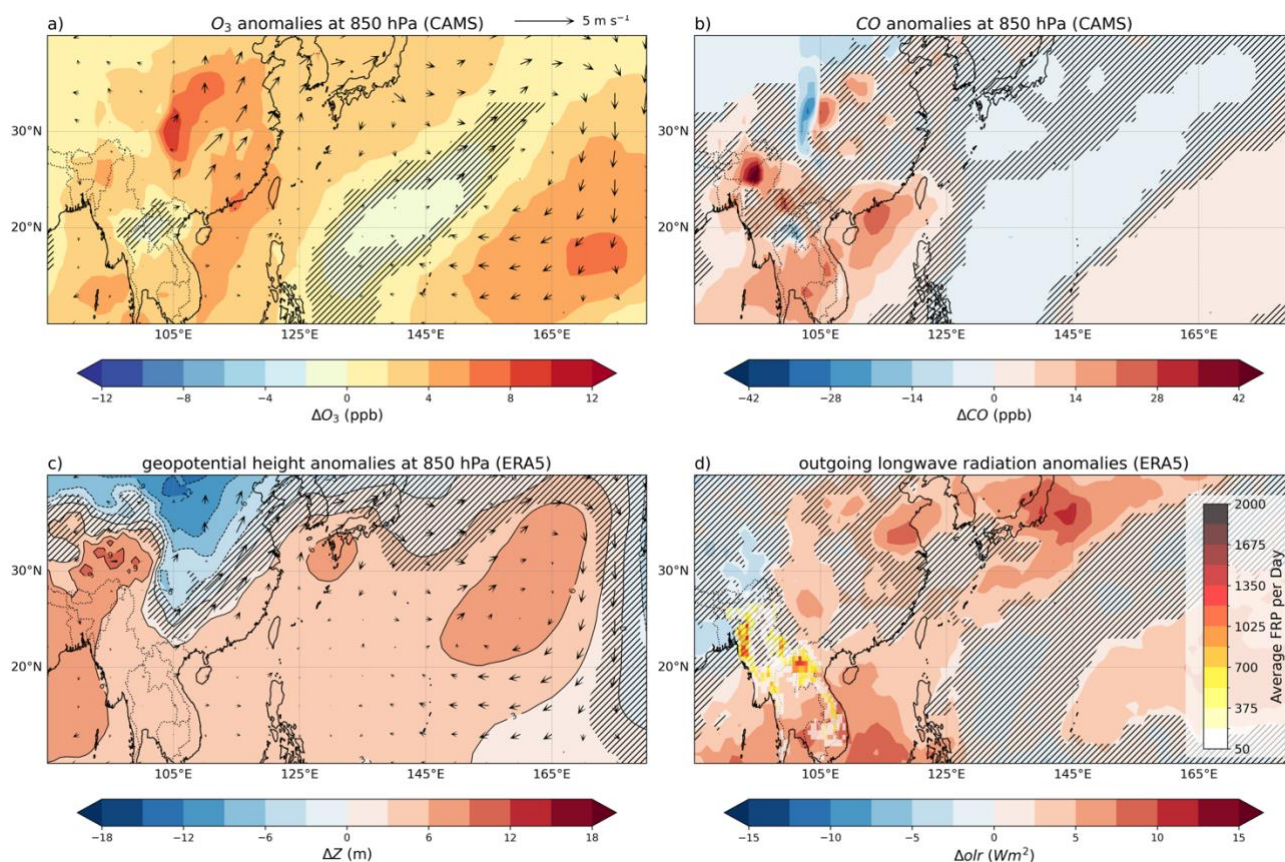


Figure 7: High pressure ozone regime (R1) and the corresponding synoptic conditions and CO field. a) O₃ anomalies (ppb) at 850 hPa from CAMS and zonal wind anomalies at 850 hPa from ERA5. b) CO anomalies (ppb) at 850 hPa from CAMS. c) geopotential height anomalies and zonal wind anomalies at 850 hPa from ERA5. d) Outgoing longwave radiation anomalies (W/m²) at the top of the atmosphere from ERA5 and averaged fire radiative power per day from MODIS MCD14ML product. The non-shaded areas represent values significant at the 95% level of confidence after the T-test. Red colours represent positive anomalies in ppb and blue colours negative anomalies.

The in-situ data from Mt. Lulin confirm that this ozone regime represents the conditions that lead to high levels of tropospheric ozone during spring. The frequency of occurrence of the high-pressure regime is positively correlated with ozone concentrations measured at Mt. Lulin ($r = +0.50$ and $p < 0.005$), indicating that periods of elevated ozone are associated with
 330 a more frequent occurrence of this circulation pattern. During extreme ozone episodes (>70 ppb), this ozone regime is the most frequent, accounting for approximately 50% of all classified days.

3.3.2 Convection in Southeast Asia (R2)

During R2, negative ozone anomalies dominate the Indochinese Peninsula and the western Pacific Ocean, where they coincide
 335 with reduced CO concentrations (Figure 8a, b), indicating a reduction in precursor emissions and ozone production. Those



anomalies are associated with a large-scale convective circulation pattern, characterized by negative geopotential height anomalies at 850 hPa and reduced outgoing longwave radiation, indicating enhanced cloudiness and enhanced deep convection over Southeast Asia (Figure 8c, d). Therefore, R2 is also referred to as “Convection” regime. Such conditions reduce biomass-burning activity and solar radiation available for photochemical reactions, limiting the production of tropospheric ozone. While
 340 ozone decreases over Indochina and the Pacific Ocean, weak positive anomalies persist east of the Chinese mainland, where transported CO can still support photochemical ozone formation under favourable radiative conditions. Nevertheless, the dominant regional signal is a substantial reduction in ozone concentrations associated with enhanced convection and cloud cover.

The occurrence frequency of this ozone regimes is significantly negatively correlated with O₃ concentrations measured at the
 345 Mt. Lulin laboratory with $r = -0.48$ and $p = 0.006$, indicating this regime is preferentially associated with low-ozone conditions. The spring of 2022 is a representative example, combining the lowest ozone concentrations of the observational record (Figure 5) with a frequent occurrence of the convection regime (59%, as shown in Figure S4 in the Supplementary Material).

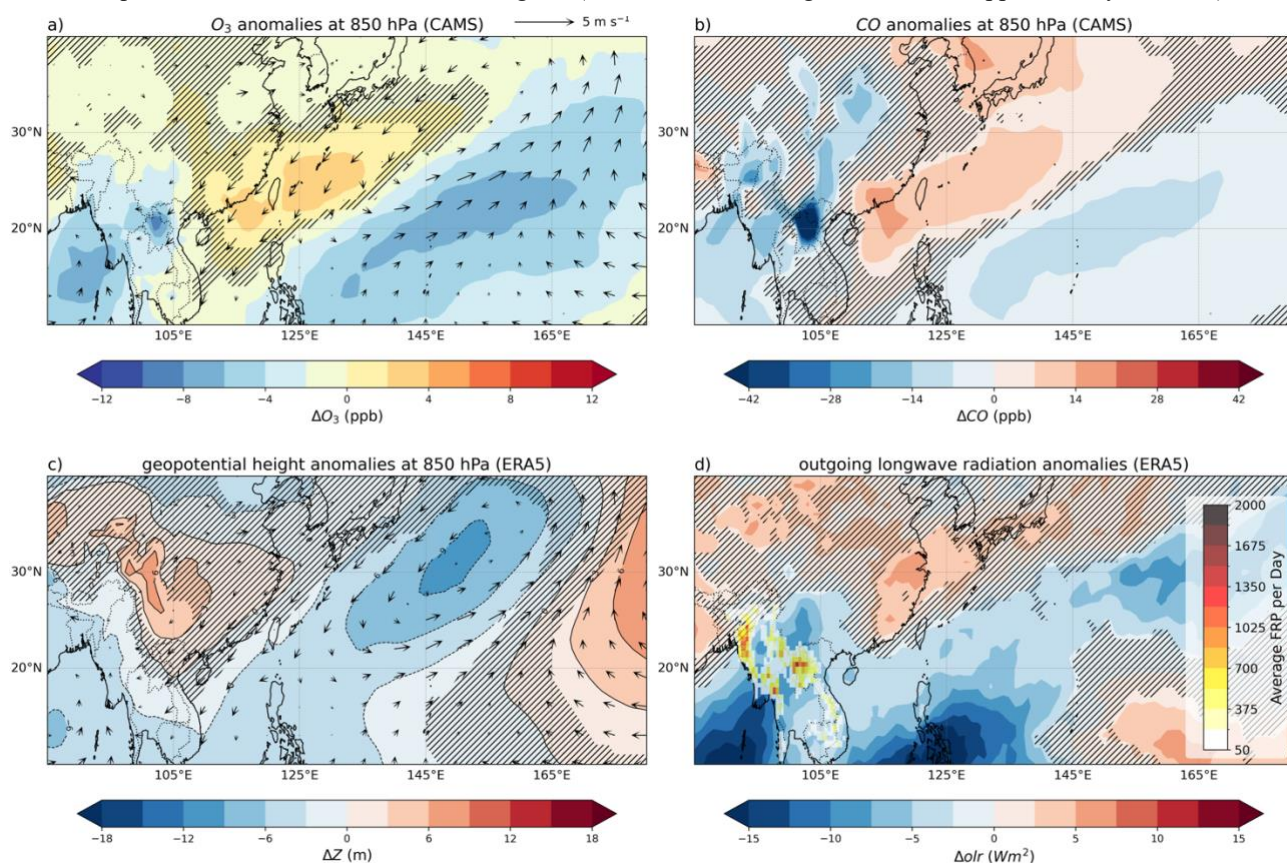


Figure 8: Same as Figure 7 but for Convection ozone regime (R2).



350 3.3.3 Enhancement of the Western Pacific Subtropical High (R3)

The main characteristic of R3 is the ozone hotspot exceeding +10 ppb over northern Laos, while negative anomalies are located over northern and eastern China and the East China Sea (Figure 9a). The spatial correspondence between the fire hotspots and positive O₃ and CO anomalies (Figure 9b and d), suggests that biomass burning is the primary source of ozone precursors. This is also supported by the previous literature (Liao et al., 2026), which shows that polluted air produced in that mountainous region is rapidly uplifted and then transported by the upper layer westerly winds.

The circulation pattern of this regime promotes both pollutant accumulation and its vertical transport. Positive geopotential height anomalies reveal a strengthened and westward-shifted of the Pacific Subtropical High (Figure 9c), known to bring warm, dry and stable conditions over northern Indochina (Wei et al., 2023). These conditions enhance biomass-burning activity and promote photochemical ozone production (Figure 9d), consistent with previous studies describing the influence of the WPSH on regional air quality (Hu et al., 2019; Huang et al., 2018). At the same time, the circulation anomalies generate contrasting conditions farther north. Enhanced cloudiness and lower geopotential heights over eastern China indicate increased precipitation and convective uplift (Figure 9c, d). We suggest that two mechanisms are at work in this situation. First, warm continental air meeting moist Pacific air likely lifts polluted air from Indochina to higher altitudes, lowering ozone near 850 hPa and letting cleaner marine air take its place (Hu et al., 2019; Wei et al., 2023). Second, the stronger westerly and southerly winds along the northern edge of the WPSH (Figure 9c) also bring in clean marine air directly, adding to the ozone decrease over eastern China. Both processes together explain why we see strong ozone production over northern Laos and a drop over eastern China within the same regime. This picture is also supported by the circulation field (Figure S7c), which shows the westward-shifted ridge and the associated flow pattern described above.

In summary, during this regime, the WPSH concentrates biomass-burning emissions and ozone production over northern Indochina while also promoting vertical redistribution and dilution of pollutants farther downstream.

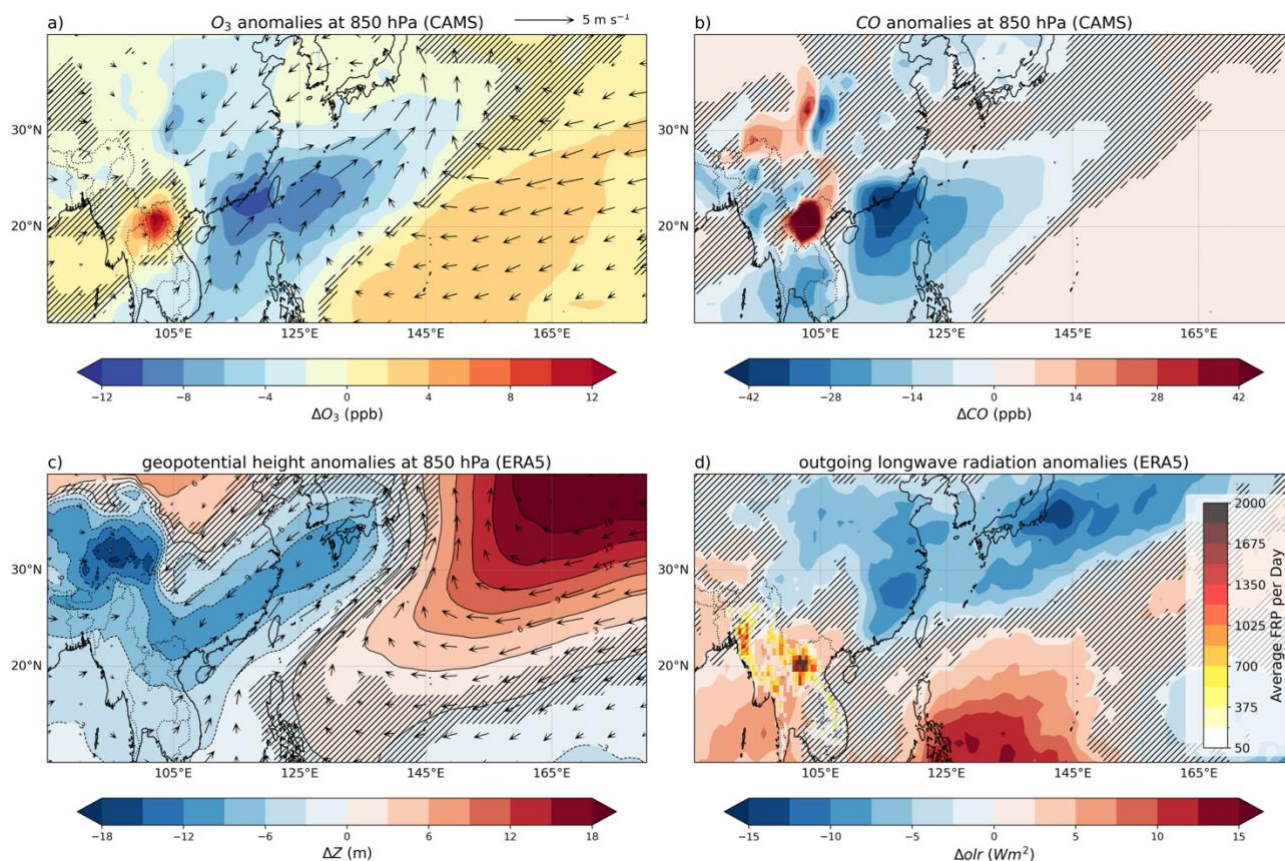


Figure 9: Same as Figure 7 but for Strong WPSH (R3).

3.3.4 Weakening of the Western Pacific Subtropical High (R4)

R4 is characterized by a weakened Western North Pacific Subtropical High, associated with a distinct circulation pattern over the western Pacific (Figure 10). Positive ozone anomalies match higher CO along the same pathway (Figure 10a, b), suggesting the transport and large-scale redistribution of polluted air between 125°–165°E and 10°–30°N. This enhancement reflects the superposition of the anomalous northerly flow (Figure 10c) onto the mid-latitude westerlies, as shown by the mean circulation field in Figure S7d. This distribution results from the interplay between the high pressure over China and the prevailing low-pressure anomaly over the northeastern Pacific Ocean, which promote the transport of polluted air masses through the anomalous northerly and the westerly flow and enhanced convection at the rear of the trough (Figure 10c, d).

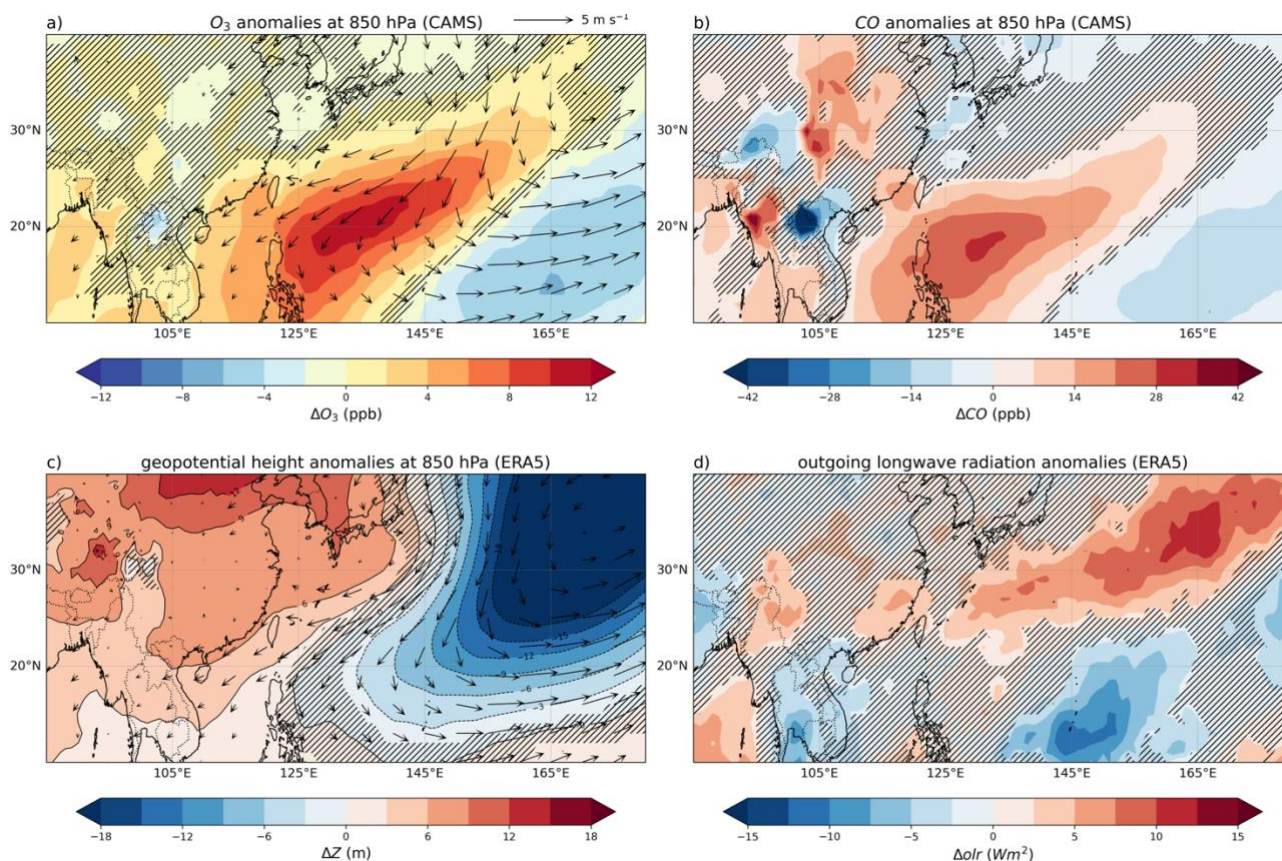


Figure 10: Same as Figure 7 but for Weak WPSH (R4).

These circulation anomalies strengthen meridional transport and modify the prevailing pathways of Asian pollution. Previous studies have linked similar circulation patterns to cold-air intrusions associated with perturbations of the Siberian High and the polar vortex, which favour the export of East Asian pollutants toward higher latitudes (Ikeda et al., 2021). Under these conditions, ozone precursors emitted over China are advected south-eastward and then northward across the Pacific. Part of the pollution plume recirculates within the large-scale circulation, producing ozone accumulation over the northwestern Pacific, while another fraction is transported poleward. The resulting ozone enhancement therefore reflects both regional photochemical production and efficient long-range transport.

3.4 Interannual influence of ENSO

Previous research has shown that ENSO influences tropospheric ozone variability over East Asia (Lin et al., 2014b; Xue et al., 2021). In this paper, we investigate the role of ENSO as source of interannual variability for the two ozone regimes controlling high- and low- ozone conditions over East Asia, namely the high pressure and the convective regimes (R1 and R2). To quantify this influence, we examined the relationship between the monthly occurrence frequency of each regime during spring (March-



April, 2004-2024) and ENSO indices, described in Section 2.4 representing both oceanic and atmospheric components of ENSO variability. It is important to note that SOI, TNI and OLR indices show opposite sign respect with ONI, PMM and the SST indices, meaning that negative values indicate El Niño phase and those positive La Niña phase.

The analysis reveals a robust and consistent relationship between ENSO variability and the occurrence of the high-pressure regime and the convective regime (Figure 11), although the strength of this relationship depends on the ENSO index considered. Most ENSO indices show a significant correlation with the occurrences with the occurrence of the high-pressure regime R1 ($0.3 \leq |r| \leq 0.6$, $p < 0.05$), indicating that high tropospheric ozone conditions occur more frequently during El Niño events. Notably, this relationship is strongest and most persistent for the central-Pacific-flavoured indices EMI, ONI, Niño 4, and Niño 3.4. The strength of the correlation decreases for the more eastern-Pacific-defined Niño 3 index, while Niño 1+2 shows no significant correlation at any lag. In contrast, the occurrence of convective ozone regime R2 increases during La Niña conditions, linking enhanced convection over Southeast Asia to reduced tropospheric ozone concentrations. Niño 4, Niño 3.4, EMI and ONI show the strongest and most consistent correlations, while Niño 3 and Niño 1+2 decrease the correlation. This asymmetry indicates that both ozone regimes respond to the central Pacific flavour of ENSO. The time lags of the correlations reflect the different temporal scales of the ENSO system. Atmospheric and coupled ENSO indices such as SOI, TNI and PMM exhibit maximum correlations at positive lags of +1 to +2 months, consistent with a rapid atmospheric response affecting regional patterns. PMM, however, is only significantly correlated with the high-pressure regime at negative lags (−3 to −1 months). OLR follows a comparable lagged pattern, with significant correlations emerging mainly at positive lags for both regimes. In contrast, Central-Pacific-SST-based indices (ONI, Niño 3.4, Niño 4) show strongest correlations at zero and negative lags, reflecting the slower evolution and persistence of tropical Pacific sea-surface temperature anomalies with respect to the atmospheric response.

The spatial distribution of the regions with significant correlations with respect to the SST anomalies confirms that the tropical Pacific variability is a primary large-scale driver of ozone regime occurrence (Figure 12). The strongest relationships are found over the central and western tropical Pacific Ocean, corresponding to the Niño 4 and Niño 3.4 regions, where significant $|r|$ values are between 0.5 and 0.8 ($p < 0.001$). This spatial pattern is consistent with the lagged correlation analysis above, confirming that ozone regime occurrence is more closely tied to Central Pacific SST variability than to canonical Eastern Pacific ENSO events. Positive SST anomalies favour the occurrence of the high-ozone regime, whereas negative SST anomalies favour the convective low-ozone regime. This pattern identifies ENSO as the dominant climate mode modulating springtime ozone interannual variability of springtime ozone and suggests the use of ENSO indices as potential indicators of seasonal predictability. In contrast, no significant and consistent correlation is found between ENSO indices and the occurrence frequency of the two WPSH regimes (R3 and R4), indicating that their interannual variability is not primarily controlled by tropical Pacific variability (Figures S8 and S9, Supplementary Material).

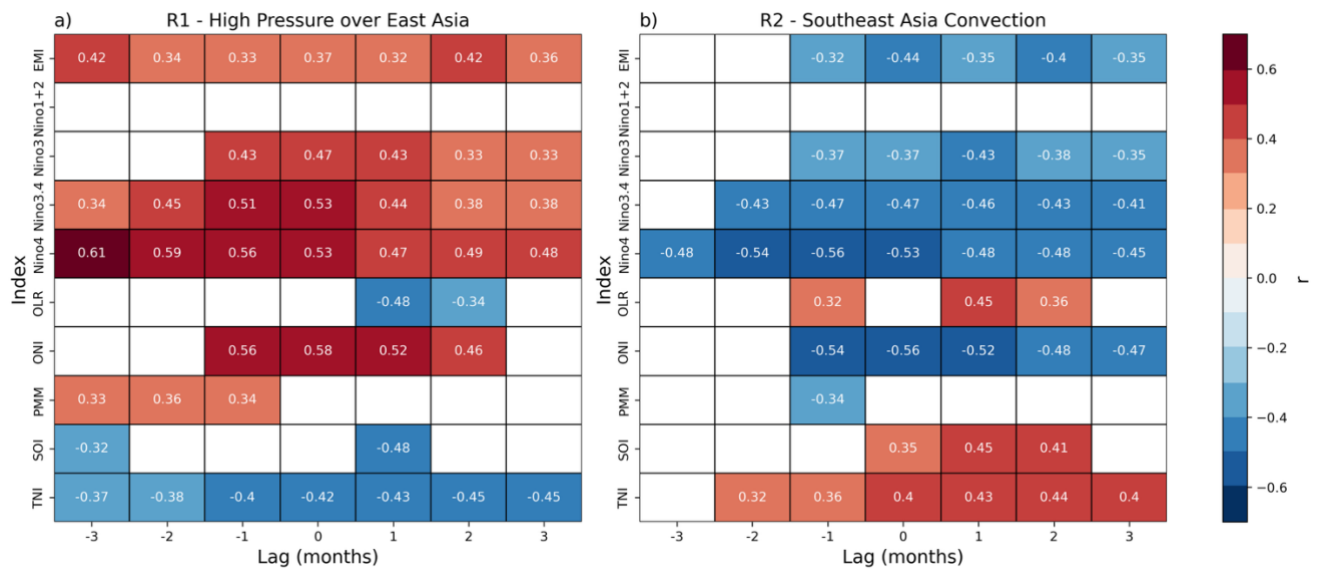


Figure 11: Lagged Pearson correlations between monthly frequencies of ozone regimes over East Asia and selected ENSO indices for (a) High pressure and (b) Convection regimes (R1 and R2). ENSO indices include SST-based indicators (EMI, Niño1+2, Niño3, Niño3.4, Niño4, ONI) and atmospheric/coupled indicators (OLR, PMM, SOI, TNI). Only statistically significant correlations ($p < 0.05$) are shown; non-significant values are masked with white.

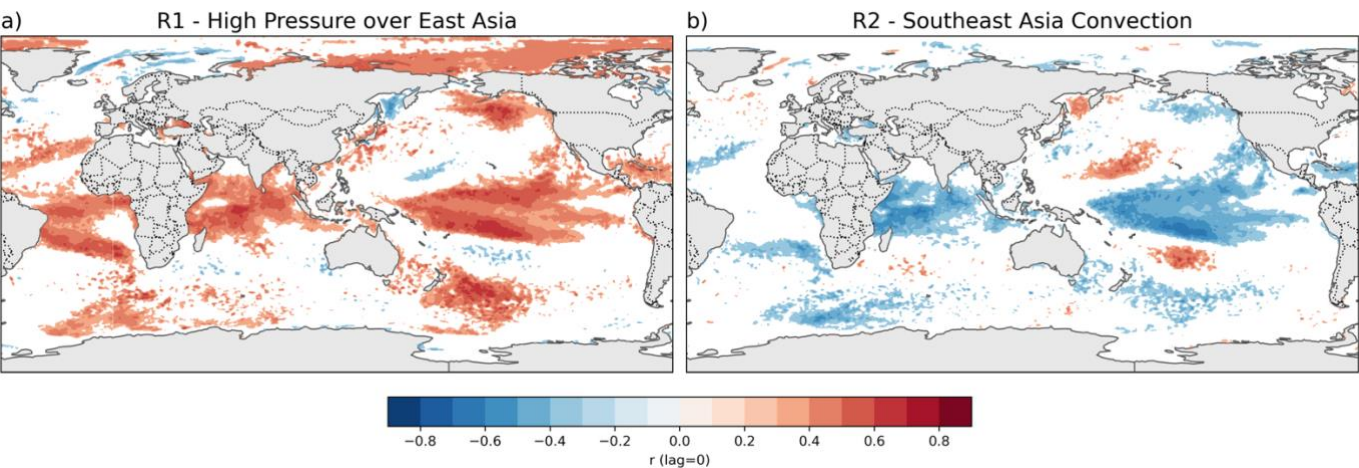
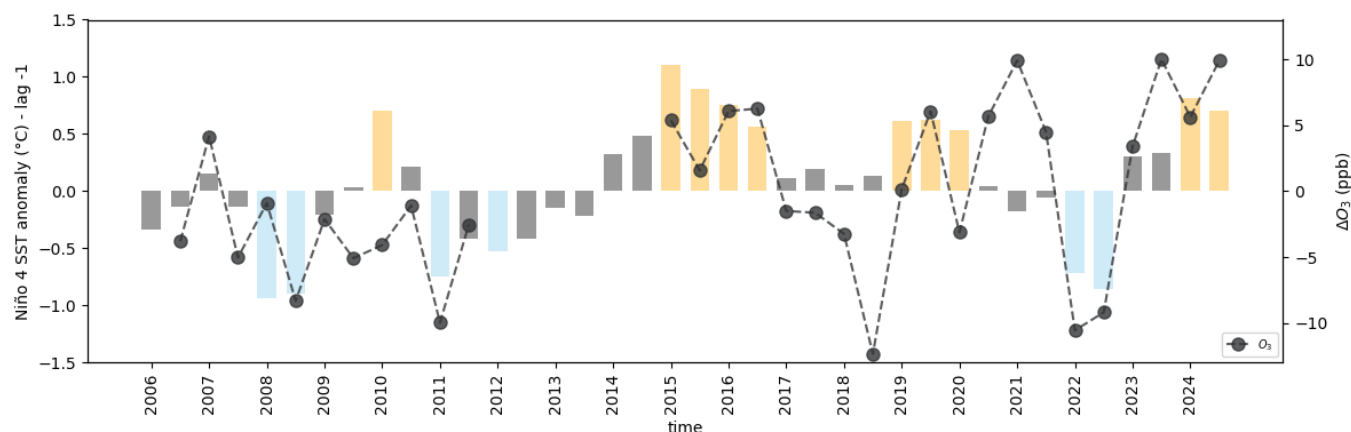


Figure 12: Global maps of the linear correlation between monthly SST anomalies and the monthly averaged occurrence of the (a) high-pressure regime R1 and (b) the convection regime R2. White areas indicate regions where the correlation is not statistically significant ($p < 0.05$).

The strong influence of ENSO on East Asian ozone variability is also detected in the in-situ observations from Mt. Lulin, Taiwan, using the Niño 4 SST index. SST anomalies exceeding $\pm 0.5^\circ\text{C}$ indicate warm and cold SST conditions, which generally correspond to El Niño and La Niña conditions. Springtime ozone anomalies measured at the station are significantly correlated with Niño 4 index ($r = +0.60$, $p = 0.001$), with the strongest relationship occurring when ENSO leads ozone variability by approximately one month (Figure 13). Positive SST anomalies are associated with higher ozone concentrations,



as observed during years characterized by warm anomalies, including 2015, 2016, 2019 and 2024, whereas negative Niño 4 SST anomalies are associated with lower ozone concentrations in 2008, 2011 and 2022.



445 **Figure 13: Springtime monthly averaged O_3 anomalies observed at Mt. Lulin laboratory (black line) and the Niño 4 index with a one-month lag (coloured bars). Bars are coloured with orange for SST anomalies $\geq 0.5^\circ\text{C}$ and with blue for values $\leq -0.5^\circ\text{C}$. For each year, only March and April monthly averages are presented.**

The stronger correlation obtained with the in-situ observations compared with the regime frequencies may suggest that ENSO influences not only the occurrence of the circulation regimes but also the intensity of ozone anomalies associated with them, although this result may be specific to the location of Mt. Lulin. These results provide independent observational evidence that
 450 tropical Pacific variability exerts a measurable control on springtime ozone concentrations over East Asia.

3.5 Long-range transport of tropospheric ozone across the Pacific

The strong influence of ENSO on the occurrence of the High-Pressure and the Convection ozone regimes (R1 and R2) may extend beyond East Asia and affect the large-scale transport of ozone across the Pacific Ocean. To investigate such a possible mechanism, we analyse ozone and circulation anomalies over an extended domain including East Asia, the Pacific Ocean and
 455 western North America (Figure 14 and Figure 15; the same analysis for the two WNPSH regimes is shown in Figures S10 and S11 of the Supplementary Material), testing if ENSO-driven circulation anomalies modulate regional ozone production and the efficiency of trans-Pacific transport.

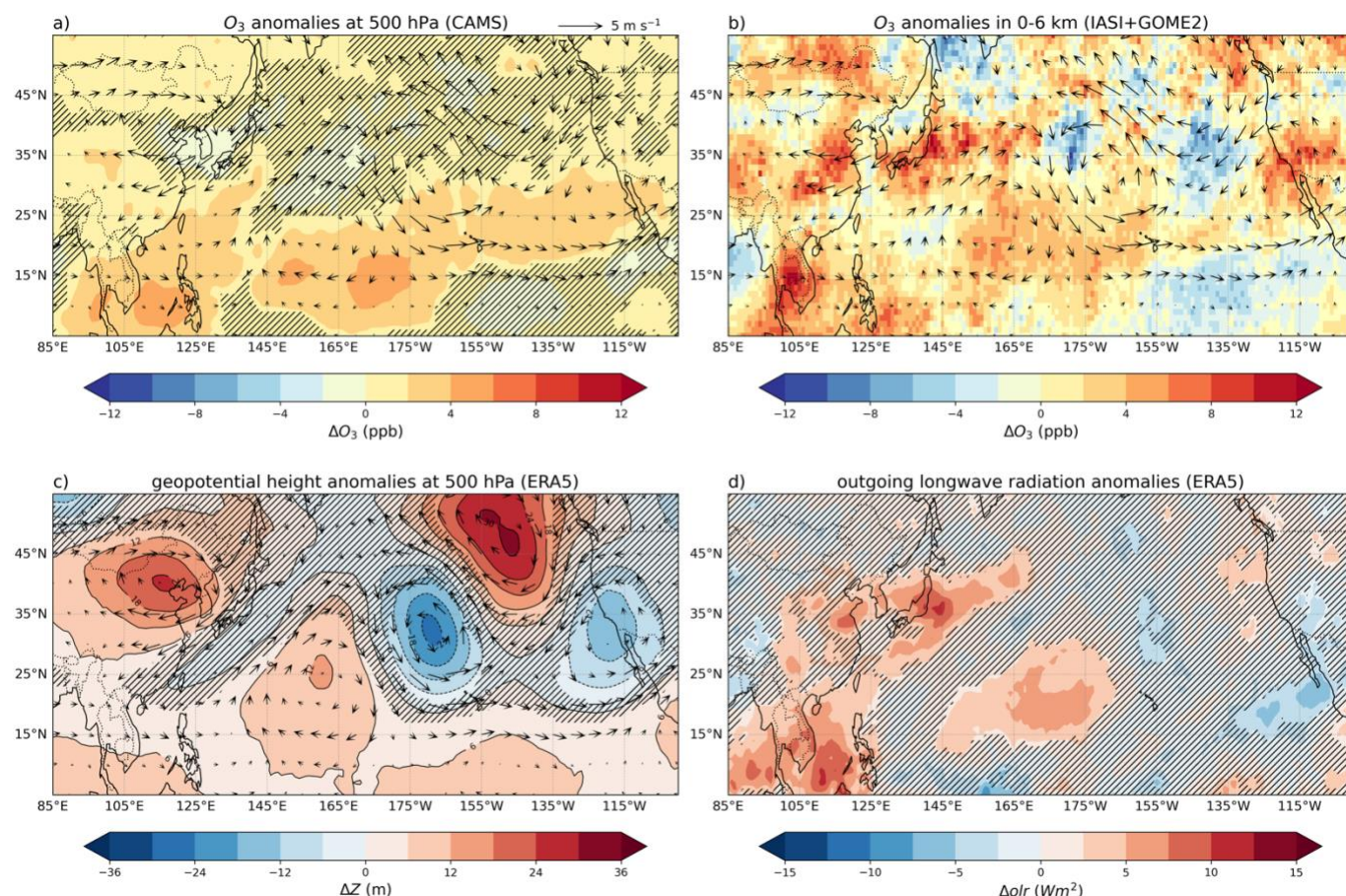


Figure 14: El Niño-induced anomalies in O_3 and atmospheric circulation during High-pressure ozone regime (R1). (a) Ozone anomalies at 500 hPa (ppb) from CAMS, with unshaded areas indicating values significant at the 95% confidence level (T-test). (b) Columnar ozone anomalies in the 0–6 km layer (ppb) from IASI+GOME2 and wind anomalies (arrows) at 500 hPa from ERA5. (c) Geopotential height anomalies (m) and zonal wind anomalies at 500 hPa. (d) Outgoing longwave radiation anomalies (W/m^2) at the top of the atmosphere from ERA5.

During El Niño-like conditions, which are linked to the high-pressure regime R1 according to the results presented in Section 3.4, enhanced ozone production over East Asia is accompanied by a coherent increase in ozone at the middle troposphere (Figure 14a at 500 hPa and b below 6 km of altitude). Positive ozone anomalies extend beyond East Asia are found across the northern part of the Tropical Pacific (10° – 30° N), indicating that the regional ozone enhancement is not confined to the continental source regions over East and Southeast Asia. As discussed in Section 3.3.1, El Niño favours subsidence over Southeast Asia, producing dry and clear skies conditions (Figure 14c, d), that in turn enhance biomass-burning and photochemical ozone production over Indochina and East Asia (Jeong et al., 2023). These regional effects are associated with positive geopotential height anomalies across the subtropical Pacific (Figure 14c and d; 0° – 25° N) and are consistent with the large-scale atmospheric response to El Niño (see Figure S13 in the Supplementary Material). The circulation anomalies also appear consistent with an enhancement of long-range transport at the subtropics (Xue et al., 2021). We observe alternating



positive and negative geopotential height anomalies, together with associated zonal wind anomalies, across the North Pacific
 (Figure 14c), forming a wave-like pattern triggered by the warm anomalies in the Central Pacific. This pattern modulates the
 475 subtropical jet stream, typically located at latitude of 20-30°N during springtime, and the associated wind anomalies may
 contribute to strengthen it (Koumoutsaris et al., 2008). Together, these anomalies are consistent with an enhanced eastward
 transport pathway that could allow ozone-rich air masses to propagate from East Asia toward North America at the subtropics
 (Figure S13a). This interpretation is supported by both CAMS and IASI+GOME2 data, which show a continuous latitudinal
 480 band of positive ozone anomalies extending across the Pacific Ocean at latitude of approximately 25°N (Figure 14a, b), in
 agreement with the enhanced trans-Pacific pollution transport during El Niño events reported by Xue et al., 2021.

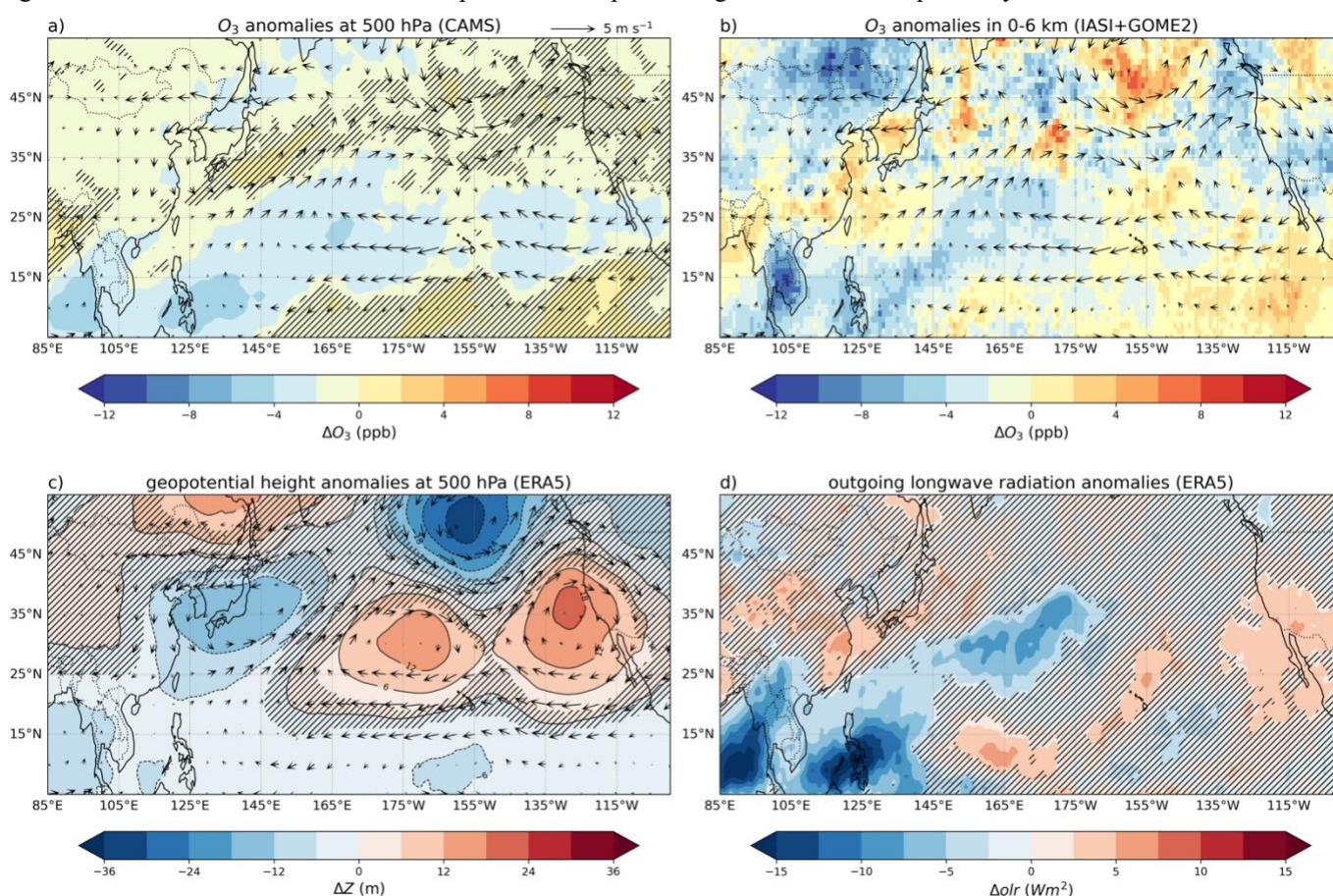


Figure 15: La Niña-induced anomalies in O₃ and atmospheric circulation during Convection regime (R2). a) Ozone anomalies at 500 hPa (ppb) from CAMS, with unshaded areas indicating values significant at the 95% confidence level (T-test). b) Columnar ozone anomalies in the 0-6 km layer (ppb) from IASI+GOME2 and wind anomalies (arrows) at 500 hPa from ERA5. c) Geopotential height anomalies (m) and zonal wind anomalies at 500 hPa. d) Outgoing longwave radiation anomalies (W/m²) at the top of the atmosphere from ERA5.

A behaviour opposite in sign occurs during La Niña-influenced conditions, associated with the convective regime R2 (Figure 15). Enhanced convection over Southeast Asia is associated by increased cloudiness and precipitation and by reduced biomass-



burning emissions and photochemical ozone production (Figure 15c and d) (Zhu et al., 2021). As a result, negative ozone anomalies develop over East Asia and persist throughout the lower and middle troposphere (Figure 15a and b). Over the Pacific, we identify a blocking high-pressure system at latitude 25°-30°N and longitude 165°E-110°W (Figure S13b), together with westward wind anomalies at approximately 25°N, co-located with the climatological position of the subtropical jet. At the same time, wind anomalies at higher latitudes (approximately at 45°N) are consistent with a possible enhancement of transport at mid-latitudes. Taken together, these circulation changes suggest a reduced efficiency of trans-Pacific transport at subtropical latitudes, which may limit the export of ozone from East Asia at subtropical latitudes producing the broad band of negative ozone anomalies observed across the Pacific basin (Figure 15a and b) (Okamoto et al., 2018).

These results indicate that ENSO is associated with both the production and the long-range transport of tropospheric ozone across the Pacific.

Our findings are consistent with El Niño conditions favouring ozone accumulation over East Asia and enhanced trans-Pacific export toward North America, and with La Niña conditions being associated with decreased ozone production and reduced transport efficiency at the sub-tropics. A schematic summary of these contrasting transport pathways changes is presented in Figure 16.

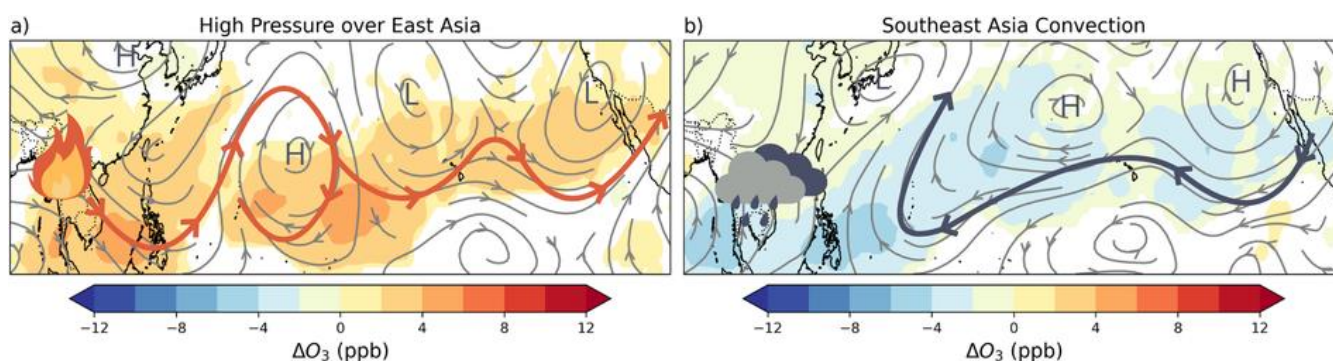


Figure 16: Scheme of the long-range anomalous transport during (a) the high-pressure and (b) the convection ozone regimes (R1 and R2). Colours indicate ozone anomalies at 500 hPa from CAMS; grey lines represent wind anomalies at 500 hPa. The bold red and blue lines represent the possible long-range transport anomalous pathways during El Niño and La Niña, respectively, together with the associated biomass-burning enhancement and precipitation over Southeast Asia.

4 Conclusions

This study presents the first objective classification of springtime lower-tropospheric ozone regimes over East Asia based on a 21-year (2004-2024) k-means clustering of daily ozone fields from the CAMS reanalysis at 850 hPa. The classification identifies four recurrent ozone regimes that capture the dominant modes of regional ozone variability and provide a physical framework for investigating the links between atmospheric circulation, CO emissions from biomass-burning and climate variability.



The identified regimes exhibit synoptic-scale persistence of approximately 4-5-days and are associated with distinct meteorological conditions controlling ozone production, accumulation and transport. High ozone concentrations (R1) occur under persistent anticyclonic conditions, which promote clear skies, enhanced photochemical activity and increased biomass-burning emissions over the Indochinese Peninsula. In contrast, enhanced convection over Southeast Asia (R2) reduces biomass burning and reduces ozone concentrations throughout the region. The other two regimes (R3 and R4) reflect variations in the strength of the Western Pacific Subtropical High and are associated with localized ozone accumulation or negative anomalies. Independent satellite observations from IASI+GOME2 and long-term in-situ measurements from Mt. Lulin confirm the robustness of the identified regimes. The agreement between reanalysis, satellite retrievals and ground-based observations demonstrates that the classification captures physically consistent patterns of ozone variability across a wide range of spatial scales.

A key result of this study is the identification of ENSO as major source of interannual variability for East Asian ozone, according to multiple ENSO indices. El Niño conditions significantly increase the occurrence of the high-ozone regime (R1), whereas La Niña conditions promote the low-ozone convective regime (R2). Beyond their regional influence, ENSO-related circulation anomalies also modify the efficiency of trans-Pacific transport. El Niño enhances the export of ozone-rich air masses from East Asia toward North America, while La Niña reduces both ozone production and long-range transport in the subtropics.

These findings have two important conclusions. First, high-ozone episodes over East Asia are consistently associated with recurrent circulation patterns, providing a basis for improved air quality forecasting and early-warning systems. Second, the sensitivity of ozone variability to ENSO identified in this study highlights the potential importance of future changes in ENSO variability for regional ozone pollution (Li et al., 2025a).

Overall, this work demonstrates that a regime-based approach provides a powerful framework for understanding the coupled influences of meteorology, emissions and climate variability on tropospheric ozone. The methodology developed here could be extended to other region and atmospheric composition variable, offering new opportunities to investigate air-quality variability from synoptic to climatic timescales.

Code and data availability

CAMS O₃ and CO data are freely available from the Copernicus Atmosphere Data Store: <https://ads.atmosphere.copernicus.eu/datasets/cams-global-reanalysis-eac4> (last access: 14/02/2025). ERA5 meteorological fields (geopotential height, zonal wind and top-of-atmosphere net long-wave radiation) can be downloaded from the Copernicus Climate Data Store website: <https://cds.climate.copernicus.eu/datasets> (last access: 21/03/2025). IASI+GOME2 satellite observations are accessible from the AERIS IASI portal: <https://iasi.aeris-data.fr> (last access: 08/01/2024). The MODIS MCD14ML fire product can be freely downloaded through the University of Maryland fuoco SFTP server: fuoco.geog.umd.edu (last access: 22/10/2025). In situ O₃ observations from the Lulin Atmospheric Background Station



(LABS) are not publicly available, but only available upon request according to their data policy by contacting Neng-Huei Lin: nhlin@cc.ncu.edu.tw. NOAA datasets related to ENSO, including the 1/4° Daily Optimum Interpolation Sea Surface Temperature (OISST) and ENSO indices, can be downloaded at: <https://psl.noaa.gov/enso/data.html> (last access: 19/08/2026). The NOAA Pacific Meridional Mode (PPM) index is available from: <https://psl.noaa.gov/data/timeseries/month/PMM/> (last access: 24/09/2025). The ENSO EMI index is available from the JAMSTEC data portal: https://www.jamstec.go.jp/virtualearth/general/en/graph_SINTEX.html#emi (last access: 25/08/2026). Python scripts used for the data analysis are available upon request from Beatrice Biagi: beatrice.biagi@lisa.ipsl.fr. The matlab code implementing the k-mean algorithm is available upon request from Benjamin Pohl: benjamin.pohl@u-bourgogne.fr.

Supplement

The supplement related to this article is available online.

Author contributions

BB: Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. JC: Conceptualization, Methodology, Writing – review & editing. BP and MG: Methodology, Software, Supervision, Investigation, Writing – review & editing. HT and YK: Methodology, Supervision, Investigation, Writing – review & editing. GD and MB: Methodology, Investigation, Writing – review & editing. COY and NHL: Resources.

Competing interests

Marco Gaetani and Yugo Kanaya are members of the editorial board of Atmospheric Chemistry and Physics.

Disclaimer

Copernicus Publications adds a standard disclaimer: “Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors. Views expressed in the text are those of the authors and do not necessarily reflect the views of the publisher.



Acknowledgements

The authors acknowledge the financial support of the Centre National de la Recherche Scientifique (CNRS), through its Mission pour les Initiatives Transverses et Interdisciplinaires (MITI), and of the Centre National d'Études Spatiales (CNES, the French Space Agency), via the TOTICE and SURVEYPOLLUTION research projects funded by the TOSCA (Terre Ocean
575 Surface Continentale Atmosphère) committee. We also acknowledge the support of the Programme National de Télédétection Spatiale (PNTS), and of the Université Paris-Est Créteil (UPEC) and the Laboratoire Interuniversitaire des Systèmes Atmosphériques (LISA), for helping in achieving this research work and its publication.

We acknowledge the Copernicus Atmosphere Monitoring Service (CAMS), implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF), for providing the CAMS global reanalysis (EAC4) ozone and carbon monoxide datasets.
580 We also acknowledge the ECMWF for providing the ERA5 reanalysis dataset, used for geopotential height, zonal wind, and top-of-atmosphere net long-wave radiation fields.

We also acknowledge the AERIS data centre for providing IASI+GOME2 data. IASI is a joint mission of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and the CNES.

Finally, we acknowledge the MODIS Fire and Thermal Anomalies team, and NASA's Terra and Aqua satellite missions, to
585 produce the MCD14ML fire product, made available through the University of Maryland fuoco SFTP data server. We also acknowledge NOAA for providing the Optimum Interpolation Sea Surface Temperature (OISST) dataset and the various ENSO indices (SOI, OLR-based index, Niño 3.4, Niño 4, and ONI) used in this study.

Financial support

Support funds and grant agreement numbers are listed as specified upon manuscript registration and reported to FundRef upon
590 publication.

Marco Gaetani was supported by the project “Dipartimento di Eccellenza 2023–2027”, funded by the Italian Ministry of Education, University and Research at IUSS Pavia.

References

Ashok, K., Behera, S. K., Rao, S. A., Weng, H., and Yamagata, T.: El Niño Modoki and its possible teleconnection, *J. Geophys. Res.-Oceans*, 112, <https://doi.org/10.1029/2006JC003798>, 2007.



- Brassington, G. B.: The Modal Evolution of the Southern Oscillation, *J. Climate*, 10, 1021–1034, [https://doi.org/10.1175/1520-0442\(1997\)010<1021:TMEOTS>2.0.CO;2](https://doi.org/10.1175/1520-0442(1997)010<1021:TMEOTS>2.0.CO;2), 1997.
- Brown-Steiner, B. and Hess, P.: Asian influence on surface ozone in the United States: A comparison of chemistry, seasonality, and transport mechanisms, *J. Geophys. Res.-Atmos.*, 116, 17309, <https://doi.org/10.1029/2011JD015846>, 2011.
- Cao, T., Wang, H., Chen, X., Li, L., Lu, X., Lu, K., and Fan, S.: Rapid increase in spring ozone in the Pearl River Delta, China during 2013–2022, *npj Clim. Atmos. Sci.*, 7, 1–11, <https://doi.org/10.1038/s41612-024-00847-3>, 2024.
- Chiang, J. C. H. and Vimont, D. J.: Analogous Pacific and Atlantic meridional modes of tropical atmosphere-ocean variability, *J. Climate*, 17, 4143–4158, <https://doi.org/10.1175/JCLI4953.1>, 2004.
- Crétat, J., Pohl, B., Chateau Smith, C., Vigaud, N., and Richard, Y.: An original way to evaluate daily rainfall variability simulated by a regional climate model: The case of South African austral summer rainfall, *Int. J. Climatol.*, 35, 2485–2502, <https://doi.org/10.1002/JOC.4155>, 2015.
- Cuesta, J., Eremenko, M., Liu, X., Dufour, G., Cai, Z., Höpfner, M., Von Clarmann, T., Sellitto, P., Foret, G., Gaubert, B., Beekmann, M., Orphal, J., Chance, K., Spurr, R., and Flaud, J. M.: Satellite observation of lowermost tropospheric ozone by multispectral synergism of IASI thermal infrared and GOME-2 ultraviolet measurements over Europe, *Atmos. Chem. Phys.*, 13, 9675–9693, <https://doi.org/10.5194/ACP-13-9675-2013>, 2013.
- Cuesta, J., Kanaya, Y., Takigawa, M., Dufour, G., Eremenko, M., Foret, G., Miyazaki, K., and Beekmann, M.: Transboundary ozone pollution across East Asia: daily evolution and photochemical production analysed by IASI + GOME2 multispectral satellite observations and models, *Atmos. Chem. Phys.*, 18, 9499–9525, <https://doi.org/10.5194/ACP-18-9499-2018>, 2018.
- Dufour, G., Hauglustaine, D., Zhang, Y., Eremenko, M., Cohen, Y., Gaudel, A., Siour, G., Lachatre, M., Bense, A., Bessagnet, B., Cuesta, J., Ziemke, J., Thouret, V., and Zheng, B.: Recent ozone trends in the Chinese free troposphere: Role of the local emission reductions and meteorology, *Atmos. Chem. Phys.*, 21, 16001–16025, <https://doi.org/10.5194/ACP-21-16001-2021>, 2021.
- Gaetani, M., Pohl, B., Alvarez Castro, M. D. C., Flamant, C., and Formenti, P.: A weather regime characterisation of winter biomass aerosol transport from southern Africa, *Atmos. Chem. Phys.*, 21, 16575–16591, <https://doi.org/10.5194/ACP-21-16575-2021>, 2021.
- Gaudel, A., Cooper, O. R., Ancellet, G., Barret, B., Boynard, A., Burrows, J. P., Clerbaux, C., Coheur, P. F., Cuesta, J., Cuevas, E., Doniki, S., Dufour, G., Ebojje, F., Foret, G., Garcia, O., Granados-Muñoz, M. J., Hannigan, J. W., Hase, F., Hassler, B., Huang, G., Hurtmans, D., Jaffe, D., Jones, N., Kalabokas, P., Kerridge, B., Kulawik, S., Latter, B., Leblanc, T., Le Flochmoën, E., Lin, W., Liu, J., Liu, X., Mahieu, E., McClure-Begley, A., Neu, J. L., Osman, M., Palm, M., Petetin, H., Petropavlovskikh, I., Querel, R., Rahpoe, N., Rozanov, A., Schultz, M. G., Schwab, J., Siddans, R., Smale, D., Steinbacher, M., Tanimoto, H., Tarasick, D. W., Thouret, V., Thompson, A. M., Trickl, T., Weatherhead, E., Wespes, C., Worden, H. M., Vigouroux, C., Xu, X., Zeng, G., and Ziemke, J.: Tropospheric Ozone Assessment Report: Present-day distribution and trends of tropospheric



- ozone relevant to climate and global atmospheric chemistry model evaluation, *Elementa*, 6, <https://doi.org/10.1525/ELEMENTA.291>, 2018.
- Giglio, L., Schroeder, W., and Justice, C. O.: The collection 6 MODIS active fire detection algorithm and fire products, *Remote Sens. Environ.*, 178, 31–41, <https://doi.org/10.1016/J.RSE.2016.02.054>, 2016.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J. N.: The ERA5 global reanalysis, *Q. J. Roy. Meteor. Soc.*, 146, 1999–2049, <https://doi.org/10.1002/QJ.3803>, 2020.
- Hu, G., Lu, M. H., Reynolds, D. R., Wang, H. K., Chen, X., Liu, W. C., Zhu, F., Wu, X. W., Xia, F., Xie, M. C., Cheng, X. N., Lim, K. S., Zhai, B. P., and Chapman, J. W.: Long-term seasonal forecasting of a major migrant insect pest: the brown planthopper in the Lower Yangtze River Valley, *J. Pest Sci. (2004)*, 92, 417–428, <https://doi.org/10.1007/S10340-018-1022-9>, 2019.
- Huang, H. Y., Wang, S. H., Lau, W. K. M., Wang, S. Y. S., and da Silva, A. M.: Impact of regional climate patterns on the biomass burning emissions and transport over Peninsular Southeast Asia, 2000-2019, *Atmos. Res.*, 297, 107067, <https://doi.org/10.1016/J.ATMOSRES.2023.107067>, 2024.
- Huang, Y., Wang, B., Li, X., and Wang, H.: Changes in the influence of the western Pacific subtropical high on Asian summer monsoon rainfall in the late 1990s, *Clim. Dynam.*, 51, 443–455, <https://doi.org/10.1007/S00382-017-3933-1>, 2018.
- Ikeda, K., Tanimoto, H., Sugita, T., Akiyoshi, H., Clerbaux, C., and Coheur, P. F.: Model and Satellite Analysis of Transport of Asian Anthropogenic Pollution to the Arctic: Siberian and Pacific Pathways and Their Meteorological Controls, *J. Geophys. Res.-Atmos.*, 126, e2020JD033459, <https://doi.org/10.1029/2020JD033459>, 2021.
- Inness, A., Ades, M., Agustí-Panareda, A., Barr, J., Benedictow, A., Blechschmidt, A. M., Dominguez, J. J., Engelen, R., Eskes, H., Flemming, J., Huijnen, V., Jones, L., Kipling, Z., Massart, S., Parrington, M., Peuch, V. H., Razinger, M., Remy, S., Schulz, M., and Suttie, M.: The CAMS reanalysis of atmospheric composition, *Atmos. Chem. Phys.*, 19, 3515–3556, <https://doi.org/10.5194/ACP-19-3515-2019>, 2019.
- IPCC: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, <https://doi.org/10.59327/IPCC/AR6-9789291691647>, 2023.
- Jacob, D. J., Crawford, J. H., Kleb, M. M., Connors, V. S., Bendura, R. J., Raper, J. L., Sachse, G. W., Gille, J. C., Emmons, L., and Heald, C. L.: Transport and Chemical Evolution over the Pacific (TRACE-P) aircraft mission: Design, execution, and first results, *J. Geophys. Res.-Atmos.*, 108, 9000, <https://doi.org/10.1029/2002JD003276>, 2003.
- Jeong, Y., Kim, S. W., Kim, J., Shin, D., Kim, J., Park, J. H., and An, S.-I.: Influence of ENSO on Tropospheric Ozone Variability in East Asia, *J. Geophys. Res.-Atmos.*, 128, e2023JD038604, <https://doi.org/10.1029/2023JD038604>, 2023.



- Kim, C., Kim, J., Park, J. H., Koo, J. H., Kwak, K. H., Boynard, A., Pan, L. L., Clerbaux, C., Hurtmans, D., Coheur, P. F., and Park, S. S.: Springtime UTLS Ozone Variability in East Asia: Insights From 16 Years of IASI Observations (2008–2023), *J. Geophys. Res.-Atmos.*, 130, e2024JD043183, <https://doi.org/10.1029/2024JD043183>, 2025.
- Koumoutsaris, S., Bey, I., Generoso, S., and Thouret, V.: Influence of El Niño-Southern Oscillation on the interannual variability of tropospheric ozone in the northern midlatitudes, *J. Geophys. Res.-Atmos.*, 113, <https://doi.org/10.1029/2007JD009753>, 2008.
- Li, J., Wang, H., Fan, Q., and Lu, X.: Tropospheric ozone responses to the El Niño-Southern Oscillation (ENSO): quantification of individual processes and future projections from multiple chemical models, *Atmos. Chem. Phys.*, 25, 12983–13006, <https://doi.org/10.5194/ACP-25-12983-2025>, 2025a.
- Li, K., Tan, R., Qiao, W., Lee, T., Wang, Y., Zhang, D., Tang, M., Zhao, W., Gu, Y., Fan, S., Zhang, J., Lyu, X., Xue, L., Xu, J., Ma, Z., Latif, M. T., Amnuaylojaroen, T., Gil, J., Lee, M. H., Bak, J., Kim, J., Liao, H., Kanaya, Y., Lu, X., Nagashima, T., and Koo, J. H.: Surface and tropospheric ozone over East Asia and Southeast Asia from observations: Distributions, trends, and variability, *Atmos. Chem. Phys.*, 25, 11575–11596, <https://doi.org/10.5194/ACP-25-11575-2025>, 2025b.
- Liao, Z., Zhu, J., Li, C., Xie, J., and Ma, Z.: Multi-scale impacts of Indochina biomass burnings on tropospheric ozone in coastal South China: Insights from long-term (2000–2024) observations, *Atmos. Res.*, 329, <https://doi.org/10.1016/J.ATMOSRES.2025.108465>, 2026.
- Liebmann, B. and Smith, C. A.: Description of a Complete (Interpolated) Outgoing Longwave Radiation Dataset, *B. Am. Meteorol. Soc.*, 77, 1275–1277, <https://doi.org/10.1175/1520-0477-77.6.1274>, 1996.
- Lin, C. Y., Zhao, C., Liu, X., Lin, N. H., and Chen, W. N.: Modelling of long-range transport of Southeast Asia biomass-burning aerosols to Taiwan and their radiative forcings over East Asia, *Tellus B*, 66, <https://doi.org/10.3402/TELLUSB.V66.23733>, 2014a.
- Lin, M., Horowitz, L. W., Oltmans, S. J., Fiore, A. M., and Fan, S.: Tropospheric ozone trends at Mauna Loa Observatory tied to decadal climate variability, *Nat. Geosci.*, 7, 136–143, <https://doi.org/10.1038/ngeo2066>, 2014b.
- Liu, H., Jacob, D. J., Bey, I., Yantosca, R. M., Duncan, B. N., and Sachse, G. W.: Transport pathways for Asian pollution outflow over the Pacific: Interannual and seasonal variations, *J. Geophys. Res.-Atmos.*, 108, <https://doi.org/10.1029/2002JD003102>, 2003.
- Lu, X., Zhang, L., and Shen, L.: Meteorology and Climate Influences on Tropospheric Ozone: a Review of Natural Sources, Chemistry, and Transport Patterns, *Curr. Pollut. Rep.*, 5, 238–260, <https://doi.org/10.1007/S40726-019-00118-3>, 2019.
- Lu, X., Liu, Y., Su, J., Weng, X., Ansari, T., Zhang, Y., He, G., Zhu, Y., Wang, H., Zeng, G., Li, J., He, C., Li, S., Amnuaylojaroen, T., Butler, T., Fan, Q., Fan, S., Forster, G. L., Gao, M., Hu, J., Kanaya, Y., Latif, M. T., Lu, K., Nédélec, P., Nowack, P., Sauvage, B., Xu, X., Zhang, L., Li, K., Koo, J. H., and Nagashima, T.: Tropospheric ozone trends and attributions over East and Southeast Asia in 1995–2019: An integrated assessment using statistical methods, machine learning models, and multiple chemical transport models, *Atmos. Chem. Phys.*, 25, 7991–8028, <https://doi.org/10.5194/ACP-25-7991-2025>, 2025.



- Michelangeli, P. A., Vautard, R., and Legras, B.: Weather regimes: recurrence and quasi stationarity, *J. Atmos. Sci.*, 52, 1237–1256, [https://doi.org/10.1175/1520-0469\(1995\)052<1237:WRRAS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1995)052<1237:WRRAS>2.0.CO;2), 1995.
- Monks, P. S., Archibald, A. T., Colette, A., Cooper, O., Coyle, M., Derwent, R., Fowler, D., Granier, C., Law, K. S., Mills, G. E., Stevenson, D. S., Tarasova, O., Thouret, V., Von Schneidmesser, E., Sommariva, R., Wild, O., and Williams, M. L.: Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer, *Atmos. Chem. Phys.*, 15, 8889–8973, <https://doi.org/10.5194/ACP-15-8889-2015>, 2015.
- NOAA: ENSO indices, <https://www.ncei.noaa.gov/access/monitoring/enso/>, last access: 24 September 2025, 2025.
- Ogino, S. Y., Miyazaki, K., Fujiwara, M., Nodzu, M. I., Shiotani, M., Hasebe, F., Matsumoto, J., Witte, J., Thompson, A. M., Nguyen-Thi, H. A., and Nguyen, T. V.: Cause of a Lower-Tropospheric High-Ozone Layer in Spring Over Hanoi, *J. Geophys. Res.-Atmos.*, 127, e2021JD035727, <https://doi.org/10.1029/2021JD035727>, 2022.
- Okamoto, S., Tanimoto, H., Hirota, N., Ikeda, K., and Akimoto, H.: Decadal Shifts in Wind Patterns Reduced Continental Outflow and Suppressed Ozone Trend in the 2010s in the Lower Troposphere Over Japan, *J. Geophys. Res.-Atmos.*, 123, 12980–12993, <https://doi.org/10.1029/2018JD029266>, 2018.
- Okamoto, S., Cuesta, J., Dufour, G., Eremenko, M., Miyazaki, K., Boonne, C., Tanimoto, H., Peischl, J., and Thompson, C.: Natural and anthropogenic influence on tropospheric ozone variability over the Tropical Atlantic unveiled by satellite, reanalyses and in situ observations, *Atmos. Chem. Phys.*, 26, 4685–4709, <https://doi.org/10.5194/ACP-26-4685-2026>, 2026.
- Ou Yang, C. F., Lin, N. H., Sheu, G. R., Lee, C.-T., and Wang, J. L.: Seasonal and diurnal variations of ozone at a high-altitude mountain baseline station in East Asia, *Atmos. Environ.*, 46, 279–288, <https://doi.org/10.1016/J.ATMOSENV.2011.09.060>, 2012.
- Ou-Yang, C. F., Babu, S. R., Lee, J. R., Yen, M. C., Griffith, S. M., Lin, C. C., Chang, S. C., and Lin, N. H.: Detection of stratospheric intrusion events and their role in ozone enhancement at a mountain background site in sub-tropical East Asia, *Atmos. Environ.*, 268, 118779, <https://doi.org/10.1016/J.ATMOSENV.2021.118779>, 2022.
- Pan, S. Y., Hsu, Y. S., Hsu, Y. C., Ngo, T. H., Chou, C. C. K., Lin, N. H., and Chi, K. H.: The Long-Term Monitoring of Atmospheric Polychlorinated Dibenzo-p-Dioxin Dibenzofurans at a Background Station in Taiwan during Biomass Burning Seasons in El Niño and La Niña Events, *Atmosphere*, 15, 1002, <https://doi.org/10.3390/atmos15081002>, 2024.
- Park, S., Son, S. W., Jung, M.-I., Park, J., and Park, S. S.: Evaluation of tropospheric ozone reanalyses with independent ozonesonde observations in East Asia, *Geosci. Lett.*, 7, 12, <https://doi.org/10.1186/S40562-020-00161-9>, 2020.
- Raktham, C., Bruyère, C., Kreasuwun, J., Done, J., Thongbai, C., and Promnopas, W.: Simulation sensitivities of the major weather regimes of the Southeast Asia region, *Clim. Dynam.*, 44, 1403–1417, <https://doi.org/10.1007/S00382-014-2156-Y>, 2014.
- Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., and Schlax, M. G.: Daily High-Resolution-Blended Analyses for Sea Surface Temperature, *J. Climate*, 20, 5473–5496, <https://doi.org/10.1175/2007JCLI1824.1>, 2007.
- Ropelewski, C. F. and Jones, P. D.: An Extension of the Tahiti–Darwin Southern Oscillation Index, *Mon. Weather Rev.*, 115, 2161–2165, [https://doi.org/10.1175/1520-0493\(1987\)115<2161:AEOTTS>2.0.CO;2](https://doi.org/10.1175/1520-0493(1987)115<2161:AEOTTS>2.0.CO;2), 1987.



- Sillman, S.: The relation between ozone, NO_x and hydrocarbons in urban and polluted rural environments, *Atmos. Environ.*, 33, 1821–1845, [https://doi.org/10.1016/S1352-2310\(98\)00345-8](https://doi.org/10.1016/S1352-2310(98)00345-8), 1999.
- 735 Sun, H. Z., van Daalen, K. R., Morawska, L., Guillas, S., Giorio, C., Di, Q., Kan, H., Loo, E. X.-L., Shek, L. P., Watts, N., Guo, Y., and Archibald, A. T.: An estimate of global cardiovascular mortality burden attributable to ambient ozone exposure reveals urban-rural environmental injustice, *One Earth*, 7, 1803–1819, <https://doi.org/10.1016/J.ONEEAR.2024.08.018>, 2024.
- Trenberth, K. E.: The Definition of El Niño, *B. Am. Meteorol. Soc.*, 78, 2771–2778, [https://doi.org/10.1175/1520-0477\(1997\)078<2771:TDOENO>2.0.CO;2](https://doi.org/10.1175/1520-0477(1997)078<2771:TDOENO>2.0.CO;2), 1997.
- 740 Trenberth, K. E., Caron, J. M., Stepaniak, D. P., and Worley, S.: Evolution of El Niño-Southern Oscillation and global atmospheric surface temperatures, *J. Geophys. Res.-Atmos.*, 107, AAC 5-1–AAC 5-17, <https://doi.org/10.1029/2000JD000298>, 2002.
- Wang, W., Van Der A, R., Ding, J., Van Weele, M., and Cheng, T.: Spatial and temporal changes of the ozone sensitivity in China based on satellite and ground-based observations, *Atmos. Chem. Phys.*, 21, 7253–7269, [https://doi.org/10.5194/ACP-](https://doi.org/10.5194/ACP-21-7253-2021)
- 745 21-7253-2021, 2021.
- Wei, J., Mao, Q., Shan, Y., Jin, Q., Yang, Y., and Chen, H.: Spring biomass burning in Indochina enhances summer Yangtze River Valley rainfall through land–atmosphere interactions, *npj Clim. Atmos. Sci.*, 6, 183, <https://doi.org/10.1038/s41612-023-00514-z>, 2023.
- World Health Organization: WHO global air quality guidelines: particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide, World Health Organization, Geneva, Switzerland, ISBN 978-92-4-003422-8, 2021.
- 750 Xue, L., Ding, A., Cooper, O., Huang, X., Wang, W., Zhou, D., Wu, Z., McClure-Begley, A., Petropavlovskikh, I., Andreae, M. O., and Fu, C.: ENSO and Southeast Asian biomass burning modulate subtropical trans-Pacific ozone transport, *Natl. Sci. Rev.*, 8, nwaal32, <https://doi.org/10.1093/NSR/NWAA132>, 2021.
- Yen, M. C., Peng, C. M., Chen, T. C., Chen, C.-S., Lin, N. H., Tzeng, R. Y., Lee, Y. A., and Lin, C. C.: Climate and weather characteristics in association with the active fires in northern Southeast Asia and spring air pollution in Taiwan during 2010
- 755 7-SEAS/Dongsha Experiment, *Atmos. Environ.*, 78, 35–50, <https://doi.org/10.1016/J.ATMOSENV.2012.11.015>, 2013.
- Zhu, A., Xu, H., Deng, J., Ma, J., and Li, S.: El Niño-Southern Oscillation (ENSO) effect on interannual variability in spring aerosols over East Asia, *Atmos. Chem. Phys.*, 21, 5919–5933, <https://doi.org/10.5194/ACP-21-5919-2021>, 2021.