



Continental precursor transport enhances ozone formation over the atmosphere of tropical coastal waters

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Abstract. Ozone (O₃) formation can regulate the atmospheric chemistry and climate, but O₃ formation over the coastal marine atmosphere remains poorly understood, particularly in the tropical regions. To address this gap, our study combines shipborne measurements, coastal observations, and WRF-Chem simulations along the East Coast of Peninsular Malaysia (ECPM) to examine the spatial distribution and controlling processes of tropospheric O₃. Shipborne observations showed a clear north-to-south offshore ozone gradient, with a maximum hourly concentration of 97.7 ppbv in the northern sector. Offshore O₃ was generally higher than at nearby coastal land stations, indicating active ozone production and/or accumulation over the coastal marine atmosphere. Model results suggest that this enhancement was mainly driven by eastward transport of anthropogenic and biogenic precursors under the south-westerly monsoon. During transport, photochemical ageing promoted O₃ formation, while lower nitrogen oxides over the marine boundary layer reduced O₃ loss through nitric oxide titration. Strong solar radiation, warm temperatures, shallow boundary layers, and weak winds further favoured ozone production and accumulation. Sensitivity simulations showed that removing biogenic volatile organic compound emissions reduced surface ozone by 6-15 ppbv over the ECPM and adjacent South China Sea, highlighting the important role of tropical vegetation emissions in O₃ formation. Our study shows that under the influence of continental precursors outflow, the atmosphere above tropical coastal waters can act as active ozone accumulation zones, with important implications for future coastal air quality management and regional ozone chemistry studies in Southeast Asia.

1 Introduction

30 Tropospheric ozone (O₃) is a key pollutant that plays important roles in atmospheric oxidation chemistry and affects the Earth's radiative balance leading to surface warming (IPCC, 2021). High tropospheric O₃ concentrations also pose substantial risks to human health, reduce agricultural productivity, and damage natural ecosystems (Fuhrer, 2009; Vongelis et al., 2025; Yin et



al., 2025). O_3 is primarily produced through photochemical reactions involving nitrogen oxides (NO_x) and volatile organic compounds (VOCs) (Gao et al., 2025; Hui et al., 2023; Kumar et al., 2008; Li et al., 2025), exhibiting significant regional variability, driven by differences in emission of precursors (i.e., NO_x , VOCs), meteorological conditions, and long-range transportations (Chen et al., 2019; Chen et al., 2025; Liu et al., 2020).

It is well-known that the net O_3 production mainly occurs over high NO_x regions and depends on the abundance of VOCs, while for the net O_3 loss, that are typically regulated by the radical chemistry (i.e., OH/HO_2 , halogens) in a low- NO_x environment, mostly occur over the remote regions, including over the open-oceans (Ayers et al., 1992; Monks et al., 1998; Conley et al., 2011; Wang et al., 2026). However, for coastal marine environments, strong thermal contrasts between land and sea drive sea- and land-breeze circulations which can modulate vertical mixing, pollutants recirculation, and precursors transport, creating chemical regimes governing O_3 production and loss that differ substantially from those occur over continental regions (Barret et al., 2011; Jonson et al., 2020; Shan et al., 2017; Zeren et al., 2019; Mathur et al., 2022).

The coastal O_3 variability can be affected by the regional background transport, synoptic and mesoscale circulation, and local precursor emissions. Recent study over North America found that regional background O_3 transport to coastal regions had increased at a rate of $0.06\text{--}0.2\text{ ppbv yr}^{-1}$ from 1990 - 2010 (Mathur et al., 2022). Over the coastal regions of eastern China, synoptic weather patterns govern surface O_3 daily variability through circulation driven regional transport, with positive O_3 anomalies reaching up to $\pm 16\%$ of the daily mean in coastal areas, particularly under typhoon systems that exert pronounced influence on the south-eastern coast (Han et al., 2020). While in the coastal of southern China, cold front passages strongly modulate O_3 through coupled physical and chemical processes, with inland Pearl River Delta precursor emissions accounting for 50-76% of O_3 at coastal receptors and driving peak mixing ratios of 120 ppbv (Wu et al., 2024). Nevertheless, these existing studies have been confined to middle latitude coastal environments. Whether the same mechanisms operate in tropical coastal regions remains unclear, owing to a lack of observations. Shipborne measurements over the Bay of Bengal during the summer monsoon documented large spatial and temporal variability in surface O_3 (in the range of 4-8 ppbv), with continental outflow from the Indian subcontinent identified as the primary driver, and the photochemical O_3 production along transport trajectories was estimated at $\sim 4.6\text{ ppb day}^{-1}$ (Girach et al., 2017). Observations over the northern South China Sea similarly revealed elevated coastal O_3 , typically associated with terrestrial precursor export (Li et al., 2026). These observations, however, were insufficient to quantitatively partition the contributions of terrestrial precursor export, photochemical ageing, and biogenic emissions at a regional scale. A recent observation in Hainan Island reported that biogenic VOC emissions were the primary driver of local photochemistry in the tropical coastal area, and the sea breeze circulation limited the boundary layer growth and regulated O_3 precursor transport within the lowest 300 m (Li et al., 2025). It shows that biogenic emissions and land-sea breeze circulation can play significant roles in the O_3 levels at the tropical coastal area. Nevertheless, the vertical distribution of O_3 and its precursors under monsoonal circulation, intense solar radiation, and abundant biogenic emissions from tropical vegetation remains insufficiently characterized at a regional scale, particularly, the relative importance of terrestrial precursor export, photochemical ageing, and biogenic emissions in controlling the coastal O_3 variability.



65 In the East Coast of Peninsular Malaysia (ECPM), prevailing south-westerly flow during the southwest monsoon promotes systematic offshore export of inland air masses toward the adjacent South China Sea (SCS), providing a particularly relevant environment for investigating influence of land-sea processes on O₃ concentrations. At the same time, the region hosts a unique juxtaposition of coastal urban corridors and extensive oil palm plantations over the peninsula Malaysia (Li et al., 2020). In this complex environment, anthropogenic VOCs from traffic and industry interact with abundant biogenic isoprene and terpene
70 emissions from tropical vegetation, and elevated temperatures combined with intense solar radiation further accelerate photochemical processing (Hamid et al., 2019; Langford et al., 2010; Stavrou et al., 2014; Uning et al., 2021). Thus, it is of interest to assess the key regulating factors for O₃ level in this tropical coastal marine region. The marine boundary layer has traditionally been treated as a net photochemical sink for ozone under low-NO_x conditions, a view grounded in classical radical chemistry (Ayers et al., 1992; Monks et al., 1998). Coastal observations near strong continental sources tell a rather different
75 story. Elevated ozone concentrations have been reported over the Bay of Bengal (Girach et al., 2017), the northern South China Sea (Lan et al., 2015; Li et al., 2026), and the Pearl River Estuary (Wu et al., 2024a), with continental outflow identified in each case as the principal driver. It remains unclear whether these coastal waters mainly receive O₃ already formed over land, or whether photochemical production continues once the air mass moves offshore. This question matters most in tropical monsoon regions, where biogenic emissions are large and persist through the season. The eastern coast of Peninsular Malaysia
80 offers a good test case for this problem, since a coastal urban corridor and extensive oil palm plantations sit close together and the monsoon carries emissions from both sources offshore along the same path, in the same season, year after year. In this study, shipborne O₃ measurements from the National Expedition Scientific Cruise (NESC'16) were integrated with ground-based observations at three representative coastal stations from 2012-2016 and WRF-Chem model simulations to characterize the spatial heterogeneity of offshore O₃, and the contrast between coastal and nearshore marine O₃ levels over the
85 ECPM. The role of south-westerly monsoonal transport in exporting anthropogenic and biogenic precursors from inland and coastal source regions toward the adjacent sea were also identified. Furthermore, the meteorological and boundary layer processes favouring O₃ retention over the nearshore marine atmosphere were elucidated. Finally, the contribution of biogenic VOC emissions to regional O₃ formation was quantified. The findings of this study are expected to provide mechanistic insights into the O₃ formation at the tropical coastal and marine environment of Southeast Asia.

90 **2 Methodology**

2.1 The cruise measurements

Shipborne measurements were conducted during the National Expedition Scientific Cruise (NESC'16) on board RV Discovery of Universiti Malaysia Terengganu (UMT) over the South China Sea (SCS) adjacent to the ECPM, between approximately 4-10° N and 105° E, from 19 to 30 August 2016. The cruise route extended from Duyung Island, Terengganu, to Mersing Island,
95 Johor, and return to Kuala Terengganu (Fig. 1).

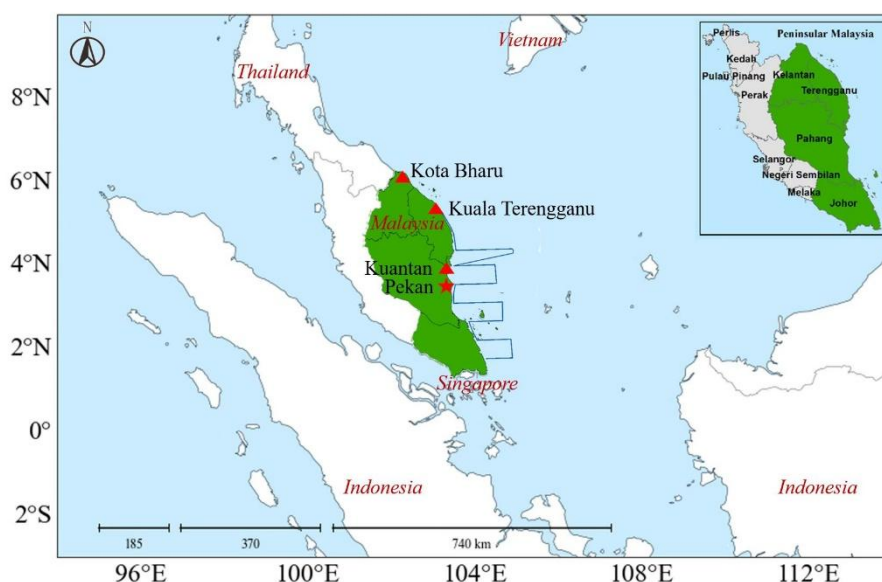


Figure 1 Overview of the study area and sampling locations. The regional map indicates the study domain on the eastern coast of Peninsular Malaysia in Southeast Asia, with red triangles marking the key cities of Kota Bharu, Kuala Terengganu, Kuantan, and Pekan. The blue lines indicate the cruise track conducted along the eastern coastal waters of Peninsular Malaysia, where monitoring stations of the Malaysian Department of Environment (DOE) were established. The inset map (upper right) shows the state-level administrative divisions of Peninsular Malaysia, with the study region highlighted in green.

2.2 Shipborne O₃ measurements

For cruise measurements, Serinus 10 ozone analyzer (Ecotech Pty Ltd., Knoxfield, Victoria, Australia), which operates based on the ultraviolet (UV) absorption principle at 254 nm. was installed on the aft deck of RV Discovery. Ambient air was drawn through a 10 m long (1/4-inch internal diameter) Teflon sampling line from an inlet mounted at the bow at the top of the forward mast, approximately 7 m above sea level as shown in Figure S1 in the supplementary information (SI). The inlet was oriented toward the prevailing apparent wind during sampling to maximize collection of undisturbed marine boundary layer air. A controlled flow rate of 5 L min⁻¹ was maintained throughout the cruise. Based on the tubing dimensions and length, the inlet line volume was approximately 0.317 L, corresponding to a residence time of about 3.8 s. This short residence time minimizes potential O₃ loss within the sampling line and preserves short term variability in ambient concentrations.

The ship exhaust outlet was in the aft section of the vessel, providing substantial horizontal and vertical separation from the sampling inlet. Although forward vessel motion generally advects exhaust emissions downstream of the bow inlet, potential contamination from the vessel was evaluated objectively. O₃ concentrations were examined as a function of relative wind direction, with particular attention to periods when relative wind originated from aft sectors. In addition, the time series was



115 screened for rapid short term O₃ depletion events characteristic of nitric oxide titration. Periods exhibiting anomalous behavior were excluded from the analysis. No systematic exhaust related O₃ depletion was observed in the retained dataset.

The O₃ analyser was calibrated using a seven-point calibration curve spanning concentrations from 0.1 to 200 ppbv, covering the full range of ambient values encountered during the cruise. Calibration gases were generated using a traceable O₃ source, and linear regression analysis demonstrated excellent linearity with a coefficient of determination ($R^2 = 0.998$). The instrument

120 limit of detection was 0.1 ppbv, consistent with high sensitivity UV photometric performance. The analyser exhibited an accuracy of ± 0.5 ppbv and a precision of 0.2 percent, meeting regulatory grade measurement standards. Daily zero checks were performed using O₃ scrubbed air to verify baseline stability and detect potential instrumental drift. Multi point calibration was conducted before and after the cruise period to confirm measurement stability. No statistically significant drift was observed over the measurement campaign.

125 **2.3 Data integration and meteorological parameters**

To complement our in-situ measurements, long term data (from 2012 to 2016) of the levels of O₃ as well as precursors were collected from three air quality monitoring stations in the cities of Kota Bharu (06° 08.44' N, 102° 14.96' E) (Kelantan state), Kuala Terengganu (05° 18.455' N, 103° 07.213' E) (Terengganu state), and Kuantan (03° 49.138' N, 103° 17.817' E) (Pahang state). The collected data included hourly average concentrations of O₃, NO_x, and CO. These data were used to determine the

130 consistency of the readings of the in-situ measurements described above.

The O₃ mixing ratios at the Alam Sekitar Malaysia Sdn Bhd (ASMA) air monitoring stations were measured with Teledyne Model 400A UV Absorption O₃ analysers (Thousand Oaks, CA, USA) which use a system based on the Beer Lambert law for measuring low ranges of O₃ in ambient air. The concentrations of NO_x were determined through chemiluminescence using Teledyne Model 200A NO_x analysers, while CO mixing ratios were determined using Teledyne Model 4020 hydrocarbon

135 analysers.

Surface air temperature at 2 m (T2m) and relative humidity (RH) were obtained directly from the ASMA monitoring stations. Planetary boundary layer height (PBLH) was derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis. The ERA5 data had a spatial resolution of $0.25^\circ \times 0.25^\circ$ and an hourly temporal resolution. These data were sampled at the locations of the monitoring stations and along the cruise track to examine the effects of vertical

140 mixing and atmospheric stability on O₃ variability.

2.4 Description and Configuration of the Chemical Transport Model

The Weather Research and Forecasting model coupled with Chemistry (WRF-Chem, version 3.9.1) was used to simulate the atmospheric dynamics and chemical processes associated with the spatial distribution of O₃. The model was configured with a horizontal resolution of 9 km (see Figure S2 in SI). A total of 40 sigma levels were used in the vertical, with the model top

145 fixed at 50 hPa. Chemical simulations were conducted online within the WRF-Chem framework using the same domain configuration as that used for the meteorological simulations. Gas-phase chemistry was represented by the SAPRC99



mechanism, which had been applied successfully in previous studies of coastal O₃ pollution (Wu et al., 2025; Wu et al., 2024b). Initial and boundary meteorological conditions were obtained from the National Center for Environmental Prediction/National Center for Atmos. Res. (NCEP/NCAR) Final (FNL) reanalysis dataset at 0.25°×0.25° resolution. Chemical boundary conditions were derived from Community Atmosphere Model with Chemistry (CAM-Chem) output for global tropospheric and stratospheric composition.

Anthropogenic emissions were taken from the 2012-2016 MIX Asian emission inventory (MIX v2.0), while biogenic emissions were calculated online using the Model of Emissions of Gases and Aerosols from Nature (MEGAN v2.04). Two model experiments were performed: a base simulation and a sensitivity simulation. In the base simulation, all VOC emissions within the model domain were included. In the sensitivity simulation, biogenic emissions were excluded across the entire domain.

Model performance was evaluated against hourly observations of O₃, NO₂, 2 m temperature, and 2 m relative humidity at Kota Bharu, Kuala Terengganu, and Kuantan for August 2012-2016. Statistical metrics, including the index of agreement (IOA), correlation coefficient (R), and root mean square error (RMSE), were used to assess model performance. Their definitions are provided in Text S1. Overall, the model reproduced the temporal variability of O₃ and the meteorological fields reasonably well, whereas NO₂ showed weaker agreement at some sites and in some years. Detailed statistics and time series comparisons are presented in Fig. S3-S4 and Table S1-S3 of the Supplement Information.

3 Results and Discussion

3.1 Surface O₃ levels over the coastal waters of ECPM

Figure 2a presents the time series of hourly average O₃ concentrations observed during the NESC'16 cruise from 19 to 30 August 2016. During the cruise, hourly O₃ concentrations ranged from 2 to 97.7 ppbv, with an overall average of 31.4 ppbv. Notably, approximately 14% of the hourly observations surpassed the 50 ppbv threshold, a concentration level equivalent to the 8-hour O₃ standard of 100 µg m⁻³ (~ 50 ppbv) stipulated under the fully implemented Malaysian Ambient Air Quality Standards (MAAQS), suggesting that O₃ pollution during certain periods had reached or approached the regulatory threshold (Ashfold et al., 2024). Meanwhile, a clear from north to south gradient was evident throughout the cruise period, with the highest O₃ mixing ratios occurring over the northern offshore sector and progressively lower values toward the central and southern regions of the study domain. The average concentrations were 33.5±16.4 ppbv and 29.2±14.7 ppbv in the northern and southern sectors, respectively, with maximum O₃ concentration reached 97.7 ppbv over the northern marine area on 20 August (Table 1). These levels were substantially higher than those reported over other subtropical marine environments, such as the Indian Ocean (17±1.8 ppbv) (Rhoads et al., 1997), the Bay of Bengal (~ 27 ppbv) (Nair et al., 2013), and the northern SCS (25±9.9 ppbv) (Lan et al., 2015). However, they remained broadly consistent with values documented at tropical and subtropical coastal sites influenced by episodic continental outflow and large-scale meteorological forcing, including the long-



term daily maximum O_3 of 29-43 ppbv at Sydney, Australia (Jiang et al., 2017), and near coast concentrations of 53.8 ± 17.2 ppbv over the tropical Indian Ocean, substantially higher than those over the remote ocean (17.7 ± 4.8 ppbv; (Lal et al., 1998).
 180 A similarly pronounced spatial gradient was observed in the present study. The magnitude of this contrast is informative. O_3 over the northern SCS averaged 25 ± 9.9 ppbv (Lan et al., 2015), a region further from the coastline and reached only after longer transport times, allowing more precursor loss enroute. O_3 over the Bay of Bengal during the summer monsoon averaged around 27 ppbv, with continental outflow from the Indian subcontinent as the main source (Girach et al., 2017). Offshore O_3 in the present study, measured within tens of kilometres of the coast, exceeded both. The northern SCS and Bay of Bengal
 185 values represent air masses that have already aged and diluted over open water. The ECPM values represent air masses still close to their source, still gaining O_3 through active photochemistry. This places the ECPM waters closer to a production zone than a receptor zone for aged continental O_3 . These regional contrasts and large spatiotemporal variability indicate that O_3 chemistry in the tropical coastal marine boundary layer is considerably more complex than can be accounted for by in-situ photochemistry alone.

Table 1 Comparison of O_3 concentrations in this study with those observed in previous marine studies.

Location	Minimum O_3 (ppbv)	Maximum O_3 (ppbv)	Average O_3 (ppbv)	References
Northern ECPM	6.6	97.7	33.5 ± 16.4	This study
Southern ECPM	5.6	70.8	29.2 ± 14.7	This study
North BOB	n.a.	~30	27.3	Nair et al., 2013
Mid BOB	n.a.	~15	11.8	Nair et al., 2013
South BOB	n.a.	~20	15	Nair et al., 2013
Pacific Ocean	5	30	n.a.	Johnson et al., 1990
Indian Ocean	10	30	17 ± 1.8	Rhoads et al., 1997
Northern South China Sea	~5	~40	25 ± 9.9	Lan et al., 2015

Note: n.a. = not available, ECPM (east coast of Peninsular Malaysia), BOB (Bay of Bengal).

To further indicate the different level of offshore O_3 , we also analyzed the O_3 levels observed in three land-based coastal sites along the ECPM. Figure 2b presents the hourly O_3 concentrations at Kota Bharu, Kuala Terengganu, and Kuantan from 19 to 30 August 2016. The average O_3 concentrations at Kota Bharu, Kuala Terengganu, and Kuantan were 23.17 ± 11.08 ppbv, 26.79 $\pm$ 15.36 ppbv and 24.92 ± 16.25 ppbv, respectively. The highest hourly O_3 mixing ratios of 69.46 ppbv, 58.56 ppbv, and 59.67 ppbv were recorded at Kota Bharu, Kuala Terengganu, and Kuantan, respectively. At all three stations, O_3 exhibited a typical unimodal diurnal cycle, with daytime maximum occurring between 12:00 and 14:00 LT and nocturnal minima frequently falling below 10 ppbv. The daytime peaks are attributable to photochemical production driven by intense solar
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radiation, while the low nighttime O_3 concentrations are primarily governed by NO titration, which rapidly consumes O_3 in the absence of photolysis (Zeren et al., 2019). The average O_3 concentrations at these coastal sites were generally lower than those observed over the offshore waters during the cruise. This contrast indicates that the offshore marine atmosphere along the ECPM functions as a receptor region, shaped by the export of precursors from inland and coastal sources. The mechanisms underlying this offshore O_3 enhancement are further explored through meteorological analysis and WRF-Chem simulations in the following sections.

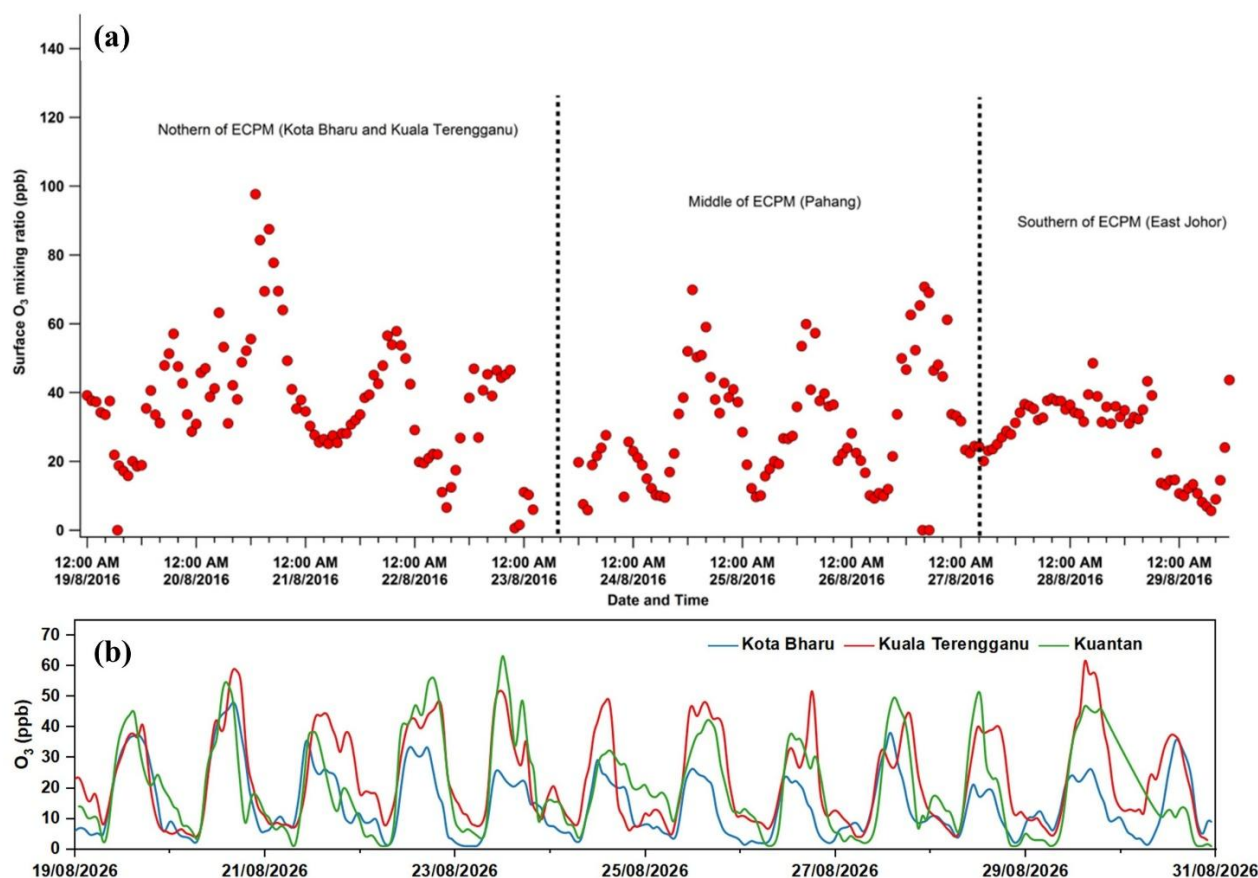


Figure 2 (a) Observation of O_3 concentrations during NESC'16; (b) Time series of O_3 concentrations at Kota Bharu, Kuala Terengganu, and Kuantan from 19 to 30 August 2016.

3.2 Meteorological conditions

Previous studies have shown that meteorological conditions played significant roles in the formation of O_3 (Santurtun et al., 2015; Piazzola et al., 2016; Wang et al., 2022). Figure 3 presents the spatial distributions of geopotential height, temperature, and wind vectors at 500 hPa for four representative dates (19, 23, 27, and 30 August). Throughout the sampling period, geopotential height remained consistently elevated (585 to 589 dagpm (decageopotential meters)) over Peninsular Malaysia



and the surrounding seas, with values gradually increasing from approximately 585 to 586 dagpm on 19 August to 588 to 589 dagpm by 27 to 30 August. This progressive increase indicates that the Western Pacific Subtropical High was strengthening and extending southward over the course of the cruise. On 19 August (Figure 3a), a closed vortex was present over the northern SCS. By 23 August, this feature had dissipated. It was subsequently replaced by a more uniform anticyclonic circulation, suggesting that the subtropical ridge had become nearly stationary by 30 August. Temperatures at the 500 hPa level (middle troposphere, ~5500 m a.s.l.) over the ECPM and the adjacent SCS generally ranged from -4 to -8 °C, with localized areas near the equator falling below -8 °C, while the northern and southern margins of the domain were slightly warmer (-2 to -4 °C). This persistent anticyclonic pattern suppressed deep convection and weakened vertical mixing, maintaining a relatively stable lower troposphere that limited the vertical dispersion of O₃ and its precursors and thereby promoted their accumulation near the surface (Adame et al., 2026). Coastal O₃ variability in mid-latitude systems is often tied to synoptic disturbances. Over eastern China, typhoon passage and frontal systems drive daily O₃ anomalies of up to ±16% (Han et al., 2020). Over the Pearl River Estuary, cold front passages set the timing and magnitude of O₃ peaks (Wu et al., 2024). No comparable synoptic trigger operated during NESC'16. The subtropical high strengthened steadily across the cruise period, the low-level south-westerly flow held its direction, and the offshore O₃ enhancement tracked this steady background state rather than any discrete weather event. The mechanism here is seasonal and persistent, not episodic.

At 925 hPa (Figure S5), a pronounced north to south temperature gradient was apparent, with warm air (23 to 26°C) covering Peninsular Malaysia and the northern SCS, while distinctly cooler air (17 to 21°C) occupied the equatorial region and the waters near Sumatra and Borneo. This thermal gradient intensified over time, with the warm sector expanding southward and reaching 25 to 26°C in the northern SCS by 27 to 30 August, consistent with the persistent clear sky radiative warming reflected in the 500 hPa fields. At the same time, the low-level wind field showed a consistent south-westerly to westerly flow directed from Peninsular Malaysia toward the SCS, which became increasingly organized and zonally coherent by 27 to 30 August, in agreement with the strengthening of the subtropical ridge. This persistent low-level flow provided an effective pathway for the eastward transport of inland and coastal emissions, while the warm and radiatively favorable lower tropospheric conditions promoted active photochemical processing of these transported precursors over the coastal marine receptor region (Kou et al., 2025). Surface meteorological observations at the three coastal stations support this assumption, with average wind speeds of 5.47 to 7.77 m s⁻¹ recorded throughout the sampling period. Such wind speeds were sufficient to limit the local accumulation of freshly emitted precursors, while also reflecting an active monsoonal transport pathway that carried inland air masses offshore (Wu et al., 2024).

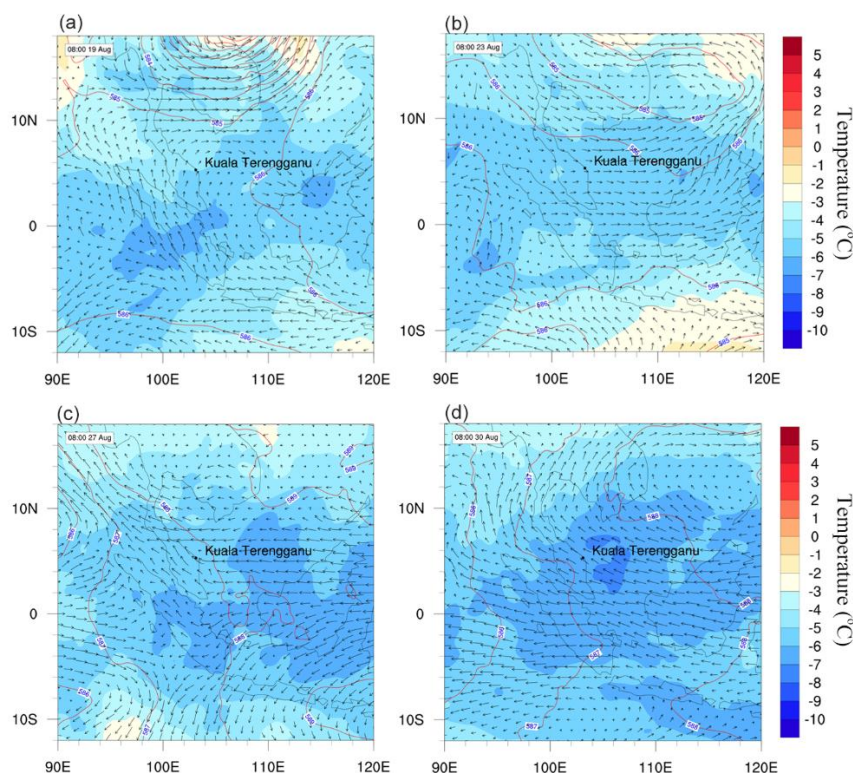


Figure 3 The spatial distributions of geopotential height (red line; units: dagpm), temperature (shaded; units: °C) and overlain by the wind vectors and wind speed (vector; units: $\text{m} \cdot \text{s}^{-1}$) at 500 hPa derived from the NCEP reanalysis data: (a) 08:00 LT on 19 August; (b) 08:00 LT on 23 August; (c) 08:00 LT on 27 August; (d) 08:00 LT on 30 August.

245 3.3 Precursor composition and its implications for coastal O₃ variability

To further investigate O₃ formation, VOCs as key O₃ precursors were also incorporated into the simulation. However, given the absence of VOC observations during 2012-2016, direct model validation for that period was not feasible. Therefore, VOC simulations were conducted for August 2017 and evaluated against concurrent observational data, demonstrating the reliability of the simulation framework and providing a basis for analyzing the mechanisms driving O₃ formation in the offshore of the

250 ECPM. The simulated and observed VOCs concentrations at three sites (Kota Bharu, Kuala Terengganu, and Kuantan) in August 2017 were compared, with the R values for alkanes, alkenes, and aromatic hydrocarbons ranging from 0.5 to 0.7 (Table S4), and the average concentration biases within $\pm 26\%$, suggesting that the model can reasonably capture both the concentration levels and temporal variation trends of VOCs, thereby confirming the reliability of the simulation results. Detailed information is provided in Text S2 of the supplementary information.

255 Figure 4 presents the simulated VOCs composition at the three coastal sites from 19 to 30 August 2016. Total VOC concentrations were 52.06, 44.77, and 41.49 ppbv at Kota Bharu, Kuala Terengganu, and Kuantan, respectively. Kota Bharu



and Kuala Terengganu were dominated by AVOCs, accounting for 46% and 38% of total VOCs, respectively. This reflects stronger urban and vehicular emission influences at these sites (Araya et al., 2025). In contrast, Kuantan showed a relatively larger BVOCs contribution (~35%), consistent with its proximity to forested areas and extensive oil palm plantations (Harper and Unger, 2018; Carrion et al., 2020). Elevated temperatures and intense solar radiation promoted BVOC emissions at Kuantan (Wang et al., 2021). The BVOCs fraction at Kota Bharu and Kuala Terengganu was 22% and 27%, respectively. BVOCs, particularly isoprene and terpenes, are highly reactive toward OH radicals and play an important role in O₃ formation in tropical environments (Harper and Unger, 2018; Bai et al., 2025). Although AVOCs constituted the dominant precursor class, the contribution of BVOCs to O₃ production may exceed their proportional share owing to their comparatively high chemical reactivity. This effect is particularly pronounced in tropical and subtropical regions where BVOC emissions are abundant (Bai et al., 2025; Khruengsai et al., 2025).

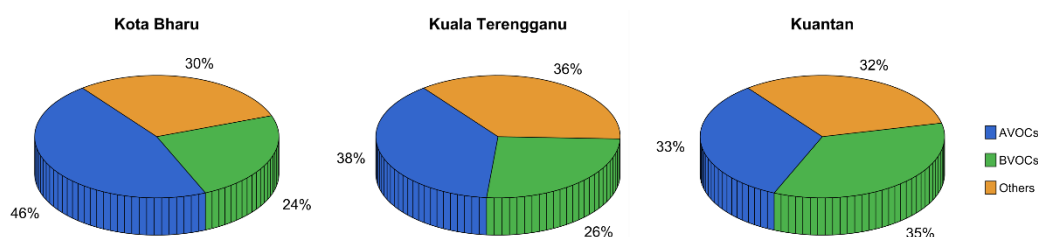


Figure 4 The simulation results of VOCs at the Kota Bharu, Kuala Terengganu, and Kuantan sites include Anthropogenic Volatile Organic Compounds (AVOCs: alkanes, alkenes, and aromatics) and Biogenic Volatile Organic Compounds (BVOCs: isoprene, terpenes, and sesquiterpenes).

The diurnal variations of O₃ and its precursors are shown in Fig. S6. NO_x concentrations exhibited a pronounced morning peak at all three sites, consistent with traffic emissions, and declined through the afternoon as photochemical consumption intensified. Alkane and alkene concentrations were highest at Kota Bharu, with morning maximum followed by daytime decreases attributable to photochemical degradation. Among BVOCs species, Kuantan exhibited higher sesquiterpene concentrations in the afternoon relative to the other two sites, consistent with its greater BVOCs fraction. Despite having the highest total VOCs (52.06 ppbv) and NO_x (8.80 ppbv) concentrations, Kota Bharu recorded the lowest average O₃ concentration. The elevated NO_x loading in the morning may have partially suppressed net O₃ accumulation through titration effects. Kuantan had the lowest total VOCs (41.49 ppbv) and NO_x (6.01 ppbv) concentrations and recorded a moderate average O₃ concentration. Kuala Terengganu exhibited the highest average O₃ concentration despite intermediate VOCs (44.77 ppbv) and NO_x (8.41 ppbv) levels. The relatively balanced AVOCs/BVOCs composition and moderate NO_x level at Kuala Terengganu may have favoured more efficient photochemical O₃ formation compared with the other two coastal sites.

3.4 O₃ production over the Malay Peninsula

3.4.1 Spatial Distribution and Meteorological Drivers of Offshore O₃ production

Figure 5 shows the simulated horizontal spatial distributions of O₃, NO_x, AVOCs, and BVOCs at 14:00 LT from 19 to 30 August 2016. The model broadly captured the occurrence of a nearshore O₃ production zone along the ECPM. Elevated O₃ concentrations of approximately 38-40 ppbv extended from the coastline into the coastal waters, particularly offshore of Kuala Terengganu (Fig. 5a). This pattern is broadly consistent with the observed contrast between higher offshore O₃ during the cruise and lower O₃ at the coastal monitoring sites described in Section 3.1. The spatial distributions of precursors provide further insight into the origin of this offshore O₃ production. NO_x was predominantly concentrated over urbanized and industrialized coastal areas, with maximum exceeding 1.2-1.4 ppbv, while offshore concentrations fell below 0.2 ppbv (Fig. 5b). AVOCs were similarly elevated over coastal source regions, with peak values reaching approximately 28 ppbv (Fig. 5c). BVOCs were more broadly distributed over the vegetated interior of the Peninsula (Fig. 5d). These findings suggested that offshore O₃ production was associated with the transport of precursors from inland and coastal sources toward the nearshore marine receptor region. Photochemical ageing during transport and reduced O₃ loss over the marine boundary layer characterised by low NO_x concentrations further contributed to this production (Wang et al., 2023).

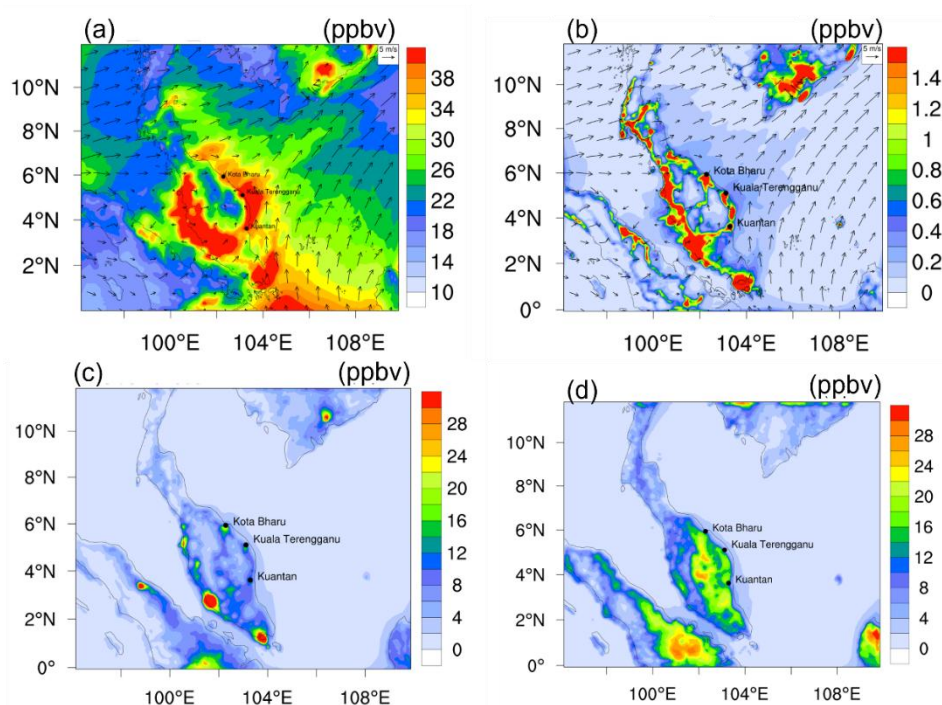


Figure 5 Spatial distribution of O₃ (a), NO_x (b), AVOCs (c), and BVOCs (d) simulation results for August 2016.



Several meteorological factors further facilitated this offshore O₃ accumulation. High surface temperatures (28-30 °C) and strong downward shortwave radiation ($> 470 \text{ W m}^{-2}$) over the east coast and adjacent marine area (Fig.S7a, b). These conditions favorable thermal and radiative conditions supported continued photochemical processing influenced by inland air masses during transport toward the nearshore marine receptor region. The planetary boundary layer over the coastal ocean was substantially lower than over land (Fig. S7), which suppressed vertical dilution and favored the retention of photochemically aged O₃ within a shallow surface layer. This was consistent with the analysis in Section 3.2 demonstrating the importance of a stable boundary layer structure for O₃ accumulation. Significantly lower wind speeds over nearshore waters compared with inland regions further reduced horizontal dispersion and extended O₃ residence time (Figure S7). Meanwhile, the prevailing south-westerly monsoonal flow continuously transported precursors from inland areas toward the SCS. Lower NO_x concentrations over the marine receptor region reduced NO titration losses, while the smaller dry deposition of O₃ over the ocean surface further suppressed O₃ loss (Wu et al., 2024a; Zeren et al., 2022).

It is noteworthy that simulations for the southwest monsoon seasons during 2012-2015 suggested that the offshore O₃ production along the east coast of Peninsular Malaysia was a recurring model feature rather than an isolated August 2016 pattern (see Fig. S8). Although the spatial extent of O₃ varied between years, the model consistently reproduced an eastward increase in O₃ from inland source regions toward the adjacent SCS, accompanied by depleted VOCs and low NO_x over the offshore receptor region. This modelling results suggested that the nearshore O₃ maximum off Kuala Terengganu may represent a recurring feature during the southwest monsoon.

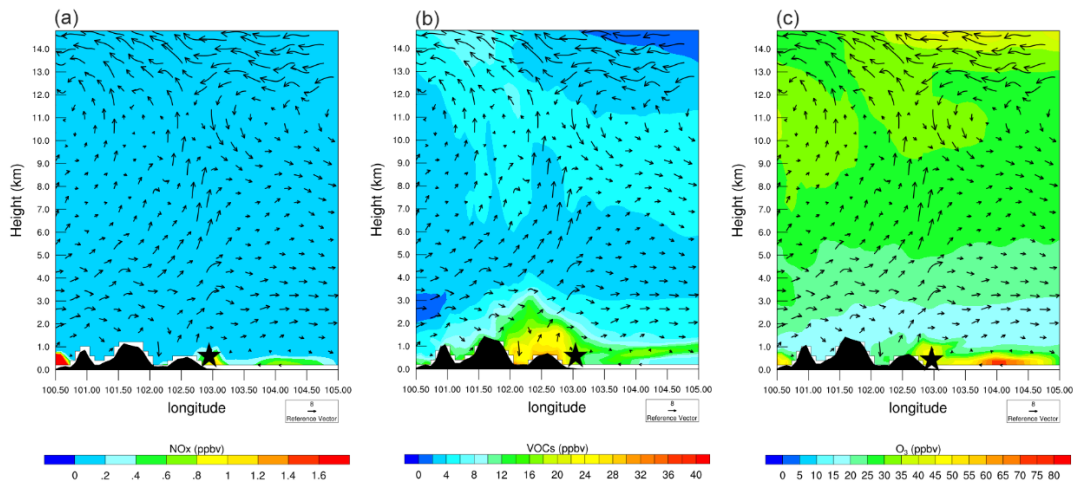
3.4.2 Vertical Structure of Precursor Transport and VOCs Composition

To further elucidate the formation mechanism of the offshore O₃ production, zonal vertical cross sections of NO_x, VOCs, and O₃ across the Kuala Terengganu transect are presented in Fig. 6. NO_x was predominantly confined to the lowest ~ 1 km over the inland and coastal source regions, while offshore concentrations east of ~ 103.5°E dropped sharply to below 0.2 ppbv (Fig. 6a). VOCs exhibited elevated concentrations over the inland Peninsula, with peak values reaching 36-40 ppbv near the surface and extending vertically to approximately 2-3 km (Fig. 6b). Air masses originating from inland regions continuously transported VOCs and NO_x toward the ECPM. Orographically driven ascent over the central highlands facilitated the vertical redistribution of these precursors into the lower troposphere. Upon reaching the nearshore marine boundary layer, these air masses encountered favorable photochemical conditions, including intense solar radiation, warm temperatures, and a lower boundary layer (Fig. S7). These conditions favored continued photochemical processing and the retention of O₃ within the lower nearshore marine boundary layer (Fig. S7c). These results highlighted that the offshore O₃ production off Kuala Terengganu was unlikely to result from direct inland O₃ transport alone. Instead, it was more likely associated with the transport and photochemical ageing of air masses rich in precursor, followed by reduced O₃ loss in the nearshore marine boundary layer. In contrast, the Kota Bharu and Kuantan transect exhibited distinct patterns. At Kota Bharu, both NO_x and VOCs were low throughout the lower troposphere east of the site (Fig. S9), with NO_x concentrations below 0.2 ppbv immediately offshore and VOC loading limited to the lowest ~1-2 km. The weak offshore precursor extension was consistent with weaker offshore O₃



production, with O₃ concentrations remaining at 25-35 ppbv. At Kuantan, elevated NO_x was confined to the surface layer west of the station (~102°E), while VOCs showed moderate vertical extension to ~2-3 km (Fig. S10). However, both precursors decreased rapidly offshore with no sustained O₃ production. The pronounced offshore O₃ maximum observed of Kuala Terengganu resulted from more efficient and sustained seaward transport of precursors from inland areas.

335 The vertical profiles of AVOCs and BVOCs revealed distinct patterns across the three coastal transects. At Kuala Terengganu, BVOCs dominated from the surface to ~2 km, while AVOCs remained moderate (refer to Fig. S11). The Kuala Terengganu transect shows that BVOCs dominate the vertical profile from the surface to 2 km and extend well past the coastline into the marine receptor region, which is different from the trend reported at Hainan Island where BVOCs drive photochemistry mainly at the point of emission, with sea breeze circulation confining the boundary layer to the lowest 300 m and limiting outward
340 transport (Li et al., 2025). These precursors at Kuala Terengganu are likely not consumed locally, instead, they are lifted, carried offshore under the monsoonal flow, and continue undergo chemical reaction over the atmosphere of coastal waters. In other words, the biogenic emissions here are not only at the scale of the source canopy, but can also act at the scale of the regional transport pathway. This result suggested that the offshore O₃ production was partly supported by inland BVOCs transported toward the sea, together with NO_x and AVOCs from coastal sources. At Kota Bharu, both AVOCs and BVOCs
345 were low, with rapid offshore decreases (Fig. S12). This can be justified by the highest surface VOC and NO_x concentrations observed at Kota Bharu in the north, where elevated NO_x loading can promote rapid near-surface O₃ titration, and the dominance of short-lived AVOCs limited the effective transport distance of reactive precursors via rapid photochemical consumption near the source region (Karl et al., 2023; Sun et al., 2024). The comparatively less favorable wind field at this northernmost station further constrained seaward precursor export, collectively accounting for the weak offshore extension
350 despite elevated surface concentrations (Wu et al., 2024). While at Kuantan, BVOCs showed coastal production but weakened rapidly offshore, while AVOCs persisted at low to moderate levels (Fig. S13). These contrasts demonstrated that Kuala Terengganu experienced sustained biogenic VOC influence extending into the marine receptor region, whereas the other transects were characterised by weaker and more rapidly attenuated precursor export.



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Figure 6 Vertical cross sections of simulated mixing ratios of (a) NO_x, (b) VOCs, and (c) O₃, with in-plane wind vectors overlaid. The vertical velocity is multiplied by 100. The cross section extends from (5.10°N, 100.50°E) to (5.10°N, 105.00°E), and the black triangle denotes the Kuala Terengganu site.

3.5 Impact of BVOCs Emissions on O₃ Formation

360 Table 2 shows that O₃ at the Pekan oil palm plantation exhibited pronounced daytime enhancement from 31 August to 30 September 2016. O₃ concentrations ranged from 9.44 to 20.95 ppbv, while maximum values reached 71.23 ppbv. The diurnal variation shown in Fig. S14, with O₃ increasing after sunrise and peaking between 11:00 and 16:00 LT, indicating active daytime photochemical processing in this plantation environment rich in BVOCs. These plantation measurements provide supporting evidence that rich in BVOCs landscapes can experience strong daytime O₃ enhancement, although the regional

365 scale contribution of BVOCs to O₃ over the ECPM and the adjacent marine atmosphere is more directly quantified by the WRF-Chem sensitivity experiments.

Table 2 Daily average O₃ concentrations (ppbv) over the oil palm plantation.

Date	Week	Min	Max	Median	Average	Stdev
1 to 2 Sep	1	4.49	58.71	17.17	20.95	12.27
3 to 10 Sep	2	4.22	69.63	17.31	20.53	12.16
11 to 18 Sep	3	1.17	71.23	7.03	12.83	13.29
19 to 25 Sep	4	1.23	41.19	6.64	9.44	7.54
28 to 30 Sep	5	1.22	29.73	7.54	9.65	6.74



Figure S15 presents the August average O_3 distributions in the Base and Case simulations. The Base simulation produced systematically higher O_3 than the Case simulation over most of Peninsular Malaysia, demonstrating that BVOC emissions exerted a positive and spatially extensive influence on regional O_3 (Fig. S15a, b). This enhancement was strongest over the central and southern vegetated interior of the Peninsula, but was not confined to the inland source region. In addition, the O_3 response to BVOC emissions extended eastward to the coastal receptor zone and the offshore atmosphere. Over the east coast and adjacent marine sector, the removal of BVOC emissions reduced August average O_3 by approximately 6-15 ppbv, with locally larger responses over parts of the Peninsula and nearby sea. This spatial pattern is consistent with the transport and ageing mechanism inferred from the vertical cross sections in Section 3.4. BVOCs emitted over inland vegetated areas were mixed upward and transported eastward under the prevailing south-westerly flow, subsequently contributing to O_3 formation over the coastal ocean alongside anthropogenic precursors exported from the coastal urban corrido (Zhao et al., 2023).

The comparison among the three sites further suggests a recurring positive BVOC contribution in the model simulations. Figure 7 presents the August O_3 distributions in the Base and Case simulations at Kota Bharu, Kuala Terengganu, and Kuantan for 2012-2016. At all three sites, the Base simulation yielded higher O_3 than the Case simulation throughout all five years, indicating a recurrent positive contribution of BVOC emissions to O_3 over the ECPM during the southwest monsoon season (Fig. 7a-c). At Kota Bharu, the median O_3 in the Base simulation generally exceeded that in the Case simulation by approximately 5-10 ppbv, with the upper part of the distribution also shifting to higher values, particularly in 2013 and 2016 (Fig. 7a). At Kuala Terengganu, the Base run consistently exhibited higher median and upper quartile O_3 concentrations than the Case run across all five years. This persistent separation in the model simulations suggested that inland BVOC emissions may have made an important and sustained contribution to O_3 formation at this coastal receptor site (Fig. 7b). At Kuantan, the Base simulation also remained higher than the Case simulation in every year, although the interannual variability was larger and high concentration outliers occurred more frequently, suggesting stronger modulation by episodic meteorological and transport conditions (Fig. 7c).

Overall, the O_3 enhancement attributable to BVOCs was approximately 15-30% across the three sites during August. These results indicate that the role of tropical vegetation in O_3 formation was not limited to local photochemistry over inland ecosystems but extended substantially to the regional O_3 burden and to the elevated O_3 observed over the east coast nearshore waters. This interpretation was supported by the Pekan plantation measurements, which showed pronounced daytime O_3 enhancement in an environment with abundant BVOC emissions. The vertical transect analysis in Section 3.4 further demonstrated the eastward export of precursor-rich air masses toward the coastal ocean. Therefore, the model sensitivity results, supported by the plantation observations, indicated that biogenic emissions constituted an important precursor source for nearshore O_3 formation over the ECPM.

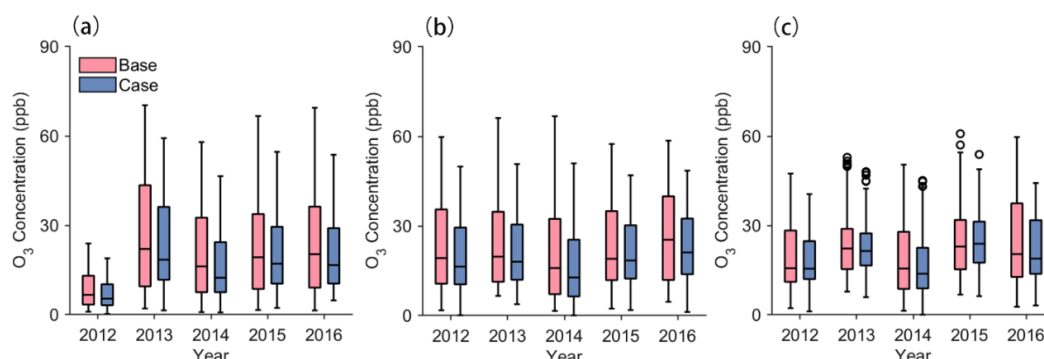


Figure 7 Distributions of simulated August surface O₃ concentrations in the Base and no-BVOC Case simulations at (a) Kota Bharu, (b) Kuala Terengganu, and (c) Kuantan during 2012 - 2016.

4 Summary and Conclusions

This study combined shipborne observations, long-term coastal monitoring data, and WRF-Chem simulations to investigate the distribution and formation mechanisms of O₃ over the ECPM. Shipborne measurements revealed a clear offshore enhancement of O₃, with an average concentration of 31.4 ppbv and a maximum value of 97.7 ppbv, which were higher than those observed at the nearby coastal stations (23-27 ppbv). These results indicate that the tropical coastal marine atmosphere can serve as an important region for O₃ production and accumulation rather than acting only as a receptor of transported O₃. WRF-Chem simulations showed that the offshore O₃ enhancement was mainly driven by the transport of anthropogenic and biogenic precursors from the Malay Peninsula under the prevailing southwest monsoon. During transport, precursor-rich air masses experienced continuous photochemical processing, while low NO_x conditions over the marine boundary layer reduced O₃ loss through NO titration. Strong solar radiation, shallow boundary layer conditions, and weak dispersion further favored O₃ accumulation over the coastal waters. Sensitivity simulations showed that tropical vegetation emissions increased August mean surface O₃ by 6-15 ppbv (15-30%) over the ECPM and adjacent South China Sea, with a consistent positive BVOC contribution identified across the three coastal sites during 2012-2016. These results demonstrate that biogenic precursors emitted from tropical vegetation and transported offshore can influence regional coastal O₃ formation beyond the immediate source regions.

The transport and chemical processes identified in this study are consistent with previous observations in other coastal and marine regions. Over the Bay of Bengal, Girach et al. (2017) reported continued O₃ formation in continental outflow during transport, with an estimated production rate of about 4.6 ppbv d⁻¹. Wu et al. (2024a) also found that O₃ over the Pearl River Estuary was strongly affected by regional transport, with precursor emissions from the inland Pearl River Delta contributing 50% to 76% of O₃ at coastal receptor sites. These studies are consistent with our results and indicate that terrestrial precursor transport can strongly affect O₃ over coastal waters and that O₃ formation can continue after air masses move from land to the marine atmosphere. Several limitations should be considered when interpreting these results. First, direct VOC measurements



were not available from 2012 to 2016, and the role of VOCs during this period was therefore mainly assessed using model simulations. Second, uncertainties in VOC emissions, precursor composition, and chemical mechanisms may affect the estimated contribution of BVOCs to O₃. Future studies combining long term observations of O₃, NO_x, and speciated VOCs with higher resolution modelling would help to better quantify precursor transport and O₃ formation over tropical coastal waters.

Overall, our results show that tropical coastal waters can become important regions for atmospheric O₃ formation and accumulation process when they are affected by the sustained terrestrial precursors transportation, illuminating the needs to consider both terrestrial precursor emissions and atmospheric processes over coastal waters when assessing O₃ pollution in tropical coastal regions.

Code and data availability

The shipborne ozone observations collected during the National Expedition Scientific Cruise (NESC'16), together with the processed coastal monitoring datasets used in this study, are available from the corresponding author upon reasonable request. Long term air quality data from the Malaysian Department of Environment (DOE) were used under permission and are therefore not publicly available. The ERA5 reanalysis data are publicly available from the European Centre for Medium Range Weather Forecasts (ECMWF) Climate Data Store (<https://cds.climate.copernicus.eu/>). The WRF Chem model (Version 3.9.1) is publicly available through the National Center for Atmospheric Research (NCAR). Model configuration files and post processing scripts used for this study are available from the corresponding author upon reasonable request.

Supplement

The supplement related to this article is available online at:

Author contributions

YJT and MSMN led and organized the research. MSMN, HHAH and NAAJ collected the observational data for this study. BW conducted the WRF-Chem simulations. BW, MSMN, HHAH and YJT analyzed the data. BW, MSMN and YJT wrote the manuscript with significant contributions from NAAJ and SNHSN. All authors contributed to the interpretation of the results and revision of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.



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