RESEARCH GRANTS COUNCIL
THEME-BASED RESEARCH SCHEME (TRS)

Completion Report on Funded Project

Project start date: *1 January 2018*
Project completion date: *31 December 2023*

1. Project Title:

Photochemical air pollution in highly urbanized subtropical regions: from micro environments to urban-terrestrial-oceanic interactions

2. Names and Academic Affiliations of Project Team Members[#]

Project team member	Name / Post	Unit / Department / Institution	Average number of hours per week spent on this project in the whole project period
Project Coordinator (PC)	Tao WANG / Chair Professor	Department of Civil & Environmental Engineering (CEE) / The Hong Kong Polytechnic University (PolyU)	15
Co-Principal Investigators (Co-PIs)	Guy BRASSEUR / Distinguished Chair Professor/Senior Scientist	CEE /PolyU & Max Planck Institute, Germany	8
	Shuncheng LEE / Professor	CEE/PolyU	8
	Hai GUO / Professor	CEE/PolyU	8
	Alexis Kai-Hon LAU / Chair Professor#	Division of Environment and Sustainability / HKUST	8
	Kin-fai HO / Professor	School of Public Health and Primary Care / CUHK	8
	Chun-Ho LIU / Associate Professor	Department of Mechanical Engineering / HKU	8
	Peter LOUIE / Adjunct Professor#	Division of Environment and Sustainability / HKUST	8
	Xinming WANG / Research Professor	Guangzhou Institute of Geochemistry / Chinese Academy of Sciences	8
	Zhe WANG / Associate Professor#	Division of Environment and Sustainability / HKUST	12

Co-Investigators (Co-Is)	Kenneth LEUNG / Principal Environmental Officer	Environmental Protection Department, of HKSAR Government (HK EPD)	6
	Yingjun LIU / Postdoctoral Fellow	Department of Environmental Science, Policy and Management, UC Berkeley	6
Collaborators	Liuju ZHONG / Professor	Institute for Environmental and Climate Research, Jinan University	N.A.
	Junyu ZHENG / Professor	School of Environment and Energy, SCUT; Institute for Environmental and Climate Research, Jinan University	N.A.
	Donald BLAKE / Professor	Department of Earth System Science, UC Irvine	N.A.
	Alex GUENTHER / Professor	Department of Earth System Science, UC Irvine	N.A.
	Allen GOLDSTEIN / Professor	Department of Environmental Science, Policy and Management, UC Berkeley	N.A.
	Steven BROWN / Research Chemist	ESRL Chemical Sciences Division, NOAA	N.A.
	Daniel JACOB / Professor	School of Engineering and Applied Sciences, Harvard University	N.A.
	Yuanhang ZHANG / Professor	College of Environmental Sciences and Engineering, Peking University	N.A.
	Gregory Carmichael / Professor	College of Engineering, The University of Iowa	N.A.

\# *Please highlight the approved changes in the project team composition and quote the date when the RGC granted approval of such changes. For changes in the project team composition, please submit a separate request, together with the justification and the curriculum vitae of the new member(s), to the RGC three months prior to the intended effective date of the change.*

\# *Mr Peter Louie joined the Division of Environment and Sustainability in HKUST as an Adjunct Professor after his retirement from HK Environmental Protection Department on 26 June 2020. The RGC approved the change of affiliation of Dr Wang Zhe from PolyU to HKUST after his assumption of duty as an Assistant Professor in HKUST on 28 October 2019 and was promoted to Associate Professor in June 2023. Prof Alexis Lau was promoted to Chair Professor and appointed as Head of Division of Environment and Sustainability in HKUST in January 2021.*

3. Project Objectives

Summary of objectives addressed/achieved:

Objectives*	Percentage achieved	Remarks**
Core area 1: Terrestrial/Biogenic Emissions		
1. Establishment of domestic BVOCs emission factors database	100%	
2. Update of landuse/LAI database in emission model	100%	
3. Development of biogenic emission model, MEGAN-China	100%	
4. Measurement of soil HONO emission fluxes	100%	
5. Development of a dynamic terrestrial HONO emission inventory	100%	
Core area 2: Reactive chlorine sources		
6. Development of anthropogenic chlorine emission inventory	100%	
7. Quantification of sea salt aerosol emission	100%	
Core area 3: Radical Chemistry and Photochemical Oxidation		
8. Develop in-situ measurement technique for OH /HO_2 /RO_2 radical	100%	
9. Comprehensive atmospheric observations on radicals and oxidation products	100%	
10. Chamber simulation of VOC oxidation and SOA formation	100%	
11. Model simulations of radical chemistry and photochemical oxidation	100%	
Core area 4: Micro- to Meso- scale Processes		
12. Development of a micro-scale LES-Chemistry coupled model	100%	
13. Application of the LES-Chemistry model in urban environments	100%	
14. Embedment of improved micro-scale parameterization into WRF-Chem-UCM	100%	
15. Multi-scales air quality predictions using the new WRF-Chem-UCM-LES model	100%	
Core area 5: Mitigation of Photochemical Pollution		
16. Improvement of air-quality models	100%	
17. Evaluating the role of terrestrial/biogenic, anthropogenic and oceanic emissions	100%	
18. Assessing the effect of climate change and the health impact of photochemical pollution	100%	

Objectives*	Percentage achieved	Remarks**
19. Assessing the efficacy of the current and near future control strategy on the air pollution	100%	

* *Please highlight the approved changes in objectives and quote the date when the RGC granted approval of such changes.*

** *Please provide reasons for significantly slower rate of progress than originally planned.*

6. Research Highlights and Outputs

6.1 What are the most exciting research accomplishments of the project?

(Please list five or more of the team's best research accomplishments, such as journal and conference papers, software codes, research infrastructure, etc. For each item, please clearly justify how it has achieved international excellence (e.g. best paper award, invited presentation, citations, product licensed to industry, etc.))

Highlight 1. Quantified soil HONO emission and impact on air quality

Nitrous acid (HONO) is a key precursor of the highly reactive hydroxyl radical (·OH), which is the most important oxidant that removes many gases emitted into the atmosphere and produces secondary air pollutants. Although soil microbial activities have been known to release reactive nitrogen such as NH_3 and NO_x, HONO from soil has received attention only in the recent decade and quantification of its emission across diverse soil types and under varying agricultural practices remains lacking. This project conducted laboratory measurements, synthesized findings from extensive experiment results, and performed model simulations to elucidate the roles of soil HONO emissions in atmospheric chemistry and air quality.

We set up a Teflon dynamic chamber system to measure the soil emissions of HONO and NO under different soil conditions in the laboratory. We measured background HONO and NO emissions (emissions during non-fertilization period) of soil samples collected from diverse soil types across 48 sites in China, and investigated post-fertilization soil HONO emissions after applying three common fertilizers. The results show much higher emissions of HONO than those of NO, especially for samples from northern China. In terms of the fertilization effects, high HONO emissions were found from moist soils, which contrasts with previous lower predictions at high soil moisture. Our project also for the first time revealed the impact of different types of fertilizers on soil HONO emissions. Urea use leads to the largest release of HONO compared to the other two commonly used fertilizers (ammonium bicarbonate and ammonium nitrate). Based on the results of laboratory experiments, the parameterization schemes for HONO emissions from fertilized and unfertilized soils were developed and implemented in the Weather Research and Forecasting model coupled with Community Multiscale Air Quality (WRF-CMAQ) model. The inclusion of the soil HONO emissions improved simulations of atmospheric HONO and revealed a significant impact of this HONO source on OH, ozone (O_3), and particulate nitrate concentrations. Our results show that soil HONO emissions had a greater effect than NO, which means the soil effects may have been underestimated in many previous studies that only considered NO_x. These results have been published in two papers in the top environmental science journal *Environmental Science & Technology* (*ES&T*) (Impact Factor (IF)=10.8) (Wang et al., *ES&T,* 2021, 2023).

To assess the soil HONO effect on a global scale, we assembled a comprehensive dataset encompassing all published measurements of soil HONO emissions across a variety of ecosystems worldwide. We derived the first global estimate of soil HONO emissions over the past four decades. Our global assessment revealed a notable increase in soil HONO emissions from 9.4 Tg N in 1980 to 11.5 Tg N in 2016 due to climate change and increased fertilizer use. Incorporating these emissions into a global chemistry-climate model, the Community Atmosphere Model with Chemistry (CAM-Chem), improved simulations of atmospheric HONO, increasing surface O_3 concentrations globally and elevating the risk of vegetation exposure to O_3, particularly in regions with low anthropogenic emissions. These results have been submitted to *Nature Communications* (IF=14.7) and has been accepted in principle subject to editorial changes.

To assess the contribution of soil emissions to air quality in mainland China, we analyzed the nationwide long-term NO_2 trends from ground-based and satellite observations. The results revealed a slower decrease of NO_2 in rural areas compared to urban areas since the implementation of clean air policies. We incorporated soil emissions of HONO and NO_x in WRF-CMAQ model, and model simulations indicated the slower rate of decrease in NO_2 column in rural areas was largely attributed to increased emissions of HONO and NO from soil. This unmanaged source undermined nationwide efforts to reduce NO_2, O_3, and particulate nitrate. In the agriculture-intensive North China Plain (NCP), soil emissions offset 46% of the NO_2 reductions achieved through clean air policies (Wang et al., *ES&T,* 2024). Moreover, we collaborated with Nanjing University and integrated the soil NO_x and HONO emission developed from this TRS project with their NH_3 emission scheme, yielding the first dynamic soil emission scheme for all three reactive nitrogen species. The team applied this integrated scheme to a Weather Research and Forecasting model coupled with Chemistry model (WRF-Chem) and demonstrated substantial impact of soil reactive nitrogen impact on ozone and $PM_{2.5}$ in the Yangtze River Delta in a typical crop fertilization period (Ren et al., *ES&T*, revised).

Overall, the comprehensive research supported by this TRS project has yielded important novel insights into the factors affecting soil reactive nitrogen emissions and has produced the most complete soil nitrogen emission schemes for model use. Our findings underscore the urgent need to integrate soil HONO emissions into air quality models, and future air improvement policies should pay attention to soil reactive nitrogen emissions to enhance the effectiveness of the policies.

Highlight 2. Quantified biogenic VOC emissions and impact on air quality

The biogenic volatile organic compounds (BVOCs) emitted by terrestrial plants have a significant impact on the formation of O_3 and secondary organic aerosols (SOA) in the troposphere. Yet, accurately estimating BVOCs emissions remains highly challenging, as models currently rely on default emission factors (EFs), which introduce significant uncertainties in regions with insufficient local data. By comparing CMAQ simulations with ambient measurements from 20 sites across China, we found that the default Model of Emissions of Gases and Aerosols from Nature (MEGAN) configuration overestimates isoprene emissions in southern China (Wang et al., *JGR*, 2023).

In this project, we designed a dynamic chamber to measure BVOCs emissions from plants under quasi-real atmospheric conditions (Zeng et al., *AMT*, 2022). A localized BVOCs emission factor (EF) database was developed for four plant functional types, based on our measurements of 20 dominant tree species in the Pearl River Delta (PRD) region. Furthermore, a pan-tropical BVOCs EF database encompassing 977 plant species was constructed based on measurements in tropical environments (Mu et al., *Frontiers in Plant Science*, 2022). These EF databases improved model estimates of BVOCs emissions in the PRD and other tropical regions. With the incorporation of the updated EFs database, the CMAQ model can better reproduce the concentrations of BVOCs, O_3, and SOA (Wang et al., *JGR*, 2023). These publications have collectively received a total of 72 citations as recorded in the Web of Science. The developed BVOCs EF database has been downloaded more than 1300 times since the publication of the papers. *The EF database is expected to be widely used by the modeling community in assesing the impact of BVOCs on air quality in the sub-tropical regions*.

Highlight 3. Developed the first high-resolution reactive halogen emission inventory for China and the first long-term biomass chlorine emission for Asia

Chlorine: The chlorine atom (Cl·) plays a crucial role in atmospheric chemistry, including destroying ozone, and oxidizing methane, other hydrocarbons, and elemental mercury. A comprehensive assessment of the role of chlorine chemistry in atmospheric chemistry and air quality requires an understanding of both natural and anthropogenic sources. The currently available anthropogenic chlorine emission inventories were compiled for 1990 globally and have not been updated since then. Given the rapid development of China's economy and industry, which has led to significant changes in fuel consumption and pollution control technologies over the past three decades, the emission inventory of 1990 is now outdated. In this project, we have developed the first high-resolution anthropogenic inventory of hydrogen chloride (HCl) and fine particulate (Cl^-) emissions in China for 2014, with a resolution of 0.1°×0.1°, encompassing sources such as coal combustion, industrial processes, biomass burning, and municipal solid waste incineration. Comprehensive local data (e.g., Cl content in coal, point source information, etc.) and county-level activity data were gathered and compiled. The results showed that biomass burning was the most significant contributor, accounting for 75% of the fine particulate Cl^- emissions and 32% of the HCl emissions (Fu et al., *ES&T*, 2018). The paper has been cited 88 times (Web of Science), and the emission inventory was used by Alfonso

Lopez (CSIC, Spain), Danial Jacob (Harvard), Rokjin Park (Seoul National University), Xuan Wang (HKCityU), and Wei Nie (Nanjing University), which demonstrates the scientific value of this work.

Biomass burning makes a significant contribution to chlorine emissions in China and the other parts of Asia, yet there is a lack of high-resolution emission inventories, long-term trends, and relevant regional or global atmospheric impacts. To fill this gap, this project has developed a comprehensive, long-term, high-resolution chlorine emission inventory for open biomass burning across Asia. Through extensive simulations and analyses of the data from 2001 to 2018, the study has indicated substantial chlorine emissions from biomass burning in key regions such as northern China, northern India, and Southeast Asia, with distinct seasonal patterns and significant spatial and interannual variability driven by changes in agricultural practices. The results demonstrate that biomass burning is not only a significant source of air pollutants, but also a key contributor to the production of atmospheric oxidants, affecting the atmospheric oxidation capacity directly. This finding suggests that biomass burning emissions have a greater impact on atmospheric chemistry than previously acknowledged. With the expected increase in global biomass burning activities due to climate change, their role in shaping atmospheric composition could become even more pronounced. The findings of this study were published in the journal *National Science Review* (*NSR*, IF=16.3), and were reported by several science media, including EurekAlert Science News (https://www.eurekalert.org/news-releases/1061671).

Bromine: In addition to chlorine, another halogen, bromine, also impacts atmospheric oxidation and potentially air quality. To assess the impact of elevated bromines discovered during winter in northern China (see next section), we compiled the first anthropogenic bromine emission inventory in China and quantified the overall impact of halogens on haze pollution in northern China. By integrating updated halogen chemistry and anthropogenic chlorine and bromine emissions into the WRF-Chem model, we demonstrated that halogens significantly increase the load of fine particulate matter, particularly its secondary components (Li et al., *ES&T*, 2021).

In summary, our projects made important breakthroughs in quantifying biogenic emissions of reactive nitrogen and VOCs, and anthropogenic reactive halogens. The emission inventories for these sources have been integrated with those of conventional anthropogenic pollutants to form the most comprehensive and updated emissions for China, which have been and will be a key resource in air quality and climate assessments.

Highlight 4. Discovered important roles of reactive halogen chemistry in the formaiton of secondary air pollutants and health impact

To investigate the impact of halogen chemistry on air quality, we conducted a series of field observations in Hong Kong and Mainland China during the project period. We discovered high concentrations of reactive halogens in southern and northern China and demonstrated their substantial impact on atmospheric chemistry and air quality.

Extradentary high Cl_2 and Br_2 in coastal environment: During the photochemically intense autumn of 2018, 2020, 2021, and 2023, we measured reactive halogens with a start-of-the-art chemical ionization mass spectrometry at the Cape D' Aguilar (Hok Tsui) Air Quality Supersite, which is operated by the Hong Kong Environmental Protection Department (HKEPD). Unexpected high levels of Cl_2 (up to 1 ppbv) were observed, which is surprising given the short lifetime of Cl_2 in the daytime (~7 min at noon). The Cl_2 concentrations peaked at noon and were well correlated with O_3. To pin down the mechanism for the high Cl_2, a series of experiments using a dynamic reaction chamber in the laboratory were carried out by illuminating the Cl-nitrate solution and aerosol collected in the field on the filters. The results reveal that photolysis of particulate nitrate under acidic conditions (pH <3.0) activate chloride, which accounts for the observed daytime Cl_2 production. These high Cl_2 concentrations observed at the site increased the atmospheric oxidation rate of VOCs and daytime O_3 production. Given the ubiquitous existence of chloride, nitrate, and acidic aerosols, we propose that nitrate photolysis is a significant daytime chlorine source globally. These results were published on *Nature Communications* (IF=14.7) (Peng et al., 2022).

Our multi-year observations verified the presence of the elevated daytime Cl_2 and a large previously overlooked source of Cl radical in coastal south China, and a recent field campaign by our team also found high Cl_2 at a rural site of the Yangtze River Delta. To assess the impact of this large Cl radical source, we parameterized Cl_2 formation from nitrate photolysis and incorporated it into the WRF-Chem model. The model reproduced ~ 70% of high Cl_2 levels observed at our site and indicated the presence of Cl_2 in coastal areas of southern China. Our simulations showed that high Cl_2 enhances the oxidative capacity of the atmosphere, increasing the concentration of surface O_3 and $PM_{2.5}$ in high-NO_x areas, and reducing O_3 in low-NO_x areas. Chlorine chemistry also shifts the O_3 formation regime from VOC-limited to NO_x-limited, increasing the benefits of NO_x reduction for O_3 mitigation. This work was submitted to *ES&T*, and the revised manuscript has been returned to the journal.

We also observed significant levels of Br_2 at the Hok Tsui site, with an average midday mixing ratio of 5 ppt, indicating a significant daytime source of Br_2 exists. Based on laboratory and field data, we demonstrate that the daytime Br_2 is also produced through the photodissociation of particulate nitrate and that the reactive uptake of dinitrogen pentoxide (N_2O_5) on aerosols serves as a crucial nighttime source. The Br atom resulted in a 13% increase in net O_3 production and nearly a 10-fold increase in the production rate of toxic Hg^{II}. These findings indicate that reactive bromines play a more significant role in the atmospheric chemistry and air quality of polluted coastal and maritime environments than previously recognized. Furthermore, our results advocate for stringent regulation of emissions from two traditional pollutants (NO_x and SO_2), thereby reducing nitrate levels and aerosol acidity, which would mitigate halogen radical production and its negative effects on air quality (Xia et al., *ES&T*, 2022).

High concentrations of BrO, which is produced from the reaction between Br radical and O_3, have been observed by researchers at Fudan University on Huaniao Island in the East China Sea under the influence of typhoons. With our experience in halogen research, our team has been invited to jointly analyse the measurement data. We simulated the impact of bromine chemistry on air quality. The results suggest that the typhoon's high wind speeds amplify sea-salt aerosol emissions, enhancing reactive bromine activation. Elevated BrO under high NO_x conditions suggests a pollution-induced bromine release mechanism, as suggested by our study in Hong Kong. The elevated BrO levels increase ozone destruction by up to ~40% across the East China Sea. Given the high frequency of cyclonic activity, reactive bromine chemistry is expected to play a more significant role than previously thought in affecting coastal air quality and atmospheric oxidation capacity. These results have been published on *NSR* (Wang et al., *NSR*, 2024).

<u>Extradentary high reactive bromine from coal burning in North China</u>: In the NCP during the winter of 2017, we detected extremely high levels of daytime bromine chloride (BrCl). The data suggest that coal combustion and daytime photochemical reactions produce substantial amounts of BrCl. BrCl accounted for approximately 55% of the bromine and chlorine atoms and increased the abundance of conventional tropospheric oxidants (OH, HO_2, and RO_2) by 26%-73%, thereby enhancing ozone production by 55%. Our study underscores the critical role of active halogens in wintertime atmospheric chemistry and highlights the adverse impact on air quality in continental areas characterized by widespread, uncontrolled coal burning. The findings of this study were published in *NSR* (Peng et al., *NSR*, 2022), and were reported by EurekAlert Science News, Science China Press, ScienMag, Phys.org, etc. The findings have contributed to the formulation of policies by the Chinese government to control rural coal burning during the winter.

To assess the impact of recent air improvement measures, especially the Clean Winter Heating initiative, we conducted another field observation in 2023 at the same site as in 2017. We found that the clean energy policy has effectively mitigated reactive bromines like BrCl and Br_2, but high concentrations of reactive chlorine persist, partly due to the use of chlorine-based fertilizers in agriculture. Additionally, the shifts in aerosol acidity and the NO_3 production rate have altered atmospheric chlorine chemistry, resulting in a significant increase in the production of $ClNO_2$. The elevated levels of $ClNO_2$ enhanced ozone production by 16%. Our results underscore the ongoing significance of chlorine in exacerbating secondary pollution on the NCP and advocate for the consideration of crop fertilization as a potentially crucial source of chlorine in air pollution control strategies. A manuscript reporting these results has been submitted to *ES&T*.

<u>*The impact of reactive halogens on health*</u>: Reactive halogens contribute to Hg oxidation and subsequent Hg deposition, bioaccumulation, and health damage. Our field observations at different sites reveal abundant reactive halogens, but their impacts on Hg's atmospheric fate and human exposure are unknown. By using the CAM-Chem model with state-of-the-art halogen emissions and chemistry, and Global European Monitoring and Evaluation Program Multimedia Modeling System (GLEMOS) with advanced Hg chemistry, we demonstrated that the inclusion of anthropogenic halogen substantially increased local Hg oxidation and deposition in/near Hg continental source regions by up to 20%. Our model results indicate higher Hg exposure in source regions, increasing health risks by 8.7% in China and 7.5% in India. These findings underscore the need to reduce local Hg and halogen emissions. These results were published on *Proceedings of the National Academy of Sciences of the United States of America* (Fu et al., *PNAS* (IF=9.4), 2024).

With our pioneering research on reactive halogens in China, we have been invited to present our findings at numerous conferences and workshops organized by the National Natural Science Foundation of China (NSFC) and Ministry of Science and Technology (MOST). And our research in this emerging area has facilitated the inclusion of reactive halogens in the MOST National Key Research and Development 2022 Funding Excise. We have been invited to write a perspective paper on halogens for the IGAC 35th Anniversary Special Issue in *Elementa* as a sole paper from the IGAC China Working Group.

<u>Highlight 5. Quantified the contribution of gas-phase oxidation to secondary organic aerosol</u>

SOA contributes a significant fraction to the particulate haze pollution in urbanized regions, with profound impacts on human health and climate. The knowledge gaps in the sources and relevant chemical processes of SOA formation are the bottleneck for implementing effective measures to mitigate haze pollution.

<u>*Oxygenated organic molecules (OOMs):*</u> Through a joint comprehensive field study (Hong Kong, Beijing, Nanjing, and Shanghai), our project demonstrated the dominant roles of anthropogenic low-volatility organic vapors as critical intermediates connecting the oxidation of VOCs to SOA and haze pollution in urban environments. For the first time, the joint research characterized plenty of highly reactive oxygenated organic molecules (OOMs) in different urban environments, and developed a novel classification framework to trace the measured OOMs and the formed SOA to different precursors. The results showed that oxidation of anthropogenic VOCs (AVOCs) dominates OOMs formation in the urban atmosphere, with approximately 40% contribution from aromatics and another 40% contribution from aliphatic hydrocarbons, a previously under-accounted class of VOCs. The study unveiled that multi-step oxidation and auto-oxidation processes play key roles in OOMs formation, and NO_x significantly affects the VOCs oxidation process, producing a considerable fraction of nitrogen-containing organic compounds. The irreversible condensation of these anthropogenic OOMs is a dominant source of SOA, even under severe haze conditions. These findings were published in *Nature Geoscience* (IF=15.7) and were reported by a lot of science media, including EurekAlert Science News, Science Daily, Nature World News – Climate Change, Verve Times, World News, Eurasia Review, Mirage News, Phys.org, etc. The paper was cited 88 times (Web of Science) since its publication in May 2022.

To further understand the oxidation chemistry and formation pathway of the semi-/low-volatile organic products, further analysis on the ambient measurement data was performed. We identified and quantified the formation mechanisms of OOMs with different functional groups. The branching of reaction pathways to form carbonyls, hydroperoxides, organic nitrate, peroxyl nitrate, dinitrates, and aromatic ring-retaining species were characterized, as well as the influencing factors on autoxidation and organic nitrate formation. The findings indicate the pivotal role of OOMs in driving sub-100 nm particle growth and SOA formation, underscoring the significance of dinitrates and anthropogenic products derived from multistep oxidation processes (Zheng et al., *ES&T*, 2023).

Organic aerosol (OA) and dynamic source contributions: Based on in-situ measurements of OA markers at Hok Tsui in 2018, we analysed the compositions, diurnal patterns, and dynamic sources of OA markers. Continental air contained higher levels of primary OA markers, such as levoglucosan from biomass burning and oleic acid from cooking, while marine and mixed air were laden with oxygenated SOA markers (e.g., hydroxyl dicarboxylic acids (OHDCA)). This study was the first attempt to resolve the dynamic contributions of specific sources, rather than lumped sources, to OA in Hong Kong (Lyu et al., *ES&T*, 2020).

In 2019, a follow-up sampling campaign was carried out at an urban site in Hong Kong. The results indicated that SOA markers were markedly elevated in short-duration cases of continental and coastal air compared to the most common marine air, with the primary markers containing mainly local features. The troughs showed enhancements of many SOA markers, which appeared to be related to high relative humidity. In the case of marine air without troughs, local cooking and vehicle emissions dominated. Even during the summer months studied, when marine air dominated, the contribution of cooking emissions to PM_1-OM was as high as 44.2 % in the evening. Our results highlighted the need to control regional anthropogenic SOA and local cooking emissions to mitigate PM pollution in Hong Kong (Zhang et al., *ACP*, 2020).

Highlight 6. Assessed impacts and mitigation of photochemical pollution

Why did not the Air Pollution Prevention and Action Plan reduce urban O_3 pollution? In 2013, the Chinese government embarked an aggressive initiative to mitigate severe haze in the country. Anthropogenic emissions of SO_2, NO_x, carbon CO, and $PM_{2.5}$ were reduced by 59 %, 21 %, 23 %, and 33 % from 2013 to 2017, respectively, while the emission of VOCs and ammonia (NH_3) slightly increased. We evaluated the effectiveness of the Action Plan by analysing data from the national environmental monitoring network with statistical and chemical transport models. Results showed that while there were significant declines in ambient concentrations of primary pollutants, surface ozone levels in many urban areas have risen. We quantified the impact of meteorological and emission changes on the O_3 levels with a modified WRF-CMAQ model. Meteorological effects vary by region and may play a dominant role in controlling the O_3 variation. The PM-targeting measures increased ozone due to reduced NO_x titration, increased solar radiation, and reduced uptake of radicals by particulates. The increasing O_3 accelerated winter haze, offsetting some effects of NO_x control. We demonstrated that VOC control would have avoided the side effects of the PM control measures on ozone. We thus recommended adding VOC to current control to tackle both $PM_{2.5}$ and O_3 and consideration of meteorology change in evaluating the anthropogenic emission-reduction measures. The results were published in two back-to-back papers on *ACP*, and have been widely cited by the research community (both ESI highly cited papers, with total 415 citations since June 2020).

Why did not NO_x emission control alleviate winter nitrate pollution? Observation data have shown that nitrate particulate concentrations remained high, and its contribution to $PM_{2.5}$ has been growing during winter in northern China, despite emission reductions of NO_x. Previous studies of nitrate formation in China mainly focused on the increasing production of ammoniate nitrate resulting from increasing availability of NH_3 accompanied with the reduction of sulphur emissions. We used the WRF-CMAQ model, which was improved with nitrate heterogeneous formation mechanism by our team, to identify key factors driving nitrate formation in northern China. The results showed that the high O_3 and OH production in winter enables rapid NO_x to nitrate conversion in the NCP. Increased O_3 and OH production due to high precursor levels and rapid RO_x cycling accelerate nitrate formation during severe pollution. A 32% reduction in NO_x emissions from 2010 to 2017 resulted in only a 0.2% decrease in surface nitrate, with some areas seeing an increase. This is mainly due to a ~30% rise in O_3 and OH, which improved NO_x to HNO_3 conversion by 39%. The findings indicate that future haze control strategies must focus on reducing photochemical oxidants through more coordinated reductions in NO_x and VOCs emissions to combat nonlinear photochemistry and aerosol chemical feedback. This work was published on *ES&T* (Fu et al., 2020) and was highly cited by the research community (with 205 citations, ESI highly cited paper).

Above policy-relevant findings have been conveyed to the National Joint Center for Air Pollution

Control and Prevention in Beijing, which is commissioned by the Ministry of Ecology and Environment, and have been taken into consideration in developing the Ozone Control Program since summer 2020 (see impact section).

Air quality Response to COVID-19 lockdown: The outbreak of coronavirus disease 2019 (COVID-19) severely threatened public health worldwide. Many countries imposed measures in 2020 to prevent the spread of the disease, including social distancing, teleworking, and closure of non-essential businesses. In 2022, the COVID-19 pandemic returned to China, affecting many cities which had to implement full or partial lockdowns again. The restrictions of human activities drastically reduced anthropogenic activities, resulting in a sharp decrease in emissions of air pollutants. The huge emission reductions during the COVID-19 lockdown can be treated as natural outdoor experiments to improve our understanding of the air pollutant's response to emission control, and the findings give guidance for future air pollution policies. The project team seized these rare opportunities and was among the first to analyse surface and satellite monitoring data and use global and regional chemical transport models to assess the impacts of COVID-19 lockdowns on atmospheric pollutants.

On a global scale, in collaborations with researchers from Germany and France, the international team constructed a dataset of adjustment factors (AFs) that can be conveniently embedded into existing global and regional emission inventories. In this project, we applied these AFs to the CAMS global inventory (CAMS-GLOB-ANT_v4.2_R1.1) and elucidated the changes in emissions of major pollutants around the world during the first six months of 2020. The results indicate that global emissions have declined. Due to differences in the implementation and lifting of lockdown policies, the emission reductions among different regions and sectors have shown significant differences (Doumbia et al., *Earth System Science Data* (IF=11.2), 2021). The team then employed the global Community Earth System Model to investigate how secondary pollutants in various parts of the world responded to changes in meteorology and emission reductions during the COVID-19 pandemic. We found that O_3 levels increased in NO_x-saturated regions like northern China, Europe, and the US, but decreased in NO_x-controlled regions (Gaubert et al., *JGR*, 2021). Overall, the averaged O_3 in the free troposphere during Northern Hemisphere spring and summer is found to be 5%–15% lower than 19-yr climatological values. About one third of this anomaly is attributed to the reduction scenario of air traffic during the pandemic, another third to the reduction scenario of surface emissions, and the remainder to 2020 meteorological conditions (Bouarar et al., *Geophysical Research Letters* (*GRL*, IF=4.6), 2021). These results highlighted meteorology as a substantial influencer in addition to emission reduction during the pandemic. The three papers have been cited 124 times.

On a regional scale, our team quickly examined changes in the primary and secondary pollutants in China, including the city of Wuhan, where the first case of COVID-19 was reported. Surface measurements made at more than 800 monitoring stations show that the mean levels of $PM_{2.5}$ and NO_2 in northern China have decreased by approximately 35% and 60%, respectively, after the lockdown following the COVID-19 outbreak of early 2020. Simultaneously, the ozone concentration has increased by a factor of 1.5–2. This rapid report of the air quality changes was published in *GRL* (Shi and Brasseur, *GRL*, 2020) and has been cited 325 times by subsequent studies. The project team then used the CMAQ model to quantify the drivers of the change of O_3 during the COVID-19 pandemic across China. The results revealed that O_3 decreased in the subtropical south while increasing in most other regions, influenced by meteorological changes and emission reductions. The plunge in NO_x emissions contributed to O_3 increases in populated regions, while VOC reductions led to O_3 decreases across the country. The varying levels of NO_x saturation from north to south resulted in O_3 increases in north China due to NO_x and VOC decreases, and O_3 declines in south China (Liu et al., *Science of The Total Environment* (IF=8.2), 2021). Similarly, during Shanghai's 2022 lockdown, despite significant precursor emission reductions, O_3 increased by 13%, primarily due to substantial NO_x reductions and the inability of VOC decreases to counteract NO titration effects (Tan et al., *ACP*, 2022; Zhang et al., *Atmospheric Environment*, 2024). Extending the analysis to 27 major Chinese cities, lockdowns, and heatwaves collectively increased O_3 concentrations in 23 cities. Machine learning results highlighted that emission reductions in transportation and industry, coupled with meteorological changes, elevated O_3 levels. In cities with substantial transportation reductions and stable temperatures, O_3 increases were chiefly attributed to NO_x emissions reduction. On the other hand, cities experiencing heatwaves and droughts saw O_3 increases driven by temperature rises and VOC emissions, offsetting NO_x reductions from transportation with increased coal-fired power emissions (Tan et al., *ES&T*, 2024). The figures in two of our papers were adopted in the Blue Book on Ozone Pollution Control in China (2023 Edition) published by the Ozone Professional Committee of China Environmental Science Society.

Overall, these findings underscore the complex and non-linear dependence of O_3 on its precursors, the importance of meteorology in short-term O_3 variability and the necessity of further curbing industrial emissions along with transportation sources and addressing heatwave effects on O_3 pollution to alleviate urban O_3 issues. These results provide guidance in design of future air policies.

Highlight 7. Comprehensive appraisal of O_3 formation under changing emission and climate

Globally, solutions to address the challenges of ozone pollution brought about by a warming climate remain under-explored. We compiled surface measurements from approximately 4,300 sites worldwide between 2014 and 2019. The results highlighted the emerging global challenge of O_3 pollution, characterized by an unintentional rise in O_3 levels due to uncoordinated emissions reductions and an increasing climate penalty. Several synergistic ozone-climate control strategies were proposed. First, an integrated management system based on the total health risks of climate change and air pollution (including O_3) should be formulated. Second, balanced emission reduction schemes and appropriate assessment methodologies that reflect the overall health risks of climate change and ozone pollution should be developed. Third, it is critical to develop and use low-carbon alternatives to address emerging sources of VOCs that sustain O_3 formation. This work has been published on a Cell Press Partner journal: One Earth (IF=15.1) (Lyu et al., 2023), which has been cited 29 times since its publication in August 2023.

In China, we explored how climate change exacerbates O_3 pollution through complex climatic, energy, and environmental interactions, with a focus on heatwaves. Research found that heatwaves and associated droughts in 2022 caused severe imbalances in energy supply and demand, increasing residential electricity consumption while reducing hydropower generation, thereby intensifying the use of fossil fuels, and sharply increasing regional NO_x emissions. The adverse weather conditions also enhance photochemical reactions and BVOCs/AVOCs emissions, significantly promoting the formation of O_3. This interaction led to severe O_3 pollution in China's central and eastern regions during the summer of 2022, posing a significant threat to public health and ecosystems. The study emphasizes that, with climate change expected to increase the frequency and intensity of heatwaves, diversifying clean energy sources and implementing stricter emission controls are crucial in addressing future climate challenges (Chen et al., *Science Bulletin* (IF=18.8), 2024).

We synthesized recent research on ozone pollution in China. We reviewed 570 English publications from 2015 to 2021, including our own papers, and investigated the variation, meteorological and chemical drivers of O_3 concentrations, and the impact of ozone pollution on human and ecological health. It not only covers the spatial distribution of O_3 in China but also specifically focuses on the key chemical processes responsible for ozone formation, including the impact of emerging halogen and HONO chemistry on ozone production. These findings provide important scientific evidence for understanding and addressing ozone pollution in China. It recommends further research needs under a changing climate and carbon neutral commitment. At the invitation of the IOP publisher, this work has been published in *Environmental Research Letters* (Wang et al., *ERL* (IF=5.8), 2022), which offers an up-to-date reference for advancing research and policy formulation on atmospheric ozone in China. This paper has been given an IOP Publishing Top Cited Paper Award 2024.

6.2 What was the added value of the TRS funding, rather than standard project grant funding?
(For example, could this work have been achieved with other funding scheme, such as the General Research Fund or Collaborative Research Fund? If not, why?)

TRS funding offers a unique set of benefits that other project grants like the General Research Fund (GRF) or Collaborative Research Fund (CRF) do not provide. By supporting interdisciplinary collaboration, collaborative efforts by multiple groups, long-duration studies, and large-scale comparative field research, TRS funding enables the research team to address the comprehensive and complex nature of environmental issues. These elements are essential for developing robust, sustainable, and effective strategies to protect and preserve our environment. Without TRS funding, achieving the same level of research depth and impact would be significantly more challenging.

(1)Interdisciplinary collaboration: The added value of the TRS funding is demonstrated by its capacity to facilitate interdisciplinary collaboration. Our project, through collaboration across various scientific disciplines such as chemistry, biology, computer science, and atmospheric science, forms a complete closed-loop from laboratory experiments, to field observations, and to model simulations, encompassing the entire process from atmospheric pollution chemical mechanisms to their impact assessments. This not only ensures that the new mechanisms we discover in our experiments can be applied to real-world environmental impact assessments, but also guarantees that our model simulations are grounded in reason and supported by evidence. Two examples are given here: we collaborated with soil microbial experts to quantify soil microbial reactive nitrogen emissions in the laboratory and worked with modelers to assess their impact on air quality; our field campaign observed high Cl_2 levels, then we demonstrated the detail generation mechanism through laboratory experiments, and finally this new mechanism is integrated into the a chemical transport model to assess its impact on air quality and to improve the model's simulation accuracy.

(2) Collaborative efforts by multiple groups: Facilitating collaboration among multiple research groups within the TRS project team is a key strength of TRS funding. Members from PolyU, CUHK, HKUST and HKEPD collaborated in field observations by bringing their advanced instruments to the EPD supersite to measure comprehensive list of gaseous and aerosol compositions which could not be achieved by any single group. Such comprehensive data and subsequent joint data analysis enabled the project to discover the novel formation mechanisms of secondary atmospheric pollutants, leading to publications in high-impact journals. The TRS project also enabled the members to integrate and apply multi-scale models to address air pollution across local, regional, and global scales (e.g., air quality response to the COVID-19 Pandemic).

(3) Long-duration studies: Another significant advantage of TRS funding is its support for long-duration studies. These studies are essential for observing and interpreting multi-year environmental changes and feedback mechanisms. Our research conducted observations at the sites in Hong Kong and North China in different years, capturing the responses of atmospheric pollutants to emission reduction measures. Observations in four autumn seasons (2018-2023) at the Hong Kong site confirmed the presence of high concentrations of reactive halogen, and the reductions in NO_x and SO_2 emissions have decreased nitrate levels and aerosol acidity, which is beneficial for mitigating the production of halogen radicals and their adverse effects on air quality. In northern China, the five-year duration between observations allowed us to visually discern the responses of reactive halogens to China's clean energy initiatives.

(4) Large-scale comparative field research: TRS funding also enables large-scale, multi-site research that can compare environmental conditions across different regions (e.g., coastal, urban and forested settings; south and north). This approach provides a broader and more comprehensive understanding of environmental issues by capturing regional variations and commonalities. For example, we have conducted halogen observations in Hong Kong, Hebei, Nanjing, and Qingdao. The formation of BrCl in Hebei is related to coal combustion, while daytime Cl_2 and Br_2 in Hong Kong are derived from nitrate photolysis. The relationship between halogen budgets and local pollution levels and air quality in different regions needs to be further investigated.

6.3 If the project has not met its original objectives, why? **NA**

6.4 (a) Please provide details of each peer-reviewed journal publication arising directly from this project by completing the table at **Annex** *(one for each publication)*. **Published 194 papers**

(b) Please provide details of recognised international conference(s) in which paper(s) related to this project was/were delivered by completing the following table:
(Please attach a copy of each conference abstract)

Month/ Year/ Place	Title	Conference name	Submitted to the RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of the RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
04/2024/ Vienna, Austria	Evaluation of Ozone Profile and NO_2 vertical column densities of Geostationary Environment Monitoring Spectrometer (GEMS) in China	European Geosciences Union (EGU) General Assembly 2024	No	Yes	Yes	Yes
05/2024/ Helsinki	Rethinking the air quality health index	The 14th International Conference on Air Quality	No	Yes	Yes	No
06/2024/ Pyeongchang, Kore	Important roles of oxygenated volatile organic compounds in photochemical pollution in Hong Kong	21st Annual Meeting of Asia Oceania Geosciences Society (AOGS)	No	Yes	Yes	No
09/2024/ Ilan, Taiwan, China	Characteristics, sources and chemical processes of organic aerosols in Hong Kong: From outdoors to indoors.	The 31st International Conference on Aerosol Science and Technology	No	Yes	Yes	No
12/2023/ San Francisco, USA	Abundant Oxygenated Volatile Organic Compounds and Their Contribution to Photochemical Pollution in Subtropical Hong Kong	American Geophysical Union (AGU) 2023 Fall meeting	No	Yes	Yes	Yes
07/2023/ Lyon, France	Molecular Characteristics, Formation and Impacts of Oxygenated Organic Vapors at a coastal site in Hong Kong	Goldschmidt 2023	No	Yes	Yes	No
11/2023/ Lisbon, Portugal	Understanding high levels of hydroxyl dicarboxylic acids (OHDCA) observed in China’s outflows	5th International Caparica Conference on Pollutant Toxic Ions and Molecules	No	Yes	Yes	No
12/2023/ San Francisco, USA	Impacts of Elevated Carbon Dioxide on the Emissions of Biogenic Volatile Organic Compounds (BVOCs) from Tropical/Subtropical Plants	AGU 2023 Fall meeting	No	Yes	Yes	No
08/2023/ Singapore	Establishment of national soil nitrous acid emissions network: parameterization and its effect on air quality	20th Annual Meeting of AOGS	No	Yes	Yes	No
12/2023/ San Francisco, USA	Changing composition and impact of reactive halogens in North China: An overview of two field studies during winter 2022	AGU 2023 Fall meeting	No	Yes	Yes	Yes
04/2023/online	Pollution-derived Cl_2 and Br_2 boost oxidation power of the coastal atmosphere	EGU General Assembly 2023	No	Yes	Yes	Yes
08/2023/ Singapore	Photochemical air pollution in highly urbanized subtropical regions: from micro environments to urban-terrestrial-oceanic interactions	20th Annual Meeting of AOGS	No	Yes	Yes	No

Month/ Year/ Place	Title	Conference name	Submitted to the RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of the RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
06/2022/ Taipei, Taiwan	Atmospheric Oxidation on Gasoline Vehicle Exhaust – Characteristics of Fresh and Aged Aerosol	The 12th Asian Aerosol Conference (AAC 2022)	No	Yes	Yes	No
04/2021/ Online	Large-Eddy Simulation for the Roughness Sublayers over Real Urban Surfaces	EGU General Assembly 2021	2021	Yes	Yes	Yes
04/2021/ Online	Wind Speed Parameterization and Turbulence Intermittency in the Roughness Sublayers over Urban Areas: a Wind Tunnel Study	EGU General Assembly 2021	2021	Yes	Yes	Yes
12/2020/ Online	Diverse response of ozone to the COVID-19 lockdown in northern and southern regions of China	AGU 2020 Fall meeting	2021	Yes	Yes	Yes
12/2019/ San Francisco, USA	Increasing trend of summertime surface ozone over China during 2013-2017: Variable meteorology and stringent emission control	AGU 2019 Fall meeting	2020	Yes	Yes	Yes
12/2019/ San Francisco, USA	The chemical and dynamic process of sea-salt chloride and its impact on ozone formation in coastal region of south China	AGU 2019 Fall meeting	2020	Yes	Yes	Yes
08/2019/ Singapore	High-resolution analysis of vehicle-related organic aerosols observed at a roadside site in Hong Kong with the application of TAG-GC-ToF-MS	16th Annual Meeting of AOGS	2020	Yes	Yes	No

(c) RGC funding should have been acknowledged in all publication(s)/conference papers listed in (a) and (b) above. If no acknowledgement has been made in any of the publications/ papers, please indicate and provide explanations. **NA**

6.5 To what extent this project has strengthened inter-institutional collaborations and other partnerships?

(1) <u>Strengthening inter-institutional collaborations</u>:

a) <u>*BVOCs measurement and model development*</u>: T. Wang's group at PolyU and X.M. Wang's group at GIG have collaborated to incorporate the measured BVOC EFs into the current MEGAN model. They also collaborated with Alex Guenther (project's advisor) from UCI to implement the drought index in MEGAN and evaluated its performance.

b) <u>*Chamber development and experiments*</u>: Groups of S.C. Lee, K.F. Ho, T. Wang, and Z. Wang jointly conducted chamber experiments on isoprene oxidation. A photochemical chamber system and photochemical flow tube reactor were also developed and characterized by the collaborative groups of S.C. Lee from PolyU and K.F. Ho from CUHK.

c) <u>*Collaboration in the 2018 field campaign*</u>: The intensive field campaign was a collaborative effort involving most of the Co-PI teams. The supersite is routinely maintained by HKEPD, and some trace gases and aerosol composition are continuously measured. Additional reactive species and secondary products are added during the two intensive campaigns by different groups, including Prof. T. Wang, Prof. S.C. Lee, Prof. H. Guo from PolyU, Dr. Z. Wang from HKUST, Dr. K.F. Ho from CUHK. The day-to-day observation plan was guided by the air quality forecast results provided by Dr. Kenneth Leung from HKEPD. Several European researchers participated in the field campaign, including Prof. Christian George from IRCELYON-CNRS, Prof. Abdelwahid Mellouki from CNRS Orleans, and Prof. Mattias Hallquist from the University of Gothenburg. Several science meetings and workshops were conducted after the field studies to discuss the data quality, data sharing, and data analysis issues. The collaboration has produced a number of jounral papers, including one published in *Nature Geoscience*, one in *Nature Communnications*, 3 in *ES&T*, and one in *GRL*.

d) *Collaboration in the 2020 field campaign*: This was a collaborative effort involving T. Wang, S.C. Lee, H. Guo from PolyU, K.F. Ho from CUHK, and Z. Wang from HKUST. The day-to-day observation plan was guided by the air quality forecast by K. Leung from HKEPD. Several workshops were conducted after the field studies on the data quality, sharing, and analysis issues.

e) *Design and test of the WRF-LES model system*: The WRF-LES-Chem was taken care by G. Brasseur (MPI) and Y.T. Wang (PolyU), while C.H. Liu (HKU) focused on the CFD-LES-Chem.

f) *Megacity OOMs working group*: A working group consisting of researchers from PolyU, HKUST, Tsinghua U, Nanjing U, Helsinki U, BJUCT, SAES, and Aerodyne Research, was formed since Feb 2019 to collaboratively investigate OOMs in polluted environments.

g) *Emission inventory*: Anthropogenic chloride emission inventory from PolyU was shared with the HKUST group and Daniel Jacob's group at Harvard University. Ship emission inventory from HKUST was shared with PolyU.

Other collaborations included OH-CIMS optimization of the initial test by T. Wang and Z. Wang, Hong Kong long-term O_3 trend by T. Wang and G. Brasseur, policy-relevant analysis by Peter Louie and Alexis Lau, sharing emission inventory of anthropogenic chlorine and ships between HKUST and PolyU groups, analysis of organic markers by H. Guo and Allen Goldstein (project's advisor), vehicle emission and aging experiments by H. Guo and K.F. Ho, N_2O_5 uptake on aerosol by T. Wang, Z. Wang, and Yuanhang Zhang (project's advisor), air quality response to COVID-19 lockdown by G. Brasseur and T. Wang; BVOC impact on HK ozone, and 2022 heave impat on China air quality by T. Wang and Brasseur.

(2) Other Partnerships: In addition to collaborations within the project team, we also collaborated with many outside groups, such as Prof. Daniel Jacob (Harvard) and Dr. Alfonso Lopez (Spain), Prof. A.R Ravishankara (CSU), Prof. Christian George (CNRS), Mattias Hallquist (Sweden), and Dr. Golam Sawar (USEPA) on modeling on halogen chemistry, several scientists at NCAR on WRF-LES model development and the COVID-19 study, and many mainland scientists. We also contributed to two comprehensive reviews of tropospheric ozone and aerosol acidity with several dozens of international researchers. The collaborations are reflected in the published papers.

6.6 Research students trained (registration/awards):

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Wang Weihao	PhD	2014.09	2020.09/2021.03
Xia Men	PhD	2016.07	2020.12/2021.05
Dai Jianing	PhD	2017.01	2020.12/2021.06
Peng Xiang	PhD	2018.09	2021.06/2021.09
Wang Yanan	PhD	2018.09	2023.07/2023.12
Zou Zhouxing	PhD	2019.01	2023.01/2023.08
Jiang Yifan	PhD	2021.01	Not yet graduated
Tan Yue	PhD	2021.09	Not yet graduated
Zeng Lewei	PhD	2015.07	2020.05
Lu Haoxian	PhD	2016.08	2021.06
Yao Dawen	PhD	2017.09	2023.07
Huo Yunxi	PhD	2019.09	Not yet graduated
Li Haiwei	PhD	2015.07	2016.03/2019.08
Cui Long	PhD	2013.09	2018.04/2018.09
Tan Yan	PhD	2017.09	2021.04/2021.08

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Zhang Zhuozhi	PhD	2017.09	2023.01/2023.02
Yuan Qi	PhD	2019.01	2023.08/2023.12
Zhang Huina	Master	2017.09	2020.05
Zeng Jianqiang	PhD	2022.03	2024.06
Pang Weihua	Master	2021.09	2024.10
Zheng Penggang	PhD	2020.02	2024.08
Feng Xin	Master	2020.09	2022.08
Meng Ying	Master	2022.02	2024.01
Chen Yiang	PhD	2017.09	2022.08
Chen Wanying	MPhil	2019.09	2021.08
Kimberly Tasha Jiayi Tang	PhD	2020.10	2023.07
Yao Lan	PhD	2020.05	2024.04
Liu Yixun	PhD	2020.09	2024.08
Du Ruiqing	PhD	2020.09	2024.08
Mei Di	PhD	2020.09	2024.08

6.7 Specific products (e.g. software or netware, instruments or equipment developed):

A first long-term and grided soil emissions of HONO and NO for the world for model use; a first high-resolution anthropogenic chlorine and bromine emission inventory for China for model use; a semi-open dynamic plant chamber for BVOC emission research (a patent was granted) ; a BVOCs emission factor database for tropical plants for model use; parameterizations for N_2O_5 uptake on aerosol and Cl_2 production and their implementation in WRF-CAMQ model and WRF-Chem model; a box model integrating NOx-VOC-halogen reactions in MATLAB environment; a novel workflow combining binPMF method to identify the precursors of various OOMs; an optimized and calibrated CIMS system for ambient multi-halogen measurement;an optimized and calibrated CIMS system for ambient OH and HO_2 measurement; an optimized Tof-CIMS system for measurement of highly oxygenated organic molecules; Chemistry-LES model to investigate the air quality on the urban-scale.

6.8 Other education activities and/or training programmes developed:

(1) Research findings were included in the lectures for under-and post-graduate courses (CSE371-Environmental Chemistry and CE633- Urban Environment and Climate Change at PolyU; and ENVR2020 Urban Air Pollution, EVSM5280 Introduction to Atmospheric Aerosols, and ENVR5410 Atmospheric Chemistry at HKUST).
(2) Training of final-year undergraduate students, research assistants, and postdocs.
(3) Lectured at the 4th Sino-Europe School on Atmospheric Chemistry in Shanghai in Nov. 2019.
(4) Tutored the Innovative Practice Training Program for College Students of the University of Chinese Academy of Sciences.
(5) Co-organized a research student exchange and workshop on photochemical air pollution with Peking University, HKUST in Shenzhen in May 2019. More than 50 research students and postdocs attended the workshop, and 20 of them presented their research findings.
(6) Hosted summer training of a local high-school student who has been admitted to the Environmental Studies Program of Columbia University in the US.
(7) Provided summer training for undergraduate students, Mr. Zhang Jingwei from the EESD program of PolyU and Miss Lina Tang from Vassar college in the US.
(8) Gave seminars in IGAC-China open seminar series and PolyU CEE seminar series.
(9) Gave lectures in the Atmospheric Chemistry Summer School organized by Shandong University and other events in mainland China.

6.9 Please highlight any deliverables indicated in the project implementation timetable endorsed by the RGC which have not been covered or achieved as per sections 6.1 to 6.8 above, and explain/ elaborate. **NA**

Project Management

6.10 Please elaborate how the PC has played his/her role in coordinating and managing the project.

The PC closely monitored the progress of the project and coordinated research activities in five core areas by holding quarterly meetings and annual science conferences (during the prolonged COVID-19 pandemic period, online meetings were organized.) Moreover, the PC organized three joint field observations participated by multiple institutions, organised and prepared project reports, including the preparation for two major reviews by the RGC Monitoring and Assessment Panel (in 2019 and 2021) and RGC TRS Public Symposium (in 2022). He also engaged in various outreach activities to disseminate project's findings to the public and governments, as well as to the research community. He managed to set up a centralized office for the PolyU's project team, which facilitated more efficient project management, and a website to timely disseminate major activities and findings of the project.

The RGC's Monitoring and Assessment (M&A) Panel commented in the feedback report after the first major review "*The project PI has done an excellent job to manage the diverse team of researchers from multi-institutions and there is clear evidence of collaboration among them, as also evident from the list of co-authors in publications and the report presented which looks quite well put together in a consistent way. It reflects individual team's contributions and cohesiveness. There is good progression of the team members, partly contributed by the success of the project. Credit should be given to the PI and the team – Well done!*".

After the second major review, the M&A Panel commented on project management "*It is a large and complex consortium. PI has done an excellent job to bring all investigators together, keep them engaged towards achieving the project goals. The team seem very well engaged and knowing their role well in the consortium. Overall, it is very good to see the team led effectively and project activities managed efficiently". "Leading the team to the top level of international research*".

Some of the PC's contributions to the project management and coordination are given below.
(1) Organized the Project's kick-off meeting cum international workshop on 7 and 8 February 2018. Nearly 50 researchers and academics involved in the project attended the workshop. Project advisors, Prof. Yuanhang Zhang, member of the Chinese Engineering Academy and Dr. Steven Brown of the NOAA Earth System Research Laboratory of USA delivered keynote speeches. All Co-PIs, and collaborator introduced research plans in five core areas of the project. The workshop facilitated fruitful discussions of the implementation and management of the collaborative project.

(2) Organized the second advisory committee meeting on 29 January 2019. The PC introduced the overall progress of the project, followed by presentations from each Co-PI. The project's advisors, Prof. Yuanhang Zhang, Prof. Gregory Carmichael, Prof. Alex Guenther, and Prof. Allen Goldstein, attended the workshop and gave their advices to the project. Invited speakers, Prof. Min Shao, Prof. Allen Zheng, and Prof. Xuemei Wang, all from the Institute for Environmental and Climate Research at Jinan University introduced three National Key Research Projects funded by the MOST, and the meeting agreed collaborations among these large projects in the Greater Bay Area.

(3) Organized the third advisory committee meeting on 9-10 November 2023. The PC introduced the overall progress and outputs of the project, followed by presentations from each Co-PI or project team. Prof. Steven Brown, Prof. Min Shao, Prof. X.M. Wang and Prof. Allen Zheng attended the workshop and introduced three Projects funded by the MOST.

(4) In December 2022, PC attended the TRS public symposium held at the University of Hong Kong, where he presented significant outcomes and findings of the project, as well as policy recommendations for the governance of air pollution in Hong Kong.

(5) The PC, through the Project Office, made arrangements with the HKEPD to use its superstation for comprehensive joint field studies by the Project. Five Co-PIs conducted two large-scale joint filed campaigns in 2018 and 2020 at the station; liaised with the EPD to resolve the issues of using the site by the team members; requested and validated EPD data for use by the project team.

(6) PC made great efforts to set up a centralized project office, which houses the project members of

PolyU Co-PIs' and facilitates frequent exchanges and collaborations among them. (Previously, the project's PolyU students and postdocs sat in offices scattered in a large building.) Due to the severe shortage of space in PolyU, the PC worked with various departments and attended numerous meetings. The project office was finally secured, and group members moved in May 2019.

7. Awards and Recognition

7.1 Have any research grants been awarded that are directly attributable to the results obtained from this project?

(1) Field and laboratory investigations of reactive bromine gases and their impact on winter air quality, RGC General Research Fund (GRF) project, $759,431, 30 months, PI: T. Wang
(2) Hydrochloric acid in the polluted coastal atmosphere of South China: abundances, sources, and impacts, RGC GRF project, $983,500, 30 months, PI: T. Wang
(3) Deciphering the formation and accumulation of photochemical ozone in the three bays of China through field observations and model simulations: relevance and uniqueness, RGC GRF project, $911,317, PI: H. Guo
(4) Organic aerosols in offshore marine atmosphere of eastern and southern China: Sources, chemical ageing, and climate consequence, NSFC/RGC Joint Research Scheme project, $1,154,954+ RMB1,000,000, PI: H. Guo
(5) Rise in summertime ozone levels in South China: Impacts of long-range transport of southeast Asia emissions, RGC GRF project, $911,317, 36 months, PI: X. Lyu
(6) Sulfate production from hypobromous acid (HOBr) oxidation: implications for tropospheric sulfate and reactive bromine budgets, RGC GRF project, $911,317, 36 months, PI: Q. Chen
(7) Investigation of local and transboundary contributions to ozone formation and pollution episodes in Hong Kong, Environment and Conservation Fund, $1,200,000, 30 months, PI: Z Wang.
(8) Highly oxygenated products from aromatic VOCs oxidation in the urban environment and their impacts on air quality, RGC GRF project, $1,115,452, 36 months, PI: Z. Wang
(9) Source, formation, and gas-particle partitioning of nitro-phenolic compounds and their environmental impacts in subtropical Hong Kong, RGC GRF project, $1,051,805, 36 months, PI: Z. Wang
(10) Next-generation air pollution physics and chemistry model for urban areas, RGC CRF: HK$7,282,073, 36 months, PC: C.H. Liu
(11) Reactive organic trace gases in surface-earth system, NSFC, $1,200,000, 36 months, PI: Y.L. Zhang
(12) Volatile Organic Compounds Gold Standard Laboratory, Innovation and Technology Fund, $14,999,999, 24 months, PI: Alexis LAU
(13) Development of nanotechnology based hybrid air cleaning system towards green transport, Green Tech Fund, $5,561,400, 24 months, PI: S.C. Lee
(14) Evaluation of the contribution of vehicular emissions on oxidation and aging of gaseous and particulate secondary products in urban roadside Hong Kong, GRF, $1,145,452, 36 months, PI: M. Wang
(15) Ministry of Science and Technology of the People´s Republic of China, $20,000,000 RMB, PI: X.M. Wang
(16) National Natural Science Foundation of China, $10,000,000 RMB, PI: X.M. Wang

7.2 Have any project team members participated as invited speakers in or organisers of international conferences as a result of this project?

(1) S.C. Lee was an invited speaker at the 6th Cross-Strait Forum on Sustainable Urban Development, Shanghai, 17-18 May 2019.
(2) T. Wang was an invited speaker at the 4th Atmospheric Composition and the Asian Monsoon (ACAM) workshop (160 attendees from US, Europe and Asia), Malaysia, 26-28 June 2019.
(3) H. Guo was an invited speaker at the 16th Annual Meeting of AOGS, Singapore, August 2019.

(4) T. Wang was an invited speaker at the Atmospheric Chemistry Mechanisms Conference (online) organized by UC-Davis, October 2020.
(5) T. Wang and K. Leung were invited panelists at the 6th International Symposium (online) on 6th Regional Air Quality Management in Rapidly Developing Economic Regions (RAQM) organized by HKUST, 21-22 October 2020.
(6) T. Wang was an invited speaker at 102th American Meteorology Society Annual Meeting, Asian Aerosol Conference, 2022,
(7) Y.L. Zhang organized the "Biogenic VOCs: Emissions, Atmospheric Oxidation, and Impacts" sections on AOGS meeting and AGU meetings, 2023.
(8) T. Wang was an invited poster presenter at AGU Fall meeting, 2023
(9) Z. Wang gave an invited talk at the 8th World Chinese Mass Spectrometry Conference, Xi'an May 2024.
(10) Z. Wang serves as one of the organization committee members and session conveyors on the 7th RAQM organized by HKUST, May 2024.
(11) T. Wang was a keynote speaker at the 7th RAQM organized by HKUST, May 2024.
(12) Z. Wang serves as the session conveyor of AOGS 2024 21st Annual Meeting, Pyeongchang, June 2024.

7.3 Have any project team members taken leadership positions in editorial boards, scientific and professional organisations?
(1) Guy Brasseur serves as the program committee chair for AGU Fall meeting from 2021 to 2023.
(2) X.M. Wang started service as an associate editor of *Journal of Geophysical Research-Atmospheres* since Jan. 2021.
(3) T. Wang started service as an editor for *Atmospheric Physics and Chemistry* since Feb 2022.
(4) T. Wang continued to serve as a vice-chairman of the Ozone Pollution Control Professional Committee of Chinese Society of Environmental Sciences , and P. Louie and Z Wang as the deputy secretary-general, A. Lau, H. Guo, Z. Wang, and K. Leung as the standing members.
(5) H. Guo serves as an associate editor of *Science of the Total Environment*, an editor of *Aerosol & Air Quality Research*, and an advisory board member of *Atmospheric Environment*.
(6) Z. Wang serve as a guest editor for *Journal of Cleaner Production and Atmosphere*.
(7) Z. Wang serves a council member of the Hong Kong Society of Mass Spectrometry and a member of International Global Atmospheric Chemistry China Youth Working Group.
(8) Y.L. Zhang served as an associate editor of *Frontiers in Environmental Science* since 2021.

7.4 Any documentary proof of the application of technologies arising directly from this project?

Removal of roadside pollution by a self-developed streetlamp-type air cleaning system

7.5 Other awards and recognitions as a result of this project (please specify):
(1) Five of our journal papers are Web of Science ESI Highly-cited Papers; one paper of which also won the IOP Top cited Award.
(2) Project team member, Y.L. Zhang was awarded the NSFC Excellent Young Scientists Fund in 2020.
(3) Z. Wang was awarded the 2021 Excellent Young Scientists Fund (Hong Kong and Macao) of the NSFC.
(4) T. Wang was awarded the President's Awards for Excellent Performance/Achievements in Research and Scholarly Activities 2017/2018.
(5) S.C. Lee was elected as a fellow of Asian Aerosol Research Assembly (AARA), 2019.

8. <u>Impacts</u>

8.1 What are the current and expected impacts of the project on the long-term development of Hong Kong (social or economic development, e.g. patent, technology transfer, collaboration with external organisations, etc.)?

(1) Supported Hong Kong Government's revision of air quality standards and policies:
The project team conducted comprehensive, in-depth research on emissions, atmospheric processes, efficacy of emission-control measures, and health impact of air pollutants in Hong Kong and the Greater Bay Area (GBA) (see publications section). They identified the key chemicals and roles of meteorology in controlling ozone and $PM_{2.5}$ pollution, and recommended local measures to continue reduce NO_x and VOC emissions and cooperation with Guangdong to mitigate regional ozone pollution. The team also recommends consideration of increasing temperature in future air pollution control strategies.

These results have been communicated to the HKEPD via the project's quarterly meeting and other specially arranged meetings. In particular, four of the project's key members (A Lau, J Fung, T Wang, K Ho) served on the Air Science and Health Taskforce for Air Objective Review 2030, and they provided their expert opinions to the government on sources and heath impact of air pollutants. Our research results on local pollution and on the critical role of ozone transport to Hong Kong have supported the development of comprehensive local emission sources control and regional cooperation plan with Guangdong and Macau, as outlined in the Clean Air Plan for Hong Kong 2030 (https://www.eeb.gov.hk/sites/default/files/pdf/Clean_Air_Plan_2035_eng.pdf.)

In particular, our analysis of the long-term background ozone data obtained from the PolyU Background Air Monitoring Station at Cape D'Aguilar and other analysis has provided important information on the transport of outside ozone to Hong Kong. As stated by Dr. Kenneth Leung in an appreciation letter (see Appendix), Principal Assistant Secretary (Air Policy) of Hong Kong Government's Ecology and Environment Bureau, "… *the long-term data collected from this station have revealed the importance of long-range transport of air pollutants to Hong Kong's air pollution. Your research findings on the impact of long-range transport on Hong Kong ozone pollution provided scientific basis for HEPD to formulate a regional strategy for controlling ozone pollution with the Guangdong Provincial Government and to establish the HKEPD's Cape D'Aguilar Air Quality Superstation, the latter of which has greatly expanded the capability of the Government's Air Quality Monitoring Network. ... Recently, you conducted another comprehensive study .. . , this study yields new insights into the challenges and measures for controlling ozone pollution under climate warming, which provides updated support for HKEPD to refine our air monitoring program and cooperation with Guangdong"* [Supporting Letter 1]

(2) Supported the mainland China government in control of summer ozone pollution and winter haze:
We identified the cause increasing ozone pollution in urban areas of mainland China after the implementation of the Air Pollution Prevention and Action Plan (2013-2017). Our results indicate that the rising ozone accelerated winter haze formation in northern China, coal burning and nitrate emitted or produced a large number of reactive halogens which aggravated winter haze pollution. We recommended that anthropogenic VOC control should be implemented in winter as well as in summer. We conveyed our results to the National Center for Joint Air Pollution Control (which is commissioned by the Ministry of Ecology and Environment to recommend measures to control summer ozone and winter haze pollution for China) and many province/city environmental authorities such as Guangdong, Shenzhen, and Shanghai. As stated by the Center's Deputy Director, " *your methodology and recommendations have been valuable to my team in the implementation and evaluation of the ozone-precursor reduction initiative which was launched in the ozone-seasons since 2020 by the Ministry of Ecology and Environment, ... your results provided new scientific evidence to strengthen the impetus to the on-going campaign to replace coal with natural gas and electricity in rural areas of north China*". [Supporting Letter 2]. The ozone pollution lessened in 2020 and 2021 and coal burning pollution significantly decreased, according to official air monitoring data.

Our research on photochemical pollution has been adopted in the Bluebook on Atmospheric Ozone Pollution Prevention and Control in China (2020 and 2023) published by the Ozone Pollution Control Professional Committee of China Environmental Science Society (Supporting Letter 3). The Bluebook is being used by national, provincial and city environmental officials, environmental professionals in enterprises, as well as students and academics in ozone control and education.. T.

Wang and H. Guo served as Vice Chair and Standing Members of the Committee and contributed to the writing/commenting of the Bluebook.

(3) Demonstration of an air cleaning system for removing roadside air pollutants:
With increased numbers of vehicles and the ageing of old vehicles, roadside air pollution, especially NO_2 pollution from direct emission and chemical conversion of locally emitted NO by regionally produced ozone, is another air quality issue in Hong Kong. In collaboration with the Highways Department and HKEPD, Co-PI, S.C. Lee applied a self-developed streetlamp-type air cleaning system for improving air quality at sidewalks near the Hung Hom Cross Harbor Tunnel in Hong Kong. The removal efficiencies of these systems were 12.7%–16.9% for NO_2, 3.5%–10.0% for NO, and 19.2%–44.9% for $PM_{2.5}$ within a 944 m^2 assessment area. Commented by Mr Eddie Lee, Principal Environmental Protection Officer of the HKEPD "*These findings demonstrate the feasibility and effectiveness of the technology in a real-world environment. ... We anticipate significant potential for applying this technology on Tsuen Wan Road. ...We strongly promote this technology to the community. ... We plan to collaborate with relevant government agencies and environmental protection organizations to jointly promote the adoption and application of this technology.*" [Supporting Letter 4]. S. Lee's team is deploying the system in other traffic affected areas of Hong Kong to reduce the air pollution levels.

8.2 Others (please specify):

Exchange policy-relevant results with the governments:

a) Organized dialogue between the Hong Kong government and academia and discussed future air pollution research and control. The event was attended by the Secretary of Ecology and Environment Bureau and other senior officials, Apr. 2019.
b) Provided comments to a Ministry of Science and Technology's Key Project "Comprehensive prevention and control of $PM_{2.5}$ and ozone", Jul. 2019, Guangzhou.
c) Provided comments at project consultative meeting for "Ozone formation research and prevention measures in Shenzhen", Aug. 2019, Beijing.
d) Presented findings at a policy forum "Photochemical smog in China, research findings and science-policy interactions", Swedish Missions in Beijing, Oct. 2019.
e) Presented ozone and ship emission control experience at a Hainan air quality meeting which was attended by the then Director of the Hainan Provincial Department of Ecology and Environment, Nov. 2019.
f) Reviewed and commented on the first Blue Book on Ozone Pollution (2020) by Chinese Ozone Control Commission in Jun. 2020.
g) Organized 6th RAQM workshop and discussed (online) air pollution improvements in Oct. 2020.
h) Commented on Shanghai Joint Control of $PM_{2.5}$ and Ozone Project in Oct. 2020.
i) Presented results on ozone control in Dec. 2020, Guangzhou Environmental Monitoring Center.
j) Provided advice to the Shanghai Key Laboratory on $PM_{2.5}$ control in Dec. 2020.
k) Commented on ozone-$PM_{2.5}$ joint control at Guangzhou Ecology Environment Bureau in Mar. 2021.
l) Contributed to an O_3 Control Consultative Paper by the Chinese Academy of Engineering in Feb. 2021.
m) Discussed project's policy-relevant findings with HKEPD officials in Mar. 2021.
n) Discussed air quality status and future direction at the Committee for Ozone Pollution Control in Apr. 2021.
o) Provided advice on PRD air-quality improvement to the State Environmental Protection Key Laboratory on Air Quality Monitoring in May 2021.
p) Commented on the first-phase strategic research for Achieving World-leading Air Quality in Hainan Province, Jun. 2021.
q) Introduced the project's findings to senior HK government officials in Oct 2021.
r) Provided advice to GD Pearl River Estuary Atmospheric Observation Network, 14 Nov 2021.
s) Gave advice to GD-HK-Macao Joint Lab on Environmental Quality, Nov 2021.

t) Gave advice to the Shanghai Key Lab on Air Pollution Control, 8 Dec 2021.
u) Prof. Alexis Lau, Prof. T. Wang, and Prof. K. F. Ho served on the Air Science and Health Taskforce for Hong Kong Air Quality Objectives Review 2030, commented on the methodology and results of the consultants.
v) Prof. T. Wang and Prof. Alexis Lau served on the Expert Panel of Hong Kong EPD's Three-Year Ozone Study in the Greater Bay Area and commented on the design and findings of the project.
w) Prof. T. Wang commented on the Blue Book on Ozone Pollution (2023) by Chinese Ozone Control Commission in June 2023.
x) Suggested to the Guangdong Provincial Government that fewer eucalyptus trees should be planted based on the project's findings.
y) Gave advice at the State Key Lab on Source and Control of Air Pollution Complex Advisory meeting, 4 Jan 2022.
z) Gave advice at MOST PRD $PM_{2.5}$-O_3 joint control project evaluation meeting, 21 Jan 2022.
aa) Gave advice to two MOST Key Development projects, March 2024.
ab) Commened on two MOST Key Development projects, Beijing, 27 March 2024.
ac) Served on the Academic Committee of the Guangdong-Hong Kong-Macao Ecology and Environment Science Center and attended its first meeting on 9 May 2024.
ad) Gave suggestions on air quality data ultiliztions at the China Supersite Consortium Meetting in Nov 2024.

<u>Disseminating project findings outside academia:</u>
a) T. Wang served as a panelist at "Imagine Hong Kong - Towards a Clear Sky, Towards Zero Emissions, Sep. 2018" organized by Asia Society.
b) A. Lau and T. Wang Interviewed by China Daily in Apr. 2020 and provided views on Hong Kong's ozone pollution.
c) T. Wang gave a public webinar on China air quality in Dec. 2020.
d) T. Wang gave an invited talk at the Government Laboratory 100th Anniversary Event in Nov. 2023.
e) T. Wang contributed a popular science video. https://www.bilibili.com/video/BV1wv4y1f79P/

9. Sustaiailnability of the Project

9.1 Whether there are new ideas evolved <u>directly</u> from this project?

(1) This TRS project demonstrated Cl atom is highly reactive and can strongly influence atmospheric oxidation, thereby boosting the production of air pollutants like ozone and particulates. As an important precursor of Cl, the sources of HCl are not well quantified in the polluted atmosphere in part due to sparse real-time measurements of HCl. As a result, its abundance and atmospheric impact are poorly predicted in current air quality models in some places. Thus, we proposed a new GRF project to measure HCl and investigate its impact on atmospheric oxidation and air quality.

(2) This TRS project observed surprisingly high concentrations of BrCl, which provides a new and significant source of Br and Cl atoms and accelerates the production of secondary pollutants. And we found evidence that intense coal burning and photochemical reactions are responsible for the observed BrCl and other reactive bromine gases. Based on these results, we proposed a new GRF project to further investigate what extent coal burning exists as a significant source of air pollutants after the implementation of the "Coal to Gas and Electricity" campaign in rural areas.

(3) Ongoing climate warming has led to more severe and frequent weather extremes, such as heatwaves, which have been shown to significantly impact BVOCs emissions. Although the tropics are among the most affected regions, the effects of heatwaves on BVOCs emissions remain poorly understood. As a continuation of this project, we will further investigate how heatwaves influence plant BVOCs emissions and their implications for plant physiology and atmospheric chemistry. To continue researching BVOCs emissions and their impact on air quality and climate change, Co-PI X.M. Wang successfully applied a project from the MOST, and another project from the NSFC.

(4) Our current TRS report has identified significant impacts of soil HONO and NO emissions on

atmospheric oxidation and air quality. Therefore, we have collaborated with The Chinese University of Hong Kong to apply for a CRF project (result pending). The proposed research aims to assess how agricultural and food system transformation can mitigate nitrogen pollution and air quality in China. We will incorporate our updated parameterization scheme for soil HONO emissions into the new model and develop a chemical transport model that includes all reactive nitrogen emission modules.
(5) Based on field observations from this TRS project, we found that ship emissions are major contributors to VOCs in offshore and adjacent coastal areas. Existing research only partially reflects VOC emissions from ships, leaving a gap in understanding the characteristics of a wide spectrum of VOCs and OVOCs and their roles in local and regional secondary pollution. We proposed a new project aimed at addressing the gap of unidentified VOCs and OVOCs from shipping emissions and clarifying their roles and significance in O_3 photochemistry and regional pollution.
(6) This TRS project explored some effective synthetic catalytic materials for pollutant removal and purification, meanwhile identified some crucial gaseous contaminants at the tunnel and roadside. So a Green Tech Fund project was proposed by S.C. Lee and funded to utilize these material to a scale-up application for attenuating the NOx and VOCs contamination at different tunnels (entry/exit), closed street canyons, under-ventilated public transport interchanges (PTI), train stations, runways, customs ports, bus stops, car parks, taxi stands, sidewalks, and construction sites etc. in Hong Kong.

9.2 Whether there are new projects evolved directly from this project? **See 7.1**

9.3 Whether there are new collaborations developed directly from this project?
(1) Collaborated with Prof. Ivonne Trebs from Luxembourg Institute of Science and Technology, Agro-environmental Systems Group on global soil HONO emissions.
(2) Collaborated with Prof. Alex Guenther from University of California, Irvine on BVOCs emissions and improvement of model simulations.
(3) Collaborated with Prof. Alfonso Saiz-Lopez from Spanish National Research Council (CSIC) on global chemistry-climate model (CAM-Chem) simulations and halogen chemistry.
The project members have collaborated with many leading international researchers and organizations, as shown in the journal papers.

9.4 Please give details on how much money and from which sources has been obtained/requested for the specific purpose of continuing the work started under this project. **See 7.1**

10. Statistics on Research Outputs

(Please ensure the statistics in this section are consistent with the information presented in other sections of this report.)

	Peer-reviewed journal publications	Conference papers	Scholarly, books, monographs and chapters	Patents awarded	Other research outputs (please specify)	
					Type	No.
No. of outputs arising directly from this research project	194*	19	0	1	NA	0

** Published 10 high impact papers in top journals, including 1 Nature Geoscience, 2 Nature Communications (1 accepted in principle), 1 PNAS, 3 National Science Review, and 1 One Earth.*

11. Public Access of Completion Report

(PCs of projects funded in 2010/11 academic year or onwards are required to release the completion reports to the public through the RGC website. Completion reports containing information such as abstracts in non-technical terms, objectives, research output including the list of conference papers / publications / journals and research findings and contact information of PCs should be open to public access.)

Please specify the information, if any, that cannot be provided for public access and give the reasons. **N.A.**

12. <u>The Layman's Summary</u>

(describe in layman's language the abstracts and research impact of the project.)

This project consists of comprehensive research investigating photochemical air pollution-a pressing environmental problem in the world's urban and industrialized regions, including Hong Kong. Ozone and fine particulate are major air pollutants. Since January 2018, the project has conducted a series of coordinated laboratory, field, and numerical studies. The major scientific achievements made thus far include the discoveries of the important roles of halogen atoms in air quality in polluted regions, the quantification of soil reactive nitrogen emissions and their impact on air quality, the new source/production pathway of organic particulate matter, and the complex responses of secondary air pollutants to emission controls. Based on the findings, the project has recommended additional measures to mitigate winter haze in north China and photochemical smog in south China. The findings have been disseminated to news media to promote public awareness of the importance of academic research and the current air pollution.

This project has significantly impacted three aspects: knowledge, policy, and capability. On the knowledge front, the project identified pathways for the generation of halogen gases and organic fine particles that exacerbate photochemical pollution in polluted areas, unveiled the emission of reactive gases from subtropical plants and soils, and published relevant research findings in high-impact journals. On the policy front, the project recommended that mainland China strengthen control over volatile organic compounds while managing other pollutants; meanwhile, Hong Kong needs to further enhance control over aromatic hydrocarbons and consider regulating halogen emissions. In terms of capability enhancement, the project ensured the reliability of accurate air quality forecasting by establishing comprehensive and detailed emission inventories and optimizing air quality prediction models. Additionally, the PhDs and postdoctoral fellows trained by this TRS project are actively contributing to air quality improvements in various positions within academia, government, and industry.