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RESPONSE TO REVIEWER

General Response: We thank the reviewer for these very helpful comments. We thank the reviewer for supporting the need of an introduction paper to this special issue and for agreeing that we have responded well the previous round of reviews.

Comment 1: Serious efforts are deemed necessary to improve the writing quality, logical flow, and clarity. The current version contains many parts that are vague, hard to follow, and abundant of grammatical errors. The manuscript also sometimes reads like a compilation of texts from multiple authors without a streamlined integration. Several issues are pointed out below in this review but the list is far from complete. A careful proofreading and English editorial job would be necessary.
Response: We have carefully re-written almost all parts of the papers to improve the writing quality, logical flow and for clarity. In order to improve the flow, the review of meteorological conditions is brought forward after the description of the campaign sites and instrumentation and before the brief review of measurement data.

Comment 2: The article is also on the long side with details that appear to be redundant and somewhat distracting.
Response: In the absence of more information, we were unable to identify the specific problems and make an informed revision. We did, however, look at the whole paper, revise the paper substantially, and removed information that we felt not critical to the paper (e.g., Fig. 1c) and moved five figures to the supplement.

Comment 3: The scientific values and innovative aspects of the project should be emphasized more.
Response: We thank the reviewer for this comment and now emphasized the novelty of the APHH-Beijing project in section 3.2.

Page 10 Line 338: " Together, this interdisciplinary APHH-Beijing programme delivers key scientific values and innovation, including:
(1) Validation of the bottom-up emission inventories by using novel eddy covariance emission flux observations from the IAP meteorological tower, integrated with satellite retrievals and numerical modelling,
(2) Improvement in understanding of air pollution processes through comprehensive observations of atmospheric gaseous and aerosol species integrated with atmospheric physics measurements, and
(3) Identification of the sources of air pollution that cause adverse human health effects by carrying out novel cardiovascular health indicator measurements, integrated with personal exposure and fixed station source apportionment studies."

Comment 4: Page 2-3, the revised abstract shows no improvement and remains ineffective. The revisions and rearrangement of the textst are sometimes confusing. For example, information on "the two campaigns" should be mentioned before the sentence on line 80. The added discussions on pollution concentrations do not fit well. The abstract should be rewrittend.
Response: In the absence of more information, we were unable to identify the problems with the abstract. Thus, we have gone back to past published introduction papers to special issues and attempted to re-write this

abstract following the styles in those papers. We put much emphasise in introducing the APHH-Beijing programme and attempted to improve the flow of information. We also moved the detailed information on air quality and meteorology during the campaigns to the end of section 5 (i.e., section 5.5. Summary of air quality during the campaigns).

Comment 5: Line 125, it is strange to claim Mexico City as a developed megacity while Beijing a developing one.
Response: Mexico City has been taken out of the list of developed megacities.

Comment 6: Line 252, is AIRPOLL-Beijing part of APHH-Beijing? Multiple acroynmed studies, sucha as AIRPRO, AIRELESS, APIC-ESTEE, INHANCE, etc, are discussed, but their relationships to APHH are unclear. It could be helpful to add a paragraph earlier in the manuscript to introduce these studies and explain their relationships with APHH.
Response: APHH-Beijing is a large research programme including four research themes delivered by five research projects. Theme 1 and 2 are addressed by AIRPOLL-Beijing and AIRPRO respectively. Theme 3 is addressed by two projects - APIC-ESTEE and AIRLESS and Theme 4 by INHANCE.

We have now added information at the beginning of Section 3 (Line 201 1):
"The APHH-Beijing programme has four themes to address the specific objectives outlined in Section 2, and is delivered through five inter-related research projects. :
- Theme 1 - Sources and emissions: delivered by the AIRPOLL-Beijing (Source and Emissions of Air Pollutants in Beijing) project;
- Theme 2 – Atmospheric processes: delivered by the AIRPRO (The integrated Study of AIR Pollution PROcesses in Beijing) project;
- Theme 3 – Health effects: delivered by the AIRLESS (Effects of AIR pollution on cardiopuLmonary disEaSe in urban and peri-urban reSidents in Beijing) and APIC-ESTEE (Air Pollution Impacts on Cardiopulmonary Disease in Beijing: An integrated study of Exposure Science, Toxicogenomics and Environmental Epidemiology) projects;
- Theme 4: Solutions: delivered by the INHANCE (Integrated assessment of the emission-health-socioeconomics nexus and air pollution mitigation solutions and interventions in Beijing) project."

Other points –
RESPONSE: All of these have been addressed in editing the text into better English.

Introduction to Special Issue - In-depth study of air pollution sources and processes within Beijing and its surrounding region (APHH-Beijing)

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Abstract. ~~APHH-Beijing~~ The ~~(~~Atmospheric Pollution and Human Health in a Chinese Megacity (APHH-Beijing) programme is an international collaborative project ~~to examine~~focusing on understanding the sources~~ the emissions~~, ~~-~~processes and health effects of air pollution in the Beijing megacity. ~~The four research themes of~~ APHH-~~China~~ Beijing brings together leading China and UK research groups, state-of-the-art infrastructure and air quality models ~~are~~to work on four research themes: (1) sources and emissions of air pollutants~~ of urban atmospheric pollution~~; (2) atmospheric processes affecting urban ~~atmospheric~~ air pollution; (3) air pollution exposure and ~~exposure science and impacts on~~ health impacts; and (4) interventions and solutions~~ to reduce health impacts~~. Themes 1 and 2 are closely integrated and support Theme 3, while Themes 1-3 provide scientific data for Theme 4 ~~on~~ to ~~the~~ develop~~ment of~~ cost-effective air pollution mitigation solutions. This ~~introduction~~ paper provides an introduction ~~of~~ to (i) the rationale of the APHH-Beijing programme, and (ii) the measurement and modelling activities performed as part of it~~ in Beijing~~. In addition, this paper introduces the meteorology and air quality conditions during two ~~the~~ joint intensive field campaigns - a core integration activity in APHH-Beijing. The coordinated ~~, and (iii) the air quality and meteorological conditions during the two field campaigns. A key activity within APHH-Beijing was the conduct of two month-long intensive field campaigns.~~campaigns provided observations of the atmospheric chemistry and physics at two sites: (i) the Institute of Atmospheric Physics in central Beijing, and (ii) ~~rural~~ Pinggu in rural Beijing during 10 November – 10 December 2016 (winter) and 21 May- 22 June 2017 (summer). ~~The coordinated campaigns provided observations of the atmospheric chemistry and physics in and around Beijing during 10 November – 10 December 2016 (winter) and 21 May- 22 June 2017 (summer).~~ The campaigns were complemented by numerical ~~air quality~~ modelling and automatic air quality ~~and meteorology data~~ ~~observations~~ and low-cost sensor observations ~~at the 12 national monitoring stations~~ in the Beijing megacity. ~~The winter campaign was characterised by several high $PM_{2.5}$ pollution events with peak hourly concentrations at the urban site~~

~~ranging up to 498 μg m^{-3}, whereas the summer experienced events of high ozone concentrations with the highest hourly average up to~~ of 176 μg m^{-3}~~ppb. Air quality was generally poor during the winter campaign with an average $PM_{2.5}$ concentration of 96 μg m^{-3}, but less severe than in the same period in 2015. Synoptic scale meteorological analysis suggests that the greater stagnation and weak southerly circulation in November/December 2016 contributed to the poor air quality during all haze events detected. $PM_{2.5}$ levels were relatively low during the summer campaign with the highest daily concentration of only 79 μg m^{-3}, matching the cleanest periods over the previous five years.~~ In summary, t~~T~~he paper provides background information on the APHH-Beijing programme, and sets the scene for more focussed papers addressing specific aspects, processes and effects of air pollution in Beijing.

1. ~~INTRODUCTION~~ Introduction

Air pollution is one of the largest environmental risks. It is estimated that air pollution has led to 7 million premature deaths per year globally (WHO, 2016a, b) and over a million in China (GBD MAPS Working Group, 2016). Air pollution also has significant impact on the healthcare system and ecosystems, which cost about 0.3% of global GDP (OECD, 2016). Air pollution related sickness also ~~reduced~~ reduces productivity and severe hazes lead to closure of transport systems, causing additional damage to the economy. Total economic losses related to China's $PM_{2.5}$ (particulate matter with aerodynamic diameter equal to or less than 2.5 μm) pollution in 2007 amounted to 346 billion Yuan (£39 billion~~s~~, approximately 1.1% of the national GDP) based on the number of affected Chinese employees whose work time in years was reduced because of mortality, hospital admissions and outpatient visits (Xia et al., 2016).

Considerable research effort has led to huge progress in understanding the sources and pollution processes in megacities in western countries, e.g., major interdisciplinary and multi-institutional programmes in ~~Mexico City,~~ Paris and London in the last few years (~~(Molina et al., 2010;~~ Beekmann et al., 2015; Bohnenstengel et al., 2014). Although air pollution in developed megacities sometimes breaks country specific limits and WHO guidelines, traditional London or Los Angeles type smogs which occurred in the early and mid-20th centuries are rare in developing cities to the same extent. In the developing countries however, the rush to industrialisation and rapid growth in vehicle populations have led to serious air pollution problems that are more complex than the London or Los Angeles smogs.

Air pollution is particularly severe in developing megacities, such as Beijing, where pollutants from traditional sources, such as solid fuel combustion are mixed with those from modern vehicles (Guan et al., 2014), on top of regional pollution from industrial and other anthropogenic activities. Air pollution in Beijing is different to that in well studied developed megacities, such as Paris and London, in a number of ways including the lack of diesel emissions in the inner city, the use of coal in surrounding rural areas for heating and domestic cooking (Tao et al., 2018), the high emissions of air pollutants in neighbouring provinces (Hebei and Tianjin) and the high oxidising power due to the complex chemistry (Zhang et al., 2009; Li et al., 2017; Lu et al., 2018). This makes Beijing a particularly interesting place to study as it provides an atmospheric environment with major contrasts to developed megacities such as London and Paris in which to investigate urban pollution processes.

~~research effort has led to huge progress in understanding the sources and pollution processes in megacities in western countries, e.g., major interdisciplinary and multi-institutional programmes in Mexico City, Paris and London in the last few years (Molina et al., 2010; Beekmann et al., 2015; Bohnenstengel et al., 2014). Air pollution in megacities in developing countries is different to that in other well studied developed megacities, such as Paris, Mexico City and London, in a number of ways including the lack of diesel emissions in the inner city, the use of coal in surrounding rural areas for heating and domestic cooking (Tao et al., 2018), the high emissions of air pollutants in neighbouring provinces (Hebei and Tianjin) and the high oxidising power due to the complex chemistry (Zhang et al., 2009; Li et al., 2017; Lu et al., 2018). This makes Beijing a particularly interesting place to study as it provides an atmospheric environment very different to developed megacities such as London and Paris to investigate urban pollution processes.~~

Many research programmes ~~were~~ have been initiated in Beijing to study the air pollution processes since the late 1990s. Earlier research programmes (e.g., early 2000) focused on primary emissions of SO_2, NO_2, CO, PM_{10}, volatile organic compounds, and ~~then~~ subsequently secondary pollutants such as ground-level ozone and secondary fine particles. Theis~~se~~ research~~es~~ contributed to the development of air pollution mitigation strategies introduced by the Beijing Municipal government.

The Beijing Olympic Games (2008) offered additional incentives to improve air quality and this led to the funding of CAREBEIJING (Campaigns of Air Pollution Research in Megacity Beijing and Surrounding Region) and other major programmes. ~~CAREBEIJING was initiated and organized by Professor Tong Zhu of Peking University, with participation of hundreds of scientist and students from China, USA, Germany, Italy, Japan, and South Korea.~~ The field campaigns were conducted in the summer of 2006, 2007, and 2008, with the objectives to learn the environmental conditions of the region, to identify and quantify the processes (transport and transformation) that lead to the impact of the surrounding area on air quality in Beijing, ~~to quantify the impact of the surrounding area on air quality in Beijing,~~ and to formulate policy suggestions for ~~the~~ air quality ~~attainment~~ improvement during the 2008 Beijing Olympic Games. ~~Other major research programmes, initiated since early 2000, aimed to provide scientific basis to deliver air pollution mitigation measures for ensuring a good air quality during the Olympics Games.~~ Measures developed as a result of ~~these~~ this and other programmes successfully ~~reduced the air pollution~~improved air quality during the Olympics Games, and provided valuable examples for developing air pollution control policy~~-making~~ in other cities (Wang et al., 2010). CAREBEIJING ~~latter on~~ was later extended to CAREBEIJING-NCP (Campaigns of Air Pollution Research in Megacity Beijing and North China Plain), ~~where~~ in which field campaigns were carried out in the summer of 2013 and 2014 to investigate the transport and transformation processes of air pollutants in ~~megacity~~ the Beijing megacity and North China Plain. The results of CAREBEIJING and CAREBEIJING-NCP have been published in three special issues of Atmospheric Chemistry and Physics (https://www.atmos-chem-phys.net/special_issue198.html) and Journal of Geophysical Research-Atmospheres (https://agupubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)2169-8996.CARBS1). ~~These large research programmes and numerous discovery science projects significantly enhanced our understanding on the emission, sources and processes of air pollutants in Beijing (Chan and Yao, 2008; Zhu et al., 2012).~~ However, our understanding of sources and emissions of key air pollutants such as $PM_{2.5}$ and ozone and the role of the interactions between physical and chemical processes in the ~~formation~~ development of pollution events in ~~the~~ Beijing ~~megacities~~ is still far from being accurate or complete. In addition, none of the abovementioned large programmes ~~are~~ have been directly linked to health effect studies.

The ~~A~~adverse health effects of air pollution ~~is~~ provide one of the key motivations to control air pollution. Research has shown that air pollution is one of the leading causes of the disease burden in China (GBD MAPS Working Group, 2016). Especially, particulate pollution, the leading cause of severe air pollution events in China, has a significant impact on human health and is associated with high mortality (Zhang et al., 2017a), with a considerable proportion of this related to cardiorespiratory diseases (namely stroke, ischemic heart disease, and chronic obstructive pulmonary disease) (Yang et al., 2013; Lozano et al., 2013). Despite this increasing evidence base, the adverse health impact of air pollution remains a complex issue. For instance, the risk assessment of disease burden due to air pollution in China has relied largely on the studies undertaken in Europe and North America, which ~~likely over-simplifies estimates~~may be subject to error due to the difference of race, life style, and air pollution settings (Lim et al., 2012). The marked change in air pollution sources and composition between the heating and non-heating seasons, and the differences between urban and rural areas may all lead to different biological responses in local ~~residents~~populations. However, to date, such comparative investigations are largely lacking. A further limitation of such work is the lack of accurate personal exposure estimates which are crucial in high quality health studies. This may be especially true when considering household air pollution (both indoors and outdoors) from traditional biomass and coal stoves which may not be easily captured by ~~ambient located~~typical outdoor monitoring instruments (Linn et al., 2001; Brook et al., 2002). Thus, ~~To address current uncertainties and challenges it is essential to improve~~ understanding ~~of~~ the health impact of air pollution ~~worldwide~~in China remains a major challenge~~, and to develop mitigation measures with limited resources onwhich reduce pressures upon health services~~.

To address these issues, the UK Natural Environment Research Council (NERC), in partnership with the National Science Foundation of China (NSFC), UK Medical Research Council (MRC) and UK-China Innovation Newton Fund funded a major joint research programme – Atmospheric Pollution and Human Health in a Chinese Megacity (APHH-Beijing). The APHH-Beijing is an integrated research programme, incorporating the capabilities~~y~~ and strengths of the UK and Chinese~~a~~ science communities~~y~~ ~~and~~ which is taking a multi-disciplinary approach to investigating the sources, processes and health effects of air pollution in the Beijing megacity~~(1) sources and emissions of urban atmospheric pollutants; (2) processes affecting urban atmospheric pollution; and (3) the exposure and impacts of air pollution on human health~~. The new scientific understanding ~~from these three themes~~ underpins the development of interventions and solutions to improve air quality and reduce health impacts.

This special issue "In-depth study of air pollution sources and processes within Beijing and its surrounding region (APHH-Beijing)" documents the research outcomes of this APHH-Beijing programme, in particular the atmospheric measurement and modelling aspects.

This introduction paper describes the motivation and background of the APHH-Beijing programme, and presents some of the background air quality and meteorological~~y~~ observations, particularly during the two intensive field campaigns. These campaigns form one of the core research activities within APHH-Beijing integrating the different themes / projects. We ~~did not intend to~~do not present the key scientific results of APHH-Beijing ~~here~~ in this introduction (not an overview) paper as much of the research activity~~ies~~ are still ongoing and unpublished. ~~Such information is more suitable to go to an overview paper instead~~Key findings will be published in the Special Issue to which this paper provides key background information.

2. APHH-Beijing Programme Objectives ~~APHH-BEIJING PROGRAMME OBJECTIVES~~

The overall aim of APHH-Beijing is to better understand the sources, atmospheric transformations and health impacts of air pollutants in the Beijing megacity and to improve the capability of forecasting air quality and developing cost-effective mitigation measures. Specific objectives include:

- to determine the emission fluxes of key air pollutants and to measure the contributions of different sources, economic sectors and regional transport to air pollution in Beijing
- to improve understanding of the processes by which pollutants are transformed or removed through transport, chemical reactions and photolysis and the rates of formation and conversion of particulate matter (PM) via atmospheric reactions
- to improve understanding on how the detailed properties of ~~particulate matter~~ PM evolve and can influence their physical properties and behaviour in the atmosphere and elucidate the mechanisms whereby those properties may interact and feedback on urban scale and regional meteorology
- to exploit new satellite observations and regional models to place the *in-situ* campaigns into a wider context
- to determine the exposure of Beijing inhabitants to key health related pollutants using personal air pollution monitors and assess the association between air pollution exposure and key cardiopulmonary measures
- to determine the contribution of specific activities, environments and pollution sources to the personal exposure of the Beijing population to air pollutants ~~derived from outdoor sources~~
- to enhance our understanding of the health effects in susceptible individuals over time periods when there are large fluctuations in pollutants compared with normal controls, and to identify health outcomes of air pollution~~.~~
- to estimate economic loss due to both physical and mental impacts of air pollution and examine how Beijing can improve its air quality more cost effectively

3. Research Themes and Integration within the APHH-Beijing Programme~~RESEARCH THEMES AND INTEGRATION WITHIN THE APHH-BEIJING PROGRAMME~~

The APHH-Beijing programme has four themes to address the specific objectives outlined in ~~(~~ Section 2~~)~~, and is delivered through five inter-related research projects~~.~~:

- Theme 1 - Sources and emissions: delivered by the AIRPOLL-Beijing (Source and Emissions of Air Pollutants in Beijing) project;
- Theme 2 – Atmospheric processes: delivered by the AIRPRO (The integrated Study of AIR Pollution PROcesses in Beijing) project;

- Theme 3 – Health effects: delivered by two projects - the AIRLESS (Effects of AIR pollution on cardiopuLmonary disEaSe in urban and peri-urban reSidents in Beijing) and the APIC-ESTEE (Air Pollution Impacts on Cardiopulmonary Disease in Beijing: An integrated study of Exposure Science, Toxicogenomics and Environmental Epidemiology) projects;
- Theme 4: Solutions: delivered by the INHANCE (Integrated assessment of the emission-health-socioeconomics nexus and air pollution mitigation solutions and interventions in Beijing) project.

3.1 Research Themes

3.1.1 Theme 1: Sources and emissions

~~This topic is addressed by the AIRPOLL-Beijing (Source and Emissions of Air Pollutants in Beijing) project.~~ AIRPOLL aims~~ed~~ to quantify the emission fluxes of key air pollutants in Beijing and the contributions of different sources, economic sectors and regional transport to air pollution in Beijing. ~~Several science topics addressed individual issues, which are integrated to achieve the overall aims.~~ The project has carried out two major field ~~measurement~~ observation campaigns jointly with the AIRPRO ~~(The integrated Study of **AIR** Pollution **PRO**cesses in Beijing)~~ and AIRLESS ~~(Effects of **AIR** pollution on cardiopu**L**monary dis**E**a**S**e in urban and peri-urban re**S**idents in Beijing)~~ projects (Sections 3.1.2 and 3.1.3) during November-December 2016 and May-June 2017. ~~-~~The campaigns were carried out at two ~~using~~ sites - one within Beijing (at the Institute of Atmospheric Physics (IAP) meteorological tower site) and the other in the local region (the rural Pinggu site – see 4.1 for site information). ~~During winter and summer sampling campaigns, AIRPOLL measured the concentrations of key tracers and reactive species indicative of sources and chemical pathways at the ground-level sites. AIRPOLL also analysed the vertical concentration profiles measured in conjunction with data from monitoring sites across Beijing. As Beijing is subject to long-range transport of pollutants from neighbouring regions, a key aim was to differentiate advected pollutants from local emissions. Local sources include road traffic, cooking, burning of fossil fuels by industry and for domestic heating. Secondary pollutants are expected to be largely advected, but the geographic scale of Beijing is sufficient for some formation of secondary pollutants within the city.~~

During the intensive campaigns, the project measured the fluxes of particulate and gaseous air pollutants from ground-level sources by sampling on ~~a~~the meteorological tower (325 m) at the IAP site, which are being compared with emissions estimates taken from the inventory for Beijing. This was complemented by top-down fluxes inferred from satellite data for nitrogen dioxide, sulphur dioxide and formaldehyde, the latter indicative of VOC oxidation processes (Palmer et al., 2003; Fu et al., 2007). Through these means, the emissions inventory ~~are~~ is being tested, allowing revisions which are being incorporated into the atmospheric modelling work.

AIRPOLL also made very detailed on-line and off-line measurements of airborne particles. This included continuous measurements of size distributions from 1 nm to >10 µm diameter. Large molecules and molecular clusters were also measured by high resolution mass spectrometry, with a view to better understanding atmospheric nucleation processes. The project has monitored the chemical composition of particles in real time by Aerosol Mass Spectrometry and analysed the time-integrated particle samples off-line for major and minor constituents, including organic molecular markers. AIRPOLL determined the carbon-14 in water soluble organic carbon, water insoluble organic carbon and elemental carbon in selected time-integrated particle samples with an aim to differentiate fossil and non-fossil particulate carbon. These data are being brought together for use in receptor modelling of ~~particulate matter~~PM sources, which are compared with other estimates of source contributions to ~~particulate matter~~PM concentrations. Measured ground-level concentrations both from our campaign sites and the Beijing monitoring network, together with vertical gradient observations at the tower and source apportionment results are compared with the predictions of a chemistry-transport model and used to provide a clear distinction between advected regional pollution and the impact of local sources. Divergences between measured and modelled pollutant concentrations will be used to provide critical evaluation of emissions inventories, which will be enhanced iteratively with a view to improving knowledge of the sources and emissions of pollutants affecting air quality in Beijing.

During the campaigns, AIRPOLL and AIRLESS measured the concentrations of key tracers and reactive species indicative of sources and chemical pathways at the ground-level sites, which complements AIRPOLL observations~~Data from AIRPOLL-Beijing measurement and modelling work will also contribute to the aims of the AIRPRO project to elucidate the atmospheric physical and chemical processes determining the measured composition~~.

3.1.2 Theme 2: Atmospheric processes

~~The aims of the~~ AIRPRO ~~aims project~~ aims ~~are~~ to study the ~~basic~~ fundamental chemical and physical processes controlling gas and ~~aerosol~~ particle pollution, localised meteorological dynamics, and the links between them within Beijing's atmosphere. ~~Once released to air, atmospheric processing controls how pollutants are subsequently deposited, transformed into secondary pollutants such as O_3 and particulate matter (PM) or transported away from or within the wider Beijing urban area. Previous studies of pollution in Beijing have shown that the interactions of physical conditions, such as the development of temperature inversions in the atmosphere, and chemical processes, e.g., formation of secondary pollutants, such as aerosol particles and ozone that modulate the most severe air quality events.~~ Central to the project were the intensive *in situ* measurements at the IAP meteorological tower (325 m) site, jointly carried out with the AIRPOLL -project~~in Beijing during November-December 2016 and May-June 2017~~. ~~We~~ AIRPRO made comprehensive and detailed local observations of both primary emitted chemicals and particles, radical intermediates and secondary products, for periods of contrasting local and regional emissions, solar insolation and air temperature. These data allow the performance of local and regional models of air pollution to be robustly tested, both for final regulated pollutant outcomes and at a more mechanistic level.

~~The o~~Observations ~~collected~~ made with instruments from multiple Chinese and UK research groups included complementary measurements of key precursor trace gases such as NO_x, HONO, SO_2, CO, O_3, VOCs and SVOCs, gas phase radicals such as OH, HO_2, RO_2, and NO_3, and PM including chemical (both on-line and offline analyses), biological, physical and optical properties. Through multiple co-located surface measurements, there was both instrumental redundancy (e.g. for equipment failures) and capacity to evaluate through inter-comparison some hard-to-measure atmospheric free radicals and gases such as OH, HO_2, N_2O_5, HCHO and other oxygenated VOCs. The project determined the local *in situ* chemical processing of air pollution in the contrasting winter/summertime periods alongside overall atmospheric reactivity, both day and at night, through a combination of modelling and proxy measurements such as measured ozone production efficiency and OH reactivity.

The IAP tower ~~is critical as it~~ allowed vertical profiles of key pollutants up to 320 m to be obtained and, with additional remote sensing of composition and meteorology, provided insight into boundary layer stability and evolution over the diurnal cycle. Quantification of shallow mixed layers proved to be vital for explaining local surface *in situ* chemical processing and also street level concentrations of relevance to exposure. The potentially significant vertical gradients anticipated in some chemicals and PM properties were further quantified using instruments installed on the tall tower and via profiling gondola measurements. The combined datasets, surface and profiles, provide the basis for evaluation of model performance, and notably comparisons for those intermediates that provide indicators of whether secondary pollution production is being correctly simulated.

3.1.3 Theme 3: Health effects

~~This theme is addressed by the AIRLESS and APIC-ESTEE (Air Pollution Impacts on Cardiopulmonary Disease in Beijing: An integrated study of Exposure Science, Toxicogenomics and Environmental Epidemiology) projects.~~ Health effects of air pollution are studied by two projects – AIRLESS and APIC-ESTEE.

AIRLESS ~~has~~ aim~~ed~~s to advance air quality and health research in Beijing by bringing together two fields of research that have made rapid advancements in recent years: measurements of a wide range of pulmonary and cardiovascular biomarkers in a panel study and personal monitoring of multiple air pollutants with high spatio-temporal resolution by sensor technology. AIRLESS is also benefiting from the use of an extensive range of pollution metrics and source apportionment results from the ~~Themes 1 and 2~~AIRPOLL and AIRPRO projects. These data are being compared with our personal air quality assessments and ~~be~~ used to further understanding of the nature of the air pollution exposures of residents and how this relates to their health status. ~~The~~

APIC-ESTEE aims to evaluate the impacts of air pollution on cardiopulmonary health through an integrated study of exposure, epidemiology, and toxicology/toxicogenomics~~study is examining different aspects of air pollution exposure and health, including population studies and toxicology~~. ~~One aspect of~~ APIC-ESTEE ~~is investigating~~has investigated the relationship between ambient air pollution and personal exposures~~,~~. This is being used to estimate personal exposures for epidemiological analyses of long term health impacts in a cohort study and of short-term effects (i.e. biomarkers, blood pressure, heart rhythm, and peak flow) in a panel study. ~~and the impacts of both ambient and personal exposures on subclinical health outcomes.~~ APIC-ESTEE also ~~Another part of the study is investigating~~ studied the real-world exposure-reduction and health ~~impact~~ benefit potential of face-masks, a commonly used personal level intervention seen in Beijing. Furthermore, to complement the human based studies into mechanisms of action, APIC-ESTEE has conducted *in vivo* analyses of mechanistic effects and early life toxicogenomics/metabonomics. ~~APIC-ESTEE also carried out laboratory toxicology studies to investigate the toxic mechanisms of PM, and a cohort of mothers and children were~~ was ~~recruited to investigate relationships between pre-natal air pollution exposures and birth and infancy outcomes.~~

3.1.4 Theme 4: Solutions

~~This theme is addressed by the INHANCE (Integrated assessment of the emission-health-socioeconomics nexus and air pollution mitigation solutions and interventions in Beijing) project.~~ INHANCE aims to quantitatively evaluate~~d~~ the performance of China's current air pollution policies and develop cost-effective solutions to mitigate the impact of air pollution in the Beijing megacity. ~~wherein regarding the effectiveness of current anti-air pollution measures. In recognition of the health and socio-economic issues associated with air pollution, China's State Council authorized a 1.75 trillion Yuan investment package: the Air Pollution Prevention Plan in 2013.~~ INHANCE ~~not only~~ considered not only the physical and mental health impacts~~,~~ and direct economic impact, but also the cascading indirect economic losses occurred through inter-industrial and inter-regional linkages on the supply side of the economy. INHANCE has established and evaluated interactive relationships among exposure, vulnerability, impact on health, implications for industry and economic consequences. INHANCE has compared and qualitatively assessed air quality policies between Beijing and other cities~~;~~, ~~undertook~~ undertaken policy performance assessment modelling~~;~~, utilised techno-economic inventories for anti-pollution measures to conduct micro cost-benefit analysis of new policies; measured health and macroeconomic costs and benefits in mitigating air pollution, and~~;~~, transformed evidence generated into practical emission alleviation pathways. On these bases, INHANCE will deliver recommendations regarding integrated policy design and an assessment for policy cost-effectiveness.

3.2 Integration Between the Themes and Novelty of the APHH-Beijing Programme

The APHH-Beijing programme is highly integrated to ensure the biggest possible scientific and policy impacts. One of the most significant integration activities between the different themes is the coordinated joint field campaigns at an urban and a rural site in Beijing for Theme 1, 2 and 3 to fully exploit the complementary measurements and expertise by different research groups, which is described in the following sections. Theme 1 and 2 are closely related and in many senses inseparable. For example, our knowledge of the sources and emissions is essential to interpret the processes while knowledge on the atmospheric physical and chemical processes will help us to more accurately quantify the source emissions, both via actual flux-based measurements and model evaluation of the emission inventories. Furthermore, t~~T~~o ensure integration, Themes 1 and 2 co-located their rural site at Pinggu as that was selected for the Theme 3 panel study.

Modelling of airborne concentrations of air pollutants within Themes 1 and 2 ~~are~~ is fully integrated, primarily via the UKCA (UK Chemistry and Aerosol), NAQPMS (Nested Air Quality Prediction Model System) and GEOS-Chem models. ~~Both~~ The models simulate spatial and temporal variations of key air pollutants and ~~will~~ are being evaluated using the new observations of pollutant emission fluxes, updated emission inventories, three-dimensional air quality low cost sensor ~~measurements~~observations, comprehensive composition and physics measurements, as well as new process understandings generated from the APHH-Beijing programme. Furthermore, in Themes 1 and 2, ADMS (Atmospheric Dispersion Modelling System) modelling results for the campaign periods facilitate the estimation of population exposure in Theme 3. Outcomes of Themes 1, 2 and 3 help to provide Theme 4 with a more accurate estimate of pollution costs and ~~help~~ to develop cost-effective air pollution control measures in Beijing.

The third stream of integration activities involves regular APHH-Beijing programme science and stakeholder engagement meetings to stimulate collaboration and knowledge transfer between different themes and stakeholders. Furthermore, sharing of data was made available via a dedicated depository in Centre for Environmental Data Analysis (www.ceda.ac.uk). All data in the depository will be made publically available by the end of 2022.

Together, this interdisciplinary APHH-Beijing programme delivers key scientific values and innovation, including:

(1) Validation of the bottom-up emission inventories by using novel eddy covariance emission flux observations from the IAP meteorological tower, integrated with satellite retrievals and numerical modelling,

(2) Improvement in understanding of air pollution processes through comprehensive observations of atmospheric gaseous and aerosol species integrated with atmospheric physics measurements, and

(3) Identification of the sources of air pollution that cause largest adverse human health effects by carrying out novel cardiovascular health indicator measurements, integrated with personal exposure, fixed station source apportionment studies and high resolution air quality modelling.

4. Overview of the Joint Field Campaigns ~~OVERVIEW OF JOINT FIELD CAMPAIGNS~~

The two intensive campaigns ~~were~~ took place from 10~~5~~th November to 10th December 2016 and ~~15th~~ -20th May to 22nd June 2017. The campaigns were carried out at both urban and rural sites.

4.1 Site Information

The winter campaign had~~s~~ two main sites. The urban site (39.97N, 116.38 E) is located in the Tower Section of the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences~~;~~ where ~~i.e. at~~ the 325 m meteorological tower is located. The site, between the fourth and third North ring roads of Beijing (Figure 1), is in a residential area. Typical of central Beijing, there are various roads nearby. To the south, north and west there are roads about 150 m away. On site there are 2 to 3 floor buildings to the south, and the east and west of the tower surrounded~~ing~~ by small trees and grass~~es~~. There is a canal right to the north of the site. Further to the west is a park covered mainly by conifer pine trees (Yuan Dynasty Wall Heritage Park).

The rural Pinggu site in Xibaidian village (40.17N, 117.05 E) in north-eastern Beijing, was collocated with the AIRLESS project cohort. Xibaidian village is about 4 km northwest of Pinggu town centre, and about 60 km from IAP. There are ~~many~~ several similar small villages nearby. The monitoring station and the clinic used an unoccupied house at the north end of the village away from significant local combustion sources. A two-lane road is about 300 m north ~~to~~ of the site. With no centralised heating infrastructure available, ~~to the local villages'~~ residents mainly use coal and biomass for heating and cooking in individual homes.

In the summer, an additional site was operated in Gucheng (39.2N 115.7E), Dingxing County, Hebei Province. This site, about 120 km to the southwest of central Beijing, is on one of the main high~~ly~~ pollutant transport pathways from Hebei province to Beijing ~~via~~ from the southwest ~~passage~~. The site ~~used~~ is in a meteorological observatory surrounded by ~~in a~~ farm fields. The nearest town is about 10 km to the northeast. The nearest road is ~~is~~ 500 m to the north and the nearest village ~~is about~~ ~1 km to the west. Several villages are located around the site.

In addition to the two highly instrumented urban (IAP) and rural (Pinggu) sites, 21 SNAQ (Sensor Network for Air Quality) boxes, which measure CO, NO, NO_2, CO_2, O_X, size resolved particulates (0.38-17.4 µm), temperature, relative humidity, wind speed and direction (Popoola et al., 2018), were deployed during the summer and winter campaigns across the urban and rural areas of Beijing to map air pollutant variations (red tags, Figure 1). Six additional SNAQ boxes were deployed at six different heights (8, 32, 102, 160, 260, and 320 m) on the IAP tower from 9-23 November 2016 and 25 January-31 December 2017.

Figure 1 also shows the location of the 12 national air quality monitoring stations. Hourly data ~~of~~ for criteria air pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and O_3) from January 2013 to December 2017 from the stations were also obtained from official sources ~~by Tsinghua University~~. The closest air quality station to the urban IAP site is about 3 km away at the Olympic Park (G11, Figure 1).

4.2 Instrumentation

4.2.1 Urban site

Table 1 lists all instruments deployed during the campaigns at the IAP site. Most instruments ran during both campaigns. A majority of the instruments were situated in t~~T~~he nine ~~instrument~~ containers, which were at ground level on the campus grass. ~~Their locations are shown in Figure 1c.~~ A number of o~~O~~nline instruments and high volume PM samplers were also deployed at different heights on the meteorological tower. ~~Most instruments ran during both campaigns.~~ Vertical profiles measurements ~~included~~ of atmospheric species including HONO were made during pollution events using baskets attached to the tower. Additional online measurements and offline ~~particulate matter~~PM samplers were deployed at ground-level, on the roof of a two storey~~ied~~ building to the west (WB) and in a third-floor laboratory at the south- end of the campus. In addition, high-, medium- and ~~low~~ low-volume PM samplers were placed on the roof of WB for offline characterization and source apportionment.

4.2.2 Rural sites

At Pinggu, online instruments (Table ~~3~~2) were run within an air-conditioned room on the ground floor with inlets on top of the building. High-, medium- and low-volume PM samplers were deployed on a newly modified flat-roof of the single storey building.

At Gucheng (summer only), a high volume Digitel sampler and a single particle sampler were set up on a deserted basketball court. An Aethalometer AE33 was located on top of a container at the edge of the basketball court. CO and O_3 were also measured in a nearby container.

4.3 Synoptic Scale Meteorology During the Field Campaigns

Synoptic circulation patterns (e.g., horizontal advection and wet deposition) play a key role in the variations of air quality in Beijing (Miao et al., 2017; Wu et al., 2017; Zhang et al., 2012). To provide the synoptic context of the APHH-Beijing observations, the daily mesoscale flow patterns have been classified and put into context using a 30-year climatology (Section 5.4).

Circulation types (CT) are classified using the software produced by the COST Action 733 "Harmonisation and Applications of Weather Type Classifications for European regions" (Philipp et al., 2010) with (ECMWF Re-Analysis) ERA-Interim 6-h 925 hPa geopotential reanalysis data (Dee et al., 2011) at its native 0.75° spatial resolution for the domain of interest (103-129° E, 31 - 49° N) centred on Beijing (40° N, 116.5° E) covering the period 1988-2017. ERA-Interim 10 m U and V wind components are used to facilitate the interpretation of the flow patterns. Of the COST733 methods (Huth et al., 2008; Philipp et al., 2010, 2016; Tveito and Huth, 2016) two are used: T-Mode PCA (Principal Component Analysis) and SANDRA (Simulated Annealing And Diversified RAndomization clustering). The former have been used in Beijing previously (e.g. Miao et al., 2017; Zhang et al., 2012). The latter is considered to perform well in clustering pressure fields and discriminating environmental variables (e.g. Demuzere et al., 2011; Philipp et al., 2016). Classification is performed with the number of CTs ranging from 7 to 18. 11 CTs from the SANDRA method are selected (Figure 2; Table 3) to adequately represent the general flow conditions around Beijing during the 30 y climatology period (Beck and Philipp, 2010).

As expected, the CTs that occurred during the two field campaign periods are different (Figure 3). During the winter field campaign, the most frequent circulation type was CT 11 (24 % of the 6 h periods) which was often preceded by a period of CT 9 (total 13%). Circulation types 9-11 are associated with air masses that may stagnate over the Beijing urban area (Figure 2). CT 1 (accounting for 12% of the time) and CT 2 (17 %) are associated with the Asian winter monsoon which brings cold and dry air masses to eastern China. North-westerly flow (over Beijing) is driven by high pressure in the west of the domain (Figure 2), which are followed by CTs 5, 3 and 7 occurred 14, 7, and 5% of the time, respectively. CTs 3 and 5 are associated with relatively low pressure in the northeast (Sep-May period) while CT 7 has a south-easterly winds from the Bohai Sea. CTs 4, 6 and 8 did not or hardly occur during the winter campaign.

During the summer campaign (Figure 3b), the most frequent CTs were 8, 7, 4, and 6 (23, 25, 19, and 10 % of the time, respectively). CTs 8 and 6, which did not occur during the winter campaign period, are associated with the summer monsoon advecting moist, warm air from the South and Southeast (Figure 2). While southerly and northerly flows converge over Beijing for CT 6, slightly weaker low pressure to the Northeast means North-westerly flow dominates for CT 4. High pressure to the West or South of Beijing is rare during the summer campaign so that CTs 1, 2, 9, and 11 do not occur and CTs 3 and 5 are rather rare (6 and 1%, respectively).

~~6.3~~4.4 Meteorological Conditions During the Field Campaigns

To assess how local-scale flow related to ERA-Interim fields (~~s~~Section ~~6.1~~4.3) compared to local conditions, the link between the coarse gridded data and tower-based sonic anemometer observations ~~is~~are explored based on wind roses (Figure ~~14~~54). The 30 y climatology (Figure ~~13~~54a, d) confirms the clear seasonality in wind direction affecting the occurrence of CTs discussed (Sect. ~~0~~4.3), i.e. during winter intensive campaign period (~~5~~10 November – 10 December) north-easterly flow clearly dominates while southerly wind directions are most common during the summer campaign period (~~15~~20 May – 22 June). The wind roses for winter 2016 and summer 2017 (Figure ~~14~~54b, e) are slightly nosier, ~~however~~but~~,~~ ~~indicating~~ show similar tendencies as the climatology. The general large-scale patterns are consistent with the in-situ wind measurements (Figure ~~14~~c, f). However, a slight diversion towards northerly and south-westerly flow and lower wind speeds occurred in winter and summer (Figures ~~14~~54c and f), respectively, when compared to the larger scale data (Figures ~~14~~54b and d). In addition, south-westerly flows were more frequent in winter 2016 (Figures ~~14~~54b and c) than during the 30 year average climatology (Figure ~~14~~54a), which had the potential to bring more polluted air in the upwind Hebei province to the observation sites in Beijing.

At 102 m, the flow is consistent with northerlies and north-westerlies in the winter campaign and dominantly southerly and easterlies during the summer campaign (Figure ~~156~~S1). The measured hourly mean wind speed, temperature and relative humidity were 3.1 m s^{-1}, 8.3 °C and 43.8 % in winter, and 3.6 m s, 25 °C and 46.7 % in summer, respectively. Typical diurnal patterns were observed with higher wind speed and temperature during the day and RH at night. During the winter haze events (defined in Figure 5) ~~the 120 m~~ wind speed at 102 m were low (an average of 1.8 m s^{-1}) and mainly from the south-west direction (Figure~~s~~ ~~156 and 27~~S1~~ and Figure 5~~).

5. Air Quality During the Field Campaigns~~AIR QUALITY DURING THE FIELD CAMPAIGNS~~

5.1 Winter

During the winter campaign, the daily average concentration of $PM_{2.5}$ at IAP ~~using Partisol gravimetric measurements~~ was 91.2 µg m^{-3} from the Partisol gravimetric measurements (Table 4) and 94.0 µg m^{-3} from an online FDMS (Filter dynamic measurement system)~~ measurements~~. The maximum hourly $PM_{2.5}$ concentration was 438 µg m^{-3} (Figure ~~27~~5 which shows the haze events listed in Table 5). $PM_{2.5}$ concentrations significantly exceeded ~~the~~ both the daily air quality limit of China (75 µg m^{-3}) and WHO (25 µg m^{-3}). During the whole winter campaign period, nearly 50% of the hours had $PM_{2.5}$ mass concentration higher than 75 µg m^{-3} (Figure ~~27~~5). The ~~O~~online PM_{10} concentration observed at the Olympic Park national air quality monitoring station was up to 560 µg m^{-3} during the campaign with an average of 130.6 µg m^{-3}. Average concentrations of NO_2, O_3, SO_2 and CO were 69.7 ± 33.3, 16.4 ± 17.0 and 14.9 ± 11.1 µg m^{-3} and 1.53 ± 1.02 mg m^{-3}, respectively (Table 4). Most of the criteria pollutants showed a similar temporal pattern (Figure ~~27~~5), except O_3.

The daily average concentration of $PM_{2.5}$ was 99.7 µg m^{-3} at Pinggu (Table 4; based on Partisol gravimetric measurements)~~ but as high as 114.0 µg m-3 from the BAM measurement~~. The maximum hourly $PM_{2.5}$ concentration was 617 µg m^{-3} (Figure ~~27~~5). Similar~~ly~~ to that at IAP, nearly 50% of the hours had $PM_{2.5}$ mass concentrations greater than 75 µg m^{-3}. Average concentrations of NO_2, O_3, SO_2 and CO are 46.4 ± 25.5, 22.3 ± 22.2, and 15.4 ± 6.7 µg m^{-3}, and 1.47 ± 1.17 mg m^{-3} respectively (Table 4). $PM_{2.5}$ was slightly higher at the rural site but NO, CO and SO_2 were comparable between the two sites. $PM_{2.5}$ and O_3 each had similar temporal patterns at the urban and rural sites (Figure ~~27~~5), indicating a synoptic scale meteorological impact. The larger difference in the temporal variation of NO, NO_2 and SO_2 may reflect the varying contribution of more local sources. Large differences in temporal patterns of air pollutants were found on 4 December 2016 when $PM_{2.5}$, SO_2 and NO concentrations were much higher at Pinggu than at IAP.

Diurnal cycles of particles, NO_2 and CO showed no distinct peak but an increment during the nighttime, suggesting the possible impact of boundary layer and/or anthropogenic emissions in winter (Figure ~~38~~6). The peak NO levels at 7 am are likely caused by the morning rush hour road traffic. $PM_{2.5}$ concentration increased sharply from 6 pm at Pinggu (not shown), suggesting important local emissions, likely domestic heating and cooking. SO_2 and O_3 had their highest levels in mid-morning or at noon (Figure ~~38~~6).

Variations of particles, NO_x and SO_2 show that higher levels of these pollutants when air masses were from the south or southwest (Figure ~~49~~S2), indicating it was impacted by regional transport. All pollutants, except O_3, had higher mass concentrations when wind speeds were low, suggesting an influence from the local sources. The NO wind rose suggests a strong local source with little contribution from long-range transport. The O_3 concentration was higher during northerlies and when the concentrations of other pollutants such as NO_x and $PM_{2.5}$ were lower (Figure ~~49~~S2).

SNAQ box measurements at six levels (8 to 320 m) during the winter campaign (Figure ~~510~~7) have similar overall temporal patterns of CO and NO to that measured by standard gas analyser (Figure ~~27~~5). In most cases, the air pollutant levels are similar at different levels of the tower. There are notable differences in NO, CO and CO_2 on 11, 12 and 16 / 17 November, which suggests that the mixed layer height was low (e.g., <150 m). Interestingly, the O_x (NO_2 + O_3) levels are relatively homogeneous across the different levels. These measurements have implications on the role atmospheric chemistry play in transformation of species in the boundary layer, and the measurements also provide useful information that confirm mixed layer height determinations from independent methods such as the ceilometer (Table 1).

According to the meteorological standards (QX/T113-2010), haze is defined as: i) visibility < 10 km at relative humidity (RH) <80%; or ii) if RH is between 80 and 95%, visibility < 10 km and $PM_{2.5}$ > 75 µg m^{-3}. During the winter campaign- 640 of the 1633 h were classified as haze periods using visibility data from Beijing Capital Airport (Figure ~~611~~S3); within the haze hours, 75% had $PM_{2.5}$ greater than 75 µg m^{-3} (Area A, Figure ~~6~~S3) and the rest had a visibility less than 10 km but with a RH <80% (Area B, Figure ~~611~~S3).

Characteristics of five major haze events during the winter campaign (Figure ~~27~~5) ~~include~~ show that $PM_{2.5}$, NO_2, SO_2 and CO had similar trends but O_3 levels dropped to very low concentration (<2 ppb). The events are defined in Table ~~2~~5.

5.2 Summer

Concentrations of air pollutants excluding ozone during the summer campaign were much lower than in winter (Figure ~~712~~8, Table 4). Average daily concentration of $PM_{2.5}$ and PM_{10} at IAP were 31.4 ± 14.7 and 74.9 ± 29.3 µg m^{-3} (based on gravimetric method), respectively. These levels were slightly higher than at Pinggu (27.8 ± 13.3 and 62.9 ± 29.3 µg m^{-3}). Concentrations of ozone were four to five times higher during the summer campaigns (106.9 ± 71.6 µg m$^{-3\cancel{3}}$ at IAP, and 91.8 ± 62.7 µg m$^{-3\cancel{3}}$ at Pinggu) than in the winter campaign. Average concentration of NO_2, SO_2 and CO ~~are~~ were 41.3 ± 23.5 and 6.3 ± 6.8 µg m^{-3} and 0.61 ± 0.32 ~~,~~mg m^{-3} at IAP respectively (Table 4). The concentrations of NO_2 and CO were lower at Pinggu while that of SO_2 was similar. All ~~Most of the criteria pollutants showed a similar~~

~~temporal pattern~~pollutants except $PM_{2.5}$ show more or less different temporal patterns ~~-~~(Figure ~~2~~78), ~~except O_3~~suggesting differences in sources at Pinggu and IAP during the summer campaign.

Diurnal patterns of NO, NO_2, and CO at IAP showed a distinct peak in the early morning, suggesting the contribution of traffic emissions (Figure ~~7~~126). O_3 and O_x concentration peaked in mid-afternoon. The IAP $PM_{2.5}$ ~~wind~~ pollution rose suggests that both local and regional sources (from the south and south-east direction) impact the site (Figure ~~4~~9S2). Unlike winter, high ozone concentrations occur during southerlies to southwesterlies, suggesting a regional source of this pollutant. NO and NO_x were largely from local sources during the summer campaign.

Characteristics of two minor haze events (IAP) during the summer campaign (Figure ~~7~~128) are shown in Table ~~2~~5.

5.3 Air quality in the Wider Beijing Megacity During the Field Campaigns

~~Average concentrations of air pollutants ($PM_{2.5}$, PM_{10}, NO_2, CO, SO_2 and O_3) at IAP and Pinggu during the two field campaigns were similar to long term averages for these times of year at the 12 national air quality monitoring sites for 2013-2017 (Table 4).~~

To assess if the IAP air quality is broadly representative of the wider Beijing megacity, variables ~~are~~ were correlated with the 12 national air quality station data (Figure ~~8~~139~~S4~~). A high correlation ~~occurs~~ is observed with $PM_{2.5}$ across all sites except the rural background air quality station at Ming Tombs (G2, Figure 1); PM_{10}, CO and NO_2 at the urban sites are highly correlated but not with the rural and suburban sites (G2, G9 and G10, Figure 1) suggesting a more local source for these pollutants, comparing to $PM_{2.5}$ and O_3; SO_2 between sites ~~have~~ shows a lower correlation compared~~ing~~ to all other pollutants. The particularly high spatial correlations of both $PM_{2.5}$ and O_3 across almost all sites indicates a regional pollution phenomenon for the two pollutants. These results suggest~~ed~~ that the air quality at the IAP urban site was broadly consistent with ~~those~~ that at the other urban sites.

~~Average concentrations of air pollutants ($PM_{2.5}$, PM_{10}, NO_2, CO, SO_2 and O_3) at IAP and Pinggu during the two field campaigns were similar to long term averages for these times of year at the 12 national air quality monitoring sites for 2013-2017 (Table 4).~~In general, $PM_{2.5}$ mass concentrations are similar at all the urban sites including IAP ~~but~~ which are higher than at the suburban and rural background national monitoring sites (~~Ming Tombs,~~ G2, G9 and G10, ~~) (~~Figure S4 ~~9~~14). The Pinggu ~~rural~~ site ~~in this study,~~ has relatively high $PM_{2.5}$ pollution ~~in~~ during the winter campaign but has the lowest concentrations during the summer campaign. This suggests that local anthropogenic sources have a major impact on $PM_{2.5}$ at this site during the winter campaign~~s~~. Source apportionment results, notably high time resolution data are being used to explore this.

~~The closest national air quality station (Olympic Park, or Aotizhongxin in Chinese Pingyin) to IAP has shows a~~ The ~~highly correlated~~ $PM_{2.5}$ concentrations measured at ~~with~~ IAP are highly correlated with those at the nearly national air quality station (Olympic Park, or Aotizhongxin ~~(~~, see Figure 1) (Figure ~~15~~S5), which gives confidence~~. This suggests~~ that national air quality stations are of sufficient quality to provide valuable information on the spatial and temporal variation of key pollutants to supplement campaign measurements.

Table 4 shows that the IAP concentration~~s~~ data for all air quality variables are very close to the five year mean of the 12 national air quality monitoring stations ~~mean~~. This lends further confidence that the chosen urban site represented well the overall pollution in the Beijing ~~megacity~~urban area.

~~6. SYNOPTIC SCALE METEOROLOGY DURING THE FIELD CAMPAIGNS~~

~~Given the importance of horizontal advection and wet deposition to air quality in Beijing, the synoptic circulation patterns are clearly important (Miao et al., 2017; Wu et al., 2017; Zhang et al., 2012). To provide the synoptic context of the APHH-China observations, the daily mesoscale flow patterns are classified (Section 6.1) and put into context using a 30-year climatology (Section 6.2).~~

~~6.1 Synoptic Circulation Types~~

~~Circulation types (CT) are classified using the classification software by the COST Action 733 "Harmonisation and Applications of Weather Type Classifications for European regions" (Philipp et al., 2010) with (ECMWF Re-Analysis) ERA-Interim 6-h 925 hPa geopotential reanalysis data (Dee et al., 2011) at its native 0.75° spatial resolution for the domain of interest (103-129° E, 31 - 49° N) centred on Beijing (40° N, 116.5° E) covering the period 1988-2017. ERA-Interim 10 m U and V wind components are used to facilitate interpretation of the flow patterns. Of the COST733 methods (Huth et al., 2008; Philipp et al., 2010, 2016; Tveito and Huth, 2016) two are used: T-Mode PCA (Principal Component Analysis) and SANDRA (Simulated Annealing And Diversified RAndomization clustering). The former have been used in Beijing previously (e.g. Miao et al., 2017; Zhang et al., 2012). The latter is considered to perform well in clustering pressure fields and discriminating environmental variables (e.g. Demuzere et al., 2011; Philipp et al., 2016). Classification is performed with the number of CTs ranging from 7 to~~

~~18. 11 CTs from the SANDRA method are selected (Figure 11; Table 5) to adequately represent the general flow conditions around Beijing during the 30 y climatology period (Beck and Philipp, 2010). The CTs are re-ordered according to the daily median PM$_{2.5}$ concentration observed at the Olympic Park (i.e. Aotizhongxin) (Figures 1 and 12) in 2013-2017 with the predominant CTs estimated from midday-midday, i.e. with a 12 h time lag.~~

~~As expected, the CTs that occurred during the two field campaign periods are different (Figures 12 and 13). During the winter field campaign, the most frequent circulation type was CT 10 (25 % of the 6 h periods) which was often preceded by a period of CT 11 (total 16%). Circulation types 9-11 are associated with air masses that may stagnate over the Beijing urban area (Figure 11). However, CT 9 did not occur during either field campaign. CT 1 (accounting for 16% of the time) and CT 2 (1 %) are associated with the Asian winter monsoon which brings cold and dry air masses to eastern China. North-westerly flow (over Beijing) is driven by high pressure in the west of the domain (Figure 11). After these conditions of stagnation or north-westerly flow, CT 3, 4, 6, and 5 were the most frequent in the winter campaign (12.5, 11.8, 8.3 and 7.6 % of the time, respectively). CTs 3 and 5 are associated with relatively low pressure in the northeast (Sep-May period) while CTs 4 and 6 have a further reduction in atmospheric pressure in the NE. One single 6 h period was classified as CT 7, i.e., winds oriented westward from the Bohai Sea.~~

~~During the summer campaign (Figure 12b), the most frequent CTs were 5, 8, 6, 7 (34, 32, 12, 11 % of the time, respectively). CT 8, which did not occur during the winter campaign period, is (like CT 6) associated with the summer monsoon advecting moist, warm air from the South and Southeast (Figure 11). Synoptic flow from the Northwest (CT 1 and 4) is relatively rare (7 and 4 %, respectively) during spring and summer (Mar-Aug) as winds start to turn over the Yellow Sea, weakening the NW flow over Beijing.~~

~~In comparison to the field campaigns, the CT frequencies range from 7.2% (CT 2, 10) to 12.9% (CT 8) during the period 1988-2017 with clear seasonal variations in their occurrence (Figure 13).~~

~~6.2~~5.4 Synoptic C~~c~~irculation and Air Quality

The average mixed layer height observed at IAP varies with season and CT type (Figure 10a). Lower mixed layer height is usually linked to air pollution events. The 11 CTs (Section ~~6.1~~4.3) are clearly associated with distinct air quality conditions based on analysis of hourly air quality data for 2013-2017 at one of the national urban air quality stations (G11~~4~~, Olympic Park, Figure 1~~s 1 and 12~~3).~~-~~ Relatively low wind speeds ~~(Figure 7)~~ of CT 7 may contribute to the long haze event from 15/11/2016 to19/11/2016~~,~~ (Fig. 5). Most haze events during the winter campaign are cleared out by fresh air masses being advected from the North in CTs 3 or 5 (Figure 3), which is also marked by the increase in wind speed observed (Figure S1~~6~~). Relatively lower $PM_{2.5}$ concentrations occurred (Figure ~~4~~10b) under NE flow conditions (CTs 1-5), and higher concentrations during southerly flow (CTs 6-8, 10). The highest $PM_{2.5}$ concentrations occur during the heating season when regional flow ~~shows~~ showed stagnation (CT 9, 11). All haze events during the winter campaign (Figures 3&~~12~~35) are dominated by those CTs although CTs with NE flow conditions occurred for short periods within the haze events (e.g. 18/11/2016, 04/12/2-16). Ozone levels are highest during CTs 5-8 (Figure ~~13c~~104c), which ~~as these~~ predominate during spring and summer (Figure ~~4~~10d).

~~Similarly, the average mixed layer height observed at IAP (Table 1) varies with season and CT type (Figure 4a). InDuring the Oct 2016 – Sept 2017 period (Figure 410e), the relative frequency of CTs differs slightly from the long-term climatology (Figure 410d). In December 2016, clearn air advection from the NE (CTs 1-3) was less frequent than in the 30-y climatology. However, while stagnation with a weak southerly component (CTs 9 and 11) was more frequentoccurred more often (Figure 410f), thus favouring haze with a large positive (4032%) $PM_{2.5}$ anomaly (Figure 510g, winter campaign period compared to cf. the 5-y average, for 2013-2017). In June 2017, south-north contrasts in geopotential were apparently reduced so CT 6 was 24% less frequent, while CTs 4, 7, and 8 were more frequent. This had minimal effect of $PM_{2.5}$. The slight relative increase in O_3 (by 9.5%, Figure 410g) during June (9%) and January (12%) might be explained by cloud cover differences, which is being investigated.~~

In the Oct 2016 – Sept 2017 period (Figure 10e), the relative frequency of CTs differs slightly from the long-term climatology (Figure 10d). During the winter campaign, clean air advection from the NE (CTs 1-3) was less frequent than in the 30-y climatology. Given synoptic circulation types associated with stagnation do have a similar occurrence during the winter campaign compared to the same time period within the previous five years (with CT 9 8% less frequent and CTs 10 and 11 2% and 10% more frequent; Figure 10f), $PM_{2.5}$ concentrations were ~~very~~ similar to the 5 year mean (Figure 10g, winter campaign period compared to the same dates during 2013-2017). During the summer campaign, south-north contrasts in geopotential were apparently reduced so CT 6 was 12% less frequent, while CT 7 was 11% more frequent (Figure 10f). The reduced advection of particles from southerly directions might have contributed to a 33% ~~reduction in~~ lower $PM_{2.5}$ concentrations ~~of 33%~~ compared to the five year average for the same time of year (Figure 10g). The relative decrease in O_3 (Figure 10g) during the winter campaign (24%) might be explained by cloud cover differences, which is being investigated.

5.5 Summary of Air Quality during the Campaigns

In summary, the winter campaign was characterised by several high $PM_{2.5}$ pollution events with peak hourly concentrations at the urban site ranging up to 617 µg m^{-3} (at Pinggu) whereas the summer experienced events of high ozone concentrations with the highest hourly average of 335 µg m^{-3} (at IAP) Air quality was generally poor during the winter campaign with an average $PM_{2.5}$ concentration of 91 µg m^{-3} in urban Beijing, but less severe than in the same period in 2015. Synoptic scale meteorological analysis suggests that the greater stagnation and weak southerly circulation in November/December 2016 contributed to the poor air quality during all haze events detected, ~~but~~and overall the $PM_{2.5}$ pollution level was similar to the five year average (2013-2017). $PM_{2.5}$ levels were relatively low during the summer campaign with the highest daily concentration of only 79 µg m^{-3}, matching the cleanest periods over the previous five years.

~~6.3 Meteorological Conditions During the Field Campaigns~~

~~To assess how local-scale flow related to ERA-Interim fields (section 6.1), the link between the coarse gridded data and tower-based sonic anemometer observations is explored based on wind roses (Figure 14). The 30 y climatology (Figure 13a, d) confirms the clear seasonality in wind direction affecting the occurrence of CTs discussed (Sect. ?), i.e. during winter intensive campaign period (5 November – 10 December) north-easterly flow clearly dominates while southerly wind directions are most common during the summer campaign period (15 May – 22 June). The wind roses for winter 2016 and summer 2017 (Figure 14b, e) are slightly nosier, however, indicating similar tendencies as the climatology. The general large-scale patterns are consistent with the in-situ wind measurements (Figure 14c, f). However, a slight diversion towards northerly and south-westerly flow and lower wind speeds occurred in winter and summer (Figures 14c and f), respectively, when compared to the larger scale data (Figures 14b and d). In addition, south-westerly flows were more frequent in winter 2016 (Figures 14b and c) than the 30 year average climatology (Figure 14a), which had the potential to bring more polluted air in the upwind Hebei province to the observation sites in Beijing.~~

~~At 102 m, the flow is consistent with northerlies and north-westerlies in the winter campaign and dominantly southerly and easterlies during the summer campaign (Figure 15). The measured hourly mean wind speed, temperature and relative humidity were 3.1 m s^-1^, 8.3 °C and 43.8 % in winter, and 3.6 m s, 25 °C and 46.7 % in summer, respectively. Typical diurnal patterns were observed with higher wind speed and temperature during the day and RH at night. During the winter haze events the 120 m wind speed were low (an average of 1.8 m s^-1^) and mainly from the south-west direction (Figures 15 and 2).~~

~~7~~6. Preliminary Air Quality Modelling and Pollution Climatology of the Campaign Periods

Air quality modelling is a key component of the APHH-Beijing programme. A range of models have been applied that span global (UKCA, GEOS-Chem), regional (WRF-Chem, CMAQ, NAQPMS) and urban to street scales (ADMS). This section provides an example of the comparison between model simulated pollutant concentrations and APHH-Beijing observations made at IAP to demonstrate model capabilities. Results from specific modelling studies will be published separately.

~~Air quality modelling is a key aspect of APHH-Beijing. This involves multiple models from regional (e.g., WRF-Chem, UKCA, NAQPMS) to urban (e.g., CMAQ, NAQPMS) and to street scales (ADMS). This section aims to provide an example comparison of model simulated pollutant concentrations against APHH-Beijing measurements made at IAP (Figure 16) to demonstrate model capabilities. Specific modelling work will be published in the special issue later.~~

Figure ~~16~~ 11 shows that the magnitude and variation of wintertime $PM_{2.5}$ concentrations are reasonably reproduced by NAQPMS during ~~November~~the winter campaign, although there are some weakness in capturing the highest $PM_{2.5}$ levels during the haze events at the end of November and start of December. This is partly due to the representation of local meteorological features during this period~~,~~, which bring these episodes to an end 6-12 hours early.~~and $PM_{2.5}$ concentrations during the major haze episode on 4 December are much more similar to those measured at Pinggu than at IAP (see Figure 27).~~ The diurnal variations in O_3 during the summertime are reproduced relatively well by UKCA, which captures the rapid daytime formation of O_3 and strong nighttime removal. The very highest levels of daytime O_3 are underestimated with the model, particularly during the episode at the end of May. However, there is a strong local contribution to this as evident from the lower concentrations measured at Pinggu (Figure 8), and these local differences are not fully resolved with the model. Despite this, the day-on-day build-up of daytime O_3 during the periods of 22-27 May and 11-16 June is captured~~ well~~, and demonstrates that the model reproduces the synoptic drivers of local O_3 formation well.

We also investigated how representative the campaign periods were of the selected seasons in Beijing by comparing pollutant levels with those from the same period each year over the 2013-2017 period. The NAQPMS model was run for the full 5-year period driven by NCEP meteorology and using temporally varying emissions for a single year that is broadly representative of 2013 conditions. The same emissions were used each year so that the meteorological contribution to pollutant levels could be assessed. This provides important information that cannot be obtained from the monitoring data (as emission varies year by year). The frequency distribution of $PM_{2.5}$ over each campaign period for each year is shown in Figure 12. Winter 2016 was broadly typical of the 5-year period, with similar characteristics to winter 2014, but both years show higher $PM_{2.5}$ under the same emissions than in 2013 or 2017. In addition, winter 2015 had substantially less favourable conditions for air quality, and more stagnant conditions led to three extended pollution episodes over the period with $PM_{2.5}$ exceeding 200 μg m^{-3}. In contrast, the summer period in 2017 was cleaner than average, with $PM_{2.5}$ levels very similar to 2015, and about 25% less than in 2013, 2014 or 2016. These results are broadly consistent with those based on synoptic weather analyses (section 5.4) as well as by Vu et al. (2019).

~~On basis ofBased on NAQPMS modelling, we also investigated how representative the campaign periods were of the selected seasons in Beijing by comparing pollutant levels with those from the same period each year over the 2013-2017 period. The NAQPMS model was run for the full 5-year period driven by NCEP meteorology and using temporally varying emissions for a single year that is broadly representative of 2017 conditions. Use of annually invariant emissions permits the effect of differing meteorology on pollutant levels to be assessed. The frequency distribution of PM2.5 for each campaign period for each year is shown in Figure 17. PM2.5 in winter 2016 is very similar in characteristics to that in 2014, and both years show 50% greater PM levels than in 2013 or 2017. However, pollutant levels are substantially lower than in the same period in 2015, when three extended pollution episodes led to period-mean PM2.5 that was significantly larger. In contrast, the summer period in 2017 was relatively clean, with PM2.5 levels very similar to 2015, and about 25% less than in 2013, 2014 or 2016.~~

~~8~~7. ~~SUMMARY~~ Summary

~~The~~ APHH-Beijing is an integrated and multidisciplinary research programme conducted by leading UK and Chinese~~a~~ researchers to (1) quantify sources and emissions of urban atmospheric pollutants; (2) elucidate processes affecting urban atmospheric pollution events; (3) estimate the personal exposure and impacts of air pollution on human health, and (4) develop intervention strategies to improve air quality and reduce health impacts in the Beijing megacity. This introduction paper outlines the motivation of the APHH-Beijing programme as well as providing~~es~~ the background air quality and meteorological conditions during the two intensive field campaigns that form the basis of data interpretation for ~~the whole programme, particularly~~campaign observations ~~during the two intensive field campaigns as a core research activity within the programme~~.

APHH-Beijing has measured the fluxes of key air pollutants, including NO_x, CO, BC, VOCs and speciated particulate matter, applied a suite of traditional and modern techniques to apportion the sources of particulate matter, determined a wide range of pulmonary and cardiovascular biomarkers linking to direct personal exposure and extensive fixed-station monitoring as well as source apportionment results, and has evaluated the effectiveness of Beijing's air pollution control policies using both chemical transport models and novel machine learning techniques. A number of papers have already been published ~~under~~ by the APHH-~~China~~ Beijing programme including those in this ~~e APHH Beijing~~ special issue (Wang et al., 2019; Pan et al., 2019; Xia et al., 2018; Zhou et al., 2018; Wang et al., 2018b; Lyu et al., 2019; Hollaway et al., 2019; Du et al., 2018; Liu et al., 2018a,b; Smith et al., 201~~8~~9; Vu et al., 2019; El zein et al., 2019). More papers are being prepared for publication in this special issue and elsewhere, which will cover (but are not limited to) emission fluxes of air pollutants, chemical composition and source apportionment of fine particles, satellite observations of trace gases and aerosols, sources and processes leading to haze events and photochemical smogs, physical and optical properties of aerosol particles, formation processes of secondary aerosols, urban meteorology, feedbacks between haze, photochemistry and meteorology, integrated regional and urban scale modelling, personal exposure to air pollutants and human health effects of air pollution.

DATA DEPOSITORY

http://catalogue.ceda.ac.uk/uuid/7ed9d8a288814b8b85433b0d3fec0300

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AUTHOR CONTRIBUTIONS

ZS drafted the manuscript and is the science coordinator of the APHH-Beijing programme. RMH, KBH, ACL, PQF, TZ, FJK, ML, ZWS, DBG and ST are lead PIs of the five research projects who led the funding applications and the research. They also drafted Section 2. TV plotted many of graphs and carried out the data analysis. SK, SG and MD carried out analysis and wrote Section ~~6.1~~4.3~~-~~ and ~~6.2~~5.4; and YLW, MH, ZFW and OW carried out modelling and plotted Figure ~~16~~ 11 and ~~17~~12. PFQ, JL and ZT led the air quality measurements at the two measurements sites. SY, JL, RED, LR, DL, JA, DB, WJ, LC, LC, HC, TD, FKD, BZG, JFH, MH, DH, CNH, MH, DSJ, XJJ, RJ, MK, LK, BL, LC, JL, WJL, KDL, GM, MM, GM (Mills), JA, XFW, EN, BO, CP, PIP, OP, CR, CY, FL, JG, JC, ~~FL,~~ LYS, YS, SRT, QQW, WHQ, XMW, ZFW, LW, XFW, ZJW, PHX, FMY, QZ, YLZ and MZ contribute to the field observations, laboratory measurements and / or modelling. ZS, SG, RMH., ZT, JL, OW, JA, JB, WJB, DC, DCC, HC, TD, RD, FKD, PQF, MFG, DBG, JFH, KBH, MH, DH, CNH, MH, XJJ, RJ, MK, FJK, LK, ACL, JL, ML, KL, GM (Mann), GM (McFiggans), MM, PM, EN, FO, PIP, CP, CR, ARR, LYS, GYS, DS (Spracklen), DS (Stevenson), YS, XJW, JFL, BB, QC, ZWS, ST, SRT, XMW, ZFW, LW, ZJW, PHX, QZ, YHZ and MZ contributed to the funding applications, programme meetings and relevant programme research and/or supervision.

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TABLE LEGENDS:

Table 1: Overview of measurements in APHH-Beijing at the urban site.

~~**Table 24:** Haze periods during the summer and winter campaign periods.~~

Table ~~3:~~2 Overview of measurements at the Pinggu site.

Table 3: Mean and standard deviation (sd) of climatological conditions in Beijing for each circulation type (CT) for 1988-20 17 from ERA-Interim data with frequency of the CT during the W (winter) and S (summer) campaigns (% of 6 h periods (p)) compared to long- term (1988-2017) averages.

Table 4: Haze periods during the summer and winter campaign periods.

Table ~~4~~5: Average air quality variables at IAP, Pinggu and 12 national monitoring sites (12N) during the field campaigns (10 November – 11 December 2016; and 21 May – 22 June 2017). The 12 national sites five-year mean concentrations for same times of the years (12N -5Y) and for the same time of the year (campaign period) (12N-campaign). Data are mean ± s.d. (range).

~~**Table 53:** Mean and standard deviation (sd) of climatological conditions in Beijing for each circulation type (CT) for 1988-20 17 from Era Interim data with frequency of the CT during the W (winter) and S (summer) campaigns (% of 6 h periods (p)) compared to A long- term 1988-2017.~~

FIGURE LEGENDS

Figure 1: Study area topography (source: googlemap) of Beijing / Tianjing / Hebei region (a) with the rectangle showing enlarged study area; locations of measurement sites (Institute of Atmospheric Physics (IAP)– urban Beijing, Pinggu – rural Beijing; and Gucheng – upwind site in Hebei province), SNAQ box sites (red symbols) and the 12 national air quality monitoring stations (G1 to G12, blue symbols) (b)~~; locations of the 9 containers at IAP (c). instrumentation at in each container is shown in Table 1~~. The shaded area

shows the Beijing built~~d~~-up area. (Source: a and b - Goggle Map topographic background imagery; c – taken by Jian Zhao from IAP).

G1: Wangshouxigong; G2: Dingling (Ming Tombs); G3: Dongsi; G4: Tiantan; G5: Nongzhanguan; G6: Guanyuan; G7: Haidianquwanliu; G8: Shunyxicheng; G9: Huairouzhen; G10:Changpingzhen; G11: Aotizhongxin (Olympic Park); G12: Gucheng. Categories: Urban: G1, G3, G4, G5, G6, G7, G8, G11, G12; Suburban: G9, G10; Rural: G2.

Figure 2: ERA-Interim (1988-2017) average 925 hPa geopotential with 10 m horizontal wind vector for 11 circulation types classified for Beijing (municipal boundary thin solid line) surroundings (103-129° E, 31 - 49° N) determined with the SANDRA method (COST733 class software). Frequency of occurrence is given in cluster caption. For discussion of conditions associated with each CT see Section 4.3.

Figure 3: Time series of circulation types (CTs) during the two field campaigns: (a) winter and (b) summer. The 11 CTs are shown in Figure 2. See text for more description. Shading shows the pollution events identified in Section 5 and Figure 5.

Figure 4: Beijing wind roses: (a, b, d, e) ERA-Interim 10 m horizontal wind (40° N, 116.5° E) and (c, f) sonic anemometer (Table 1) at IAP 320 m agl for (a) 5 November – 10 December in 1988-2017, (d) 15 May – 22 June in 1988-2017, (b, c) 5 November – 10 December 2016, and (e, f) 15 May – 22 June 2017.

Figure ~~27~~5: Time-series of air quality variables at the urban and rural sites during the winter campaign; Five haze events are indicated (shading; see also Table 4).

Figure ~~38~~6: Diurnal patterns of gaseous pollutants normalized by average concentrations at IAP during winter and summer campaigns. Line shows the mean concentrations and shaded area as 95% confidence interval in the difference in mean concentrations

~~**Figure 49:** Air pollutants concentrations (colour) with wind direction (angle) and wind speed ($m\ s^{-1}$) at IAP during the winter and summer campaigns. Data are hourly in time resolution and were from 10 November to 11 December 2016 (winter) and 21 May to 22 June 2017~~

~~(summer). The colour scale is for "weighted.mean" where the mean wind speed/direction bin is multiplied by the bin frequency and divided by total frequency.~~

Figure ~~5~~~~10~~7: Time series of CO_2, CO, NO, O_x (NO_2+O_3) and wind speed at six heights (colour) measured with SNAQ boxes on the IAP tower during the winter intensive field campaign.

~~**Figure 6~~11~~:** Hourly $PM_{2.5}$ mass concentrations versus visibility (at the Beijing Capital Airport) during the winter campaign. Data source: visibility downloaded using R "worldmet" package: date of last access: 27/02/2018).~~

Figure ~~7~~~~12~~8: Time-series of air quality variables at the urban and rural sites during the summer campaign. Two minor haze events are indicated (shading).

Figure ~~8~~~~13~~9: Correlations between the air quality at IAP, PQ and 12 monitoring station around Beijing. Stations G1-G12 (Figure ~~2~~1(b)) are labelled 01-12, PG = Pinggu.

Figure 10: Analysis by circulation type (CT; Sect. 4.3) of: (a) daily maximum mixed layer height (MLH) determined from ALC observations at IAP between November 2016 – June 2017 (analysis method, Kotthaus and Grimmond, 2018b); concentration of (b) $PM_{2.5}$ and (c) O_3 at the Olympic Park (i.e. Aotizhongxin) in 2013-2017 from the national air quality network for different CTs; occurrence of CTs in (d) 1988-2017 and (e) Oct 2016 – Sept 2017; (f) anomaly of CT frequency during the campaigns compared to 5 y (2013-2017) averages; and (g) anomaly of $PM_{2.5}$ and O_3 during the campaigns compared to 5 y (2013-2017) averages. IOP = intensive observation period (i.e., campaign period).

Figure 11: Comparison of observed (at IAP) and modelled pollutant concentrations showing (a) $PM_{2.5}$ concentrations during the winter campaign compared with NAQPMS simulations, and (b) O_3 mixing ratios in summer compared with UKCA simulations.

Figure ~~17~~12: Frequency distribution of $PM_{2.5}$ in Beijing over the winter (~~left~~top) and summer (~~right~~bottom) campaign periods from the NAQPMS model compared with those from the same periods over the past five years under the same emission conditions.

Table 1: Overview of measurements in APHH-Beijing at the urban site.

	Instrument	Measurements	Institute	References
Container 2	FAGE	OH (Chem and Wave)^{X}, HO_2, RO_2	Leeds	Whalley et al. (2010)
	OH reactivity	OH reactivity	Leeds	Stone et al. (2016)
	Spectral radiometer	Photolysis rates	Leeds	Bohn et al. (2016)
	Filter radiometer	$J(O^1D)$	Leeds	Bohn et al. (2016)
	Dew point hygrometer	Water vapour	Leeds	Whalley et al. (2010)
	Davis met station	Wind speed, direction, temp, RH, pressure	Leeds	
	Vaisala CL31 ALC Ceilometer $^{+}$	Cloud-base height, mixing height, attenuated backscatter profiles	Reading	Kotthaus and Grimmond (2018a)
	Personal air monitors (PAMS)	CO, NO, NO_2, PM_1, PM_{10}, $PM_{2.5}$	Cambridge	Moore et al. (2016)
	MicroPEMs	Personal PM exposure	IOM	Sloan et al. 2015
Container 2	DC-GC-FID	C2-C7 VOCs and oVOCs	York	Hopkins et al. (2011)
	GCxGC FID	C6 - C13 VOCs and oVOCs	York	Dunmore et al. (2015)
	TEI 42i	NO	Birmingham	
	Teledyne CAPS	NO_2	York	
	TEI 42c	Total NO_y	York	
	TEI 49i	O_3	York	
	TEI 43i	SO_2	York	
	Sensor box	CO	York	Smith et al. (2017)
	BBCEAS	HONO, NO_3, N_2O_5	Cambridge	Le Breton et al. (2014)
Container 3	LOPAP	HONO	Birmingham	Crilley et al. (2016)
	LIF HCHO	HCHO	Leeds	Cryer et al. 2016
	LOPAP	HONO	IC-CAS	Zhang et al. (2019~~8~~)
	GC-MS	Organic nitrates	East Anglia	Mills et al. (2016)
	ROS online analyser	Reactive Oxygen Species	Cambridge	Wragg et al. (2016)
Con tain	FAGE	OH (wave)^{x}, HO_2	Peking	Lu et al., 2012

	FAGE	OH (chem)[x]	Peking	Tan et al., 2017
	TEI 42i	NO	Peking	Tan et al., 2017
	Teledyne CAPS	NO2	Peking	
	TEI 42c with Moly converter	NO_2	Peking	
	TEI 49i	O_3	Peking	
	TEI	CO	Peking	
	Spectral radiometer	Photolysis rates	Peking	
	GC-ECD	PAN	Peking	Zhang et al., 2011
	GC-MS	VOCs	Peking	Wang et al., 2015a

Container 5 [*]	H-TDMA/V-TDMA	Hygroscopicity/volatility	Peking	Wu et al., 2013
	SMPS+APS	Particle Number size distribution	Peking	Wu et al., 2016
	Particle size magnifier	Size distribution of < 3nm particles	Peking	Vanhanen et al., 2011
	IGAC-IC	Water-soluble ions	Peking	Yu et al. (2018)
	Xact	Metal	Peking	Yu et al. (2018)
	Sunset OC/EC	EC/OC	Peking	Zhang et al. (2017b)

Container 6	IBBCEAS	HONO, NO_2	AIOFM	Duan et al. (2018)
	CRDS	NO_3 and N_2O_5	AIOFM	Li et al. (2018)
	Nitrate Api-TOF-CIMS	Organics, clusters (HOMs)	Birmingham	Junninen et al. (2010)
	SMPS	Particle size distribution	Birmingham	Shi et al. (1999)
	Particle size magnifier	Size distribution of < 3 nm particles	Birmingham	Vanhanen et al. (2011)

Container 7	Fast NO_x	NO_x fluxes	York	Vaughan et al. (2016)
	AL5002 CO analyser	CO fluxes	York	Gerbig et al. (1999)
	HR-TOF-AMS	Fluxes of PM_1 non-refractory (NR) species	CEH	Nemitz et al. (2008)
	SP2	BC fluxes	Manchester	Liu et al. (2017)
	PTR-TOF-MS	VOC fluxes	GIG Lancaster	Huang et al. (2016)

	SYFT-MS Voice 200 Ultra	VOC fluxes	York	Storer et al. (2014)
Container 8	SMPS3968-APS3321	Particle number size distribution	BNU	Du et al. (2017)
	H/V TDMA	Particle hygroscopicity	BNU	Wang et al. (2017b)
	CCNC-100	CCN	BNU	Wang et al. (2017b)
	PAX (870nm)	Extinction & absorption coefficient	IAP	Xie et al. (2018)
	Ammonia analyzer	NH_3	IAP	Meng et al. (2018)
	Sunset OC/EC analyzer	Online OC/EC	IAP	Zhang et al. (2017b)
Container 9	Iodide FIGAERO-TOF-CIMS	Particle and gas phase molar molecule	Manchester	Le Breton et al. (2018)
	CPMA-SP2	Black carbon mass and mixing state	Manchester	Liu et al. (2017)
	Micro reactor	oVOCs	York	Pang et al. (2014)
Tower ~100 m	QCL NH_3	Ammonia fluxes	CEH	McManus et al. (2010)
	IRGA LiCOR-7500	CO_2 / H_2O flux	CEH	McDermitt et al. (2011)
	DMT UHSAS	Size resolved particle flux (0.06-1 µm)	CEH	Deventer et al. (2015)
	TSI APS3021	Size-resolved particle flux (0.5-25 µm)	CEH	Nemitz et al., (2002)
	TSI CPC3785	Total particle number flux	CEH	Petäjä et al., (2006)
	ROFI	O_3 flux	CEH	Coyle et al., 2009
	Sonic anemometer R3-50	Turbulence, sensible heat flux	CEH	Högström and Smedman (2004)
	WXT530 weather station	T, P, RH, wind speed & direction, precipitation	CEH	

	2B O_3 analyser	O_3 concentration	CEH	Johnson et al. (2014)
Tower ~120 m	High-vol sampler	$PM_{2.5}$ filter samples	IAP	
	Anderson sampler	Size-resolved PM samples	IAP	
Tower ~260 m	High-vol sampler	$PM_{2.5}$ filter samples	IAP	
	Anderson sampler	Size- resolved PM samples	IAP	
	ACSM	NR PM_1 species	IAP	Sun et al. (2012)
	CAPS-PM-$_{Ext}$ (630nm)	Extinction	IAP	Wang et al. (2015b)
	SMPS 3938	Particle Number size distribution	IAP	Du et al. (2017)
	Gas analyser	CO, O_3 and SO_2	IAP	Zhou et al. (2018)
	Aethalometer AE33	Black carbon	IAP	Xie et al. (2018)
	Single particle sampler	Individual particles	CUMTB	Wang et al. (2018a)
Tower and tower basket measurements	SNAQ boxes (x 6 at different heights)	CO, NO, NO_2, SO_2, PM_1, PM_{10}, $PM_{2.5}$	Cambridge	Popoola et al. (2018)
	LOPAP	HONO (3 min avg)	Birmingham	Crilley et al. (2016)
	Spectral radiometer	Photolysis rates	Leeds	Bohn et al. (2016)
	SNAQ	CO, NO, NO_2, SO_2, PM_1, PM_{10}, $PM_{2.5}$	Cambridge	Popoola et al. (2018)
	WIBS	Fluorescent biological aerosol particles (FBAP)	IAP	Yue et al. (2016)
	AE33	BC	IAP	Xie et al. (2018)
	Los Gatos NH_3 Analyzer	NH_3	IAP	Meng et al. (2018)
	PAX	Light scattering / absorption	IAP	Xie et al. (2018)
IAP ground	High-Vol sampler	$PM_{2.5}$ filter samples	Peking	
	4-channel sampler	$PM_{2.5}$ filter samples	Peking	

	High Vol sampler	*High time resolution $PM_{2.5}$ filter samples*	York	
IAP roof/lab	FDMS+Thermo Scientific 1405-DF	Online $PM_{2.5}$ mass conc.	IAP	
	Partisol sampler	$PM_{2.5}$ + $PM_{2.5-10}$	Birmingham	Taiwo et al. (2014)
	Streaker sampler	Hourly elements in $PM_{2.5}$ and $PM_{2.5-10}$	Birmingham	Taiwo et al. (2014)
	Digitel High Vol	$PM_{2.5}$ daily	IAP	
	Digitel High Vol	PM_1 - 3 hourly	IAP	
	Andersen sampler	Size resolved PM	IAP	
	WIBS	Fluorescent biological particles	IAP	Yue et al. (2016)
	CAPS-NO_2	NO_2	IAP	Ge et al. (2013)
	Aethalometer AE33	Black carbon	IAP	Xie et al. (2018)
	CAPS-PM_{SSA} (630nm)	Extinction, Scattering	IAP	Han et al. (2017)
	HR-ToF-AMS	NR-PM species	IAP	Sun et al. (2016)
	SP-AMS	Refractory BC and coated aerosol composition		Wang et al. (2017a)
	Iodide FIGAERO-ToF-CIMS	Particle and gas phase molar molecule	IAP	Zhou et al. (2018)
	Single particle sampler	Individual particles	CUMTB	Wang et al. (2018)

Institution names: AIOFM = Anhui Institute of Fine Optics and Mechanics; BNU = Beijing Normal University; CEH = Centre for Ecology and Hydrology; CUMTB = China University of Mining and Technology (Beijing); GIG = Guangzhou Institute of Geochemistry, Chinese Academy of Sciences; NUIST = Nanjing University of Information Science &Technology; IC-CAS = Institute of Chemistry, Chinese Academy of Sciences

[+] Deployment of instruments both campaigns unless: 10/11/2016 to 25/6/2017

[*] Winter campaign only

[X] OH wave and OH chem refer to the method used to obtain the background signal for the FAGE instruments which are equipped with a scavenger inlet

Table ~~3~~2: Overview of measurements at the Pinggu site.

Instruments	**Measurements**	**Insitutue**	**Reference**
Thermo gas analysers	$NO_x/SO_2/CO/O_3$	Peking	Liang et al., 2017
BAM 1020	$PM_{2.5}$ mass concentration	Peking	Liang et al., 2017
High vol sampler	$PM_{2.5}$ samples	IAP	Zhao et al., 2018
Medium vol sampler	$PM_{2.5}$ samples	IAP	Zhao et al., 2018
Low vol Andersen sampler	Size resolved PM samples	IAP	Zhao et al., 2018
Partisol sampler	$PM_{2.5}$ samples	Birmingham	Taiwo et al. (2014)
Streaker sampler	Hourly elements in $PM_{2.5}$ and $PM_{2.5\text{-}10}$	Birmingham	Taiwo et al. (2014)
High vol sampler	Filters of $PM_{2.5}$; high time resolution	Birmingham	
Four Channel sampler	$PM_{2.5}$ samples	Peking	Liang et al., 2017
Thermo MAAP	Online Black Carbon	Peking	Lin et al., 2011
Sunset OC/EC analyzer	Online OC/EC	Peking	Han et al., 2014
Xact	Hourly metals	Peking	Yu et al. (2018)
TOF-ACSM	NR-chemical composition (summer)	Peking	Sun et al., 2012
Thermo Metone	Meteorological parameters	Peking	Liang et al., 2017
SNAQ	Meteorological parameters	Cambridge	Popoola et al. (2018)
SP-AMS	Individual particle composition	CQIGIT	Chen et al. (2017)
SMPS	Size distribution	Tsinghua	Wang et al., 2009
ACSM	NR-chemical composition (winter)	Tsinghua	Li et al. (2016)

CQIGIT = Chongqing Institute of Green and Intelligence Technology, Chinese Academy of Sciences

Table 3: Mean and standard deviation (sd) of climatological conditions in Beijing for each circulation type (CT) for 1988-2017 from ERA-Interim data with frequency of the CT during the W (winter) and S (summer) campaigns (% of 6 h periods (p)) compared to long- term (1988-2017) average-A

		WS	WS_{sd}	WD	WD_{sd}	T2m	$T2m_{sd}$	TD2m	$TD2m_{sd}$	MSLP	$MSLP_{sd}$	RH	RH_{sd}	Season	Frequency (%)		
CT	Description	m s^{-1}	m s^{-1}	°	°	°C	°C	°C	°C	hPa	hPa	%	%		W	S	A
1	H - west of the domain	3.38	1.63	298.3	62.6	0.1	7.1	-12.6	7.9	1026.50	4.14	41	18	Winter monsoon	16	7	9.3
2	H - west of the domain	2.91	1.49	265.9	107.0	-2.8	6.2	-13.8	7.5	1034.34	4.47	45	18	Winter monsoon	1	0	7.2
3	relatively L in NE	3.21	1.65	281.2	71.3	6.8	8.9	-6.4	9.3	1017.77	4.35	43	20	Sep- May	12.5	0	8.3
4	further reduction L (cf. CT3, 5) in NE winds start to turn over Yellow Sea	3.05	1.73	240.1	104.1	19.2	7.5	7.0	10.4	1007.20	3.63	50	24	Mar-Aug Spring - summer	11.8	4	7.8
5	relatively L in NE	2.57	1.37	189.1	125.0	8.2	8.9	-0.9	10.4	1020.82	4.62	57	23	Sep-May	7.6	34	8.3
6	further reduction L (cf. CT3, 5) in NE	2.58	1.32	197.4	87.6	24.6	5.9	14.7	8.0	1000.99	2.96	59	23	Summer monsoon	8.3	12	8.9
7	when winds are oriented westward from the Bohai Sea	2.29	1.12	167.5	100.2	18.9	7.8	10.7	9.5	1012.59	3.61	63	21		1 p	11	10.2
8	like CT 6	2.35	1.11	165.4	75.4	24.0	5.3	15.9	6.8	1006.47	2.69	65	21	Summer monsoon		32	12.9
9	Air mass stagnant over Beijing	2.03	0.94	208.7	107.4	2.1	7.9	-6.2	8.4	1028.66	4.18	58	20			0	9.6
10	Air mass stagnant over Beijing	2.67	1.17	211.1	68.7	14.2	9.4	3.1	10.0	1013.98	3.84	52	22		25	0	7.2

11	Air mass stagnant over Beijing	2.23	0.98	209.1	86.5	8.1	9.4	-0.4	9.6	1021.83	4.06	59	20		16	0	10.3

Note: WS- wind speed, WD wind direction, T2m – 2 m air temperature, TD2m – 2 m dewpoint temperature, MSLP – mean sea level pressure, RH – relative humidity; L – low pressure; H – High pressure

Table 4: Average air quality variables at IAP, Pinggu and 12 national monitoring sites (12N) during the field campaigns (10 November – 11 December 2016; and 21 May – 22 June 2017). The 12 national sites five-year mean concentrations for same times of the years (12N -5Y) and for the same time of the year (campaign period) (12N-campaign). Data are mean ± s.d. (range).

Pollutant[1]	**Winter** *(10 Nov-11 Dec 2016)*				**Summer** *(21 May-22 June 2017)*			
	IAP	PG	12N-5Y	12N - campaign	IAP	PG	12N-5Y	12N- campaign
$PM_{2.5}$ [2]	91.2 ± 63.7 (10.3-239.9)	99.7 ± 77.8 (13.3-294.3)	84.01 ± 89.1 (3.2-593.3)	95.3 ± 79.6 (4.7-408.8)	31.4 ± 14.7 (12.2-78.8)	27.8 ± 13.3 (10.6-70.3)	58.7 ± 40.0 (4.2-250.3)	41.7 ± 22.3 (8.9- 134.1)
PM_{10} [2]	130.6 ± 87.0 (20.0-329.2)	121.9 ± 80.4 (10.4-312.1)	112.8 ± 102.2 (5-662.0)	134.5 ± 100.4 (6.0-550.1)	74.9 ± 29.3 (22.5-164.6)	62.9 ± 29.3 (15.1-141.9)	94.6 ± 52.7 (5.0-463.2)	81.9 ± 37.1 (6.0-277.8)
NO_2	69.7 ± 33.3 (10.2-167.3)	46.4 ± 25.5 (2.3-132.4)	57.7 ± 33.9 (3.9-166.4)	66.4 ± 31.3 (7.3-156.6)	41.3 ± 23.5 (9.2-142.9)	29.3 ± 10.3 (9.3-84.0)	40.6 ± 17.9 (8.1-132.4)	37.6 ± 16.2 (12.5-92.8)
SO_2	14.9 ± 11.1 (0.1-50.8)	15.4 ± 6.7 (6.2-44.4)	16.6 ± 16.2 (1.4-112.0)	14.2 ± 9.4 (2.1-51.4)	6.3 ± 6.8 (0.1-38.2)	8.9 ± 4.7 (4.2-41.2)	10.1 ± 10.6 (1.8-82.3)	7.4 ± 6.6 (1.8-64.5)
CO ~~[2]~~	1.53 ± 1.02 (0.7-5.0)	1.47 ± 1.17 (0.1-6.9)	1.65 ± 1.38 (0.1-9.6)	1.86 ± 1.17 (0.3-5.7)	0.61 ± 0.32 (0.1-2.5)	0.52 ± 0.29 (0.1-2.3)	0.93 ± 0.74 (0.2-8.7)	0.74 ± 0.33 (0.2-2.5)
O_3	16.4 ± 17.0 (0.3-63.3)	22.3 ± 22.2 (2.9-78.0)	21.8 ± 20.5 (1.0-72.9)	17.5 ± 19.2 (2.1-67.4)	106.9 ± 71.6 (2.0-349.3)	91.8 ± 62.7 (0.2-291.4)	100.4 ± 67.8 (2.2-343.5)	110.8 ± 66.5 (3.6-335.9)

[1], Units: $\mu g\ m^{-3}$ except CO units: $mg\ m^{-3}$

[2], $PM_{2.5}$ and PM_{10} from IAP and Pinggu measured by a gravimetric method; all other data are online measurements hourly mean.

Table 5: Haze periods during the summer and winter campaign periods.

Event	Time	$PM_{2.5}$ (μg m^{-3})	Visibility (km)
Winter Haze Event 1	11/08 21:00- 11/10 16:00	158 (79 - 229)	4.1 (2.3-8)
Winter Haze Event 2	11/15 21:00- 11/19 08:00	143 (56 - 244)	4.2(0.6-8)
Winter Haze Event 3	11/24 12:00- 11/27 02:00	210 (68-363)	4.2(1.5-8)
Winter Haze Event 4	12/02 16:00- 12/05 02:00	239 (58 -530)	3.9(0.9-8)
Winter Haze Event 5	12/06 09:00- 12/08 10:00	144 (64 -229)	4.6(2.2-8)
Summer Haze Event 1	27/05 12:00 -28/05 13:00	107(62- 163)	6.8(4.5-9)
Summer Haze Event 2	17/06 09:00-18/06 17:00	90.5(60-153.3)	9.3(7-13)

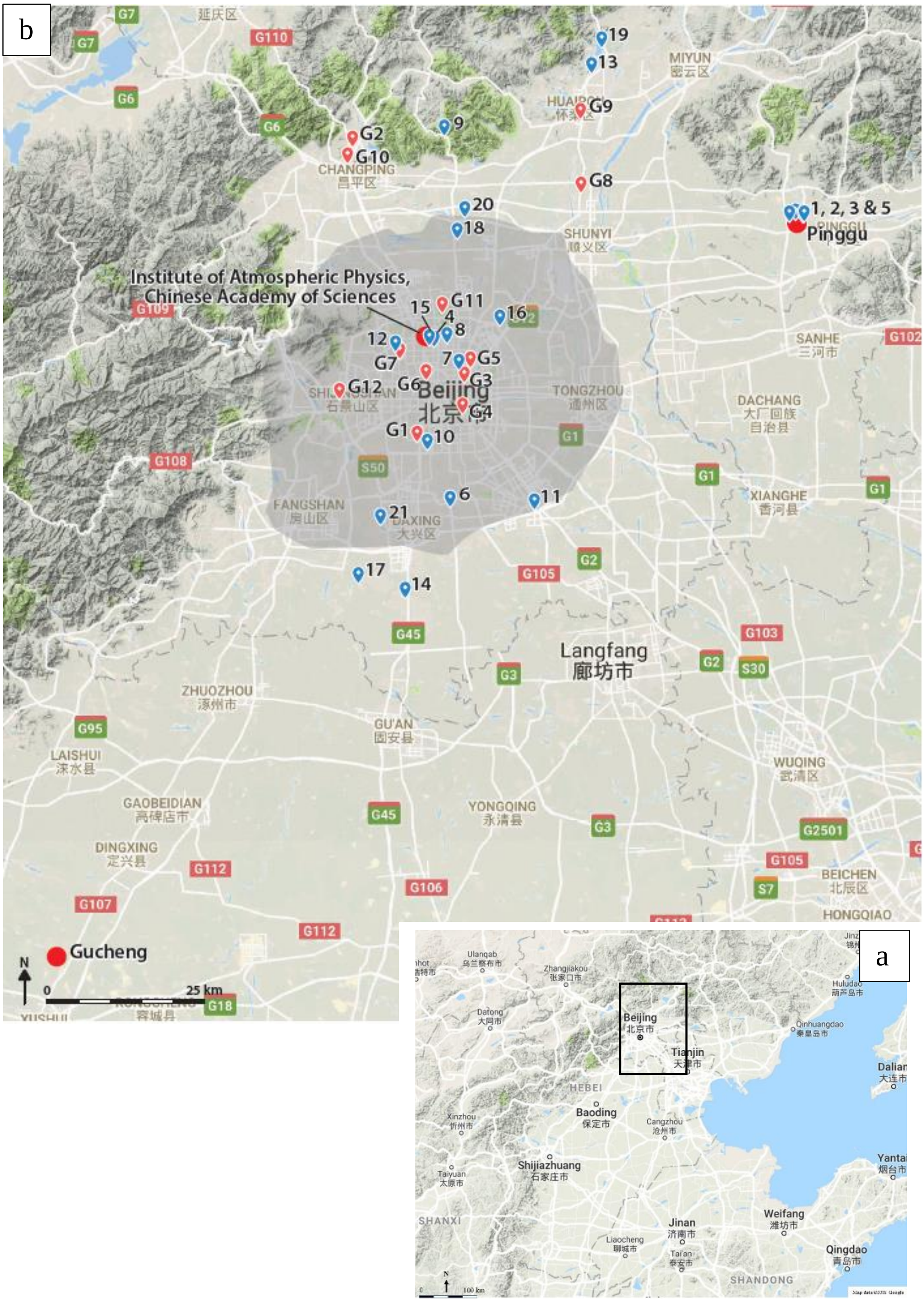
Note: data in parentheses show the range

~~**Table 53:** Mean and standard deviation (sd) of climatological conditions in Beijing for each circulation type (CT) for 1988-20 17 from Era Interim data with frequency of the CT during the W (winter) and S (summer) campaigns (% of 6 h periods (p)) compared to A long- term 1988-2017.~~

CT	Description	WS m s^{-1}	WS$_{sd}$ m s^{-1}	WD °	WD$_{sd}$ °	T2m °C	T2m$_{sd}$ °C	TD2m °C	TD2m$_{sd}$ °C	MSLP hPa	MSLP$_{sd}$ hPa	RH %	RH$_{sd}$ %	Season	Frequency (%) W	S	A
1	H west of the domain	3.38	1.63	298.3	62.6	0.1	7.1	-12.6	7.9	1026.50	4.14	41	18	Winter monsoon	16	7	9.3
2	H west of the domain	2.91	1.49	265.9	107.0	-2.8	6.2	-13.8	7.5	1034.34	4.47	45	18	Winter monsoon	1	0	7.2
3	relatively L in NE	3.21	1.65	281.2	71.3	6.8	8.9	-6.4	9.3	1017.77	4.35	43	20	Sep–May	12.5	0	8.3
4	further reduction L (cf. CT3, 5) in NE winds start to turn over Yellow Sea	3.05	1.73	240.1	104.1	19.2	7.5	7.0	10.4	1007.20	3.63	50	24	Mar-Aug Spring–summer	11.8	4	7.8
5	relatively L in NE	2.57	1.37	189.1	125.0	8.2	8.9	-0.9	10.4	1020.82	4.62	57	23	Sep-May	7.6	34	8.3
6	further reduction L (cf. CT3, 5) in NE	2.58	1.32	197.4	87.6	24.6	5.9	14.7	8.0	1000.99	2.96	59	23	Summer monsoon	8.3	12	8.9
7	when winds are oriented westward from the Bohai Sea	2.29	1.12	167.5	100.2	18.9	7.8	10.7	9.5	1012.59	3.61	63	21		1 p	11	10.2
8	like CT 6	2.35	1.11	165.4	75.4	24.0	5.3	15.9	6.8	1006.47	2.69	65	21	Summer monsoon		32	12.9
9	Air mass stagnant over Beijing	2.03	0.94	208.7	107.4	2.1	7.9	-6.2	8.4	1028.66	4.18	58	20			0	9.6
10	Air mass stagnant over Beijing	2.67	1.17	211.1	68.7	14.2	9.4	3.1	10.0	1013.98	3.84	52	22		25	0	7.2

~~11~~	~~Air mass stagnant over Beijing~~	~~2.23~~	~~0.98~~	~~209.1~~	~~86.5~~	~~8.1~~	~~9.4~~	~~-0.4~~	~~9.6~~	~~1021.83~~	~~4.06~~	~~59~~	~~20~~		~~16~~	~~0~~	~~10.3~~

~~Note: WS- wind speed, WD wind direction, T2m – 2 m air temperature, TD2m – 2 m dewpoint temperature, MSLP – mean sea level pressure, RH – relative humidity; L – low pressure; H – High pressure~~


b
Institute of Atmospheric Physics,
Chinese Academy of Sciences
Beijing
北京市
1, 2, 3 & 5
Pinggu
Gucheng
Langfang
廊坊市
G1
G2
G3
G4
G5
G6
G7
G8
G9
G10
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G12
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25 km
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Beijing
北京市
Tianjin
天津市
Baoding
保定市
Shijiazhuang
石家庄市
Jinan
济南市
Weifang
潍坊市
Qingdao
青岛市
HEBEI
SHANXI
SHANDONG

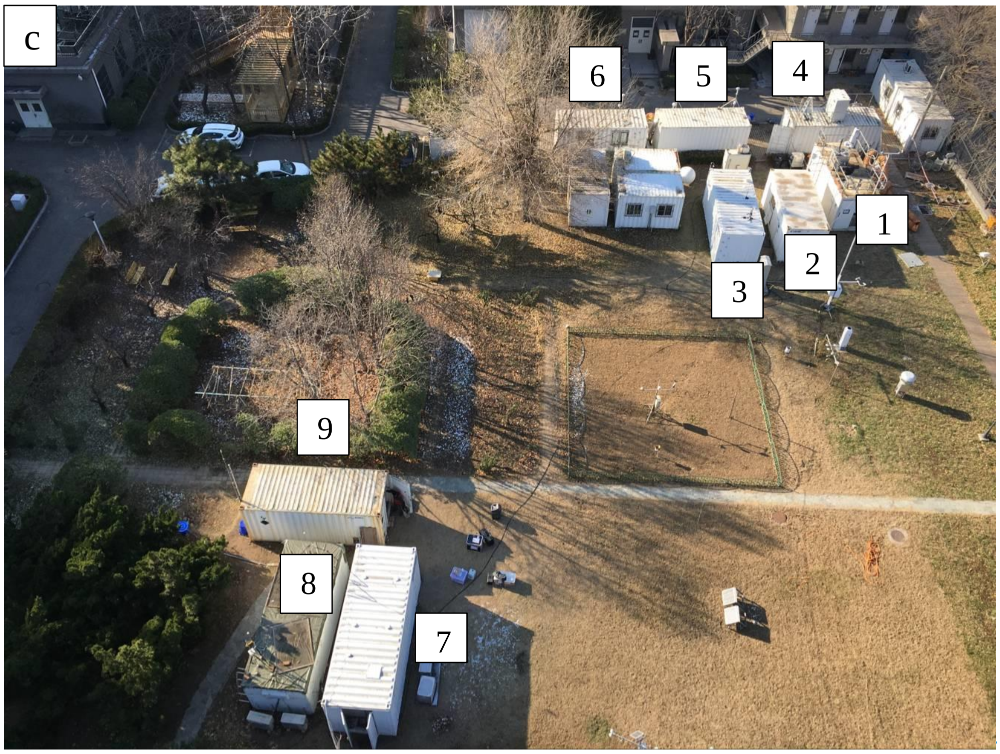


Figure 1: Study area topography (source: googlemap) of Beijing / Tianjing / Hebei region (a) with the rectangle showing enlarged study area; locations of measurement sites (Institute of Atmospheric Physics (IAP)– urban Beijing, Pinggu – rural Beijing; and Gucheng – upwind site in Hebei province), SNAQ box sites (red symbols) and the 12 national air quality monitoring stations (G1 to G12, blue symbols) (b)~~; locations of the 9 containers at IAP (c) – instrumentation at in each container is shown in Table 1~~. The shaded area shows the Beijing buildup area. (Source: a and b - Goggle Map topographic background imagery~~; c – taken by Jian Zhao from IAP~~).

G1: Wangshouxigong; G2: Dingling (Ming Tombs); G3: Dongsi; G4: Tiantan; G5: Nongzhanguan; G6: Guanyuan; G7: Haidianquwanliu; G8: Shunyxicheng; G9: Huairouzhen; G10: Changpingzhen; G11: Aotizhongxin (Olympic Park); G12: Gucheng. Categories: Urban: G1, G3, G4, G5, G6, G7, G8, G11, G12; Suburban: G9, G10; Rural: G2.

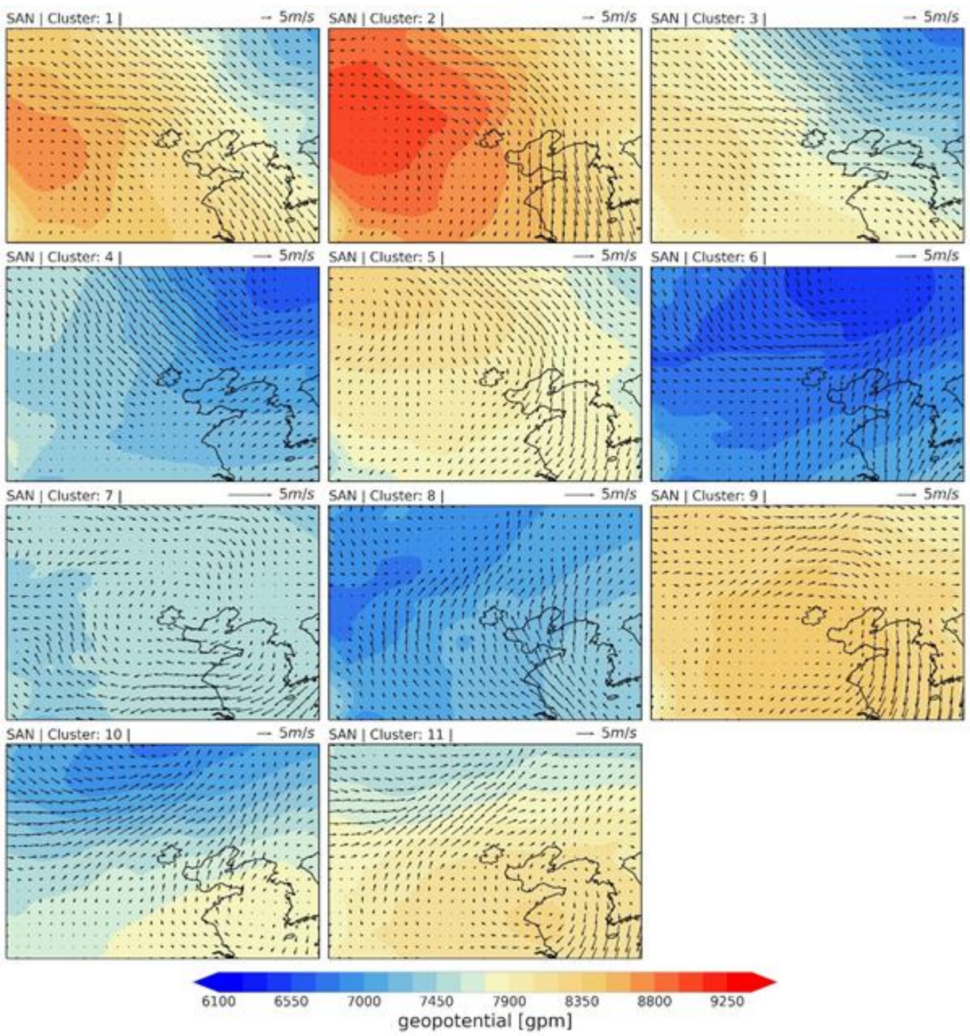


Figure 2: ERA-Interim (1988-2017) average 925 hPa geopotential with 10 m horizontal wind vector for 11 circulation types classified for Beijing (municipal boundary thin solid line) surroundings (103-129° E, 31 - 49° N) determined with the SANDRA method (COST733 class software). Frequency of occurrence is given in cluster caption. For discussion of conditions associated with each CT see Section 4.3.

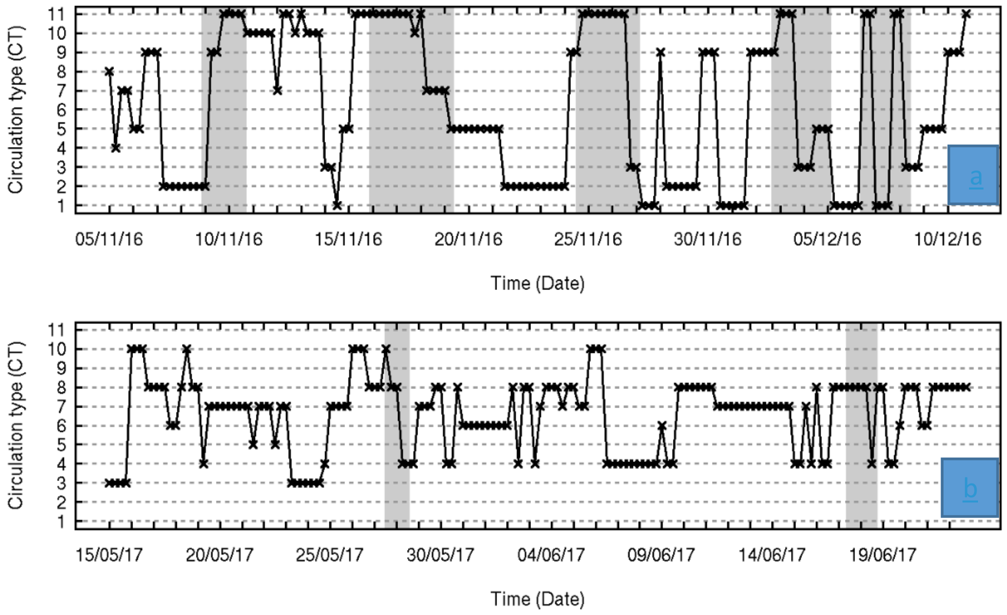


Figure 3: Time series of circulation types (CTs) during the two field campaigns: (a) winter and (b) summer. The 11 CTs are shown in Figure 2. See text for more description. Shading shows the pollution events identified in Section 5 and Figure 5.

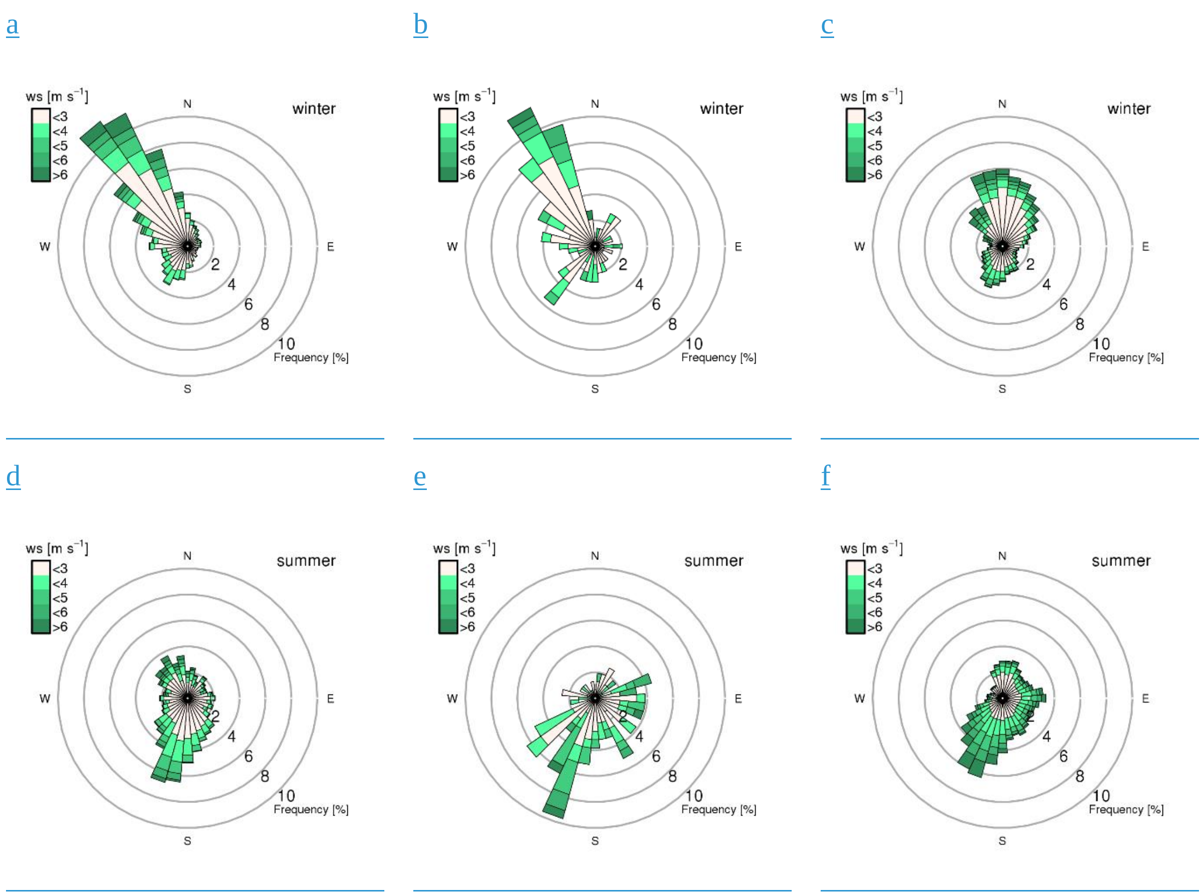


Figure 4: Beijing wind roses: (a, b, d, e) ERA-Interim 10 m horizontal wind (40° N, 116.5° E) and (c, f) sonic anemometer (Table 1) at IAP 320 m agl for (a) 5 November – 10 December in 1988-2017, (d) 15 May – 22 June in 1988-2017, (b, c) 5 November – 10 December 2016, and (e, f) 15 May – 22 June 2017.

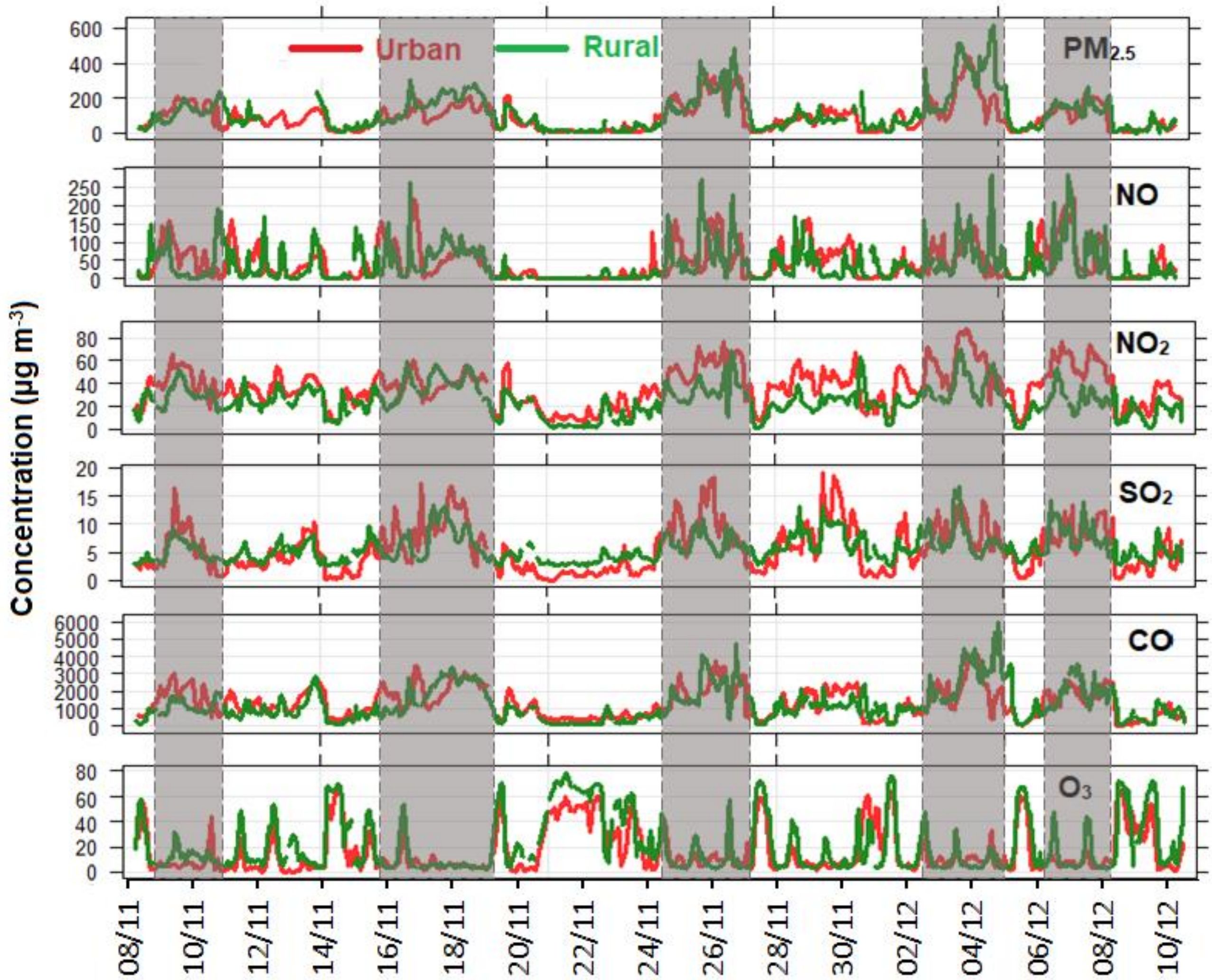


Figure ~~27~~5: Time-series of air quality variables at the urban and rural sites during the winter campaign; Five haze events are indicated (shading; see also Table 4).

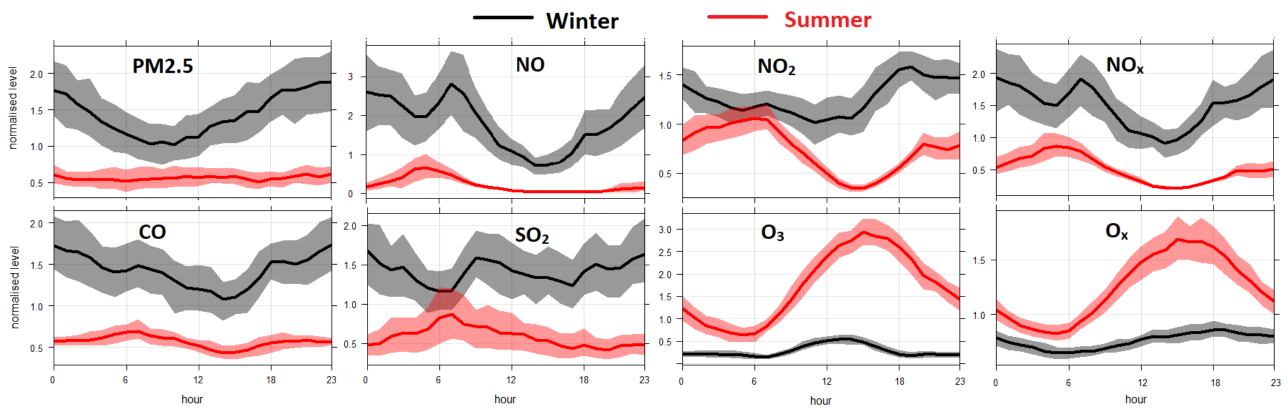
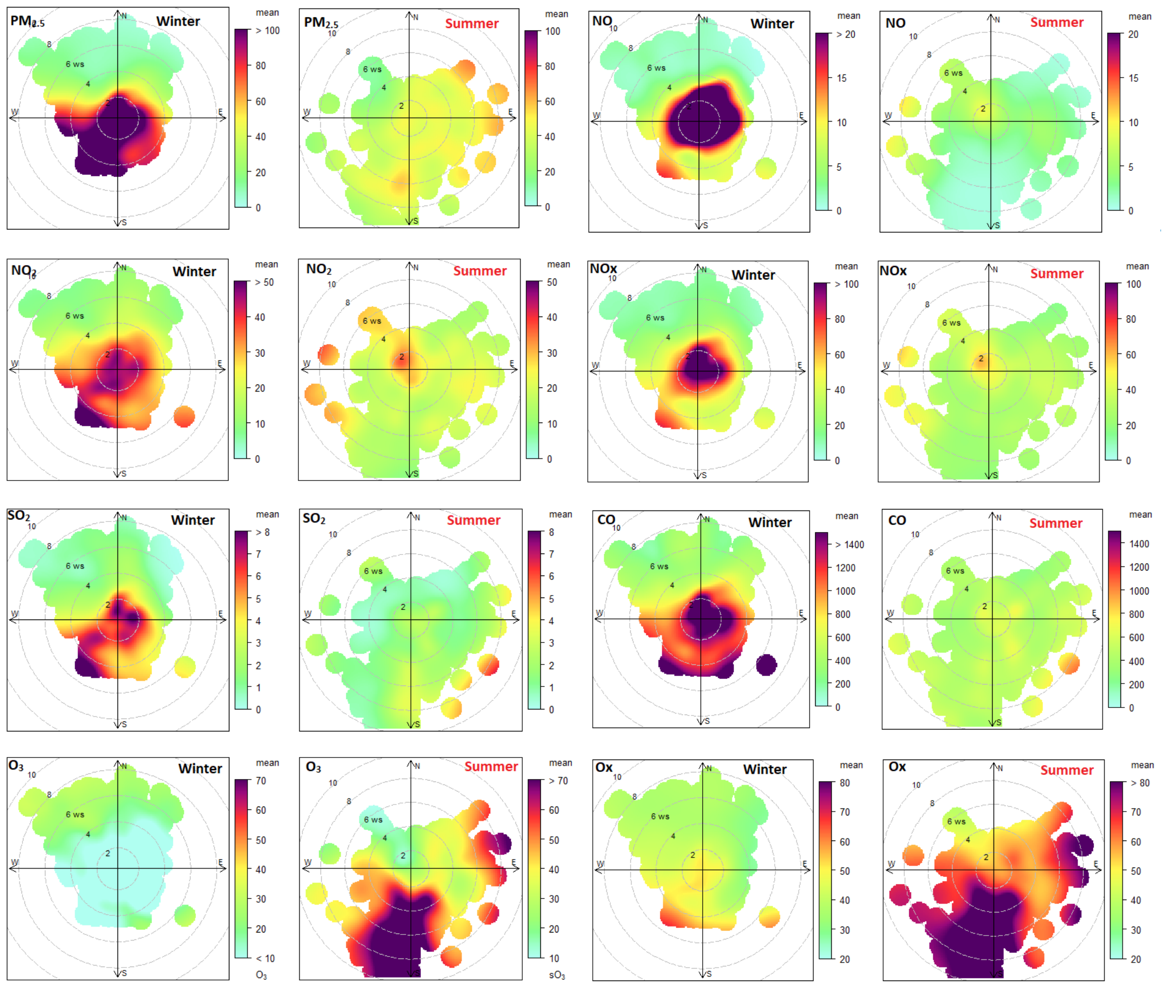


Figure 6: Diurnal patterns of gaseous pollutants normalized by average concentrations at IAP during winter and summer campaigns. Line shows the mean concentrations and shaded area as 95% confidence interval in the difference in mean concentrations.



~~**Figure 49:** Air pollutants concentrations (colour) with wind direction (angle) and wind speed (m s^{-1}) at IAP during the winter and summer campaigns. Data are hourly in time resolution and were from 10 November to 11 December 2016 (winter) and 21 May to 22 June 2017 (summer). The colour scale is for "weighted.mean" where the mean wind speed/direction bin is multiplied by the bin frequency and divided by total frequency.~~

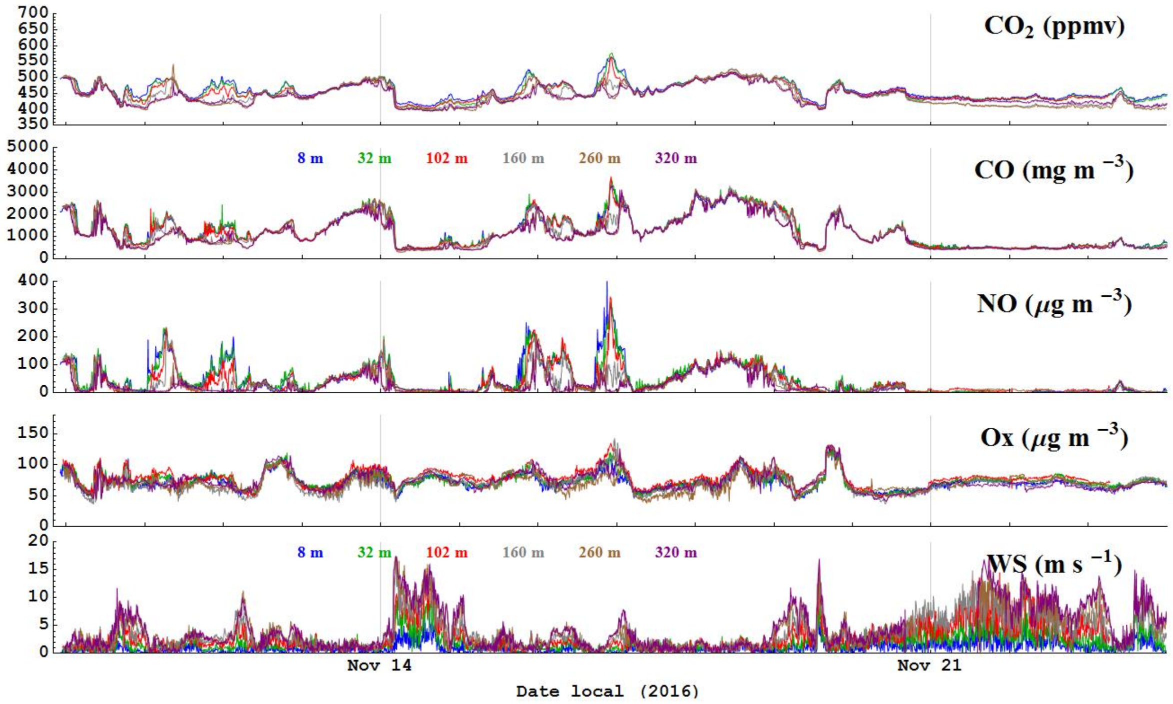
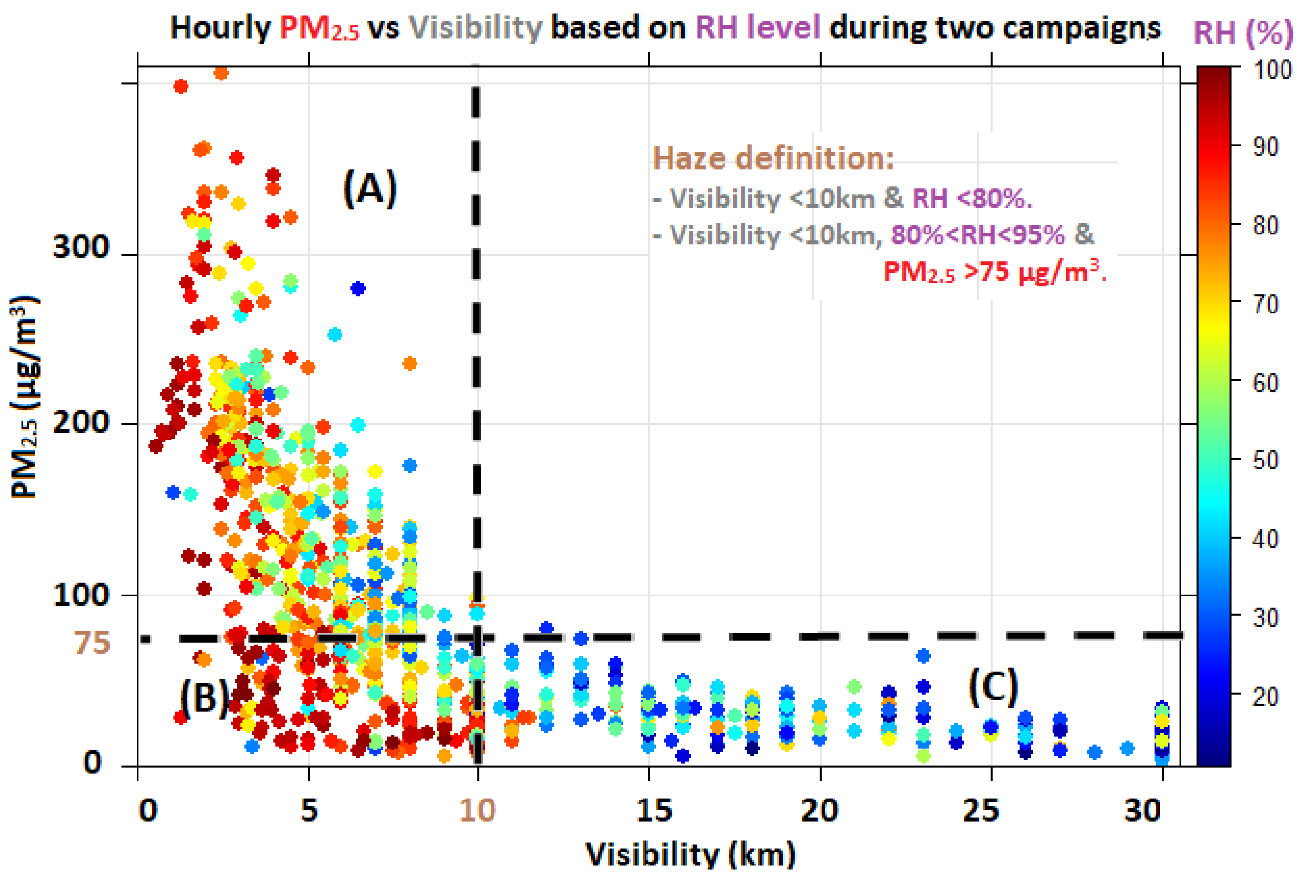
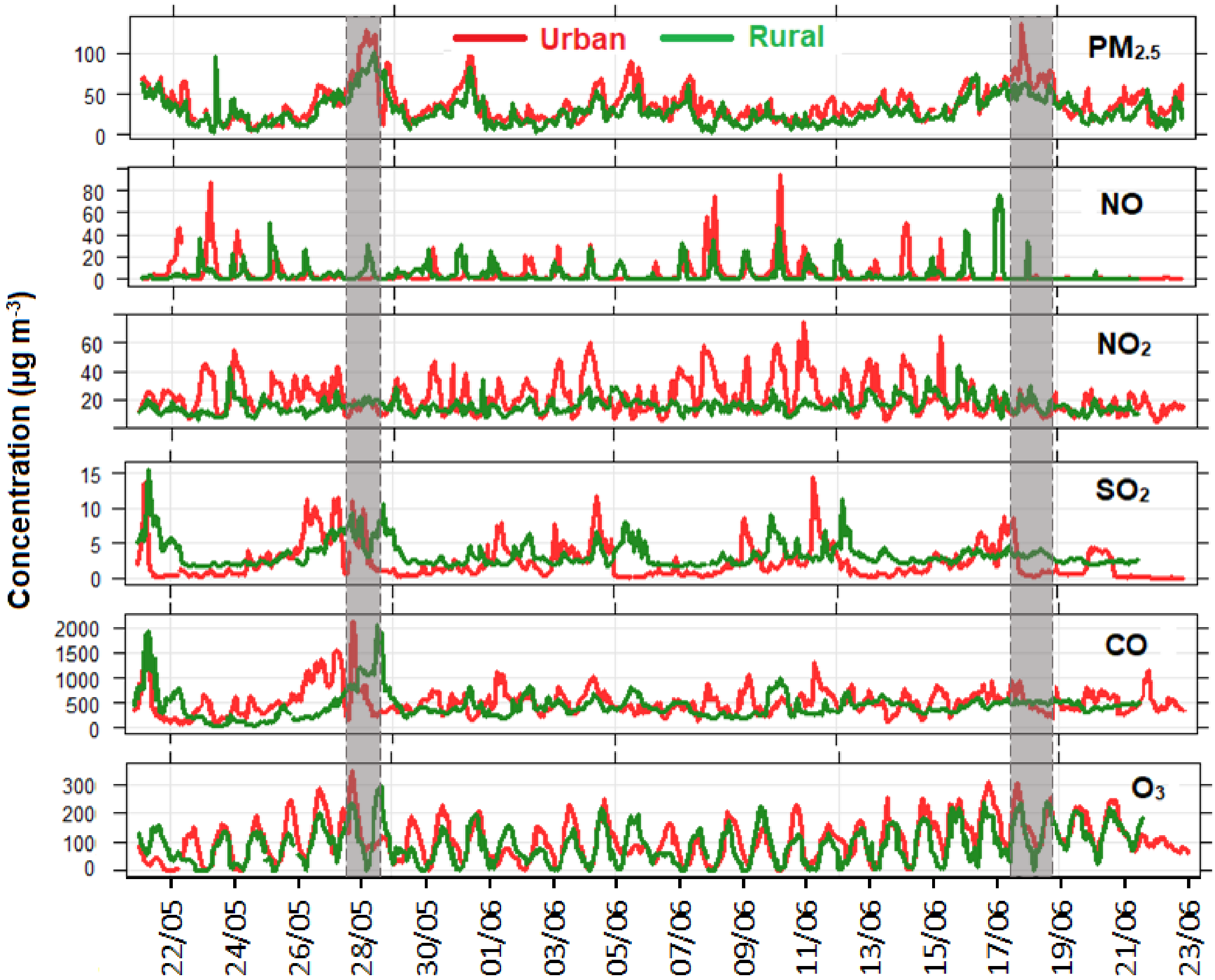


Figure ~~5~~~~10~~7: Time series of CO_2, CO, NO, O_x (NO_2+O_3) and wind speed at six heights (colour) measured with SNAQ boxes on the IAP tower during the winter intensive field campaign.



~~**Figure 6**~~**11**~~**:** Hourly PM~~$_{2.5}$ ~~mass concentrations versus visibility (at the Beijing Capital Airport) during the winter campaign. Data source: visibility downloaded using R "worldmet" package: date of last access: 27/02/2018).~~



Urban
Rural
PM2.5
NO
NO2
SO2
CO
O3
Concentration (µg m-3)
100
50
0
80
60
40
20
0
60
40
20
15
10
5
0
2000
1500
1000
500
0
300
200
100
0
22/05
24/05
26/05
28/05
30/05
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19/06
21/06
23/06

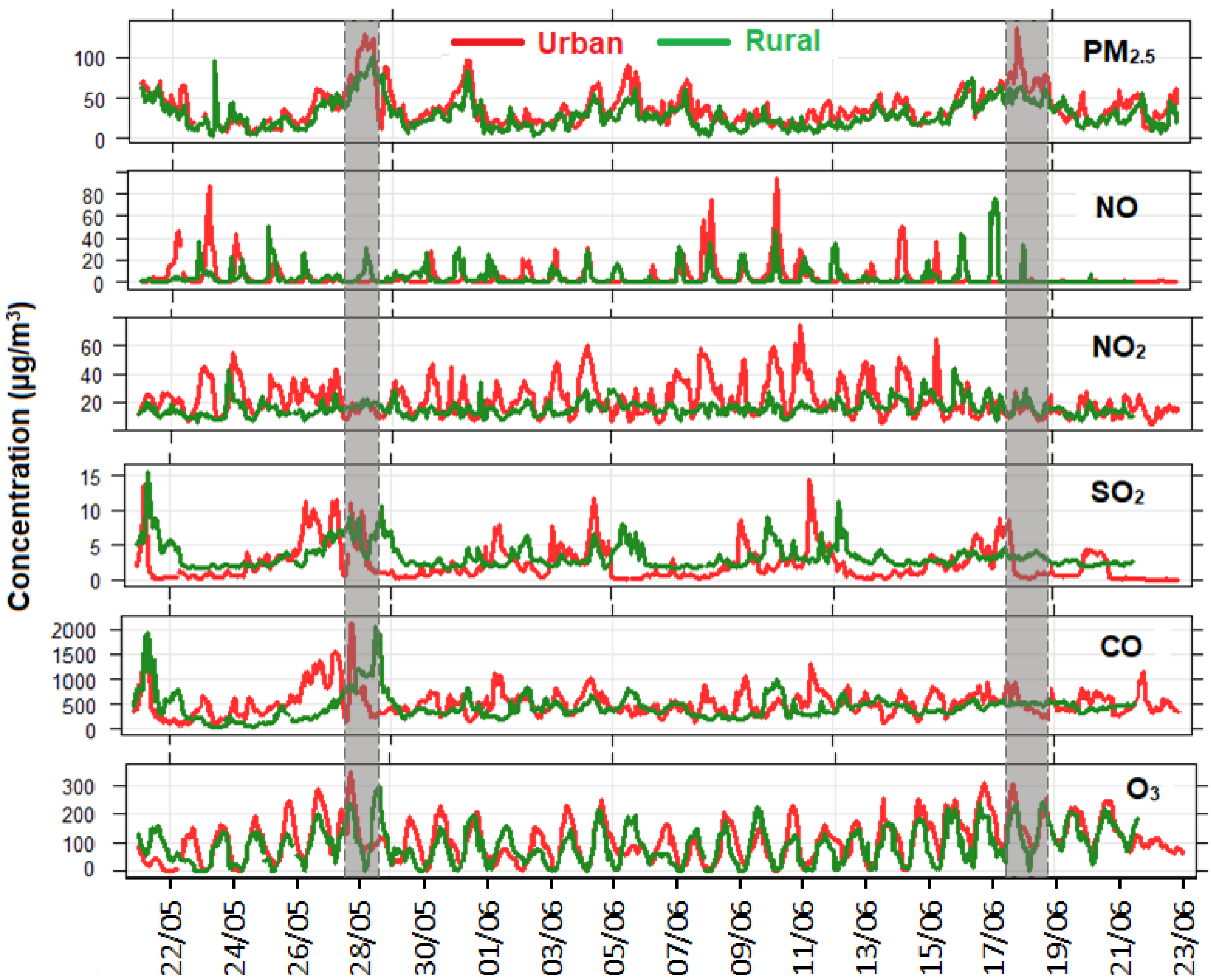


Figure ~~7~~~~12~~8: Time-series of air quality variables at the urban and rural sites during the summer campaign. Two minor haze events are indicated (shading).

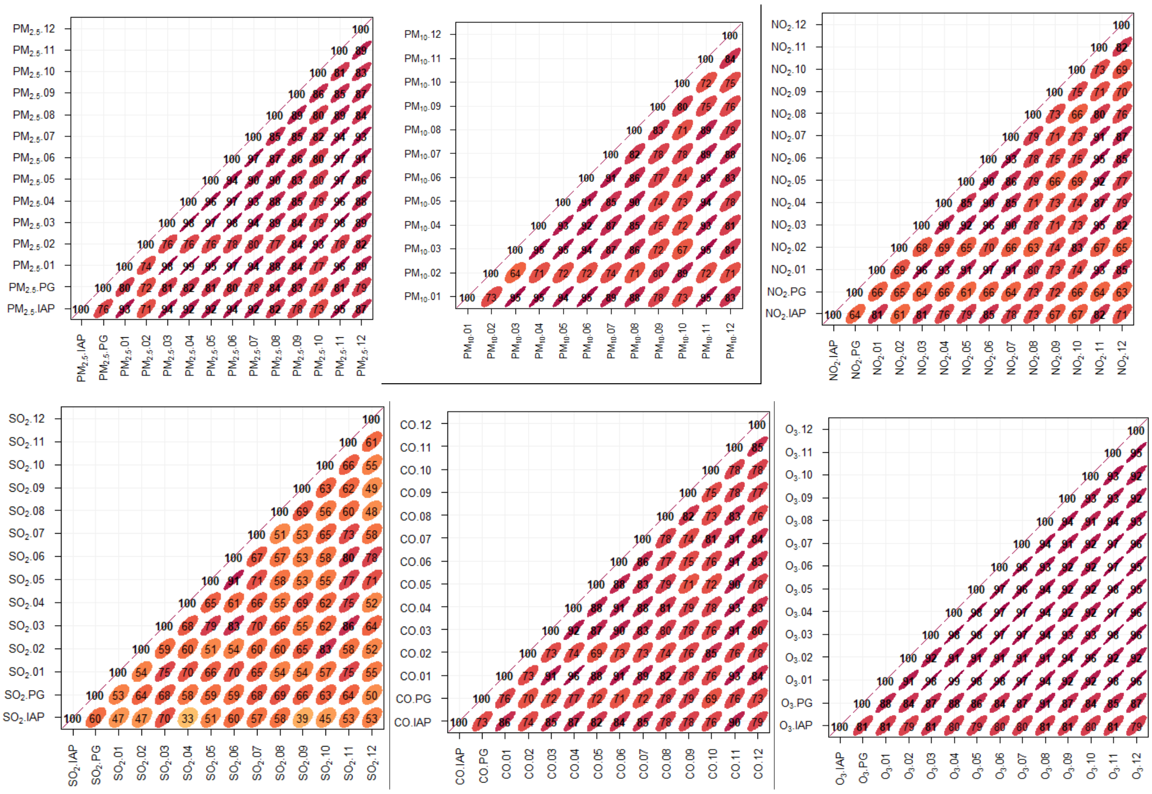
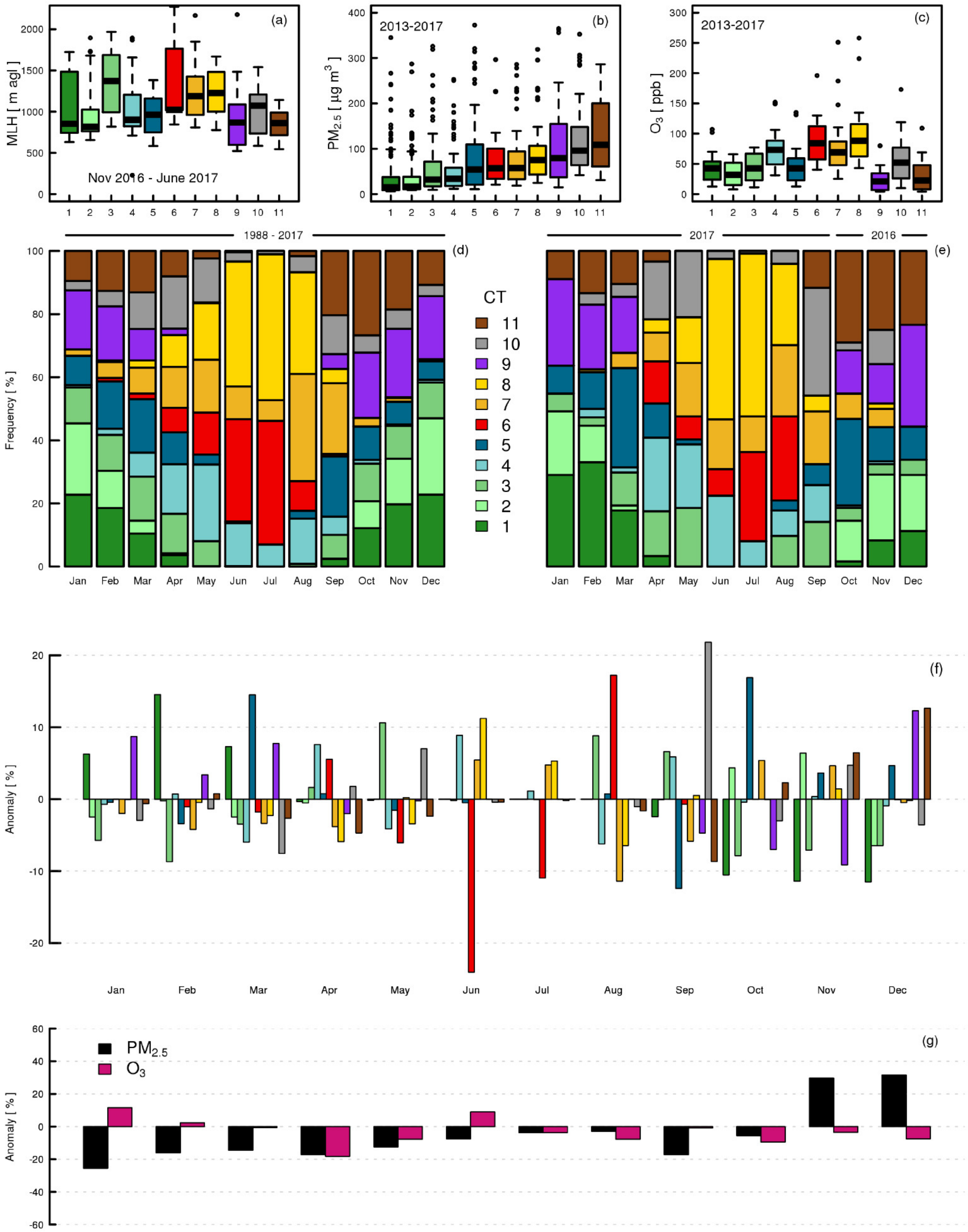


Figure ~~8~~~~13~~9: Correlations between the air quality at IAP, PQ and 12 monitoring station around Beijing. Stations G1-G12 (Figure ~~2~~1(b)) are labelled 01-12, PG = Pinggu.


(a)
MLH [m agl]
Nov 2016 - June 2017
(b)
2013-2017
PM2.5 [µg m3]
(c)
2013-2017
O3 [ppb]
1988 - 2017
(d)
Frequency [%]
CT
11
10
9
8
7
6
5
4
3
2
1
2017
2016
(e)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
(f)
Anomaly [%]
(g)
PM2.5
O3
Anomaly [%]

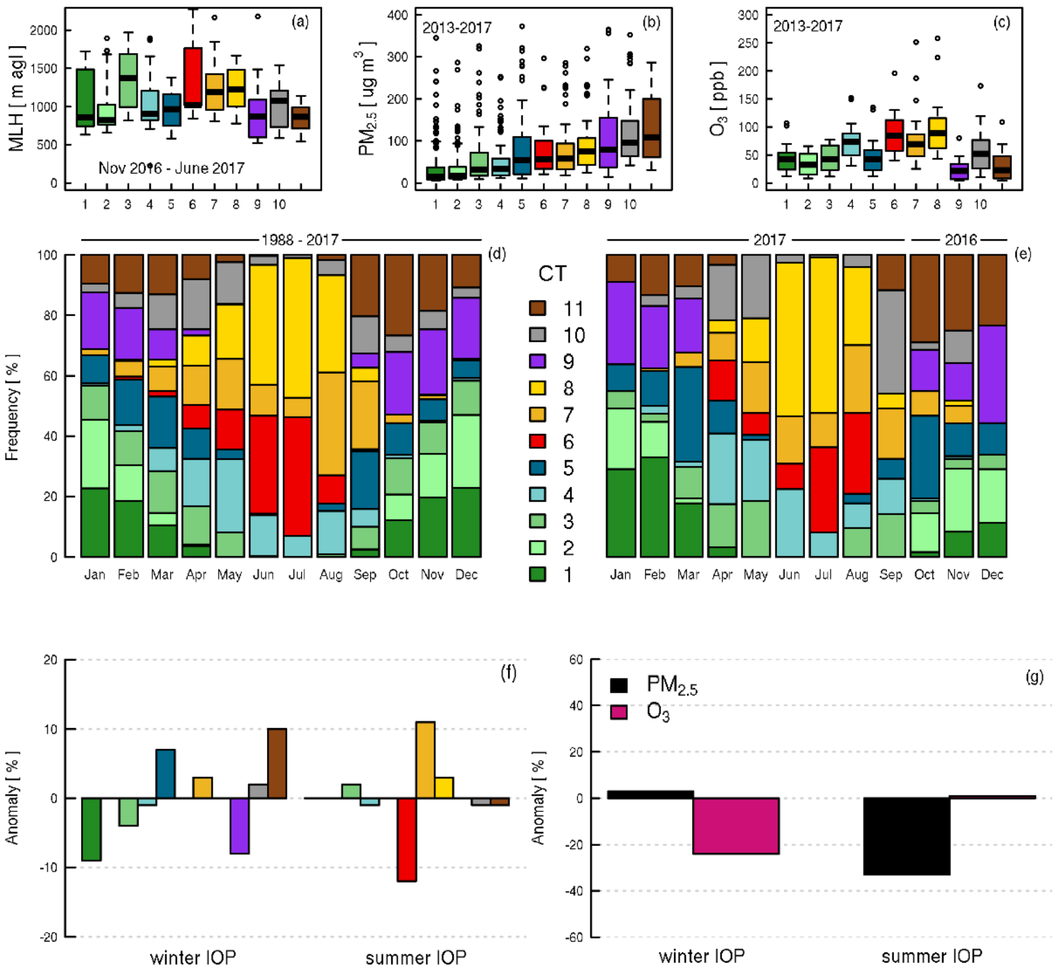
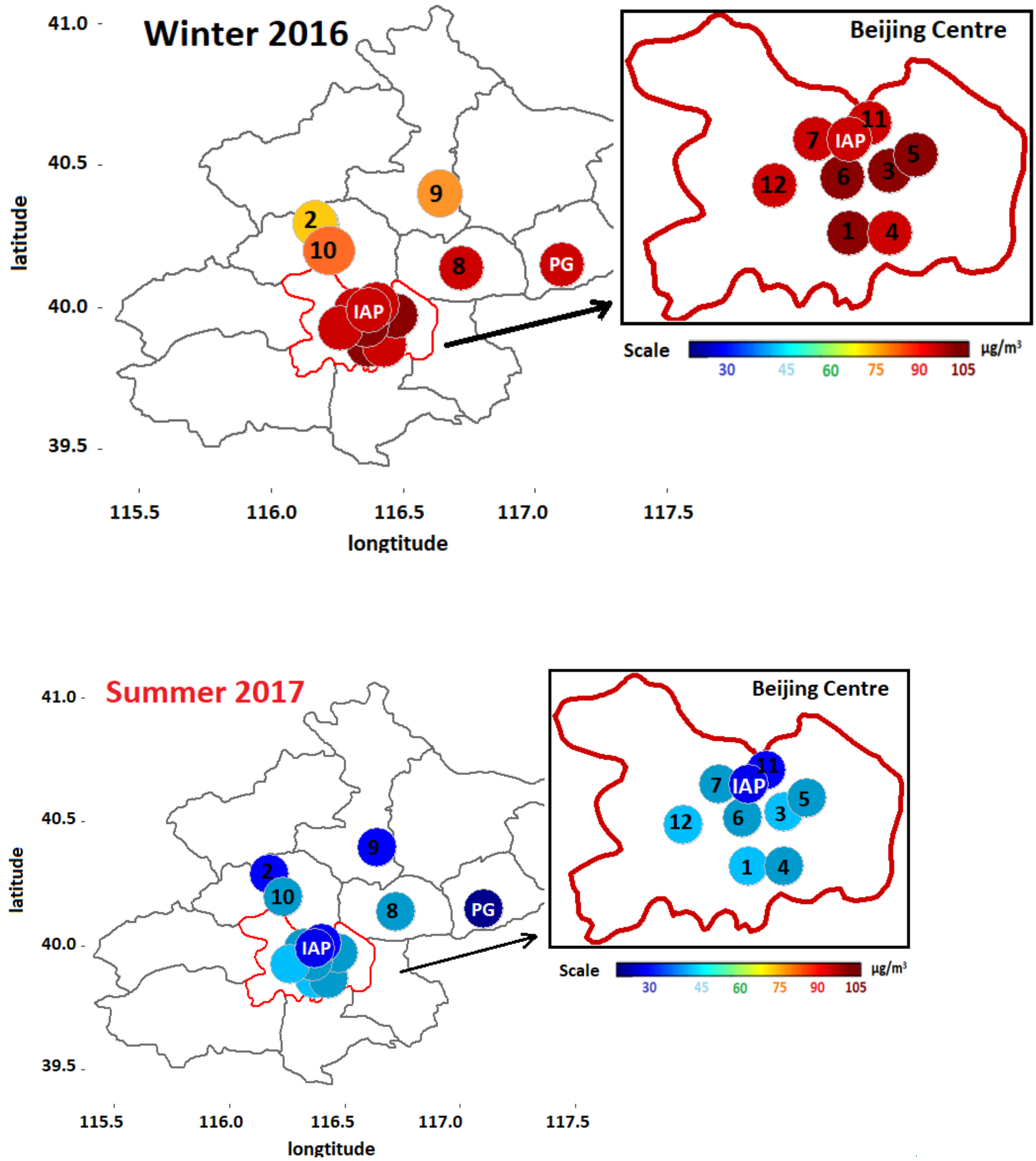


Figure 10: Analysis by circulation type (CT; Sect. 4.3) of: (a) daily maximum mixed layer height (MLH) determined from ALC observations at IAP between November 2016 – June 2017 (analysis method, Kotthaus and Grimmond, 2018b); concentration of (b) $PM_{2.5}$ and (c) O_3 at the Olympic Park (i.e. Aotizhongxin) in 2013-2017 from the national air quality network for different CTs; occurrence of CTs in (d) 1988-2017 and (e) Oct 2016 – Sept 2017; (f) anomaly of CT frequency during the campaigns compared to 5 y (2013-2017) averages; and (g) anomaly of $PM_{2.5}$ and O_3 during the campaigns compared to 5 y (2013-2017) averages. IOP = intensive observation period (i.e., campaign period).

~~**Figure 10**: Analysis by circulation type (CT; Sect. 4.3) of: (a) daily maximum mixed layer height (MLH) determined from ALC observations at IAP between November 2016 – June 2017 (analysis method, Kotthaus and Grimmond, 2018b); concentration of (b) $PM_{2.5}$ and (c) O_3 at at the Olympic Park (i.e. Aotizhongxin) in 2013-2017 from the national air quality network; occurrence of CTs in (d) 1988-2017 and (e) Oct 2016 – Sept 2017; (f) anomaly of CT frequency during Oct 2016 – Sept~~

~~2017 compared to 30 y climatology; and (g) anomaly of $PM_{2.5}$ and O_3 during Oct 2016 – Sept 2017 compared to 5 y (2013-2017) average (same data as in b, c).~~



~~**Figure 9**~~**14**~~: Spatial distribution of hourly mean concentration of $PM_{2.5}$ in Beijing during two sampling campaigns.~~

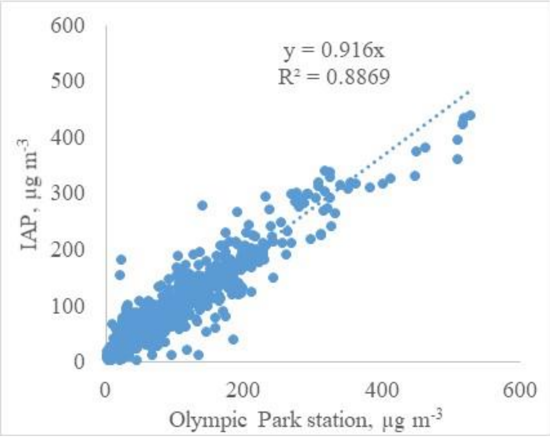


Figure 1015: ~~Hourly $PM_{2.5}$ at IAP (roof of a two storeyied building) and the neighbouring Olympic park national air quality monitoring station during the winter and summer intensive field campaigns.~~

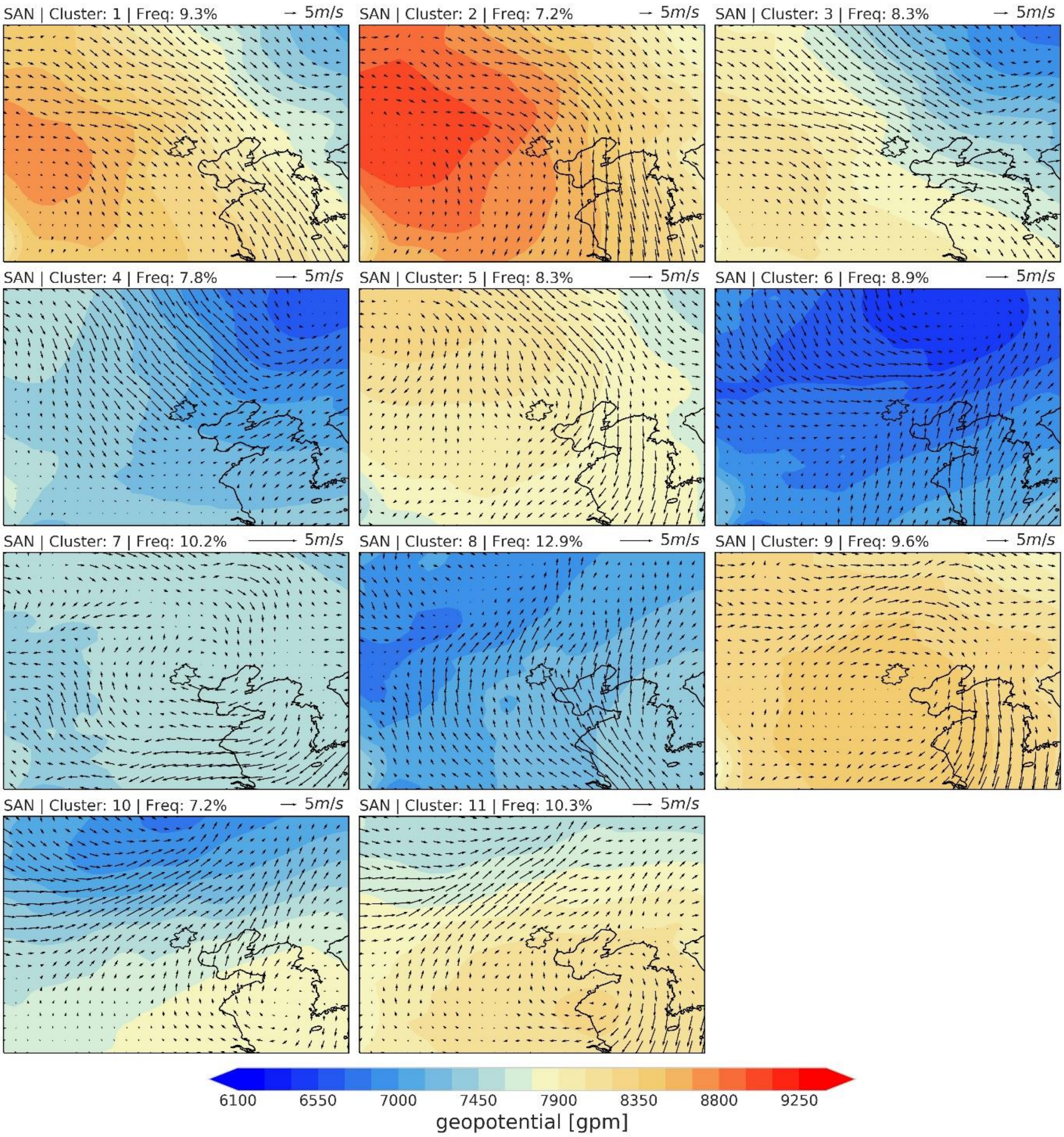
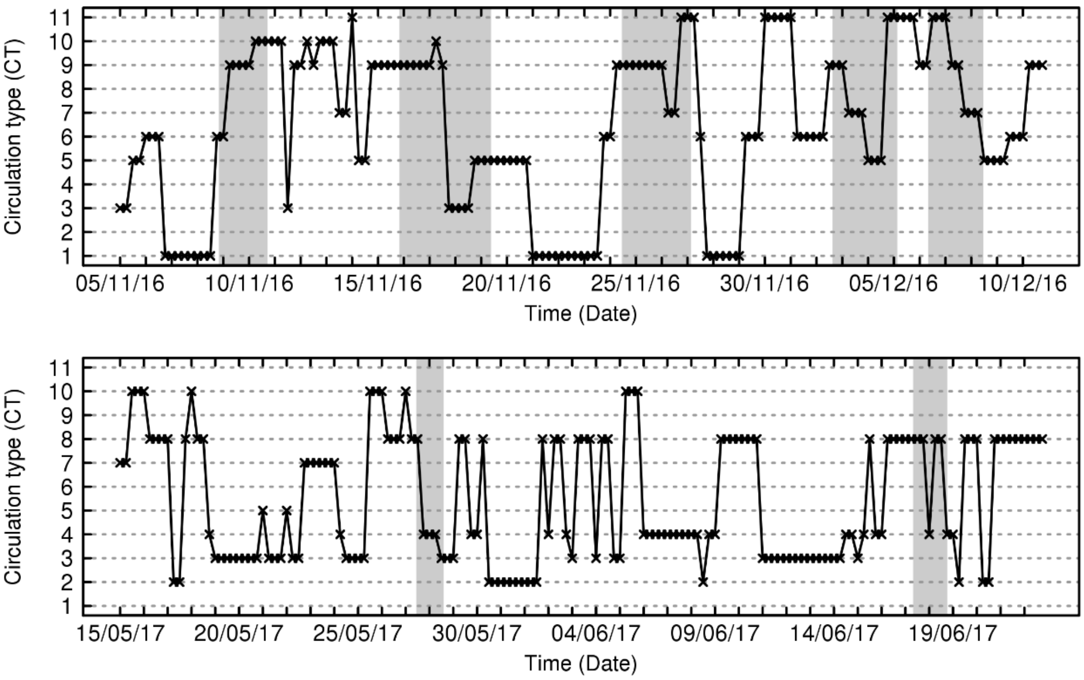
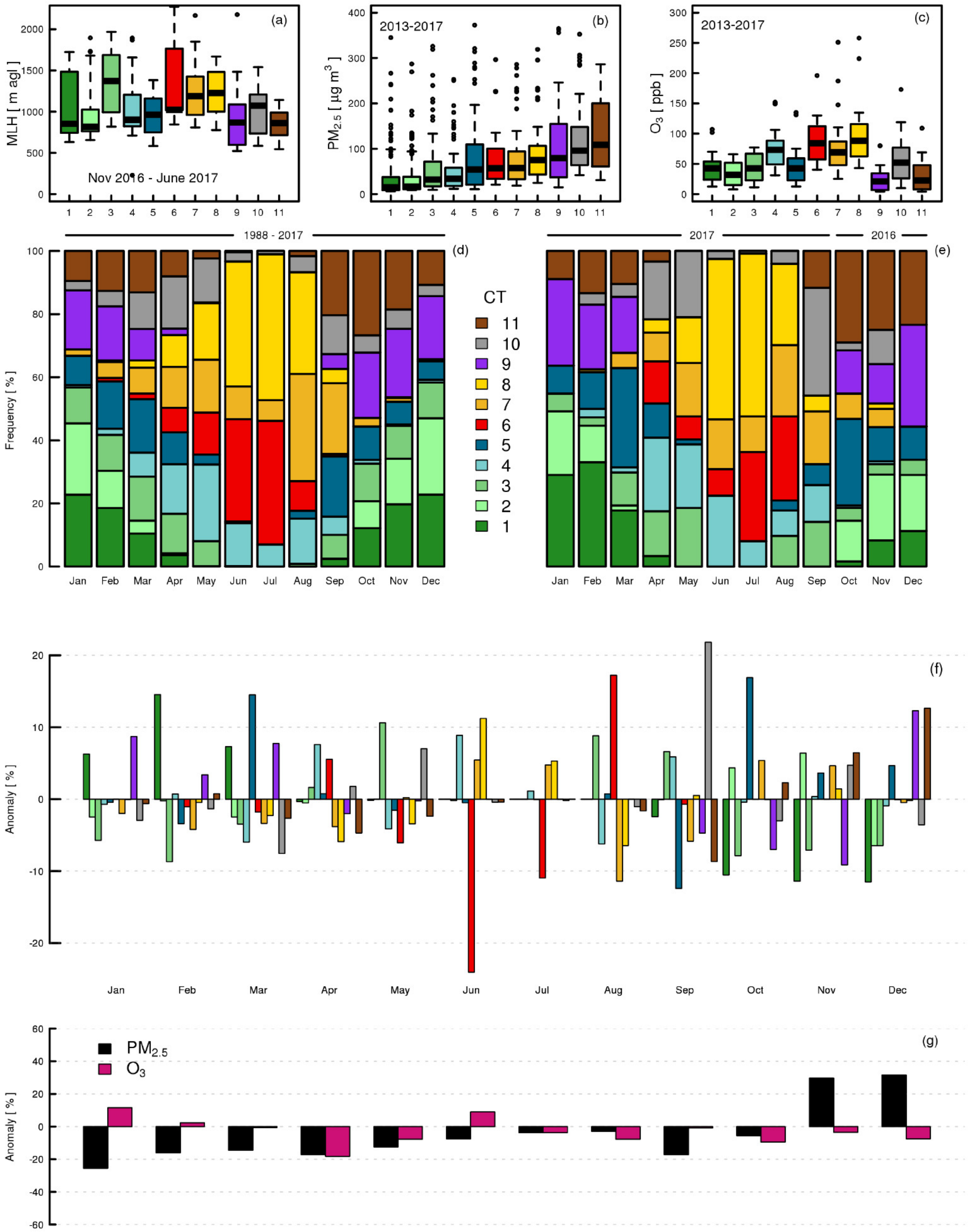


Figure 112: ~~ERA-Interim (1988-2017) average 925 hPa geopotential with 10 m horizontal wind vector for 11 circulation types classified for Beijing (municipal boundary thin solid line) surroundings (103-129° E, 31 - 49° N) determined with the SANDRA method (COST733 class software). Frequency of occurrence is given in cluster caption. For discussion of conditions associated with each CT see Section 6.14.3.~~

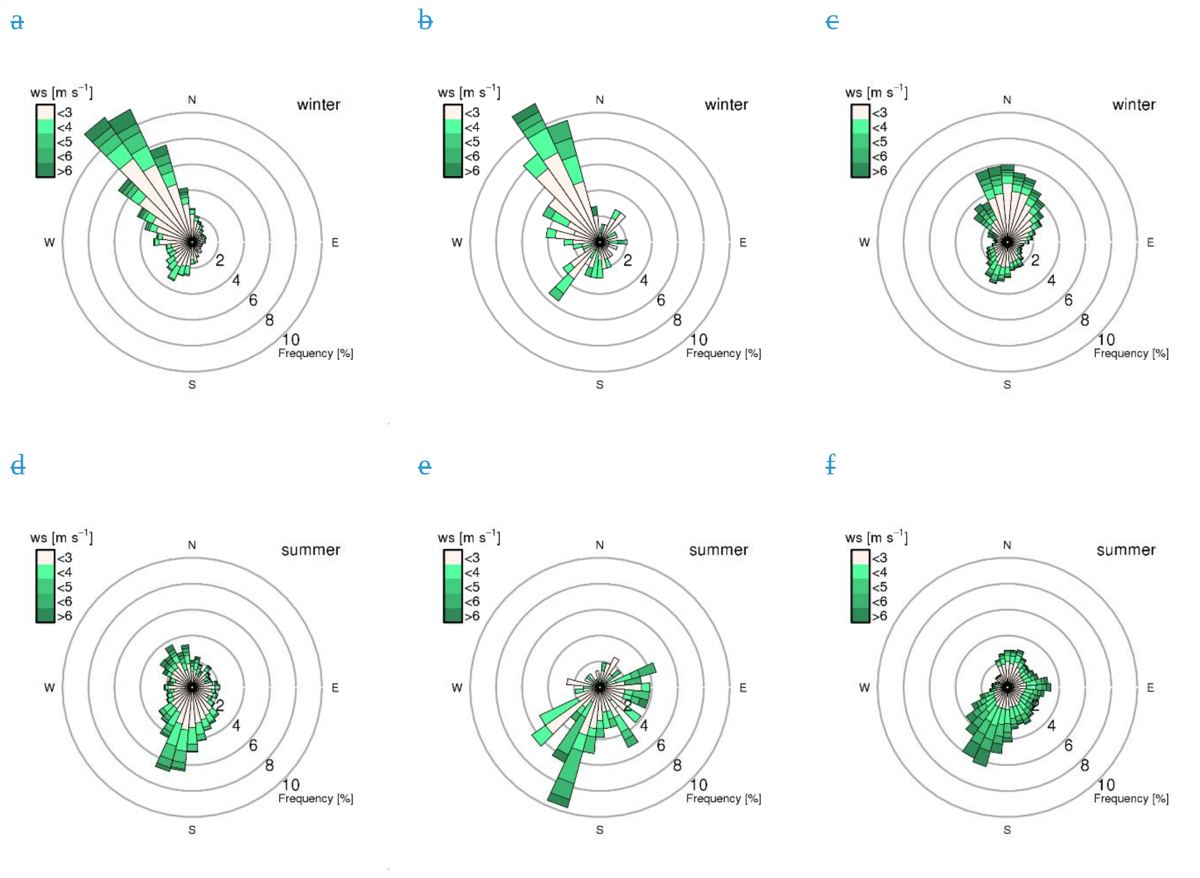


~~**Figure 123:** Time series of circulation types (CTs) during the two field campaigns: (a) winter and (b) summer. The 11 CTs are shown in Figure 112. See text for more description. Shading shows the pollution events identified in Section 5.~~

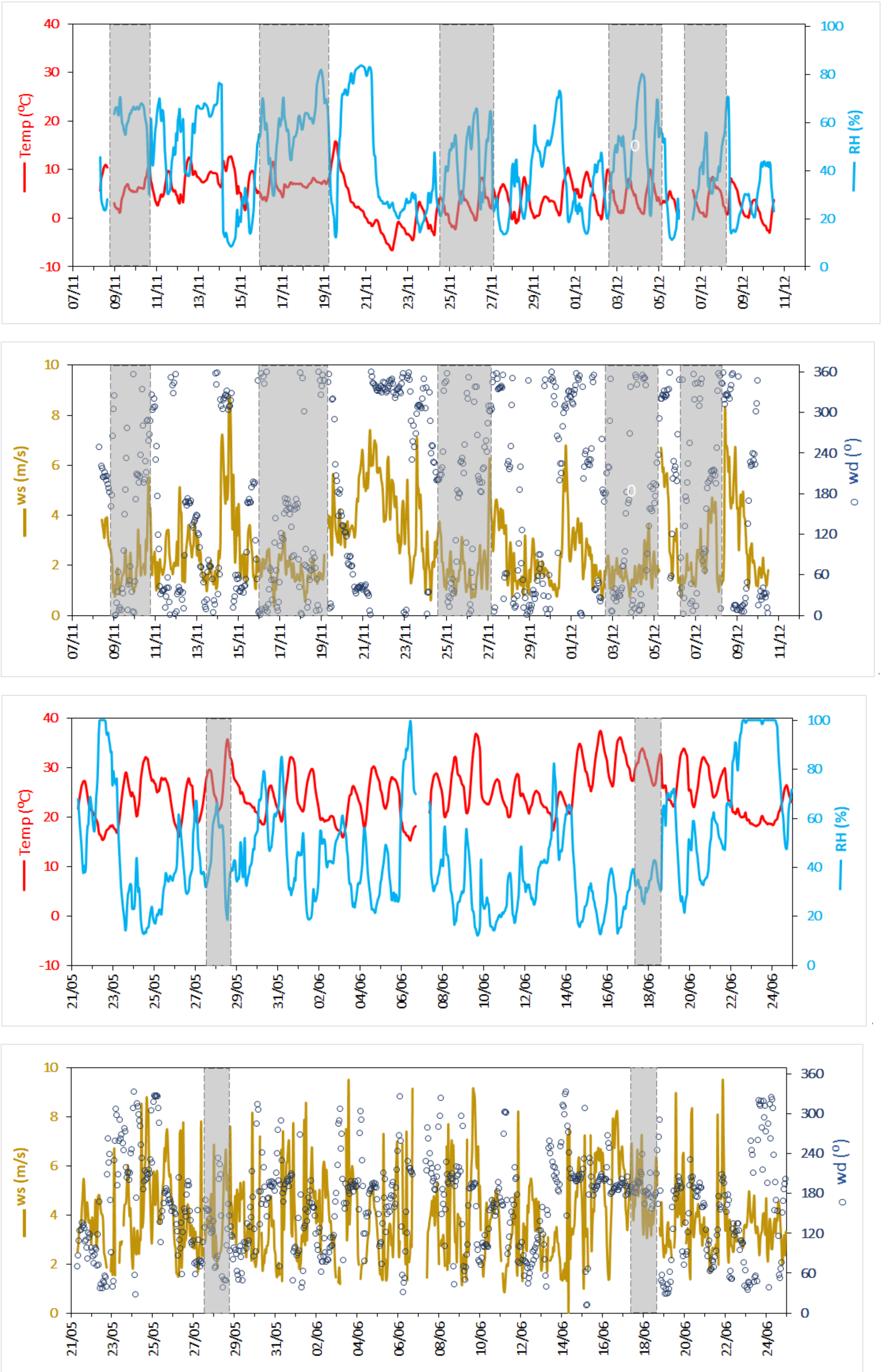


~~**Figure 134**: Analysis by circulation type (CT; Sect. 4.3) of: (a) daily maximum mixed layer height (MLH) determined from ALC observations at IAP between November 2016 – June 2017 (analysis method, Kotthaus and Grimmond, 2018b); concentration of (b) $PM_{2.5}$ and (c) O_3 at at the Olympic Park (i.e. Aotizhongxin) in 2013-2017 from the national air quality network; occurrence of CTs in~~

~~(d) 1988-2017 and (e) Oct 2016 – Sept 2017; (f) anomaly of CT frequency during Oct 2016 – Sept 2017 compared to 30 y climatology; and (g) anomaly of $PM_{2.5}$ and O_3 during Oct 2016 – Sept 2017 compared to 5 y (2013-2017) average (same data as in b, c).~~



~~Figure 14~~5: ~~Beijing wind roses: (a, b, d, e) ERA-Interim 10 m horizontal wind (40° N, 116.5° E) and (c, f) sonic anemometer (Table 1) at IAP 320 m agl for (a) 5 November – 10 December in 1988-2017, (d) 15 May – 22 June in 1988-2017, (b, c) 5 November – 10 December 2016, and (e, f) 15 May – 22 June 2017.~~



~~**Figure 156:** Hourly meteorological variables measured at 120 m during the (a) winter and (b) summer campaigns. The shaded areas highlighted are the haze periods (Table 35, Figures 2 7 and 712).~~

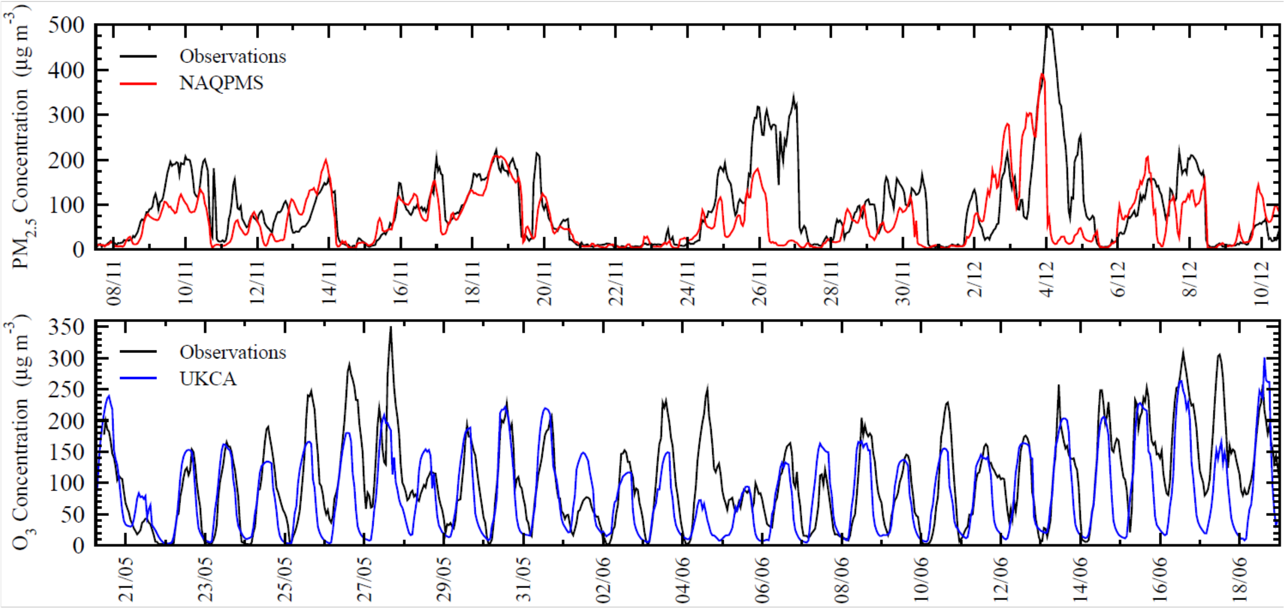
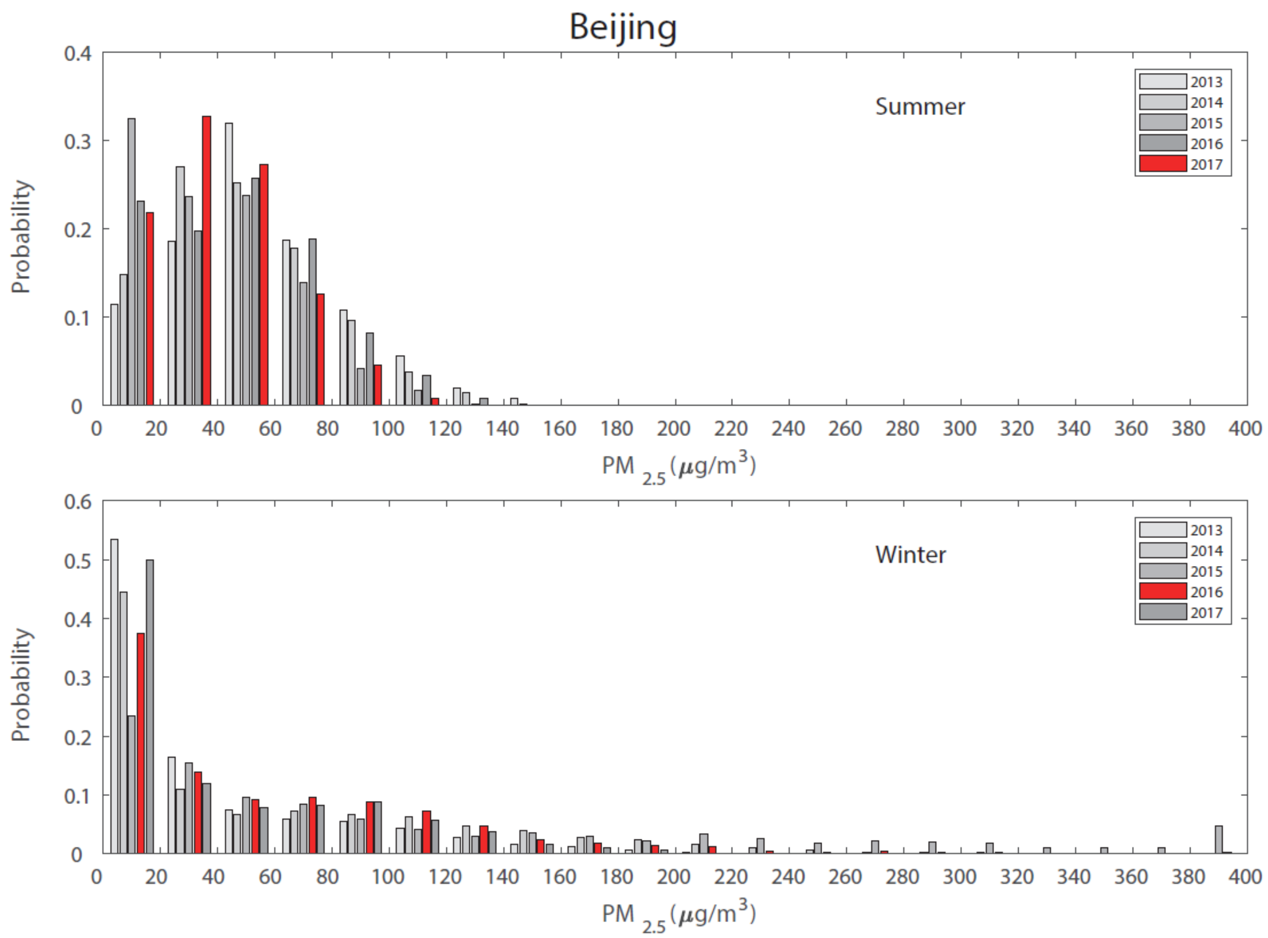


Figure ~~16~~11: Comparison of observed (at IAP) and modelled pollutant concentrations showing (a) $PM_{2.5}$ concentrations during the winter campaign compared with NAQPMS simulations, and (b) O_3 mixing ratios in summer compared with UKCA simulations.



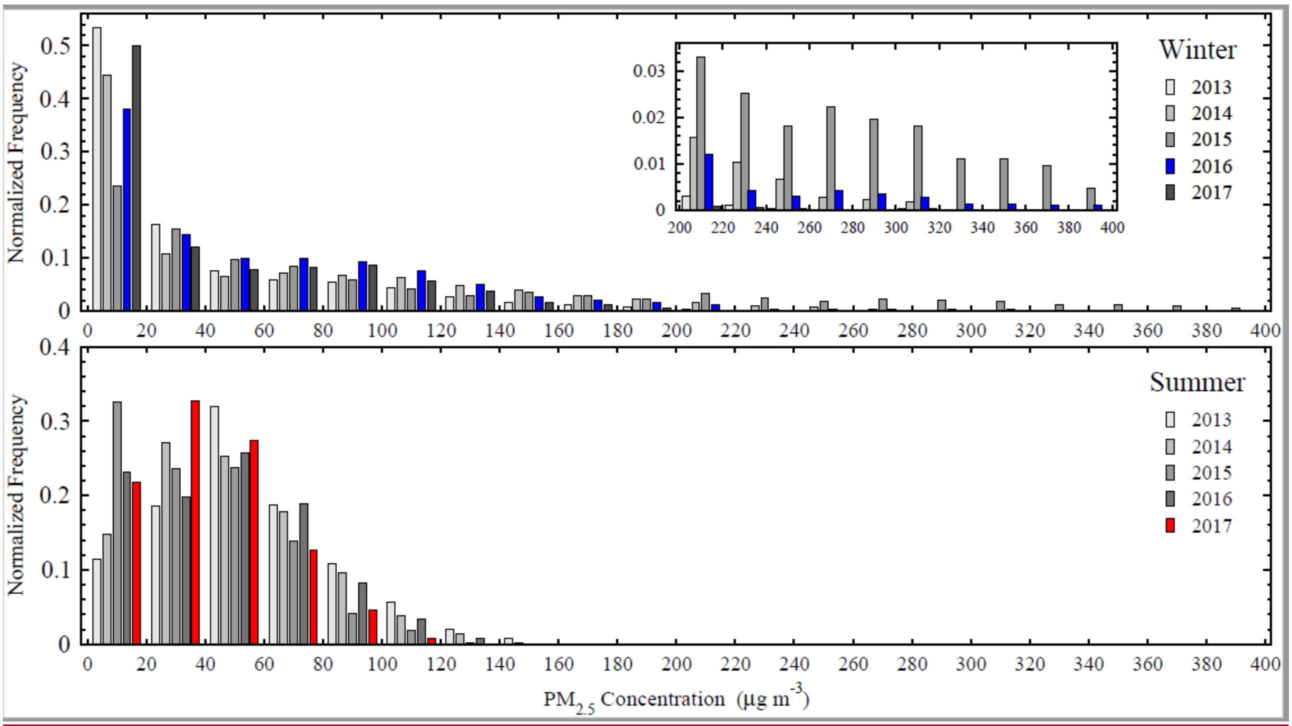


Figure ~~17~~12: Frequency distribution of $PM_{2.5}$ in Beijing over the ~~summer~~ winter (top) and ~~winter~~ summer (bottom) campaign periods from the NAQPMS model compared with those from the same periods over the past five years under the same emission conditions

1745