CENTER FOR GLOBAL HEALTH DELIVERY
HARVARD MEDICAL SCHOOL

PROCEEDINGS

The Nexus of Climate and Health: Pollution Trends and Their Effects on Health

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The Nexus of Climate and Health: Pollution Trends and Their Effects on Health

WEBINAR PROCEEDINGS

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February 23 and 24, 2021

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Harvard Medical School Center for Global Health Delivery - Dubai
Belfer Center's Middle East Initiative at Harvard Kennedy School
Harvard Global Health Institute

Contents

Abbreviations

ALRI	acute lower respiratory infections
ALS	amyotrophic lateral sclerosis
AML	acute myeloid leukemia
AOD	aerosol optical depth
ASAS	Ali Sabah Al-Salem
ASD	autism spectrum disorder
AUC	area under the curve
BBB	blood-brain barrier
BV	background value
CARRS	Cardiometabolic Risk Reduction in South
COPD	chronic obstructive pulmonary disease
CRP	C-reactive protein
EMR	electronic medical record
EPA	Environmental Protection Agency
EU	European Union
FVC	forced vital capacity
IARC	International Agency for Research on Cancer
KEPA	Kuwait Environmental Protection Agency
LIDAR	light detection and ranging
MAIAC	multi-angle implementation of atmospheric correction
MENA	Middle East North Africa
MPH	Master of Public Health
NAAQS	National Ambient Air Quality Standards
NASA	National Aeronautics and Space Administration
NDVI	normalized difference vegetation index
OR	odds ratio
PM	particulate matter
PMF	positive matrix factorization
SCRC	Soroka Clinical Research Center
SDG	Sustainable Development Goal
SOC	secondary organic carbons
UAE	United Arab Emirates
VA	Veterans Affairs
WHO	World Health Organization

1 Introduction

Introduction and Organization of the Proceedings

On February 23 and 24, 2021, the Center for Global Health Delivery, the Belfer Center's Middle East Initiative at Harvard Kennedy School, and Harvard Global Health Institute hosted a panel of engineers and epidemiologists invested in planetary health. The panel focused on the conconstitutive nature of human health and the environmental systems on which humans depend. The first day of the webinar focused on the production of fine airborne particles and pollution. Presentations and discussions from Day 1 are described in Chapters 2 and 3 of these proceedings. The second day focused on the epidemiological and health effects that these exposures may produce, and these presentations and discussions are described in chapter 4 of these proceedings.

1.1 Opening remarks

In his opening remarks, Petros Koutrakis, professor of environmental sciences at Harvard University and director of the EPA/Harvard University Center for Ambient Particle Health Effects, discussed his experience in researching regional air pollution characteristics. In the early 2000s, a group from Harvard School of Public Health went to Kuwait to study the environmental impacts, including air pollution, of the Iraqi invasion. In a two-year study, they measured exposure to particulate matter (PM) and other pollutants. The concentration of PM_{10} in Kuwait was 110 micrograms per cubic meter (μg/m^3) and the concentration of $PM_{2.5}$ was 45 μg/m^3. These measurements were excessively high in comparison to the United States, where the standards for PM_{10} and $PM_{2.5}$ are 50 and 12 μg/m^3, respectively. This research was an early indication that pollution would be a serious problem for Kuwait and the entire region.

In 2008, Koutrakis had the opportunity to organize a regional meeting on air quality and health that was sponsored by the Environmental Center of Arab Towns in Dubai. After reading several reports and learning from regional colleagues, he became aware of the excessive urbanization in the Middle East North Africa (MENA) area. Dramatic population growth and development of many cities has created serious environmental and pollution problems in this area. Major cities such including Damascus, Baghdad, and Cairo suffer from air pollution levels that sometimes exceed World Health Organization (WHO) guidelines. Air pollution sources include vehicle emissions, industrial processes, inappropriate disposal of solid and hazardous waste, burning of oil, and oil refinery activities. In addition, 1-3 billion tons of dust are moved around the world each year. The MENA area is heavily impacted by dust storms from the Sahara Desert as well as the Arabic Peninsula desert, Southwest Iran desert, and Gobi Desert. Thus, residents of the MENA area experience an excess of exposure to dust particles. While it was previously believed that exposure to dust particles was not toxic because they were naturally occurring, it is now known that particles from the desert carry microbes and metals that are harmful to humans. Today, satellite technology can be utilized to assess exposures to dust and other pollution. However, there is little pollution monitoring in the MENA area. One aim of this webinar was to discuss alternative methods for assessing pollution exposures to better understand the effects of pollution on human health.

Koutrakis noted that pollution enters the MENA area via air masses from western Europe, Eastern Europe, Central Asia, and East Asia. Weather conditions in MENA exacerbate these issues, as the region experiences high temperatures most of the year, which enhance photochemical reactions in the formation of toxic secondary pollutants and high home air exchange rates. Lastly, climate change will impact the area in many ways, including desert dehumidification, increasing dust emissions, and increasing photochemical activity. Climate change can directly affect human health and indirectly affect indoor air quality, which ultimately affects human health as well. He expressed his hope that the webinar would prove a valuable opportunity for various groups to learn from one another and form relationships for future collaborations

2 Regional air pollution: monitoring, trends, and climate change

2.1 Regional air pollution characteristics

In his presentation, Petros Koutrakis, professor of environmental sciences at Harvard University and director of the EPA/Harvard University Center for Ambient Particle Health Effects, explored regional air pollution characteristics by analyzing several recent studies from Kuwait and the surrounding region. He noted that the results of these studies are relevant to other areas and can be used to inform future research, policy making, and technology transfers.

2.1.1 Study 1: assessment of particulate air pollution and sources in Kuwait

Koutrakis first discussed a two-year assessment of particulate air pollution and sources in Kuwait.[1] The research was partially funded by the US Department of Veterans Affairs (VA), which is interested in the exposure of deployed soldiers during the Iraq War. The VA supported the monitoring network of two sites that enable data collection used to develop retrospective exposure models. Funding also came from the US National Aeronautics and Space Administration (NASA) due to its interest in establishing stationary satellites to measure air pollution continuously in different areas worldwide, including the Middle East. Data collected on exposure could be used to inform future health studies. The publication was also made possible by the Kuwait Institute of Scientific Research and the Kuwait Environmental Protection Agency (KEPA).

Two site locations were used to collect PM data over a two-year period in Kuwait. One site was in Kuwait City and another in the south near the industrial facilities in Ali Sabah Al-Salem (ASAS). Koutrakis explained that a major challenge was measuring PM in a region with excessive dust levels. Conventional particle samplers can be overloaded during severe dust storm episodes and are prone to particle bounce, which can lead to exposure overestimation. The issue was addressed by using a custom-designed particle sampler built to withstand high levels of air pollution. He remarked on the importance of using the right equipment to measure particles for future studies.

Koutrakis reviewed the number and percentages of days where PM concentrations exceeded the 24-hour standards from October 2017 to October 2019 in both sites. They found that PM_{10} and $PM_{2.5}$ concentrations at both sites exceeded WHO and US National Ambient Air Quality Standards (NAAQS) 24-hour standards on most days. He noted the KEPA 24-hour standard is very high—at 75 micrograms per cubic meter ($\mu g/m^3$)—which is not an appropriate standard to protect human health. The KEPA 24-hour standards were only exceeded in 6.6% and 8.5% of days in Kuwait City and ASAS, respectively. He added that PM concentrations are high in Kuwait City and frequently exceed international air quality standards.

Koutrakis then reviewed source contributions of $PM_{2.5}$ in the two locations of Kuwait. Understanding source apportionment is essential for Kuwait and the surrounding region to successfully address air pollution. In Kuwait City, 43.6% of $PM_{2.5}$ came from regional pollution (ie, originating from surrounding countries), 19.9% from

1 Alahmad et al 2021

sand/dust storms, 17.5% from road dust, 16% from traffic, and the remaining 3% from marine pollution. Similarly, in ASAS, 46.4% of $PM_{2.5}$ came from regional pollution, 28.8% from sand/dust storms, 11.4% from road dust, 8.4% from traffic/other, and 5% from industrial emissions. He noted that for Kuwait and many other countries of a small size and similar geographic proximity, the major contribution is from regional pollution. Thus, it is difficult to reduce pollution exposure only at a national level. Governments need to collaborate to achieve effective air pollution management. To confirm that the primary source is from regional pollution, $PM_{2.5}$ mass and elemental concentrations from Kuwait City and ASAS sites were compared. The analysis examined concentrations of sulfur, black carbon, soil/dust elements (Ca, Fe, Al, Si), and industrial elements (Cu, Ba, Sr, Ni, V, Mn, Sb, Ti, Zn). Levels were similar in both sites, indicating a significant regional-level rather than local-level contribution. Furthermore, the regional pollution needs to be addressed by industries both in Kuwait and the surrounding region, he added.

2.1.2 Study 2: dust events and indoor air quality in Kuwaiti residential homes

Koutrakis then discussed a study on dust events and indoor air quality in Kuwaiti residential homes.[2] The study was sponsored by the Belfer Center at the Harvard Kennedy School, which is supported by the Kuwait Foundation for the Advancement of Sciences. Many countries are impacted by frequent dust storms from regional and/or remote deserts. The aim of the study was to determine the effect of dust storms on indoor environments. Researchers also assessed the effectiveness of keeping homes tightly closed during dust storm events to reduce dust exposures by analyzing indoor and outdoor particle samples at 10 residences in Kuwait City. Results revealed that indoor/outdoor ratios of $PM_{2.5}$, BC, and 19 elements were significantly lower during dust storm events than non-dust events. Particle penetration efficiencies were lower during dust storm events (less than 20-30%) than during non-dust storm events (40–60%). This is likely secondary to keeping homes tightly closed during dust storm events, he noted. These findings suggest that increasing home insulation could be an effective strategy to reduce indoor exposure to crustal particles from dust storm events. The findings could also facilitate public health policy for warning systems and advisories to stay indoors to protect against dust storms. Koutrakis remarked that the study was based on data collected only from Kuwait, a developed country with well-constructed homes that can be kept tightly closed. However, less developed countries may not have as well-constructed homes, and people in the desert may be exposed to excessively high levels of particulate pollution. He suggested that further studies on crustal particles from dust storms and their penetration should be conducted in less developed countries in the Middle East where homes may be leaky and without central ventilation systems.

2.1.3 Study 3: impacts of meteorology and vegetation variations on surface dust concentrations in Middle Eastern countries

Lastly, Koutrakis presented a study on the impacts of meteorology and vegetation variations on surface dust concentrations in Middle Eastern countries.[3] To take into account regional effects, the researchers looked at a large study region with shared climate characteristics that included Kuwait, Saudi Arabia, Iran, Iraq, and Syria. Dust, Normalized Difference Vegetation Index (NDVI), and meteorology data from between 2001 and 2017 were analyzed in the study. Surface dust concentrations were

2 Yuan et al 2020
3 Li et al 2020a

provided by NASA's Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) at a spatial resolution of a 0.625° (longitude) × 0.5° (latitude). The NDVI was used to evaluate variation in vegetation, or "the greenness of the desert," with a 1,000 m spatial resolution and monthly temporal resolution. He noted that NDVI is an important parameter for understanding how dust levels affect the region. Finally, meteorological data were obtained from the MERRA-2 dataset; parameters included total column precipitation, relative humidity, surface temperature at 2 m, and wind speed at 10 m. Data on dust storm days in Kuwait were obtained from the Kuwait official meteorological station. The meteorological data have the same temporal and spatial resolution as the surface dust concentrations.

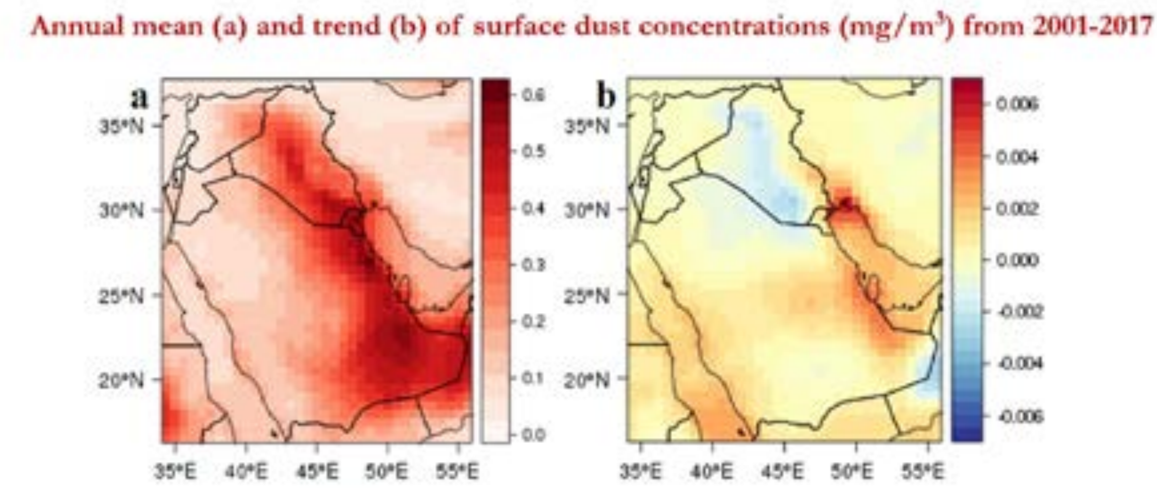
The study examined surface dust concentrations and trends of dust levels by using country-average surface dust concentrations (μg/m^3). The highest concentrations of surface dust were observed in Kuwait (0.53 μg/m^3), followed by Iraq (0.25 μg/m^3), Saudi Arabia (0.23 μg/m^3), Iran (0.16 μg/m^3), and Syria (0.13 μg/m^3). During the study period, a yearly increase of 0.0005 μg/m^3 in the regional annual mean of surface dust concentration was observed. In contrast, annual decreases of 0.0005 and 0.0003 μg/m^3 were observed for Iraq and Syria, respectively. Koutrakis also presented an image of the annual mean (a) and year trend (b) of surface dust concentrations (μg/m^3) in the study region (see Figure 2-1). He noted that dust levels start in southern Iraq and track into southwestern Saudi Arabia, with Kuwait at the center. The trends also reflect decreases in dust levels in Iraq and Syria from 2001 to 2017. In the early 2000s, the Iraq War resulted in military activities, destabilization, and reduced irrigation and agriculture, which collectively increased dust levels. Dust levels and NDVI slowly recovered with the end of the war. He added that areas of Southwest Iran, Kuwait and near the western coast of the Persian Gulf have increasing dust levels.

Data collected on meteorological changes revealed an increase in average temperature secondary to climate change that was observed in the entire study region. The increases ranged from 0.0054 to 0.0331°C per year, which is higher than the global average. The mean wind speed in the study region was also analyzed, with Kuwait having the largest. The annual trend of the NDVI in Syria was negative, likely due to war in the country, and NDVI trends were also negative for Kuwait. In contrast, positive annual mean trends of NDVI were observed in Saudi Arabia, Iraq, and Iran. Koutrakis noted that the change in Iraq is likely associated with the end of the war in the 2000s. Furthermore, a significant negative correlation was found between the number of dust storm days for each year and the yearly NDVI in Kuwait; low NDVI is associated with more dust storm days. He added that desertification expansion precipitated by human activities, such as wars and vacations, destabilize the desert surface and reduce greenness, which impacts dust levels.

Koutrakis summarized the results of the study:

- A positive association between wind speed and surface dust concentration in Kuwait indicates dust levels were impacted by deserts in Kuwait and surrounding areas. Moreover, desert destabilization activities will impact dust levels.
- A positive association was found between wind speed in the four countries surrounding Kuwait and surface dust concentration in Kuwait. Wind speed in Iraq had the highest impact on the dust levels in Kuwait.
- A negative association between NDVI in Kuwait, Iraq, and Saudi Arabia and surface dust concentration in Kuwait were also observed. Climate change and human activities impact the desert, which results in higher levels of dust in the region.

Figure 2-1. Annual mean and trend of surface dust concentrations in the study region (2001-2017)



Note: mg/m^3 = micrograms per cubic meter
Source: Koutrakis presentation

2.1.4 Conclusions and recommendations

Koutrakis ended his presentation with an overview of his conclusions and recommendations. First, PM mass and composition measurement studies have addressed major measurement challenges with recent sampling and analysis methods. Thus, he recommended establishing adequate methodologies for the region in the monitoring networks. PM mass and composition measured between 2004-2005 and 2017-present demonstrate levels exceeding the national and international ambient particle standards. Therefore, it is necessary to identify and quantify the sources contributing to the observed levels. Notably, transported pollution (eg, regional anthropogenic and dust storms) are major contributors. However, it is likely that even drastic emissions reduction will not significantly reduce PM levels, so the development of regional policies must become a priority. The study of the impact of dust storms on indoor air quality demonstrated that home tightness during storms reduces particle penetration. Thus, dust storm forecasting could be very effective and future indoor air quality studies should address air conditioner duct cleaning and incense use. Finally, using historical satellite data to examine spatial and temporal dust storm events, daily $PM_{2.5}$ levels, and surface dust showed that Kuwait has been affected by climatic changes that likely adversely impact air quality, underscoring the need for strategies to mitigate the effects of climate change.

2.1.5 Discussion

Souzana Achilleos asked about average Kuwaiti houses and the characteristics that can reduce particle penetration. Koutrakis replied that most homes in Kuwait are well-sealed and well-built. For example, doors are insulated, and air conditioning is used excessively. Issues with air conditioning include dust deposition in ducts compounded by poor air conditioning maintenance. He added that in humid areas such as the United Arab Emirates (UAE), mold—which is associated with respiratory problems—grows on settled dust in ducts.

2.2 Dust storms over the Arabian Peninsula: sources, transport, site visit, health, and rehabilitation

Ali Al-Hemoud, research scientist at the Environment and Life Sciences Research Center in Kuwait Institute for Scientific Research, focused on dust storms over the Arabian Peninsula, including dust storm sources, transportation, health impacts, and methods of mitigation. He explained that high resolution (250 meters per pixel) MODIS Aqua and Terra, soil sampling from a "hot spot" in southern Iraq, and WHO's AirQ+ model were used to better understand dust storms over the Arabian Peninsula and in Kuwait.

2.2.1 Sources and transport pathways over the Arabian Peninsula

Al-Hemoud began by discussing dust storms that occurred over the Arabian Peninsula from 2010 to 2018. On March 18, 2012, the MODIS instrument on the Terra satellite identified a dust storm that blew from western Iraq and moved eastward, covering south of Baghdad and crossing the Iraqi border into Kuwait and westernmost Iran. Northwestern wind blew the dust from western Iran to the northern part of the Arabian/Persian Gulf. The dust storm also curved toward the south and southwest over Saudi Arabia and carried more aerosol particles from the large Al-Dahna Desert located in the eastern-central division of the Arabian Desert. After hovering over Bahrain, Qatar, and parts of UAE, the dust storm then moved 2,500 km further south into the Empty Quarter, which is one of the largest sources of dust in the world. The dust storm was eventually blocked by Jabal Ru'yan mountain, south of Najran, alongside the borders of Saudi Arabia and Yemen. He noted that without the high mountain to block the storm which originated in Iraq, it would have gone into the Red Sea. A backward trajectory from July 2012 shows a major dust source with a pathway from Iraq into Iran, covering Kuwait, moving into eastern Saudi Arabia (ie, the oil industry sector) until terminating in the Empty Quarter.

During the same time period, another source from Qatar and some from the UAE also moved into the Empty Quarter. Another backward trajectory from July 2018 illustrates a dust storm originating from the Empty Quarter of Saudi Arabia, traveling in the clockwise direction, and terminating into the Arabian Sea. The dust storm also covered the oil industrial sector of Saudi Arabia, parts of UAE including Dubai and Ras Al Rhaimah, and into Oman. An additional backward trajectory from September 2015 demonstrates a dust source from Bandar, Iran, and the Persian Gulf coast of Iraq, which traveled in a counterclockwise fashion to cover Bahrain, Qatar, all major areas of UAE (ie, Dubai, Abu Dhabi, Sharjah), and parts of Iran. Al-Hemoud noted that a single source can cover a broad area. Another backward trajectory from December 2010 illustrates that some dust sources covering the Arabian Peninsula originate externally—for example, from the Iran-Afghanistan-Pakistan border. The final trajectory, also from December 2010, demonstrates a major dust source from the Indian subcontinent, the Pakistan-Indian border, and southern Iran traveling into the Arabian Sea and Oman.

2.2.2 Sources and transport pathways over Kuwait

Al-Hemoud reviewed dust source and transport pathways that specifically affect Kuwait by referencing recent publications from his research team.[4,5] A MODIS image of a white dust stream showed an Iraqi "hot spot" carried by the northwestern wind toward Kuwait. Other dust storms originate from Iran and southern Iraq and go east into Kuwait and Iran. Another dust storm mentioned covers Bahrain, Qatar, and parts of the Arab Emirates, travelling more than 2,500 kilometers to the Empty Quarter. Agricultural land based on the Iraqi Euphrates and Dijla rivers can be seen on satellite images as a brown region north of Kuwait. He noted that the farmland was abandoned during the war, contributing to airborne organic carbons and other materials.

Al-Hemoud presented a series of other dust storm sources and transport pathways, including:

- Dust storm that traveled from Iraq to Iran through Kuwait to eastern Saudi Arabia and then to the Empty Quarter
- Dust storm that started in the Empty Quarter in Saudi Arabia and into the Arabian Sea,

4 Al-Hemoud et al 2020
5 Yassin et al 2018

affecting Saudi Arabia, UAE (Dubai, Ras Al Kaimah), and Oman

- Dust storm that came from Iran and Iraq to Bahrain, Qatar, and UAE
- Dust storm that originated from the Afghanistan area and Pakistan-Iran border that went into Oman
- Dust storm that traveled from the India-Pakistan border, into the Arabian Sea and then to Oman

He noted that monitoring stations throughout Kuwait measured visibilities and wind speed. The Salmi and Managish stations measured the lowest visibilities and high wind speed. Salmi was affected by another storm source, which appeared as a dust plume left of the station. Furthermore, an analysis of a 5-day diurnal variation (2 days prior to the event and 2 days after) from July 26-30, 2018, in Salmi, Kuwait explored the hourly patterns of visibility and wind speed during a dust storm event. In general, the highest wind speed and lowest visibility values peaked around noon on dust storm days; suspended dust consisting of fine PM remained sustained for 2 days following. Another dust storm originating in Iraq occurred on July 3-7, 2012. The brown area in the satellite image represented farmland that was abandoned between the Euphrates and Dijla in Iraq; this area is rich in organic carbons. The 5-day diurnal showed the highest wind speed and lowest visibility values at noon and ranged from 7am-5pm. Dust storm length is dependent on wind speed and, in this case, the event lasted 7 hours. Poor visibility and high wind speed also lasted for 2 days following the day of the dust storm event.

Another MODIS satellite image identified two dust plumes that blew southeastward through Iraq to Kuwait. The two dust plumes varied in color from white to dark brown. The white dust plume traveled through southern Iraq toward urban Kuwait, into Bahrain and as far as Qatar. The dust traveled up to 1,200 km. The second dark brown dust plume to the east of the first one originated from another "hot spot" area; the plume stretched down toward the Gulf without affecting Kuwait.

Al-Hemoud discussed a site visit to the Iraqi "hot spot" to collect soil samples. The spot is approximately 250 km from Kuwait and consists of sand dunes and sheets. On the major road from Iraq to Kuwait there is a warning sign posted about the sandstorms and sand dune zone. Large amounts of sand encroachment occur on the road, especially in June and July. Soil samples were analyzed at Kuwait Institute for Scientific Research for grain size distribution to better understand grain size compositions and sediment transport mechanisms. Samples were taken during a one-week field visit (April 20–26, 2019) from seven locations within the sand dunes and sand sheets areas. One of the seven samples was taken near Sawa Lake just south of the primary hot spot. He noted that fine particles mostly originated from the center and western border of the hot spot area; coarse sand was more apparent from the Sawa Lake sample. Due to the relatively heavy particles, dust storm jets from the Sawa Lake area cannot remain airborne over long enough distances to affect Kuwait. Conversely, the samples from the sand dune and sheets hot spot consisted of fine particles that can travel to Kuwait and remain suspended for 2 days after a dust storm event.

2.2.3 Dust storm impacts on Kuwait

Al-Hemoud examined the impact of dust storms on Kuwait.[6] Five hot spots were identified for wind erosion located within three major wind corridors, which run from the northwest toward the southeast. However, the urban areas are densely located on the coast, which are not affected by any of the wind corridors. Thus, dust storms do not pass through the urban areas where they would impact the majority of the population. One effect of dust storms on Kuwait is sand encroachment. The major economic industry of the country, oil, is especially impacted. For example, oil pipes in the Al-Raudhatain (August 2008), Wafra (September 2018), and Minagish (July 2008) oil fields have been buried in sand. Sand encroachment also affects roads, resulting in car acci-

6 Al-Hemoud et al 2019a

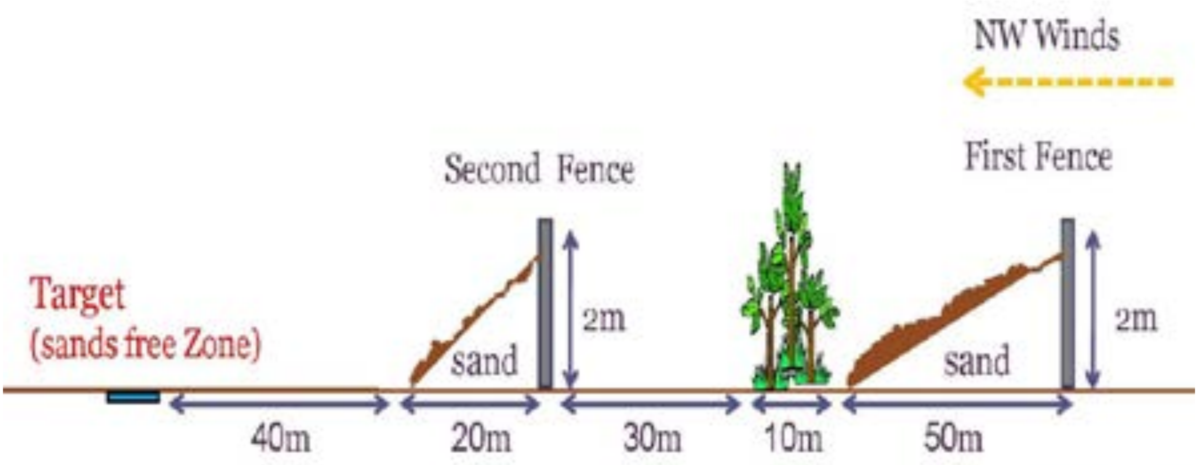
dents, as occurred on the Wafra Road in June 2015 and on Mina Abdallah Road in June 2017.

Al-Hemoud then examined the health impact of dust storms using the WHO AirQ+ model to estimate the burden of disease and disability-adjusted life years for $PM_{2.5}$, PM_{10}, ozone and nitrous dioxide.[7,8] The endpoints analyzed included long-term and short-term exposure effects on all-cause mortality, specific-cause mortality from ischemic heart disease, stroke, lung cancer, chronic obstructive pulmonary disease (COPD), and acute lower respiratory infections, as well as hospital admission rates from respiratory and cardiovascular disease. Over a span of a four-year period (2014–2017), the annual $PM_{2.5}$ concentration levels ranged from 38.0 micrograms per cubic meter (μg/m³) to 75.2 μg/m³. Higher $PM_{2.5}$ levels were recorded during rush hours (ie, early morning and early evening), weekends (particularly Saturdays), and summer (ie, August and September). For $PM_{2.5}$, the highest number of excess cases and attributable proportions of premature mortalities were related to ischemic heart disease and stroke. For $PM_{2.5}$, respiratory diseases showed a higher number of excess cases and attributable proportions than cardiovascular diseases. Expected life remaining analyses showed that 30- and 65-year-old persons would gain 2.34 years and 1.93 years, respectively if the current $PM_{2.5}$ exposure levels were reduced to the WHO interim targets (IT-1 = 35 μg/m³). Newborns and 1-year old children may live 79.81 and 78.94 years, respectively, with an increase in average life expectancy.

2.2.4 Dust storm mitigation

Al-Hemoud discussed an example of successful dust source mitigation in Kuwait.[9] He presented a sketch diagram of the mitigation method used in a dust storm source area (see Figure 2-2). The technique consists of two impounding fences (2-meter chain-link fences with slats) situated between 90 meters and 100 meters apart, with native vegetation in the middle distance between the two fences. Sand encroachment is caught at the fence line. Palm leaves were used to protect native plants from sand covering. After 2 years, native animals and plants returned to the area.

Figure 2-2. Two fence dust storm mitigation strategy



Source: Al-Hemoud presentation

7 Al-Hemoud et al 2019b
8 Al-Hemoud et al 2018b
9 Al-Hemoud et al 2019a

2.3 Air pollution in Cyprus

Souzana Achilleos, postdoctoral research associate for LIFE MEDEA public health intervention study at Cyprus University of Technology provided an overview of air pollution in Cyprus, which is an island nation in the Eastern Mediterranean Sea that is located near Turkey, Egypt, and the Middle East. The island has an area of 9,251 km^2 (3,572 sq mi) and a population of 838,897, according to the 2011 census. Cyprus has a typical Mediterranean climate with mild winters and hot, dry summers; temperatures in the cities range from 10 to 30 °C. Cyprus became a member of the European Union (EU) in 2004 and, thus, the country follows EU air quality standards.

Cyprus maintains an air quality monitoring network overseen by the Air Quality Section in the Ministry of Labour, Welfare and Social Insurance.[10] The air quality monitoring network includes 9 stations founded between 1993 and 2006, including five traffic stations located in each major city, two industrial stations, one residential station, and one rural background station. The background station participates in the European Monitoring and Evaluation Programme, which monitors and evaluates the long-range transmission of air pollutants in Europe. Continuous monitoring assesses the concentration of various pollutants in the atmospheric environment including nitrogen oxides (NO_x), ozone (O_3), sulfur dioxide (SO_2), carbon monoxide (CO), PM ($PM_{2.5}$, PM_{10}) and benzene (C_6H_6).

2.3.1 Particulate matter in Europe

Achilleos stated that PM is one of the most difficult pollutants to manage in Europe and the Eastern Mediterranean countries. Presently, most of Europe has decreased PM to meet standards; however, Eastern Mediterranean countries continue to have high levels. In 2018, Poland, Italy, Slovakia, the Balkan region, Turkey, and Cyprus had annual PM_{10} levels exceeding WHO limits of greater than 20 µg/m^3. Factors that contribute to high PM levels in the Eastern Mediterranean include anthropogenic and natural sources.[11] Anthropogenic sources include traffic volume, regionally transported pollution from industrialized European countries, and local industrial pollution. Local soil resuspension and sea salt significantly contribute to background PM levels while dust storms from North Africa and the Arabian Peninsula also add to natural sources of PM.

2.3.2 Particulate matter in Cyprus

Regarding PM in Cyprus, a sampling campaign found major contributors of $PM_{2.5}$ were regional sulfur (32-48%), traffic emissions (14-21%), and biomass burning (14-20%).[12] Achilleos explained that the main sources of coarse particles ($PM_{10-2.5}$) were resuspended dust, road dust, and sea salt. Dust storms are the main cause of elevated average daily PM_{10} in Cyprus. PM_{10} mass concentration levels from 2000-2017 collected by urban and rural monitoring stations illustrate the effect of dust days on PM. At baseline, PM_{10} levels rest around the EU daily limit of 50 µg/m^3. During dust storms, levels normally rise to 100-200 µg/m^3, but can exceed 1000-1500 µg/m^3. The Sahara is the greatest source of dust storms for Cyprus. For example, a dust storm event originating from the Sahara in February 2006 resulted in the highest PM_{10} levels (24-hour PM_{10} average >1000 µg/m^3) since 2000. Cyprus is also affected by the Syrian and Arabian deserts in the Middle East. One of the most recent and intense dust storm events occurred in September 2015 when a storm originating from the Middle East lasted 6 days.[13] The event started on September 6th and reached peak particle load on September 8th. At its peak, horizontal visibility was limited to approximately 500m and resulted in the closing of the Cyprus airport.[14]

10 More information on the air quality monitoring network available at https://www.airquality.dli.mlsi.gov.cy/ (accessed May 10, 2021)
11 More information about air quality in Europe in 2020 is available at https://www.eea.europa.eu/publications/air-quality-in-europe-2020-report (accessed July 20, 2021).
12 Achilleos et al 2016
13 Source: Department of Labour Inspection
14 Mamouri et al 2016

Achilleos discussed criteria for dust announcements in Cyprus. The Air Quality Section uses station monitors, weather models and satellite data to detect upcoming dust storms. A dust announcement is made to the public when at least two of the following three criteria are met:

- Criterion 1: the pollution level in at least one station is high (PM_{10} concentration of 100-200 μg/m^3)
- Criterion 2: the pollution level in at least three stations are moderate (PM_{10} concentration of 50-100 μg/m^3)
- Criterion 3: the pollution level at the background station is moderate (PM_{10} concentration of 50-100 μg/m^3)

In addition, the Department of Labour is collaborating with the LIDE MEDEA research group to provide early warnings and evidence-based protection measures to the public.

Achilleos reviewed the number of daily PM_{10} levels that exceeded the EU limit value of 50 μg/m^3. The number of permitted exceedances in a year is 35, but Cyprus often exceeds the limit and has recorded up to five times more exceedance days in a year than permitted. From 2000-2009, the number of days per year that exceeded the daily EU limit value ranged from 73 to 199. From 2010-2017, it ranged from 36 to 102. The Air Quality Section regularly performs chemical analyses of collected air filters to determine the contribution of natural sources, such as desert dust, to the overall PM_{10}. According to the EU Directive, natural sources can be omitted when determining exceedances. She noted that if exceedance due to transboundary dust (ie, desert and sea salt) is omitted, the number of daily exceedances drops to below the limit of 35 for most years from 2010-2018 in Cyprus. Thus, consideration of PM_{10} sources has important policy implications, especially within the EU.

Achilleos presented recent findings regarding air pollution in Cyprus from 2000 to 2017.[15] During that period, Cyprus averaged 30 dust days per year. The number of dust days increased from 2000 to 2010 and peaked in 2010. The most dust days during that period occurred in 2008, with PM_{10} levels at the urban monitoring station exceeding the EU daily limit. In 2011 and 2012, dust days were considerably less frequent. However, no statistically significant trend of dust day frequency was observed from 2000 to 2017. Dust increases seasonally and the dust season in Cyprus occurs from late winter to spring and, less frequently, in the fall.[16] In a time series analysis, 2008 had the highest PM_{10} concentration median during dust storms; dust PM_{10} annual median ranged from 30.1 μg/m^3 (2012) to 79.3 μg/m^3 (2008). 2008 also had the lowest precipitation observed within this time period. She added that no statistically significant trends in dust intensity were found over the study period.

2.3.3 Conclusion

Achilleos concluded by summarizing the state of air pollution in Cyprus. Cyprus is greatly affected by the two largest, non-polar deserts in the world: the Sahara and Arabian Peninsulas. A high variability in the frequency and intensity of desert dust was observed during the last two decades, which was characterized by a steady trend with sporadic peaks. The year with the highest frequency and intensity—2008—was also the year with the lowest precipitation.

Other Mediterranean countries have seen different trends. No change of African dust contribution to PM_{10} was observed in central and southern Mediterranean countries (Greece, Italy, Cyprus) from 2001-2011.[17] However, dust trend analysis differs between studies, locations, and time periods. For example, increased frequency of African desert dust was observed in Southeastern Mediterranean from 1958-2006.[18] Israel had increased intensity of PM_{10} concentrations over the last 3 years of the period 2001–2012.[19] Frequency and intensity decreased in north-central Spain from 2003-

15 Achilleos et al 2020
16 Pikridas et al 2018
17 Pey et al 2013
18 Ganor et al 2010
19 Krasnov et al 2016a

2014.[20] One study found decreases in African dust emissions from a historic reanalysis of 1851 to 2011.[21] A recent model projection suggested an increase in dust storm events intensity.[22]

Achilleos suggested that future studies should examine changes in dust storm characteristics over decades to better evaluate patterns. In addition, dust storm events should be examined in relation to climate change, including synoptic-scale conditions. She added that the future of desert dust is uncertain and likely dependent on anthropogenic pressure on desert surfaces, natural climatic variability, and climate change.[23]

2.4 Discussion

2.4.1 Impact of pollution on eye health

A participant asked about the impact of pollution on eye health. Koutrakis acknowledged the importance of this issue and noted that there has been research published on this topic.[24]

2.4.2 Dust storm mitigation measures using planting of trees

Achilleos asked about the mitigation measures discussed by Al-Hemoud. Al-Hemoud explained that if one wanted to protect a vital area such as an airport or an oil refinery, they would start by placing special fences in front of the vital area, called double-stranded fences, with native trees planted between the two fences. He noted that his method was successful in Kuwait. Al Jahar is an urban area located about 20 kilometers from a dust storm host spot affected by northwest wind blowing particles directly from a desert area into the urban center. Before mitigation efforts began, the people of Al Jahra were suffering from the health effects of dust storms and there were high levels of hospital admissions. Historical records show the success of mitigation efforts, as described in Al-Hemoud's presentation. Al Jahra now has the cleanest air in all of Kuwait, as measured by $PM_{2.5}$ and PM_{10}. This success story can serve as an example for other areas, including Iraq. The Kuwait Institute for Scientific Research, Harvard University, and universities in southern Iraq have created a team to target and mitigate this hotspot area. There has also been interest in funding for this project from the Kuwait Fund. This hotspot area is the origin of dust storms in southern Iraq, and it impacts the environment of Kuwait, Saudi Arabia, Bahrain, Qatar, and the UAE. Al-Hemoud expressed their hope that similar mitigation efforts can be applied in other areas in the region.

2.4.3 Defining a dust storm

A participant asked the panel to define a "dust storm day" and queried whether the definition includes thresholds for PM levels or length of the episode. Al-Hemoud stated that a dust storm is defined by visibility below 1,000 meters. There are three types of dust storms: (1) severe visibility dust storms, where one cannot see beyond 200 meters; (2) normal visibility, where one can see between 200 to 600 meters; and (3) visibility between 600 meters and 1 kilometer. The World Meteorological Organization and pioneer experts in the area define a dust storm as an event with visibility below 1,000 meters and a wind speed of 8.5 meters per second or greater. Al-Hemoud said there are instances where wind speeds are high, but visibility is over 1,000 meters in Kuwait; these events are not considered dust storms. Instead, they are called rising dust or blowing dust.[25] Achilleos pointed out that different studies use different cutoff points for PM_{10}, which alters the definition of a dust storm. The cutoff point depends on PM_{10} background levels and the intensity of the dust. In general, there are different tools to identify dust from PM_{10} trends, such as satellite data and other projections of air masses.

20 Cachorro et al 2016
21 Evan et al 2016
22 Lelieveld et al 2014
23 Goudie 2014
24 Nwanaji-Enwerem et al 2019
25 Hoffmann et al 2008a; Hoffmann et al 2008b

2.4.4 Stability of hotspots

A participant asked how hotspots around Kuwait move and how predictable they are over time. Al-Hemoud explained that in Kuwait there are several major hotspots: two are in southern Iraq and one is in eastern Saudi Arabia. Generally, these hotspots are stable, but extreme wind erosion can turn the sources into sand dunes. When there are many sand dunes, the particles are coarse and heavy, so they do not travel long distances. Al-Hemoud said hotspots can expand or shrink depending on the surrounding vegetation. He noted that the hotspot in Iraq is shrinking from the sides due to improvements in vegetation. However, the middle of the hotspot is most severe. Al-Hemoud stressed that this hotspot, despite the recent shrinking, is still very large (two-thirds the size of Kuwait) and poses a regional threat due to its high wind speed.

2.5 Dust and air pollution in the arid, urban environment of Israel

Itzhak Katra, geomorphologist, head professor of the department of geography and environmental development at Ben-Gurion University, presented research focused on the effect of dust storms on air pollution in southern Israel from Ben-Gurion University and Soroka University Medical Center. Dust storms affect air quality and hundreds of million people around the world are frequently exposed to this natural phenomenon. Most severe exposures occur within the global dust belt, which extends from West Africa to the Arabian Desert. Quantitative information on air pollution, exposure risk, and health impacts are limited for urban areas located near the dust belt. He highlighted the significance of dust storms in Israel using an image of Ben-Gurion University from February 29, 2012, during an intense dust storm, which illustrates the severity of air pollution at PM_{10} (5197 µg/m^3) and $PM_{2.5}$ (of 911 µg/m^3) levels that greatly exceed WHO guidelines.

Katra noted that several projects on dust and air pollution have been conducted in Beer Sheva in the northern Negev Desert, Israel. The area is ideal for studying air pollution and health impacts from dust for two reasons. First, the semi-arid region is a case study for future effects of global warming and climate change in southern Europe due to its location at the margins of the global dust belt and frequent dust storms. Second, access to complete health outcomes of almost a million residents is accessible from the regional hospital, Soroka University Medical Center. He identified the different study aspects of dust PM in the urban area of Beer Sheva. The research investigated identification of dust events, intensity of dust events, dust particle characteristics, spatial distribution of dust PM, and indoor air pollution.

Figure 2-3. Ben-Gurion University during an intense dust storm (February 29, 2012)

Source: Katra presentation

2.5.1 Identification of a 'dust event'

The first aim was to identify dust storms using PM_{10} concentrations, said Katra. To do so, the distribution of daily PM_{10} averages in Beer Sheva during the study period of 2001–2012 was analyzed.[26] Dust days were excluded based on synoptic data during the study period. The average PM for non-dust days—the background value (BV)—was calculated for each year and averaged for the total period. The BV was calculated using the area under the curve (AUC) for the time series in a "dust-free" season (summer). The average BV for the study period was 42 µg/m^3, which is just below the BV recommended in WHO guidelines. The threshold for the classification between possible "dust days" and non-dust days was determined as two standard deviations above the average BV (BV [42 µg/m^3] +2sd ≥71 µg/m^3.) Daily synoptic conditions and back trajectories (HYSPLIT) were used for validation.

After calculating the BV for the region, the relative contribution of anthropogenic sources of the PM_{10} level was determined. To assess the net contribution of anthropogenic PM, hourly PM_{10} and $PM_{2.5}$ concentrations during a background period in Beer Sheva were analyzed.[27] The analysis of the hourly PM concentrations was conducted for days with anthropogenic activities (ie, natural + anthropogenic, weekdays) and days without anthropogenic activities (ie, natural, weekends and holidays). In Israel, the least active days are Saturdays (weekends) and holidays, especially for Yom Kippur. Observance of the holy holiday Yom Kippur involves prohibition

26 Krasnov et al 2014
27 Krasnov et al 2016b

of certain activities and reductions in road traffic; thus, this day has the lowest amount anthropogenic activity in the year. Results indicate the difference between the two curves (ie, days with versus days without anthropogenic activity), or the net contribution of anthropogenic PM to BV, is approximately 15%. Consequently, most BV is generated from local soils in the region.

2.5.2 Intensity of dust events

Another research aim in Beer Sheva was to determine dust storm intensity, said Katra. The dust storm intensity value (Ai) was calculated using plots of hourly PM_{10} levels and determining the area under the storm curve.[28] The evaluation considered both the concentration and duration of PM_{10} during the storm. Katra compared three dust storms to illustrate the important of considering duration and concentration when determining dust storm intensity. An on-and-off storm in February 2012 had the most extreme PM_{10} value recorded, reaching more than 5000 μg/m^3, but this peak had a short duration. Another dust storm in December 2009 had a much lower peak of about 2000 μg/m^3 PM_{10}, but a longer duration. Despite this event having a lower peak concentration, the AUC was greater for the December 2009 dust storm, meaning the intensity calculated was greater than that of the storm recorded in February 2012. However, the storm with the highest intensity occurred in December 2010, secondary to its long duration (almost 3 days) in combination with consistently high PM_{10} values. Thus, the greater the AUC, the greater the storm intensity and—possibly—its danger to human health.

2.5.3 Dust particle characteristics

Katra discussed physicochemical characteristics of dust particles, such as daily particle size distribution and chemical composition, as well as organismal diversities of dust.[29] Two storm events in December 2012 and January 2013 affected Negev, southern Israel. Both storms were associated with a trajectory extending over North Africa and into Negev. The December 2012 air mass originated in North Africa and the January 2013 air mass originated in South Europe. The distributions of eukaryotic (18S, kingdom-class levels) and prokaryotic (16S, class levels) rRNA gene reads were retrieved from both dust storm samples collected in the Negev, southern Israel. Patterns of biological richness and diversity differed between the two events, suggesting that biological material in dust—not just chemical composition—should be considered.

2.5.4 Spatial distribution of dust PM

Another aspect of dust storms is the specific PM distributions at the city level.[30] Cities typically lack enough PM monitoring sites, and satellite data provides resolution that is too low to enable identification of intra-urban pollutant variability. Thus, PM spatial distribution at the city scale is difficult to collect and analyze for human health outcomes. To address this challenge, a campaign of mobile measurements during non-dust days (background) and dust storms was used to construct spatial distribution models of PM_{10} concentrations in dust storms. PM data were recorded for several dust episodes and the distribution models show that the windward side of the city had higher PM_{10} levels.

2.5.5 Indoor air pollution

Katra remarked that understanding indoor air pollution is important, because people spend most of their time inside. A study aimed to investigate the influence of dust storms on PM in the indoor environment [31] by simultaneously measuring PM_{10} and $PM_{2.5}$ levels in outdoor and indoor air during dust events and non-dust days in Beer Sheva. The results revealed a significant contribution of dust events to the indoor $PM_{2.5}$ and PM_{10} levels.

Katra also presented a case study demonstrating how indoor PM levels respond over time to a strong dust event.[32] Additionally, real-time

28 Krasnov et al 2014
29 Katra et al 2014
30 Krasnov et al 2016b
31 Krasnov et al 2015
32 Katra and Krasnov 2020

dust event measurements of hourly indoor and outdoor variations in PM_{10} and $PM_{2.5}$ were recorded and averaged from several houses, then compared with the concentrations recorded in the houses during non-dust days. The results show that simultaneously measured indoor levels fluctuated in parallel with the outdoor levels during dust storms. Indoor PM levels also tended to remain high for several hours after the dust event. These findings suggest individuals sheltering at home during dust events may not be protected from elevated PM levels.

2.5.6 Discussion

Souzana Achilleos referred to Petros Koutrakis' presentation, which discussed a study on dust storms and indoor air quality in Kuwait. Its results indicated that indoor air pollution levels were significantly lower during dust storms than non-dust days secondary to keeping homes tightly sealed. This is contrary to findings reported by Katra, so Achilleos asked for clarification about the contribution of dust events to indoor air pollution in Israel. Katra acknowledged that Israelis do seal their homes, but dust continues to penetrate average homes. He suggests penetrance through windows and doors is partially contingent on wind speed. Victor Novack clarified that Petros Koutrakis' presentation showed that the indoor/outdoor ratios is different during dust and non-dust events. Moreover, approximately 50% of dust will penetrate indoors during a dust storm event. Assessing indoor air pollution concentrations is a challenge for research on air quality, he noted, and suggested that Koutrakis' work provides a useful equation to assess indoor dust concentration based on outdoor measurements. Additionally, his work shows that typical items in the home such as carpets and pets can increase indoor dust concentration. Petros Koutrakis added that Israel possesses more high-rise apartments compared to Kuwait, which has more single-family homes. This difference could be partly responsible for the discrepancy in indoor air pollution levels during dust events. Kuwait also has higher winds and more exposure. Victor Novack affirmed that Israeli building quality tends to be poor. For example, gaps under the doors are common, and are likely the main source of dust into households. He added that further research should investigate the effect of air conditioning on air quality in the region. Petros Koutrakis acknowledged that air conditioning is a powerful and reliable tool in Kuwait. He also posited that dust storm conditions including meteorological circumstances may differ between Israel and Kuwait.

2.6 Characteristics of PM pollution in Qatar's atmospheric environment

Wasim Javed, assistant research scientist in the department of mechanical engineering at Texas A&M University, reviewed the characteristics of PM pollution in Qatar's atmospheric environment. He explained that high PM is the most significant environmental challenge in the Middle Eastern region due to the arid desert climate. In particular, the capital of Qatar, Doha, has high PM levels that regularly exceed WHO PM standards.[33,34,35] Doha is experiencing rapid economic and population growth, which contribute to its excessive PM concentrations. Doha PM pollution is higher than most other Middle Eastern cities and averages 7-fold higher than WHO 24-hour limits.[36] Overall, however, the Middle East has limited data on PM pollution, especially Qatar. Furthermore, Qatar is a desert country situated on a peninsula on the west coast of the Arabian Gulf. Its geography and climate, as well as its petroleum industry, make it unique among other studied areas of the world.

Javed described the results of a PM sampling campaign that was carried out at the Solar Test Facility in the Qatar Foundation (at latitude 25º19'32.68" N and longitude 51º25'59.55"

33 Engelbrecht et al 2009
34 Saraga et al 2017
35 Javed et al 2019
36 Javed and Guo 2021a

E) located in Doha, Qatar between May-December 2015. Every other day, 24-hour $PM_{2.5}$ and PM_{10} filter samples were collected for PM mass, trace elements, soluble ions, and organic carbon and elemental carbon analysis, with 105 samples each. On every sixth day, 34 filter samples were also collected for organic compound analysis. Along with filter sampling, real-time measurements were collected by using DustTrack DRX for PM and Aethalometer for black carbon from 2014-2019. The key conclusions of this study are provided in Box 2-1.

2.6.1 PM mass concentrations

Javed reported that the $PM_{2.5}$ and PM_{10} annual means were approximately 40 μg/m³ and 146 μg/m³, respectively. For $PM_{2.5}$, average levels were four times the WHO annual limit and 78% of days exceeded the WHO 24-hour limit. For PM_{10}, average levels were 7.3 times the WHO annual limit and 92% of days exceeded the WHO 24-hour limit. The average $PM_{2.5}/PM_{10}$ ratio was 0.30, indicating 70% of atmospheric PM_{10} mass consisted of coarse particles. The predominance of coarse PM is due to the desert environment. Additionally, 20% of sampling campaign days were dust storm days, defined as those with PM_{10} greater than 200 μg/m³. $PM_{2.5}$ and PM_{10} levels were 1.5-2.5 times higher on dust storm days than non-dust storm days. However, $PM_{2.5}$ and PM_{10} levels on non-dust storm days (36.3 and 83 μg/m³, respectively) were similar to the annual mean levels. Comparable non-dust storm day and annual mean values indicate that dust storms, in addition to non-natural sources, contribute to the higher $PM_{2.5}$ concentration in the area.

2.6.2 Elemental carbon & organic carbon analysis

Javed discussed the organic carbon and elemental carbon analysis of PM in Qatar.[37] Average elemental carbon was 2.61 μg/m³ and 3.0 μg/m³ in $PM_{2.5}$ and PM_{10}, respectively; 80% of elemental carbon was in $PM_{2.5}$ fractions. Average organic carbon was 1.8 μg/m³ and 7.0 μg/m³ in $PM_{2.5}$ and PM_{10}, respectively; 70% of organic carbon was associated with PM_{10} fractions. These results indicate that elemental carbon and organic carbon originate from vehicular exhaust and other combustion sources. Total secondary organic carbons (SOC) account for 60% and 70% of organic carbon in $PM_{2.5}$ and PM_{10}, respectively. Elevated SOC suggest more photochemical conversion of organics to the secondary organics due to favorable meteorological conditions—most likely in higher temperatures and solar radiation—in the region.

2.6.3 Sulfate and nitrate contents

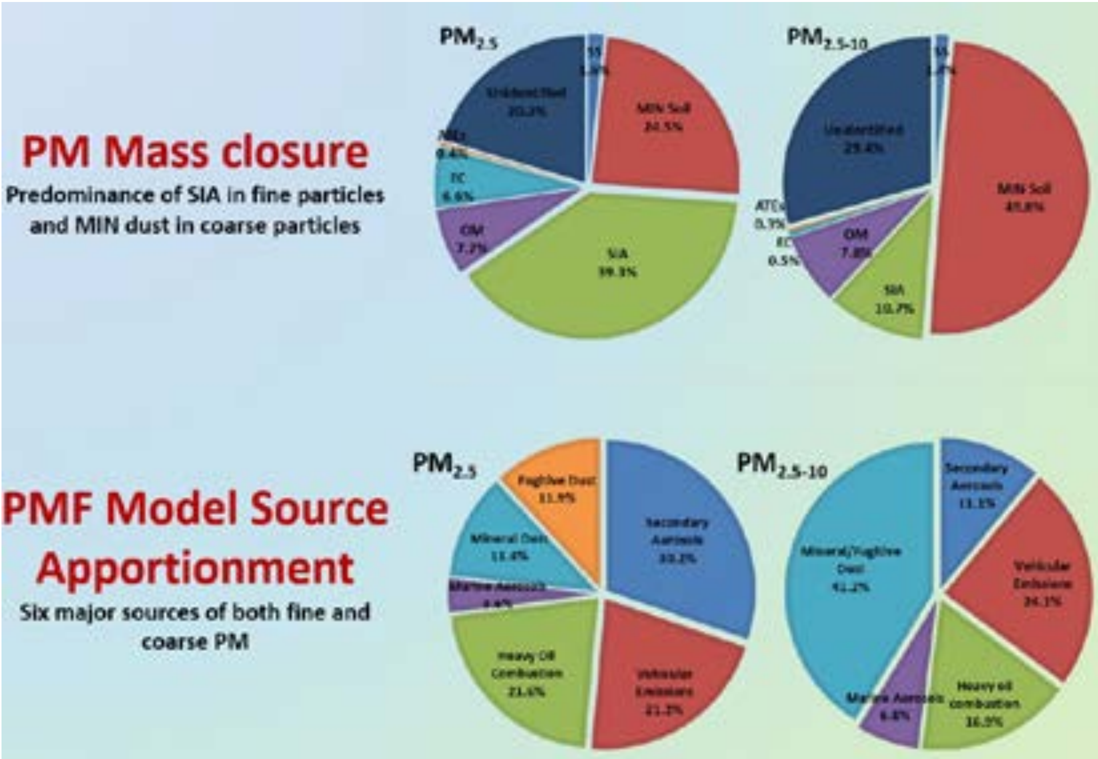
Sulfate and nitrate were also analyzed in PM. Average sulfate was 14.2 μg/m³ and 5.3 μg/m³ in $PM_{2.5}$ and PM_{10}, respectively. 75% of sulfate was in the fine, $PM_{2.5}$ fraction. Average nitrate was 1.5 μg/m³ and 6.2 μg/m³ in $PM_{2.5}$ and PM_{10}, respectively. 80% of nitrate was the coarse PM ($PM_{2.5\text{-}10}$). Significantly elevated sulfate concentration is indicative of regular photochemical reactions in this harsh, arid region, Javed noted.

2.6.4 PM mass closure and positive matrix factorization model source apportionment

Javed explained that a mass closure analysis and positive matrix factorization (PMF) model were used to quantify and identify the probable sources of both PM size fractions (see Figure 2-4). Mass closure showed the prevalence of secondary inorganic aerosol (39.3%) in fine PM, while mineral dust contributed 50% to the total mass of coarse PM. PMF was used to identify six major sources of PM: (1) secondary inorganic aerosols, (2) vehicular emissions, (3) heavy oil combustion, (4) marine aerosols, (5) minerals, and (6) fugitive dust. Secondary aerosols (30.2%) and heavy oil combustion (21.6%) predominate the $PM_{2.5}$ fraction. Mineral and fugitive dust contribute 41.2% of $PM_{2.5\text{-}10}$ fractions.

37 Javed et al 2019

Figure 2-4. Particulate matter closure and mass closure and Positive Matrix Factorization model source apportionment



Notes: $PM_{2.5}$ = particulate matter with diameter ≤2.5µm; $PM_{2.5\text{-}10}$ = particulate matter with diameter between 2.5µm and 10µm; SIA = secondary inorganic aerosols; MIN Soil = mineral dust
Source: Javed presentation

2.6.5 Wind direction analysis of PMF-derived sources

A detailed wind direction analysis was conducted with the PMF model data and conditional bivariate probability function plots.[38] Wind analysis indicated that both local and regional PM sources impact Qatar's air quality, said Javed. Local sources such as vehicular emissions are associated with low wind conditions. Long-distance regional sources like secondary and mineral aerosols were linked to high wind conditions, mostly from the northwest direction. Moreover, Qatar has unique wind patterns. For the duration of the study period, 60% of winds came from a northwest prevailing direction traveling over the Arabian Gulf. Winds primarily originate from the desert areas of Iraq and Kuwait and travel over the Gulf before arriving to Doha.

2.6.6 Potential source contribution function plots

PMF-identified sources were characterized by the potential source contribution function plots using backwind trajectory data to identify regional sources affecting PM concentrations in Qatar. Local sources include heavy oil combustion and secondary aerosols, which are closely related to regional emissions from shipping vessels and the petrochemical industry in the Arabian Gulf region. Mineral dust and marine aerosols appear to be long-distance sources. The distant desert regions of Iraq and Kuwait, located northwest of Doha, are the poten-

38 Javed and Guo 2021b

tial source areas of the mineral dust particles. Marine aerosols are associated with strong winds from the northwest and east directions under the transport of air masses from the sea.

2.6.7 Real-time PM measurements and trends

Along with filter sampling, real-time measurements were collected by using DustTrak DRX and corrected with gravimetric measurements.[39] Data were collected over 6 years (2014-2019) at the sampling site in Qatar. The DustTrak DRX monitor demonstrated high precision, but significant deviation from the gravimetric method in measuring both PM size fractions. It overestimated $PM_{2.5}$ concentration by a factor of 2 and underestimated PM_{10} by about 20%. The proposed correction factors can be used for bias correction of DustTrak monitors, Javed noted.

The DustTrak measurements were then used to create temporal trends of PM concentration between 2014-2019. For diurnal trends, average PM concentrations peaked in the morning around 6am, decreased until 4pm, and then increased again during the night. The morning peak may be related to increased boundary layer height. Boundary layer height provides a larger volume for dilution which lowers the PM concentration from morning to afternoon. Additionally, the morning peak in PM concentrations is not associated with traffic rush hours, because it is also seen on the weekends.

Monthly trends were also analyzed to determine frequency of dust storm days and impact on PM_{10} concentrations. PM levels were increased during the summer season (ie, June-September), which is characterized by the most frequent dust storms and low rainfall. The analysis of overall and non-dust storm PM averages found that dust storms contribute to 16% (range of 5%-25%) of the annual average of PM_{10}. Moreover, on average, 60% of PM_{10} mass is contributed by dust storm days.

Lastly, annual trends were analyzed for the study period. The data underwent meteorology normalization through Boosted Regression Tree machine learning technique, which minimized meteorological influence on PM variations.[40] The most influential meteorological variables were dust storms, wind speed, and relative humidity. The analysis of annual trends after weather normalization determined annual average $PM_{2.5}$ and PM_{10}. 2015 and 2016 were the most polluted years in the study period, with the highest $PM_{2.5}$ and PM_{10} concentrations. Overall, normalized and observed PM levels trended down. From 2015, the annual average weather-normalized concentrations in 2019 reduced 26% in $PM_{2.5}$ and 15% in PM_{10}. $PM_{2.5}$ and PM_{10} decreased 2.49 $\mu g/m^3$ and 4.78 $\mu g/m^3$ per year, respectively. Although PM concentrations are reducing, the levels are still higher than recommended values.

39 Javed and Guo 2021b
40 Grange and Carslaw 2019

Box 2-1. Key Conclusions from PM Sampling Campaign in Qatar (May-December 2015)

- $PM_{2.5}$ and PM_{10} levels exceeded 4-7 times the WHO limits for 80-90% of days.
- Fine and coarse PM sources were identified and quantified by PMF model and wind direction analysis.
- The results identify two main sources—heavy oil combustion and secondary aerosols—that are closely related to regional emissions from shipping vessels and the petrochemical industry in the Gulf region.
- The desert dust transport mixed with local resuspended dust and sea salt particles also contributes considerably to the local PM concentrations.
- The significant contributions of regional anthropogenic and natural emissions pose a substantial challenge in meeting local PM standards, signifying the importance of regional collaboration for better control policies on reducing transboundary air pollution.

2.7 Estimation of ambient PM2.5 in Iraq and Kuwait (2001-2018) using machine learning and remote sensing

Jing Li, postdoctoral fellow at Harvard T.H. Chan School of Public Health focused on a study recently published by *Environment International* on the estimation of ambient $PM_{2.5}$ in Iraq and Kuwait from 2001 to 2008 using machine learning and remote sensing.[41] She began by providing background information on Iraq and Kuwait. Since 2001, nearly 3 million US military and coalition military personnel have been deployed in support of operations in the Middle East. Land-based military personnel were frequently exposed to high levels of PM. However, the lack of a ground-based PM monitoring network has limited the ability to assess health effects related to PM exposure. The aim of the study was to assess daily $PM_{2.5}$ exposures for Iraq and Kuwait, which could help design health effect studies both in the native populations and previously deployed military personnel. Satellite-based aerosol optical depth (AOD) has been widely used to estimate $PM_{2.5}$ exposure, given its high spatial and temporal resolutions. However, this method has not been applied to areas with a lack of $PM_{2.5}$ monitoring sites. During the study, a calibration model was developed to convert visibility to $PM_{2.5}$ based on satellite AOD. This approach takes advantage of the large database of historical visibility collected by airports and the high spatial-temporal resolution of satellite-based AOD.

2.7.1 Data collection

Li explained that the study spanned 2001-2018 and used global public data sets; AOD, visibility and $PM_{2.5}$ were the important variables in the model. AOD data were collected from NASA Multi-Angle Implementation of Atmospheric Correction (MAIAC) with 1 km spatial resolution and daily temporal resolution. Visibility data were provided by 263 United States Air Force airports with hourly temporal resolution. $PM_{2.5}$ monitoring data in the study regions were available for three different time periods and sites, including daily $PM_{2.5}$ concentrations from the US Embassy Kuwait air quality monitor from 2017-2018. $PM_{2.5}$ concentrations were also collected in three monitoring sites in Kuwait from 2004–2005 and daily $PM_{2.5}$ observations from two monitoring sites from 2017-2018 in Kuwait. A total of 1942 daily $PM_{2.5}$ and concurrent visibility data were used in the model. Dust variables from the NASA Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) dataset and land use data (NDVI, road density, distance to industrial area, elevations) were also collected as confounders. Meteorological data were

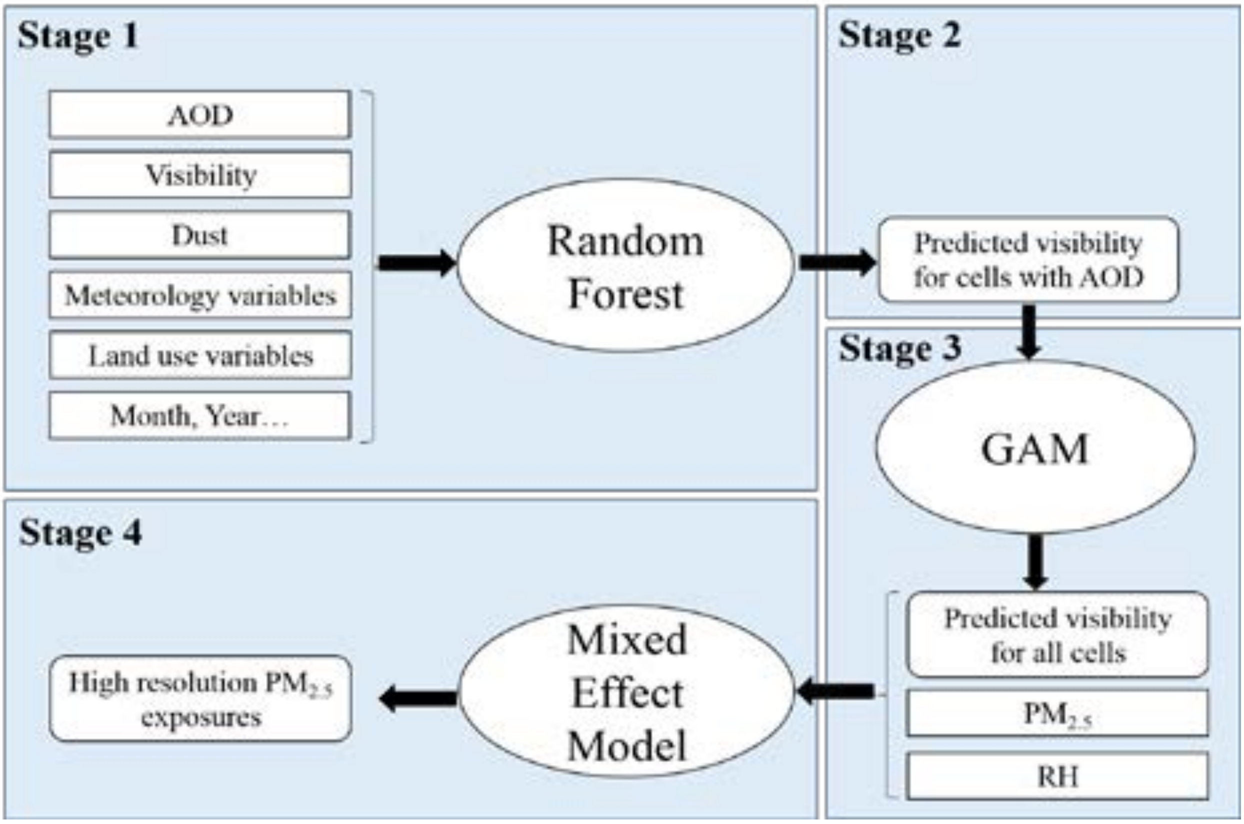
41 Li et al 2021

obtained from the fifth-generation European Centre for Medium-Range Weather Forecasts reanalysis (ERA5) to serve a control in the model.

2.7.2 Model

A hybrid model including four stages was developed to estimate $PM_{2.5}$ concentrations in each 1 km by 1 km grid cell (see Figure 2-5). In Stage 1, a random forest model based on machine learning was used to predict daily visibility using AOD, visibility, dust variables, meteorology variables, land use variables, and timeframe data. Stage 2 involved using grid cells with AOD, but without visibility measurements, to predict daily visibility for each 1 km by 1 km grid cell from the Stage 1 model. For grid cells without AOD data, a generalized additive mixed model was used to predict daily visibility based on the output from Stage 2 model for Stage 3. Stage 4 used a calibrated model to predict $PM_{2.5}$ for each grid cell.

Figure 2-5. Hybrid model for PM2.5 estimation



Notes: AOD = aerosol optical depth; GAM = generalized additive mixed model; PM = particulate matter; RH = relative humidity
Source: Li presentation

2.7.3 Model performance

Li discussed the model's performance in Stage 1 and 4. For Stage 1, an "out of sample" 10-fold cross-validation was used to estimate the visibility prediction model results and avoid overfitting. All visibility stations were randomly divided into 10-90% splits. The cross-validation R^2 (CV R^2) between fitted and predicted daily visibility was 0.71. Moreover, the random forest model is commonly used to predict $PM_{2.5}$ based on AOD because it can determine variable importance. The top-five most important variables for the random forest model predicting daily visibility were MAIAC AOD, year, dust column mass density, dust extinction AOD, and dust surface mass concentration.

In Stage 4, data during 2017-2018 was used to train the model. Data during 2004-2005 were used for evaluation, which helped to understand the model's ability to estimate historical $PM_{2.5}$. The model resulted in a high CV R^2 value of 0.70 in the modelling year (2017-2018) and R^2 value of 0.74 in the evaluating year (2004-2005), indicating good model fit. The comparison of long-term variation of satellite-derived and ground-observed $PM_{2.5}$ also indicated good model performance.

2.7.4 Results

Considerable spatial and temporal variations were found over the study region, said Li. The annual mean predicted $PM_{2.5}$ concentrations for Kuwait (41 μg/m^3) and Iraq (37 μg/m^3) were considerably higher than the US National Air Quality Standard of 12 μg/m^3 and the WHO guideline of 10 μg/m^3. The highest annual $PM_{2.5}$ concentration for both Kuwait and Iraq were observed in 2008, followed by 2009. The lowest values for both Iraq and Kuwait were observed in 2014. It is possible that the extreme drought in 2008-2009 contributed to the high $PM_{2.5}$ level in 2008 and that heavy rain at the end of 2013 contributed to lower levels in 2014. For monthly average predictions, July had the highest predicted concentrations and November had the lowest values. This is consistent with seasonal patterns of $PM_{2.5}$ observations, she added.

In general, the $PM_{2.5}$ concentrations in Kuwait were slightly higher than in Iraq between 2001-2018. As expected, the predicted $PM_{2.5}$ concentrations were higher in urban areas compared to rural areas. Some big cities such as Baghdad, Karbala, Najaf, and Diwaniya have annual average $PM_{2.5}$ concentrations above 45 μg/m^3. It is notable that many US bases are in these cities, but some bases were in regions with lower $PM_{2.5}$ concentrations (averages below 30 μg/m^3), such the West desert region of Iraq. Thus, deployers in Iraq and Kuwait experienced variability in $PM_{2.5}$ exposures.

Li presented a set of maps depicting the spatial distribution of predicted mean $PM_{2.5}$ concentrations (μg/m^3) for each year. In 2008 and 2009, $PM_{2.5}$ concentrations were very high for the whole region, while for some years (eg, 2004 and 2014) the exposures were relatively lower. To glean more detail on exposure data, the study investigated weekly average $PM_{2.5}$ concentrations at important sites. For instance, the weekly average $PM_{2.5}$ at Baghdad International Airport ranged to more than 150 μg/m^3 in summer of 2008 and 2009.

2.7.5 Relevance of study findings

Li compared the results of the study with other available literature. Although very few studies have conducted $PM_{2.5}$ measurements in Kuwait or Iraq, one study collected $PM_{2.5}$ samples approximately four times per month at five sampling sites in Iraq and four sampling sites in Kuwait in 2006.[42] Other studies have assessed daily air concentration of PM_{10} in 2012 in a suburban area of Kuwait[43] and collected $PM_{2.5}$ measurements in three monitoring stations in Kuwait from 2014-2017.[44] The estimates have the same spatial distribution with the $PM_{2.5}$ samples reported by Engelbrecht et al.[45] Further, the study predictions and the PM_{10} in Al-Hemoud et al.[46] have the same seasonal pattern. The $PM_{2.5}$ concentrations predicted in this study are also consistent with a previous WHO air pollution database. However, the $PM_{2.5}$ concentrations reported by Al-Hemoud et al.[47] (34-80 μg/m^3) are generally higher than this model's results, possibly because they selected hourly $PM_{2.5}$ values above a minimum background concentration of 8.83 μg/m^3 to report.

Li also highlighted the major findings of the study with public health significance. In previ-

42 Engelbrecht et al 2009
43 Al-Hemoud et al 2018a
44 Al-Hemoud et al 2019b; Al-Hemoud et al 2018b
45 Engelbrecht et al 2009
46 Al-Hemoud et al 2018a
47 Al-Hemoud et al 2019b

ous studies, the AOD-$PM_{2.5}$ relationship was directly used to examine the spatial distribution of $PM_{2.5}$. However, for many countries, there are no available historical $PM_{2.5}$ measurements. This novel exposure assessment approach indicates that it is possible to assess air pollution exposures in countries without extensive $PM_{2.5}$ monitoring locations or historical data. The other predictors used in the model are predominantly from global public datasets, thus the method could be applied in other countries. Secondly, the random forest model approach provided the relative importance of each factor associated with historical $PM_{2.5}$ concentrations to assess exposures in this region or similar areas. For example, in addition to AOD, surface dust related variables were found to also be associated with $PM_{2.5}$ in arid environments.[48] Finally, based on available literature, this is the first model to estimate historical $PM_{2.5}$ concentrations at a high resolution in the region.

2.7.6 Question

Achilleos asked about use restrictions for the model—for instance, if it can only be used in arid and semi-arid areas. Petros Koutrakis replied that the model does not have restrictions. He added that it is advantageous to use visibility data in the Middle East due to the generally low relative humidity. Some areas in the region have high humidity levels, like the US. Another advantage is the prevalence of high concentrations, which allows for significant analysis of visibility data.

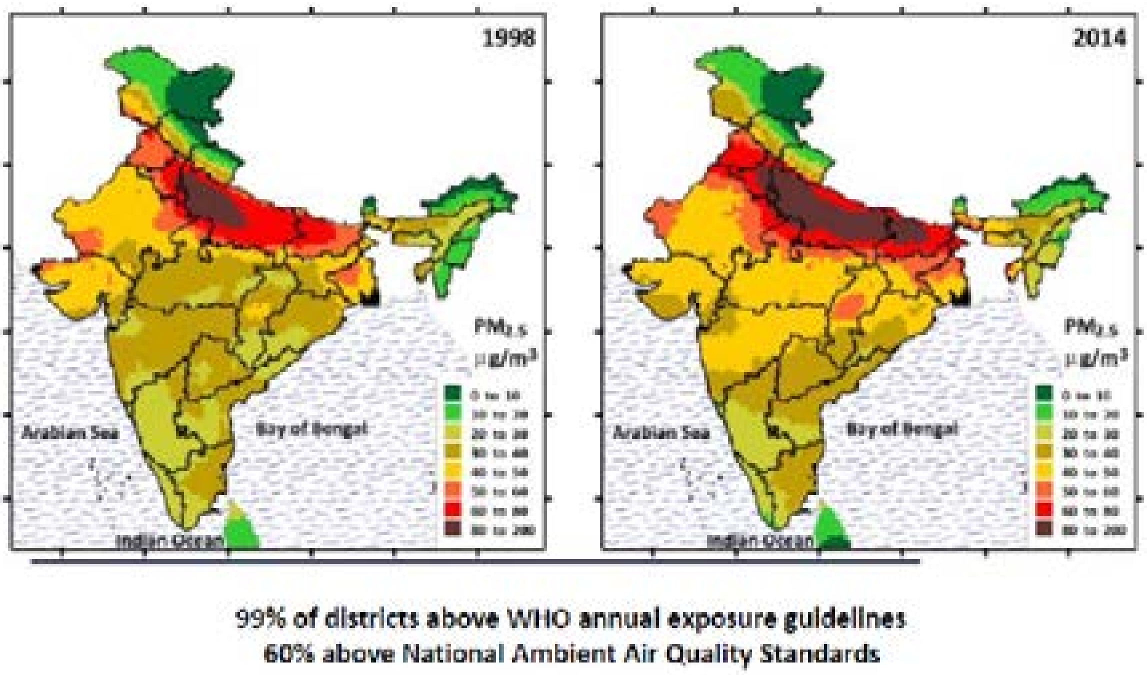
2.8 Modelling of air pollution and health effects in India

Poornima Prabhakaran, additional professor, head - environmental health, deputy director of the Centre for Environmental Health at the Public Health Foundation of India, Senior Research scientist, at Centre for Chronic Disease Control, reviewed the modelling of air pollution and health effects in India, which she described as the "air pollution capital of the world." WHO reported that 15 of the 20 most polluted cities in the world are located in India. She noted that India was also previously known as the "diabetes capital of the world," which brings to the fore questions about the link between air pollution and health effects. Furthermore, air pollution in India is increasing.[49] Ambient $PM_{2.5}$ variation trends upwards from 1998 to 2014, with 99% of districts above WHO annual exposure guidelines of 10 μg/m^3 and 60% above the less stringent Indian National Ambient Air Quality Standards (see Figure 2-6). Air pollution severity is disproportionately distributed within the country, with the northern, Indo-Gangetic Plain region most heavily affected. The Indo-Gangetic Plain is the focus of a yearly winter discourse around deteriorating air quality. In general, however, most regions are affected by poor air quality.

Prabhakaran presented the 2017 findings from a Lancet publication on Indian air pollution.[50] It found that annual population-weighted mean exposure to ambient $PM_{2.5}$ in India was 90 μg/m^3, which is more than twice the recommended value by the Indian National Ambient Air Quality Standards. The Indo-Gangetic Plain had the highest exposure. In addition to ambient air pollution, household air pollution is also a concern that is frequently omitted in air pollution discussions. Solid fuels are an unclean biomass often used for cooking, lighting, and heating. The proportion of population using solid fuels in India was 55.5% nationwide, but more than 75% in the low social development index states of Bihar, Jharkhand, and Odisha. In 2017, 1.24 million deaths (ie, 1 in 8 total deaths) in India were attributable to air pollution. Furthermore, the air quality issue in India is twofold: 0.67 million deaths were from ambient PM pollution and 0.48 million from household air pollution. Premature deaths within the working population are increasingly problematic for the growing Indian economy. Of the deaths attributable to air pollution, more than 50% were premature deaths affecting people younger than 70. Moreover, if the air pollution level in India was lower than the minimum level causing loss of health, the average life expectancy in India 2017 would have been 1.7 years higher.

48 Li et al 2020a
49 More information on air pollution trends available at Urbanemissions.info (accessed May 24, 2021)
50 India State-Level Disease Burden Initiative Air Pollution 2019

Figure 2-6. Ambient $PM_{2.5}$ variation over time in India (1998-2014)



Source: Prabhakaran presentation; urbanemissions.info

2.8.1 Disease linked to air pollution

In addition to increasing mortality, air pollution also affects morbidity. Prabhakaran remarked that air pollution is linked to well-known acute respiratory effects as well as various chronic diseases. Air pollution affects the heart, brain, peripheral blood vessels, and causes conditions such as gangrene and COPD. Increasing worldwide evidence is also establishing the connection between exposure to poor air quality and conditions such as heart failure, dementia, and cognitive impairment. Poor air quality is also associated with poor birth outcomes among exposed pregnant individuals. Intermediate risk factors for other chronic diseases such as hypertension, diabetes, and obesity, especially central adiposity, are also increased. She added that the Indian population has one of the highest risks for cardiovascular disease (CVD) and diabetes in the world.

Prabhakaran summarized the mechanisms of increased risk of CVD from air pollution, noting that the evidence primarily originates from developed countries. $PM_{2.5}$ and other air pollution components cause underlying changes such as endothelial dysfunction, inflammation/lipid peroxidation, increased blood pressure, and heart rhythm abnormalities. Consequently, conditions such as metabolic abnormalities, atherosclerosis (ie, deposition of plaque and hardening of arteries), hypertension, arrhythmias (ie, irregular heart rhythms), and left ventricular dysfunction can occur. These changes can culminate in ischemic heart disease, peripheral vascular disease, congestive heart failure, and arrhythmias/sudden death.

Policies based on health effects of air pollution, however, are often not instituted due to the lack of evidence from the corresponding country, said Prabhakaran. In India, some evidence for health effects of air pollution is available from studies linking maternal exposure and birth outcomes as well as adult exposure and respiratory health. Cross-sectional studies have linked acute air pollution episodes and rise in emergency room footfall for acute respiratory infections. India is also a part of the global burden of disease estimates studies conducted by the Health

Effect Institute, which develops exposure-response functions using data from developed countries. She emphasized that India needs contextualized local studies based on exposure assessments as well as modelled/measured and longitudinal datasets of health outcomes. Randomized control trials and longitudinal cohort studies are the preferred study designs, but conducting randomized control trials of air pollution exposure raises ethical concerns.

2.8.2 Center for Cardiometabolic Risk Reduction in South Asia surveillance study

Prabhakaran reviewed an ongoing study on air pollution in India. The Center for Cardiometabolic Risk Reduction in South Asia (CARRS) surveillance study was established in 2010 and is a collaboration between the Center for Chronic Disease Control, Public Health Foundation of India (PHFI), All India Institute of Medical Sciences, Madras Diabetes Research Foundation, and Emory University. All India Institute of Medical Sciences is a tertiary care institute in Delhi. The jointly funded collaboration established a longitudinal study examining cardiometabolic risk reduction in South Asia. The study sites were metropolitan urban settings which included the Indian capital, Delhi, and the southern city, Chennai. Approximately 4000 people aged 20 or older were selected from each city using a multi-stage cluster random sampling and gender stratification. The sampling method of Delhi was explained. Sampling started with the 9 districts of the city, with 143 wards and subsequent Census Enumeration Blocks used as sampling frames to randomly select households. Two participants, one male and one female, aged 20 years or older, were selected from each household. Starting in 2010, an annual survey was conducted on the participants. The survey included extensive phenotypical exposure assessments. Participants underwent anthropometric measurements, blood pressure assessment, and provided blood specimens for tests including fasting glucose and lipid levels. The result is a longitudinal dataset with a rich repository of cardiometabolic risk factors for Indian adults. A concurrent, second cohort was established in 2014.

2.8.3 The GEOHealth project

Delhi regularly draws WHO, national, and international media attention regarding its poor air quality. The 2016 "airpocalypse" in Delhi was the one of the city's worst years for air quality and initiated discourse on air pollution in India. Prabhakaran explained how the CARRS cohort and established infrastructure was leveraged to conduct a study on air pollution in India. The Global Environmental and Occupational Health (GEOHealth) project is a partnership between the Public Health Foundation of India, Centre for Chronic Disease Control, and the Harvard T.H. Chan School of Public Health. The project started in 2016 when air quality in Delhi was at its worst. The principal investigators were Joel Schwartz and Richard Cash from HSPH and Dr. D. Prabhakaran and Dr. Srinath Reddy from the Centre for Chronic Control and PHFI. The investigators were supported by a US National Institutes of Health grant to establish 1 of 7 GEOHealth hubs around the world in India. The main objectives were to obtain a robust exposure assessment ($PM_{2.5}$) at fine resolution, link exposure to CV risk factors and outcomes, and build capacity in the science of air pollution for Indian researchers. Given the contextual and topical relevancy of air pollution, the goal of the project was to establish a fully integrated research and training program on air pollution and cardiometabolic diseases with policy relevance to improve the health of Indians.

Prabhakaran reviewed the results from the main objective to link $PM_{2.5}$ levels to incident CVD risk factors and outcomes in Delhi. The objective is complete for Delhi and Chennai. To assess exposure, a unique "ensemble" exposure model was developed to predict daily $PM_{2.5}$ concentrations at a fine spatial resolution (1 km^2) for Delhi. The city was divided into a total of 1635 grids and data were collected for 7 years (2010-2016) or a total of 2557 days. In sum, 4180695 observations were collected. The air quality data in Delhi came from multiple sources. The Central Pollution Control Board is the regulatory authority in India that collaborates with the Ministry of Environment to establish ground monitoring stations. However, the distribution of the monitoring stations is inequitable throughout the large country. Delhi has 25 monitoring stations that monitor pollutants for daily average $PM_{2.5}$ and PM_{10} concentrations. Satellite data were also collected to obtain AOD, vegetation index, ultraviolet emissions, and active fire information. Emission inventories provided data on grid level area emissions for $PM_{2.5}$ and accounts for industries and brick kilns. Meteorological data such as temperature (air and dewpoint), relative humidity, wind speed, precipitation, cloud cover, evaporation, and soil temperature were also collected. Lastly, land use information including length of roads and runways, built up areas, ward-level population density, and locations of bus stops, bus terminals, railway stations, markets, malls, industries, power plants, and solid waste dumpsites were assessed. The data were used for the "ensemble model."[51] The model used monitoring data, satellite data, land use variables, chemical transport variables, and adjusted for meteorological variables to predict daily average $PM_{2.5}$ concentrations at a fine spatial resolution over the state of Delhi, India from 2010 to 2016. The model showed a clear seasonal pattern with air quality worsening in the winter months from November to February.

The modelled data allowed analyses of associations between exposure to $PM_{2.5}$ in Delhi and various health outcomes from the CARRS cohort. The association between long- and short-term ambient $PM_{2.5}$ exposure predicted from the model and longitudinally measured blood pressure and incident hypertension in Delhi was evaluated.[52] In this study, 3296 individuals were evaluated from 2248 households with 3 BP measures over a period of 7 years. Results indicated long- and short-term exposure to elevated PM concentrations were associated with increased BP and risk of developing hypertension. For every 25 μ/m^3 increase of $PM_{2.5}$, blood pressure increased by 3.5-5mmHg depending on body mass index. Average systolic and diastolic blood pressure increased per interquartile increase in $PM_{2.5}$, which has an interaction with central adiposity (waist, hip).

Given that high blood pressure is an important risk factor of cardiovascular disease, reducing ambient air pollution is likely to have meaningful clinical and public health benefits, said Prabhakaran. The findings suggest that ensuring national ambient air quality standards could potentially decrease the prevalence of hypertension by 15% in urban Delhi. These results have implications for health care access and delivery. The health system is already overburdened, and poor air quality brings more people into the system for blood pressure management. She suggested that policymakers should be apprised about how health effects of air pollution are impacting cities, because policy interventions can have major benefits for treating sick populations. Further analysis is ongoing to evaluate the relationship between $PM_{2.5}$ and fasting plasma glucose, hemoglobin A1C, and other cardiovascular risk factors in Delhi and Chennai.

2.8.4 Personal exposure monitoring study

Prabhakaran reviewed a personal exposure monitoring study that aimed to characterize personal exposure of $PM_{2.5}$, black carbon, and heavy metals among a subset of 100 adults from the CARRS longitudinal cohort. Participants belonged to various age and socioeconomic groups residing in Delhi. The group included a diverse range of professions encapsulating the profile of the working class with more than 40 occupations listed. In addition, participants were from urban and rural Delhi including slum, JJ Colony, and non-slum neighborhoods. Smokers and pregnant individuals were excluded from the study. Sampling was completed for two 24-hour periods in summer and winter using a backpack worn by participants equipped with a personal air pollution monitor (DataRAM™ pDR-1500 Aerosol Monitor) along with a GPS-enabled tri-axial accelerometer. $PM_{2.5}$ exposure differed based on activity. For example, the activity and $PM_{2.5}$ exposure profile of one office assistant

51 Mandal et al 2020
52 Prabhakaran et al 2020a

in New Delhi during summer 2019 monitored her during commute, work, cooking and sleeping time. In general, the participant's exposure was increased during traveling and cooking and lower during work and sleep. Results also found varied personal $PM_{2.5}$ exposures across occupations with the informal sector experiencing worse exposure than housewives or the formal sector. Exposures were even different between individuals of the same household. For example, a wife had significantly higher exposures than her husband secondary to living in a one-room tenement while regularly using unclean cooking fuels. Although this type of study is resource intensive, the results can be greatly insightful for understanding exposure within a population.

2.8.5 Capacity building initiatives

Prabhakaran explained that as a part of the GEOHealth hub program, capacity building initiatives were introduced that aimed to establish a critical mass of environmental health researchers and policymakers in India. Short-term initiatives included 1-2-week training programs for faculty and health system professionals which established student/researcher exchange programs with various national and international institutions. Short-term training courses started in 2016, with topics ranging from study methods and modelling for air pollution, climate, and health to NASA's short course on satellite-based exposure assessment. Plans for transitioning some of the course material into an online-based model are being made for more course self-sustainability. More than 300 beneficiaries from many national institutions including medical colleges, universities, research organizations, government institutions, and think tanks have taken part in the short-term training. Most participants are from a public health or medical background with master's level or higher training, but a variety of disciplines are represented in the student profiles. Participants from the Bangladesh and Ghana GEOHealth hubs have also attended courses, and joint programs are planned in the coming years. Medium-term initiatives included pilot grants for young researchers/faculty at PHFI and TISS, short-term exchange programs, career development workshops with national and international experts, and aid in the development of evidence informed policy. Finally, long-term goals involve developing an integrated MPH/PhD program in environmental health and establishing systematic evidence for multiple exposures and health impacts.

2.8.6 Future directions

Prabhakaran described future projects, including the nationwide expansion of the $PM_{2.5}$ model. The Consortium for Health Effects of Air Pollution in India (CHAIR-India) was established in May 2019 with the aim of expanding the model built for Delhi and Chennai to the whole of India.[53] The consortium includes Harvard T.H. Chan School of Public Health, Centre for Chronic Disease Control, Centre for Environmental Health, Public Health Foundation of India, Karolinska Institute, Ben-Gurion University of the Negev, and Boston University. The vision is for exposure scientists and health researchers to collaborate in establishing a national $PM_{2.5}$ model on a 1 × 1 km grid surface providing daily predictions between 2008 and 2020 in rural and urban areas to expand the evidence of ambient air pollution health effects. The model will be linked up with existing ongoing or completed health cohorts including those for maternal and child health, cardiovascular health, pulmonary health, diabetes and metabolic health, and cognitive function.

The consortium also won a grant to start the Climate, Health and Air pollution Research Study in India (CHAIR-India) to address gaps in achieving sustainable development goals. Its aim is to develop a nationwide exposure model for daily ambient $PM_{2.5}$ and ambient temperature from 2008-2020 at a spatial resolution of 1x1 km and locally at 200x200 m to assess the interactions between heat and flooding. The research will link exposure data to health data to quantify the independent and joint associations between $PM_{2.5}$ and ambient temperature to the following major public health endpoints: total mortality, cardiometabolic outcomes, and lung function outcomes. Other health outcomes

53 Prabhakaran et al 2020b

will be assessed from the multiple studies and research groups in the CHAIR consortium. A public website will also be made with environmental data on a 1x1 km grid that can be used by planners, policy makers and the general public to increase awareness and aid in decision-making. During the research, a dedicated communications strategy will be used to engage with key stakeholders to increase the efficiency of the project, disseminate results well beyond the scientific community and facilitate translation of project deliverables into policy action.

In sum, the CHAIR consortium model results will be highly relevant to Indian environmental health policy. The open-source $PM_{2.5}$ model could accelerate research activity by granting access to $PM_{2.5}$ predictions, temperature, greenspace, population data, and land use data. It is anticipated that the model will facilitate public health planning and interventions, increase public awareness, and develop capacity building through training programs.

Prabhakaran concluded by highlighting research areas of concern related to air pollution and health in India. Overall, there is a lack of access to data and funding. Sustainability also remains an issue of concern, however, the consortium's success will hopefully contribute significantly to sustainable development. The final area of concern is capacity building. Despite initiatives, job creation strategies and integration for both public health and environmental sciences is needed to balance the demand and supply ratio in the field of air pollution epidemiology. This ensures that all trained professionals are usefully contributing.

2.8.7 Question

Souzana Achilleos asked about causes of the increasing PM levels in India. Prabhakaran explained the rise in PM is due to a combination of factors. In addition to an increasing population, India has undergone rapid industrialization. Fossil fuel combustion also contributes as it is still the primary source of electricity (70%). Air pollution causes differ between cities, but other common factors include vehicular pollution, construction and demolition dust, industrial, and household pollution.

3 Air pollution regulations

3.8.1 Air quality and health in the Eastern Mediterranean region: predictions and regulations

Mazen Malkawi, environmental health regional advisor at WHO Eastern Mediterranean Region Office's Regional Center for Environmental Health Action, reviewed air quality and health with a focus on predictions and regulations in the Eastern Mediterranean Region. The region consists of 22 countries—spanning from Afghanistan in the east to Morocco in the west—and comprises a population of 670 million people living in diverse socioeconomic conditions. However, countries in the region share an arid climate with high levels of indoor and ambient air pollution.

3.8.2 Sources for indoor and outdoor air pollution in the Eastern Mediterranean region

Malkawi described how data for sources of outdoor air pollution in the region are based on WHO's database of ambient air quality collected from 202 urban areas in 14 Eastern Mediterranean countries. There are gaps in air quality data in the region, and there is a lack of published source apportionment studies in the region. He noted that the WHO Database of Source Apportionment Studies, which consists of data from 194 countries—including the 22 countries of the Eastern Mediterranean region—is being updated for a new air pollution Health Impact Assessment for 2021. A composite model from satellite data and chemical models is used to bridge the gap in data in areas that do not monitor air quality. The exposure data are being used to estimate the health impacts of air pollution. Up to 50% of the outdoor air pollution is natural (ie, dust and sea salt). 50% or more of outdoor pollution sources are anthropogenic, including transport, power generation, industry, and waste burning—particularly agricultural waste burning. Transportation accounts for 80% of air pollution in some of the region's large cities, such as Tehran, Iran. Malkawi explained that some political tension has arisen around the belief that dust is harmless and can be deducted from the PM_{10} or $PM_{2.5}$ measurements. Epidemiological evidence does not support this belief; rather, epidemiological evidence suggests that natural dust may affect health in the same manner as other pollutants. Thus, the entire mixture of natural and anthropogenic pollutants is poisonous, and all pollutants should be included in pollution measurements.

Malkawi explained that indoor air pollution is chronic in the Eastern Mediterranean region. In the least developed countries in the region, the use of solid fuels and kerosene for cooking, heating, and lighting is a major source of indoor air pollution. 180 million people in the region rely on solid fuel for cooking and heating, and the number of people relying on kerosene and other dirty fuels is unknown. The WHO Eastern Mediterranean Regional Office aims to collect data on the use of kerosene and update WHO's database. He emphasized that other sources of air pollution, including secondhand tobacco smoke, construction materials, furniture, and incense burning, are often neglected. These sources of air pollution are not monitored, reported, or included in WHO's Health Impact Assessment.

3.8.3 Air pollution and public health risk

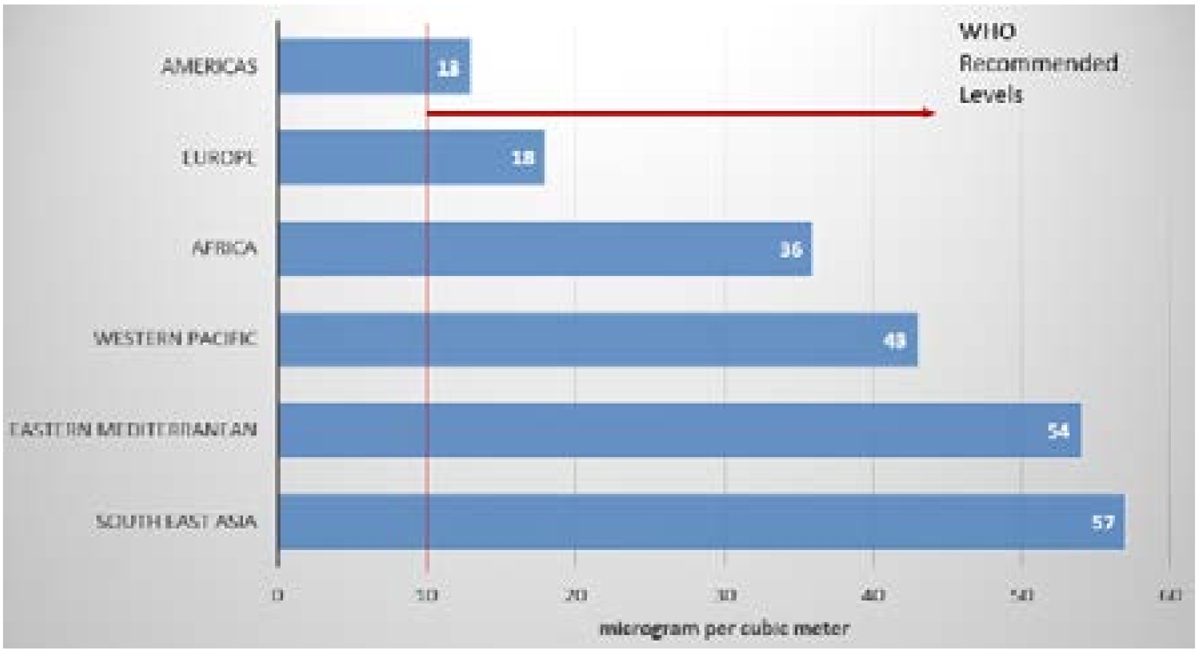
Malkawi discussed the impacts of air pollution on public health. In 2018, WHO estimated that air pollution causes 50% of deaths from pneumonia in children aged <5 years, 36% of deaths from lung cancer, 35% of deaths from COPD, 34% of deaths from stroke, and 27% of deaths from heart disease.[54] The figures are based on hundreds of epidemiological studies that were systematically reviewed in preparation for the Health Impact Assessment. A causality relationship has been established through published systematic reviews.

54 More information about the burden of disease from the joint effects of household and ambient air pollution is available from https://www.who.int/airpollution/data/AP_joint_effect_BoD_results_May2018.pdf (accessed July 15, 2021).

Malkawi explained that air pollution is a major risk to public health in the region. Because of heightened air pollution rates, he suggested that the public health risk associated with air pollution in the Eastern Mediterranean region tmay be the highest of any region in the world. In 2018, WHO conducted a Health Impact Assessment of the joint effects of indoor and outdoor air pollution around the world.[55] They found that 493,000 deaths in the region were attributable to air pollution. In 2020, the Institute for Health Metrics and Evaluation reported 589,000 premature deaths secondary to exposure of indoor and outdoor air pollution.[56] WHO is expected to publish updated air pollution data in 2021. He predicted that these data would reveal an even higher number of deaths attributable to air pollution.

Malkawi compared the mean urban air pollution of $PM_{2.5}$ in the Eastern Mediterranean region with other regions of the world as per Sustainable Development Goal (SDG) 11.6. In 2018, the Eastern Mediterranean region is the second highest in the world after Southeast Asia, with air pollution that is almost five times the WHO recommended level (see Figure 3-1). The data are expected to be updated in 2021. Malkawi continued by comparing the proportion of population with primary reliance on clean fuels and technologies by country in the region (SDG 7.1). Many countries in the region—including Somalia, Djibouti, Afghanistan, Pakistan, Sudan, and Yemen—are highly reliant (>95%) on unclean fuels for cooking in the household. He reiterated that the region is socioeconomically diverse, and the mortality attributed to indoor and outdoor air pollution disproportionately affects the least developed, poorest countries (see Figure 3-2). In addition, those countries with higher mortality also tend to experience other types of emergencies as well.

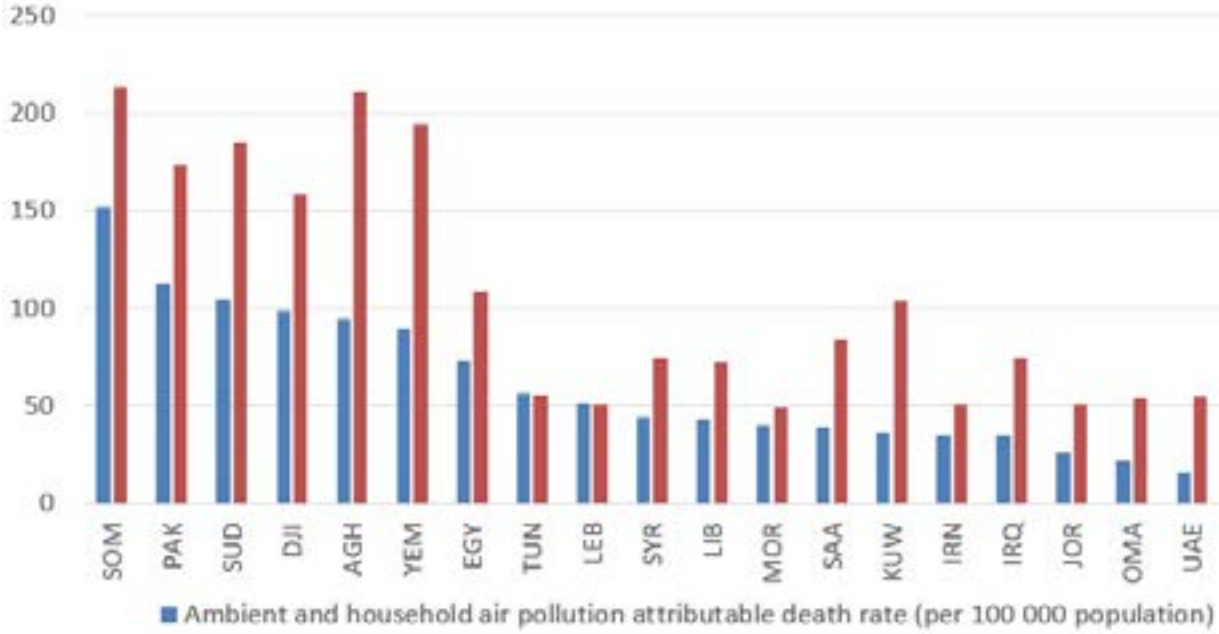
Figure 3-1. Mean urban air pollution of particulate matter ($PM_{2.5}$) by world region (2018)



Source: Malkawi presentation Source: Malkawi presentation

55 More information about the joint effects of air pollution is available at https://www.who.int/data/gho/data/themes/topics/indicator-groups/indicator-group-details/GHO/joint-effects-of-air-pollution (accessed April 14, 2021).
56 More information about the State of the Air report is available from https://vizhub.healthdata.org/gbd-compare/ (accessed April 14, 2021).

Figure 3 2. Mortality attributed to indoor and outdoor air pollution in the Eastern Mediterranean region (2018)



Source: Malkawi presentation

3.8.4 WHO assessment of ambient air quality standards by region

A 2017 publication analyzed the status of the ambient air quality standards in the six WHO regions.[57] It compares air quality standards around the world with WHO guidelines. Of the 21 countries included from the Eastern Mediterranean region, only 11 (52%) have standards in place for at least one pollutant, although those standards are not necessarily in compliance with WHO standards. The other 48% are either without standards or no information could be found. Other regions have greater percentages of countries with standards for at least one pollutant: Europe (94%), Americas (57%), and Southeast Asia (64%).

Malkawi discussed country compliance with WHO recommendations for the classical pollutants $PM_{2.5}$, PM_{10}, NO_2, SO_2. To illustrate, he focused on the $PM_{2.5}$ 1-year average. Only 62 of 194 countries have standards, of which, only six (3%) countries are in line with the WHO recommended air quality guidelines for $PM_{2.5}$.

3.8.5 Impact of climate change on air quality in the region

Malkawi emphasized that climate change and air quality are related, with climate change worsening air quality in the region.[58] Natural dust is a major component of the air pollution. The duration and frequency of dust is increasing. Climate change is an important potential driver of future wind erosion and sand and dust storm risk, especially the occurrence of more extreme wind events and movement to drier climates, but reverse effects are also possible. Simulations suggest that global dust emissions have increased by 25% to 50% over the last century due to a combination of land use and climate changes. This increase is mostly in the Eastern Mediterranean region. Sand and dust storm frequency and severity have increased in recent decades in some areas but decreased in

57 Kutlar Joss et al 2017
58 UNEP 2016

other areas. Climate change projections suggest that regions that are currently dusty areas and which are likely to become drier include most of the Mediterranean areas of Europe and Africa, northern Sahara, central and west Asia, southwest USA, and southern Australia. As a recent example, Malkawi referenced the latest dust event that covered Europe. In some of the countries of the region, the number of dusty days is exceeding 200, underscoring the need for more health impact and epidemiological research. He pointed out that dust storms of 1000s of μg/m^3 drive people indoors, so there should be a focus on the indoor environment in addition to the ambient levels.

Air quality management actions and policies are still far below the optimal levels that controls air pollution in the region, said Malkawi. The common gaps and challenges faced include:

- poor monitoring, lack of available data and communication mechanisms
- poor commitment at the political level
- poor coordination between the different related sectors
- lack of health-based standards, and policies and information in almost all countries of the region

He noted that a holistic approach of dealing with air pollution is needed to achieve tangible effects. In addition, it is problematic that most monitoring of standards is not based on health outcomes.

After WHO issued the global roadmap for addressing health impact of air pollution, the Eastern Mediterranean region developed a plan of action in response.[59] The plan of action takes into consideration the regional context, including climate and local air pollutants, as well as the availability of monitoring data, the status of national surveillance systems, and policies for controlling air pollution. He stated that health data are missing along with air quality data. Moreover, the region faces difficulties in measuring health outcomes. The plan is linked to relevant targets of the SDGs and considers developments as opportunities for synergies at global and regional levels, including: the Paris Agreement on Climate Change (2015),[60] Marrakech Declaration on Health, Environment and Climate Change (2016)[61], and the Arab Strategy on Health and Environment 2017–2030.[62]

3.8.6 Discussion

Petros Koutrakis commented that he sympathizes with the challenges of resources, the size of the region, lack of commitment and understanding, and other problems facing the region. He recognized that the challenges are large and hoped the scientific community would assist with providing data or in some other capacity.

Malkawi was asked to comment on why Somalia has air pollution levels below the WHO recommendation, yet has the highest mortality due to air pollution. He replied that some countries have a dual burden of indoor and outdoor pollution, but only the ambient air quality is primarily known in most countries. For example, in Somalia, more than 90% of the population uses solid fuel for cooking and heating, which greatly impacts health. The data shared are for the combined effect of indoor and outdoor air pollution. He suggests that the ranking of the countries would be different if ambient air pollution were analyzed separately.

Achilleos was asked about evidence regarding the relationship between the particulate health effects and source-specific PM. She responded that there have been studies looking at the health effects of source-specific PM,

59 More information about the Eastern Mediterranean region's plan for responding to the adverse health effects of air pollution is available from https://applications.emro.who.int/docs/RC_technical_papers_2017_inf_doc_3_20013_en.pdf?ua=1 (accessed July 15, 2021).

60 More information about the Paris Agreement is available from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed May 4, 2021).

61 The Marrakesh Ministerial Declaration on Health, Environment and Climate Change is available from https://www.who.int/globalchange/mediacentre/events/Ministerial-declaration-EN.pdf (accessed May 4, 2021).

62 More information about the Arab Strategy on Health and Environment 2017–2030 is available from http://www.emro.who.int/ceha/ceha-news/summit-of-arab-league-adopts-arab-strategy-on-health-and-the-environment.html (accessed May 4, 2021).

finding that the effects are similar to those seen in studies of general PM. She noted that the association may be different depending on the source. John Vanderberg added that studies have been conducted on US sources that aimed to determine if certain source types are of greater concern than others. Results showed that from a national perspective, the best indicator for controlling PM is simply mass—that is, not a specific mass such as mass of metals or sulfates. He noted that some metals of considerable concern (eg, lead and chromium) come from various sources and are present as PM.

Vanderberg was asked to remark on black carbon. He stated that the power industry, which emits sulfates and nitrates creating PM, would likely blame traffic as the source of health problems. In opposition, the traffic industry attributes the power plants as the source of health problems. He emphasizes that both industries have exposures of concern. Therefore, it is a balancing act that has driven the US toward a mass-based standard at the national level regardless of sources (eg, metals, black carbon, sulfates).

Malkawi noted that over the last five years, WHO have been working to update their air quality guidelines based on the best-available evidence, including two commissioned systematic reviews. One review focused on partial toxicity—that is, if dust differs from other pollutants—and the other review on black carbon. He said that the guidelines would be published in April 2021; however, there is not strong evidence to support the contention that black carbon is different from dust. Rather, the entire mixture of pollutants is toxic. He remarked that the Eastern Mediterranean region wanted a different result to mitigate the impact of dust. The natural inclination is to believe, for example, that silica is different than other chemicals. The recent IHME impact assessment came to the same conclusion, he added.

3.1 Connecting air quality research, risk assessment and policy: US air quality management

John Vandenberg, retired division director at US Environmental Protection Agency (EPA), Health and Environmental Effects Assessment Division, Center for Public Health and Environmental Assessment, reviewed US air quality management with a focus on air quality research, risk assessment, and policy. He presented the US air quality management framework as an example of how science can inform regulatory decisions, as well as describing actions that can be taken to protect public health, with an emphasis on ozone and hazardous air pollutants. He noted that the US approach is only one method of air quality management.

3.1.1 Framework and approaches to air quality management

Vandenberg presented the US framework for air quality management based on the 1970s Clean Air Act Amendments. In this framework, air quality standards are established with the aim of achieving those standards. Environmental conditions are measured using monitoring studies, modelling studies, and emission inventory information to compare conditions to air quality standards and determine air pollution sources. If air pollution control is necessary, then responsibility is delegated to the states to address stationary and mobile sources to meet standards. The EPA employs enforcement and compliance measures and tracks trends in air pollution, cost and benefits, and other information useful for decision makers. He emphasized that health and environmental effects research, exposure research, and atmospheric science and engineering inform the air quality management process (Figure 3-3).

Varying standards are used in the US, depending upon the type of pollutant in question, Vandenberg explained. Criteria air pollutants have ambient standards based on air concentration measured in micrograms per cubic meter ($\mu g/m^3$), parts per million (ppm), or parts per billion (ppb). The six criteria air pollutants are tropospheric ozone (O_3), $PM_{2.5}$, PM_{10}, lead (Pb), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO). PM_{10} is coarse PM, such as the dust commonly found in the Middle East, and $PM_{2.5}$ is fine PM, commonly generated from combustion processes. Hazardous air pollutants have emission standards based on what is emitted from emission sources (eg, chemical plants), and for pollutants associated with acid deposition (sulfur dioxide and nitrogen oxides) a market-based approach is used to control these sources. Vandenberg noted that a broader climate approach can be used to manage air quality; however, these large-scale approaches are not within the purview of the Clean Air Act. Instead, such measures would be implemented through global treaties and agreements.

Figure 3-3. Framework for air quality management

Source: Vandenberg presentation

3.1.2 Approach 1: ambient standards for criteria air pollutants

Vandenberg presented data on the number of people living in areas with air quality concentrations above the level of the US NAAQS in 2019.[63] For the criteria air pollutants there are many decades' worth of data from extensive air quality monitoring, with more than 1,000 sites operating at present. In 2019, approximately 82 million people in the US lived in counties with one or more air quality concentrations above NAAQS. Ozone was the most common criteria pollutant found, affecting nearly 74 million people.

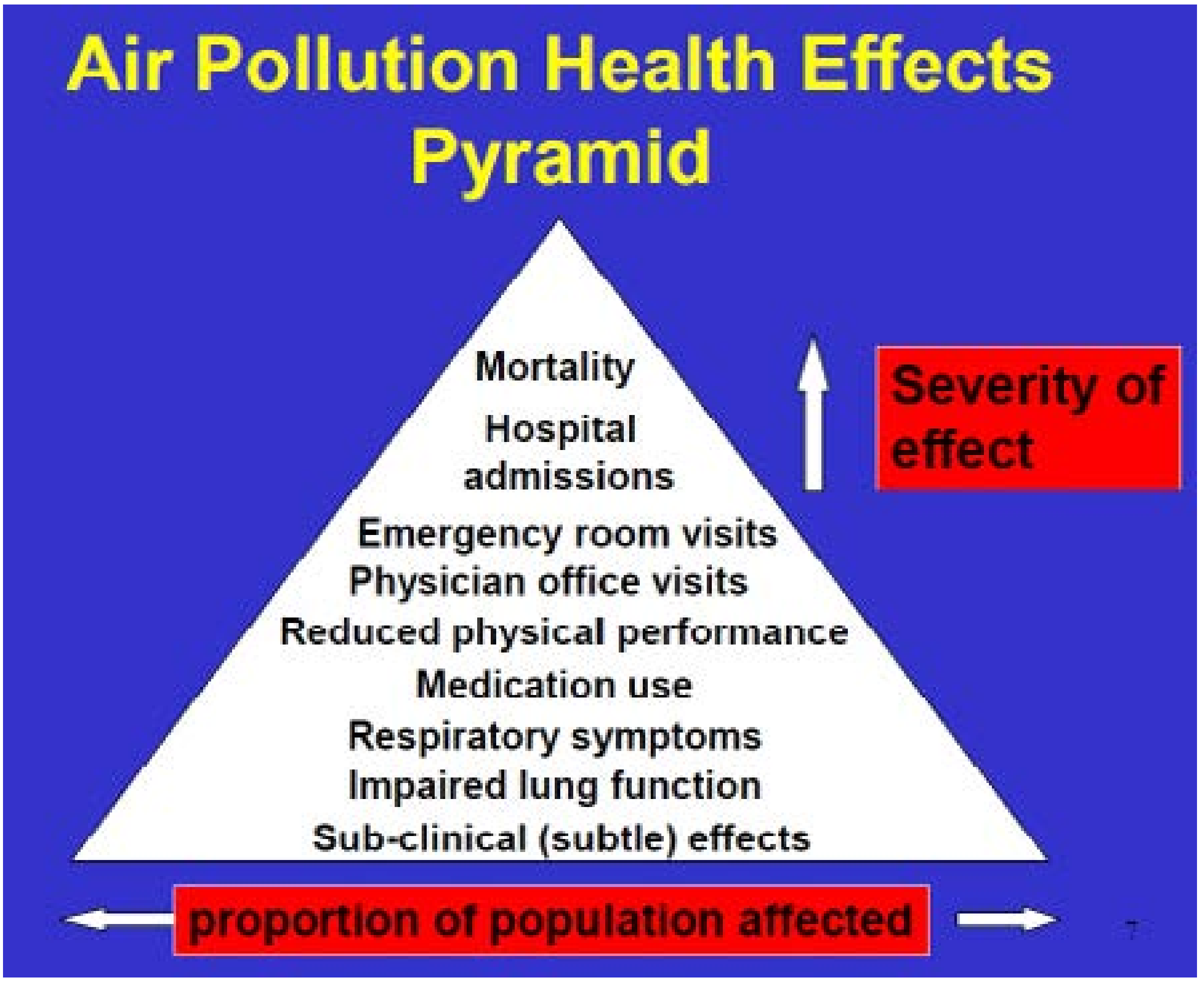
In the pyramid model of air pollution health effects, the severity of air pollution effects is inversely related to the proportion of the population affected (see Figure 3-4). Vandenberg explained that the effects of air pollution are often subclinical, and individuals who are not extremely physically active may not become aware of impaired lung function caused by

63 More information about the Air Trends Report is available at http://epa.gov/airtrends/aqtrends.html (accessed April 15, 2021).

such subclinical effects. Air pollution can cause numerous respiratory symptoms, including cough and sore throat, increased medication use, reduced physical performance, and increased use of medical services (physician office visits, emergency services, and hospital admission). Among a small proportion of the affected population, the health effects of air pollution may culminate in mortality.

Vandenberg also described how scientific evidence is evaluated and used to determine causality. First, a systematic review of the available worldwide studies is conducted for broad outcome categories. A standardized approach is used to evaluate, characterize, and extract the data from those studies. The evidence is then integrated across disciplines for outcome categories. The elements that determine causality directly inform one another. For example, atmospheric chemistry directly informs exposure science which in turn informs dosimetry, epidemiology, animal toxicology, etc. The causality determinants are developed for human health outcomes and welfare (ie, the environmental effects of air pollution) using an established framework. Evidence is then synthesized for populations potentially at increased health risk, including those with preexisting conditions, children, and the elderly. This strategy assures protection to the population at large by protecting the most at-risk and sensitive individuals.

Figure 3-4. Air pollution health effects pyramid



Source: Vandenberg presentation

3.1.2.1 Determining air pollution health effects

Vandenberg expanded on the types of evidence used to determine air pollution health effects, using evidence on the effects of ozone exposure as an example. The respiratory effects from short-term exposure to ozone arise from a range of potential biological pathways (see Figure 3-5). Information from various experimental or epidemiologic sources is consolidated to understand how exposure results in health outcomes. For short-term ozone exposure, controlled human exposure studies provide experimental evidence for ozone-induced lung function decrements.[64] He noted that some of the studies used are older than might be desired, but these studies are the most recent studies available. Cross-study comparisons of mean decrements in ozone-induced forced expiratory volume in 1 second (FEV_1) in young, healthy adults following 6.6 hours of exposure to ozone show a positive, curvilinear relationship between amount of ozone (ppb) and FEV_1 decrement. Some studies show a 2%-4% reduction in FEV_1 with exposure to around 60 ppb, which is less than the current ozone ambient standard of 70 ppb in the US.

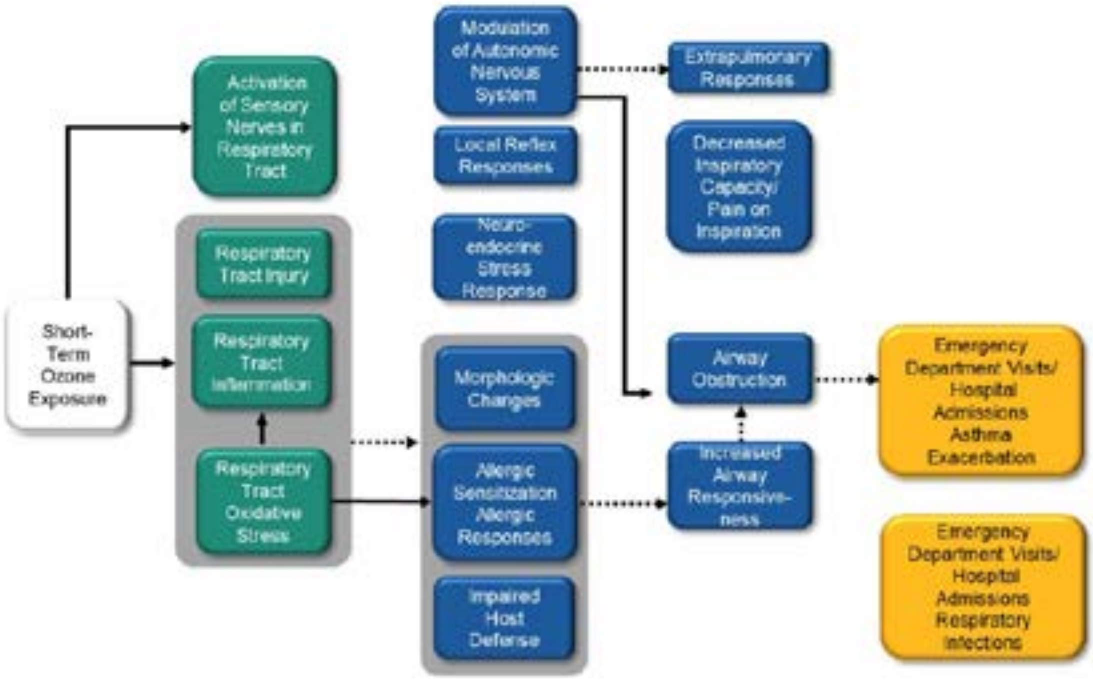
Epidemiology is also used to determine air pollution health effects, said Vandenberg. For example, the Integrated Science Assessment for Ozone and Related Photochemical Oxidants found a significant increase in respiratory, asthma, COPD, and pneumonia-related hospital admission and emergency department visits associated with ozone exposure.[65] He noted that exposure science, controlled human exposure studies, and epidemiology are employed together to determine air pollution health effects and inform air quality policy. The EPA also examines the quality of evidence for casual determinations. For example, the quality of evidence has been assessed for the causality determinations for health effects of short- and long-term exposure to ozone.[66] The EPA has rated evidence for respiratory health outcomes from short-term ozone as "causal." The causality determination of respiratory health outcomes and long-term ozone exposure is "likely causal." Evidence for metabolic health outcomes and short-term ozone exposure is also "likely causal." The causality determinations for cardiovascular, neurologic, reproductive, cancer, and mortality health effects of short- and long-term exposure to ozone are "suggestive." The causality determination for short-term exposure on cardiovascular health outcomes has been changed from "likely causal" to "suggestive" due to new evidence. This change demonstrates that causality determinations can change over time as new evidence becomes available. In October 2015, the ozone primary standard—protection for human health—was lowered from 0.075 ppm to 0.070 ppm; the secondary standard—protection for public welfare—was equivalent to the primary standard. In December 2020, the 2015 NAAQS for ozone were upheld.

Vandenberg summarized the approach for criteria air pollutants:

- The goal is to achieve and maintain levels of exposure that meet the NAAQS which are set with an adequate margin of safety.
- Criteria air pollutants come from numerous and diverse stationary and mobile sources.
- Cost is not considered when setting standards—only health and welfare outcomes. However, cost can be considered in implementing control programs. For example, decision makers can determine stricter controls for power plants versus automobiles.
- In the US, each state is responsible for its air quality management programs, and a variety of tools are implemented by the states to meet standards.

64 More information available at www.epa.gov/isa (accessed April 17, 2021)
65 More information is available at https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=247492 (accessed June 17, 2021).
66 More information is available at www.epa.gov/isa (accessed April 19, 2021).

Figure 3-5. Potential biological pathways for respiratory effects following short-term ozone exposure



Notes: Solid lines denote evidence of essentiality as provided by experimental studies involving ozone exposure. Dotted lines represent non-essentiality connections.
Source: Vandenberg presentation, www.epa.gov/isa

3.1.3 Approach 2: emission standards for hazardous air pollutants (air toxics)

The Clean Air Act defines hazardous air pollutants as pollutants that increase mortality or serious irreversible or reversible incapacitating illness. Emission standards are set to protect public health with an ample margin of safety, which differs from the adequate margin of safety employed for criteria air pollutants. The Clean Air Act Amendments of 1990 list 188 chemicals as hazardous air pollutants; these were determined by a political and scientific process.[67] The chemicals have a variety of adverse health outcomes, including non-cancer and cancer effects. Non-cancer biological endpoints result in multiple adverse outcomes and include reproductive, developmental, neurologic, and immunologic effects, acute changes (eg, edema and central nervous system depression), and various systemic damage to the liver, kidneys, and lungs. For example, lead toxicity leads to neurological and developmental changes (lead is also a criteria air pollutant). Cancerous biological endpoints include mutations and DNA damage, which result in uncontrolled growth of cells. Hazardous air pollutant outcomes differ from criteria air pollutants, which primarily cause pulmonary, cardiovascular, and mortality effects. One study evaluated the 188 hazardous air pollutants and their impact on health outcomes.[68] The study recorded the number of compounds reported to produce effects in humans or animals. In addition, the time frame of effects

67 The Clean Air Act Amendments of 1990 list of hazardous air pollutants is available at https://www3.epa.gov/ttn/atw/orig189.html (accessed June 4, 2021).
68 EPA 1993

was recorded, including acute (ie, less than 24 hours), sub-chronic (ie, up to 10% of the lifespan), and chronic durations. The results were most significant for respiratory, neurological, and developmental adverse health outcomes.

Vandenberg explained how risk assessment is conducted for hazardous air pollutants. An exposure assessment is used to identify the source of chemical release. A fate and transport analysis enables the modelling and monitoring of chemical concentrations in air, soil, water, and food. Chemical concentrations and population characteristics from census data are used to estimate exposure. Concurrently, toxicity assessment identifies health outcomes and evaluates the dose/response relationship. The exposure and toxicity assessment data facilitate risk characterization with quantitative and qualitative expressions of risk/uncertainty. Cancer risk analyses can also be used to inform regulatory decisions. Under the Clean Air Act Amendments of 1990, standards for lifetime cancer risk from exposure to carcinogens were established. If the risk for cancer is below 1 in 1,000,000, then the risk is considered to be acceptable. If the risk exceeds 1 in 10,000, then the risk is not acceptable, and action must be taken to reduce the risk. Frequently, the cancer risk for hazardous pollutants is within the acceptable risk range. States determine whether additional controls are necessary to reduce exposure and health risks. Vandenberg remarked that the process by which hazardous air pollutants are managed is complex. These pollutants can cause adverse health outcomes and are a serious public health concern.

Vandenberg summarized the approach for hazardous air pollutants in the US:

- The pollutants were listed by Congress and are identified from more than 100 different source categories including pulp mills, paper mills and oil and gas exploration.
- National Emission Standards for Hazardous Air Pollutants are generated, and emissions limits are applied. The standards are based on Maximum Achievable Control Technology (similar to "best-available control technology").
- Residual risks are evaluated to ensure protection of public health with an ample margin of safety.

Vandenberg affirmed the value of air pollution management, noting that in 2017, the US Office of Management and Budget reported that (1) the rules created by the EPA's Office of Air and Radiation have the highest benefits and costs and (2) the reduction in public exposure to fine PM can be attributed to these rules.[69] He emphasized the importance of air quality, especially the $PM_{2.5}$ standards that protect public health.

3.1.4 Determination of criteria versus hazardous air pollutants

Petros Koutrakis asked how specific chemicals are categorized as either criteria or hazardous air pollutants. Vandenberg explained that the original set of criteria pollutants included chemicals contributing to photochemical smog. Ozone was then identified as the key indicator. However, the criteria air pollutants have changed over time. Particulate matter changed from total suspended PM to PM_{10} and then $PM_{2.5}$ was added, as new evidence indicated particle size reflected varying sources and health outcomes. The chemicals have changed, but the typical six criteria air pollutants have not changed. A political process determines which pollutants are consistent with the phrasing of "emitted from numerous or diverse stationary and mobile sources." Benzene, for instance, could be consistent with this phrasing, and benzene is commonly emitted from automobiles, oil production, and gas exploration, but it has not been added to the list of criteria air pollutants by EPA. The list of hazardous air pollutants has largely remained the same with only a few deletions and one addition since 1990. He asserted that the system has worked well without

69 More information about the 2017 Report to Congress on the Benefits and Costs of Federal Regulations and Agency Compliance with the Unfunded Mandates Reform Act is available at https://www.whitehouse.gov/wp-content/uploads/2019/12/2019-CATS-5885-REV_DOC-2017Cost_BenefitReport11_18_2019.docx.pdf (accessed June 4, 2021).

changes and suggested that efforts be directed toward addressing air quality within existing frameworks, rather than working to change the framework. Koutrakis remarked that the original ambient standards for criteria air pollutants focused on respiratory effects. In contrast, the emission standards for hazardous air pollutants focus on cancer, cognitive, reproductive, and developmental effects. At the time, the adverse health outcomes could have provided a distinction, but new evidence suggests PM also causes developmental and cognitive effects. He noted that the overlap of comparable adverse health outcomes is growing. Vandenberg noted that lead is considered both a criteria and hazardous air pollutant, which was partially due to the neurological effects of lead exposure in children.

3.2 Day 1 Closing remarks

Garshick noted the need to identify next steps for parts of the world experiencing high $PM_{2.5}$ levels and other pollutants. He raised the question of whether it may be necessary to repeat certain studies, particularly those demonstrating local effects, before making efforts to reduce the level of pollution. Some pollutants, such as dust, are more prevalent in certain regions, and these pollutants can be studied more widely.

Koutrakis remarked that studying pollution and air quality is exceedingly challenging. Still, optimism may be warranted as new tools are becoming available, such as remote sensing and retrospective assessments, which is particularly relevant in regions without a history of air quality monitoring. Koutrakis expressed his hope that these efforts will continue, and that these data will be made available to scientists in the region so that they can study health effects. Currently, the field is using standards developed in the US and Europe to regulate a region of 1 billion people with unique genetic makeups, distribution of comorbidities, climate (especially extreme heat), and composition of aerosols. While research has historically focused on western countries, it is important that future research be conducted in the MENA region so that policies can be better tailored to this particular setting, especially in the Gulf area, where pollution is particularly problematic and international cooperation may be necessary. Koutrakis noted that political conflicts in the region may stymie a coordinated approach. One of the goals of the webinar was to connect people from across the region and foster international collaborations. Given the disproportionate level of global disease burden in the MENA area and in Southeast Asia and the looming threat of climate change, it is imperative that action be taken to address the environmental drivers of disease in these regions.

4 Health effects of air pollution and climate change

4.1 Day 2 Opening remarks

Petro Koutrakis, professor of Environmental Sciences at Harvard School of Public Health, remarked that much work is still needed to fully understand the air quality of the MENA region, but recent studies conducted to investigate source apportionment in Qatar and Kuwait show great promise. He expressed his belief that more research will soon be conducted to understand the sources of air pollution, transboundary pollution, the effects of climate change on air quality, and other issues that must be addressed so that policymakers can make informed decisions.

The second day's presentations were set to focus on the health effects of air pollution. As recently as 10 years ago, it was thought that dust storms did not represent a health risk because dust particles were natural and people have lived in the desert for thousands of years. However, it has since been confirmed that dust can be toxic, serving as a vector for microorganisms, metals, and radioactive particles that should be considered environmental threats. The threat of climate change to the MENA region poses an additional challenge.

4.2 Air quality and health

Eric Garshick, associate chief of Pulmonary, Allergy, Sleep, and Critical Care Medicine Section at VA Boston Healthcare System and Professor of Medicine at Harvard Medical School, explored the health effects of air pollution with a focus on PM. He opened by providing a historical perspective on the health effects of air pollution. He described the London Fog in December 5-9, 1952, as the major sentinel event linking PM to increased mortality. Kuwait City during a sandstorm was compared as "the modern-day London Fog." Contributing factors to the London Fog included (1) the use of coal, oil, and coke combustion for heating, (2) diesel buses replacing electric trams in July 1952, and (3) a temperature inversion in London. During the event, there was a positive correlation between the concentration of smoke and sulfur dioxide in the air and subsequent deaths.[70] In a week, there were an estimated 4,500 excess deaths; mortality remained elevated for about 3 months after the fog, with an estimated 13,500 excess deaths from December 1952 to March 1953. Compared to November 1952, deaths reported in December increased 14-fold for bronchitis, 12-fold for influenza, 5-fold for pneumonia, and 3-fold for heart disease. He noted there was no influenza epidemic at the time to explain these winter deaths. Using modern imaging, carbonaceous aggregates (≤ 0.1 μm) and ≤ 1.0 μm inorganic particles were found in all lung compartments of archived tissue samples, indicating that the lungs were overloaded with carbonaceous air pollution particles.

Garshick presented a study on mortality and long-term exposure to particulate air pollution from the extended follow-up of the Harvard Six Cities study.[71] Mortality was examined in 6 US cities using a central site monitor during period 1 (1979-1989) and period 2 (1990-1998). During period 1, the city-specific mortality risk was associated with $PM_{2.5}$ concentration. The city with the highest $PM_{2.5}$—Steubenville, Ohio—had a decrease from 40 μg/m^3 to approximately 25 μg/m^3 in 1979-1998. Cleaner cities (eg, Portage, Wisconsin and Topeka, Kansas) ranged from 10 to 15 μg/m^3. In period 1, the overall and cardiovascular mortality risk per 10 μm/m^3 $PM_{2.5}$ increased to 1.18 and 1.28, respectively. Additionally, there was evidence suggestive of increased respiratory and lung cancer mortality risk. The study also indicated an improvement in health if increased $PM_{2.5}$ levels were mitigated. The reduction in $PM_{2.5}$ levels from period

70 Bell et al 2004; Hunt et al 2003
71 Laden et al 2006

1 to period 2 was associated with reduction in overall mortality of 27% in addition to a reduction in respiratory and cardiovascular mortality risk. He noted that other studies also show evidence for the benefits of reducing $PM_{2.5}$ levels and remarked that the $PM_{2.5}$ levels in the Harvard Six Cities study are significantly below levels found in the Middle East's exposure assessment.

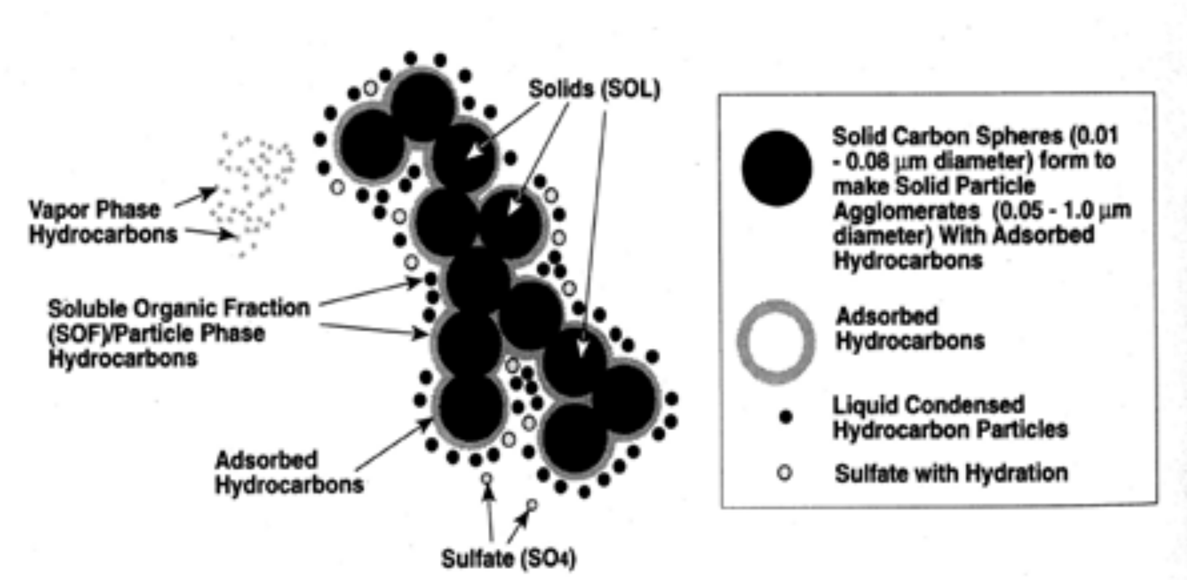
4.2.1 Particle deposition and clearance

Garshick explained the structure of air pollution particles from combustion sources with a schematic (see Figure 4-1). These particles consist of solid carbon spheres (0.01-0.08 µm) that coalesce into larger solid particle agglomerates (0.05-1.0µm). The agglomerates are less than a micron and frequently are in the ultrafine range. The carbon-based particles are coated with organic carcinogenic compounds, metals, and other chemicals. Carbon particles are thought to act as a vector for other chemicals and metals into the lower respiratory tract. Measurement of ambient black carbon concentration can be used as a measure of exposure to particles of combustion origin.

Garshick discussed where particles deposit by considering the respiratory tract into the nasopharyngeal, tracheobronchial, and alveolar regions. Size determines where particles deposit.[72] Ultrafine particles deposit in the nasopharyngeal area. Particles ≤1 micron in size deposit both in the tracheobronchial and alveolar region. Furthermore, the deposition location of $PM_{2.5}$ (<2.5 µm) is likely responsible for its toxicity.

Garshick also reviewed particle clearance mechanisms.[73] There is evidence from animal studies that ultrafine PM (<0.1 µm) can be transported to the brain from the nose via an olfactory pathway. In the airway region, PM approximately 1-10 µm is cleared relatively rapidly (within 24-48 hours) by mucociliary transport and airway macrophages (ie, scavenger cells). In the alveolar region, particles reside from >48 hours to months and are cleared by alveolar macrophages and particle translocation across the alveoli into the lymphatics and blood. The particles can be transported to other organs, a pathway that is hypothesized to promote systemic effects of particulate air pollution. For example, recent studies have demonstrated carbonaceous PM in placental tissues.

Figure 4-1. Combustion particle air pollution



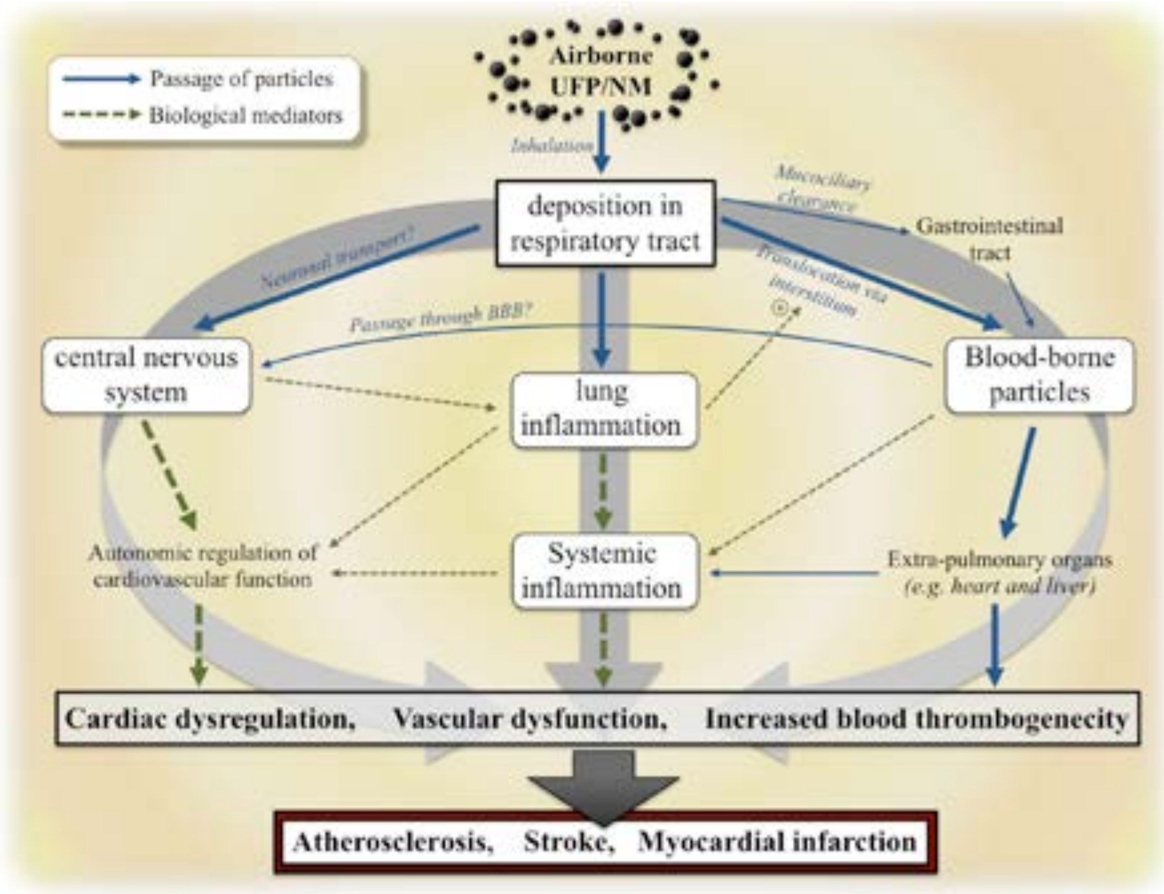
Source: Garshick presentation, Health Effects Institute 1995

72 Moller et al 2008; Moller et al 2004; Nemmar et al 2002; Oberdorster et al 2005; Schmid et al 2009; Stone et al 2017
73 Nemmar et al 2002

4.2.2 Mechanisms of particle toxicity

Garshick presented a model for PM toxicity mechanisms after deposition in the respiratory tract (see Figure 4-2). There are three potential pathways that may result in adverse effects: central nervous system transport, lung inflammation, and translocation into blood from the lung. Lung inflammation presumably promotes systemic inflammation that could also promote systemic effects. Cardiac arrhythmia studies suggest that inhaled PM may cause dysregulation of autonomic nervous system regulation of cardiovascular function via sympathetic receptors resulting in cardiac dysregulation. Systemic inflammation may also be associated with cardiac dysregulation, vascular dysfunction, and increased clotting. Increased blood thrombogenicity can also contribute to by bloodborne particles causing systemic effects. These mechanisms culminate in cardiovascular complications such as atherosclerosis, stroke, and myocardial infarction.

Figure 4-2. Key mechanisms of PM toxicity



Notes: UFP = ultrafine particles; NM = nanometer
Sources: Garshick presentation, Stone et al 2017

4.2.3 Health outcomes

4.2.3.1 Short-term (daily) mortality

Garshick discussed ambient particulate air pollution ($PM_{2.5}$) and daily mortality by describing the results of a study conducted between 1986 and 2015 that included 652 cities in 24 countries.[74] The countries that contributed the most data were China (272 cities) and US (107 cities). Little data were collected from the Middle Eastern region. The $PM_{2.5}$ annual median was 31.9 μm/m^3 with a wide range of 4.1-116.99 μm/m^3 (IRQ 21.5 - 43.5). Based on a 2-day average of $PM_{2.5}$, all-cause mortality increased 0.55% (0.45-0.66) per 10 μm/m^3. Cardiovascular and respiratory mortality increased 0.68% (0.59-0.77) and 0.74% (0.53-0.95), respectively. An increase in mortality associated with $PM_{2.5}$ was also observed in 2-pollutant models with $PM_{2.5}$ that included ozone, nitrogen dioxide, and sulfur dioxide. He presented a graph that demonstrated a curvilinear relationship between $PM_{2.5}$ concentrations and percentage increase in daily mortality with a plateau at the height of the curve at concentrations of 100-150 μm/m^3. Mortality increased continuously over the entire range of $PM_{2.5.}$ studied, a range that included the WHO (25 μm/m^3), China Air (75 μm/m^3), and US (35 μm/m^3) air quality standards. Evidence indicates no minimum threshold for $PM_{2.5}$'s effect on short-term mortality.

4.2.3.2 Disease development

4.2.3.2.1 Cardiovascular disease

Evidence indicates that $PM_{2.5}$ contributes to the progression of atherosclerosis, said Garshick. A meta-analysis of 5 US trials with 1,483 subjects noted an increase in carotid artery intima-media thickness over 5 years positively associated with $PM_{2.5}$ concentrations.[75] In these studies, the thickness of the common carotid arteries (ie, major blood vessels in the neck that supply blood to the brain) was measured with ultrasound using a standardized method. The mean $PM_{2.5}$ for the population was relatively low, at 20.8 μm/m^3. Results demonstrate that IMT progression was related to both $PM_{2.5}$ (p=0.08) levels and by living within living 100 meters from a highway (p=0.04), a finding that suggests links between $PM_{2.5}$ and progression of atherosclerosis. In addition, a coronary artery calcification score measured via CT imaging can be used to predict risk for coronary artery disease.[76] The MESA air study was a large (n=5,834) US study spanning 10 years that found that increased coronary artery calcification scores (total area/density) were related to long-term average $PM_{2.5}$ levels. There was a positive, continuous relationship between $PM_{2.5}$ concentrations and coronary artery calcification scores.

4.2.3.2.2 Reduced FEV1 and chronic obstructive pulmonary disease

Garshick stated that greater concentrations of $PM_{2.5}$ are linked to pulmonary disease. Pulmonary function testing (ie, spirometry) includes measuring forced expiratory volume over the first second (FEV1) and forced vital capacity (FVC). FEV1 is the amount of air that an individual can forcibly blow out in one second after a full inhalation. FVC is the total amount of air that can forcibly be blown out after full inhalation. A reduction in FEV1/FVC is a characteristic of airflow obstruction. The UK Biobank study from 2006-2010 assessed people aged 40-69 years (n=303,887) using spirometry and $PM_{2.5}$ estimates from a land use regression model (2010) linked to home addresses.[77] The results showed a decrease in FEV1 (-83.1 ml; 95%CI -92.5-73.8) for every 5 μg/m^3 increase in $PM_{2.5}$ as well as a decrease in FVC and FEV1/FVC. COPD prevalence (defined by a FEV1/FVC ratio below the lower limit of normal) was associated with higher concentrations of $PM_{2.5}$ (OR 1.52, 95% CI 1.42-1.62, per 5 μg·m-3). Garshick also discussed the Framingham study from Massachusetts, USA as one of the few longitudinal studies available.[78] FEV1 and FVC were measured up to two times between 1995 and 2011 for 6,339 people. The pulmonary function data were linked to a satellite-based $PM_{2.5}$ land use regression model. The results showed a 13.5 ml (95% 26.6 to 20.3) lower FEV1 and 2.1

74 Liu et al 2019a
75 Kunzli et al 2010
76 Kaufman et al 2016
77 Doiron et al 2019
78 Rice et al 2016

ml/year (95% CI -4.1 to -0.2) faster decline in FEV1 for every 2 μg/m^3 increase in average $PM_{2.5}$.

4.2.3.2.3 Lung cancer

Garshick explained that $PM_{2.5}$ in outdoor air pollution and diesel exhaust were designated as Group I lung carcinogens by the International Agency for Research on Cancer (IARC) in 2013 and 2012, respectively. Other Group I carcinogens include smoking and asbestos. From 14 studies, IARC estimated an increased lung cancer mortality risk of 1.09 (95% CI 1.04-1.14) per 10 μg/m^3 of outdoor $PM_{2.5}$ exposure.[79] The risk was greater in studies that assessed incident lung cancer cases; 6 studies observed an increased lung cancer incidence risk of 1.25 (95% CI 1.12-1.40) per 10 μg/m^3 of outdoor $PM_{2.5}$ exposure.

Garshick also discussed quantitative, exposure-response risk estimates for diesel engine exhaust and lung cancer mortality with a meta-regression of three studies that includes coal miners and trucking industry workers.[80] The relationship between cumulative exposure to elemental carbon (representing the carbon core of combustion particles) and lung cancer mortality is curvilinear. Higher estimates were observed in coal miners with exposure to underground diesel engines. He noted that truck drivers would have similar exposures as the general population while driving on the highway. For environmental exposures, assuming an average exposure of elemental carbon of 0.8 μg/m^3 over 80 years (with a 5-year exposure lag), there were 21 excess lung cancer deaths per 10,000 individuals. The average exposure of 0.8 μg/m^3 is relatively low compared to some occupational exposures and exposures in the dirtiest cities around the world. He added that because of these data, many countries such as India are phasing out diesel engines in light-duty vehicles.

4.2.3.2.4 Diabetes

Diabetes is a major point of discussion in the Middle East and is linked to $PM_{2.5}$ exposure. Garshick reviewed two meta-analyses which found a positive association between $PM_{2.5}$ and new-onset diabetes. A meta-analysis in 2019 found a prevalence odds ratio (OR) of 1.09 (95% CI 1.05-1.13) per 10 μg/m^3 using data from 11 studies and an incidence OR of 1.10 (95% CI 1.04-1.16) per 10 μg/m^3 using 12 studies.[81] A second meta-analysis in 2020 found similar results with a prevalence OR of 1.08 (95% CI 1.04-1.12) and an incidence OR of 1.10 (95% CI 1.04-1.17) from 11 studies per 10 μg/m^3.[82] The latter study also found that glucose homeostasis was impaired among diabetics with a 0.05-24.7 mg/dl increase in fasting blood glucose per 10 μg/m^3 of $PM_{2.5}$.

4.2.4 Susceptibility

Garshick considered which populations are more susceptible to air pollution. The risk factors for susceptibility are unclear—although age is likely a risk factor—and additional studies are needed to determine the vulnerability of those with underlying diseases associated with systemic inflammation or other comorbidities. He presented data from the VA Boston COPD study that demonstrated that large studies are not necessary to provide insight into the biology of the health effects associated with particulate air pollution.[83] The study was conducted between 2012-1017 and included 144 patients with physician-diagnosed COPD (FEV_1/FVC ratio <0.70 or emphysema by clinical CT scan), ≥10 packyear cigarette smoking history, and age ≥40. Black carbon in $PM_{2.5}$ was measured in subject's homes (in the room where they spent the majority of their time) using a home particle sampler over the course of a week up to four times seasonally over a year. Current smokers were excluded; therefore, indoor black carbon was primarily a measure of infiltrated outdoor black carbon. After the completion of sampling, spirometry and blood testing including plasma C-reactive protein (CRP) was obtained. CRP is a protein synthesized mainly by hepatocytes in response to an inflammatory stimulus, has a half-life of 18-20 hours, and is a marker of

79 Hamra et al 2014
80 Vermeulen et al 2014
81 Liu et al 2019b
82 Yang et al 2020
83 Garshick et al 2018

cardiovascular risk. He discussed the effect of black carbon on CRP in COPD patients with concurrent statin[84] use and diabetes. Effect estimates for CRP were larger among non-statin users compared to statin users for all black carbon exposures. CRP increased by approximately 20% among non-statin users per interquartile range increase in black carbon. Participants with diabetes also had a greater increase in CRP for all black carbon exposures compared to participants without diabetes. The results suggest that black carbon has greater effects on systemic inflammation (CRP) in persons not taking statins and among those with diabetes. The anti-inflammatory effects of statins may be a way to mitigate some effects of pollution.

4.2.5 Summary

Garshick summarized key conclusions from his presentation:

- Fine particulate air pollution has pulmonary, cardiac, and systemic effects that results in illness and increased mortality.
- Most influential studies to date have not been conducted in the Middle East or India.
- The mix of pollutants that includes a contribution of desert dust unique to the region and pollutants from vehicles and industrial sources are likely adversely affecting the health of persons in the region. Thus, there should be a focus on mitigating and studying the effects further.

4.2.6 Discussion

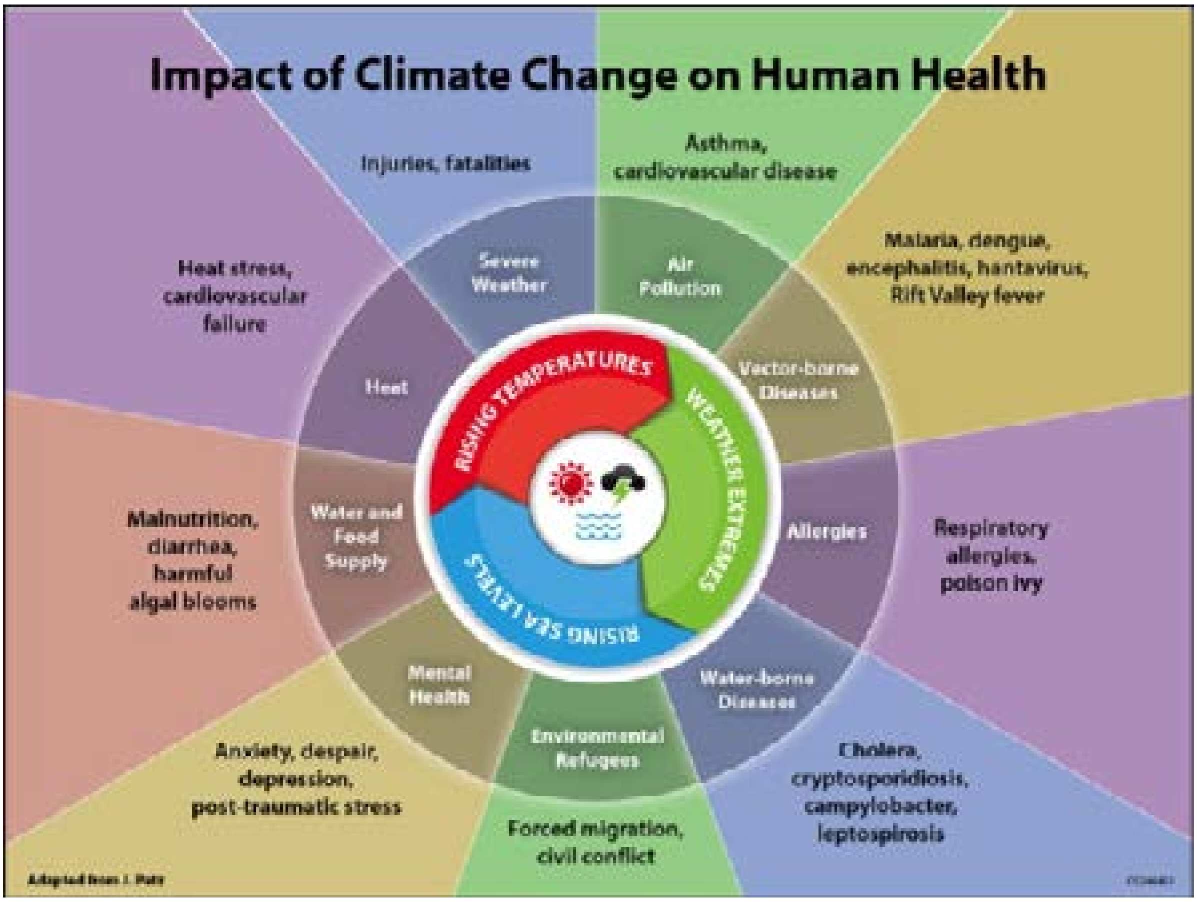
A participant asked whether PM impacts mucociliary beat frequency and/or rhythm and, if so, whether it caused by direct and/or indirect inflammation. Garshick replied that he did not have a specific answer; however, COPD patients have reduced airway clearance of PM. Increased inflammation and mucus in airways from cigarette smoking results in reduced ciliary activity and particle clearance. He is unsure if a person with normal airway clearance and cilia who is exposed to PM would have reduced ciliary beat.

4.3 Climate change and health in inherently hot regions: the case of Kuwait

Barrak Alahmad, physician, PhD candidate in Population Health Sciences specializing in environmental health at the Harvard T.H. Chan School of Public Health, Mission Scholar from the Faculty of Public Health in Kuwait University, focused on climate change and health in inherently hot regions, using Kuwait as a case study. He opened by presenting a graphic from the US Center for Disease Control and Prevention (CDC) to illustrate the numerous pathways by which climate change can impact health (see Figure 4-3).[85] The most significant climate change stressors—such as rising temperatures, extreme weather events, and rising sea levels—can influence health outcomes through a number of pathways: severe weather, air pollution, vector-borne disease, allergies, water-borne diseases, environmental refugees, mental health, water and food supply, and heat. Heat is a particularly important factor in health outcomes in the Middle East. He also reviewed a different schema for how climate change affects health from the Intergovernmental Panel on Climate Change.[86] Human health is affected by indirect and direct impacts. Indirect impacts are mediated through ecosystem-mediated factors like air pollution that affect health, while direct impacts relate primarily to increasing outside temperatures resulting in heat exposure which will result in significant adverse health outcomes.

84 Statins are drugs that reduce cardiovascular risk.
85 More information from the CDC about the impact of climate change on human health available at https://www.cdc.gov/climateandhealth/effects/default.htm accessed April 25, 2021
86 https://www.ipcc.ch/report/ar5/syr/

Figure 4-3. Impact of climate change on human health



Source: Alahmad presentation, https://www.cdc.gov/climateandhealth/effects/default.htm

4.3.1 Overview of heat effects

Alahmad discussed increasing temperature mean and variance due to climate change (see Figure 4-4).[87] Increasing mean temperature is often the primary focus when discussing climate change. The distribution curve of mean temperatures shifts to the right secondary to higher-than-average temperatures. The right shift leads to more exposure at the upper end of the curve. An increase in temperature variance results in wider tails/flattening of the distribution curve. In climate change, both variance and mean temperatures are increasing. For inherently hot regions, an increase in temperature mean and variance bolsters heat effects by frequency and magnitude of occurrence.

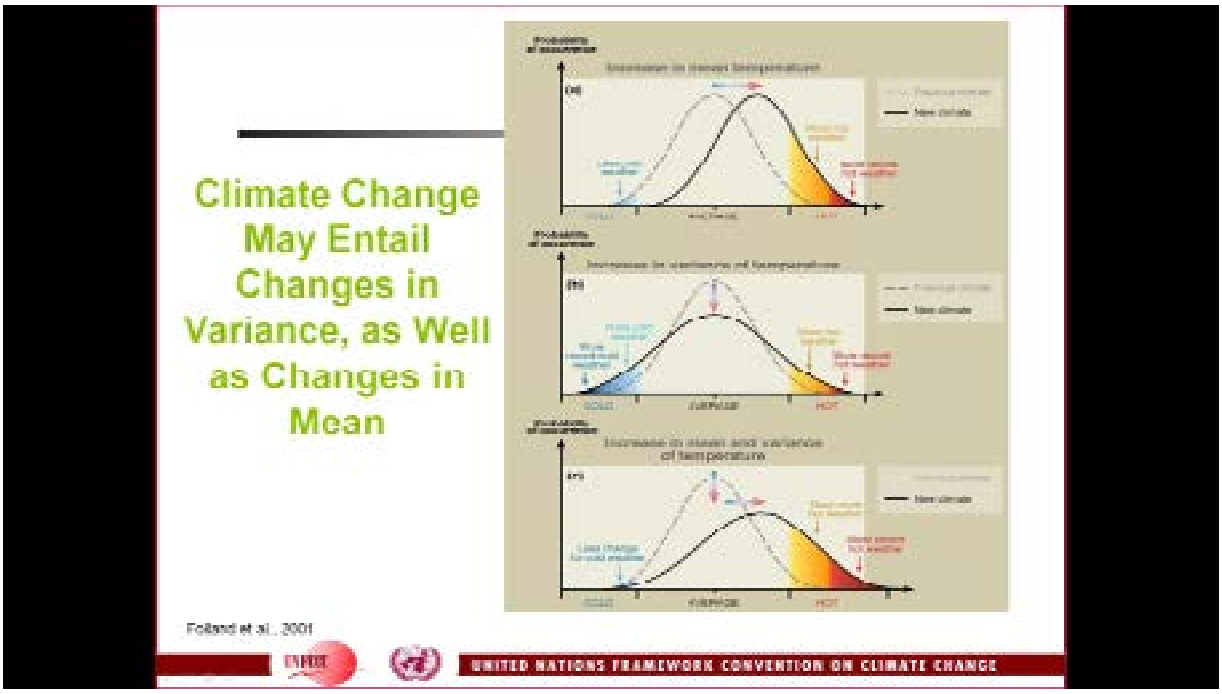
Studies have generated projections of heat effects on mortality in the Middle East. Alahmad quoted from one such study: "Under the business-as-usual scenario [continuing current emissions], our results expose a specific regional hotspot [Arabian Peninsula] where climate change is likely to severely impact human habitability in the future."[88] Thus, the authors question human habitability of the region secondary to extreme temperatures. He also quoted a second study: "Results show that the mortality risk will increase in the distant future to 8-20 times higher than that of the historical period."[89] Heat studies in the Middle East differ from European in that they examine

87 Folland et al 2001
88 Pal and Eltahir 2015
89 Ahmadalipour and Moradkhani 2018

higher magnitudes and amplified exposures in the future due to climate change, he added.

Alahmad described health endpoints commonly used in heat studies. Heat stroke is one potentially fatal, measurable outcome of heat exposure, with an ICD 10 code of T67 (effects of heat and light) or T67.0 (heatstroke and sunstroke). Death certificates require documentation of a disease or condition directly leading to death. The problem with using heat stroke as a study endpoint is twofold: (1) the diagnosis of heatstroke as a cause of death is chronically underestimated and (2) heat can exacerbate existing conditions and be a contributing factor to death and not the immediate cause of death. With the endpoint of heat stroke, a study would find few observations secondary to chronic underestimation in addition to missing deaths in which heat was the trigger but not the direct cause of death. Many epidemiological studies instead rely on total, non-accidental cardiovascular or respiratory mortality.

Figure 4-4. Increase in temperature mean and variance



Source: Alahmad presentation, Folland et al 2001

4.3.2 Heat effect in Kuwait

Kuwait is a pertinent case study due to its unprecedented temperatures, said Alahmad. The World Meteorological Organization conducted a metrological and meteorological evaluation of the 54.0°C observations in Kuwait and reported that 2016-2017 temperatures were the highest officially recognized temperatures recorded in 76 years.[90] The extreme temperatures and arid region of Kuwait led to a study on the effects of temperature on short-term mortality risk.[91] The study compared the 99th percentile temperatures (average 42.7°C) with the optimum (ie, associated with the least

90 Merlone et al 2019
91 Alahmad et al 2019

mortality) temperature (32°C) resulting in the relative risk of total, non-accidental death of 1.65 (1.09 – 2.46) or a 65% increase in mortality risk. When comparing the 97.5th percentile to the optimum, the relative risk of total death was 1.42 (1.03 – 1.95). He noted that reducing the percentile threshold evidences some attenuation, but risk of mortality remains elevated.

Alahmad then discussed a study on how heat exposure affects cardiovascular mortality in Kuwait and implications for climate change.[92] The study compared the 99th percentile temperature with optimum temperature resulting in a relative risk of cardiovascular death of 3.09 (95% CI: 1.72-5.55). The cardiovascular mortality risk is double to triple on days with 99th percentile temperatures compared to the optimum temperature in the country. The mortality risk is calculated using historical temperature data from 2010-2017. He suggested that the relationship between predicted future temperatures due to climate change and mortality risk should be studied further.

4.3.3 Susceptibility to temperature in Kuwait

Alahmad discussed a study on vulnerability to temperature-related mortality in Kuwait.[93] Heat studies from other parts of the world cannot be generalized to the Middle East because of varying vulnerable subpopulations. Factors that affect susceptibility include prevalence of disease and composition of the population (eg, gender, age, nationality). Indeed, the vulnerable subpopulations themselves may change over time. To illustrate the need for local contextualization in heat studies, Alahmad explored the Middle Eastern vulnerable subpopulations of males, elderly, non-Kuwaitis (mainly migrant workers), and people with cardiovascular disease that have an increased risk mortality from extreme heat.

The study found that the risk of death from heat exposure was significantly high among males. Previous studies in other parts of the world have shown different gender risk patterns including similar risk between males and females, higher risk among males, and higher risk among females. This indicates that susceptibility by gender could be contextual based on geographic and socioeconomic factors. In Kuwait, culture and gender norms can play a role in determining outdoor exposure (including choice of clothes and staying indoors).

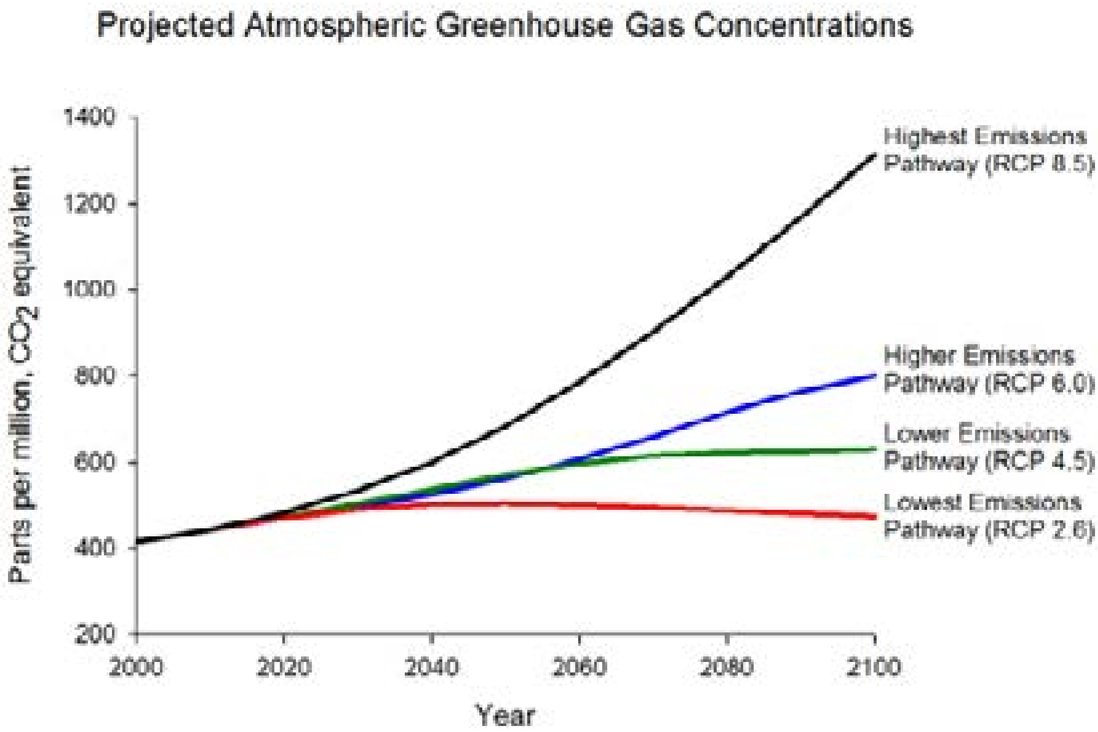
Moreover, the risk of death from heat exposure was also significantly high among the non-Kuwaiti subpopulation composed mainly of male laborers within working age, who are more likely to work physically demanding labor with higher exposure to heat. Higher susceptibility in non-Kuwaitis was also seen in a previous study on poor air quality effects and dust storms which found a higher risk of death in non-Kuwaiti males.[94] Thus, nationality is an important effect measure modifier in Kuwait. To emphasize the need for local contextualization, Alahmad presented population pyramids for Kuwaitis, non-Kuwaitis and total groups.[95] The Kuwaiti population pyramid is expansive and consistent with a developing country. The non-Kuwaiti population pyramid shows a significant increase in middle-aged, working-age men. Finally, the total population pyramid is reflective of the combination. A time series study on only the total population may miss fine distinctions of susceptibility such as the location of heat effects or which subpopulations are more vulnerable. Nationality is a unique effect modifier common to Middle Eastern countries such as Bahrain, Qatar, UAE and, to a lesser extent, Saudi Arabia. In contrast, it may not be a significant effect modifier in European or South Asia regions. Hence, the local context is important in understanding the effects of heat on mortality amid climate change.

92 Alahmad et al 2020a
93 Alahmad et al 2020c
94 Achilleos et al 2019
95 Data are from the Public Authority for Civil Information, Government of Kuwait

4.3.4 Temperature mortality projections

Alahmad discussed temperature mortality projections in Kuwait by first explaining which emissions pathway was used for the estimate. The IPCC produced four projections of atmospheric greenhouse gas concentration based on different emissions pathways (see Figure 4-5).[96] The highest emissions pathway, representative concentration pathway (RCP) 8.5, is analogous to current emission levels. The lowest emissions pathway is RCP 2.6. The lower emissions pathway, RCP 4.5, was used for a study on temperature mortality projections in Kuwait from 2021-2060 based on it being the most optimistic and realistic scenario.[97] The study compared the observed (historical temperature data) and modelled (predicted) temperature distribution patterns. The results demonstrated that the global models overestimate cold temperatures and underestimate high temperatures in Kuwait. The historical data was used to calibrate RCP 4.5-based temperature predictions. Projections in Kuwait indicated a mean temperature increase under RCP 4.5 of 1.84°C by 2060, which is higher than the Paris Agreement target of 1.5°C. The projections were then used to estimate the effect on mortality using several other assumptions. The 2051-2060 future period under RCP 4.5 was compared to the 2006-2016 historical period, which predicted 2.95% excess mortality from heat attributable to climate change.

Figure 4-5. Projected atmospheric greenhouse gas concentrations



Note: RCP = representative concentration pathway
Source: Alahmad presentation

96 US EPA
97 Alahmad et al 2020b

4.3.5 Need for Middle Eastern collaboration

Alahmad highlighted the rationale for supporting Middle Eastern collaboration on climate change. He acknowledged the many differences in the region but emphasized the similarities in exposure distribution. First, there are uniquely vulnerable subpopulations common in the region and more studies are needed on identifying them. Second, decision makers need more information on climate change to make interventions in the interests of public health protection. Third, collaborating on growing the literature in the Middle East may broadly improve the understanding of climate change and its effect on health, especially in regard to heat in this region. Finally, collaboration is needed to develop the science to support climate adaptation plans to fulfil the commitment made in the Paris Climate Accord.

4.3.6 Conclusion

In the hot and hyper-arid Middle Eastern region, it is problematic that population health data are not abundantly available while temperatures increase to unprecedented record high levels. Moreover, vulnerabilities to temperatures are being uncovered in a region that is overshadowed by the question of human inhabitability by the end of the century due to extreme heat. Alahmad emphasized that serious questions about environmental injustices that could be exacerbated by climate change need to be addressed by policymakers—for example, the vulnerability within the migrant worker population. In addition, alarming evidence is emerging on cardiovascular mortality from heat exposure. Lastly, more research is needed in the region on the links between climate change and health.

4.4 Desert dust and respiratory health effects

Panayiotis Yiallouros, pediatric pulmonologist, professor of pediatrics at the University of Cyprus Medical School, head of the respiratory physiology laboratory and the primary ciliary dyskinesia service at the University of Cyprus, project coordinator of LIFE MEDEA project, and work package leader in other projects focusing on respiratory disease and public health, presented on desert dust storms and short-term respiratory outcomes, focusing mostly on a systematic review of the available data. He explained the findings of this review including associations of desert dust exposure and respiratory mortality and morbidity such as hospital admissions, emergency department visits, all respiratory, asthma, COPD, and pneumonia, as well as the cumulative and chronic effects of dust on health.

4.4.1 Desert dust and short-term respiratory outcomes

Desert dust is shown to be repeatedly associated with health effects across different populations, said Yiallouros. The most frequently observed and assessed are respiratory and cardiovascular effects. Respiratory outcomes range from subtle respiratory symptom changes to increased morbidity indices (eg, hospital admissions, emergency department visits) and respiratory mortality. Based on past narrative literature reviews, the direction and magnitude for the association between desert dust and respiratory health effects was inconclusive.

In 2020, a Japanese systematic review and meta-analysis was conducted on the relationship between Asian dust and various health outcomes.[98] It examined dust days versus non-dust days—without considering different PM_{10} concentrations—by reviewing the available literature since 1980, which included 89 articles for the qualitative assessment and 21 for the meta-analysis. The impact of desert dust on all-cause (11 studies), circulatory (9 studies), and respiratory (7 studies) mortality across different lags showed a significant effect on respiratory mortality, especially on lag 3 (or Day 3 after the dust event). The impact of desert dust on hospital admission for respiratory disease, asthma, pneumonia, and ischemic heart disease/acute myocardial infarction was also evaluated. Lag 3 was also significant and had the most profound associations in the pooled analysis for respi-

98 Hashizume et al 2020

ratory disease, asthma, and pneumonia. Yiallouros summarized the evidence from Asian dust storms as "a positive association between Asian dust exposure and mortality and hospital admissions for circulatory and respiratory events. However, the number of studies included in the meta-analysis was not large and further evidence is warranted. Furthermore, a variety of definitions of Asian dust, study designs, confounder controls, and model specifications have been applied in the original studies that makes appraisal of the evidence difficult."[99]

4.4.2 Systematic review of available data on respiratory health effects of desert dust across the world

Yiallouros discussed a systematic review of the literature from the University of Cyprus Medical School on respiratory health effects of desert dust storms across the world aiming to critically appraise and synthesize the relevant evidence. The search strategy involved four electronic databases (PubMed, Global Health Database, Embase, Web of Science) using an algorithm with keywords to search available literature from database inception until July 2020. After screening and selecting eligible articles, a total of 42 studies were included in the qualitative synthesis: 14 studies on respiratory mortality and 28 on respiratory morbidity. The median duration of data collection (assessment) was 5 years (min: 1 year, max: 14 years) and publications spanned from 2007-2018; 42% originated in Europe, 40% in the Far East, 11% in the Middle East, 5% in Australia and 2% in North America. Two designs were used for the main comparisons of respiratory outcomes: a time stratified case cross-over design using logistic regression and a time series design using Poisson regression. The time stratified case cross-over assessed the effect of dust days versus non-dust days on respiratory outcomes. The non-dust days were controls and were selected in a time stratified manner, typically by choosing a similar day of the week 7 or 14 days before or after the event. The time series design assessed change in the risk of respiratory outcome per 10-unit increase in PM_{10} during dust days. PM_{10} is the metric of particles' mass suspended in air most closely related to dust. A minority of studies calculated change in risk per interquartile range in PM_{10} concentration.

4.4.3 Desert dust and respiratory mortality

Yiallouros reviewed the main findings of the systematic review starting with respiratory mortality. Four studies investigated the effect of dust days versus non-dust days on relative risk of respiratory mortality in all ages. Three of the studies demonstrated a null relationship[100], while one study in Korea demonstrated a significant association on lag 3.[101] Five studies investigated the change in relative risk of respiratory mortality per 10 μg/m^3 increase in PM_{10} for all ages. Three studies demonstrated a null relationship[102], whereas two studies from Spain and Sicily had positive associations with significant increases in lag 1 and lags 0-5, respectively.[103]

4.4.4 Desert dust and respiratory morbidity

Yiallouros reviewed the findings on respiratory morbidity from 16 studies that assessed all respiratory outcomes, 13 studies that assessed asthma, 5 that assessed COPD, and 3 that assessed pneumonia. He noted that 67% of studies evaluated hospitalizations, 26% evaluated emergency/outpatient visits, and 7% evaluated both.

4.4.4.1 Desert dust effect on hospital admissions

Four studies assessed the effect of dust days versus non-dust days on all respiratory hospital admissions, with two stud-

99 Arnold 2020
100 Al-Taiar and Thalib 2014; Chan and Ng 2011; Johnston et al 2011
101 Lee et al 2013
102 Stafoggia et al 2016; Mallone et al 2011; Neophytou et al 2013
103 Diaz et al 2012; Renzi et al 2018

ies finding no significant association.[104] Two studies from Kuwait[105] and China[106] showed positive associations between dust days and all respiratory admissions that were significant in lag 0 and lag 4, respectively.

Five studies examined the change in risk for all respiratory admissions per 10 μg/m³ of PM_{10} (all ages). Three studies demonstrated a null relationship.[107] Two studies from Israel[108] and Spain[109] showed positive associations in lags 0 and 7, respectively.

Five studies assessed the effect of dust days on asthma hospital admissions (all ages). One study found no significant association[110] and four studies conducted in Kuwait, Taiwan, Australia, and Korea demonstrated positive associations between dust days and asthma admissions at different lags.[111] A study in Israel evaluated change in risk for asthma hospital admissions per 10 μg/m³ of PM_{10} in all ages and found a significant increase in lags 0 and 1.[112]

Three studies assessed the effect of dust days on COPD hospital admissions. One study found no significant association[113]; one study from Israel[114] found a significant increase at lag 0 and a study from Korea found a significant increase at lag 4.[115]

One study investigated the effect of dust days versus non-dust days on pneumonia hospital admissions and found a marginal positive association at lags 1 and 2.[116] Another study also evaluated change in risk for pneumonia hospital admission per 10 μg/m³ of PM_{10} and found no association in lags 0-3.[117]

4.4.4.2 Desert dust effect on emergency department visits

Four studies evaluated the effect of dust days versus non-dust days on all respiratory emergency department visits. All studies found a positive relationship at various lags ranging from 0 to 5.[118]

Three studies assessed the effect of dust days versus non-dust days on asthma emergency department visits. One study from Korea found no significant association[119] and two studies from Australia and Greece found positive associations between dust days and asthma emergency department visits at lag 0.[120]

Two studies from Korea[121] and Greece[122] evaluated the effect of dust days versus non-dust days on COPD emergency department visits, finding significant increases in lags 0 and 5 and in lag 0, respectively. Two studies from Hong Kong[123] and Greece[124] evaluated change in risk for COPD emergency department visits per 10 μg/m³ of PM_{10} in all ages, finding increased risk in lag 2 and lag 0, respectively.

A study in Greece evaluated the effect of dust days versus non-dust days on emergency department visits for all respiratory infections (including pneumonia) as well as change in risk per 10 μg/m³ of PM_{10}.[125] The relative risk when evaluat-

104 Merrifield et al 2013; Middleton et al 2008
105 Thalib and Al-Taiar 2012
106 Tao et al 2012
107 Alessandrini et al 2013; Renzi et al 2017; Tam et al 2012
108 Ebenstein et al 2015
109 Reyes et al 2014
110 Grineski et al 2011
111 Bell et al 2008; Merrifield et al 2013; Park et al 2015; Thalib and Al-Taiar 2012
112 Ebenstein et al 2015
113 Chiu et al 2008
114 Vodonos et al 2014
115 Park et al 2015
116 Cheng et al 2008M.
117 Tam et al 2012
118 Lin et al 2016; Merrifield et al 2013; Park et al 2016; Trianti et al 2017
119 Park et al 2016
120 Merrifield et al 2013; Trianti et al 2017
121 Park et al 2015
122 Trianti et al 2017
123 Tam et al 2012
124 Trianti et al 2017
125 Trianti et al 2017

ing effect of dust days versus non-dust days was 1.60 (CI: 1.35-190); the relative risk per 10 μg/m^3 of PM_{10} was not significant at 1.01 (CI: 0.99-1.04).

4.4.5 Desert dust effect on lung function and daily symptoms

Two studies from Japan evaluated the effect of dust days on respiratory symptoms and lung function. One was an observational study of adult asthma patients that used self-measured peak expiratory flow to evaluate lung function on dust days versus non-dust days, finding that lung function was significantly reduced at lags 0 and 1.[126] The other evaluated respiratory symptoms by questionnaire, which demonstrated increased symptoms on dust days.[127]

4.4.6 Cumulative effects of desert dust

Yiallouros noted that data in the available literature on the cumulative effects of desert dust on lung function are weak and limited, although two studies focusing on this issue were published in 2015. One evaluated the impact of chronic exposure to dust episodes on lung function, finding a significant inverse correlation between spirometric values and duration of inhabitation in Ilam city, West Iran as demonstrated by an obstructive pattern in 21% of participants and a mean FEV1 of 95% the predicted value.[128] He noted that the authors did not have a comparison site and compared findings to mean reference values. Another study evaluated the prevalence of upper and lower respiratory disease between the two regions of China.[129] Minqin county was the desert dust exposure region with a high desert dust burden and Pingliang City was the control region with low desert dust burden. The study found higher prevalence of outcomes such as chronic rhinitis, chronic pharyngitis, bronchitis, emphysema, pulmonary tuberculosis, and chronic cough in Minqin county. However, the study had several limitations including lack of adjustment for anthropogenic pollution at the study sites.

4.4.7 Summary of findings

Yiallouros concluded by summarizing the findings he presented on the effects of desert dust on respiratory health:

- In the last decade, knowledge of the short-term effects of desert dust on respiratory health has greatly expanded from an epidemiological standpoint.
- Some positive and few null associations have been reported, primarily for dust days and—to a lesser extent—for the association between respiratory health outcomes per 10 μg/m^3 increase of PM_{10}. Positive associations are more consistent with emergency department visits and hospitalizations and less established for respiratory mortality.
- Available studies have significant heterogeneity in study designs, desert dust event definitions, and adjustments for covariates, which at present precludes a quantitative synthesis of the existing epidemiological evidence.
- Future studies should focus on cumulative or chronic effects of desert dust, incidence of chronic diseases, and mechanisms implicated in causing harmful effects.
- Further research should focus on the effects of smaller dust size fractions and the effects of specific chemical components of desert dust on human health.
- Research findings should be linked to policy decisions and prevention measures.

4.5 Impact of desert dust on cardiovascular morbidity and mortality

Souzana Achilleos, postdoctoral research associate for LIFE MEDEA public health intervention study at Cyprus University of Technology reviewed the impacts of desert dust on cardiovascular morbidity and mortality. She explained that research on emissions from desert regions, including its atmospheric transportation, has

126 Watanabe et al 2016
127 Majbauddin et al 2016
128 Amarloei et al 2015
129 Wang et al 2016

increased over the past few decades.[130] The increase in research has been driven by enhanced recognition of the impacts dust has on climate, air quality, and human health. Many different studies have researched dust effects on morbidity and mortality; however, the available evidence from the literature is not fully conclusive.

To describe the impact of dust on the circulatory system, she differentiated between cerebrovascular and cardiovascular disease.[131] Cerebrovascular diseases refer to conditions affecting brain blood vessels and includes stroke, meningitis, and trigeminal neuralgia. Cardiovascular disease refers to conditions affecting heart blood vessels and includes myocardial infarction, heart failure, arrhythmias, hypertension, and atherosclerosis. She noted that cerebrovascular and cardiovascular diseases are generally referred to as cardiovascular diseases.

4.5.1 Literature review methodology

Achilleos presented unpublished findings from a literature review conducted in July 2020 that assessed the influence of desert dust on human health. It aimed to assess all available epidemiological studies that investigated the associated between desert dust and health effects. After identification, screening, and eligibility determination, 69 total studies were included in the qualitative synthesis. Of studies published through July 2020, 39 addressed acute cardiovascular effects of desert dust. The study designs were primarily time series or case crossovers. Of the 39 studies, 17 examined cardiovascular mortality, 21 studied cardiovascular morbidity, and one study examined both. The publication year of morbidity studies ranged from 2005-2020 with an increase in number of studies after 2012. The publication year of mortality studies ranged from 2010-2020 and frequency peaked in 2011-2012. The majority of studies examined Asian dust from the Gobi Desert located in China and Mongolia. 22 of the 39 studies originated from China, Japan, South Korea, or Taiwan with one possessing a study region of Japan, South Korea, and Taiwan. Most of the morbidity studies were based on Asian dust. 12 studies originated from Europe including Cyprus, Greece, Italy, and Spain. She noted that the Sahara Desert mostly impacts Greece, Italy and Spain; Cyprus is affected from both the Arabian Peninsula desert and the Sahara. Only three studies were included from the Middle East: one study from Kuwait on mortality effects, and one each from Iran and Israel on morbidity. Finally, two studies originated from Australia.

4.5.2 Modelling the impact of dust on human health

Achilleos reviewed how desert dust is used as an exposure metric in study models. Determining if desert dust impacts human health can be studied in different ways. The literature describes five different methodologies to determine the association.[132] Three of the most common were used in the studies included in the systematic review: (A) dust as risk factor, (B) dust as effect modifier, and (C) two-sources model (see Figure 4-6).

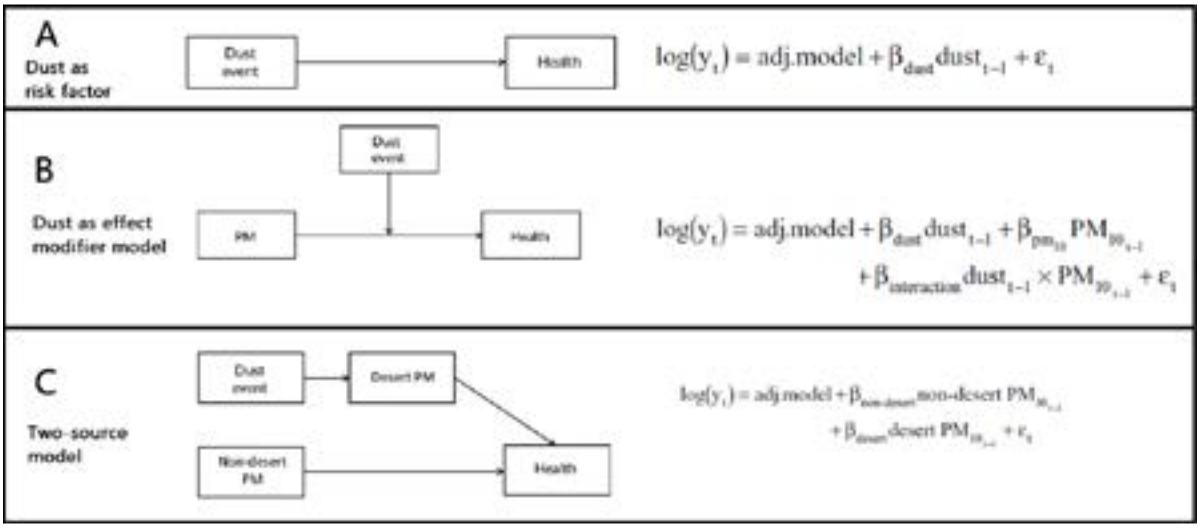
In the first two models, a binary metric is used for dust exposure. In these models, the first step is to identify desert dust events during the study period. As a binary metric, dust is defined as an indicator variable with a value of zero for non-dust days and one for dust days. In model A, the dust binary exposure variable is added to the adjustment model, which includes confounders such as day of the week and ecological variables. The analysis of the association between dust exposure as a binary metric and mortality addresses the following question: "Is mortality higher on dust days compared to non-dust days?" In model A, dust is treated as a risk factor. In model B, the binary dust exposure variable is considered an effect modifier of the association between PM and mortality. Doing so addresses the question: "Is the association between daily PM_{10} and mortality/morbidity different on dust versus non-dust days?" She noted that model B is most commonly used.

130 Domínguez-Rodríguez et al 2021
131 Zhang et al 2016
132 Tobias and Stafoggia 2020

In model C, a continuous metric is used for dust exposure. It is not frequently used in the literature; however, it is more commonly used in European and Asian studies. For dust quantification, the EU Reference Method can determine desert dust contribution to PM_{10}. It involves excluding dust days from the time series and computing a 30-day moving 40th percentile of the daily PM_{10} concentrations for each day of the series which represents the expected PM_{10} concentrations. Next, dust contribution (desert PM_{10}) is quantified by taking the difference between the observed and the expected PM_{10} concentrations for dust days. Finally, assuming the load of particles during dust days is similar or distributed equally across the area, the non-desert PM_{10} contribution can be estimated by determining the difference between PM_{10} levels and desert PM_{10}. The quantification of source-specific contributions (desert and non-desert) to total PM_{10} allows for a two-source model. Thus, the two-source model addresses the following question: "Are desert and non-desert sources of PM_{10} independently associated with mortality?"

Achilleos noted that alternative methods of dust quantification are available in other regions. For example, studies conducted in Asia use a continuous metric of Asian dust using light detection and ranging (LIDAR) observations. LIDAR is a remote sensing technology that measures Asian dust aerosols with the size of less than 10 micrometers. By measuring laser reflections from the ground, it can distinguish non-spherical versus spherical mineral dust particles from anthropogenic sources. Typically, Asian dust variables are added to the model to assess the association between Asian dust and health effects.

Figure 4-6. Three models of dust exposure metrics



Source: adapted from Achilleos presentation; Tobias and Stafoggia 2020

4.5.3 Impact of desert dust on cardiovascular mortality

Achilleos discussed epidemiological evidence on desert dust and cardiovascular mortality from the 18 studies included the systematic review.

Eleven studies examined cardiovascular mortality on dust days compared to non-dust days, four of which found a significant positive association for mortality on dust days. Of the studies showing a positive association, three originating from Asian countries (China, South Korea, and Taiwan) found an increased effect on cardiovascular mortality among elderly.[133] Another study from Athens, Greece also showed an increased mortality risk for elderly.[134]

Seven studies examined the association between PM during desert dust days and cardiovascular mortality, all of which found significant positive associations. Five of the seven studies also examined if the association between daily PM and cardiovascular mortality was different on dust versus non-dust days. One of the seven studies originated from Cyprus in the Middle Eastern region, which found a 2.43% (95% CI: 0.53, 4.37) increase in daily cardiovascular mortality for every 10 μg/m^3 increase in PM_{10} on dust days at lag 0; no association was found for non-dust days.[135] The remaining six studies originated primarily from Europe with one from Seoul, South Korea. Two studies from Madrid, Spain found a significant increase in mortality risk per 10 μg/m^3 increase in PM_{10} in the general and elderly population.[136] A study from Barcelona, Spain examined fine (PM with diameter between 1 μm and 2.5 μm) and coarse (PM with diameter between 2.5 and 10 μm) PM fractions with findings indicating significantly higher mortality risk during dust days.[137] A study from Rome, Italy found statistically significant percentage increases for rises in $PM_{2.5\text{-}10}$ and PM_{10} during dust days.[138] In Athens, Greece, a study found no statistically significant association between PM_{10} and mortality during dust events, but effects were significantly higher during non-desert dust days for elderly (75+).[139] Finally, a study in Seoul, Korea, found a statistically significant association between $PM_{2.5}$ and mortality during smog-Asian dust days among the elderly.[140]

Of the three studies that examined dust as a continuous variable, two studies originated from Europe and examined desert PM_{10} and non-desert PM_{10} using the two-pollutant model, finding a statistically significant association between the desert PM_{10} and cardiovascular mortality. The study conducted in Sicily, Italy, found lower effects for non-desert PM_{10} [141] and the study conducted across 13 cities in Greece, Italy, and Spain found no significant effect for non-desert PM_{10}.[142] The third study was conducted in 47 cities in Western Japan using Asian dust as a continuous variable; they found a statistically significant positive association between Asian dust and heart disease, ischemic heart disease, and arrhythmia-based cardiovascular mortality.[143]

4.5.4 Impact of desert dust on cardiovascular morbidity

Achilleos reviewed the association between desert dust and cardiovascular morbidity using evidence from the 22 studies included in the systematic review.

Three studies examined the association between desert dust and cardiovascular diseases in the Middle Eastern region. In the study from Iran, they found a significant increase in hospital admissions with a lag of 5 days for total cardiovascular hospital admissions (relative risk= 1.39 [95% CI: 1.08, 1.78]), coronary artery disease (relative risk = 1.08 [95% CI: 1.02,1.14]), and ischemic heart disease (relative risk = 1.09 [95% CI: 1.02,1.17]) per 10 μg/m^3 increase in PM_{10} during dusty days.[144] A study from Israel found the estimated relative risk for dust storm day (yes/no variable) was 1.051 (95% CI:1.005, 1.100) on the same day of the hospitalization due to acute coronary syndrome.[145] In addition, hospitalization was significantly associated with PM_{10} during dust storm days with a delayed response of one day (OR = 1.007 [95% CI: 1.002, 1.012]).

133 Li et al 2020b; Chan and Ng 2011; Lee et al 2013
134 Samoli et al 2011
135 Neophytou et al 2013
136 Diaz et al 2012; Jiménez et al 2010
137 Perez et al 2012
138 Mallone et al 2011
139 Samoli et al 2011
140 Kim et al 2012
141 Renzi et al 2018
142 Stafoggia et al 2016
143 Kashima et al 2012
144 Soleimani et al 2019
145 Vodonos et al 2015

The effect size for the dust exposure association was larger for older (>65 years), female, or Bedouin patients. A study from Cyprus found that cardiovascular admissions were nearly statistically significantly increased at 10.4% (95% CI: -4.7%, 27.9%) on dust storm days.[146] However, when restricting the analysis to the highest fourth quarter, they found a statistically significant 7.1% increase in cardiovascular admissions.

The remaining 19 studies were primarily conducted on Asian dust. The association between exposure to desert dust and total cardiovascular diseases was examined in six studies, of which four (conducted in Taiwan, Japan, Hong Kong, and Italy) found statistically significant associations between different PM metrics ($PM_{2.5}$, $PM_{10-2.5}$, and suspended PM) and emergency room/hospital admissions.[147]

The association between desert dust and acute coronary syndrome/ischemic heart disease and acute myocardial infarction was examined in eight Asian studies, six of which found significant associations between Asian dust and admissions for acute myocardial infarction and ischemic heart disease.[148] The association between exposure to desert dust and cerebrovascular disease such as stroke was examined in seven studies; of the five studies that found statistically significant associations, four were based in Asia (Japan and Taiwan) and one in Italy.[149] Most of the studies examined dust versus non-dust days; one found a significant increase in cerebrovascular hospital admissions, with PI = 5.04% (95% CI: 0.39, 9.91) per 19.8 μg/m^3 increase in PM_{10} during dust days.[150]

Achilleos also discussed Asian dust and its association with other circulatory diseases. A significant association between dust events and hypertension in males with a lag of three days was found (relative risk= 1.30 [95% CI: 1.03,1.64]) in Minqin, China.[151] No evidence was found for an association between Asian dust events and out-of-hospital cardiac arrests in Japan[152] or for an association between Asian dust events and hospital admission for heart failure in Taipei, Taiwan or in Hong Kong, China.[153]

4.5.5 Conclusion

Achilleos summarized the findings of the systematic review.

- Evidence indicates cardiovascular mortality and morbidity increase during desert dust events. Most studies indicated a statistically significant association, although it varied according to what exposure metrics were used including PM (fine, coarse) and lags.
- Available evidence suggests that the elderly and males are at increased risk.
- Little information is available about the association between desert dust and cardiovascular effects in the Middle East, as most studies are based on Asian dust.
- Standardization of epidemiologic studies is needed to make short-term estimates of desert dust comparable between different regions/studies. Variations on use of dust as an exposure metric and model differences between studies make analysis difficult.
- Presently, there is no evidence of the long-term cardiovascular effects of desert dust, but this issue warrants future research.

4.6 Discussion

4.6.1 Toxins in dust

Koutrakis questioned whether it is possible for dust from different deserts to have different toxicities. He also asked how housing and comorbidity factors may have affected the outcomes of the studies that Yiallouros discussed. Yiallouros replied that dust would

146 Middleton et al 2008
147 Kashima et al 2014; Liu et al 2017 Alessandrini et al 2013; Tam et al 2012
148 Bell et al 2008; Ishii et al 2020; Kojima et al 2017; Matsukawa et al 2014; Tam et al 2012; Teng et al 2016
149 Alessandrini et al 2013; Kamouchi et al 2012; Kang et al 2013; Kashima et al 2014; Yang et al 2005
150 Alessandrini et al 2013
151 Meng and Lu 2007
152 Nakamura et al 2015
153 Yang et al 2009; Tam et al 2012

likely pick up different toxins during the course of its trajectory and, theoretically, the toxins contaminating the dust could differ in level of toxicity. Yiallouros stressed the need for further research investigating the elemental composition of dust to conclusively answer the question of varying toxicity of dust. Koutrakis commented that comorbidities of populations, such as the high smoking rates in Greece, likely affect the effects of toxins carried by dust.

4.6.2 Variability of criteria

Weisskopf asked about the difficulty of assessing PM on dust days because of the variability of PM and about the overlap of PM levels on dust days compared to non-dust days. Achilleos said that on dust days, while there are particles that originated from anthropogenic sources, her group is attempting to assess the difference between PM levels on dust days versus non-dust days. The dust mostly originates from the desert. Yiallouros explained that about a quarter of the studies that have been published so far have also done comparisons of the estimated effects of PM_{10}. Initial data suggest that the effect of PM_{10} is the same on dust and non-dust days. However, further research on this topic is required. Achilleos pointed out that particle size must also be considered. Typically, courser particles are dominant and have a greater effect on desert dust days, but this may vary when measuring PM_{10} and $PM_{2.5}$.

Papatheodorou asked if visibility was used as a criterion in health-related studies. Achilleos explained that the criteria of visibility to define dust depended on the geographical region. While many Middle Eastern countries use visibility as an indicator, many Asian countries do not. Measures of human health effects and exposure criteria may also vary. The variability of definitions makes it difficult to compare studies conducted in different regions. Yiallouros said that this barrier is one reason that new studies are needed to assess the effects of dust on health. The variations in criteria are a methodological challenge, as academic centers and countries have established widely varying criteria. He praised Achilleos' work to help standardize methodologies for assessing desert dust events and their trends in the Eastern Mediterranean. She conducted this work while comparing data from Greece, Cyprus, and Israel.[154]

Weisskopf noted that there is a steeper response to pollutants at lower levels. However, as levels of PM rise, the effects plateau. For example, this trend can be observed in the relationship between lead levels in children's blood and the cognitive effects of lead. This trend could be caused by biological factors or behavioral modifications – ie, people go inside if the PM levels are too high. He asked if the effects of PM on health might plateau on dust days. Yiallouros commented that this relationship depends on the definition of a dust storm. In older studies, a dust storm was defined as an event where a certain PM_{10} threshold was exceeded. Yiallouros asked whether assessing particles on days with lower concentrations of dust might foster a better understanding of the effects in the lower range. Achilleos said that, in her experience, there is typically a linear relationship between PM_{10} and health effects on dust days.

4.6.3 Effects on mental health

A participant asked about the effects of dust on mental health and the endocrine system. They asked if cortisol levels had been measured during dust storms. Yiallouros said that he was not aware of any such studies; however, there was a 2016 publication that analyzed the quality of life using SF-36 questionnaires for allergic Turkish patients with or without asthma during dust storms. The group found an association between reduced mental health scores and dust storms.[155] Novack commented that he knew of several studies assessing the effect of dust storms on mental health. One was conducted in Israel, where researchers analyzed the relationship between suicide attempts, heat, and dust. While they did not find an association between dust and suicide attempts, they observed an association between high temperatures, low

154 Achilleos et al 2020
155 Gülen et al 2016

precipitation, and suicidal behavior.[156] Furthermore, they observed an increase in psychosis and psychosis-related hospital admissions during heat waves. Limited information is available on the effects of meteorological conditions on cortisol, as such studies would be difficult to conduct. It is also known that exposure to $PM_{2.5}$ or smaller particles can trigger insulin resistance.

4.6.4 Personal protection

A participant asked if personal protective measures, such as clothing, might affect exposure outcomes from dust. Achilleos said that she believed personal protection, such as masks or behaviors—eg, staying indoors—may reduce the exposure to dust and therefore reduce the risk of negative health outcomes.

4.7 Air pollution and pediatric health effects

Yiallouros explored the pediatric health effects of air pollution, drawing upon an extensive body of available evidence. He presented findings from several meta-analyses for pediatric health outcomes including chronic/cumulative and acute respiratory effects, central nervous system effects, leukemia, and congenital heart disease.

4.7.1 Respiratory outcomes

Children are particularly vulnerable to respiratory disease from air pollution, explained Yiallouros. They have narrower airways and breathe more air per pound of body weight than adults, which increases exposure to air pollutants. Air pollution influences the risk, prevalence, and incidence of the following cumulative/chronic respiratory outcomes: asthma and/or wheeze, allergic sensitization, allergic rhinitis/rhinoconjunctivitis and/or eczema, and lung function. Short-term outcomes include increased incidence of asthma exacerbations, pneumonia, otitis media, and respiratory mortality. Yiallouros examined some of the evidence on pediatric respiratory health effects by discussing relevant studies.

4.7.1.1 Cumulative effects of traffic-related air pollution on asthma/wheeze

Yiallouros explained that traffic-related air pollution is the most well-studied type of air pollution for pediatric health outcomes. A systematic review and meta-analysis analyzed the association between traffic-related air pollution and asthma development in childhood.[157] In the 42 studies included, nitrogen dioxide (NO_2) was the most commonly used surrogate traffic-related air pollution marker in exposure assessments. Traffic-related air pollution exposure was estimated at the participant's residential address. Most studies assessed exposure time at the birth year, and a few considered different and/or multiple exposure time windows. Studies had notable variability in asthma definitions and confounders' adjustment. The overall random-effects risk estimates (95% CI) were 1.08 (1.03, 1.14) per $0.5 \times 10^{-5}\ m^{-1}$ black carbon (BC), 1.05 (1.02, 1.07) per 4 $\mu g/m^3$ nitrogen dioxide (NO_2), 1.48 (0.89, 2.45) per 30 $\mu g/m^3$ nitrogen oxides (NO_x), 1.03 (1.01, 1.05) per 1 $\mu g/m^3$ PM <2.5 µm in diameter ($PM_{2.5}$), and 1.05 (1.02, 1.08) per 2 $\mu g/m^3$ PM <10 µm in diameter (PM_{10}). NO_2, black carbon, $PM_{2.5}$ and PM_{10} had statistically significant positive associations with the development of asthma and wheezing.

Another study evaluated traffic-related air pollution and its association with different phenotypes of asthma. Asthma is typically characterized as transient, persistent, and late-onset asthma/wheezing in preschool age children. A systematic review looked at seven studies on traffic-related air pollution exposure and development of childhood asthma and wheezing phenotypes.[158] They found that traffic-related air pollution exposure was associated with both transient and persistent asthma/wheezing phenotypes, but little evidence was found to suggest a relationship between traffic-related air pollution exposure and late-onset asthma/wheezing.

Another meta-analysis aimed to clarify the potential associations between traffic-re-

156 Yarza et al 2020
157 Khreis et al 2017
158 Lau et al 2018

lated air pollution-related organic and inorganic pollutants ($PM_{2.5}$, NO_2, benzene, and total volatile organic pollutants) and childhood asthma.[159] The results of the 27 studies included in the meta-analysis showed that traffic-related air pollution increased the risk of asthma among children: $PM_{2.5}$ (meta-OR=1.07, 95% CI:1.00-1.13), NO_2 (meta-OR = 1.11, 95% CI:1.06-1.17), benzene (meta-OR=1.21, 95% CI:1.13-1.29) and total volatile organic pollutants (meta-OR=1.06, 95% CI: 1.03-1.10). Regional analysis showed that ORs of inorganic traffic-related air pollution ($PM_{2.5}$ and NO_2) on the risk of childhood asthma were significantly higher in Asia than those in Europe and North America.

A study examined traffic-related air pollution-attributable burden on childhood asthma incidence (estimated in terms of NO_2 exposure) in children aged 1-18 years in 194 countries and 125 major cities.[160] The authors estimated 4 million (95% uncertainty interval [UI] 1.8-5.2) new pediatric asthma cases globally could be attributable to NO_2 pollution annually with 64% of cases occurring in urban centers. The burden accounts for 13% (6-16) of global asthma incidence. It was also estimated that about 92% of pediatric asthma incidence attributable to NO_2 exposure occurred in areas with annual average NO_2 concentrations below the WHO recommended threshold of 21 parts per billion.

Another study examined the traffic-related air pollution burden on childhood asthma in the United States in 2000 and 2010 using NO_2, $PM_{2.5}$ and PM_{10} as surrogates of traffic-related air pollution exposures.[161] Asthma incidence rates and exposures to each pollutant were obtained from the literature. They found that asthma incident cases due to traffic-related air pollution represented 27%-42% of all cases in 2000 and 18%-36% in 2010. Additionally, the percentage of cases due to traffic-related air pollution were higher in urban areas than rural areas, as well as in block groups with the lowest median household income.

4.7.1.2 Air pollution cumulative effects on asthma/wheeze

Yiallouros presented two meta-analyses that studied the impact of prenatal exposure to air pollution and development of childhood wheezing and asthma in the first years of life. One reviewed 18 studies that analyzed the association between exposure to different pollutants during pregnancy and the development of childhood wheezing and asthma.[162] The studies in the final analysis had notable variability in exposure assessment. The overall random-effects risk estimates of different pollutants were 1.04 (CI: 0.94-1.15) aromatic hydrocarbons (PAH), 1.04 (CI: 1.01-1.07) NO_2, 1.4 (CI: 0.97-2.03) $PM_{2.5}$ for childhood wheeze and 1.07 (CI: 1.01-1.14) NO_2, 1 (CI: 0.97-1.03) $PM_{2.5}$, 1.02 (CI: 0.98-1.07) SO_2, 1.08 (CI: 1.05-1.12) PM_{10} for childhood asthma. Therefore, the study showed statistically significant associations between prenatal exposures to NO_2 and risk of wheezing, as well as prenatal exposures to NO_2 and PM_{10} and the risk of asthma development in childhood.

The second meta-analysis examined the relationship between prenatal exposure to $PM_{2.5}$ and childhood asthma and wheezing, with nine studies included in the final analysis.[163] Findings indicated that prenatal exposure to $PM_{2.5}$ significantly increased the risk of childhood asthma and wheezing (OR=1.06, 95% CI:1.02–1.11; per 5 $\mu g/m^3$). Additionally, maternal exposure was more strongly related to childhood asthma and wheezing before age 3 (OR=1.15, 95% CI: 1.00–1.31; per 5 $\mu g/m^3$) than after (OR=1.04, 95% CI:1.00–1.09; per 5 $\mu g/m^3$), while children in developed countries showed more severe effects (OR=1.14, 95% CI:1.02–1.27; per 5 $\mu g/m^3$).

4.7.1.3 Air pollution cumulative effects on allergic sensitization

Yiallouros also presented two meta-analyses that studied the effects of air pollution on the development of allergic sensitization.

159 Han et al 2021
160 Achakulwisut et al 2019
161 Alotaibi et al 2019
162 Hehua et al 2017
163 Yan et al 2020

One analysis[164] included 19 articles based on 11 birth cohorts, seven of which were based in Europe and four were based in North America. Traffic-related air pollution was defined as NOx and PM, or as proximity to roads. All studies assessed sensitization using serum immunoglobulin E levels. Findings indicated no association of sensitization to indoor aeroallergens with early childhood exposure to NO_2 or $PM_{2.5}$. Results also showed an increased risk of sensitization to outdoor aeroallergens with increased exposure to $PM_{2.5}$, but not with NO_2. Moreover, early childhood exposure to NO_2 significantly increased the risk for sensitization to food allergens at the age of 4 years. These associations were modest at the age of 8 years for both NO_2 and $PM_{2.5}$.

The second meta-analysis assessed blood samples drawn from five European birth cohorts at 4-6 years of age and 8-10 years.[165] The samples were analyzed for allergen-specific serum immunoglobulin E against common allergens. Overall findings indicated air pollution exposure was not associated with sensitization to any common allergen: odds ratios ranged from 0.94 (95% CI: 0.63-1.40) for a 1x10-5.m-1 increase in measurement of the blackness of $PM_{2.5}$ filters to 1.26 (95% CI: 0.90-1.77) for a 5 mg/m^3 increase in $PM_{2.5}$ exposure at birth address.

4.7.1.4 Air pollution cumulative effects on rhinitis/rhinoconjunctivitis and eczema

Two meta-analyses reviewed the effects of air pollution on rhinitis, rhinoconjunctivitis, and eczema. One examined 13 studies (8 cross-sectional and 5 cohort studies) to evaluate exposure to air pollution and risk of prevalence of childhood allergic rhinitis.[166] They found significant associations with exposure to NO_2 (OR=1.138, 95% CI: 1.052-1.231, P =0.001), SO_2 (OR=1.085, 95% CI: 1.013-1.163, P =0.020), PM_{10} (OR=1.125, 95% CI: 1.062-1.191, P=0.000), and $PM_{2.5}$ (OR=1.172, 95% CI: 1.095-1.254, P=0.000). The other analyzed the association between long-term air pollution levels at the home address and pediatric eczema, rhinoconjunctivitis, and asthma prevalence in five European birth cohorts, finding no increase in the prevalence of these outcomes at 4 or 8 years with increasing air pollution exposure.[167]

4.7.1.5 Air pollution cumulative effects on lung function

Two meta-analyses reviewed the effects of air pollution on lung function, one of which included 11 articles on ambient air pollution and children's lung function from seven cities in China published from 1985 to 2006.[168] Lung function was significantly lower in areas with heavy ambient air pollution than in areas with light ambient air pollution. Analysis also showed significant negative correlation between the levels of total suspended particles and SO_2 and children's FVC and FEV1, as well as the levels of NO_x and children's maximal mid-expiratory flow. The results also suggested that girls had significantly greater decreases in lung function due to increasing ambient air pollution than boys.

The second meta-analysis evaluated the association between residential exposure to air pollution and lung function in five European birth cohorts.[169] Lung function was measured at 6-8 years of age with a sample size of 5,921. Estimated levels of NO_2, NOx, $PM_{2.5}$ absorbance, and $PM_{2.5}$ at participant's current address were associated with small decreases in lung function. Changes in FEV1 ranged from −0.86% (95% CI: −1.48, −0.24%) for a 20 µg/m³ increase in NOx to −1.77% (95% CI: −3.34, −0.18%) for a 5 µg/m³ increase in $PM_{2.5}$.

4.7.1.6 Short-term air pollution effects

Yiallouros also presented studies on the short-term effects of air pollution. Two meta-analyses and one multicenter study on asthma morbidity were discussed. The multicenter study found that daily emergency room visits for asthma

164 Bowatte et al 2015
165 Gruzieva et al 2014
166 Zou et al 2018
167 Fuertes et al 2020
168 Liu and Zhang 2009
169 Gehring et al 2013

during years 1986-1992 in Barcelona, Helsinki, Paris, and London increased significantly with SO_2 (RR=1.075, 95% CI: 1.026, 1.126) and NO_2 exposures, only in cold seasons (RR=1.080, 95% CI: 1.025, 1.140).[170] No association was observed for ozone and black carbon. A meta-analysis of 87 studies was conducted on the association of six major air pollutants with asthma emergency room visits and hospital admissions.[171] Results found stronger associations between emergency room visits and hospital admissions in children than in adults [CO: 1.018 (1.013, 1.023); NO_2: 1.018 (1.013, 1.023); SO_2: 1.016 (1.011, 1.022); PM_{10}: 1.013 (1.008, 1.018); $PM_{2.5}$: 1.025 (1.013, 1.037)]. The final meta-analysis included 22 studies that evaluated emergency departments, emergency calls, or hospitalizations due to asthma exacerbations in children aged 0-18 years.[172] Results indicated a significant association with NO_2 (OR=1.040; 95% CI: 1.001, 1.081), SO_2 (OR=1.047; 95% CI: 1.009, 1.086), and $PM_{2.5}$ (OR=1.022; 95% CI: 1.000, 1.045).

One meta-analysis and one multicenter study were presented on the short-term effect of air pollution on acute lower respiratory infections (ALRI). A systematic review and meta-analysis of ambient particulate air pollution and hospitalizations for ALRI in young children found the relative risk of ALRI per 10 μg/m^3 of $PM_{2.5}$ increase was estimated to be 1.12 (CI: 1.03, 1.30) from four eligible studies.[173] The multicenter study found that the strongest overall association of ozone and pediatric respiratory disease was in Atlanta (OR = 1.08, 95% PI: 1.06, 1.11), followed by Dallas (OR = 1.04, 95% PI: 1.01, 1.07) and St. Louis (OR = 1.03, 95% PI: 0.99, 1.07).[174] The stronger ORs were observed in low socioeconomic status areas.

Two meta-analyses and two studies on multi-cohort combined data examined the short-term effects of pneumonia and otitis media. A meta-analysis of 17 studies on the association between ambient air pollution and hospitalization of children due to pneumonia found the excess risk percentage per 10 unit increase of pollutants was 1.5% (95% CI: 0.6%-2.4%) for PM_{10}, 1.8% (95% CI: 0.5%-3.1%) for $PM_{2.5}$, 2.9% (95% CI: 0.4% -5.3%) for SO_2, 1.7% (95% CI: 0.5%-2.8%) for ozone, and 1.4% (95% CI: 0.4%-2.4%) for NO_2.[175] MacIntyre et al[176] studied the association between air pollution and parental reports of physician-diagnosed pneumonia in ten European birth cohorts. Adjusted odds ratios were elevated and statistically significant for all pollutants except $PM_{2.5}$ (OR = 1.30; 95% CI: 1.02, 1.65 per 10 μg/m^3 and OR = 1.76; 95% CI: 1.00, 3.09 per 10 μg/m^3, for NO_2 and PM_{10} exposures respectively). Fuertes et al[177] examined the associations between 8 PM elements and parental reports of physician-diagnosed pneumonia between 0-2 years in seven European birth cohort studies with a sample size of 15,980. Pneumonia was weakly associated with PM_{10}-derived zinc (OR=1.47 (95% CI: 0.99, 2.18) per 20 ng/m^3 increase), but no other associations with the other elements were observed. A meta-analysis[178] of 12 studies of PM concentration and the development of otitis media found pooled odds ratios for each 10 μg/m^3 increase in $PM_{2.5}$ and PM_{10} concentrations were 1.032 (95% CI: 1.005, 1.060) and 1.010 (95% CI: 1.008 1.012), respectively.

Yiallouros noted that few studies have been conducted on respiratory mortality as a short-term effect of air pollution in pediatric populations. One of the most prominent studies evaluated the effect of air pollution on childhood respiratory mortality in four large urban centers: Mexico City, Santiago in Chile, Sao Paulo and Rio de Janeiro in Brazil.[179] Researchers created a daily time series of mortality due to respiratory diseases in infants and children,

170 Sunyer et al 1997
171 Zheng et al 2015
172 Orellano et al 2017
173 Mehta et al 2013
174 CR et al 2017
175 Nhung et al 2017
176 MacIntyre et al 2014
177 Fuertes et al 2014
178 Lee et al 2020
179 Gouveia et al 2018

and levels of PM_{10} and ozone. For PM_{10}, the percentage increase in risk of death due to respiratory diseases in infants in a fixed effect model was 0.47% (0.09-0.85). For respiratory deaths in children 1-5 years old, the increase in risk was 0.58% (0.08-1.08) while a higher effect was observed for lower respiratory infections in children 1-14 years old (1.38% [0.91-1.85]).

4.7.2 Central nervous system outcomes

Yiallouros examined some of the evidence available on pediatric central nervous system health effects of air pollution.

4.7.2.1 Air pollution cumulative effects and autism

Two meta-analyses and one study on multi-cohort combined data evaluated cumulative effects of air pollution and autism. The first meta-analysis included 23 studies of multiple airborne pollutants prenatal exposure and ASD.[180] Results found significant summary ORs of 1.07 (95% CI: 1.06, 1.08) per 10 μg/m^3 increase in PM_{10} exposure (n=6 studies) and 2.32 (95% CI: 2.15, 2.51) per 10 μg/m^3 increase in $PM_{2.5}$ exposure (n=3 studies). The second meta-analysis of 25 studies examined the association between maternal exposure to outdoor air pollution and ASD in children by trimester of pregnancy.[181] Frequentist meta-analysis yielded significant pooled ORs of 1.06 (1.01,1.11) for $PM_{2.5}$ and 1.02 (1.01,1.04) for NO_2. A Bayesian meta-analysis showed similar ORs with 1.06 (1.00,1.13) for $PM_{2.5}$ and 1.02 (1.00,1.05) for NO_2. Third trimester appeared to have higher pooled ORs for $PM_{2.5}$, PM_{10}, and ozone. Finally, a study of air pollution exposure during pregnancy and childhood autistic traits assessed four European cohort studies that included 8,079 participants aged 4-10 years.[182] Results indicated that prenatal air pollution exposure was not associated with autistic traits within the borderline/clinical range.

4.7.3 Air pollution cumulative effects and psychomotor outcomes

One meta-analysis and five studies on multi-cohort combined data evaluated psychomotor health effects of air pollution. Four multi-cohort data studies found significant association of air pollution, especially motorized traffic pollutants, with delayed psychomotor development during childhood.[183] In addition, synthesis of data from eight European cohorts found no air pollution association with depressive, anxiety, or aggressive symptoms in children.[184] A meta-analysis of 10 studies estimated that every 10 μg/m^3 increase of NO_2 exposure during pregnancy was associated with a 0.76-point decrease in global psychomotor (95% CI: −1.34, −0.18) and a 0.62-point decrease in fine psychomotor for children (95% CI: −1.09, −0.16).[185] Researchers also indicated that further studies are needed for determining the effects of prenatal air pollution exposure on attention, IQ, and behavior.

4.7.4 Air pollution cumulative effects and leukemia

Yiallouros also evaluated the evidence on the association between leukemia and air pollution by presenting four meta-analyses. One found that childhood leukemia was positively associated (OR=1.53, 95% CI: 1.12, 2.10) with residential traffic exposure among 7 studies using a postnatal exposure window.[186] There was no association (OR=0.92, 95% CI: 0.78, 1.09) among 4 studies using a prenatal exposure window (eg, pregnancy period or birth address). Another meta-analysis examined 26 studies: 6 ecologic and 20 case-control. Results for NO_2 exposure found an OR of 1.21 (95% CI: 1.04 – 1.41) for acute lymphoblastic leukemia and 1.06 (95% CI: 0.51-2.21) for acute myeloid leukemia (AML);

180 Lam et al 2016
181 Chun et al 2020
182 Guxens et al 2016
183 Fuertes et al 2016; Guxens et al 2014; Lubczyńska et al 2017; Sentís et al 2017
184 Jorcano et al 2019
185 Shang et al 2020
186 Boothe et al 2014

for benzene exposure ORs were 1.09 (95% CI: 0.67 – 1.77) for acute lymphoblastic leukemia and 2.28 (95% CI: 1.09-4.75) for AML.[187] Estimates were generally higher for exposures in the postnatal period compared to the prenatal period. A third meta-analysis included 15 studies analyzing exposures to traffic density or traffic-related air pollution published from 1999 to 2014.[188] The summary relative risk for childhood leukemia was 1.48 (95% CI: 1.10, 1.99; n = 12). The summary relative risk was also higher for AML than for acute lymphoblastic leukemia. The fourth meta-analysis used 29 case-control and cohort studies and found little association between disease risk and overall traffic indicators near the child's residence for most of the exposure range.[189] However, benzene exposure was positively and approximately linearly associated with risk of childhood leukemia, particularly for AML, among children under 6 years of age. Exposure to NO_2 showed little association with leukemia risk, except at the highest levels.

4.7.5 Air pollution cumulative effects and congenital heart defects

Yiallouros summarized the evidence from two meta-analyses for the effect of air pollution on congenital heart defects. The first meta-analysis included five studies (3 cohorts and two case-control) to evaluate maternal exposure to $PM_{2.5}$ during the first trimester (weeks 1–12) of fetal development and found no association with the following congenital heart defects: atrial septal defect (OR=0.65, 95% CI: 0.37-1.15), ventricular septal defect (OR=1.02, 95% CI: 0.75-1.37), and tetralogy of Fallot's (OR=1.16, 95% CI: 0.78-1.73).[190]

An additional meta-analysis of 26 studies on the relationship between maternal air pollution exposure and congenital heart disease risk in the offspring showed high versus low carbon monoxide exposure was associated with an increased risk of tetralogy of Fallot's (OR=1.21, 95% CI: 1.04-1.41).[191] Results also showed an increased risk of atrial septal defects for each 10-unit increment in PM_{10} (OR=1.04, 95% CI: 1.00-1.09) and ozone (OR=1.09, 95% CI: 1.02-1.17). Categorical NO_2 exposure was associated with an increased risk of coarctation of the aorta (OR for high versus low=1.14, 95% CI: 1.02-1.26). Finally, analyses for other combinations yielded no statistically significant associations.

4.7.6 Conclusion and perspectives

Yiallouros concluded by summarizing key conclusions from the research he presented:

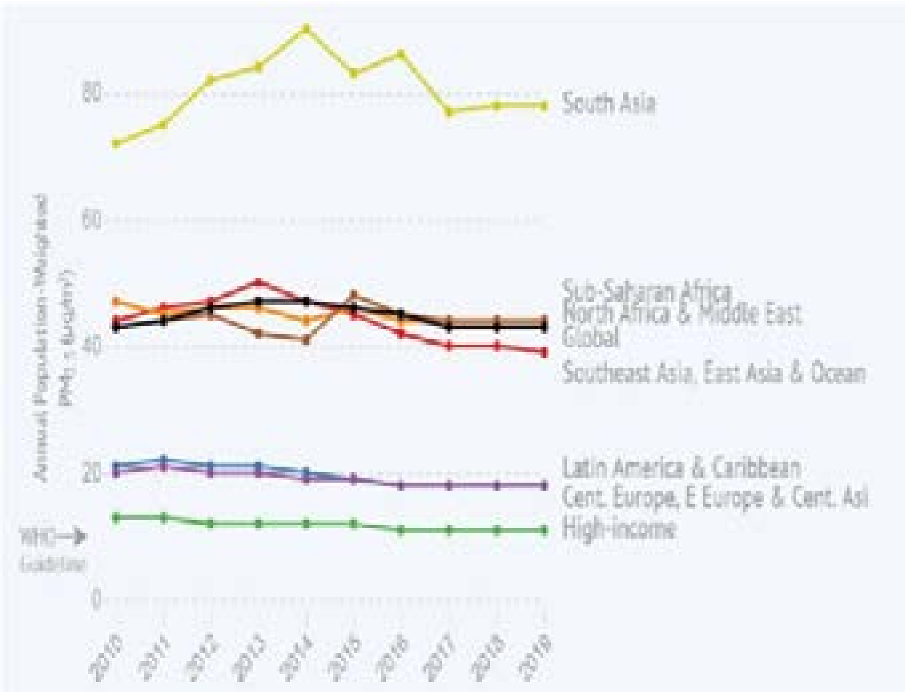
- An extensive body of epidemiological and mechanistic knowledge has accumulated on the associations between air pollution and children's health.
- Overall, many positive and few null associations are reported for cumulative effects of air pollution on the development of pediatric respiratory disease. Positive associations have also been established for short-term morbidity including hospitalizations and ED visits for overall respiratory, asthma and ALRI-pneumonia.
- Positive relationships were more frequently reported between traffic-related air pollution-related pollutants, NO_2, PM_{10}, and $PM_{2.5}$.
- More attention should be paid to the association between air pollution and other pediatric diseases, such as those affecting the nervous system and hematological malignancies.
- Future studies should focus on the implicated mechanisms through which air pollution is causing harmful effects in children, especially in respiratory, central nervous system, and hematological diseases.
- More intervention studies are needed to reduce children's exposure to air pollution and link findings with possible policy decisions and prevention measures.

187 Filippini et al 2015
188 Carlos-Wallace et al 2016
189 Filippini et al 2019
190 Hall and Robinson 2019
191 Hu et al 2020

4.8 Effects of air pollution on perinatal outcomes

Stefania Papatheodorou, lecturer in Department of Epidemiology at Harvard T.H. Chan School of Public Health, obstetrician and gynecologist, reviewed perinatal and reproductive effects of air pollution in the MENA region. She opened by presenting pollution data from the region and discussing how it compares globally. $PM_{2.5}$ exposures are highest in Asia, Africa, and the Middle East.[192] In general, pollution levels are higher in the MENA region than the rest of the world. Several of the top-10 countries with the highest $PM_{2.5}$ levels are located in the region, including Qatar and Egypt. Some governments in the region are restricting activities or emissions in order to reduce $PM_{2.5}$ levels, while others are increasing the use of coal and other major drivers of $PM_{2.5}$ pollution. On average, global $PM_{2.5}$ exposures declined from 2010 to 2019 (see Figure 4-7). Notable improvements in air pollution have occurred in some Global Burden of Disease Super Regions, while other regions, particularly in Africa and the Middle East, have seen increases in $PM_{2.5}$ exposures. Many researchers are worried about the health effects from exposures in regions with high and increasing $PM_{2.5}$ levels.

Figure 4-7. Air pollution trends 2010 - 2019



Source: Papatheodorou presentation; stateofglobalair.org

4.8.1 Adverse pregnancy outcomes of air pollution exposure

Papatheodorou examined common adverse pregnancy outcomes in the region by examining (1) the mechanisms of adverse pregnancy outcomes from air pollution exposure and (2) the association with common adverse pregnancy outcomes such as preterm birth and gestational diabetes. Pregnant women are specifically vulnerable to the effects of air pollution, due to physiologic changes that occur throughout pregnancy such as increased rate of breathing. Air pollution affects health outcomes

192 More information about the state of global air pollution available at stateofglobalair.org accessed June 4, 2021

by many mechanisms.[193] Once inhaled into the lungs, air pollution causes oxidative stress and systemic inflammation. Particles can also translocate into circulation and into different organs. Black carbon and polonium found in the placenta reveal that the fetus can be directly affected by air pollution. Particles also cause placental inflammation and oxidative stress. Via circulation, air pollution can cause endothelial dysfunction and cardiovascular inflammation. Air pollution exposure is associated with increased beta-cell stress and dysfunction in the pancreas which can contribute to insulin resistance and/or gestational diabetes. Exposure can increase adipose tissue inflammation and alter adipokines, important molecules in pregnant women's metabolisms. Additionally, air pollution is associated with decreased glucose uptake and increased insulin resistance in muscle. In the digestive system, the gut microbiota is altered, and gut permeability is increased. Overall, these changes contribute to adverse outcomes such as gestational hypertension, gestational diabetes, or preterm birth.

Papatheodorou discussed evidence related to the association between air pollution and pregnancy outcomes. Air pollution exposure is associated with preterm birth and low birth weight, gestational diabetes, hypertensive disorders of pregnancy, and epigenetic changes transferable to subsequent generations. Although the association between air pollution and hypertensive disorders of pregnancy has been established, there remains debate about in which trimester pregnant women are most susceptible.

Papatheodorou expanded on preterm birth as a pregnancy complication of air pollution. Preterm birth is the leading cause of death in children younger than 5 years worldwide and a major contributor of morbidity. However, the global rate of preterm birth has remained stable at approximately 10%, despite advances in prenatal care and pharmaceutical and clinical interventions.[194] The MENA region has a relatively high prevalence of preterm birth, with rates between 10% and 14%. For instance, Jordan has an estimated preterm birth rate between 15% and 20%. One study assessed preterm birth associated with maternal fine PM exposure.[195] The study calculated the percentage of total preterm births, which were associated with ambient $PM_{2.5}$ using low concentration cut-offs of 4.3 μg/m^3 and 10 μg/m^3. Compared to other regions of the world, the MENA region has a large percentage of preterm births attributable to $PM_{2.5}$ air pollution. Therefore, identification and regulation of modifiable risk factors could greatly influence health outcomes and the prevalence of preterm birth in the region. Gestational diabetes is another adverse outcome associated with air pollution; these outcomes are prevalent in the MENA region. For instance, one meta-analysis found high prevalence of gestational diabetes in Egypt (24.2%), Saudi Arabia (17.6%), and Morocco (15.6%).[196] The researchers suggested that the variance between these findings could be due to the methodological differences between the original studies, or due to factors such as age demographics or higher body mass indices in certain countries.

4.8.2 Available evidence on air pollution and pregnancy outcomes in the region

Papatheodorou summarized evidence about the association between air pollution and pregnancy outcomes from the region, beginning with an overview of a systematic review of the effects of air pollution on pregnancy outcomes published in 2016.[197] The review included 12 studies: three studies each were conducted in Iran, Jordan, and Saudi Arabia and one study each were conducted in Palestine, Iraq, and Pakistan. Six of the studies employed a retrospective cohort design, four were cross-sectional, and two were case-control studies. The studies' sample sizes varied between 223 births and 8,490 births, and the studies were

193 Zhang et al 2020
194 Chawanpaiboon et al 2019
195 Malley et al 2017
196 Badakhsh et al 2019
197 Khader et al 2016

conducted between 2004-2012. Seven of the studies examined secondhand smoke, which is a widespread issue in the MENA region and a prominent contributor to poor indoor air quality. Three of the studies examined PM_{10}; three examined gaseous air pollutants; two studied indoor wood fuel smoke; and one examined polycyclic aromatic hydrocarbons. The methods of data collection used in the studies were not optimal, said Papatheodorou. Exposure to secondhand smoke and wood fuel smoke was measured via self-reporting, and exposure to outdoor air pollutants—including PM_{10} and gaseous pollutants—was measured using only data from the nearest central site monitoring station, which provides limited temporal or spatial resolution. The study examined polycyclic aromatic hydrocarbons using maternal blood testing.

Papatheodorou discussed the findings from the systematic review. Two studies in the Iranian cities of Tehran and Isfahan investigated the association between outdoor air pollutants and low birth weight. In Tehran, 225 pregnant women within 5 km of a monitoring station had average daily exposure estimated for PM_{10}, CO, SO_2, NO_2, and O_3 during the entire pregnancy period and during each trimester. The study found CO exposure to be the only significant risk factor for low birth weight during the whole pregnancy (OR=2.08, 95% CI: 1.7, 4.6), and during the second trimester (OR=3.96, 95% CI: 1.83, 12.5). In Isfahan, a pollutant standards index was used to estimate exposure during the entire pregnancy period and during each trimester for 4,758 pregnancies. A pollutant standards index is a type of air quality index based on several air pollutants; this index has included $PM_{2.5}$ only since 2014. The review found no association between pollutant exposure and low birth weight for any exposure period, before or after adjustment for confounders. Papatheodorou stated that the lack of significant associations between low birth weight and outdoor pollutants may or may not be accurate given potential errors in exposure assessment and the methods used to collect health data.

The systematic review also examined the connection between birthweight and indoor biomass fuel smoke. In a study based in Pakistan, infants born to biomass fuel users averaged 82 g lighter than infants born to natural gas users when weight was adjusted for confounders. Another study in Palestine found birthweight was significantly lower (by 309 g) in infants born to women who were exposed to biomass fuel smoke than in the unexposed group. Both studies reported similar odds ratios with approximately 2-fold higher risk of delivering an infant with low birth weight among women exposed to biomass fuel smoke after adjustment for confounders.

Only one retrospective cohort study from Iran reported on the effect of outdoor exposure to pollutants on preterm birth. A pollutant standards index was used to estimate exposure during the entire pregnancy period and during each trimester. The only significant association between pollutant standards index levels and preterm birth was during the entire pregnancy (odds ratio for interquartile range increase in pollutant standards index =1.26, 95% CI: 1.20, 1.33).

The systematic review also evaluated the association between spontaneous abortions and outdoor air pollution. In Tehran, a case-control study used data on outdoor air pollutants including PM_{10}, CO, SO_2, NO_2, and O_3 from fixed-site air-monitoring stations to estimate exposure during the entire pregnancy. Among the five pollutants, exposure to ambient CO showed the strongest association with spontaneous abortions (OR for 1 ppm increase in concentration=1.95, 95% CI: 1.49-2.54). Exposure to NO_2, PM_{10}, and O_3 showed weak, but statistically significant, effect on spontaneous abortions (OR for 1 $\mu g/m^3$ increase in PM_{10}: 1.00, 95% CI: 1.00-1.01; OR for 1 ppb increase in NO_2: 1.03, 95% CI: 1.01-1.05; and OR for 1 ppb increase in O_3: 1.09; 95% CI: 1.05-1.13). No association was found for SO_2.

4.8.3 Additional studies

Papatheodorou reviewed more recent research conducted in the region that utilized methodological advances. A time series study assessed the association between air pollution and the risk of stillbirth March 2015 and March 2018.[198]

198 Ranjbaran et al 2020a

Researchers evaluated O_3, CO, NO_2, SO_2, and $PM_{2.5}$; they found a 5 parts per million increase in the SO_2 concentration in lag 0 increased the risk of stillbirth with marginal significance (RR=1.062; 1.002-1.125). Another time series analysis in Tehran, Iran, evaluated the impacts of air pollution on preterm birth from March 2015 to March 2018.[199] Findings indicated risk of preterm birth increased by 0.8% and 0.6%, on the same day for each 10-unit increase in $PM_{2.5}$ and NO_2, respectively. A case-control study conducted in Tehran, Iran examined the correlation between ambient concentrations of air pollutants and spontaneous first-trimester abortions using data from monitoring stations.[200] The study method was of higher quality than other case-control studies in the region, as researchers examined 148 cases and 148 controls matched by maternal and paternal age, gravidity, pregnancy spacing, history of miscarriage, body mass index, education, secondhand smoke, and socioeconomic status. Significant relationships were found for CO (OR=1.95, 95% CI: 1.5, 2.5), NO_2 (OR=1.03, 95% CI: 1.02, 1.05), O_3 (OR=1.09, 95% CI: 1.06, 1.13), and PM (OR=1.01, 95% CI: 1.00, 1.02). SO_2 had no significant association with spontaneous abortion. Lastly, Papatheodorou listed several studies conducted in Israel that used large administrative databases and high-quality exposure data. These studies investigated the correlations between: green space, low birth weight, and preterm birth[201]; temperature and air pollution exposure and preterm birth and preterm pre-labor rupture of membranes[202]; air pollution and preterm birth; and traffic air pollution and pregnancy loss.[203]

4.8.4 Gaps in knowledge and recommendations

Papatheodorou concluded by identifying gaps in knowledge and offering recommendations. The available literature has several prevalent epidemiological issues. The limited number of studies, study outcomes, and (in some cases) lack of high-quality evidence in the region makes proper assessment of air pollution impact difficult. In addition, some available epidemiological studies contain misclassified exposures. Even the best quality studies in the region use data from monitoring stations, which can cause significant misclassification in exposure associations. Moreover, studies have poor confounder control and use inconsistent exposure metrics which limit study comparison. She noted that methods of obtaining health data are often flawed—for example, recall bias is a common systematic error when collecting self-reported data. Finally, studies for the area are small and lack proper power calculations that can address the impacts of chance, bias, and confounder influence.

4.9 The Middle East as a time machine for climate change research

Victor Novack, head of Clinical Research Center and director Department of Medicine at Soroka University Medical Center, Professor of Medicine at Ben-Gurion University, and adjunct lecturer at Harvard University, described his research conducted in the Negev region with a focus on the various health effects of air pollution and climate characteristics. He proposed that the Middle East is like a time machine for climate change research, as the current state of the Middle East is similar to the predicted global outcomes of climate change. Thus, research from the region will be highly relevant in the near future for efforts to curb the effects of climate change globally. Novack's research focuses on the Negev: a semi-arid desert region located in the global dust belt. It is situated in southern Israel and covers more than half the country. The Negev area is frequently subjected to dust storm events that exceed recommended PM_{10} levels, such as WHO's guideline of 50 μg/m^3. In the northern Negev, PM_{10} concentrations during dust storm events can reach levels as high as 4,200 μg/m^3.

199 Ranjbaran et al 2020b
200 Moridi et al 2014
201 Agay-Shay et al 2014
202 Gat et al 2021
203 Kioumourtzoglou et al 2019

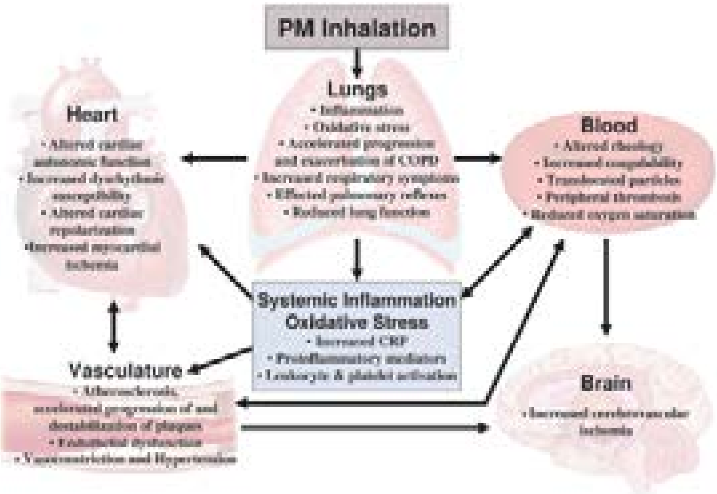
4.9.1 The Negev region

Novack called the Negev an "ideal laboratory" for studying the future of climate change and its effects on human health. Negev has numerous features that make it well suited for climate research. The region has a hot climate with desert effect exposure. It is possible to accurately assess exposure in the region, and researchers can access health outcome data for the region's population. The area's hot climate is a comparable representative of the climate throughout the Middle East. Desert temperatures are excessively hot in the summer but cold during the winters.

Novack explained that Negev is impacted by local and regional deserts. In February 2003, NASA satellite images captured a dust event originating from the Sahara that approached Israel's western shoreline and affected the Negev region. In addition to satellite imaging, exposure assessment is conducted via monitoring sites around Beersheba. Exposure data can then be compared with complete health outcomes recorded in Israel's centralized electronic medical record (EMR) system. Established in the early 1990s, this centralized EMR system has enabled the decades-long, longitudinal compilation of patient data including lab testing, imaging, hospitalizations, and medications. The population of almost 1 million residents is comprised of two main ethnic groups: Jews and rural Arab Bedouins. A quarter of the population are Arab Bedouins; 40% of these Arab Bedouins live in temporary dwellings or unrecognized villages and experience higher outdoor climate exposure. The region's main city, Beersheba, has a population of about 240,000. Novack noted the juxtaposition of the region's urban landscape in Beersheba with its rural, temporary settlements that house the Arab Bedouin population. The region has one hospital, Soroka University Medical Center, located in Beersheba. The health system in Negev is unique in its reliance on a single tertiary teaching hospital with 1,100 beds. Similarly, one health maintenance organization in the region, which owns Soroka Hospital, covers nearly 70% of the population. The hospital uses Israel's centralized EMR system and maintains complete patient records. Due to Israel's national identification system, no patients are lost to follow-up. With regard to air pollution and health outcomes in the region, PM exposure is predominantly non-anthropogenic as the region has no major roads, low traffic density, and regulated industrial activity producing little emissions.

Novack explained that air pollution affects health through many biological mechanisms (see Figure 4-8). Unfortunately, physicians rarely consider the impacts of climate and air pollution exposure on diseases, and it is uncommon for physicians to discuss exposure with patients.

Figure 4-8. Potential general pathophysiological pathways linking PM exposure with cardio-pulmonary morbidity and mortality



Notes: COPD=chronic obstructive pulmonary disease; CRP= C-reactive protein
Source: Novack presentation; Pope III and Dockery 2006

4.9.2 Soroka Clinical Research Center projects

Novack remarked that since the founding of Soroka Clinical Research Center (SCRC), they have developed robust research capabilities and published numerous articles on environmental medicine.[204] SCRC collaborates with researchers from various research institutions including Harvard University. Their projects have assessed various aspects of human health including the impact of air pollution on cardiovascular, respiratory, perinatal, and mental health. Still, many questions on the health impacts of air pollution remain.

4.9.3 Effect of air pollution on respiratory health

One study examined the effect of dust exposure on COPD exacerbation.[205] Researchers studied the change in the number of daily COPD exacerbations associated with daily average concentration of PM_{10} ($\mu g/m^3$). Results indicated a positive association between dust storms and the rate of hospitalization for COPD exacerbation (IRR=1.16,95%CI, 1.08-1.24, $p<0.001$). Incidence relative risk of dust storm on hospital admission for COPD exacerbation stratified by patients' age and gender found the effect was greater among women and those aged >50 years. Another study evaluated change in lung function for participants with COPD exposed to dust storms. Subjects were assessed at baseline and 2 days after a dust storm. Analysis found no significant relationship between dust storms and relative change in FEV1 or relative change in FEV1/FVC. Similar results were observed when this methodology was applied to participants with asthma.

4.9.4 Effect of air pollution on cardiovascular risk factors and diseases

Novack pointed out that research has been conducted for many cardiovascular health outcomes, including myocardial infarction, ischemic heart disease, cerebrovascular event, diabetes mellitus, hypertension, dyslipidemia, serum cholesterol and glucose, and blood pressure. One study investigated the effect

204 More information about SCRC's clinical research is available at https://sorokacrc.org/publications/#1503238292225-1695eb04-fc89 (accessed June 15, 2021).
205 Vodonos et al 2014

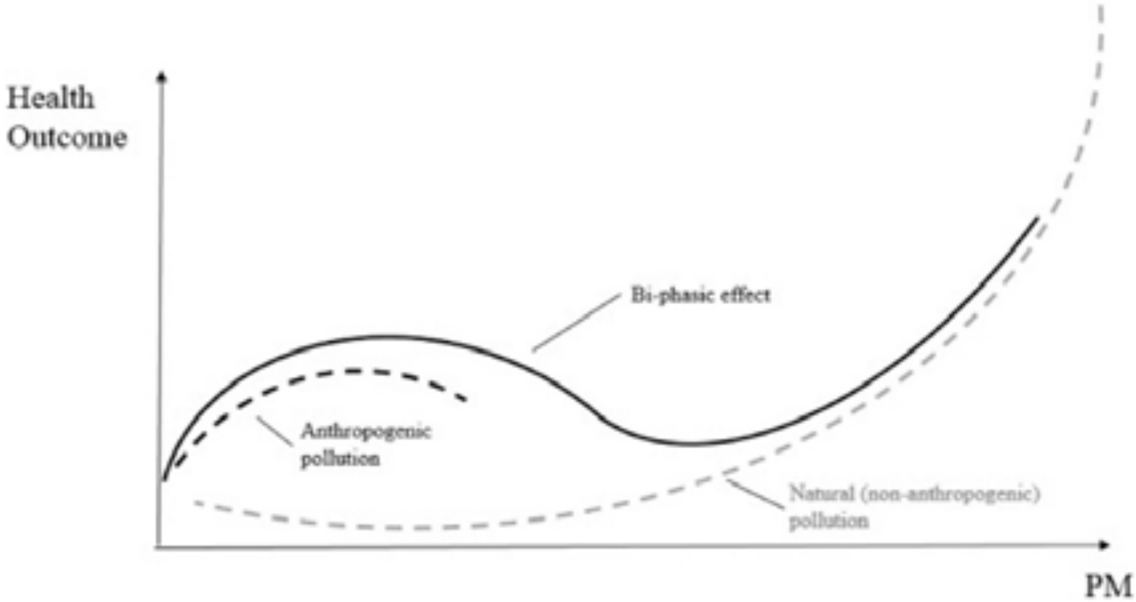
of air pollution on ischemic stroke.[206] Using a case-crossover design, positive significant associations between ischemic stroke and PM_{10} or $PM_{2.5}$ concentrations were observed among subjects <55 years of age (OR=1.11, 95% CI: 1.02–1.20 and OR=1.10, 95% CI: 1.00–1.21, respectively). No associations were found in other age groups including 55-65 and >65 years. Among subjects <55 years of age, the associations were more pronounced in the lower range of PM. These particles most likely originate from traffic, and those subjects often reside in proximity to main roads. Thus, the unexpected finding of higher risk for ischemic stroke associated with PM among young adults can be explained by the link between air pollution and stroke.

4.9.5 Effect of anthropogenic and non-anthropogenic PM

Recent studies have revealed a biphasic pattern in the function relating health outcomes with exposure to PM, said Novack (see Figure 4-9). Increased PM is generally associated with increased morbidity; however, there is often a plateau or decrease in the health effects once PM reaches a certain threshold. Novack and his colleagues have hypothesized that the biphasic pattern is the fusion of two exposure curves.[207] This could be due to the differing nature of PM in question, with the first peak reflecting the effects of stronger, more biologically active anthropogenic particles and the second peak reflecting the impacts of weaker, non-anthropogenic particles. Novack and his colleagues distinguished between the anthropogenic and non-anthropogenic PM using NO_2 as a proxy for anthropogenicity. They hypothesized that the effect of anthropogenic sources would be evident at the low levels of PM exposure, while the effect of non-anthropogenic dust would require high PM levels to become clinically evident. The analysis focused on the biphasic pattern of the associations between PM levels with blood glucose levels and asthma exacerbations. Consistent with their hypothesis, they showed that the variant effect of PM_{10} on blood glucose levels was explained by NO_2. That is, on non-dust storm days, PM_{10} was almost linearly associated with blood glucose levels in the presence of high NO_2 levels, as opposed to a non-linear association for low NO_2 values. However, a similar association was not found between NO_2 and asthma exacerbations.

206 Yitshak Sade et al 2015
207 Novack et al 2020

Figure 4-9. The two bumps question: biphasic function of health outcomes and particulate



Notes: PM=particulate matter
Source: Novack presentation

4.9.6 Exposure assessment methods

Novack discussed new methods for measuring exposure levels. An ecological approach based on monitoring stations and validated models has traditionally been used for exposure assessment. However, these methods measure ambient outdoor exposure, which does not always reflect indoor exposure or the internal levels of pollution absorbed in the body. An ongoing study aims to explore the feasibility of using the Israeli national blood banking system to assess exposure via human biologic monitoring.[208] About 1,000 blood units daily from around the country are collected, and all blood donors give consent for their donations to be used for research purposes. Personal and population-level exposure level can be measured from blood samples using human biologic monitoring methodology. This research will focus on measuring heavy metals. Experience from this research may also be applied to develop a human biologic monitoring platform.

4.9.7 Health implications of environmental research

Novack concluded by emphasizing the relevancy of exposure for human health. The health effects reported in environmental studies are often relatively small. However, when applied to large populations, the overall effect translates to significant adverse health outcomes. When addressing health implications of environmental exposures, policy should address both the broad extent of the exposed population and the continuous nature of exposure. For policymakers, unanswered questions remain regarding what policies to implement, what changes to make, and regulatory oversight. Finally, clinical guidelines should include environmental aspects and address susceptible populations.

4.10 Air pollution, cognitive function, and dementia

Marc G. Weisskopf, Cecil K. and Philip Drinker Professor of Environmental Epidemiology and Physiology at Harvard T.H. Chan School of Public Health, discussed the effect of air pollution on

208 Hassan et al 2020

cognitive function and dementia. As interest in dementia has become a global issue, the effects of air pollution on dementia have become a subject of interest. Between 1950 and 2000, the prevalence of Alzheimer's disease cases increased worldwide, and it has been estimated that there will be over 115 million cases by 2050.[209] To address this trend, it is necessary to study and understand the modifiable risk factors for dementia. The study of dementia is complicated by the ongoing debate regarding its definition, however. Weisskopf defined dementia as a significant decline in one or more domains of cognitive function that interferes with activities of daily living that cannot be better explained by another disorder and has not occurred exclusively within a period of delirium.[210] Despite a relatively simple definition, the disorder is difficult to precisely diagnose due to clinical and pathological heterogeneity. Clinical symptoms may be attributable to various conditions, including Alzheimer's disease, vascular disease, frontotemporal lobar degeneration, Lewy Body disease, traumatic brain injury, HIV infection, prion disease, substance abuse, or medication side effects. Further, individuals diagnosed with dementia may frequently exhibit more than one potentially dementia-causing condition. One study determined pathologic diagnoses from autopsies of those with and without clinically diagnosed dementia.[211] Of those clinically diagnosed with dementia, approximately 30% had Alzheimer's disease, 10% had infarction, <5% had Parkinson's disease/Lewy Body disease, and 55% exhibited a mixture of possible causes. A small number of deceased with clinically diagnosed dementia had no observable pathology found during autopsy. This finding adds complexity to the epidemiological study of the causes of dementia and raise new considerations, such as the environmental influence on dementia and other risk factors. Many studies investigating these factors strategically focus on closely related outcomes to dementia – eg, cognitive function and cognitive decline – rather than studying clinical dementia per se.

4.10.1 Increase in research on air pollution and cognitive function

Weisskopf discussed various research studies conducted on the link between air pollution effects and cognition. In 2002, a study evaluated brain histopathology from dogs in Mexico City, a highly polluted urban region.[212] Cortical sections evidenced abnormal neuropathology consistent with neurodegeneration including reactive astrocytes, degenerating neurons, apolipoprotein E, plaques and neurofibrillary tangles, tau-positive neurons, activated microglia in the cortex and white matter, and vascular abnormalities including blood-brain barrier damage. The authors suggested that air pollution contributed to these neurodegenerations. Findings were compared to those in dogs from Tlaxcala, a less polluted city, and the results indicated that dogs from more polluted areas have more abnormal neuropathology. After these findings were published, epidemiologists began to evaluate the association between air pollution and cognitive function. Researchers in Germany investigated the link between cognitive impairment and exposure to traffic-related PM in elderly women.[213] Exposure was assessed by comparing the distance from residential addresses to busy roads, and neuropsychological tests were used to determine cognitive impairment. Researchers observed a significant association between distance to busy streets and performance in the CERAD-Plus battery, a neuropsychological test that is used to identify the early cognitive changes related to Alzheimer's disease. Researchers at Harvard University examined the neurobehavioral effects associated with long-term exposure to ambient PM and ozone in US adults.[214] Researchers observed consistent associations between estimated annual ozone exposure and reduced performance in all neurobehavioral tests. Each 10 parts per billion ozone was associated with

209 Prince et al 2013
210 American Psychiatric Association 2013
211 Schneider et al 2007
212 Calderon-Garciduenas et al 2002
213 Ranft et al 2009
214 Chen and Schwartz 2009

reduced cognitive performance equivalent to 3.5-5.3 years of aging-related decline. No associations were found between PM_{10} exposure and cognitive decline in this study. Finally, one study assessed the association between black carbon, a marker of traffic-related air pollution, and cognition in older men from the US Department of VA Normative Aging Study in Boston.[215] Researchers estimated black carbon exposures using a validated model[216] that provides daily estimates of black carbon concentrations throughout the greater Boston, Massachusetts, area starting in 1995. Results of the black carbon study showed that elevated black carbon exposure was associated with increased odds of having a lower score on the Mini-Mental State Examination, a dementia screening tool. In a multivariable-adjusted model for global cognitive function, which combined scores from six cognitive tests, a doubling of black carbon was also associated with significantly lower scores. This suggests that some aspects of air pollution are related to worse cognitive function.

These studies are representative of the rise in research on air pollution and cognitive function and dementia, said Weisskopf. Between 2006 and 2018, the annual number of publications on the topic has increased from 1 to at least 14. Notably, the Lancet Commission on Dementia published their report in 2020, which listed air pollution as a dementia risk factor.[217] In addition, several reviews have been published that outline the available research on the topic.[218] One such review went so far as to review the epidemiological difficulties associated with these kinds of studies.[219] In sum, there is a wealth of research linking air pollution to adverse health outcomes, including reduced cognitive function and dementia.

4.10.2 Study limitations

Numerous studies worldwide, particularly in the US, Canada, and Europe, have been conducted on various aspects of air pollution, including $PM_{2.5}$, PM_{10}, chemical species in PM, black carbon, nitrogen dioxide, nitrogen oxide, ozone, woodsmoke PM, and traffic-related air quality indices (eg, distance to road). Weisskopf noted that each of these air pollution factors has been associated with cognitive effects. Among these, the strongest evidence links $PM_{2.5}$ and nitrogen oxide to cognitive impairments. However, current epidemiological studies have important limitations to consider. Many studies, including two of the aforementioned publications,[220] only examined cognitive function at a single point in time. One-time cognitive assessment is biologically and epidemiological problematic when evaluating dementia, and this methodology reduces study relevancy. It is preferred that researchers evaluate changes in cognitive function over time, since cognitive function over time and the impacts of cognitive decline on daily functioning are fundamental aspects of dementia disease. He noted that few air quality impact studies examine longitudinal cognitive decline. Another issue with current studies is the reliance on passive surveillance such as claims data and medical record data. Dementia is challenging to diagnose, and passive surveillance is limited by reporting. Weisskopf concluded that the best approach for research is to conduct longitudinal, cohort studies that examine either (1) cognitive decline over time or (2) onset of dementia when the whole cohort is tested for dementia.

4.10.3 The cerebrovascular link

Weisskopf discussed evidence linking air pollution and cerebrovascular function. Air pollution has well established associations with the development of cardiovascular disease. Damage to the vascular system can adversely affect the brain and causes cognitive decline. Thus, vascular risk factors are often associated with cognition effects and dementia, and even subclinical cerebrovascular disease is implicated

215 Power et al 2011
216 Weisskopf explained that this validated model was developed in Gryparis et al 2007.
217 Livingston et al 2020
218 Schikowski and Altuğ 2020
219 Dimakakou et al 2018; Kilian and Kitazawa 2018; Power et al 2016; Russ et al 2019; Schikowski and Altuğ 2020; Tham and Schikowski 2021
220 Power et al 2011; Ranft et al 2009

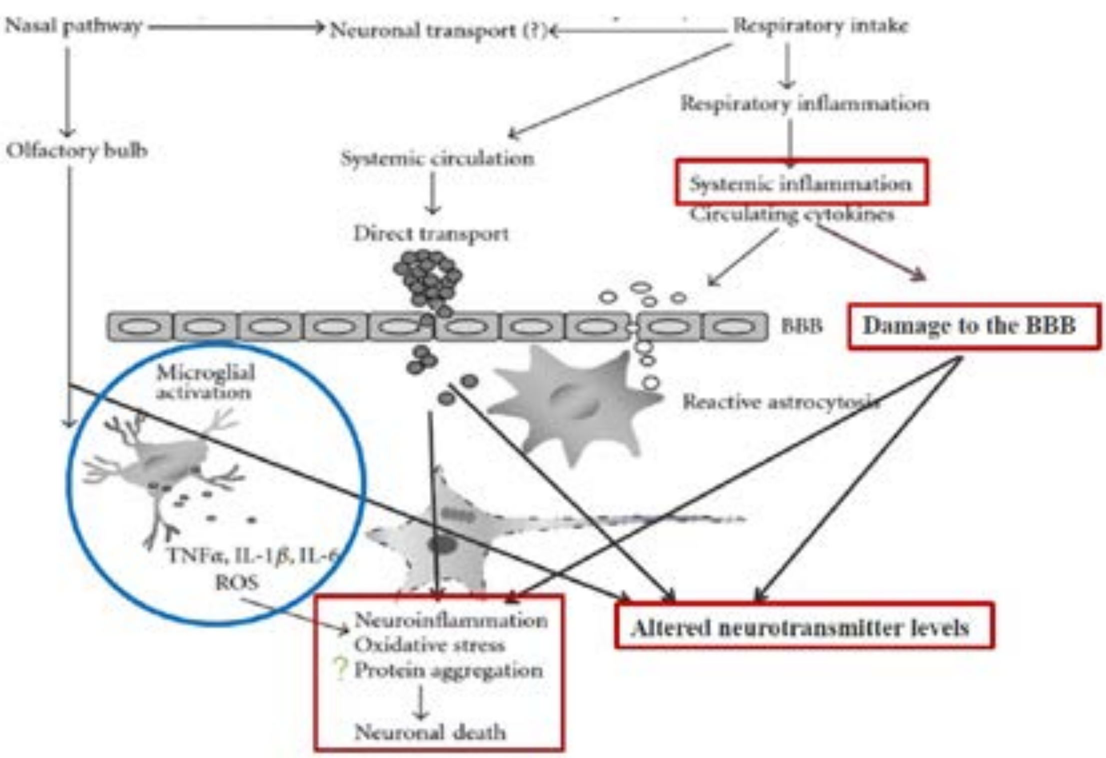
in dementia pathophysiology. Furthermore, evidence shows that air pollution particles can be deposited directly in the brain, particularly the olfactory bulb.[221] In direct contact with the environment, nasal olfactory receptor neurons responsible for smell project from within the olfactory bulb in the brain. The nasal olfactory area provides access to the central nervous system, which bypasses the circulatory and respiratory system. The regions within the brain to which the olfactory nerve projects – the limbic and temporal lobe – are associated with Alzheimer's disease pathology. Consequently, the nose-brain pathway grants access to critical brain regions involved in learning, memory, and dementia. Given the nose-brain pathway for dementia-related air pollutants, it might be expected that sense of smell would be affected in such cases; in fact, evidence has been found that younger adults with olfactory impairment have a greater risk of cognitive impairment.[222]

Other studies have used brain imaging to explore the underlying biology of dementia and cognitive decline. A 2016 study found that $PM_{2.5}$ exposure was associated with diminished cortical gray matter and subcortical white matter volumes.[223] A review of the emerging body of evidence regarding neuroimaging has been conducted.[224] Weisskopf noted that it is unclear whether brain image findings associated with air pollution correspond to brain findings from cardiovascular damage. Exploring the connections between environmental studies and neuroimaging studies is an evolving area of research. He noted potential epidemiological concerns when using brain imaging data. This methodology may introduce bias by the nature of participant selection. Furthermore, the interpretation of imaging data may introduce distortions in findings.

Animal neuroimaging studies have suggested that air pollution can produce its adverse effects in the central nervous system through a variety of cellular and molecular mechanisms (see Figure 4-10).[225] Air pollutants typically travel from the nasal pathway to the respiratory system and translocate into circulation. Resulting systemic inflammation can disturb the integrity of the blood-brain barrier (BBB), the physical barrier protecting the central nervous system. Damage to the BBB causes altered neurotransmitter levels and neuronal death through neuroinflammation, oxidative stress, and protein aggregation. As previously mentioned, air pollutants can also travel directly to the brain via nasal pathways and the olfactory bulb, causing the same damage. This pathway also results in activation of specialized immune cells of the central nervous system called microglia. Microglia respond to environmental insults (such as air pollution) and play a crucial role in sculpting connections between brain cells. These cells maintain healthy neuronal connectivity by removing unneeded synapses and re-routing connections. However, aberrant pruning of neural connections from toxic microglia activation could contribute to neurological disorders such as Alzheimer's disease through the destruction of critical brain function and memory cells.[226] Various neurodegenerative diseases (eg, Alzheimer's disease, dementia) are linked with the same mechanisms of neural damage, including systemic inflammation, BBB damage, altered neurotransmitter levels, protein aggregation, oxidative stress injury, neuroinflammation, and microglial activation. These mechanisms of neural damage ultimately result in the loss of neurons.

221 Ajmani et al 2016; Oberdorster et al 2004
222 Chen et al 2021
223 Casanova et al 2016
224 de Prado Bert et al 2018
225 Adapted from Genc et al 2012
226 Hong et al 2016

Figure 4-10. Particulate matter exposure pathway



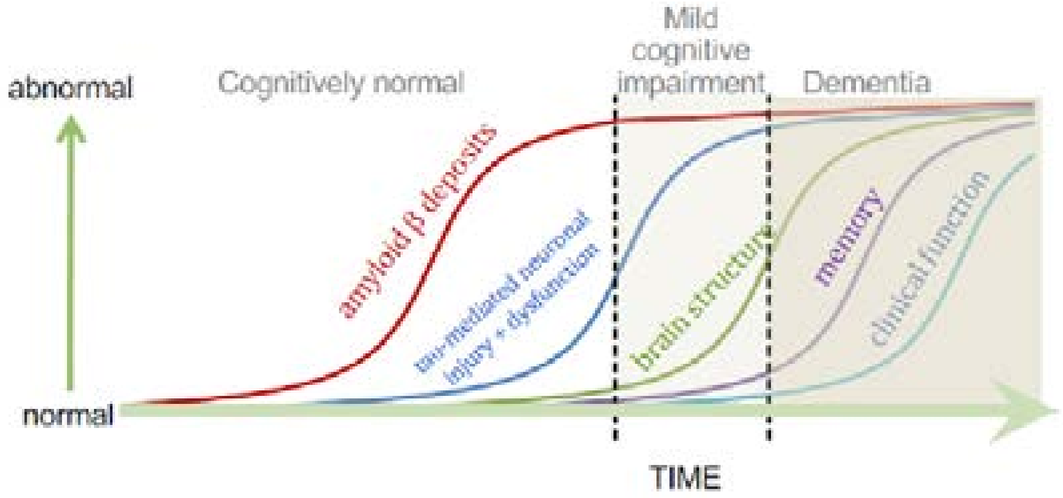
Note: BBB=blood-brain barrier
Sources: Weisskopf presentation, Genc et al 2012

4.10.4 Summary and conclusion

Weisskopf summarized the current understanding of how air pollution affects cognitive function and dementia. The association between air pollution and diminished cognitive function has been established by a large body of evidence. The best studies analyze longitudinal cognitive decline, but few cohort studies have been conducted to explore the environmental risk factors of dementia. More evidence is needed to determine the impact of individual pollutants. Generally, $PM_{2.5}$ and gases have been linked to cognitive function. However, little research has been conducted on the impacts of individual components of PM and other hazardous air pollutants. There is little evidence exploring the cognitive effects of exposure to ultrafine pollutants. Further study of ultrafine pollutants may be warranted, as these pollutants can more easily access the brain. Research in this area is limited by insufficient ultrafine exposure models and exposure assessment. Thus, future studies should further evaluate the association between cognitive function and ultrafine pollutants.

Weisskopf noted that many questions remain with regard to the effects of air pollution on cognition. Future research efforts should aim to clarify the mechanisms by which inflammation and damage to the cardiovascular system affect cognitive function. Finally, more research is needed to determine when exposure is most significant. Typically, studies exploring the cognitive impacts of air quality consider only recent air pollution exposures. While the relevant exposure window is not known, research indicates that by the time dementia emerges, the mechanisms of cognitive decline have long been underway (see Figure 4-11).[227] The diagnosis of cognitive impairment or dementia is preceded by the creation of amyloid beta deposits, tau-mediated neuronal injury and dysfunction, changes in brain structure, and memory issues. More research is needed to determine the cognitive impact of air pollution exposure at various times throughout the life-course in order to understand how air pollution may be accelerating or exacerbating abnormal neurological processes.

Figure 4-11. The emergence of dementia and cognitive impairment over the life-course



Sources: Weisskopf presentation, Jack Jr et al 2013

4.11 Discussion

4.11.1 Effects of smoking on cognition

A participant asked whether researchers have studied the effects of smoking on cognition. Weisskopf noted that smoking has an effect on human biology, and there is a genetic component to persons' disposition toward smoking. In the 1970s and 1980s, it was thought that there may be a protective effect of smoking against dementia. However, smoking has since been identified as a risk factor for dementia and cognitive decline. It is strongly suspected that smoking is linked to competing effects, such that many smokers do not live long enough to experience late-life cognitive effects. This can create a selection bias whereby smokers living past age 70 are an atypical group. Thus, cohorts that recruit at later ages often see a different association with smoking than cohorts that follow people from earlier ages.

4.11.2 Mood disorders and pollution

A participant asked if any studies had been done on mood disorders in areas with higher pollution levels. Novack said that attempts have been made to find associations between acute, short-term disturbances in mood with meteorological factors. No such attempts have been made to find long-term mood effects. Weisskopf agreed, noting that work in the Nurses' Health Study performed by his group found an association between PM and anxiety, but the study was not the appropriate setting for examining acute (eg, recent days) effects of PM on symptoms like anxiety. The evidence in that study suggested that more recent PM exposure, such as within the last month, had a greater effect than less recent exposure, such as within the last year.[228]

227 Jack CR Jr, Lancet Neurology 2013
228 Power et al 2015

4.11.3 Late-life consequences of early-life exposure to toxins

Papatheodorou asked about studies that have investigated air pollution conditions over the course of a person's life, prior to their clinical diagnosis. Weisskopf said that such studies have not been conducted. Most studies look at exposures in the year of testing or diagnosis. Assessing conditions retrospectively over a longer duration is challenging, in part because models for air pollution do not extend very far into the past. Weisskopf suggested it might be possible to categorize cohorts aged 70 and 80 into high and low earlier life exposure groups, but more detailed exposure assessment for earlier life is difficult. However, it is not clear whether long-term exposure would be more important than recent exposure. For instance, a recent exposure may lead to acute neuroinflammation, which may accelerate processes already underway. Weisskopf added that an ongoing study is using elderly persons' teeth as a biomarker of early-life exposure to metals. This study is exploring the possible relationship to Alzheimer's disease later in life. He cited the Nun Study of Aging and Alzheimer's Disease, which found that subjects who developed dementia later in life showed patterns of less complex writing in their entry essays to the convent when they were 18 years of age.[229] This suggests a link between early-life factors and long-term health consequences.

4.11.4 Radionuclides in the brain

A participant commented that a paper had been published that found radon progeny in different locations in the brain. Koutrakis commented that this finding confirms the hypotheses that ultrafine particles can travel through nerves to the frontal lobe of the brain. Measuring radionuclides in the brain is a very sensitive way to understand exposure amount and duration. Weisskopf added that a group in Sao Paulo found accumulation of radon progeny in the brain, which may be a risk factor for the development of chronic disease.[230]

4.11.5 Increase in brain diseases

Koutrakis remarked that brain diseases have been increasing due to an aging population. Weisskopf agreed that the aging population has contributed greatly to the increase in brain disease. He mentioned, however, that some evidence suggests that the incidence of Alzheimer's disease and dementia may be decreasing. The reasons for this trend are not clear, but the decrease is beyond what would be expected from the decrease in known risk factors, such as cardiovascular issues. This is an area requiring further research. However, such research is challenging to conduct because there are many factors that affect the overall trend.

4.11.6 Mental health and extreme weather events

Vandenberg raised the issue of meteorological events causing behavioral changes with mental health impacts. He asked whether there is any evidence of behavioral changes caused by environmental conditions affecting people's mood or wellbeing. Weisskopf commented that studies have found a relationship between pollutant levels and depression and anxiety. However, he was less familiar with literature on the connection between environmental conditions and behavioral change. Vanderberg discussed the wildfires in Oregon in the summer of 2020. Residents were encouraged to make behavioral changes by public health authorities, including staying indoors to reduce their exposure to high levels of PM.

4.11.7 Discussion closing remarks

Garshick stressed the importance of studying the source of PM. He commented that particle mass is used as an indicator of exposure in the US, Europe, and China. However, it is more challenging to mitigate dust storms than local or regional pollution. He suggested that the source of PM might explain some of the heterogeneity of short-term health effects of dust storms. Perhaps pollution from various sources were carried into regions along with desert dust during

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dust storms. This could be a topic of further research. Koutrakis concluded by highlighting the importance of collaboration and knowledge sharing in the field of planetary health.

4.12 Workshop closing remarks

Salmaan Keshavjee discussed the great need to think about these topics across sectors to create better and more actionable public policy regarding air pollution and climate change that affects human health. Garshick reflected that regulators, healthcare administrators, and healthcare providers are all impacted by the topics discussed during the webinar. The EPA has conducted a number of cost benefit analyses investigating the effects of controlling pollution. Even though there is an initial expense, this investment pays off in the long run. Vanderberg commented that while there are significant benefits to public health from these investments, there are parallel cost benefit analyses that take place. The economists who typically perform these cost benefit analyses are usually searching for evidence that allows them to evaluate the risk and exposure costs as well as the benefits of intervention. Air pollution and climate change in the MENA region are particularly unusual with extreme cases of dust exposure. He expressed the importance of delineating between total suspended particulate versus PM_{10}, or the inhalable fraction versus the fine fraction. It is an important distinction for decision makers to consider when they are setting standards, as PM_{10} captures both the fine and coarse fraction. In the US and Europe, there is a distinction between fine fraction and coarse fraction, which is often combustion sources and crustal sources. In the case of dust in the Middle East, it is some combination of fine and coarse fraction. He encouraged researchers to delineate between PM_{10} less $PM_{2.5}$, $PM_{2.5}$, and total suspended particulate. Such a distinction can help inform both standard setting and risk exposure assessment.

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6 Appendix

6.1 Appendix 1. Featured speaker biographies

Petros Koutrakis

Dr. Koutrakis is a Professor of Environmental Sciences in the Department of Environmental Health at the Harvard T.H. Chan School of Public Health. His research activities focus on the development of human exposure measurement techniques and the investigation of sources, transport, and the fate of air pollutants. In collaboration with his colleagues in the Environmental Chemistry Laboratory, he has developed ambient particle concentrators and high-volume samplers that can be used to conduct human and animal inhalation studies. He has also developed a personal ozone monitor, a continuous fine particle measurement technique and several other sampling methods for a variety of gaseous and particulate air pollutants. These novel techniques have been used extensively by air pollution scientists and human exposure assessors in United States and worldwide. Dr. Koutrakis has conducted a number of comprehensive air pollution studies in the United States, Canada, Spain, Chile, Kuwait, Cyprus and Greece that investigate the extent of human exposures to gaseous and particulate air pollutants. Other research interests include the assessment of particulate (PM) exposures and their effects on the cardiac and pulmonary health. He is the Head of the Exposure, Epidemiology and Risk Program and the Director of the EPA/Harvard University Center for Ambient Particle Health Effects and he is a member of national and international committees and the past Technical Editor-in-Chief of the Journal of the Air & Waste Management Association.

Ali Al-Hemoud

Dr. Al-Hemoud is a Research Scientist at the Environment and Life Sciences Research Center at the Kuwait Institute for Scientific Research. Ali does research in Environmental and Occupational Health and Safety, Risk Assessment, and Natural and Anthropogenic Hazards.

Souzana Achilleos

Dr. Achilleos is currently a Postdoctoral Research Associate for the LIFE MEDEA public health intervention study at Cyprus University of Technology. Her expertise lies at the intersection of atmospheric exposure assessment and public health and her research focuses on air pollution exposure assessment and epidemiological investigations of its health effects, with a special interest in dust storms originated from Sahara and Sahel region, following my doctoral thesis work at the Harvard School of Public Health. She received her Doctor of Science from the Harvard T.H. Chan School of Public Health in Environmental Health.

Itzhak Katra

Professor Itzhak Katra is the head of the Aeolian Simulation Lab in the Department of Geography and Environmental Development at Ben-Gurion University of the Negev, Israel. Hi research focuses on sources and emissions of desert dust to the atmosphere, aeolian processes of sand and dust, dynamics of dust storms and their impacts and dust control and soil stabilization.

Wasim Javed

Dr. Javed is a Research Scientist in the Department of Mechanical Engineering at Texas A&M University at Qatar. His research focuses on aerosol monitoring, sampling, characterization, modelling and source apportionment; air pollution research and modelling; developing strategies and measures for pollution control; and aerosol pollution impact assessment of solar energy, health and plants.

Poornima Prabhakaran

Trained as a physician in Bangalore Medical College, Poornima Prabhakaran has a Master's in Epidemiology from the London School of Hygiene and Tropical Medicine and a PhD in Social Medicine from the University of Bristol, UK. Her doctoral work in the Andhra Pradesh Children and Parents Study brought to focus the importance of a life-course approach in the prevention and management of lifestyle and metabolic disorders. Since 2015, Poornima moved her focus to the study of environmental health risk factors and is currently Additional Professor, Head, Environmental Health and Deputy Director of the Centre for Environmental Health at the Public Health Foundation of India where she leads a team of nearly 20 researchers and consultants on research, training, advocacy and capacity building for environmental health issues spanning air pollution, climate change, water, sanitation and hygiene, chemical and heavy metal exposures and children's environmental health. She is a member of technical expert groups providing inputs from a health perspective to various national programs related to climate change, air pollution and urban resilience and heads the Centre of Excellence at PHFI providing an implementation framework to the National Program for Climate Change and Human Health under the Ministry of Health and Family Welfare on the transition to green and climate resilient healthcare facilities across the public health system in India. Additionally, she is a Senior Research Scientist at the Centre for Chronic Disease Control, New Delhi and leads work engaging the private health sector as well in India on environmental issues including a strong advocacy and movement towards climate resilient and climate smart sustainable health care systems in India. This includes a strong focus on resource efficiency including the transition to renewable sources of energy and effective water and waste management to optimize both climate and health benefits. She is also leading a consortium of exposure scientists and health researchers to build a national model for exposure to $PM_{2.5}$ to health outcomes in India and will present this work today.

Jing Li

Dr. Li received her PhD from Peking University. Now she is a postdoctoral fellow work with Professor Petros Koutrakis at the Harvard T.H. Chan School of Public Health. Her research focuses on the application of remote sensing in environmental exposure modelling.

Mazen Malkawi

Mazen Malkawi holds advanced degrees in Water and Environment Information Management from the Free University of Brussels (1998) and in Water Resources and Environmental Engineering from the Jordan University of Science and Technology (1988) and holds a degree in Civil Engineering from the University of Jordan (1985). Mr. Malkawi has served since 1988 at different positions at the WHO Centre for Environmental Health Action. Most recently in 2012, he started coordinating several regional programs related to monitoring and controlling exposures to environmental risk factors with special focus on Environmental Health Planning and Air Quality and Health in the 22 countries of the Eastern Mediterranean region.

John Vandenberg

Dr. Vandenberg is Director of the Health and Environmental Effects Assessment Division of the Center for Public Health and Environmental Assessment, US Environmental Protection Agency. He is responsible for leadership, planning and oversight of EPA's Integrated Science Assessments for the major (criteria) air pollutants, for assessments of high priority hazardous air pollutants, for stressors such as land use change on environmental endpoints across both terrestrial and aquatic systems, and for the development of new risk assessment methodologies. He has testified to Congressional committees, serves on a variety of advisory boards and is an adjunct professor at the Nicholas School of the Environment, Duke University where he teaches a graduate course on air quality management. He received his B.A. from the College of Wooster, Ohio, and the MS and PhD from Duke University in biophysical ecology.

Eric Garshick

Dr. Eric Garshick is Associate Chief, Pulmonary, Allergy, Sleep, and Critical Care Medicine Section at VA Boston Healthcare System, and Professor of Medicine, Harvard Medical School. He received his MD degree in 1979 from Tufts Medical School and a Master of Occupational Health degree from the Harvard T.H. Chan School of Public Health in 1984. He is Board Certified in Internal Medicine, Pulmonary Disease, and Critical Care Medicine. As well as practicing medicine, he has expertise in the health effects of air pollution, with a focus on the effects of particulate air pollution and diesel exhaust on health. Major research activities have included the study of diesel exhaust and lung cancer, effects of particulate air pollution on patients with chronic obstructive pulmonary disease, and the study of the health effects of exposure to PM in US military personnel previously deployed to Iraq and Afghanistan. His research funding has come from the US National Institutes of Health and the Department of Veteran's Affairs Cooperative Studies Program. He has also served on a number of advisory committees, including the EPA Clean Air Scientific Advisory Committee Diesel Review Panel and working group to assess diesel exhaust as a carcinogen at the International Agency for Research on Cancer.

Barrak Alahmad

Dr. Alahmad is a PhD candidate in Population Health Sciences, specializing in Environmental Health at the Harvard T.H. Chan School of Public Health, and a Mission Scholar from the Faculty of Public Health, Kuwait University. He holds a medical degree from the University of Liverpool, United Kingdom, and a Master of Public Health (MPH) from the Johns Hopkins Bloomberg School of Public Health with a concentration in Global Environmental Sustainability & Health, and certificates in Environmental & Occupational Health and Risk Sciences & Public Policy. He is working with his advisor Professor Petros Koutrakis on air quality, climate change & health in the Middle East, specifically the adverse impacts of dust storms and extreme temperatures. His other research interests include migrant workers health, environmental risk assessment, and environmental cardiology. Prior to his work at Harvard, he was a physician at the Directorate of Public Health, Ministry of Health, Kuwait, where he implemented environmental health initiatives, led teams of public health inspectors and supervised environmental surveillance data.

Panayiotis Yiallouros

Professor Panayiotis Yiallouros is a pediatric pulmonologist and is the head of the respiratory physiology laboratory and the primary ciliary dyskinesia service at the University of Cyprus. Professor Yiallouros is also the project coordinator of LIFE MEDEA project and participates as a Work Package leader in other projects focusing on respiratory disease and public health.

Stefania Papatheodorou

Dr. Papatheodorou is a Lecturer in Reproductive Epidemiology at the Harvard T.H. Chan School of Public Health and was previously a Lecturer in Epidemiology at the University of Cyprus. She received both her MD and PhD from the University of Ioannina School of Medicine.

Victor Novack

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