# Climate changes effects on future air quality


## Abstract

Emissions of air pollutants determine regional air quality and can alter climate. On the flip side of the coin, climate change can perturb atmospheric chemical processes, meteorology (ventilation and dilution), precipitation and other air pollution removal processes, degrading air quality in many polluted regions. Several methods are being used today in order to estimate the way climate affects air quality, using observed correlations of air quality with meteorological variables, perturbation analyses in chemical transport models (CTMs), and CTM simulations driven by general circulation model (GCM) simulations of 21st century climate change. This work presented main findings of the three approaches. A decrease in frequency of mid-latitude cyclones due to weaker global circulation will generate a more stagnant climate, and together with the expected temperature raise will induce an increase in summertime ozone concentrations of 1–10 ppb (forced by climate alone) in polluted regions. Projected PM changes are of high uncertainty due to unreliable projections of precipitation frequency and mixing depth, the two most important variables negatively correlated with PM. Other studies took into consideration both projected climate changes and projected future changes in anthropogenic emissions. Reduction in anthropogenic emissions worldwide should eventually cause a decrease in both PM and ozone levels. A ″penalty″ due to climate change can be defined, requiring more stringent emission controls along the coming years in order to meet a given ozone air quality target in the future.


## 1. Introduction

### 1.1. Air pollutants and their effect on climate

Climate change is driven by air pollution, as many air pollutant sources emit carbon dioxide ($CO_2$), the dominant anthropogenic greenhouse gas (GHG), other GHG or particles, all of which affect earth's climate, as will be discussed here shortly (Fiore, Naik, & Leibensperger, 2015).

Earth's surface temperature is determined by the balance between incoming solar radiation and outgoing infrared radiation. The steady state condition in earth's energy balance is disturbed when these air pollutants interact with solar and terrestrial radiation, leading to changes in earth's surface temperature and in climate (IPCC, 2014). It is common to use the definition of radiative forcing (RF) as a measure of the influence a certain pollutant has on the climate system. RF is defined as the perturbation in the net radiative flux (in W $m^{-2}$), at the top of the atmosphere, that occurs due to a change in the atmospheric abundance of a radiatively active atmospheric constituent. RF is usually reported as that induced by differences between present-day and preindustrial (1750) atmospheric

burdens of a certain atmospheric constituent, in order to quantify the anthropogenic contribution (Fiore et al., 2015; IPCC, 2014)

GHG and particles can induce different RF effects, depending on their atmospheric concentration, warming or cooling capacity (how well they absorb IR radiation), residence time and spatial distribution in the atmosphere. Positive RF induces warming, whereas negative RF induces cooling of the earth's surface and troposphere. For example, **Figure 1** illustrates how the increase in globally averaged $CO_2$, tropospheric ozone ($O_3$) and its precursor methane ($CH_4$) over the past few centuries have caused a worming influence.

The net effect of PM (or aerosols) on the other hand is cooling, though high uncertainty (marked in black vertical bars, **Fig.1**) exists for the magnitude of the effect. In general, all aerosol components scatter sunlight ("Nasa earth observatory," 2019), and so directing back into space a fraction of it and creating a cooling effect of earth's surface. A portion of aerosol components (e.g. Black carbon (BC)) additionally absorbs solar radiation, warming the atmosphere. Another indirect effect is altering the vertical temperature profile by warming the top of the atmosphere, enhancing atmospheric stability and pollutant accumulation rates. Aerosols, both natural and anthropogenic, also serve as cloud condensation nuclei (CCN), assisting in the formation of liquid droplets or ice crystals. A liquid cloud with more anthropogenic aerosols contains more CCN and produces more cloud droplets, which are necessarily smaller than a "clean cloud". Greater number of smaller droplets modify cloud optical properties, making clouds brighter and more reflective, increasing cloud-albedo effect. Smaller cloud drops also slow the droplet growth rates, prolonging the lifetime of a cloud before precipitation. Both effects indirectly increase the amount of solar radiation scattered to space by clouds and change precipitation patterns. They are referred to as RF due to "aerosol-cloud" interactions. **Figure 1** shows how BC warming influence is balanced by the cooling effect of "aerosol-cloud" interactions, sulfate, nitrate, and other organic carbon (OC) particles (Fiore et al., 2015).

## 1.2. Expected climate changes

The Intergovernmental Panel on Climate Change (IPCC) 2013 report (IPCC, 2014) present several possible scenarios (Representative Concentration Pathways or RCPs) by the end on the 21st century, each inducing different changes in annual mean surface temperature, precipitation and more (i.e., different projections). These projections are based on future emission trajectories for greenhouse gases and on global climate models (commonly called general circulation models or GCMs). In the best-case scenario (RCP 2.6), most places in the world will not experience temperature anomaly of more than 1.5 degrees, while in the worst-case scenario (RCP 8.5), most settled areas will experience 4-7 degrees rise in annual mean surface temperature (**Figure 2a**). All RCPs show strong warming over the northern mid-latitude continents, generally increasing in magnitude with increasing

latitude. Global precipitation are expected to increase slightly due to enhanced evaporation from the oceans but there is considerable regional variability (**Figure 2b**). For example, precipitation will increase in the northern parts of North America and Europe but decrease in the southern parts. It will increase in northern Asia but decrease in the Middle East. Models agree in general that high latitudes will become wetter and subtropical latitudes drier. Other aspects of the hydrological cycle that are relevant for air quality (humidity, cloudiness, wet convection) follow qualitatively the precipitation projections (Jacob & Winner, 2009; Wu, Mickley, Leibensperger, et al., 2008). Most GCMs project a decrease in mid-latitude cyclone frequency and a shift poleward in cyclone tracks. This will decrease the frequency of cold frontal passages in mid-latitude regions and increase the frequency and duration of stagnation episodes. Cold fronts spawned by mid-latitudes cyclones are major agents of pollutant ventilation in eastern North America, Europe, and eastern Asia (Jacob & Winner, 2009; Leibensperger, Mickley, & Jacob, 2008). The effect of climate change on mixing depth is uncertain. GCM simulations for the 21st century find increases and decreases of mixing depths in different regions with no consistent patterns. The connection between above-mentioned climate changes and air pollution concentrations will be thoroughly explained in section 3. Other relevant expected changes and their connection to air quality are the increase in frequency of climatological extreme events such as heat waves or prolonged dry episodes, which might induce wildfires or droughts. Increasing frequency of wildfires and droughts in the future climate could be an important factor driving PM increases (Jacob & Winner, 2009; Wu, Mickley, Leibensperger, et al., 2008).

## 1.3. Pollutants of focus

Most research work focuses on surface ozone and PM, as both are important climate forcing agents and are responsible for the most widespread violations of air quality standards worldwide (Fiore et al., 2015). In addition, Ozone, PM and their precursors raise the highest concern for public health. Silva et al. (2013) estimated that, at present, almost 500,000 premature respiratory deaths globally are associated every year with anthropogenic ozone, and more than 2 million deaths with anthropogenic $PM_{2.5}$ (particles with diameter less than 2.5 mm)-related cardiopulmonary diseases and lung cancer. These are of most concern for human health, as they are capable of penetrating deep into lung passageways and entering the bloodstream (WHO, 2019).

Ozone is produced naturally in the troposphere by photochemical oxidation of CO, methane, and non-methane volatile organic compounds (NMVOCs) by the hydroxyl radical (OH) in the presence of reactive nitrogen oxides ($NO_x \equiv NO + NO_2$). Ozone's precursors have large combustion sources, as well as natural (e.g., NMVOC from vegetation, methane from wetlands) (Jacob & Winner, 2009). OH originates mainly from atmospheric oxidation of water vapor by excited oxygen atoms $O(^1D)$,

which itself is produced by a photochemical reaction - absorption of solar ultraviolet radiation of wavelength shorter than 320 nm by ozone (Lagzi, Meszaros, Gelybo, & Leelossy, 2013):

$$O_3 + h\nu\ (\lambda < 320\ nm) \rightarrow O_2 + O(^1D) \qquad \textbf{Reaction 1}$$

$$O(^1D) + H_2O \rightarrow 2OH + O_2 \qquad \textbf{Reaction 2}$$

Ozone pollution is in general mostly a summer problem because of the photochemical nature of the source. Ozone production is usually limited by the supply of $HO_x$ and $NO_x$, but can also be NMVOC-limited under highly polluted conditions and outside the summer season. Tropospheric ozone's principal global sink is photolysis in the presence of water vapor. Other sinks include vegetation uptake (dry deposition) in the continental boundary layer. Since ozone and its major precursors have low solubility in water, wet deposition is negligible (Jacob & Winner, 2009), and their transporting in the free troposphere can add a significant background to local surface ozone (Wu, Mickley, Jacob, Rind, & Streets, 2008).

PM includes as principal components sulfate, nitrate, organic carbon, elemental carbon, soil dust, and sea salt. The first four components are mostly present as $PM_{2.5}$. Sulfate, nitrate, and organic carbon are produced within the atmosphere by oxidation of $SO_2$, $NO_x$, and NMVOCs. Nitrate and organic carbon exchange between the particle and gas phases, depending, in particular, on temperature. Seasonal variation of PM is complex and location-dependent, but generally is a year-round pollution problem. PM is efficiently scavenged by precipitation and this is its main atmospheric sink, resulting in atmospheric lifetimes of a few days in the boundary layer and a few weeks in the free troposphere (similar to ozone). Unlike for ozone, however, export of PM from the source continents is limited by the precipitation scavenging. The PM background in the free troposphere is thus generally unimportant for surface air quality. Exceptions are plumes from large dust storms and forest fires which can be transported on intercontinental scales (Jacob & Winner, 2009).

## 2. Methods for estimating effects

Changes in climate affect air quality by hindering the rates of ventilation mechanisms (wind speed, mixing depth, convection, frontal passages), precipitation scavenging, dry deposition, background concentrations, by influencing atmospheric chemistry and by altering the frequency, severity, and duration of heat waves, and other meteorological processes (Fiore et al., 2015; Jacob & Winner, 2009).

Three main approaches are used to study the effects of climate change on ozone and PM air quality: (i) using observed correlations with meteorological variables, (ii) using chemical transport models

(CTMs) for perturbation studies, and (iii) combining CTM simulations with general circulation models (GCMs), driven by future climate projections.

Estimating effects through empirical correlation of air quality with meteorological studies (first approach) has great importance for the removal of meteorological variability in analyses of long-term trends of air quality. The second approach provides a diagnostic tool for more complex GCM–CTM simulations. Both first and second approaches help to gain insights on processes affecting pollutant concentrations and on the sensitivity of the pollutants to these processes. However, Empirical correlations and CTM perturbation studies cannot capture the complex coupling between meteorological variables involved in climate change nor the parallel change in anthropogenic emissions. The integrated approach (third approach) is hence preferable in order to best evaluate future concentrations of air pollutants.

## 3. Impact mechanisms – summary of research results

**Figure 3 and Figure 4** present results from studies performed by the first approach. **Figure 3** shows long-term trends (top) and correlations (bottom) of the number of ozone pollution days in Northeast U.S. and the number of mid-latitudes cyclones, illustrating the importance of frontal passages for pollutant ventilation (Leibensperger et al., 2008).

**Figure 4** shows a positive observed correlation between temperature and July mean daily maximum ozone at Pennsylvania State U.S. for 1988–2001 (black line) and 2002–2014 (red line). The shift in trend (from 4.1 ppb for every degree Celsius to only 2.4 ppb) after 2002 is induced by regional $NO_x$ emission controls (Fiore et al., 2015).

**Table 1** summarizes principal findings obtained by CTM perturbation studies (second approach), and those will be briefly presented. Temperature is the most important meteorological variable affecting ozone concentrations in polluted regions. This is attributed to two main factors: (i) the lifetime of peroxyacetyl-nitrate (PAN), a major sequestering reservoir for $NO_x$ and $HO_x$ radicals, is strongly dependent on temperature. In high temperatures, PAN is less stable, resulting in an increase in $NO_x$ concentrations. (ii) Biogenic emissions of isoprene, a potential ozone precursor under high-$NO_x$ conditions, increase with temperature. PM on the other hand is generally negatively correlated with temperature, although the effect depends on the PM component. Sulfate concentrations increase with temperature due to faster $SO_2$ oxidation but nitrate and organic semi-volatile components shift from the particle phase to the gas phase with increasing temperature, resulting in a decrease in PM concentrations. The second effect will dominate in regions where nitrate is a relatively large component. Regional stagnation is strongly positively correlated with both ozone and PM. Cold fronts, formed by mid-latitudes cyclones, are responsible for pollutant ventilation in North America, Europe and Eastern Asia. Longer stagnation periods are hence

expected to infer an increase in the frequency of high-ozone events and higher PM concentrations. Perturbation investigation of the sensitivity of ozone and PM to ventilation has been conducted in models by perturbing wind speeds or mixing depths. Weaker wind speed in polluted areas cause an increase in ozone levels due to longer reaction time. Mixing depth usually show positive correlation with ozone levels where surface ozone is low and a negative dependence where it is high. At northern mid-latitudes for example, ozone concentrations in the lower free troposphere are typically about 60 ppb, so that increasing mixing depth entrains relatively high-ozone air and a diluting effect in ozone concentrations is not achieved. In addition, diluting $NO_x$ in a deeper mixed layer increases its ozone production efficiency. For PM, increasing ventilation rates (higher wind speed or deeper mixed layer) has a simple diluting effect, stronger than the effect on ozone, due to lower background concentrations. However, an increase in mixing depth, as projected by some of the models in certain areas, is generally associated with a decrease in precipitation, representing a compensating effect.

As for humidity, an increase in water vapor increases ozone loss, since the reaction described in **Reaction 2** competes with the reaction of the excited oxygen atom $O(^1D)$ with $N_2$ or $O_2$, a reaction that can eventually form ozone. Under polluted conditions however, the effect is more complicated, because the OH radicals, produced by **Reaction 2**, react with VOCs and CO to produce ozone, while also converting $NO_2$ to nitric acid to suppress ozone formation. Under very dry conditions, drought stress on vegetation can suppress stomatal uptake of ozone and hence dry deposition, resulting in elevated concentrations of ozone. Relative humidity has a positive effect on PM since it increases the PM water content and hence the uptake of semi-volatile components, mainly nitrate and also possibly organics. Increasing solar radiation (less cloud cover) in CTM perturbation studies causes an increase of ozone, but the effect is weak since the increased UV flux stimulates both ozone production and loss (**Reaction 1**). The effect of cloud cover on PM is weak as well, despite the importance of clouds for sulfate production by aqueous-phase oxidation of $SO_2$. Ozone have little sensitivity to precipitation. As mentioned before, wet deposition for ozone is negligible as ozone and its major precursors have low solubility in water. PM concentrations decrease with increasing precipitation, as wet deposition provides the main PM sink. Since scavenging within a precipitating column is highly efficient, the critical variable is the frequency of precipitation rather than precipitation rate (Jacob & Winner, 2009).

Jacob and Winner (2009) listed several major GCM–CTM studies in the literature and summarized their result regarding projected changes in surface ozone. They reviewed studies which examined the effect of climate change only, holding anthropogenic emissions of ozone and PM precursors constant. Their summary indicates that polluted regions at northern mid-latitudes will experience higher surface ozone as a result of 21st century climate change. The projected summertime increases are typically 1–10 ppb and are found to be driven primarily by temperature, as seen in both empirical correlation and CTM perturbation studies. Increases from climate change is largest in urban areas

where present-day ozone is already high. Decreases are expected only in relatively clean areas where ozone is largely determined by its background, which is expected to decrease. Across all GCMs, projected lower frequency of frontal passages is consistent, and induce a significant ozone increase. It should be noted that great variability exists between studies due to different used models and climate change scenarios.

According to Jacob and Winner (2009), projected changes in surface PM concentrations in polluted regions due to 21st century climate change are in the range ±0.1–1 $\mu gm^{-3}$, but little consistency is seen between studies, including in the sign of the effect. The regional-dependent changes in precipitation patterns force different effects in different areas of the world. Here as well, increased stagnation in the future climate causes PM to increase in polluted regions.

Other GCM–CTM studies took into account projected changes in anthropogenic emissions as well, in addition to projected climate changes. **Figure 5 and Figure 6** shows projected annual mean surface ozone changes and PM changes, respectively, over the 21st century for different world regions, generated by chemistry–climate models using the RCP trajectories. Under all RCP scenarios, surface ozone concentrations in all regions by 2100 are expected to decrease, with the exception of RCP8.5 (**Fig. 5**). Over most of the globe, and in some industrial regions (North America, Europe, and Central Eurasia), an overall decline in PM2.5 is projected, with little difference across the four scenarios (Fiore et al., 2012).

## 4. Discussion and relation to air pollution management

Comparison between GCM–CTM studies that took into account projected changes in anthropogenic emissions and studies that examined the effect of climate change only, implies that the range in surface ozone and PM projections is mainly dominated by emission changes.

Global $NO_x$ emissions are expected to decline over the next century (**Fig. 7**), decreasing surface ozone. However, under RCP8.5, the rise in $CH_4$ (**Fig. 7**) increases surface ozone levels, as seen in **Fig. 5**. Over South Asia, the PM2.5 projections are strongly tied to the OC emissions (**Fig. 8**). South Asian $SO_2$ emissions decline similarly under all RCPs, with the exception of RCP6.0 in which $SO_2$ emissions between 2050 and 2070 may contribute to raising PM2.5 relative to the other RCP scenarios (**Fig. 8**). Over East Asia, the different PM2.5 projections likely reflect a combination of the changes in $SO_2$ and carbonaceous aerosols. Climate influences are seen in the particularly noisy projections of PM2.5 surface concentrations over Africa, the Middle East, and to some extent Australia, which reflect the dominance of dust sources in these regions and the strong dependence on inter-annual meteorological variability (Fiore et al., 2012).

Despite the dominant influence of emission changes on ozone and PM projections observed in the reviewed study above, we can see a clear indication that climate change will partly offset the benefit of the projected emissions reductions, through the different mechanisms described in section 3. Wu et al. (2008) defined it as a "climate change penalty", referring to ozone only. A climate penalty is either the increase in surface ozone resulting from regional climate warming in the absence of precursor emission changes or the additional precursor emission reductions needed to achieve a targeted level of air quality in a warmer climate. For example, we can express the climate change penalty as the amount of additional $NO_x$ emission controls that will be required as a result of climate change to attain a given air quality target, considering that $NO_x$ is usually the limiting precursor for ozone formation. Wu et al. (2008) showed that if we want anthropogenic emissions to drop by 40% by 2050, we actually need to decrease emissions by 50%.

Another important issue that should be addresses by stakeholders, is the future necessity to deal with extreme events, such as heat waves, wildfires and dust events. Frequency increase of these events will eventually cause an increase in pick pollution episodes, even if the overall mean concentrations are expected to decrease, making it difficult to attain short term air quality standards.

Other aspects that were not discussed in this work are the possible response of pollutant emissions to climate change. Higher temperatures increase the demand for air conditioning in summer. Abel et al. (2017) tried to quantify historical trends and found for example that electricity generating units in the Eastern U.S. region from 2007 to 2012 exhibited almost 4% increase in electricity generation per °C increase during summer months. This was associated with a 3-4%/°C increase in $SO_2$, $NO_x$ and $CO_2$ emissions.

## 5. Summary and conclusions

This work dealt with the effect of climate change on air quality, and presented the projected surface concentrations changes of two major pollutants, ozone and PM, by the end of the 21st century, summarized from different studies. We first reviewed the different methods in use today for the estimation of climate-pollution relationships. These include observed correlations of ozone and PM with meteorological variables, perturbation studies using regional chemical transport models (CTMs), and future-climate simulations with general circulation models (GCMs) coupled to CTMs.

Main findings from the first two approaches clearly show that ozone is positively correlated with temperature and regional stagnation. Both are expected to raise in the future and will induce an increase in ozone concentrations of 1–10 ppb (forced by climate alone) by the end of the century, depending on the time horizon, region, climate scenario, and model used. PM is positively correlated with regional stagnation but negatively correlated with precipitation and mixing depth.

High uncertainty exists in the expected changes of these variables, resulting in a projected PM change in the range $\pm 0.1–1\ \mu g m^{-3}$.

Nevertheless, future ozone and PM surface concentrations are expected to be driven by changes in both climate and emissions. Reduction in anthropogenic emissions worldwide should eventually cause a decrease in both PM and ozone levels. A "climate change penalty" can be defined as the additional precursor emission reductions needed to achieve a targeted level of air quality in a warmer climate. This penalty will require more stringent emission controls to meet a given ozone air quality target in the future.

Challenges still exist in the field, including examination of regional climate change effects in areas other than North America and Europe, studying the response of natural emissions to climate change or dealing with computational limitations that still restrict the length and the resolution of the simulations.

## References


Abel, D., Holloway, T., Kladar, R. M., Meier, P., Ahl, D., Harkey, M., & Patz, J. (2017). Response of Power Plant Emissions to Ambient Temperature in the Eastern United States. *Environmental Science and Technology*, *51*(10), 5838–5846. https://doi.org/10.1021/acs.est.6b06201

Fiore, A. M., Naik, V., & Leibensperger, E. M. (2015). Air quality and climate connections. *Journal of the Air and Waste Management Association*, *65*(6), 645–685. https://doi.org/10.1080/10962247.2015.1040526

Fiore, A. M., Naik, V., Spracklen, D. V., Steiner, A., Unger, N., Prather, M., … Zeng, G. (2012). Global air quality and climate. *Chemical Society Reviews*, *41*(19), 6663–6683. https://doi.org/10.1039/c2cs35095e

IPCC. (2014). *Climate Change 2013. the Fifth Assessment Report* (Vol. 5).

Jacob, D. J., & Winner, D. A. (2009). Effect of climate change on air quality - citation. *Atmospheric Environment*, *43*(1), 51–63. https://doi.org/https://doi.org/10.1016/j.atmosenv.2008.09.051

Lagzi, I., Meszaros, R., Gelybo, G., & Leelossy, A. (2013). *Atmospheric Chemistry*. Retrieved from http://elte.prompt.hu/sites/default/files/tananyagok/AtmosphericChemistry/index.html

Leibensperger, E. M., Mickley, L. J., & Jacob, D. J. (2008). Sensitivity of US air quality to mid-latitude cyclone frequency and implications of 1980-2006 climate change. *Atmospheric Chemistry and Physics*, *8*(23), 7075–7086. https://doi.org/10.5194/acp-8-7075-2008

Nasa earth observatory. (2019). Retrieved March 10, 2019, from https://earthobservatory.nasa.gov/features/Aerosols/page3.php

Silva, R. A., West, J. J., Zhang, Y., Anenberg, S. C., Lamarque, J. F., Shindell, D. T., … Zeng, G. (2013). Global premature mortality due to anthropogenic outdoor air pollution and the contribution of past climate change. *Environmental Research Letters*, *8*(3). https://doi.org/10.1088/1748-9326/8/3/034005

WHO. (2019). Ambient air pollution: Health impacts. Retrieved March 10, 2019, from https://www.who.int/airpollution/ambient/health-impacts/en/

Wu, S., Mickley, L. J., Jacob, D. J., Rind, D., & Streets, D. G. (2008). Effects of 2000-2050 changes in climate and emissions on global tropospheric ozone and the policy-relevant background surface ozone in the United States. *Journal of Geophysical Research Atmospheres*, *113*(18). https://doi.org/10.1029/2007JD009639

Wu, S., Mickley, L. J., Leibensperger, E. M., Jacob, D. J., Rind, D., & Streets, D. G. (2008). Effects of 2000-2050 global change on ozone air quality in the United States. *Journal of Geophysical Research Atmospheres*, *113*(6), 1–12. https://doi.org/10.1029/2007JD008917

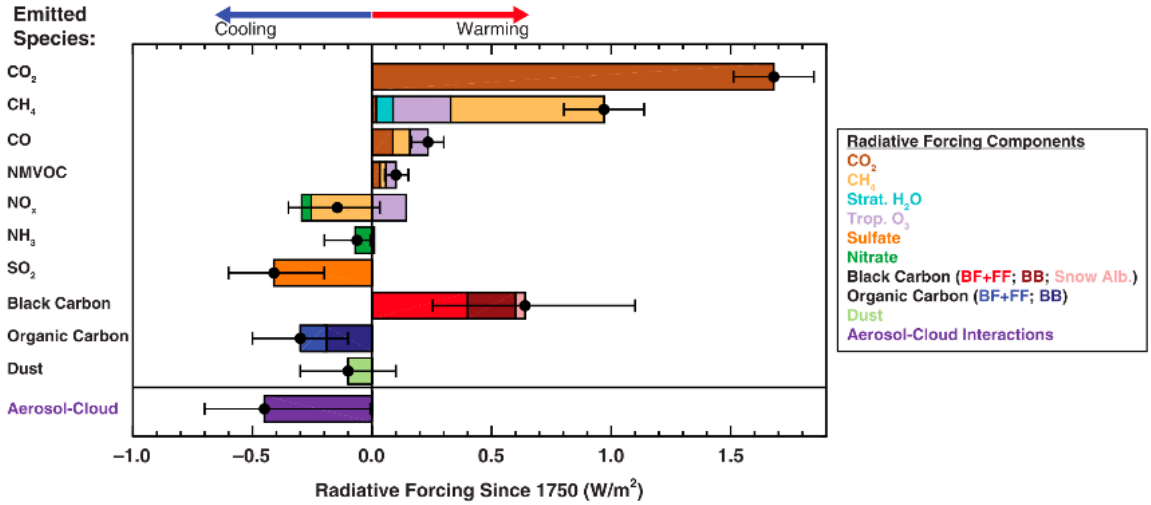


**Figure 1.** Globally averaged radiative forcing (RF) of climate from preindustrial (1750) to 2011 of air pollutants and their precursor emissions, as compared to carbon dioxide ($CO_2$) emissions (Fiore et al., 2015).

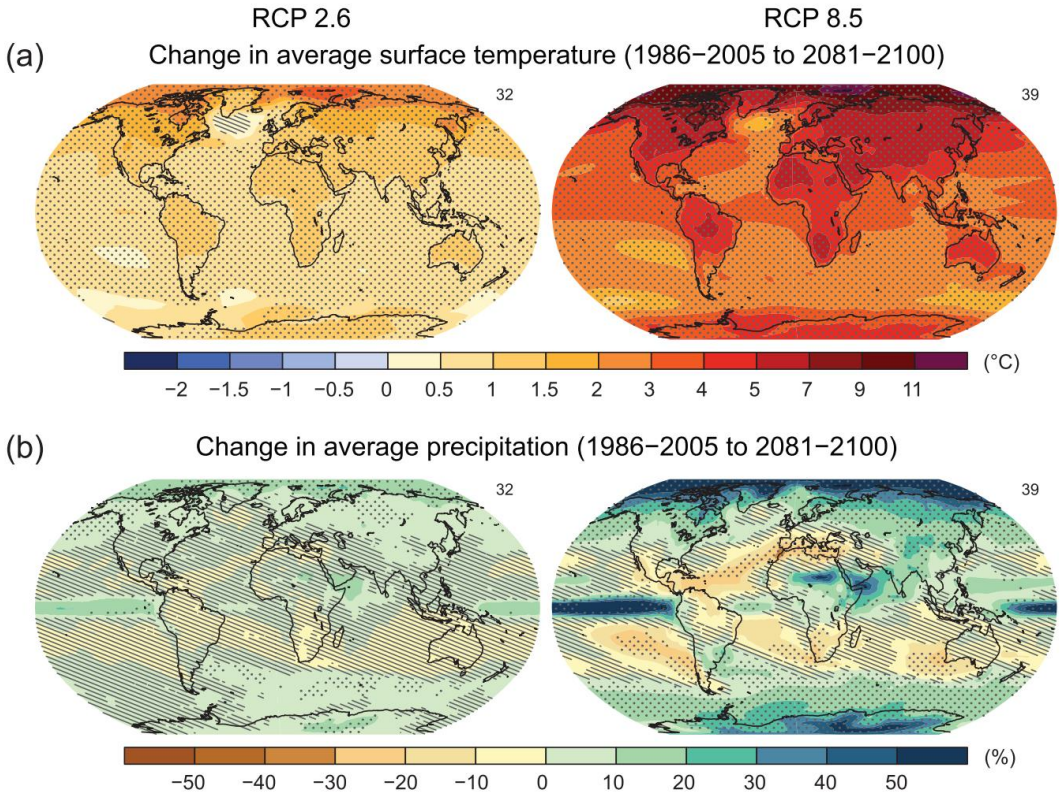


**Figure 2.** Maps of IPCC multi-model mean results for the scenarios RCP2.6 and RCP8.5 in 2081-2100 of (a) annual mean surface temperature change, (b) average percent change in annual mean precipitation (IPCC, 2014).

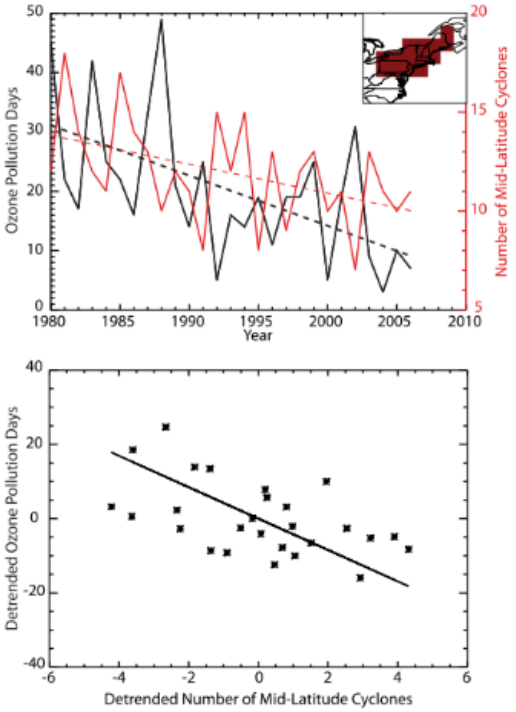


**Figure 3. Top:** 1980–2006 trend in the number of ozone pollution episodes (black) and the number of mid-latitude cyclones (red) in the northeastern U.S. in summer (Jun–Aug). Ozone pollution days are defined by the occurrence of a daily maximum 8-h average ozone concentration exceeding 84 ppb in one of the 2.5°×2.5° grid squares) in the north-eastern U.S. **Bottom:** a scatterplot of the number of ozone pollution days vs. the number of mid-latitude cyclones in the southern climatological track, for individual years in the 1980–2006 record and after removal of the long-term linear trend (Leibensperger et al., 2008).

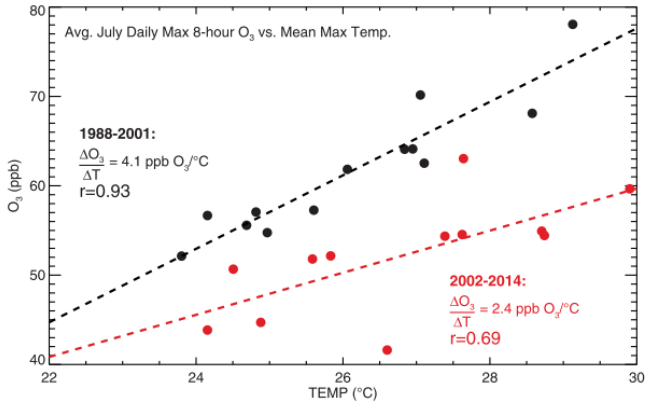


**Figure 4.** A scatterplot of the number of ozone pollution days vs. temperature in July at a site in Pennsylvania, U.S. for 1988–2001 (black) and 2002–2014 (red). ordinary least squares slopes and correlation coefficients are shown, illustrating the shift after 2002 induced by regional $NO_x$ emission controls (Fiore et al., 2015).

**Table 1.** Dependence of surface ozone and PM on meteorological variables, as obtained from CTM perturbation studies. Results are summarized as consistently positive (++), generally positive (+), weak or variable (=), generally negative (-), and consistently negative (--) (Jacob & Winner, 2009).

| Variable | Ozone | PM |
|---|---|---|
| Temperature | ++ | − |
| Regional stagnation | ++ | ++ |
| Wind speed | − | − |
| Mixing depth | = | − − |
| Humidity | = | + |
| Cloud cover | − | − |
| Precipitation | = | − − |

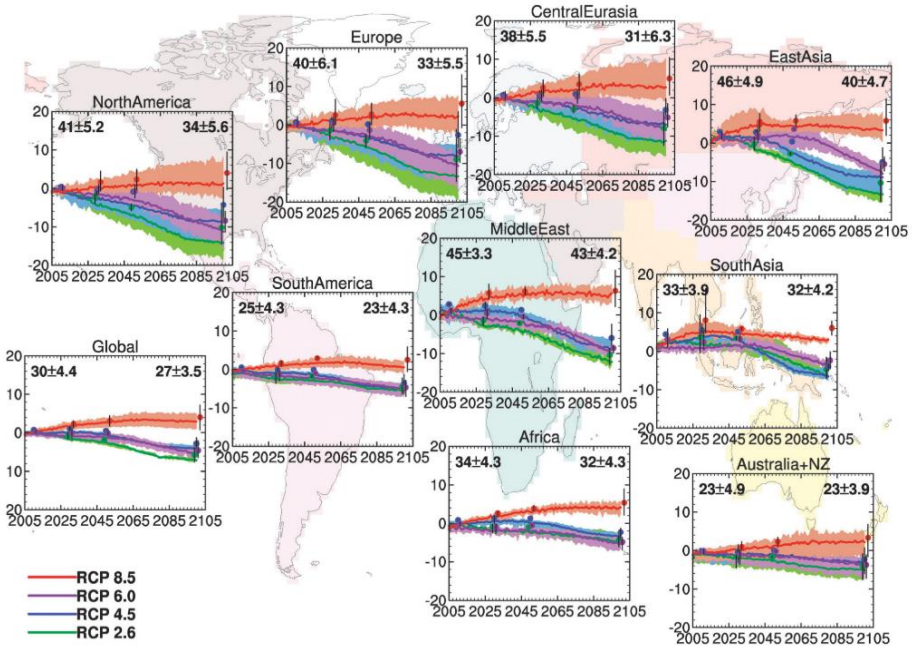


**Figure 5.** Changes in annual mean surface ozone (ppb mole fraction) averaged over selected world regions (shaded land regions) following the RCP scenarios. Filled circles with vertical lines represent decadal multi-model averages from the 2010, 2030, 2050, and 2100 time-slice simulations (Fiore et al., 2012).

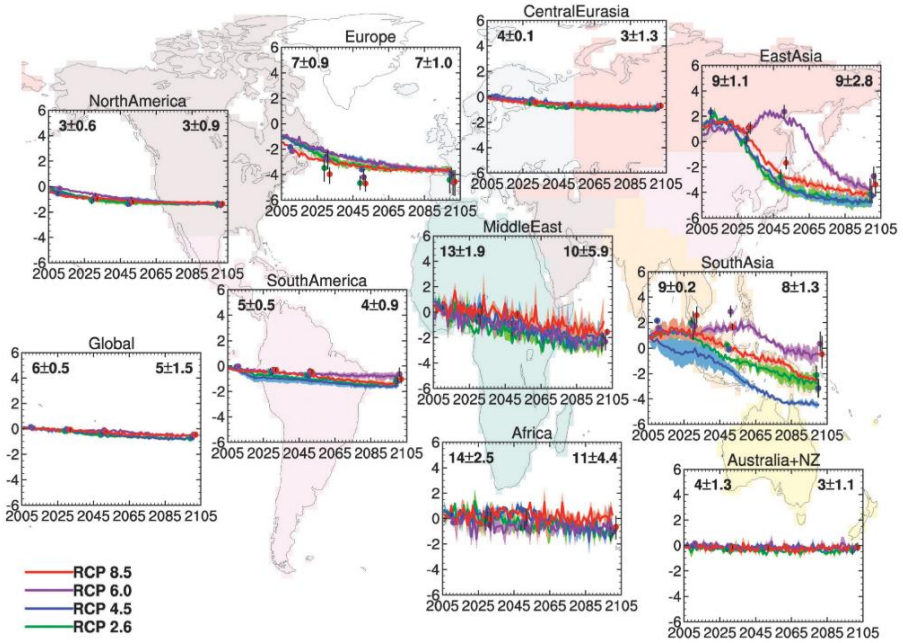


**Figure 6.** Changes in annual mean surface PM2.5 (ng per g-air) averaged over selected world regions (shaded land regions) following the RCP scenarios. PM2.5 is calculated as the sum of individual aerosol components (black carbon + organic carbon, + sulfate + secondary organic aerosol + 0.1*dust + 0.25*sea salt). Nitrate was not reported for most models and thus is not included here (Fiore et al., 2012).

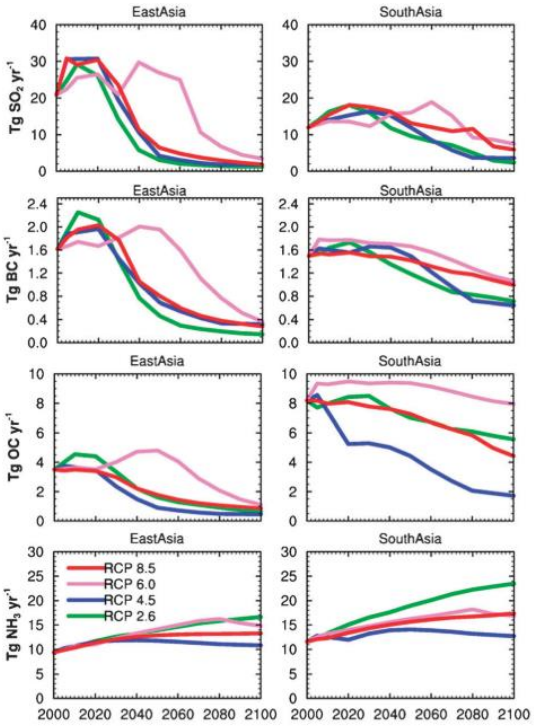


**Figure 7.** RCP emissions (2000-2100) of aerosols and precursor emissions from anthropogenic plus biomass burning sources, averaged over East Asia (left column) and South Asia (right column) (Fiore et al., 2012).

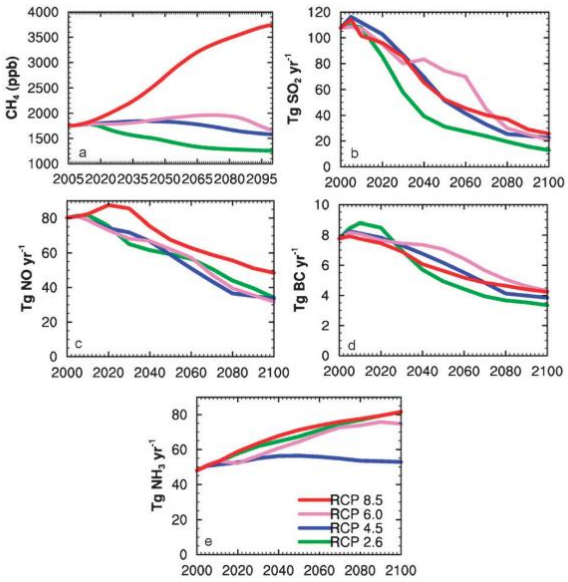


**Figure 8.** Future evolution of (a) $CH_4$ abundance and selected global emissions of air pollutants and precursors, (b) $SO_2$, (c) NO, (d) BC, and (e) $NH_3$, from anthropogenic plus biomass burning sources combined, under the RCP scenarios (Fiore et al., 2012).