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Integrated assessment of air quality and climate change for policy-making

—Highlights of IPCC AR5 and research challenges

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Recently, air quality in China has received significant attention, especially since the unprecedented heavily polluted haze episodes were observed in populated areas of central and eastern China [1]. Major atmospheric air pollutants include tropospheric ozone (O_3) and aerosols (small liquid or solid particles, also called $PM_{2.5}$ when referring to particles with diameters of 2.5 μm or less), which result mainly from emissions of methane (CH_4), carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organics (NMVOCs), sulfur dioxide (SO_2), ammonia (NH_3), black carbon (BC), organic carbon (OC), and dust from human activities, such as energy production, industry, transportation, and agricultural and residential activities [2]. Emissions from natural sources, such as lightning NO_x, NO_x from soil, biogenic hydrocarbons, dimethyl sulfide (DMS) and sea salt from the oceans, as well as emissions from wild fires, also contribute to the formation of air pollutants.

ROLE OF AIR POLLUTANTS IN CLIMATE CHANGE

Tropospheric O_3 and aerosols have made significant contributions to climate change since pre-industrial times, as summarized by the Intergovernmental Panel on Climate Change (IPCC) Working Group I Fifth Assessment Report (WGI AR5) [3]. From 1880 to 2012, the globally averaged combined land and ocean surface temperature exhibited a warming of 0.85°C (0.65–1.06°C). The IPCC report provides radiative forcing values to quantify the role of human influence on the Earth's energy budget (Fig. 1) and hence on past climate change. While carbon dioxide (CO_2) provides the largest radiative forcing on climate, short-lived species (CO, NMVOCs, NO_x, and aerosols) exert important climatic forcings with either positive or negative signs. Radiative forcing values by well-mixed greenhouse gases (CO_2, CH_4, N_2O, and halocarbons), tropospheric O_3, and aerosols are $+2.83$, $+0.40$, and -0.90 W m^{-2}, respectively, indicating that air pollutants play important roles in climate change. It should be noted that following advances in global modeling of the formation and removal of chemical species in the atmosphere, the IPCC WGI AR5 presents for the first time emission-based estimates of radiative forcing values. It also provides a number of metrics to quantify and communicate the relative and absolute contributions to climate change of emissions of different substances, and of emissions from various regions/countries, sources, and sectors. Furthermore, the IPCC AR5 presents for the first time the radiative forcing by emissions of short-lived gas-phase species of NO_x, CO, and NMVOCs. These species do not participate in radiative transfer in the atmosphere, but influence the concentrations of many greenhouse gases and aerosols through chemical processes, reflecting the strong link between air quality and climate change.

Air pollutants are short-lived species that have a lifetime from just days up to about a decade. Different air pollutants have either a warming or a cooling effect on climate depending on their chemical and physical characteristics. Emissions of CO and NMVOCs are virtually certain to have induced a positive radiative forcing on climate because they lead to increases in the concentrations of CO_2, CH_4, and O_3 through chemical reactions. NO_x is estimated to have a net negative radiative forcing through altering the concentrations of nitrate aerosol, CH_4, and tropospheric O_3 (Fig. 1). Among the major anthropogenic aerosol species in the atmosphere, sulfate, nitrate, ammonium, and OC have a cooling effect through aerosol–radiation and aerosol–cloud interactions, whereas BC has a warming effect via the absorption of sunlight. Air quality controls that target tropospheric O_3 or aerosols (or particulate matter) might lead to complex effects on the climate (Fig. 2). Air quality controls might also target specific sectors of anthropogenic activity, such as transportation or energy production. Thus, co-emitted species within the targeted sector could lead to a complex mix of chemistry and climate perturbations.

REDUCTIONS OF AIR POLLUTANTS TO MITIGATE CLIMATE CHANGE

To protect human health, strategies for air pollution abatement must be pursued aggressively. However, in the meantime, rapid climate change is of worldwide concern. In the 2009 Copenhagen Accord, many nations agreed to limit the increase in global temperature since

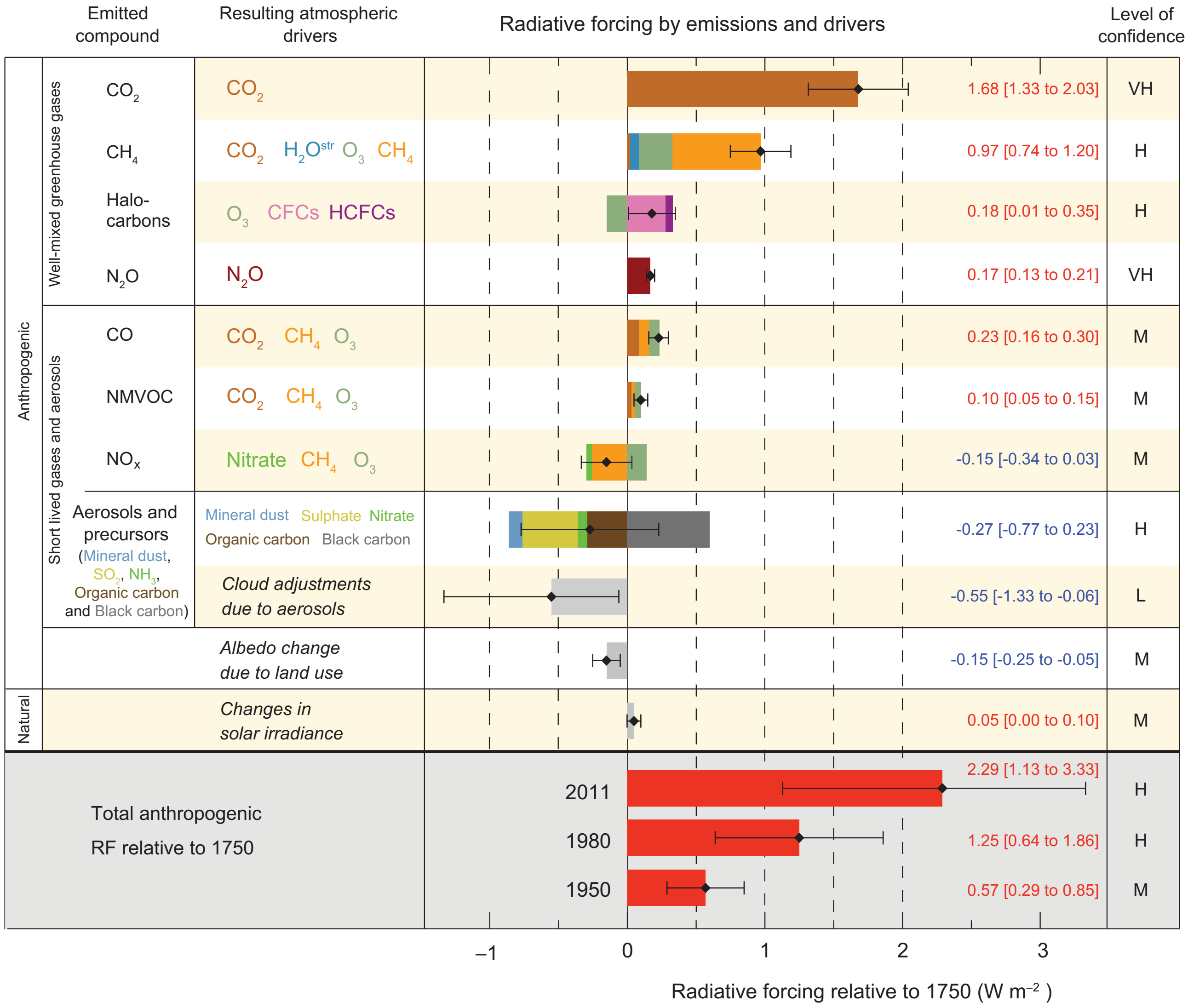

Figure 1. Radiative forcing estimates in 2011 relative to 1750 and aggregated uncertainties for the main drivers of climate change. Positive (or negative) radiative forcing indicates a warming (or cooling) effect on climate. (Published by the IPCC WGI AR5 [3], p. 14.)

pre-industrial times to below 2°C by initiating significant cuts in global emissions of greenhouse gases [4]. Because of the long lifetime of CO_2 in the atmosphere, reductions in CO_2 emissions are essential for any climatological long-term benefits. Compared with CO_2, short-lived species, such as CH_4, tropospheric O_3, and BC aerosol, persist for just a short time in the atmosphere and have positive radiative forcing values (Fig. 1). Urgent action to reduce the concentrations of these short-lived species in the atmosphere will improve air quality (reducing risks to health and crop yields) and combat short-term accelerated warming (reducing risks of crossing a critical temperature threshold) [5]. Therefore, both

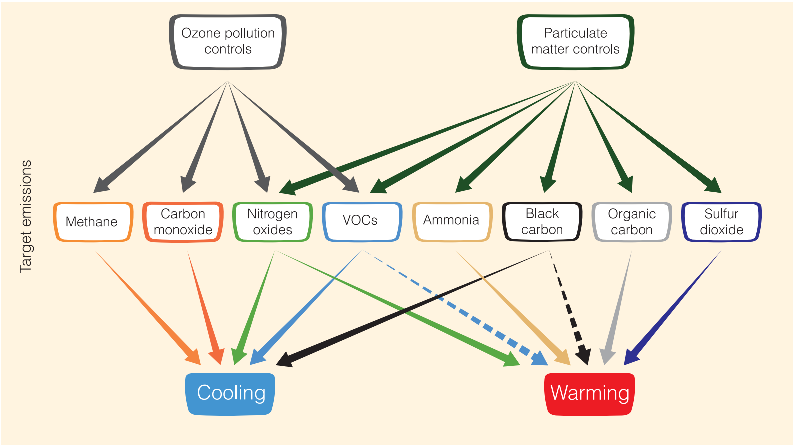

Figure 2. Schematic of the impact of pollution controls on specific emissions and climate impact. Solid black line indicates known impact; dashed line indicates uncertain impact. (Published by the IPCC WGI AR5 [3], p. 684.)

near-term and long-term strategies have been proposed to protect the climate [6]. Reductions in near-term warming can be achieved by control of the short-lived climatic forcers, whereas reductions in CO_2 emissions are required to limit long-term climate change.

RESEARCH CHALLENGES

The important scientific question is whether the policies intended to reduce air pollutants can also benefit the climate. The integrated assessment of air quality and climate change is a challenge and one that requires the coupling of socio-economic models with advanced atmospheric chemistry–climate models. Model predictions depend critically on the assumed future emission scenarios [7–9]. Therefore, interaction among economic analysts, emissions experts, and atmospheric scientists will be paramount for the creation of decision-support tools to evaluate policy options for air quality and climate. The climatic effects of reducing air pollution over the next few decades, including those that result from the implementation of specific policies designed to mitigate climate change, need to be understood and communicated to those who will bear the burden. Integrated scientific research on air quality and climate should emphasize both the long-term climatic benefits and, more importantly, the immediate benefits for air quality and energy security.

During the past decade, important advances have been made with regard to air pollutants and their roles in climate change in China. Emission inventories of tropospheric O_3, aerosol precursors, and aerosols have become available for the China domain, which allow the simulation of air pollutant concentrations and the estimation of their climatic effects using numerical models. Increasing numbers of ground measurements of air pollutants in China, together with satellite measurements of aerosol optical properties and cloud properties, have provided data sets to constrain the simulated climatic effects of short-lived species. However, estimates of the climatic effects of air pollutants in China are still subject to large uncertainties. The fundamental requirements of science pertaining to the integrated assessment of air quality and climate policy, to achieve sustainable development and a low carbon society, are as follows.

(1) Continued improvement in economics, emissions, and policy cost models for analysis of the interaction of human activities with climate processes. Simultaneous changes in the emissions of air pollutants and greenhouse gases need to be developed based on economic analyses of different sectors and regions. A flow chart presenting the integrated assessment of air quality and climate to support policy making is given in Fig. 3.

(2) Nationwide long-term measurements of concentrations of well-mixed greenhouse gases and pollutants are needed. Ground measurements of speciated aerosol mass concentrations and size-resolved aerosol number concentrations are important for evaluation of emission inventories and for improving the representations of chemical species in climate models. Satellite measurements have excellent spatiotemporal coverage, which are useful for analyses of the physical/chemical/optical characteristics of air pollutants and for source attribution.

(3) Improved understanding of aerosol–cloud interactions. How aerosol particles influence clouds is one of the most difficult challenges in climate simulation because the microphysical processes involved are very complex. Aerosol–cloud feedbacks also influence concentrations and distributions of air pollutants through processes such as aqueous aerosol formation and the wet deposition of both gas-phase and aerosol species. Measurements and modeling of aerosol microphysical properties and cloud properties are required to reduce uncertainties associated with the quantification of air pollutants and climatic effects of aerosols.

(4) Continued development of Earth System Models that account for coupled dynamic and chemical atmosphere, ocean, land, and natural ecosystem interactions and feedbacks.

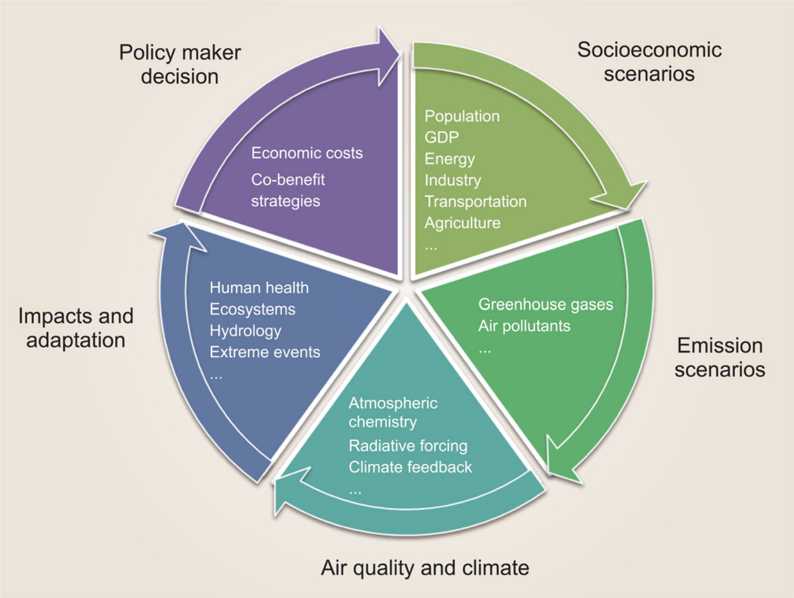

Figure 3. Integrated assessment of air quality and climate to support policy making.

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