The joint economic consequences of climate change and air pollution

Submission for the 2017 GTAP conference

Draft version; **not to be cited or quoted**

Rob Dellink* and Elisa Lanzi

OECD Environment Directorate

*presenter and contact person: rob.dellink@oecd.org

Keywords

General equilibrium modelling; climate change; air pollution; environmental feedbacks

Abstract

The need for integrated analysis of climate change and air pollution policies is widely acknowledged, often referred to as co-benefits. Much less is known, however, about how damages from climate change and damages from air pollution affect regional economies in the coming decades.

This paper focuses on the economic consequences of both climate change and outdoor air pollution until 2060. We build a dynamic CGE model with a common methodology for evaluating the joint economic consequences of climate change and air pollution. We use a production function approach that specifies sectoral and regional climate and air pollution impacts on specific inputs into the economy.

The modelling results highlight that despite significant climate forcing from various air pollutants, the net interaction effects through emission feedbacks are limited. Furthermore, the effect of climate damages on air pollution emissions and thus air pollution impacts, and the effect of air pollution damages on GHG emissions and thus climate damages are relatively small in comparison to the uncertainties surrounding the damage estimates.

Although the effects of climate change play out over a longer time horizon than those of air pollution, the coming decades are projected to have significant economic repercussions from both. For both cases, the majority of damages are located in relatively fragile economies in Asia and Africa. The largest percentage losses are observed in agriculture, where both climate change and air pollution have significant adverse effects. Furthermore, in the most affected regions and sectors there is a small but positive interaction effect: the damages from both types of impacts together is smaller than the sum of individual damages.

We finally quantify the non-market damages on premature deaths from heat stress and air pollution. These are not integrated in the modelling exercise, but their sheer size warrants that they are considered.

1. Introduction and background

While a certain amount of environmental degradation is already happening, the range of possible outcomes over the course of this century and beyond is very wide. A modelling analysis of the economic consequences of environmental damages at a global level can offer clear insights into the big picture: the direction of change and the interactions that they induce in the economic system. The need for integrated analysis of climate change and air pollution is widely acknowledged. Co-benefits of climate policies for improved health and reduced air pollution are widely cited as a reason for immediate climate action. Similarly, the links between both issues through the energy system are ample.

What is much less known, however, is how the damages from climate change and the damages from air pollution will affect regional economies in the coming decades. Full quantitative assessments of simultaneous damages for both issues simultaneously are very scarce. Such a joint assessment is vital, however, for identifying the benefits of integrated climate and air pollution policies, and avoid suboptimal policy responses to two major environmental issues. To gain better insight into the joint economic repercussions of both issues a common methodology is required, building on a model that can translate sectoral and regional climate and air pollution impacts in shocks to the global economy.

This paper aims to fill that gap by applying a systematic approach to evaluating the economic consequences of climate change and air pollution for a range of sectoral impacts, using a production function approach. This allows studying the economic interactions between the costs of inaction on climate change and air pollution. The analysis builds on the separate assessment of the economic consequences of climate change (OECD, 2015) and air pollution (OECD, 2016).

The paper does not try to quantify the benefits of policy action. While it is a priori clear that major synergies can be raped by integrating climate change mitigation and air pollution control policies, this is left for future research.

This paper is set up as follows: Section 2 describes the modelling tools and the methodology to incorporate environmental damages. Section 3 presents the results of the modelling analysis, while Section 4 quantifies some of the most important non-market impacts: premature deaths caused by climate change and air pollution. Section 5 concludes.

2. Methodology

2.1. Modelling tools

The core tool used in this paper is the dynamic global multi-sector, multi-region model ENV-Linkages (with a disaggregation in 25 regions and 35 sectors), which is coupled to biophysical and other impact models for an integrated assessment. Using a systems approach allows detailed assessments of how environmental feedbacks affect the economy at global, regional, macroeconomic and sectoral levels.

ENV-Linkages is a global dynamic computable general equilibrium (CGE) model that describes how economic activities are linked to each other between sectors and across regions. The version used for the current analysis contains 35 economic sectors (see Table 1) and 25 regions (reproduced in Table 2), bilateral trade flows and has a sophisticated description of capital accumulation using capital vintages, in which technological advances only trickle down slowly over time to affect existing capital stocks. It also links economic activity to environmental pressure, specifically to GHG emissions. In ENV-Linkages, sectoral and regional economic activities are projected for the medium- and long-term future, up to 2060, based on socio-economic drivers such as demographic developments, economic growth and development in economic sectors.

Table 1. Sectoral aggregation of ENV-Linkages

Agriculture	Manufacturing
Paddy Rice	Paper and paper products
Wheat and meslin	Chemicals
Other Grains	Non-metallic minerals
Vegetables and fruits	Iron and Steel
Sugar cane and sugar beet	Metals n.e.s.
Oil Seeds	Fabricated metal products
Plant Fibres	Food Products
Other Crops	Other manufacturing
Livestock	Motor vehicles
Forestry	Electronic Equipment
Fisheries	Textiles
Natural Resources and Energy	**Services**
Coal	Land Transport
Crude Oil	Air and Water Transport
Gas extraction and distribution	Water services
Other mining	Construction
Petroleum and coal products	Trade Other Services and Dwellings
Electricity (7 technologies)	Other Services (Government)
Fossil-Fuel based Electricity; Combustible renewable and waste based Electricity; Nuclear Electricity; Hydro and Geothermal; Solar and Wind; Coal Electricity with CCS; Gas Electricity with CCS	

Table 2. Regions in ENV-Linkages

Macro regions	ENV-Linkages countries and regions
OECD America	Canada Chile Mexico United States
OECD Europe	EU large 4 (France, Germany, Italy, United Kingdom) Other OECD EU (other OECD EU countries) Other OECD (Iceland, Norway, Switzerland, Turkey, Israel)
OECD Pacific	Australia & New Zealand Japan Korea
Rest of Europe and Asia	China Non-OECD EU (non-OECD EU countries) Russia Caspian region Other Europe (non-OECD, non-EU European countries)
Latin America	Brazil Other Lat.Am. (other Latin-American countries)
Middle East & North Africa	Middle-East North Africa
South and South-East Asia	India Indonesia ASEAN9 (other ASEAN countries) Other Asia (other developing Asian countries)
Sub-Saharan Africa	South Africa Other Africa (other African countries)

The regional and sectoral structure of the models, as well as the energy details, can be exploited to produce projections of GHG emissions so as to obtain an emission pathway. CO_2 emissions from combustion of energy are directly linked to the use of different fuels in production. Other GHG emissions are linked to output with an elasticity to reflect the associated marginal abatement cost curves. The following non-CO_2 emission sources are considered: *i)* methane from rice cultivation, livestock production (enteric fermentation and manure management), fugitive methane emissions from coal mining, crude oil extraction, natural gas and services (landfills and water sewage); *ii)* nitrous oxide from crops (nitrogenous fertilizers), livestock (manure management), chemicals (non-combustion industrial processes) and services (landfills); *iii)* industrial gases (SF6, PFC's and HFC's) from chemicals industry (foams, adipic acid, solvents), aluminium, magnesium and semi-conductors production. Once the emissions are obtained, MAGICC (Meinshausen *et al*., 2011) is used to translate the emission pathway into emission concentrations and temperature changes. These temperature changes are the basis for assessing the impacts of climate change.

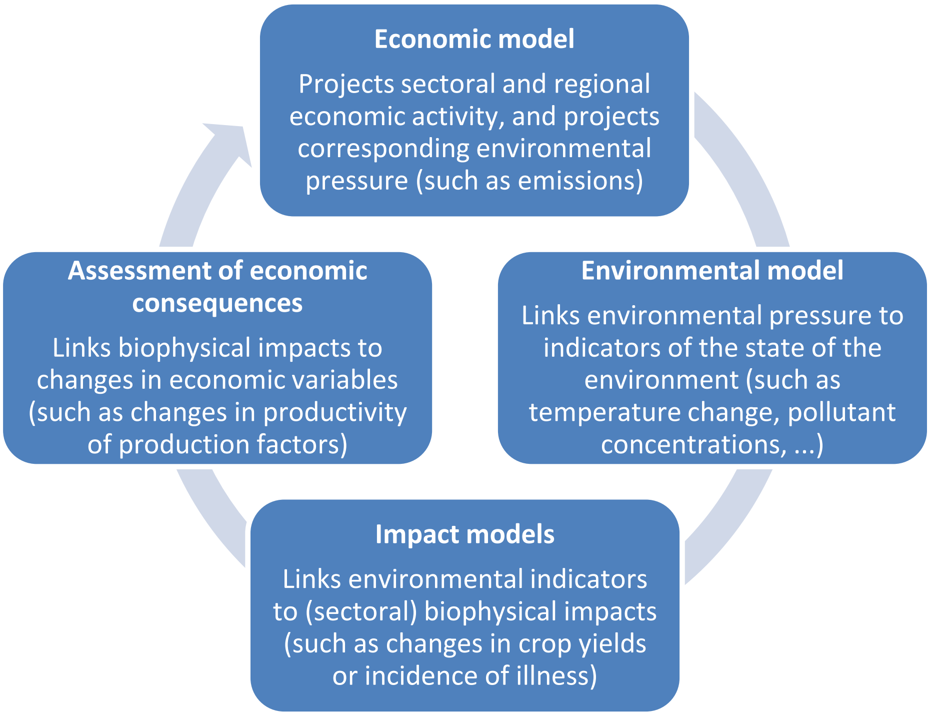
Emissions of air pollutants have been included in the ENV-Linkages model linking them to production activities in different key sectors. The main emission sources are power generation and industrial energy use, due to the combustion of fossil fuels; agricultural production, due to the use of fertilisers; transport, especially due to fossil fuel use in road transport, and emissions from the residential and commercial sectors. In this study, estimates for selected air pollutants were included: sulphur dioxide (SO_2), nitrogen oxides (NO_x), black carbon (BC), organic carbon (OC), carbon monoxide (CO), volatile organic compounds (VOCs) and ammonia (NH_3). Even if this list does not cover all air pollutants, it includes the main precursors of PM and ground level ozone, which are the main causes of impact on health and on crop yields. The data on air pollutants used for this report is the output of the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model (Amann et al., 2013; Wagner et al., 2007). The coefficients are sector- and region-specific to reflect the different implementation rates of respective technologies required to comply with the existing emission legislation in each sector and region. They also change over time to reflect technological improvements, the change in the age structure of the capital stock (more recent generations of equipment submitted to environmental policies replacing the older ones), and the influence of existing policies. Between 2050 and 2060, the emission coefficients (but not total emissions) are assumed to be constant.

Emission projections of precursor gases are used to calculate the associated concentrations of $PM_{2.5}$ and ground level ozone (O_3). The concentrations of ozone and $PM_{2.5}$ have been calculated using the EC-JRC's TM5-FASST model (Van Dingenen and Dentener, forthcoming). As impacts are related to exposure, the concentrations are calculated as population-weighted mean concentrations, rather than average concentrations across areas with widely varying population densities. Concentrations of $PM_{2.5}$ that are used for the calculations of the health impacts are quantified as population-weighted $PM_{2.5}$ values per country. For the O_3 impact on human health, the maximal 6-months mean of daily maximal hourly ozone (M6M) is most appropriate. For damages to crops, an average is taken of the ozone impacts as calculated using AOT40, which is the accumulated hourly ozone above 40 parts per billion (ppb) during a 3-monthly growing season; and using M12, which is the daytime (12 hours) mean ozone concentration during a 3-monthly growing season. These indicators for concentrations of $PM_{2.5}$ and ozone are the starting points to calculate impacts on health and on crop yields.

2.2. A production function approach

The modelling approach is to specify the effects of a selected set of environmental impacts on the drivers of economic growth, such as the productivity and supply of specific production factors, as well as changes in consumer demand and international trade; this is called the production function approach. This entails a closed loop of interacting model calculations (see Figure 1).

Figure 1. The modelling framework



First, baseline socioeconomic projections that exclude environmental damages are used to calculate environmental pressures and – using external models –the resulting greenhouse gas and air pollutant concentrations, temperature change and other environmental indicators such as carbon stocks; these trends abstract from short-term disruptions and business cycles. Secondly, these are used to calculate a set of biophysical impacts, such as changes in crop yields and labour productivity losses. Thirdly, the biophysical impacts are fed into the ENV-Linkages model to assess the implications for different economic activities and the overall macroeconomic costs. This approach allows teasing out the direct and indirect consequences of environmental damages for the global and regional economy.

The projection of economic activity with environmental damages is thus contrasted with the “no-damage ‘baseline’ projection”, which reflects the trend development of the socioeconomic drivers of economic growth. The logic of this approach is not to deny that environmental impacts are already affecting the economy, but rather to measure the total economic consequences of environmental damages.

By modelling climate change and air pollution impacts with a production function approach, it is possible to obtain, as for integrated assessment models, the total economic costs of the selected impacts on GDP. The overall GDP costs are in turn an indicator of the extent to which climate change and air pollution have an impact on future economic growth; as in this approach damages can also affect capital stocks, it includes a potential direct effect on the growth rate of the economy. Compared to integrated assessment models in which damages are subtracted as a total from GDP, the production function approach can also explain how the composition of GDP is affected over time by environmental degradation: what sectors are most affected (for the impacts that have been assessed) and what changes in production factors mostly contribute to changes in GDP.

Environmental impacts have the potential to directly affect sectors' use of labour, capital, intermediate inputs and resources.[1] But they will also affect the productivity of inputs to production. Adverse shocks to the economy therefore act in the same manner as technological retrogressions, necessitating the use of more inputs to generate a given level of output.

Explicitly linking climate and air pollution impacts to the sectoral economic variable works well for those impacts that are directly affecting economic markets. For non-market impacts, such a direct link with a part of the production function does not exist, and the damages need to be evaluated separately. In principle, the utility function could be used to incorporate both market and non-market damages in one quantitative framework, but specifying such a utility function is far from obvious and left for future research. Thus, in this paper non-market damages are not included in the economic modelling, but some of the main non-market damages are quantified and discussed in Section 4.

2.3. Assessing climate change impacts

The quantification of climate change impacts in ENV-Linkages relies on available information on how climate impacts affect different economic sectors. The information sources are mostly derived from bottom-up partial-equilibrium models, climate impact models and econometric studies.[2] Table 3 provides a summary of the impacts considered and their respective sources from the literature. They refer to the consequences of climate-related changes in agriculture and fisheries, coastal zones, health, and changes in the demand for tourism services and for energy for heating and cooling. A detailed description of how these impacts are quantified is given in OECD (2015).

Where possible, impacts are assessed for the specific Representative Concentration Pathway (RCP) 8.5 scenario, which describes a pathway of climate change resulting from a fast increase in global emissions. The RCPs were developed by Van Vuuren *et al*. (2012) and adopted by the IPCC (2013; 2014a,b). Where necessary, the impacts are related to the slightly older IPCC A1B SRES scenario, which describes a future world of very fast economic growth, global population that reaches its maximum number by 2050 and declines thereafter, and the rapid introduction of new and more efficient technologies for all energy sources (Nakicenovic and Swart, 2000). The usage of different scenarios introduces only a minor approximation problem in specifying the RCP 8.5 reference, however, because until 2060 the temperature profiles of RCP 8.5 and A1B are reasonably close. Both scenarios are also similar to the ENV-Linkages model baseline with respect to GHG concentrations.

Wherever possible, the central projection uses results from the HadGEM3 model (Madec *et al*., 1996) from the Hadley Center of the UK Met Office, for the specification of the climate system variables. However, for certain climate impacts the data was only available from other climate models.

All source studies have a global coverage. As most studies come from grid-based data sets and models, they report data with a high spatial resolution, which permits the aggregation of data to match the regional aggregation of the ENV-linkages model. In some cases the source studies specified impact data with a regional aggregation tailored for other CGE models, including the ICES model (Eboli *et al*., 2010; Bosello *et al*., 2012; Bosello and Parrado, 2014), which was used as a reference for several climate impacts. The ICES model presents a regional detail very close to that of ENV-Linkages. Simple averaging processes or

---

1 An example is loss of coastal land, buildings and infrastructure due to inundation as a result of sea level rise.

2 Much of the information used is an elaboration of data provided by recently concluded and ongoing research projects, including both EU Sixth and Seventh Framework Programs (FP6 and FP7) such as ClimateCost, SESAME and Global-IQ and model inter-comparison exercises such as AgMIP. These data have been kindly provided by the researchers involved in these projects.

other simplifying ad hoc assumptions have been used to determine impacts for those few regions not perfectly matching across the two models.

In cases where the data sources were only available until 2050, the trends between 2040 and 2050 have been extrapolated to 2060. In principle, the impacts are not provided for a specific year, but rather for a period of multiple years. Where applicable, the sectoral assessments of impacts for a future period, e.g. a period of 2045-2055, have been translated into impacts for the middle year (in this case 2050) and then annual trends have been interpolated for earlier periods when no further information was available.

Table 3. Climate impact categories included in ENV-Linkages

Climate Impacts	Impacts modelled	Source	Project	Time frame
Agriculture	Changes in crop yields	IMPACT model - Nelson *et al*. (2014)	AgMIP	2050
	Changes in fisheries catches	Cheung et. al (2010)	SESAME	2060
Coastal zones	Loss of land and capital from sea level rise	DIVA model - Vafeidis *et al*. (2008)	ClimateCost	2100
Extreme events	Capital damages from hurricanes	Mendelsohn *et al*. (2012)		2100
Health	Mortality and morbidity from infectious diseases, cardiovascular and respiratory diseases	Tol (2002)		2060
	Morbidity from heat and cold exposure	Roson and Van der Mensbrugghe (2012) and Ciscar et al. (2014) for Europe	World Bank ENVISAGE model & Peseta II (Europe)	2060
	Mortality from heat stress	Not covered in the modelling exercise (non-market costs assessed in Section 4)		
Energy demand	Changes in energy demand for cooling and heating	IEA (2013a)	WEO	2050
Tourism demand	Changes in tourism flows and services	HTM - Bigano et. al (2007)	ClimateCost	2100
Ecosystems	No additional impacts covered in the modelling exercise			
Water stress	No additional impacts covered in the modelling exercise			
Tipping points	Not covered in the modelling exercise			

Two broad categories of climate change impacts can be distinguished. The first affects the supply-side of the economic system, namely the quantity or productivity of primary factors. Land and capital destruction from sea level rise, crop productivity impacts in agriculture, and labour productivity impacts on human health belong to this category. The second category of climate change impacts affects the demand side. Impacts on health expenditures[3] and on energy consumption are of this kind.

3 Health impacts are calculated with a cost of inaction approach, which does not account for other costs to society. A valuation of full economic impacts would imply higher costs.

2.4. Assessing outdoor air pollution impacts

The effects of air pollution on health are assessed with concentration-response functions, which link health impacts to the population-weighted mean concentrations of $PM_{2.5}$ and O_3. The following *health impacts* of $PM_{2.5}$ and O_3 were assessed in this analysis: mortality, hospital admissions related to respiratory and cardiovascular diseases, cases of chronic bronchitis in adults and in children ($PM_{2.5}$ only), lost working days ($PM_{2.5}$ only), restricted activity days, and minor restricted activity days due to asthma symptoms ($PM_{2.5}$ only). For the base year, 2010, the impacts of $PM_{2.5}$ on mortality assessed in this study are based on the results of the Global Burden of Disease studies as described in Forouzanfar et al. (2015) and Brauer et al. (2016).[4] Effects of ozone on mortality in 2010 are based on the earlier Global Burden of Disease results of Lim et al. (2012) and Burnett et al. (2014).

Crop yield changes have been estimated following the methodology described in Van Dingenen et al. (2009). Crop losses for rice, wheat, maize and soybean are calculated in TM5-FASST based on concentrations of ozone during the growing season.[5] Crop yield changes for those crops that are not covered by the calculations with TM5-FASST are projected using the information in Mills et al. (2007), following the methodology of e.g. Chuwah et al. (2015): yield changes for these crops are based on their relative sensitivity to ozone as compared to rice. It should be acknowledged that the projected crop yield changes are less robust than the projections of health impacts, owing to a much smaller underlying scientific literature.

Three market impacts are included in the model: changes in health expenditures due to increased incidence of illnesses, changes in labour productivity due to increased incidence of illnesses, and changes in agricultural crop yields. Table 4 summarises the impacts modelled and the data sources.

Table 4. Air pollution impacts included in ENV-Linkages

Impact categories	Impacts modelled	Data sources
Health - illness	Changes in health expenditures due to changes in incidences of bronchitis, respiratory and cardiovascular diseases, etc. Changes in labour productivity due to lost working days caused by changes in incidences respiratory and cardiovascular diseases.	Calculations based on Holland (2014) and on results from the Global Burden of Disease studies (Forouzanfar et al., 2015, and Brauer et al., 2016 for PM; Lim et al., 2012, and Burnett et al., 2014 for ozone).
Health - mortality	Not covered in the modelling exercise (non-market costs assessed in Section 4)	
Agriculture	Changes in crop yields	Calculations by the EC-JRC Ispra with the TM5-FASST model (Van Dingenen et al., 2009).
Tourism, leisure	Not covered in the modelling exercise	
Ecosystems, biodiversity, forestry	Not covered in the modelling exercise	

4 By building on the GBD studies, the implicit weaknesses of those studies are included also here. For instance, there may be a risk that interactions between air pollution and tobacco smoking are not adequately addressed in attributing mortality to outdoor air pollution. Nonetheless, the GBD studies provide the most robust and comprehensive information available for assessing the impacts of air pollution on mortality at a global level.

5 Rice, wheat, maize and soybean represent more than half the total volume of global agricultural production, but less than half of the value.

Changes in health expenditures are implemented in the model as a change in demand for the aggregate non-commercial services sector. The amount of additional health expenditures introduced in the model is calculated multiplying the number of cases of illnesses and of hospital admissions by the unit values for healthcare specified in OECD (2016). It is assumed that the additional health expenditures affect both households and government expenditures on healthcare.[6] The extent to which households or governments are affected depends on regional characteristics of the health system in terms of their relative contribution to healthcare. The distinction between households and government expenditures has been done using World Bank data on the proportion of healthcare expenditures paid by households and by the government (World Bank, 2015). A close relationship is noted between healthcare expenditure and GDP per capita for all but a few countries (World Bank, 2015), facilitating extrapolation of data on specific health endpoints between countries.

Changes in labour productivity are directly implemented in the model as percentage changes in the regional productivity of the labour force. Productivity losses are calculated from lost working days, following the methodology used in Vrontisi et al. (2016), using assumptions on the average number of work days per year in each region (World Bank, 2014). The approach to reduce labour productivity rather than labour supply is more appropriate when the dominant effect of the illness is to reduce average output per worker, rather than total labour costs borne by employers. This holds especially when employees are compensated for sick leave, or when workers show up to work while being ill (presenteeism).

Changes in mortality are not captured in the modelling exercise. These represent non-market costs, and cannot be adequately captured in a CGE model. Therefore, premature deaths, and the welfare costs associated with these, have been assessed separately. As part of the Global Burden of Disease studies, Forouzanfar et al. (2015) adopt a non-linear response function for PM mortality, with the rate of increase of mortality declining as PM concentrations rise. This assumption has been followed to generate lower projections of mortality. Upper projections are based on a linear relationship between mortality and concentrations. The use of a range recognises potentially significant uncertainty in the development of the non-linear relationship.

Changes in crop yields are implemented in the model as a combination of changes in the productivity of the land resource in agricultural production, and changes in the total factor productivity of the agricultural sectors. This specification, which is in line with the assumptions for climate damages, mimics the idea that agricultural impacts affect not only purely biophysical crop growth rates but also other factors that affect output, such as the effectiveness of other production inputs. Air pollution affects crop yields heterogeneously in different world regions, depending on the concentrations of ground level ozone.

3. Results

3.1. Socioeconomic trends in absence of damages

Demographic trends play a key role in determining economic growth. Population projections by age, together with projections of participation and unemployment rates, determine future employment levels. Human capital projections, based on education level projections by cohort, will drive labour productivity. Demographic projections, including effects of changes in fertility, death rates, life expectancy and international migration, are taken from the UN population prospects (2012). The labour force database (participation rates and employment rates by cohort and gender) is extracted from ILO (2011) active

---

6 In reality, private sector business also plays a role in the supply of healthcare through employer-based insurance. These expenditures are not considered separately in the modelling framework. Further, an alternative assumption on governments and households, is that they could decide not to increase their health expenditures and accept a lower level of health care. Such a response will, however, likely result in larger welfare costs. The approach used here can therefore be seen as a lower bound for the health costs.

population prospects (up to 2020) and OECD Labour Force Statistics and Projections (2011). These megatrends are country-specific. For example, the age structure of China's population is quite different from that of India: aging will become a major force in China in the coming decades, while India has a much younger population.

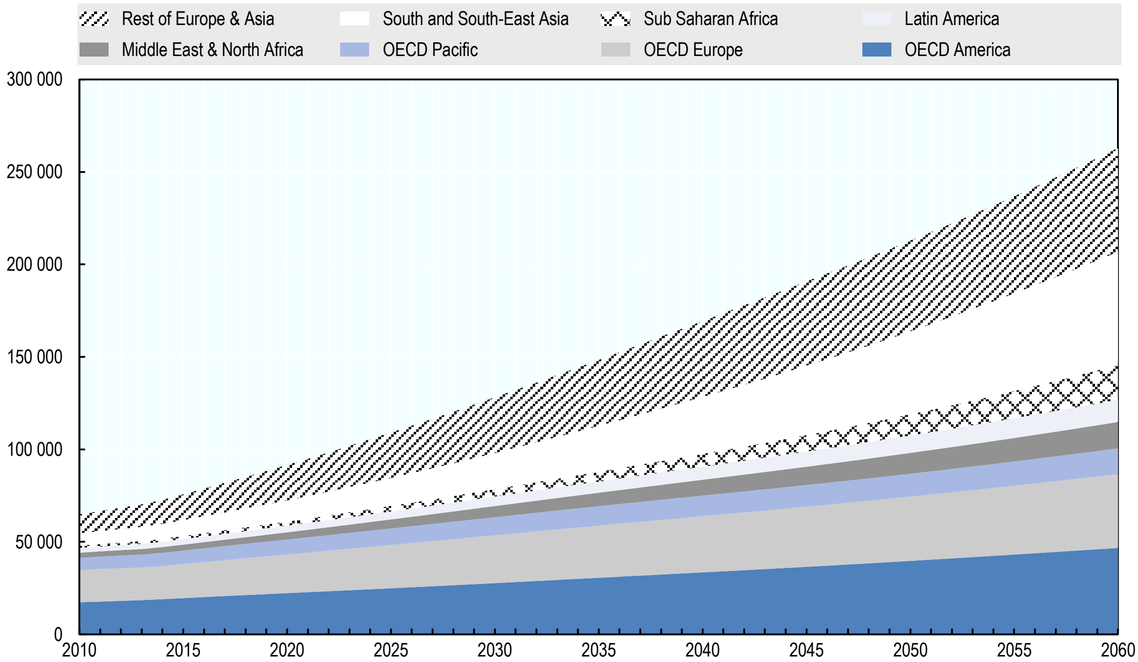
Macroeconomic projections for OECD countries are aligned with OECD (2014). Projections on the structure of the economy, and especially on future sectoral developments, are fundamental for the analysis in this report as they affect the projected emissions of air pollutants. The sectoral assumptions are particularly important as different emission sources are linked to different sectoral economic activities. For instance, final energy demand and power generation affect emissions of a range of pollutants from combustion processes, and in agriculture emissions, especially of NH_3, are linked to the production processes of agricultural goods.

Projections of sectoral energy intensities until 2035 are in line with the IEA's World Energy Outlook "Current Policy Scenario" (CPS) (IEA, 2013b). After 2035, the IEA trends are extrapolated to fit the macroeconomic baseline thereafter. In fast-growing economies such as China, India and Indonesia, the IEA projects coal use to increase in the coming decades. In OECD regions, however, there will be a switch towards gas, not least in the USA, and this especially in the power generation sector. Further, in OECD economies, energy efficiency improvements are strong enough to imply a relative decoupling of energy use and economic growth, while for emerging economies the decoupling will only be effective in the coming decades. The increase in final energy demand is driven by electricity and by transport; in particular in emerging economies. In line with the trends of the IEA's CPS scenario, electrification of transport modes is assumed to be limited globally.

The projections on agricultural yield developments (physical production of crops per hectare) as well as main changes in demands for crops as represented in the ENV-Linkages baseline are derived from dedicated runs with the International Food Policy Research Institute (IFPRI)'s IMPACT model (Rosegrant et al., 2012) using the socioeconomic baseline projections from ENV-Linkages and excluding feedbacks from climate change on agricultural yields. The underlying crop model used for the IMPACT model's projections is the DSSAT model (Jones et al., 2003). As IMPACT only provides projections to 2050, the trends are linearly extrapolated to 2060. The detailed projections of agricultural production and consumption from IMPACT are then summarised and integrated in ENV-Linkages. According to the projections, while population will increase by 50% from 2010 to 2060, average per capita income is projected to more than double in the same time span. Agricultural production as measured in real value added generated in the agricultural sectors will also more than double by 2060, partially reflecting a shift in diets towards higher-value commodities. The large increase in agricultural production is characterised by a growing share of production in African countries. On the contrary, the market share of OECD countries is projected to decrease.

Figure 2. Trend in real GDP, no-damage baseline projection

(Billions of USD, 2010 PPP exchange rates)



The regional projections of GDP indicate that the slowdown in population growth does not imply a slowdown in economic activity. While long run economic growth rates are gradually declining, Figure 2 shows that GDP levels in the no-damage baseline are projected to increase more than linearly over time. The largest growth is observed outside the OECD, especially in Asia and Africa, where a huge economic growth potential exists. The share of the OECD in the world economy is projected to shrink from 64% in 2010 to 38% in 2060. GDP growth is driven by a combination of increased supply of the production factors (labour, capital, land), changes in the allocation of resources across the economy, and improvements in the productivity of resource use (the efficiency of transforming production inputs into production outputs). Short-term growth is primarily driven by the characteristics of the current economy. In the longer run, a transition emerges towards a more balanced growth path in which labour productivity as a driver of economic growth is matched by increases in capital supply.

Figure 3 shows how the sectoral structure evolves in the regional economies. The shares of the various sectors in OECD economies tend to be relatively stable, with the services sectors accounting for more than half of GDP (i.e. value added). However, there are undoubtedly many fundamental changes at the sub-sectoral level that are not reflected here.

The major oil exporters in the Middle East and Northern Africa are projected to gradually diversify their economies and rely less on energy resources. In developing countries the decline of the importance of agriculture is projected to continue strongly. Given the high growth rates in many of these economies, this does not mean an absolute decline of agricultural production, but rather an industrialisation process, and, in many cases, a strong increase in services. Energy and extraction increases especially in the South and South-East Asia and Rest of Europe and Asia regions, reflecting a higher reliance on fossil fuels and a strong increase in electricity use. This has significant consequences for emissions of air pollutants.

Figure 3. Sectoral composition of GDP by region, no-damage baseline projection

(Percentage of GDP, 2010, 2035 and 2060)

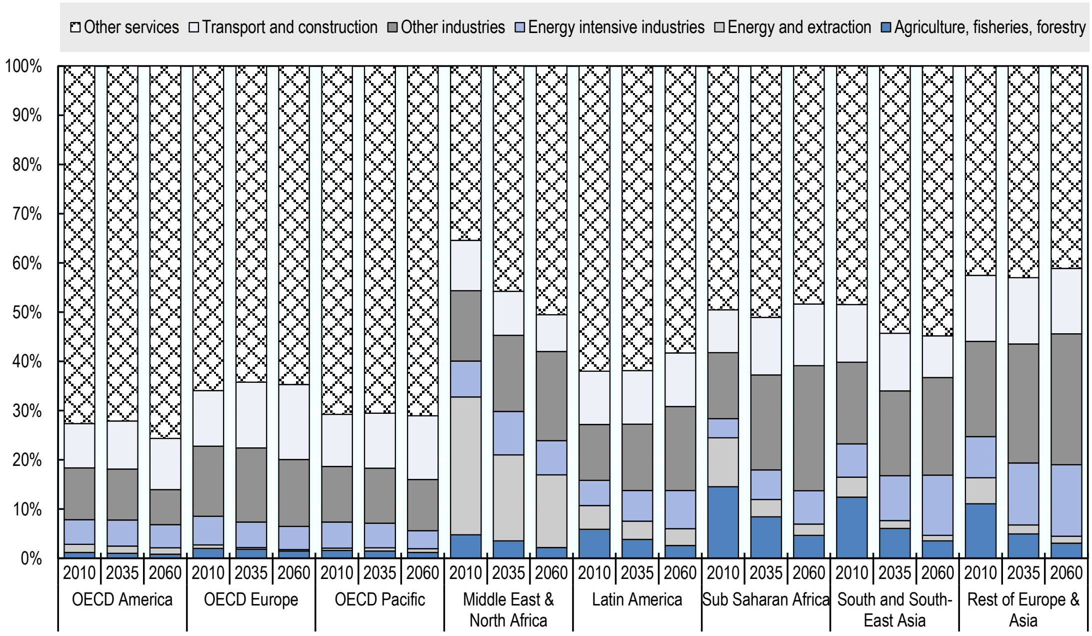
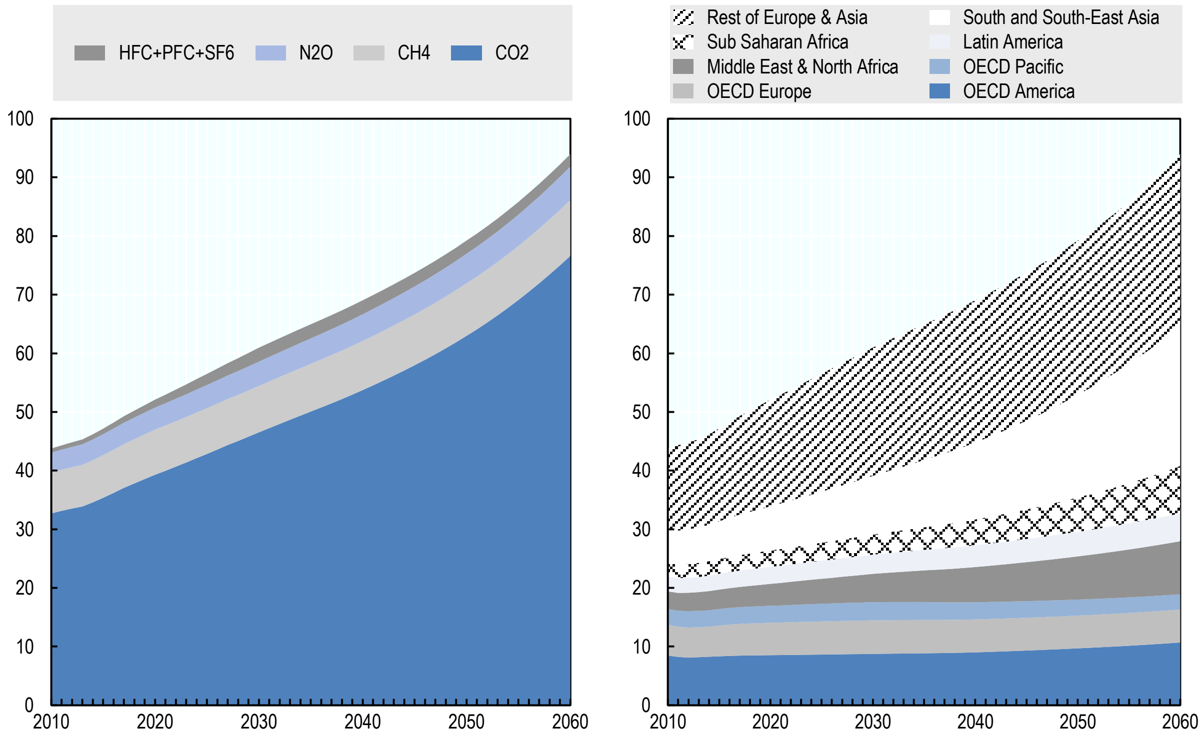


Figure 4 illustrates how baseline economic activities lead to a steady increase in regional and global emissions. Global anthropogenic greenhouse gas (GHG) emissions (excl. emissions from land use, land-use change and forestry, which are treated exogenously) are projected to rise from around 45 Gigatonnes (Gt) of CO_2 equivalent (CO_2e) in 2010 to around 95 GtCO_2e in 2060. Carbon dioxide (CO_2) is projected to remain the dominant greenhouse gas. The rapid emission growth follows the key demographic projections of larger populations, increased economic activity and greater consumption of fossil fuel energy. Despite slowdowns in the growth rates of population and GDP, the shift in economic significance to emerging and developing economies, and – in the absence of new climate policies – unabated use of fossil fuels lead to a sharp increase in GHG emissions. In particular, the increased consumption of coal (as explained in the previous section) accelerates increases in emissions. Nonetheless, there is some relative decoupling: emissions grow less rapidly than production.

Figure 4. Evolution of greenhouse gas emissions, no-damage baseline projection

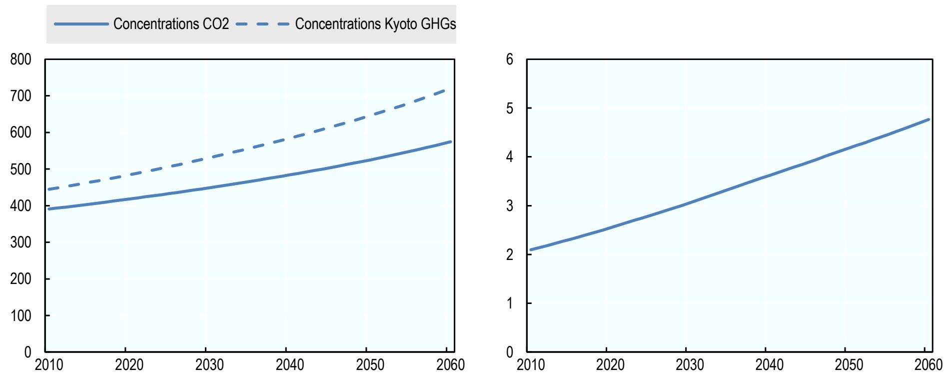
(Gigatonnes of CO2 equivalent)



The rapid increase in GHG emissions accelerates climate change. Although the climate system is very complex and a whole range of biophysical processes are triggered by higher carbon concentrations (IPCC, 2014a), the focus of this report is on the economic consequences of climate change. Thus, only the main steps in the relation between economic activity and climate change are summarised: global concentrations from CO_2, and from the full basket of GHGs in CO_2 equivalents (Figure 5, left panel), radiative forcing (i.e. the change in the earth's radiation due to increased concentrations of GHGs) from anthropogenic sources (Figure 5, right panel) and global average temperature increases above pre-industrial levels (Figure 6). Concentrations of CO_2 in the atmosphere rise from 390 parts per million (ppm) to 590 ppm between 2010 and 2060. These concentration levels, plus forcing from other GHGs and aerosols lead to an increase in total radiative forcing from anthropogenic sources from just over 2 to almost 5 Watts per square meter (W/m^2).

Figure 5. Key climate indicators, no-damage baseline projection

Concentrations (ppm) Anthropomorphic radiative forcing (W/m²)

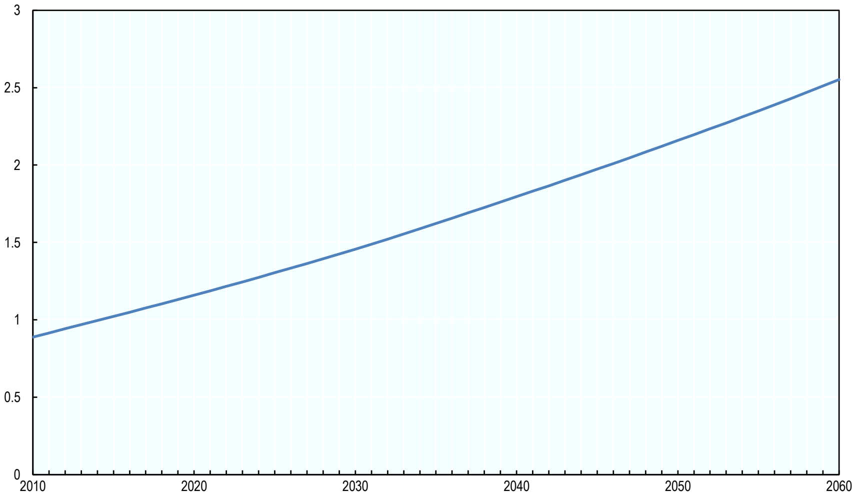


There is substantial uncertainty on the temperature changes implied by these carbon concentrations and radiative forcing. The equilibrium climate sensitivity (ECS) reflects the equilibrium climate response, i.e. the long-run global average temperature increase, from a doubling in carbon concentrations, and is often used to represent the major uncertainties in the climate system in a stylised way. According to IPCC (2013), "ECS determines the eventual warming in response to stabilization of atmospheric composition on multi-century time scales". There are different ways to estimate ECS values, the most common being the use of instrumental climate system models or paleo-climatic observations. The central projection uses an ECS value of 3°C, even though the IPCC has not specified a median value. Where applicable, the ECS is varied between 1.5°C and 4.5°C in the likely uncertainty range, and between 1°C and 6°C in the wider uncertainty range, in line with the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Rogelj *et al*., 2012; IPCC, 2013). The central projection delivers temperature increases of more than 2.5°C by 2060, as shown in Figure 2.7. This global temperature increase by 2060 is affected by the uncertainty on the ECS; the likely range equals 1.6 to 3.6°C, while the larger range is 1.1 to 4.3°C.

The regional impacts of climate change that are quantified in this study (cf. Chapter 1) are based on more detailed projections of regional changes in temperatures and precipitation patterns. The uncertainties on these regional patterns of climate change exist even for a given ECS, and are wider than the global average temperature change, but cannot be fully accounted for in the simulation of the economic damages. More elaborate robustness analysis, by varying the underlying climate model, and using results from a range of models for the climate system, crop yields and hydrology, is left for future research. The ISI-MIP project (Schellnhuber *et al*., 2014) provides some preliminary insights into the potential of using a multi-model comparison exercise to clarify various uncertainties.

Figure 6. Global average temperature increase, no-damage baseline projection

(Degrees Celsius above pre-industrial)

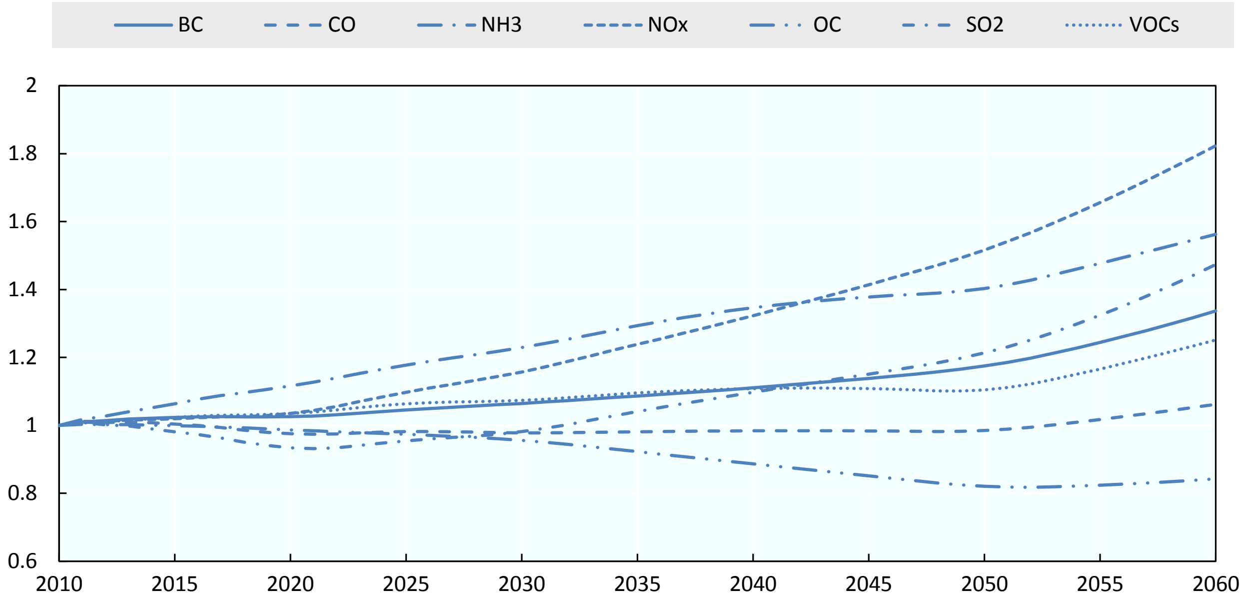


For most air pollutants, emissions are projected to increase in the coming decades, as illustrated in Figure 7. Rising emissions reflect the underlying baseline assumptions on economic growth. With increasing GDP and energy demand, especially in some fast growing economies such as India and China, emissions of air pollutants rise at global level. Emissions of NO_x and NH_3 are projected to have a particularly strong increase, with NO_x emissions almost doubling by 2060. These large changes are due to the projected increase in the demand for agricultural products and energy (incl. transport and power generation) and a rather limited control of NO_x emissions from power plants and industrial boilers in the developing world. Interestingly, emissions of SO_2 are projected to initially decrease but increase again after 2030. The initial decline is due to current policies that require flue gas desulphurization even in several developing countries (primarily in the power sector), but is later offset by the continuing increase in energy demand, which eventually leads to higher emissions.

There are large differences among countries and regions in emissions of the different pollutants. Emissions are generally projected to increase in non-OECD countries, with the highest increases taking place in the South and South East Asia region. The exception to this is emissions of OC and CO that decline in South and South East Asia and Sub-Saharan Africa. This is mostly thanks to improvement in the residential sectors, i.e. access to cleaner energy for households, linked to general megatrends, including urbanisation and electrification. Emissions from OECD countries tend to be stable or to slightly decline, although the projections show a small increase in emissions of all gases but NO_x and SO_2 in the OECD America region.

Figure 7. Air pollutant emission projections over time, no-damage baseline projection

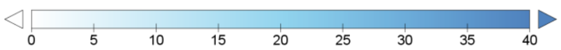
(Index with respect to 2010)

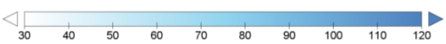


With emissions of air pollutants generally rising over time, the concentrations of $PM_{2.5}$ and ozone are also projected to increase in most regions, although, as discussed in Chapter 2, climatic conditions and several other factors influence concentrations. The maps in Figure 8 illustrate the annual average of anthropogenic $PM_{2.5}$ concentrations in the reference year (2010) as well as in the projected years 2030 and 2060 (maps for overall emissions, including the natural components of dust and sea salt, are presented in the right panels). As illustrated in Figure 8, several world regions, and especially China and India, were already above the highest interim target in 2010 and are projected to reach even higher levels by 2060. While the maps in Figure 8 show lighter colours for OECD regions, these levels are above the recommended WHO guidelines in most areas, implying that there are still strong impacts on human health and the environment (WHO, 2006).

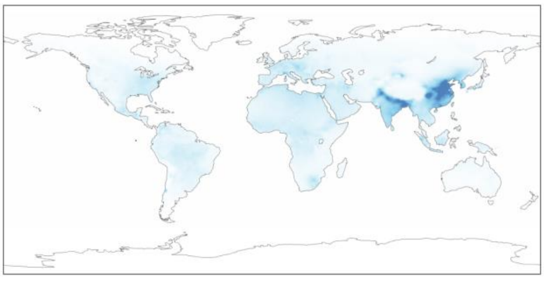
Figure 8. Particulate matter and ozone concentrations, no-damage baseline projection

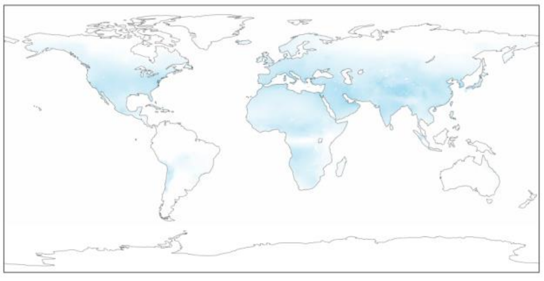
(Annual average anthropogenic $PM_{2.5}$, µg/m^3, on left panel and
Maximal 6-month mean of daily maximal hourly ozone, M6M, in ppb, on right panels)



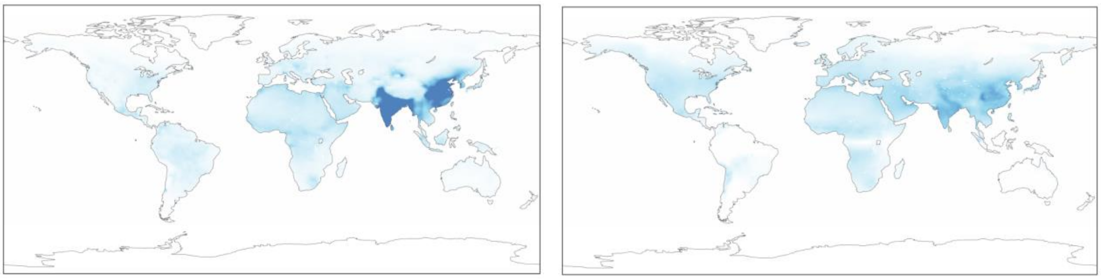


Panel A. Concentrations in 2010





Panel B. Concentrations in 2060



Note: The maps are based on concentrations specified at a 1°x1° resolution.

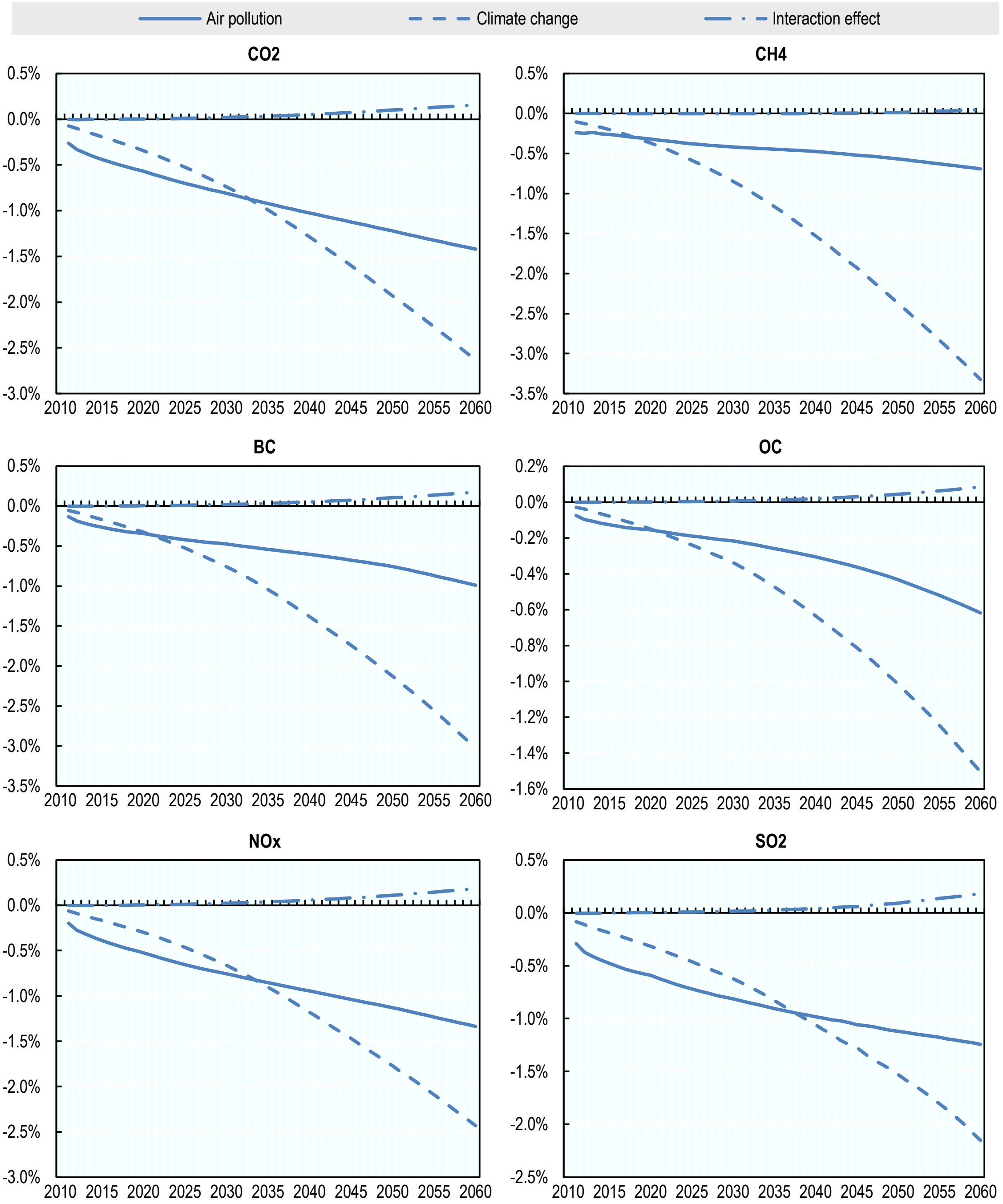
3.2. The interactions between climate change and air pollution damages through changes in emissions

Climate change and air pollution will interact and affect emission levels of both greenhouse gases and air pollutants, even in the absence of policies to reduce emissions. There are a number of feedback effects between both issues; one of the most direct ones is through the effect of economic damages of one issue on emissions of the other. Effectively, as the damages from climate change reduce economic activity in almost all sectors, the activity levels of the processes that emit air pollutants in these sectors will also be reduced. Similarly, air pollution damages that negatively affect economic activity reduce greenhouse gas emissions in the affected sectors.

The modelling results highlight that despite significant warming effects from air pollutants such as black carbon, aerosols have a cooling effect, and the net interaction effects through emission feedbacks are limited. In the model projections without damages, the direct cooling effect of aerosols (excl. indirect cloud albedo effects) is projected to be around 0.5 W/m2 in 2060 (up from 0.4 W/m2 currently), while the warming effect of ozone is also around 0.5 W/m2 in 2060 (up from 0.4 W/m2 currently).

Furthermore, the effect of economic damages due to climate change on air pollution emissions and thus air pollution impacts, and the effect of air pollution damages on GHG emissions and thus climate damages are relatively small (Figure 9), especially in comparison to the uncertainties surrounding the damage estimates. Therefore, further iterative loops within the modelling framework are not needed and economic interaction effects can be directly assessed.

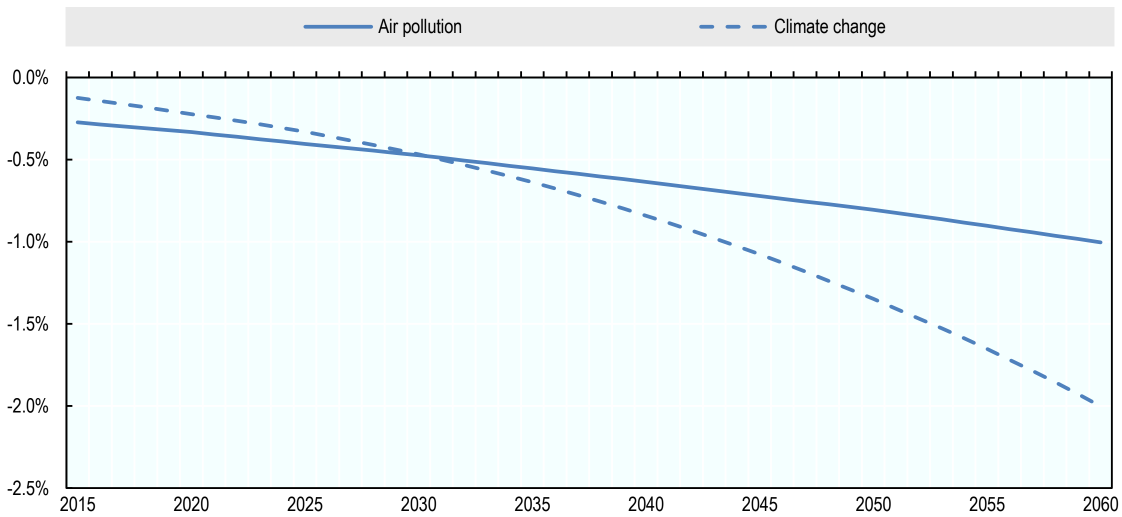
Figure 9. Changes in global emissions of selected pollutants from climate change and air pollution damages



3.3. The interactions between climate and pollution damages through changes in economic activity

The economic interactions between climate and pollution damages are more significant.[7] Although the effects of climate change play out over longer time horizons than those of air pollution, the coming decades are projected to have significant economic repercussions from both (Figure 10).

Figure 10. Changes in global GDP from climate change and air pollution damages



Given the partial overlap in sectors that are affected by climate change and air pollution, and the global nature of both problems, there are modest but significant interaction effects. Figure 11 presents macroeconomic results at the regional level, and highlights that for both cases, the majority of damages are located in relatively fragile economies in Asia and Africa. It also highlights that the joint absorption of both shocks allows economies to adapt in an integrated manner, and thus there is a positive interaction effect: the damages from both types of impacts together is smaller than the sum of individual damages. In most regions, the effect is rather small however.

Trade effects play an important role in determining the sign of the interaction effect. In Brazil, climate impacts are negative and air pollution impacts are positive, and the interaction effect is negative. This positive interaction effect stems from improvements in international trade conditions, i.e. the direct domestic impacts from air pollution are negative, but less so than those of competitors, thus leading to an increase in relative competitive position. The combination with climate damages – which are also fairly limited vis-à-vis their competitors –implies these trade benefits multiply. In contrast, in Russia, where climate impacts can boost the economy but air pollution impacts are negative for the economy, the interaction effect is negative. In the former case, the gains from climate impacts stem from improvements in climate conditions, i.e. the impacts are directly beneficial (due to positive impacts on agriculture, labour productivity and tourism; see OECD, 2015), but negative health impacts from air pollution drag down these benefits and there is no significant international competeveness effect.

[7] Note that due to minor model revisions carried out in the specification of air pollution damages, the numerical results for damages from climate change may differ slightly from those presented in OECD (2015).

Figure 11. Changes in regional GDP from climate change and air pollution damages

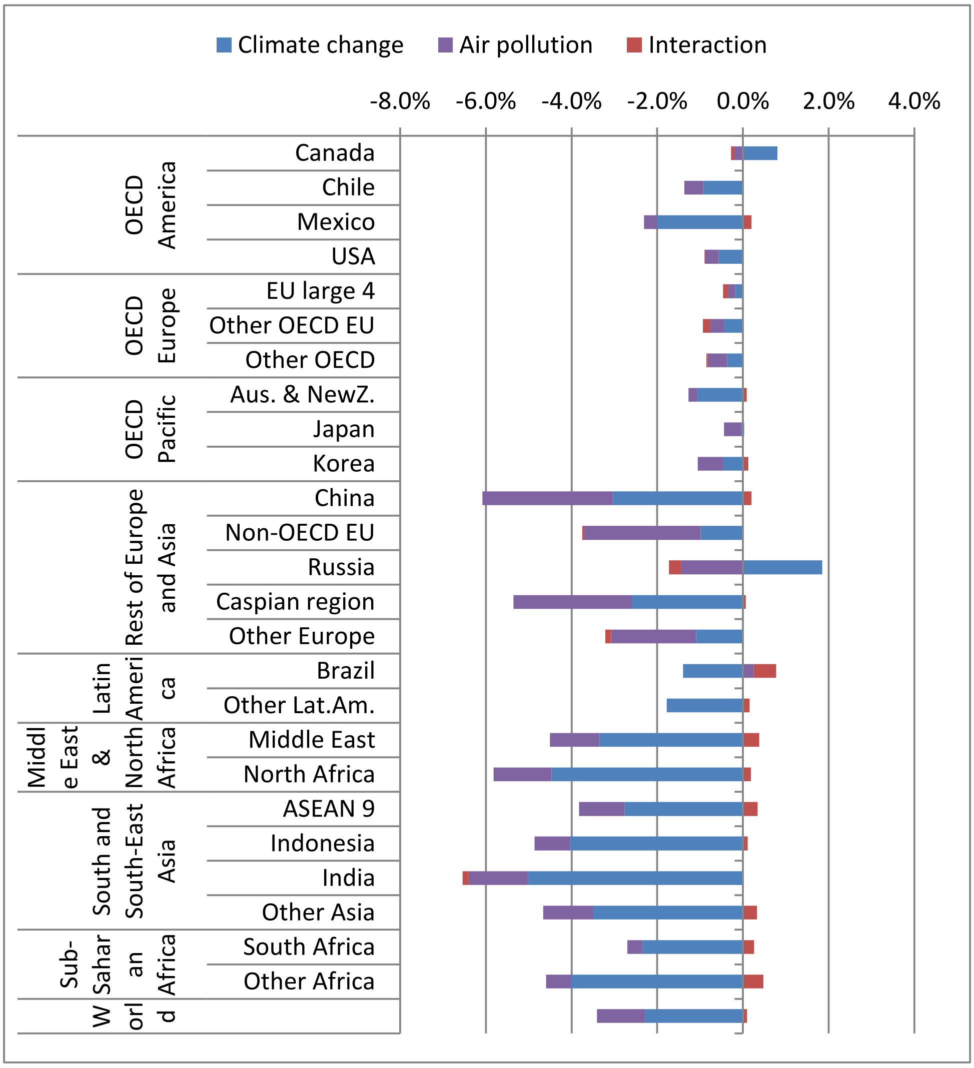


Figure 12 shows the effects of climate change and air pollution damages for the various sectors.[8] It is not surprising that the largest percentage losses are observed in agriculture, where both climate change and air pollution have significant adverse effects.[9] For the OECD region, wheat production is most severely hit, and there is very little interaction effect between both types of damages. This suggests that wheat yield losses can only marginally be compensated for with increasing the land allocated to this crop. For rice production in the OECD, climate change is projected to have a positive effect. This does not reflect a positive yield shock per se, but is rather the result of endogenous adaptations in the economic system: as rice producers in the OECD are relatively less affected by climate change than their competitors in Asia, they can keep price increases limited, and thus increase their market share on the global market. Such endogenous effects show the importance of using a systems approach to evaluate the economic consequences from environmental damages rather than relying on partial estimates of direct effects on

[8] This graph shows results for aggregated sectors; the analysis is done at the 25-sector level.

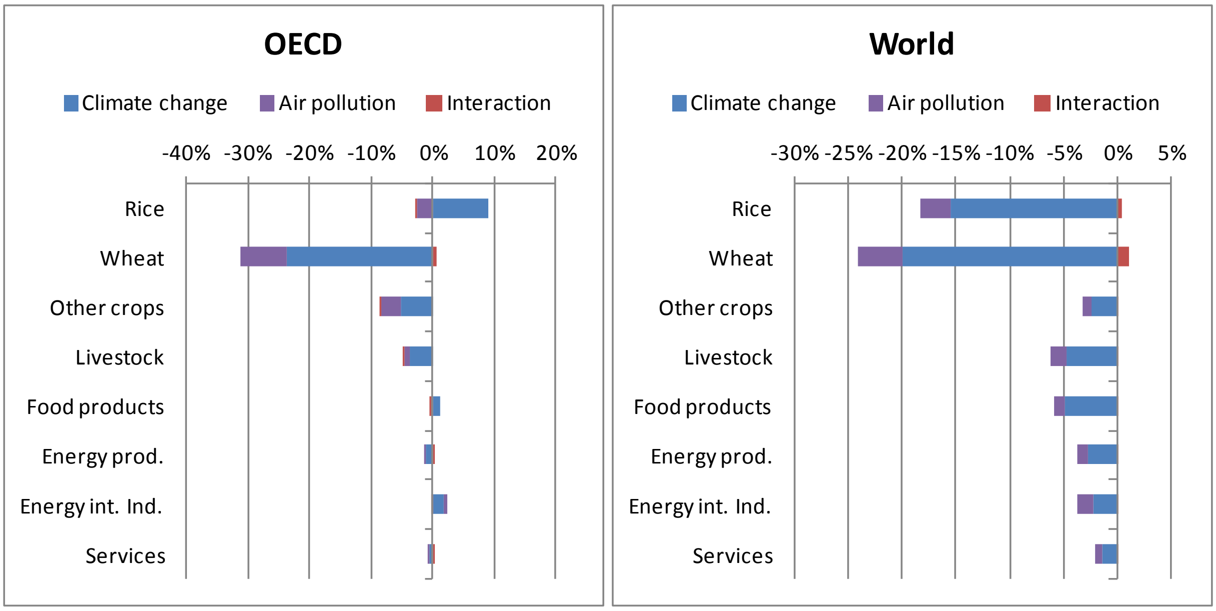
[9] These results exclude the effect of CO_2 fertilisation; see OECD (2015) for an investigation of the effect of this assumption.

specific sectors in specific regions alone. As the OECD is only a relatively small producer of rice, the global results are quite different: rice production losses are almost as large as those for wheat.

The modelling analysis excludes effects on energy supply, and the consequences on energy demand are rather small: increased energy demand for cooling in summer is almost completely offset by reduced energy demand for heating in winter (IEA, 2013a).[10] The overall effects on energy production are therefore very limited. In OECD countries, energy-intensive industries can even benefit from the reduction, while the services sector slightly contracts. This is a typical trend for countries that have very modest domestic impacts: trade-exposed industries can benefit from improved international trade (as competitors are more severely hit), whereas the more sheltered services sectors are hurt by domestic tourism and health impacts, but also by reduced availability of capital from coastal damages. At the global level, the depressive effect of both climate change and air pollution damages has a negative effect on all sectors, and the trade gains in some regions are mirrored by trade losses in others.

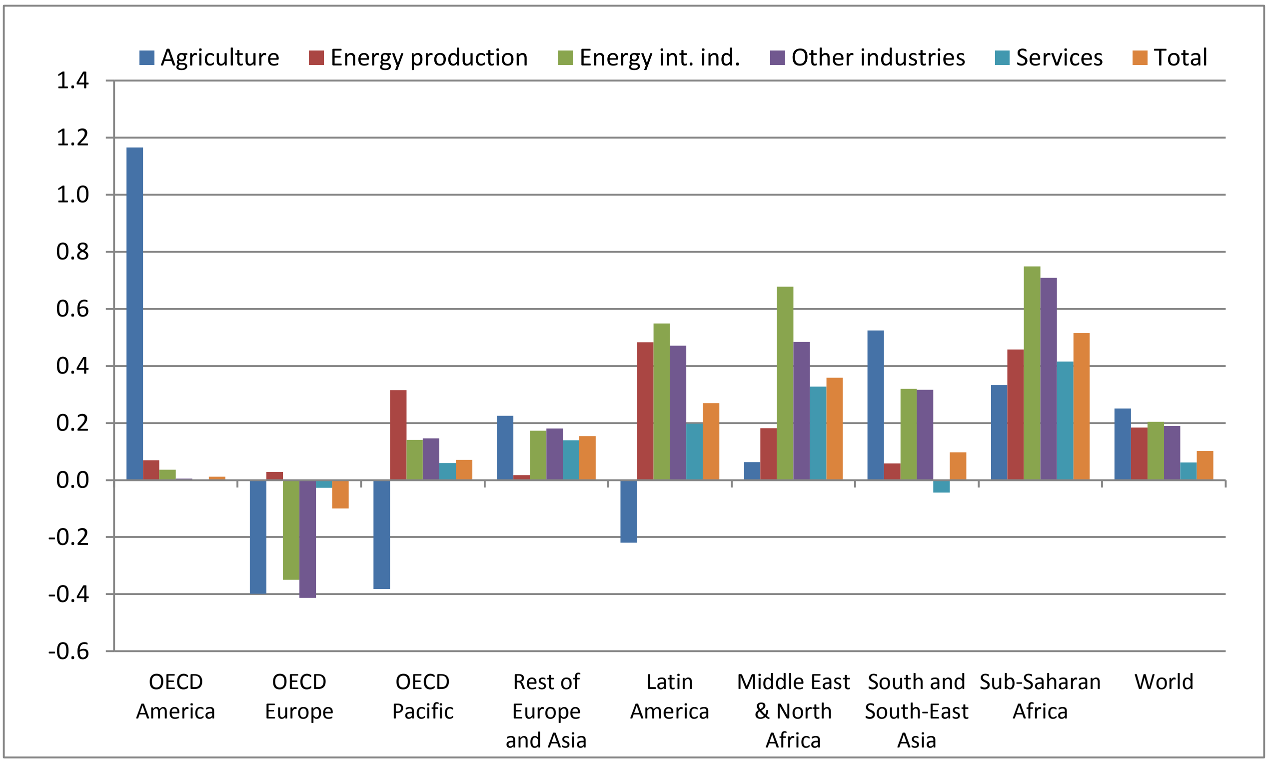
Figure 12. Changes in sectoral production from climate change and air pollution damages

Panel A. Selected sectors (percentage change from baseline)



[10] An important underlying trend is the change in buildings in emerging economies in the baseline: as these countries develop further, significant increases in electrification are projected, which especially affect heating systems (IEA, 2013a).

Panel B. Regional interaction effects (percentage-points change)



Panel B further teases out the regional and sectoral differences. In all regions except OECD Europe, the macroeconomic interaction effects are positive; this extends to all major sectors of production. At the global level, the overall interaction effect is around 0.1%-point of GDP, i.e. the GDP losses of climate and air pollution combined are around 0.1% smaller than the sum of the individual effects. In the regions where the total damages are strongest, the interaction effects are also strongest, in line with Figure 11. But this does not extend uniformly to all sectors. For instance, in the OECD Pacific region and Latin America, where the interaction effect is positive due to trade effects, this does not hold for the agricultural sectors. The key reason for this is that some of the agricultural trade gains from air pollution impacts cannot be realised when climate impacts are jointly considered; this thus mirrors the positive interaction effect in OECD America, South-East Asia and Sub-Saharan Africa. The strong positive interaction effect in OECD America is driven by the impacts of climate change and air pollution on wheat yields in the USA.

The model projections indicate a strong negative effect from both climate change and air pollution impacts, and this offers some room for re-arranging land use to accommodate both shocks simultaneously. The economic consequences of the climate change and air pollution impacts are further differentiated by production factor in Figure 13. The overall effects are by definition in line with the effects in Figure 11. For each production factor – capital, labour and other, which includes land and sector-specific resources – the contribution to the overall GDP effect is decomposed into direct effects from climate change, direct effects from air pollution, and indirect effects.[11] At the global level, indirect effects are clearly dominating. In fact, almost half of the total GDP loss from climate change and air pollution can be attributed to slower capital accumulation. This is driven by the effect of income losses on savings and hence investments in

[11] The direct effects have been calculated by multiplying the percentage change in productivity and supply of these factors at their no-damage baseline levels of use, i.e. before any endogenous market adaptation effects. The indirect effects are then calculated as the difference between the total effect on that production factor and the sum of the direct effects.

future capital stock. This large indirect capital effect highlights that climate change and air pollution not only affects the level of GDP, but also its growth rate. In other words, by 2060 the projected economic consequences on GDP *levels* and on GDP *growth* are of similar size. Long-run supply of labour and other production factors are much less flexible than capital, and thus the indirect effects for these factors are largely proportional to the macroeconomic consequences. In terms of direct effects, labour productivity losses related to health impacts are largest, as it is directly affected by both types of impacts, whereas capital supply is only directly affected by climate change.

At the level of the 8 macro regions, macroeconomic consequences of climate change and air pollution are negative in all regions. But that does not imply that the effects are negative for all production factors in all sectors in all countries. One important positive impact is the direct labour productivity gain in Canada. While such productivity gains stem from for both climate change and air pollution, only the air pollution gains are strong enough to dominate negative effects in the USA and Mexico.

4. Selected non-market damages: mortality impacts

The quantitative analysis presented above highlights the effects of climate change and air pollution on economic systems. Thus, it focuses on market damages. It should be acknowledged that non-market damages are also very important, and for air pollution potentially even substantially more important (OECD, 2015; OECD, 2016).

Although there is a wide variety of non-market impacts, and some of them are potentially very significant – not least the effects of major tipping points and large-scale disruptive events from climate change –, this section limits itself to a quantification of the mortality effects from heat stress due to climate change and outdoor air pollution.

4.1. Mortality impacts from heat stress due to climate change

The modelling of health impacts in ENV-Linkages accounts for labour productivity changes due to occupational heat stress. However, it does not take into consideration premature deaths related to heat-related mortality (including heat waves), nor cold-related health effects. Non-health consequences of heat stress, such as disruptions of transport, are also not considered here.

Research on the impacts of climate change on cold-related morbidity remains scarce and inconclusive. The IPCC (2014a) states that there could be modest reductions in cold-related morbidity in some areas due to fewer cold extremes, yet it has only low confidence in this finding.

The evidence on the magnitude of the benefits of changes in premature deaths from reductions extreme cold is also mixed. According to Bosello et al. (2006) and Watkiss and Hunt (2012), the number of avoided premature deaths and the related welfare benefits of reduced winter mortality from climate change could outweigh the negative impacts from heat on mortality in certain regions. Bosello et al. (2006) project that in the European Union, the United States, Eastern European and Former Soviet Union countries, Japan, other Annex 1 countries (as defined in the United Nations Framework Convention on Climate Change), China and in India reductions in cold-related deaths from cardiovascular disease will more than offset additional deaths from heat-related and other diseases spurred by climate change in 2050. Globally, they project that climate change may lead to 849,252 fewer deaths by the middle of the century as compared to the baseline scenario. Likewise, Watkiss and Hunt (2012) find that the decrease in winter in the European Union mortality due to climate change is larger than increases in summer mortality in most of their near- to medium-term (2011-2040) and long-term (2071-2100) projections. Watkiss and Hunt (2012) point to uncertainties related to the omission of extreme and urban heat island effects, however, thereby suggesting that a direct comparison of heat- with cold-related mortality in their study might not be entirely adequate.

Other studies, including by Kinney et al. (2012) and Ebi and Mills (2013), contest whether beneficial changes in winter mortality will outweigh the negative effects from increased heat-related mortality. The

IPCC (2014a) also cites papers by Wilkinson et al. (2007) and regional studies by Doyon et al. (2008) and Huang et al. (2012) to conclude that “the increase in heat-related mortality by mid-century will outweigh gains due to fewer cold periods” in temperate zones and especially in tropical zones, where large populations in developing countries have limited capacity to adapt (IPCC, 2014a). Building on past empirical evidence from the United Kingdom, Staddon et al. (2014) stress that in temperate zones the link that many papers make, namely that low temperatures during winters are correlated with excess winter deaths, is empirically weak. They suggest that influenza-like illnesses – whose positive correlations with climate change remain to be proven – are the main driver for cold-related deaths. In the same vein, Honda and Ono (2009), using data from Japan, argue that risks from cold may not be ameliorated with higher average temperatures.

While the economic costs of heat-related mortality could not be accounted for in the model, they were calculated separately; this excludes any assessment of the consequences of cold-related deaths. The Japanese National Institute for Environmental Studies (NIES) and the University of Tsukuba (Japan) carried out calculations on the number of premature deaths from heat-related mortality, including heat waves. To properly align with the other projections, the RCP8.5 climate scenario is used in combination with the Hadley Centre’s HadGEM climate model. Using projections of future temperature, NIES has calculated a heat index as well as an indicator of relative risk depending on temperatures. The number of additional premature deaths due to heat stress has then been calculated using the risk coefficient, baseline mortality levels as well as daily grid-level temperature data (Takahashi *et al*., 2007; Honda *et al*., 2014).[12]

The results of this analysis are presented in Table 5 for the ENV-Linkages regions. The regions with the highest number of premature fatalities are ones like China and India where the population is larger. Many premature deaths also take place in regions such as the EU and the US, where aging population increases the size of the vulnerable population at risk. The global death toll from heat stress is projected to increase from less than 150 thousand people annually in the current climate, to more than a million by the 2050s and close to 3 million by 2080s. However, these results do not factor in the potential for natural acclimatisation, which could reduce the number of fatalities. As regional temperatures keep rising, the number of heat stress days increases, and spells of continuous hot days get prolonged. This in turn leads to more than proportionate increases in premature deaths, in the absence of further policies. In particular, the number of premature deaths would be lower in presence of adaptive investment, including better air conditioning or wider use of early warning systems and information campaigns for the population at high risk.

---

[12] There is a discussion in the literature over the extent to which these premature deaths represent short-term displacement mortality (“harvesting”), i.e. people that die from heat stress may have serious existing health conditions or are very old, i.e. such that that the period of life lost is small. Following Honda et al. (2014), this is (crudely) taken into account in the calculations through a lag term.

Table 5. Heat stress mortality by region

(Thousands of people)

	Current climate	2030	2050
Canada	1	3	8
Chile	0	1	1
Mexico	1	7	12
USA	11	27	63
EU large 4	11	31	66
Other OECD EU	8	22	44
Other OECD	1	5	13
Australia and New Zealand	1	2	3
Japan	3	7	10
Korea	1	3	6
China	27	88	161
Non-OECD EU	2	5	8
Russia	12	20	28
Caspian region	2	8	21
Other Europe	5	11	16
Brazil	2	8	23
Other Latin America	2	9	24
Middle East	2	10	38
North Africa	2	8	22
ASEAN 9	2	16	39
Indonesia	1	6	23
India	25	55	139
Other Asia	10	24	78
South Africa	2	3	4
Other Africa	11	47	177
World	145	426	1023

4.2. Mortality impacts from outdoor air pollution

The number of premature deaths due to outdoor air pollution have already been estimated to be high in recent years (see e.g. Lim et al., 2012 and Forouzanfar, 2015), with elderly people and children being most affected (WHO, 2014). The fundamental issue in estimating the number of premature deaths due to air pollution is the shape of the concentration-response function over a wide range of observed concentrations. For the base year 2010, the calculations of premature deaths are based on the Global Burden of Disease work reported by Forouzanfar et al. (2015) for $PM_{2.5}$ and Lim et al. (2012) for ozone. For future projections, the concentration-response function for $PM_{2.5}$ in particular becomes more uncertain as the population-weighted concentrations of $PM_{2.5}$ become much higher in some countries. To reflect this uncertainty two different functions are used for $PM_{2.5}$: (i) a linear function showing a simple linear relationship between concentrations and the number of premature deaths adjusted for changes in mortality rates, and (ii) a non-linear function, which considers that the incremental number of deaths decreases as concentrations become higher. OECD (2016) outlines in more detail the two different formulations of the concentration-response function.

According to the calculations, premature deaths caused by outdoor air pollution in the reference year 2010 amounted to almost 3 million people globally (in line with the results of Forouzanfar et al., 2015). Premature deaths from outdoor air pollution are projected to reach a global total of 6 to 9 million people in

2060 (considering a non-linear and a linear concentration-response function respectively). This large increase is not only due to higher concentrations of $PM_{2.5}$ and O_3, but also to an increasing and aging population and to urbanisation (which also leads to higher exposure).

High concentrations of $PM_{2.5}$ account for most of the premature deaths. In 2010, PM is linked to around 95% of premature deaths from air pollution at the global level. The contribution of PM to mortality varies across regions. This fraction is lowest in India (89%) and highest in regions such as Canada where PM is responsible for almost all premature deaths linked to outdoor air pollution. Whilst PM accounts for the highest share of deaths, mortality due to ozone is projected to increase over time as ozone concentrations become higher and more dangerous for human health. By 2060, premature deaths due to ozone are projected to increase to 7-10% of the total. In India, they could account for up to 20%.

The number of premature deaths is unequally distributed across the world. As illustrated in Table 6, the highest number of deaths takes place in non-OECD countries and particularly in China and India. These regions also experience the highest increase in the number of premature deaths to 2060. China's premature deaths account for 31% of the global total in 2010 and for 30-34% in 2060. While China's share of premature deaths is rather stable over time, premature deaths in India increase substantially over time and increase from 21% of the global total in 2010 to 27-35% in 2060. A smaller increase is projected in OECD countries, with the number of premature deaths increasing from around 430 thousand people in 2010 to around 570-580 thousand in 2060. The share of premature deaths caused by outdoor air pollution in OECD countries decreases over time (from 15% of the global total in 2010 to 6-9% in 2060). In particular the share of premature deaths of the United States decreases from 3% of the global total in 2010 to 1-2% in 2060, and from 8% in 2010 to 2-3% for the EU.

The range of projected results in 2060 is larger in some regions than in others. For regions where the increase in concentrations is limited, there is hardly any difference between the results obtained with the two alterative functions. For regions with high increases in concentrations, such as India and China but also South and South East Asia, the range can be quite large. The projected concentrations are larger with the linear function as it considers that premature deaths will continue increasing strongly even with high concentrations of PM.

Table 6. Premature deaths from exposure to particulate matter and ozone

(Thousands of people)

		2010	2030		2060	
			Non-linear	Linear	Non-linear	Linear
OECD America	Canada	8	10	10	13	14
	Chile	3	4	4	7	6
	Mexico	14	21	21	42	42
	USA	93	92	99	122	128
OECD Europe	EU large 4	111	97	98	89	95
	Other OECD EU	90	87	84	99	97
	Other OECD	28	37	35	65	64
OECD Pacific	Aus. & New Z.	2	2	3	3	4
	Japan	60	78	76	77	80
	Korea	17	31	30	52	54
Rest of Europe & Asia	China	905	1374	1492	2065	2711
	Non-OECD EU	33	26	25	23	22
	Russia	119	106	107	93	93
	Caspian region	44	69	69	111	116
	Other Europe	74	57	56	49	49
Latin America	Brazil	36	48	48	73	73
	Other Lat. Am.	38	52	53	87	87
Middle East & North Africa	Middle East	52	85	95	191	229
	North Africa	52	65	62	107	112
South and South-East Asia	ASEAN 9	102	152	155	286	343
	Indonesia	57	80	81	113	116

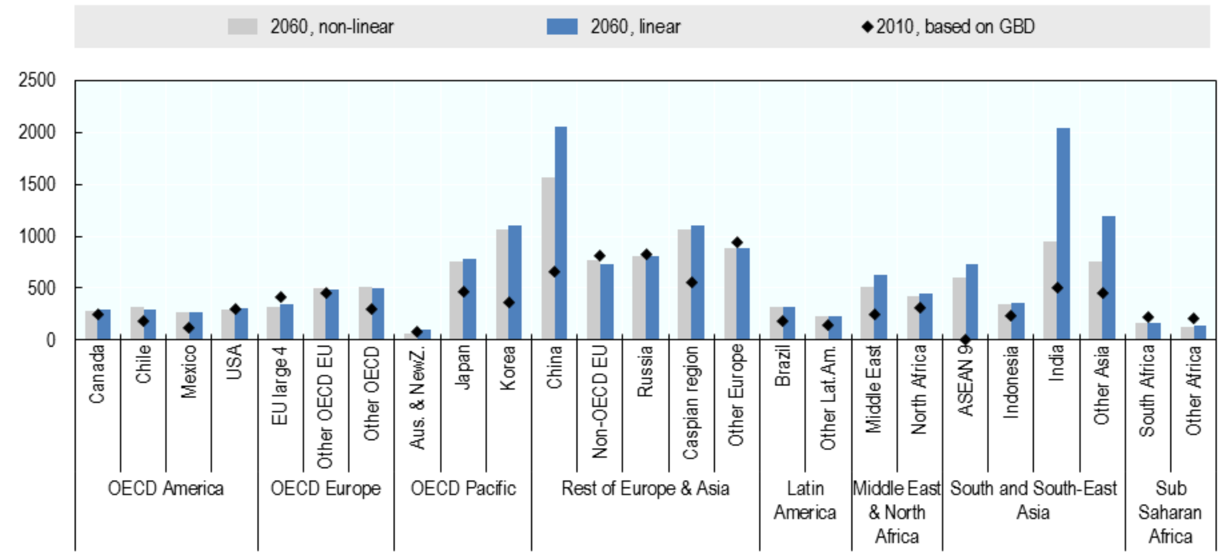
	India	613	788	926	1553	3351
	Other Asia	202	253	253	509	811
Sub-Saharan Africa	South Africa	12	8	9	11	11
	Other Africa	167	178	180	323	334
OECD		*428*	*459*	*460*	*569*	*584*
Non-OECD		*2505*	*3339*	*3610*	*5593*	*8459*
World		*2933*	*3799*	*4070*	*6162*	*9043*

Note: Due to the curvature of the functions and rounding, the effects of the non-linear projection can in some cases be reported to be slightly higher than the linear projection; this only affects the results for low and modest concentration levels.

As already discussed, the increasing number of deaths is partly due to increasing populations, which also lead to a higher number of people being exposed to air pollution. Some of the most affected areas are also highly populated. Nevertheless, even considering the number of premature deaths per million people (Figure 12), India and China are projected to have an extremely high number of deaths. Africa, Oceania and Latin America are by contrast the regions with the lowest number of premature deaths per million people.

Figure 13. Premature deaths from exposure to particulate matter and ozone

(Number of deaths caused by outdoor air pollution per year per million people)



5. Discussion

Trying to understand what climate change and outdoor air pollution may mean for the future of our economies is daunting. What is needed is a nuanced understanding of how climate change and air pollution impact sectoral and regional economic activity, how these impacts propagate through our economic system, and how both issues interact in their economic consequences.

This paper presents one possible economic scenario and largely ignores the uncertainties surrounding the consequences of climate change and air pollution. Many of these uncertainties have been identified for climate change and air pollution individually (see OECD, 2015, and OECD, 2016). More robust quantitative insights require more elaborate modelling analysis, using multiple scenarios on the major modelling assumptions, and ideally comparing different models. That is beyond the reach of this paper. Therefore, the results in this paper should be regarded mostly as a first attempt to quantify the joint economic consequences of climate change and outdoor air pollution; the direction of effects and orders of magnitude matter more than the precise numbers.

The analysis in this paper cannot capture all impacts of climate change and air pollution, nor can it identify the myriad of ways in which both issues interact with each other. In some cases, the economic modelling tools are just not the right instrument to assess the welfare costs of the impacts; this holds especially for premature deaths caused by climate change and air pollution (as shown in Section 4). OECD (2015) and especially OECD (2016) discuss in detail how stated preference methods can be used to value these premature deaths, and find that they can be very significant.

More research is needed to quantify how the impacts of climate change and air pollution affect each other, not least for the effects on agriculture and health. It is clear that both issues have strong effects on agricultural productivity and labour productivity, but the non-linearities in the biophysical responses are not well known. Therefore, this paper limits itself to the economic interaction effects: as economic sectors are confronted with a range of different impacts, how can they respond to minimise the consequences for production and welfare?

The interactions between climate change and air pollution are likely much larger when looking at policy responses to reduce emissions, than for the calculation of the costs of inaction that are outlined above. The principal reason for this is that integrated policy action can exploit the fact that many, but not all, emission sources overlap between climate change and air pollution. And certain types of interventions, e.g. reducing coal-fired power generation, will have much stronger co-benefits than others, e.g. end-of-pipe exhaust control. Thus, a policy intervention that aims at reducing the economic consequences of one issue will have significant co-benefits for the other issue. But integrated policy responses also imply a harmonisation of the short- and longer-term benefits of action: while air pollution benefits largely accrue in the short term, many avoided climate damages slowly accumulate over the course of several decades. An integrated policy analysis therefore implies more attention to longer-term benefits than a typical isolated air pollution policy would, and more attention for short-term reductions than a typical isolated climate mitigation policy would.

These caveats notwithstanding, this paper contributes to understanding the interactions between climate change and air pollution damages. It is clear that interaction effects are strongest in those regions that are hurt significantly by both climate change and air pollution impacts, as some synergies can be found when dealing with both issues simultaneously. Furthermore, quantitative analysis of the joint impacts of climate change and air pollution is still scarce, and this paper provides a wide-ranged overview of how both issues affect different economic sectors in different regions around the world. The findings in this report could thus help to focus future research and priorities for policy responses for jointly addressing climate change and outdoor air pollution.

References

Amann, M. et al. (2013), “Regional and Global Emissions of Air Pollutants: Recent Trends and Future Scenarios”, *Annual Review of Environment and Resources*, Vol. 38, pp. 31-55.

Bigano, A., J.M. Hamilton and R.S.J. Tol (2007), “The Impact of Climate Change on Domestic and International Tourism: A Simulation Study”, *Integrated Assessment Journal,* Vol. 7, pp. 25-49.

Bosello, F, and R. Parrado (2014), “Climate Change Impacts and Market Driven Adaptation: the Costs of Inaction Including Market Rigidities”, FEEM Working Paper, No. 64.2014.

Bosello, F., F. Eboli and R. Pierfederici (2012), “Assessing the Economic Impacts of Climate Change. An Updated CGE Point of View”, *FEEM Working Paper,* No. 2.2012.

Bosello, F., R. Roson and R.S.J. Tol (2006), “Economy wide estimates of the implications of climate change: human health”, *Ecological Economics*, Vol. 58, pp. 579-591.

Brauer, M. et al. (2016), "Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013", *Environmental Science and Technology,* Vol. 50, pp. 79-88.

Burnett, R.T. et al. (2014), "An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure", *Environmental Health Perspectives*, Vol. 122, pp. 397-403.

Cheung, W.W.L., V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, R., D. Zeller and D. Pauly (2010), "Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change", *Global Change Biology*, Vol. 16, pp. 24-35.

Chuwah, C. et al. (2015), "Global impacts of surface ozone changes on crop yields and land use", *Atmospheric Environment*, Vol. 106, pp. 11-23.

Ciscar. J.C. et al. (2014), "Climate impacts in Europe. The JRC PESETA II project", *JRC Scientific and Policy Reports*, No. EUR 26586EN, Luxembourg: Publications Office of the European Union.

Doyon, B., D. Belanger, and P. Gosselin (2008), "The potential impact of climate change on annual and seasonal mortality for three cities in Quebec, Canada", *International Journal of Health Geographics*, Vol. 7(23).

Ebi, K.L. and D. Mills (2013), "Winter mortality in a warming climate: a reassessment", *WIREs Climate Change*, Vol. 4, pp. 203-212.

Eboli, F., R. Parrado and R. Roson (2010), "Climate-change feedback on economic growth: explorations with a dynamic general equilibrium model", *Environment and Development Economics*, Vol. 15, pp. 515-533.

Forouzanfar, M.H. et al. (2015), "Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990-2013: a systematic analysis for the Global Burden of Disease Study 2013", *The Lancet*, Vol. 386(10010), pp. 2287-2323.

Holland, M. (2014), Cost-benefit analysis of final policy scenarios for the EU Clean Air Package. Corresponding to IIASA TSAP report no.11, Version 2a. Report to European Commission DG Environment. March 2014, *http://ec.europa.eu/environment/air/pdf/TSAP%20CBA.pdf* (last accessed on 3 May 2016).

Honda, Y. and M. Ono (2009), "Issues in health risk assessment of current and future heat extremes", *Global Health Action*, Vol. 2. 10.3402/gha.v2i0.2043.

Honda, Y. *et al*. (2014), "Heat-related mortality risk model for climate change impact projection", *Environmental Health Prevention Medicine*, Vol. 19, pp. 56-63.

Huang, C. et al. (2012), "The impact of temperature on years of life lost in Brisbane, Australia", *Nature Climate Change*, Vol. 2(4), pp. 265-270.

IEA (2013a), *Redrawing the energy climate map*, IEA, Paris.

IEA (2013b), *World Energy Outlook 2013*, IEA, Paris.

ILO (International Labour Organisation) (2011), Estimates and Projections of the Economically Active Population: 1990-2020, 6th ed. ILO.

IPCC (2013), *Climate Change 2013: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2014a), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

IPCC (2014b): *Climate Change 2014: Mitigation of Climate Change*, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jones, J. et al. (2003), "The DSSAT cropping system model", *European Journal of Agronomy*, Vol. 18, pp. 235-265.

Kinney, P.L., et al. (2012), "La mortalité hivernale va-t-elle diminuer avec le changement climatique ?" [Winter mortality in a changing climate: will it go down?], *Bull Epidémiol Hebd* Vol. 12-13, pp. 148-151.

Lim, S.S. et al. (2012), "A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: A systematic analysis for the Global Burden of Disease Study 2010", *The Lancet*, Vol. 380, pp. 2224-60.

Madec, G., and M. Imbard (1996), "A global ocean mesh to overcome the north pole singularity". *Climate Dynamics*, Vol. 12, p381-388.

Meinshausen, M., S.C.B. Raper and T.M.L. Wigley (2011), "Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6: Part I – Model Description and Calibration", *Atmospheric Chemistry and Physics*, Vol. 11, pp. 1417-1456.

Mendelsohn, R., K. Emanuel, S. Chonabayashi, and L. Bakkensen. 2012. "The Impact of Climate Change on Global Tropical Cyclone Damage", *Nature Climate Change* 2: 205-209.

Mills, G. et al. (2007), "A synthesis of AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops", *Atmospheric Environment*, Vol. 41, pp. 2630-2643.

Nakicenovic, N. and R. Swart (eds.) (2000), *Special report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge University Press: Cambridge, UK and New York.

Nelson, G. C. *et al*. (2014), Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences*, Vol. 111(9), pp. 3274-3279.

OECD (2016), The Economic Consequences of Outdoor Air Pollution, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264257474-en

OECD (2015), The Economic Consequences of Climate Change, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264235410-en.

OECD (2014), *OECD Economic Outlook*, OECD Publishing, Paris, http://dx.doi.org/10.1787/eco_outlook-v2014-2-en.

OECD (2011), “Labour Force Statistics : Population projections”, OECD Employment and Labour Market Statistics (database), http://dx.doi.org/10.1787/data-00538-en (last accessed on 3 May 2016).

Rogelj, J., M. Meinshausen and R. Knutti (2012), “Global warming under old and new scenarios using IPCC climate sensitivity range estimates”, *Nature Climate Change*, Vol. 2, pp. 248–253.

Rosegrant, M.W. et al. (2012), “International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) Model Description”, International Food Policy Research Institute, www.ifpri.org/sites/default/files/publications/impactwater2012.pdf (last accessed on 3 May 2016).

Roson, R. and D. van der Mensbrugghe (2012), “Climate change and economic growth: impacts and interactions”, *International Journal of Sustainable Economy,* Vol. 4, pp. 270-285.

Staddon, P.L., H.E. Montgomery, and M.H. Depledge (2014), “Climate warming will not decrease winter mortality”, *Nature Climate Change*, Vol. 4 (March 2014), pp. 190-194.

Takahashi, K., Y. Honda and S. Emori (2007), “Assessing mortality risk from heat stress due to global warming”, *Journal of Risk Research*, Vol. 10(3), pp. 339-354.

Tol, R.S.J. (2002), “New Estimates of the Damage Costs of Climate Change, Part I: Benchmark Estimates”, *Environmental and Resource Economics*, Vol. 21 (1), pp. 47-73.

UN (United Nations) (2015), World Population Prospects: The 2015 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP.241.

Vafeidis, A.T., R.J. Nicholls, L. McFadden, R.S.J. Tol, J. Hinkel, T. Spencer, P.S. Grashoff, G. Boot and R.J.T. Klein (2008), “A new global coastal database for impact and vulnerability analysis to sea level rise”, *Journal of Coastal Research*, Vol. 24(4), pp. 917-924.

Van Dingenen, R. and F.J. Dentener (forthcoming), “TM5-FASST: a global source-receptor model for particulate matter, trace gases and radiative forcing”, manuscript in preparation for the special HTAP issue in ACP.

Van Dingenen, R. et al. (2009), “The global impact of ozone on agricultural crop yields under current and future air quality legislation”, *Atmospheric Environment*, Vol. 43(3), pp. 604-618.

Van Vuuren, D.P., K. Riahi, R. Moss, J. Edmonds, A. Thomson, N. Nakicenovic, T. Kram, F. Berkhout, R. Swart, A. Janetos, S.K. Rose and N. Arnell (2012), “A proposal for a new scenario framework to support research and assessment in different climate research communities”, *Global Environmental Change*, Vol. 22(1), pp. 21–35.

Vrontisi, Z. et al. (2016), “Economic impacts of EU clean air policies assessed in a CGE framework”, *Environmental Science and Policy* 55, pp. 54-64.

Wagner, F. et al. (2007), The GAINS Optimization Module as of 1 February 2007, Interim Report IR-07-004, IIASA, Laxenburg, Austria.

Watkiss, P., and A. Hunt (2012), "Projection of economic impacts of climate change in sectors of Europe based on bottom up analysis: human health", *Climatic Change*, Vol. 112, pp. 101-126.

WHO (2014), Burden of disease from Household Air Pollution for 2012. The World Health Organization, Geneva 2014.

WHO (2006), Air Quality Guidelines: Global Update 2005. *www.euro.who.int/__data/assets/pdf_file/0005/78638/E90038.pdf?ua=1*(last accessed on 3 May 2016).

Wilkinson, P., et al. (2007), "A global perspective on energy: health effects and injustices", *Lancet*, Vol. 370(9591), pp. 965-978.

World Bank (2015), *World Development Indicators*, Washington D.C., http://data.worldbank.org/indicator (last accessed on 3 May 2016).

World Bank (2014), Doing Business 2015: Going Beyond Efficiency, The World Bank, Washington, DC. http://dx.doi.org/ 10.1596/978-1-4648-0351-2.