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Economic interactions between climate change and outdoor air pollution

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Economic interactions between climate change and outdoor air pollution - ENVIRONMENT WORKING PAPER N° 148

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Keywords: Climate change, air pollution, computable general equilibrium models.
JEL codes: C68, Q54, Q53.

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Abstract

Climate change and outdoor air pollution are two of the most challenging environmental issues that modern society faces. These challenges are strongly linked through their emission sources, the sectors they affect and the policies that can be implemented to reduce emissions. They also interact in the way they affect economic growth in the coming decades, although this aspect has been neglected in the literature.

This paper presents the first global analysis of the joint economic consequences of climate change and outdoor air pollution to 2060, in the absence of new policies to address these challenges. A common methodology and a consistent modelling framework is used to specify the main economic interaction effects. While this paper provides a useful framework to analyse the interactions between two environmental issues in the economic system, the results need to be interpreted carefully, because of limited data availability.

This limitation notwithstanding, this paper presents a number of interesting insights. In the central scenario considered in this paper, the effect of climate damages on air pollutant emissions and of air pollution damages on emissions of greenhouse gases remain limited. The net cooling effect of air pollutants is less than 0.5 W/m2, and slowly becomes less important over time. While initially the consequences of air pollution tend to dominate, the long-run economic repercussions from climate change are projected to be significantly larger. The damages from climate change amount to almost 3% of GDP by 2060, those from air pollution to around 1%. For both environmental issues, the majority of damages affect relatively fragile economies in Asia and Africa, with damages in many regions exceeding 3% of GDP and in some 5%. The largest percentage losses are observed in agriculture, where both climate change and air pollution have significant adverse effects.

Keywords: *Climate change, air pollution, computable general equilibrium models.*

JEL codes: *C68, Q54, Q53.*

Résumé

Le changement climatique et la pollution de l'air extérieur sont deux des défis environnementaux les plus difficiles auxquels la société moderne est confrontée. Ces défis sont reliés par leurs sources d'émission, les secteurs qu'elles affectent et les politiques pouvant être mises en œuvre pour réduire les émissions. Ils interagissent également par la manière dont ils affectent la croissance économique au cours des prochaines décennies, bien que cet aspect ait été négligé par la littérature.

Ce document présente la première analyse globale des conséquences économiques du changement climatique et de la pollution de l'air extérieur à l'horizon 2060, en l'absence de nouvelles politiques publiques dédiées. Une méthodologie commune et un cadre de modélisation cohérent sont utilisés pour spécifier les principaux effets d'interaction économique. Bien que ce document présente un cadre utile pour analyser les interactions entre deux problèmes environnementaux dans le système économique, les résultats doivent être Interprétés avec prudence étant donnée la disponibilité limitée des données.

Malgré cette limitation, ce document présente un certain nombre de résultats intéressants. Dans le scénario central considéré, les impacts des dommages de la pollution de l'air extérieur sur les émissions de gaz à effet de serre, et inversement, les impacts des dommages climatiques sur les émissions de substances liées à la pollution de l'air restent limitées. L'effet net de refroidissement de la pollution de l'air extérieur est inférieur à 0.5 W/m2, et décroît avec le temps. Les conséquences de la pollution atmosphérique tendent initialement à dominer. En revanche, à long terme, les répercussions économiques du changement climatique devraient être considérablement plus importantes. Les dommages causés par le changement climatique représentent près de 3% du PIB d'ici 2060 et ceux dus à la pollution de l'air extérieur environ 1%. Pour les deux problèmes environnementaux, la majorité des dommages affecte des économies relativement fragiles en Asie et en Afrique. Pour ces pays, les dommages peuvent excéder 3% du PIB, et jusqu'à 5% pour certains pays. Les pertes les plus importantes sont observées pour l'agriculture, où les changements climatiques et la pollution atmosphérique ont des effets négatifs importants.

Mots clés : *changement climatique, pollution de l'air, modèles d'équilibre général calculable.*

Codes JEL : *C68, Q54, Q53.*

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Executive Summary

Climate change and outdoor air pollution are two of the most challenging environmental issues that modern societies face. Trying to understand what these challenges mean for the future of our economies is crucial. Equally important is to understand how these challenges mutually affect each other: they interact both in terms of the emission sources, which are often caused by the same sectors, but also in terms of the sectors they affect and the policies that can be implemented to reduce emissions.

The interactions between climate change policies and outdoor air pollution are widely acknowledged. Much less is known, however, about how damages from climate change and from air pollution affect economies across the world in the coming decades. What is needed is a nuanced understanding of how these two environmental issues impact sectoral economic activities in different regions of the world, how these impacts propagate through the economic system, and how both issues interact in their economic consequences.

This report addresses this issue and presents the first global analysis of the joint economic consequences of climate change and outdoor air pollution (from $PM_{2.5}$ and ozone) until 2060, in the absence of new policies to address these challenges (i.e. cost of inaction). While major synergies can be reaped by integrating climate change mitigation and air pollution control policies, a thorough analysis of benefits from integrated policy action is left for future research.

A common methodology and a consistent modelling framework is used to specify the main economic interaction effects. This is done using a production function approach, in which climate change and air pollution affect specific production factors in the different sectors and countries, which are all interlinked in the global economic system.

Four main types of interactions between climate change and air pollution are identified: (1) the effect of economic damages on emission levels; (2) the polluting effects of greenhouse gases, and the radiative forcing potential of air pollutants; (3) interactions in the biophysical impacts; and (4) interactions in the economic system. The modelling framework allows quantifying each of these effects, but insufficient data is available to robustly quantify the full spectrum of effect 3, even though these are potentially very significant. Therefore, this report does not attempt to reflect the total interaction effects between climate and air pollution.

In the first few decades of the modelling projections, the consequences of air pollution tend to dominate, and overall damages are still relatively small. But over time, feedbacks from both climate change and air pollution become stronger, and represent an increasing cost. As the effects of climate change play out over a longer time horizon than those of air pollution, the long-run economic repercussions from climate change are projected to be significantly larger. For both environmental issues, 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. Especially global wheat production is significantly affected, although crop-specific results tend to be rather sensitive to the underlying assumptions on regional changes in temperature and precipitation patterns and thus the related uncertainties are high at the individual crop level.

The modelling results highlight that the effects of the economic damages on emissions (effect 1) are relatively small. While there may be some larger reductions in emissions from reduced economic activity in the most affected regions (e.g. India), these mostly remain limited. Furthermore, despite significant climate forcing from various air pollutants, the net effects of air pollutants on global average temperature (effect 2) is relatively small, as some pollutants (e.g. black carbon) have warming effects, while others (aerosols, not least SO2) have a cooling effect.

In most regions and sectors, there is a small positive interaction effect from the interactions in the economic system (effect 4).[1] This results from the possibility to adjust the structure of the economy to the damages of climate change and air pollution together. Adjustments of international trade patterns to accommodate both shocks simultaneously also facilitates the economic response. Changes in international trade patterns limit costs in most emerging and developing economies, and can in some cases provide a significant boost to the economy. In other regions – most notably India – the economic consequences are larger when the two impacts are considered together (i.e. a negative interaction effect). This can happen when the two environmental issues together aggravate the burden of the damages on the economy: air pollution and climate change both have negative consequences on labour productivity, thereby forcing sectors to take more costly measures to absorb the negative productivity shocks.

While this report provides a useful framework to analyse the interactions between two environmental issues in the economic system, the results need to be put into the context of the limited data availability. This is particularly relevant for the interactions in the biophysical system, where data on interaction effects are completely lacking. It also gives a partial account of the economic consequences of climate change and air pollution, excluding for example the economic consequences of premature deaths, and extreme climate events.

These limitations notwithstanding, this report presents a first quantitative analysis of the joint macroeconomic impacts of climate change and air pollution, as well as the modelling framework that is needed for a joint evaluation of the macroeconomic consequences of different environmental themes. It also provides a wide-ranged overview of how both issues affect different economic sectors in different regions around the world. The findings in this report thus help to focus future research on the benefits of integrated climate change and air pollution policies.

[1] In this report, an interaction effect is called positive if it reduces damages, i.e. if it positively affects GDP levels. Negative interaction effects worsen the damages.

1. Introduction

Co-benefits of climate policies for reduced outdoor air pollution and improved health are an increasingly recognised motivation for immediate climate action. But climate change and outdoor air pollution interact at several different levels, ranging from the sources of emissions, to chemical interactions between different pollutants, interactions in the biophysical system and through the impacts on the economy.

The need for integrated analyses of climate change and outdoor air pollution is widely acknowledged and there is a large literature on quantifying the co-benefits of climate policies for air quality (see for example Bollen and Brink (2014[1]); Bollen (2015[2]); Matus et al. (2008[3]); Nam et al. (2010[4]); (IEA, 2018[5])). A recent study by Markandya et al. (2018[6]) finds that the health co-benefits from different climate mitigation scenarios substantially outweigh the policy costs. A similar result is found by Vandyck et al. (2018[7]), who show that the air quality co-benefits for human health and agriculture counterbalance the costs to meet the Nationally Determined Contributions in Paris Agreement. What is much less known, however, is how the damages from climate change and from air pollution interact and affect regional economies.

This report presents a first quantitative assessment of economic damages for climate change and outdoor air pollution simultaneously. Such a joint assessment is vital for identifying the benefits of integrated climate and air pollution policies, and to avoid suboptimal policy responses to two these major environmental issues. A modelling analysis of the economic consequences of environmental damages at a global level can offer insights into the direction of the changes that climate change and air pollution damages jointly induce in the economic system. Such a modelling assessment allows studying the economic interactions between the costs of inaction on climate change and on air pollution.

Four main types of interactions between climate change and outdoor air pollution are identified: (1) the effect of economic damages on emission levels; (2) radiative forcing effects of air pollutants; (3) interactions in the biophysical impacts; and (4) interactions in the economic system. The modelling framework allows quantifying effects 1, 2 and 4; insufficient data is available to quantify effect 3, even though these effects may be very significant. Therefore, the contribution of this report is to highlight the relevance of the interaction between different environmental issues in the economic system, rather than providing precise quantitative estimates of the total interaction effects between climate and outdoor air pollution. The results described should be considered in the context of these data limitations.

To study the economic repercussions of both issues simultaneously, a common methodology is required, building on a model that can translate sectoral and regional climate and air pollution impacts in changes to the global economy. The methodology used in this report builds on the separate assessment of the economic consequences of climate change (OECD, 2015[8]) and outdoor air pollution (OECD, 2016[9]), in which an impact system approach was used. This relies on coupling an economic model, which can create economic projections for the coming decades, to biophysical and impact models, which can quantify environmental impacts.

The analysis is based on the OECD's computable general equilibrium (CGE) model ENV-Linkages (Chateau, Dellink and Lanzi, 2014[10]), which is used to create economic projections and to study the economic consequences of the damages to 2060. The impacts from climate change and air pollution are linked to the economic model using a production function approach in which each impact is linked to a specific component of the model's production function.

The report studies the consequences of a specific set of impacts of climate change and outdoor air pollution: changes in agriculture and health due to climate change and air pollution, as well as climate-related changes in fisheries, coastal zones, demand for tourism services and in energy demand for heating and cooling. Other impacts, such as those on ecosystems and tipping points, could not be included due to lack of available data at global level. The air pollution impacts considered are those from concentrations of PM2.5 and ozone. Impacts from other emissions, such as the direct health impacts of nitrous oxides, cannot yet be quantified at the global level. Furthermore, the modelling exercise on economic feedbacks also excludes non-market impacts, such as welfare costs from mortality and pain and suffering linked to illness.2 These impacts affect the economy for instance through changes in saving and labour supply decisions, as described in Marten and Newbold (2017[11]). However, their main implications (i.e. a direct welfare loss) cannot be directly linked to sectoral and regional economic activity as done for the other impacts in the modelling setting used in this report.

The remainder of the report is set up as follows. Section 2 describes the different interaction effects between climate change and air pollution and the modelling framework. Section 3 presents the results of the modelling analysis. Section 4 provides a discussion of the results.

[2] The welfare impacts of air pollution on mortality and pain and suffering are quantified and presented in OECD (2016[9]). However, they are not included in the assessment of the economic feedbacks and interactions presented in this paper.

2. Background and methodology

2.1. Different types of interaction effects

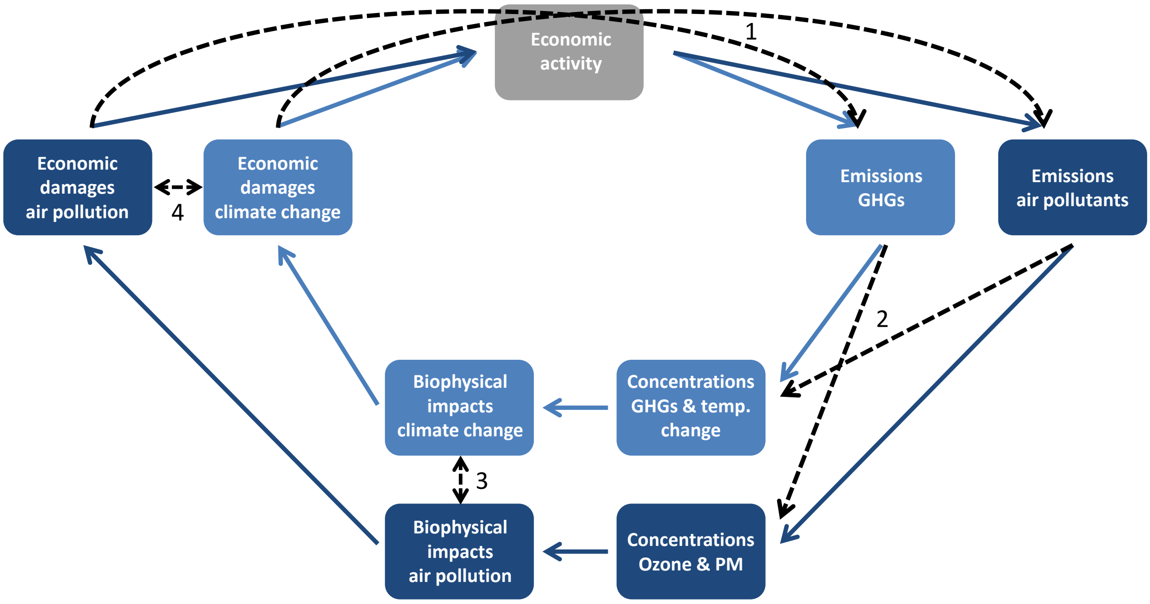
Climate change and outdoor air pollution interact in various ways. In general, interactions can affect four different parts of the impact cycle: (1) the effect of economic damages on emission levels, due to the fact that environmental damages reduce production and thus the associated emissions; (2) cross-effects of emissions on concentrations; (3) interactions in the biophysical system; and (4) interactions in the economic system. The sources of these interaction effects can also be related to three main variables: emissions, biophysical impacts, and economic consequences. Table 1 summarises the main interaction effects that occur.

Table 1. Main interactions between climate change and outdoor air pollution in the modelling framework

Effect Source	Emissions	Biophysical impacts	Economic consequences
Emissions		(2) Cross-effects of emissions on concentrations	
Biophysical impacts		(3) Health impact interactions; Agricultural impact interactions	
Economic consequences	(1) Damages reduce production and associated emissions		(4) Economic interaction effects and non-linearities

The approach used in this report is based on coupling an economic model, which can create economic projections for the coming decades, to biophysical and impact models, which can quantify environmental impacts (see Annex B). Figure 1 visualises the interaction effects in the modelling framework. Within the economic model, changes in economic activities due to environmental damages lead to changes in emissions (1). In the biophysical model used to calculate concentrations of greenhouse gases, emissions of local air pollutants are also included; similarly, concentrations of ozone and PM depend on their greenhouse gas precursors (2). There are also interactions in the calculations of the biophysical impacts through the impacts models (3). For instance climatic changes over time are considered when calculating the impact of air pollution on crop yields. Finally, within the economic model, there are interactions in the economic systems (4), for instance through production and trade adjustments.

Figure 1. Interaction effects in the modelling framework



Note: The arrows in the figure correspond to the linkages between the different variables in the impact pathway. Solid lines reflect the direct effects: light blue for climate change and dark blue for air pollution. Black dashed lines reflect the interaction effects.

2.1.1. Effect of economic damages on emission levels

Climate change and air pollution damages interact and affect emission levels of both greenhouse gases and air pollutants, even in the absence of policies to reduce emissions. When the same economic activity generates both GHG and air pollutant emissions, for instance in fossil fuel combustion, there is an important link between both topics but in itself not an interaction effect. Rather, the interaction effect comes through policies: reducing these cogenerating activities for one challenge will automatically also reduce emissions of the other. This implies that baseline trends that affect sectoral production levels influence both climate change and air pollution emission levels, even in absence of policies to reduce emissions.

There is a feedback effect through the 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. This also applies to the damages from air pollution, which reduce economic activities in certain sectors that emit GHGs. One particular example is the effect of climate change on energy demand, which influences power generation and thus air pollutant emissions. Another example is the reduction in income caused by climate and air pollution damages, which translates into reduced consumption and thus reduced production levels, with accordingly reduced emissions associated with production.

2.1.2. Cross-effects of emissions on concentrations

Climate change and air pollution have strong interactions in the way air pollutants and greenhouse gases affect concentrations and radiative forcing. Many air pollutants have a direct as well as an indirect effect on radiative forcing and thus on climate change. On the other hand, some greenhouse gases affect the concentrations of air pollutants.

Some air pollutants, which are referred to as climate forcers (IPCC, 2013[12]), have a warming effect and thus potentially contribute to aggravate the climate change issue and increase climate damages. Black carbon is the pollutant having the strongest warming effect, as the black particles absorb light and heat their surroundings. Other pollutants have a cooling effect (sulphate aerosols such as SO_2, organic carbon, nitrates). Enhanced aerosol concentrations can also lead to a cloud albedo effect (IPCC, 2007[13]).

The contribution of climate forcers to climate change, is included in the assessment of this report, as air pollutants are part of the carbon cycle model (MAGICC; Meinshausen, Raper and Wigley (2011[14])) that calculates radiative forcing and temperature change from a specific projected emission profile.[3]

There are also greenhouse gases that have an impact on air pollution. In particular, methane contributes to the formation of ozone, which has impacts on crop yields and health. The effect of methane on ozone formation is taken into account in the calculations of ozone concentrations (Van Dingenen et al., 2018[15]).

Other types of potential interactions between greenhouse gases and other air pollutants cannot be considered due to lack of information. One example is the effect of climate change on ozone through changes in sunlight exposure of the relevant gases (Ebi and McGregor, 2008[16]). Small particles also cause a decrease in the albedo of snow and affect snowmelt (IPCC, 2007[13]). In particularly vulnerable areas, such as the Arctic and glaciated regions, this can result in melting snow and negative effects on the local climate.

2.1.3. Interactions in the biophysical system

Climate change and air pollution interact in the biophysical system through several channels. Climate change and air pollution both affect health and can lead to premature deaths. Furthermore, interactions occur within the agricultural system, especially on crop yields. There are also other potential interactions, such as in the tourism sector or in ecosystems.

Health effects from climate change and air pollution are the main point of interaction when considering the effects on the economy. It is logical to assume that these effects are not independent. A number of publications from the Lancet Commission deal with pollution and health (Wang and Horton, 2015[17]; Haines, 2017[18]; Landrigan et al., 2017[19]). The Global Burden of Disease (GBD) studies quantify the effects of air pollution on health (Forouzanfar and et al., 2015[20]; Brauer et al., 2016[21]; Lim et al., 2012[22]; Burnett et al., 2014[23]). These studies find very significant health impacts of air pollution.

However, there are no estimates available on the way in which climate change changes the effects of air pollution on health. Orru, Ebi and Forsberg (2017[24]) give a very comprehensive overview of the possible health interactions between climate change and air pollution, but do not provide a quantification of size of the effects. Rao et al. (2017[25]) take a quantitative scenario approach and discuss how climate change scenarios can affect future air pollution, but without quantifying interaction effects. The Haines (2017[18]) study on global health aims to look at a broad set of environment-health linkages. Unfortunately, one of the conclusions of this study – and the related papers that are part of the same Lancet

[3] Note that the damage calculations in this report depend on global average temperatures, so changes in regional climates due to spatial differences in air pollutant emissions are not considered.

Commission study – is that interaction effects between climate change and air pollution are largely unknown and cannot be quantified yet.

Thus, while it is clear that these biophysical interaction effects are potentially very important, there is a lack of robust literature to quantify them on a global scale.[4] Following the existing literature (Haines, 2017[18]; Amann, Klimont and Wagner, 2013[26]; Van Dingenen et al., 2018[15]), the assumption in this report is therefore that 'you can only die once', and no specific interaction effects are included in the analysis. For agriculture, crop models should in principle be capable of assessing the interaction effects within the biophysical system, but no global assessment is readily available for incorporating into the current analysis so this is left for future research.

Mortality interactions can happen when adverse climatic conditions, most notably heating days, happen in coincidence with pollution peaks. In the coming decades, such environmental conditions are likely going to increase with climate change and without additional policy action to reduce air pollution. Some studies have attempted to quantify this interaction effect on mortality for specific regions (Li et al., 2014[27]; Basu, 2009[28]; Stafoggia et al., 2008[29]; Willers et al., 2016[30]). The results show that a positive interaction effects can lead to additional premature deaths when heating days coincide with high pollution levels. The quantification of this interaction effects however is heavily dependent on the region considered. Thus, the literature on the topic is not yet robust enough to be used in a modelling analysis at global level. While air pollution mortality risks are evaluated in this report on the basis of the large-scale assessment of the Global Burden of Disease (GBD) studies (Forouzanfar and et al., 2015[20]; Brauer et al., 2016[21]; Lim et al., 2012[22]; Burnett et al., 2014[23]),[5] such an assessment does not exist yet on the interactions between climate and air pollution.

Agricultural interactions are also important as both climate change and air pollution affect crop productivity. However, there are large uncertainties as it is difficult to quantify the feedback mechanisms between climate change and ozone levels, as well as the effect of changing CO_2 levels on the way ozone is absorbed by plants (Van Dingenen et al., 2009[31]). Van Dingenen et al. (2009[31]) highlight the main sources of interaction between climate and air pollution in agriculture: (i) climate-related changes in meteorology (temperature, humidity, soil water, etc.) affect ambient ozone levels as well the growing season, crop distribution, and the effect of ozone on vegetation; (ii) increase in CO_2, reduce the plants' ability to absorb ozone, while simultaneously increasing ambient ozone levels; (iii) emissions of ozone precursors can also be affected by changing climate.

These effects can be limited in the short term but can have significant impacts in the long run. These interaction effects are taken into account in this report as the future climate conditions are included in the modelling framework used to assess the effect of air pollution on crop yields (TM5-FASST model). However, it is not possible to study the interactions in detail as only the total effect on crop yields from climate and air pollution is available.

There are numerous **other potential interactions** in the biophysical system that cannot be quantified. For example, one can wonder how air pollution and climate change affect

4 In fact, the scarcity of the literature extends even to the air pollution analysis itself, which – due to lack of data – assumes that mortality and morbidity effects are proportional to each other (OECD, 2016[9]).

5 See Section 2.2 and Annex B for more information on the mortality risk modelling in this report.

ecosystems, ecosystem services and biodiversity, cultural heritage or the environment in urban areas. These impacts can also have effects on economic sectors such as tourism, with possible positive or negative interaction effects. Quantification of such effects is well beyond reach given the current state of literature.

2.1.4. Interactions in the economic system

There are interactions between climate change and air pollution that stem from the simultaneous consideration of the two environmental issues in the economic system. These are due to the interconnectedness of economic activities through production patterns and international trade. For example, as climate change affects labour productivity of outdoor workers, it affects the relative prices of commodities, and thus international trade patterns. At the same time, relative prices and trade patterns are affected by the air pollution damages; for example, increased health expenditures imply a shift in consumption to more health services.

In general, sector- and region-specific shocks to the economy tend to propagate to other sectors and regions, as firms and consumers change their spending patterns to adapt to the climate and air pollution impacts, moving away from those commodities where the environmental feedbacks cause the largest price increases. Similarly, the competitiveness of various exporters are affected by the domestic impacts, leading to shifts in trade patterns towards those regions that can keep output prices low compared to their competitors.

The joint consequence of climate change and air pollution damages is not simply the addition of the effects caused by the two issues. There can be significant non-linear effects that affect the final economic outcome. On the one hand, the interaction effects can be positive, as agents can absorb both shocks simultaneously and thus find least-cost solutions. On the other hand, marginal costs of absorbing shocks tend to increase more than proportionally and thus the effects of one negative shock on top of another will lead to more than proportionally higher overall costs.

Given these contrasting effects, it is difficult to determine whether the overall interaction effect between climate and air pollution damages will be positive or negative. A modelling analysis can help better understand this as well as the relative size of the different effects.

2.2. Overview of the modelling framework

The core tool used in this report is the global dynamic computable general equilibrium (CGE) model ENV-Linkages (Chateau, Dellink and Lanzi, 2014[10]) (see Annex A). In ENV-Linkages economic activities for 35 sectors (Table A.1) and 25 regions (Table A.2) are projected for the medium- and long-term future, up to 2060. ENV-Linkages also links economic activity to environmental pressure, specifically to emissions of greenhouses gases (GHGs) and outdoor air pollutants (see Annex A).

This report presents a projection of economic activity, which reflects a baseline evolution of the drivers of economic growth. Such a scenario includes environmental policies that are already in place (e.g. the European Union's Emissions Trading Scheme and the US Clean Air Act), but not targets that have been agreed upon but that still lack the actual translation into policy measures (e.g. the nationally determined contributions within the Paris Agreement, and the most recent Chinese five-year plans). As such the projections presented in this report can be considered as a reference to calculate the costs and benefits of policy scenarios.

This report compares a projection that includes the economic consequences of environmental damages with a counterfactual “no-damage projection”. The “no-damage projection” is not a projection where emissions are sufficiently reduced to avoid climate change and air pollution; rather, it makes the counterfactual assumption that climate change and air pollution will not affect the economic system, i.e. it ignores their damages. By using reference projections of economic activity that ignore environmental damages, this approach allows measuring the economic consequences of climate change and air pollution.

This report studies the consequences of a specific set of impacts of climate change and air pollution (see Annex B). The impacts include changes in agriculture and health due to climate change and air pollution, as well as climate-related changes in fisheries, coastal zones, demand for tourism services and energy demand for heating and cooling. The impacts included are those for which there was enough data to perform a modelling assessment at global level. The modelling exercise also excludes non-market impacts (i.e. impacts that affect well-being but not directly economic activity as measured in the national accounts), as the report focuses solely on economic interactions as linked to specific sectoral and regional economic activities.

The analysis is based on a production function approach. The effects of the selected set of environmental impacts are linked directly to specific drivers of economic growth and structural change of the production function underlying the model. The drivers considered include the productivity and supply of specific production factors (e.g. labour productivity that is negatively affected by air pollution, or the supply of land, which can be reduced by sea level rise), or the demand for specific goods (e.g. healthcare expenditures increasing due to climate and air pollution related illnesses).

The approach used allows quantifying the macroeconomic costs, which are calculated using the Gross Domestic Product (GDP), as well as effects on the different activities, which are used to tease out the direct and indirect consequences of environmental damages for the global and regional economies. The direct consequences stem directly from the biophysical impacts (e.g. crop yield changes), while the indirect ones are the result of adjustments throughout the economic system (e.g. changes in production choices in agriculture). These include changes in consumption patterns, in international trade but also in capital stocks, which can limit the extent to which capital accumulates over time.

3. Results

3.1. Overview of the "no-damage projection"

GDP levels in the no-damage projection are projected to increase more than linearly over time, despite a gradual declining in economic growth rates. 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.

The sectoral structure of the economy is also projected to evolve over time. The shares of the various sectors in OECD economies tend to be relatively stable. 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. 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.

These sectoral trends lead to a steady increase in regional and global emissions. Global anthropogenic 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 carbon dioxide (CO2) equivalent (CO2-e) in 2010 to around 95 GtCO2e in 2060. CO2 is projected to remain the dominant greenhouse gas. These changes in emissions can be translated to temperature increases of more than 2.5°C by 2060 and are on a pathway that would lead to around around 4°C temperature increase by the end of the century.

For most air pollutants, emissions are also projected to increase in the coming decades, with the highest increases taking place in the South and South East Asia region. Emissions from OECD countries tend to be stable or to slightly decline. With emissions of air pollutants generally rising over time, the concentrations of PM2.5 and ozone are also projected to increase in most regions. 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.

More detailed results of the "no-damage projection" are provided in Annex C, which includes details on the economic projections and the consequences for climate change and air pollution.

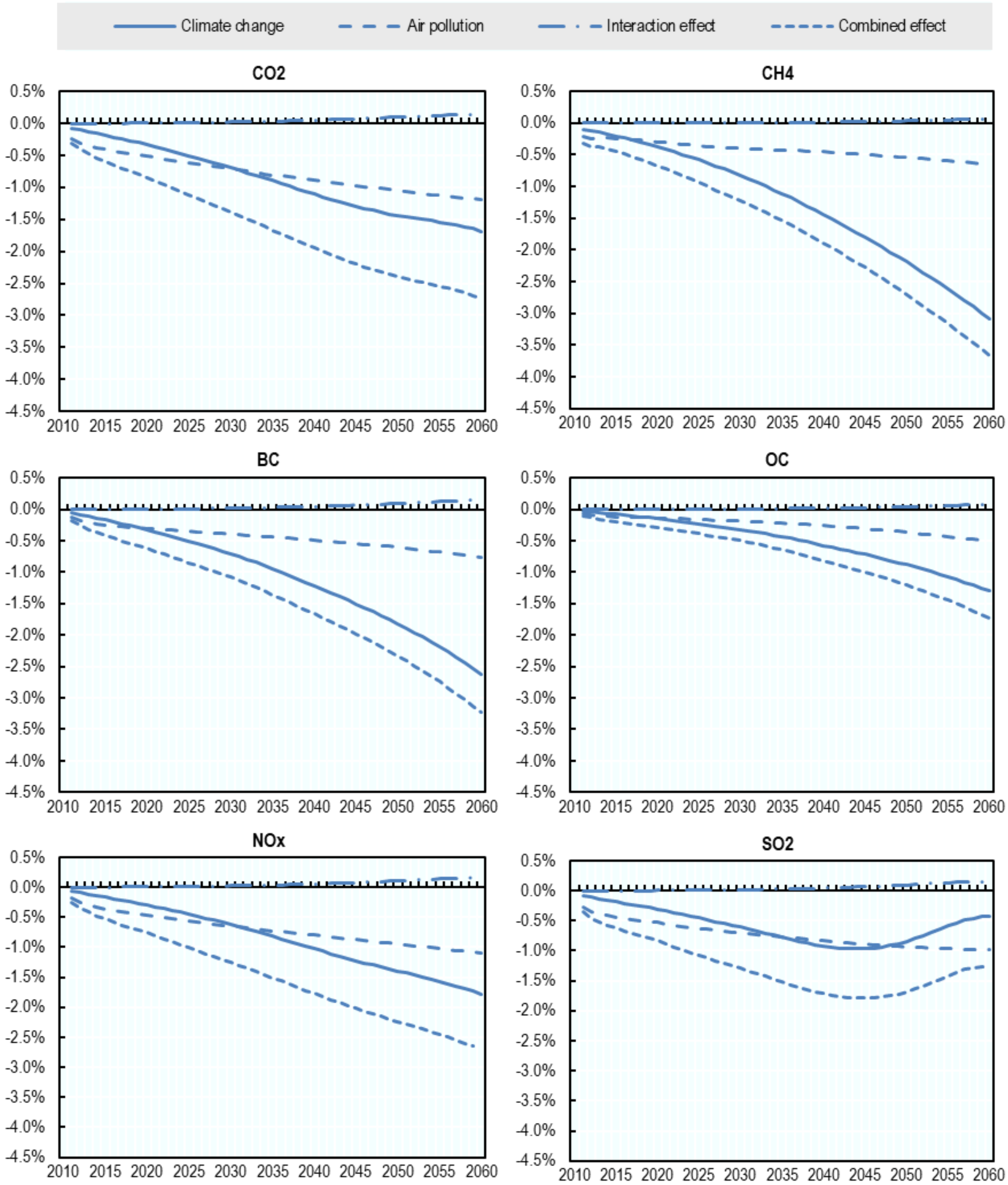
3.2. Interactions through changes in emissions

Climate change and air pollution will interact at the level of emissions 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; the two most direct ones considered here are through the effect of economic damages of one issue on emissions of the other and through the radiative forcing effect of air pollutants.

3.2.1. Effect of economic damages on emission levels

Climate and air pollution damages affect sectoral economic activities and thus the emission levels associated with these activities. Figure 2 shows that the effect of economic damages due to climate change on air pollution emissions, and the effect of air pollution damages on GHG emissions are relatively small.

Figure 2. Changes in global emissions from climate change and outdoor air pollution damages



Note: Interaction effect measures the difference between the combined effect and the sum of the two individual effects. A positive interaction effect implies that when the individual effects are negative (positive), the combined change is smaller (larger) than the sum of the individual effects.

While climate and air pollution impacts may have significant effects on specific economic sectors, in many cases the changes in activity level of polluting activities remain limited. Therefore, the associated changes in emissions are also limited. Emission levels of both GHGs and air pollutants decline roughly proportionally to the scale of the macroeconomic damages. The direct interaction effect of climate damages on air pollution emissions is thus increasing by 2060 to between 2 and 3 percent. Organic carbon, which has a very specific profile of emission sources, tends to be less correlated with macroeconomic damages and is projected to be less affected by the climate (and air pollution) damages.

Sulphur dioxide effects follow the general pattern only until 2040, after which there is an additional effect from climate damages that is a priori not intuitive. The increased demand for cooling (incl. air conditioners) in many countries drives up the use of fossil fuels. Furthermore, part of renewable electricity depends on agricultural inputs, which are severely hit by climate damages. This invokes a shift in the fuel mix for power generation towards more fossil-fuel based electricity, including coal. As not all countries are assumed to have SO_2 scrubbers on coal-fired power plants (OECD, 2016[9]), this induces a small but non-negligible increase in SO_2 emissions. All these effects are most prominent in India: a significant increase in electricity demand, large agricultural losses that induce a shift towards more fossil fuels, a large share of coal in power generation, and high SO_2 emissions from coal-fired power plants. As a consequence, SO_2 emissions in India in 2060 rise to 3.5% above the no-damage baseline level.

The interaction effect from air pollution damages on GHGs remains limited to around 1 percent, and the pattern is very similar across gases, showing that the cross-effect on GHGs is mostly driven by macroeconomic changes rather than by changes in the sectoral structure of the economy.

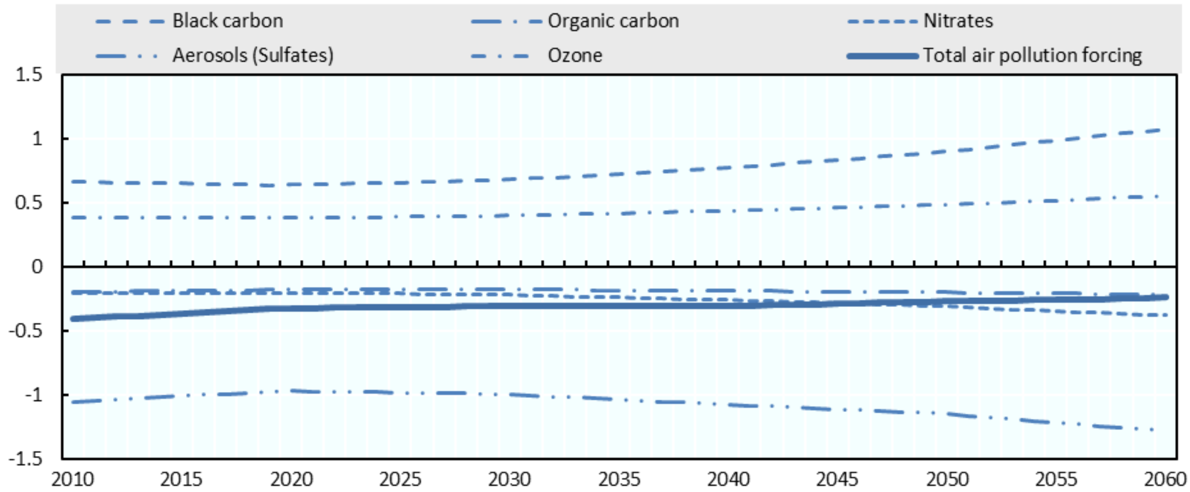
When both types of damages are simultaneously considered, there is a small additional effect. This effect (labelled “Interaction effect” in Figure 2) comes from the economic interactions discussed in Section 3.3 below, and leads to a very small increase in global emissions of GHGs and air pollutants.

3.2.2. Cross-effects of emissions on concentrations

Many air pollutants have a direct (and indirect) effect on radiative forcing and thus on climate change. The net effects on climate change are limited as some pollutants have a cooling effect and others a warming effect (IPCC, 2013[12]). Figure 3 shows the projected evolution of the radiative forcing effects that are related to air pollution.

Figure 3. Evolution of radiative forcing effects related to outdoor air pollutants

Radiative forcing effects in W/m^2



Source: Own calculations using MAGICC (Meinshausen, Raper and Wigley (2011[14])).

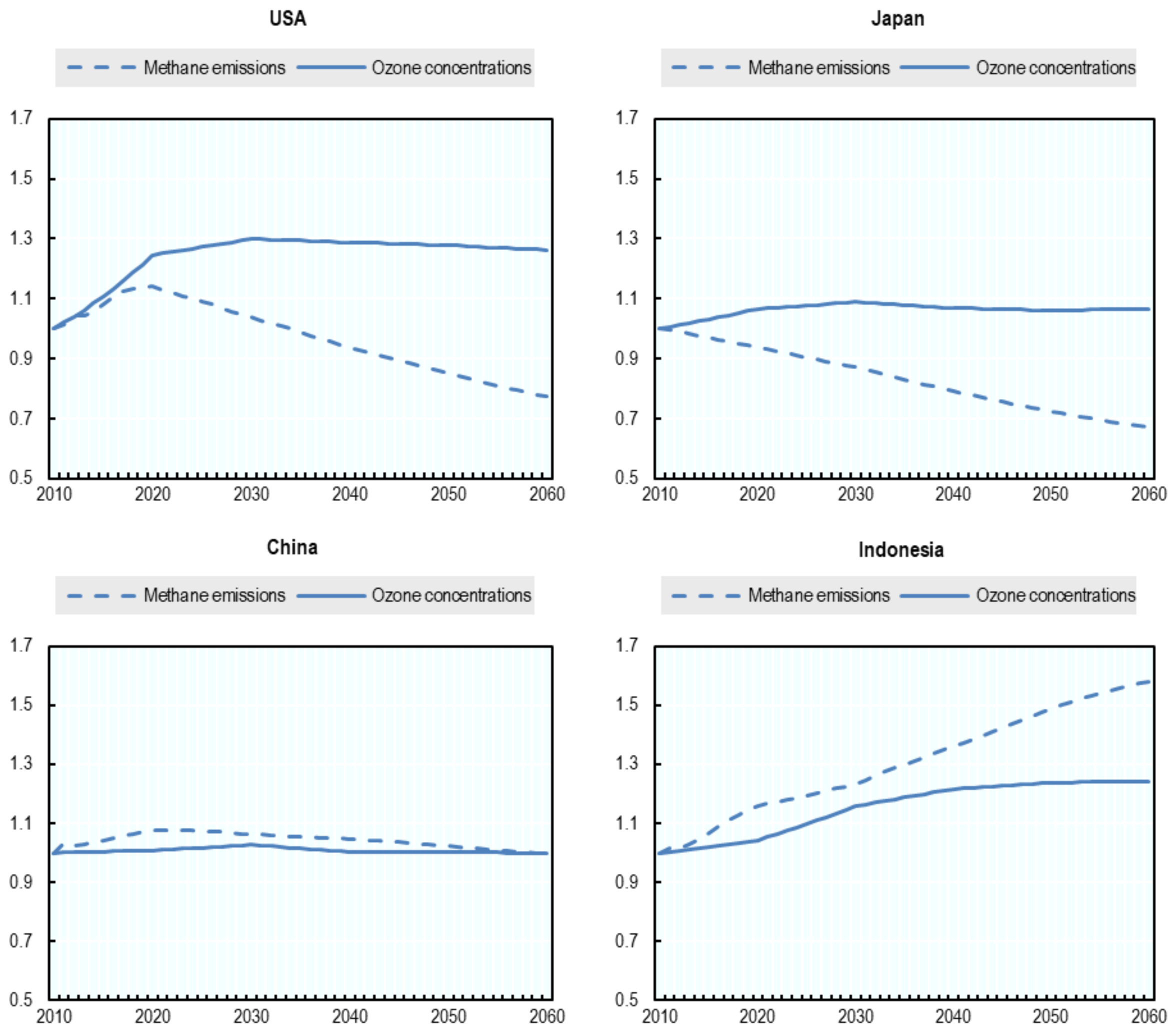
The total net effect of all air pollution related forcing is projected to be negative, at around 0.4 W/m^2 currently, and gradually diminishing to a little more than 0.2 W/m^2 by 2060. This reduction is primarily driven by increased black carbon emissions that have a strong warming effect; the increased cooling effect from higher SO_2 emissions after 2020 can only partially compensate for this. It should be emphasised that the size of these effects is uncertain; see (IPCC, 2013[12]) for more details. Thus, the net effect is also uncertain.[6] According to the MAGICC model calculations (Meinshausen, Raper and Wigley (2011[14])), the strongest warming effect comes from black carbon (incl. the effect of black carbon on snow albedo). The strongest cooling effect comes from the aerosols (incl. SO_2): these have a direct effect (which amounts to around 0.4 W/m^2 and only increases marginally over time), as well as an indirect effect through cloud albedo (rising from 0.7 to 0.8 W/m^2 cooling between 2010 and 2060). For the projection period 2015-2060, both the warming and cooling effects are amplified, as emissions of the relevant pollutants increase. While these numbers are not negligible, they are much smaller than the warming effect of greenhouse gases, which are projected to rise from 2.8 W/m^2 to 5.2 W/m^2 between 2010 and 2060.

The radiation interaction effects that arise from the joint economic consequences of climate change and air pollution comes through the changes in emissions as outlined in Section 3.2.1. As these amount on average to a few percent of baseline emissions, these interaction effects on radiative forcing are also limited to around 0.01 W/m^2.

[6] Furthermore, one cannot conclude from this that air pollution control will lead to net warming, as that crucially depends on how much emissions of each pollutant are reduced.

Figure 4. Evolution of methane emissions and ozone concentrations

Standardized to unity in 2010



Source: Own calculations using ENV-Linkages and TM5-FASST.

Methane emissions are a main contributor to ozone formation. Ozone concentrations respond to changes in volatile organic compounds, including methane, and NO_x emissions. The relation is however non-linear and depends on other determinants, such as sunlight, presence of other gases and the geographical situation. Thus, it is impossible to find a similar indicator to the global warming potential for the climate effects of air pollutants.

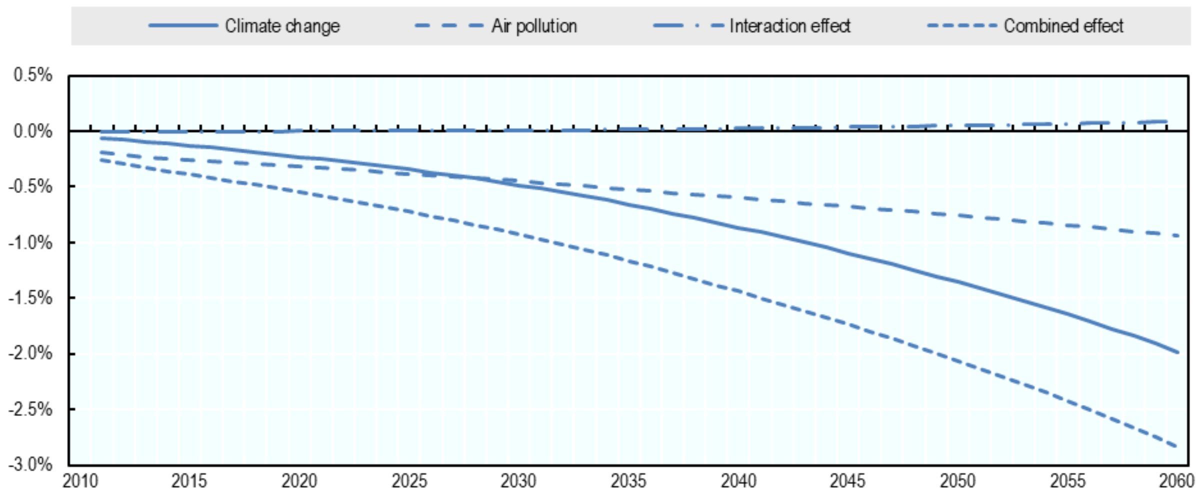
Figure 4 illustrates the change over time in methane emissions and in ozone concentrations for selected countries. The aggregation to national levels ignores the essential non-linear region-specific relationship, as well as transboundary emissions. Nevertheless, Figure 4 highlights the importance of the greenhouse gas methane on air pollution through ozone formation.

3.3. Interactions through changes in the economic system

3.3.1. Interactions at the macroeconomic level

The economic interactions between climate and pollution damages are also driven by the interaction effects in the economy as it absorbs both sets of impacts (Section 2.1). 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 5).[7]

Figure 5. Changes in global GDP from climate change and outdoor air pollution damages



Note: Interaction effect measures the difference between the combined effect and the sum of the two individual effects. A positive interaction effect implies that when the individual effects are negative (positive), the combined change is smaller (larger) than the sum of the individual effects.

In the first few decades, the consequences of air pollution tend to dominate, and overall damages are still relatively small. But over time, both feedbacks become stronger, and represent an increasing cost, both in absolute terms as when expressed as percentage deviation from the no-damage projection.

The interaction effect is calculated as the difference between the combined effect and the sum of the two individual effects, and reflects the difference in macroeconomic consequences from the simultaneous absorption of both shocks in the economic system. As both climate and air pollution damages are small in the short-run, the interaction effect is also very small. But the interaction effect gradually rises to around 0.1% of GDP, implying that the joint consequences of climate change and air pollution are smaller than the sum of the individual effects.

Figure 6 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 react

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[8]).

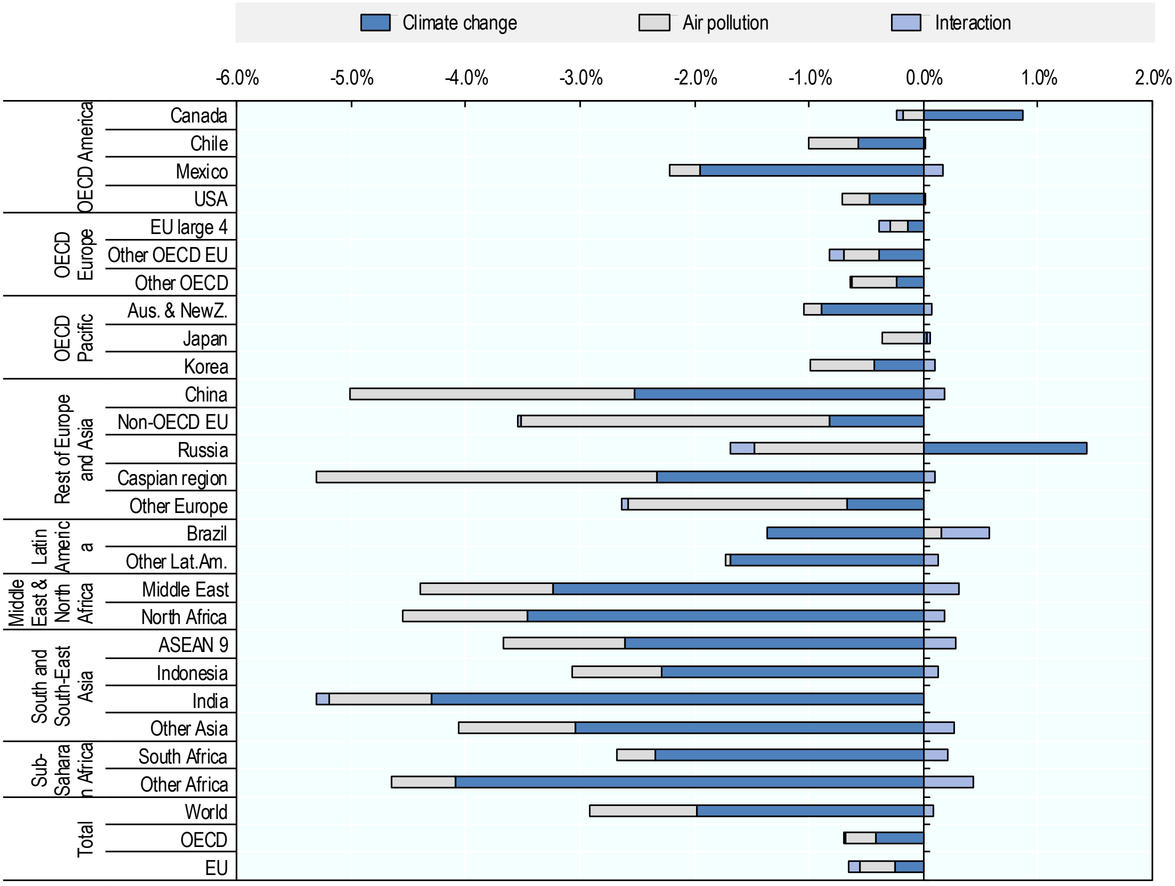
in an integrated manner, and thus there is a positive interaction effect: the damages from both types of impacts taken together are smaller than the sum of individual damages. In most regions, the effect is small however, and dominated by other effects.

In Brazil, climate impacts are negative and air pollution impacts are positive, and the interaction effect is positive. 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 limited vis-à-vis their competitors – implies these trade benefits multiply (see also the discussion of trade interactions below).

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. 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 (OECD, 2015[8]). However, negative health impacts from air pollution drag down these benefits and thus limit any international competiveness effect.

India is an exceptional case as well, as it is the only country in Asia where the interaction effect is projected to be negative. Most emerging and developing economies can benefit from the simultaneous absorption of both shocks (and have a positive trade interaction effect, see below). But in India, where both shocks are relatively severe, the dominant effect is that non-linearities in the economic system hurt the economy. Simply put, when economies need to adjust to more severe negative shocks, they run out of cheap options and more productive parts of the economy are affected as well. Income losses then turn into reduced savings rates, slower capital accumulation and thus a slowdown of economic growth and even larger income losses in the future.

Figure 6. Changes in regional GDP from climate change and outdoor air pollution damages



Note: Interaction effect measures the difference between the combined effect and the sum of the two individual effects. A positive interaction effect implies that when the individual effects are negative (positive), the combined change is smaller (larger) than the sum of the individual effects.

3.3.2. Interactions at the international trade level

Trade effects play an important role in determining the sign of the interaction effect. Panel A of Figure 7 shows how climate change and air pollution damages affect exports.[8] In qualitative terms, export consequences follow GDP; thus, the largest export losses occur as a result of climate change, and in non-OECD countries.

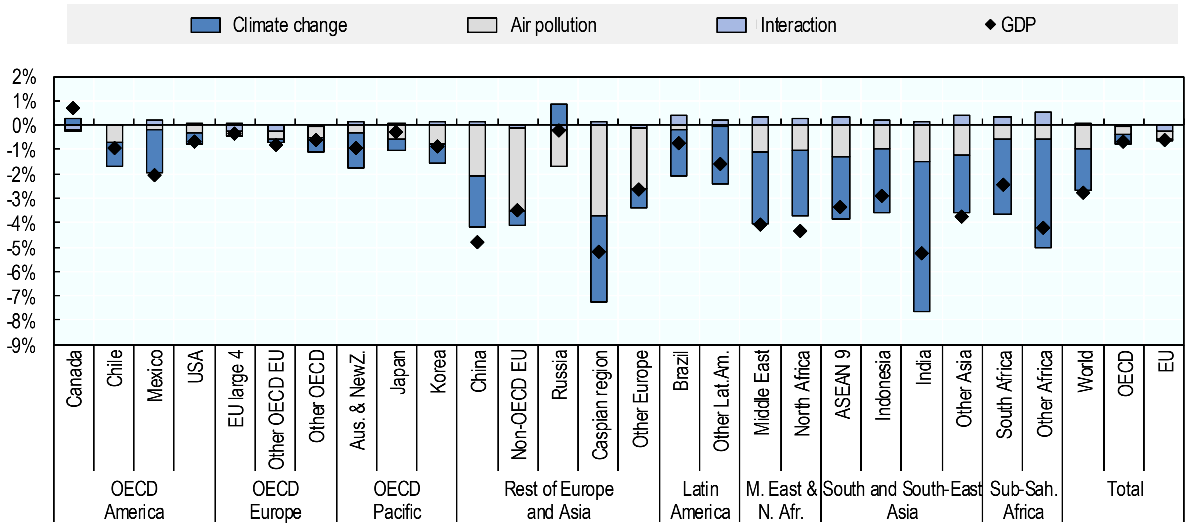
In Latin America, Asia and Africa, the export interaction effects are invariably positive. In essence, this is a result of the relatively strong GDP and export losses: the larger shock implied by the joint damages is cushioned by a less than proportional reduction in exports. This is driven by the key modelling assumption for representing trade that consumers have an implicit preference to remain trading with the same partners, and reductions in trade

[8] The trade consequences of environmental feedbacks are not straightforward to assess, and effectively requires a detailed assessment at the level of individual sectors for specific trade relations to understand how the various mechanisms interact to determine changes in terms of trade and thus export and import patterns (Dellink et al., 2017[60]).

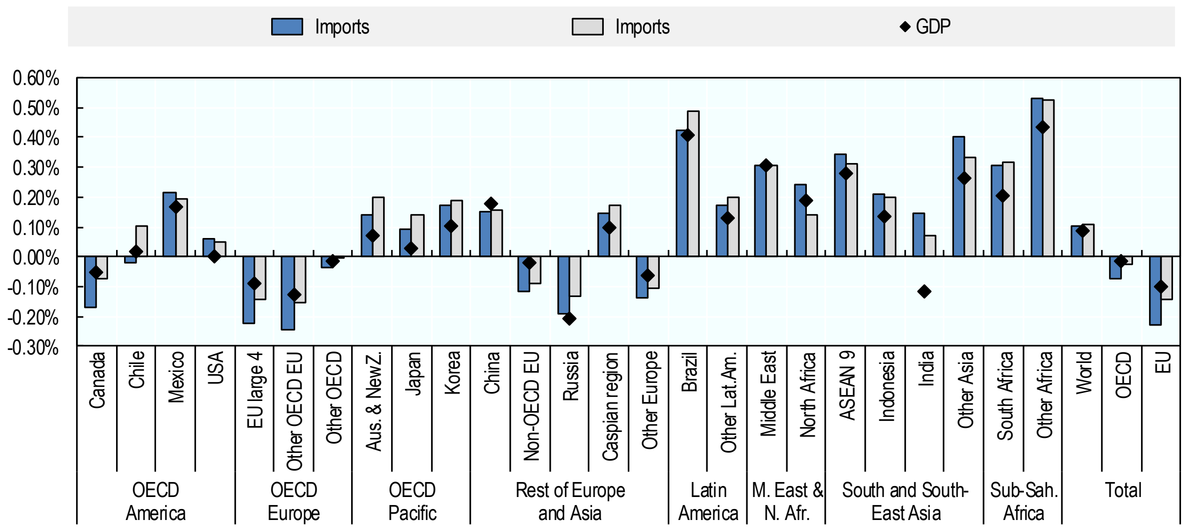
shares follow a non-linear pattern where larger changes become less preferable, as even in the case of large cost increases a relatively large part of the export market remains.

Figure 7. Changes in international trade from climate change and outdoor air pollution damages

Panel A. Consequences for exports



Panel B. Interaction effects for exports and imports



Note: Interaction effect measures the difference between the combined effect and the sum of the two individual effects. A positive interaction effect implies that when the individual effects are negative (positive), the combined change is smaller (larger) than the sum of the individual effects.

Panel B of Figure 7 presents the interaction effects or exports (as also presented in panel A) and the interaction effects for imports. The graph clearly shows that these interaction effects work in the same direction, even if the size is different. This result is at least partially driven by the assumption that trade balances are cleared through adjusting exchange rates. There is thus little room for the effects on total imports to deviate from those on total exports.

The panel also shows that trade effects can explain part of the interaction effects found for GDP; this holds for countries with a negative effect as well as for those with a positive effect.[9] A major exception is India, where the interaction effect for GDP is negative, despite a positive trade interaction effect. This confirms the importance of the non-linearity effect for India as discussed above.

3.3.3. Interactions at the sectoral level

Figure 8 shows the effects of climate change and air pollution damages for the various sectors.[10] It is not surprising that the largest percentage losses are observed in agriculture, where both climate change and air pollution have significant adverse effects.[11] 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 adaptation mechanisms (such as land reallocation towards this crop, better management practices or other adjustments of the inputs in wheat production).

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 responses 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 modelling framework that links all parts of the economy to evaluate the economic consequences from environmental damages rather than relying on partial estimates of direct effects on 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 small: increased energy demand for cooling in summer is almost completely offset by reduced energy demand for heating in winter (IEA, 2013[32]).[12] The overall effects on energy production are therefore very logically limited.

In OECD countries, energy-intensive industries can even benefit from the environmental impacts, while the services sector slightly contracts. This is a typical characteristic of countries that are faced with relatively modest domestic impacts from environmental damages: 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.

9 As trade is only a part of GDP, it cannot explain the full effect.

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

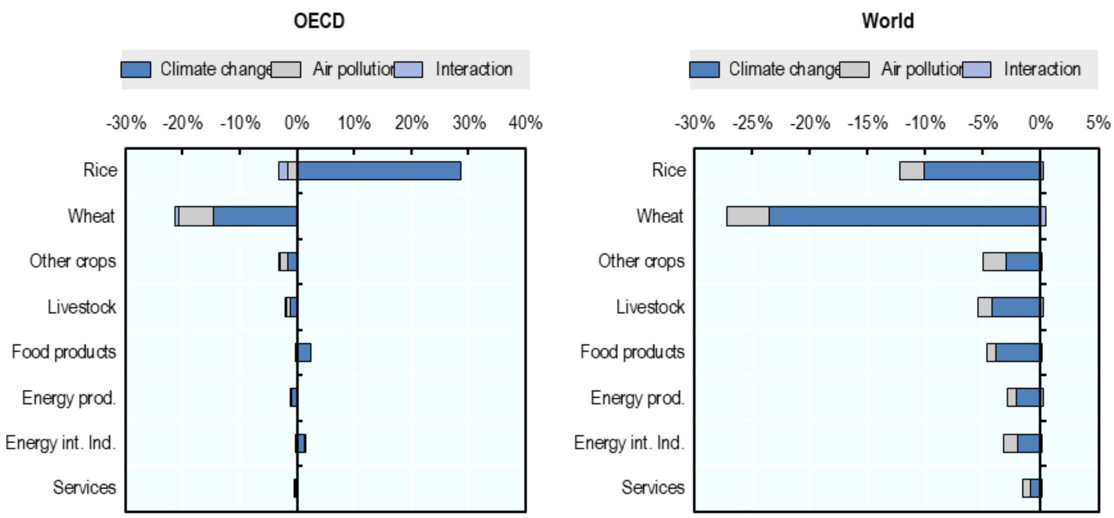
11 These results exclude the effect of CO_2 fertilisation; see (OECD, 2015[8]) for an investigation of the effect of this assumption.

12 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, 2013[32]).

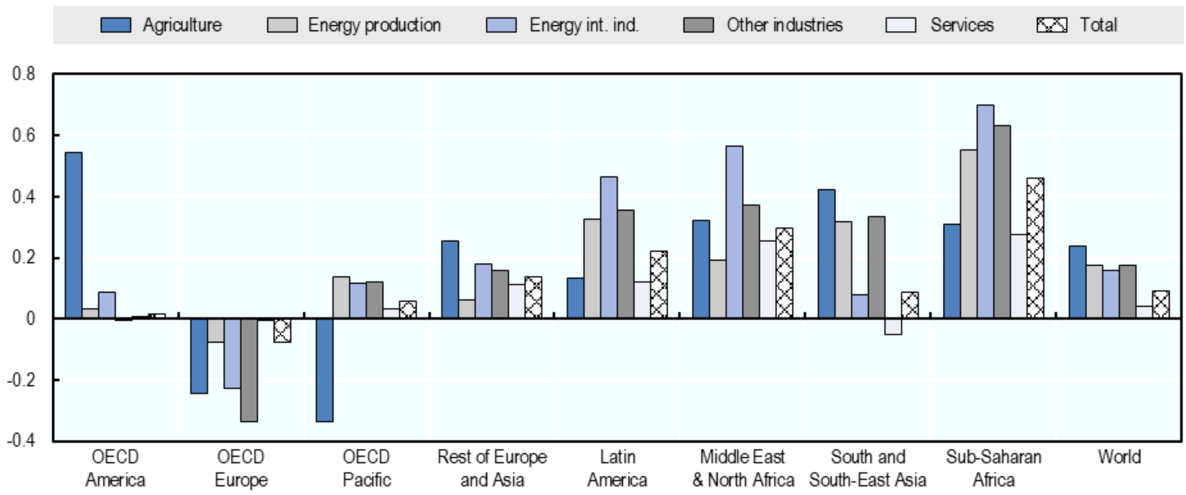
At the global level, climate change and air pollution damages have a negative effect on all sectors, mostly driven by the negative macroeconomic consequences. Trade gains in some regions are mirrored by trade losses in others.

Figure 8. Changes in sectoral production from climate change and outdoor air pollution damages

Panel A. Selected sectors (percentage change from baseline)



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



Note: Interaction effect measures the difference between the combined effect and the sum of the two individual effects. A positive interaction effect implies that when the individual effects are negative (positive), the combined change is smaller (larger) than the sum of the individual effects.

Panel B further teases out the regional and sectoral differences in the interaction effects.[13] In all regions except OECD Europe, the total economic interaction effects are positive; this extends to all major sectors of production. In the regions where the total damages are

13 The results for the USA are influenced by the model closure rules related to ensuring the current account is balanced globally, and should be interpreted with caution.

strongest, the interaction effects are also strongest, in line with Figure 6. 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.

3.3.4. Interactions at the production factor level

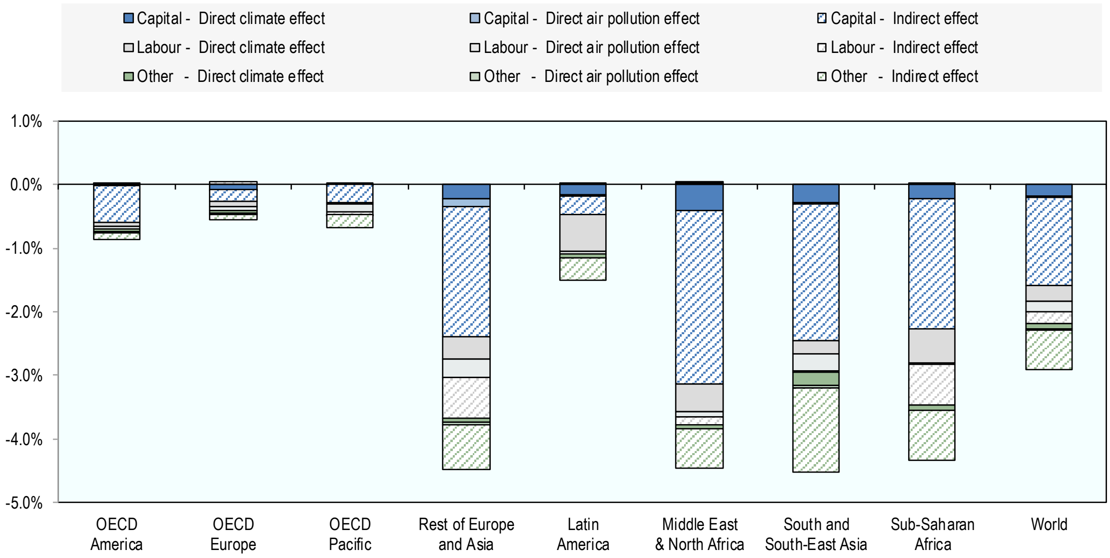
The model projections indicate a negative effect from both climate change and air pollution impacts, and this offers some room for reallocation of factors across sectors to accommodate both shocks simultaneously. The economic consequences of the climate change and air pollution impacts are further differentiated by production factor in Figure 9. The overall effects are by definition in line with the effects in Figure 6. 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.[14]

At both global and regional 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 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 on average half of the projected economic consequences on GDP *levels* come from the indirect effects on capital accumulation. 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 environmental impacts, whereas the capital stock is only directly affected by climate change (but indirectly also by air pollution).

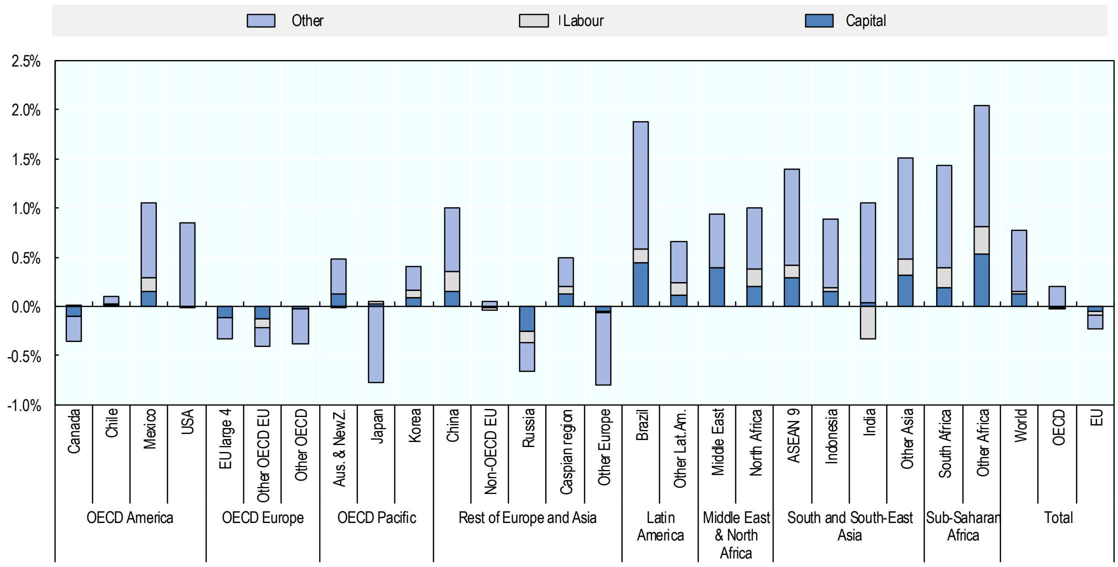
[14] The direct effects have been calculated by multiplying the percentage change in productivity and supply of these factors at their no-damage baseline levels of use, i.e. before any endogenous market responses. The indirect effects are then calculated as the difference between the total effect on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

Figure 9. Changes in production factors from climate change and outdoor air pollution damages

Panel A. Decomposition of total joint impact by production factor (percentage change from baseline)



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



Note: Interaction effect measures the difference between the combined effect and the sum of the two individual effects. A positive interaction effect implies that when the individual effects are negative (positive), the combined change is smaller (larger) than the sum of the individual effects.

Panel B of Figure 9 presents the regional interaction effects by production factor. In most regions, the ability to absorb both shocks together dampens the negative effects on all three production factors. This largely reflects macroeconomic shifts: the changes in GDP translate into changes in all production factors. The major exception is India, where the interaction effect is negative for labour, but positive for capital and other production factors. This highlights the difficulty of India to cope with two strong negative shocks on agricultural and labour productivity.

4. Discussion

The projections presented in this report are subject to different sources of uncertainty. These include uncertainties on the economic projections but also sources of uncertainty that are more specific to climate change and outdoor air pollution individually (see OECD (2015[8]) and (2016[9])). More robust quantitative insights require using multiple scenarios, sensitivity analysis to major modelling assumptions, and ideally comparing different models. That is beyond the scope of this report. Therefore, the results in this report should be regarded mostly as a first attempt to quantify the joint economic consequences of climate change and outdoor air pollution in a single coherent framework; the direction of effects and mechanisms at play matter more than the precise numbers.

This report ignores specific biophysical interaction effects for climate change and outdoor air pollution, e.g. that heatwaves make people more vulnerable to air pollution. Quantifying them would – with the current state of the literature and lack of reliable data – be pure speculation, as even the sign of the interaction effects cannot be robustly established. The small interaction effects that are found in this report can therefore not be used to infer that interactions between climate change and air pollution are not important; there are simply too many unknowns. However, the report shows that these interaction effects in the economic system exist and that they can potentially be assessed in an applied economic modelling framework, with further availability of data.

The analysis presented in this report focuses on the effects of climate change and outdoor air pollution on economic systems; hence on market damages. However, non-market damages, and particularly the premature deaths caused by climate change and air pollution, also lead to high economic costs (OECD, 2015[8]; OECD, 2016[9]). Further, the analysis cannot capture all impacts of climate change and outdoor air pollution, nor can it identify the myriad of ways in which the two issues interact. For several impact categories, data to quantify impacts are missing. This holds for the potentially important impacts on ecosystems and biodiversity, as well as for large-scale singular climate events.

These caveats and remarks notwithstanding, this report contributes to understanding the economic interactions between climate change and outdoor air pollution damages. This is important as a basis for understanding the magnitude of the issues at stake, and forms the appropriate basis for evaluating the integrated benefits of policy action. While the interactions between the economic consequences of air pollution and climate change are limited in a no-policy setting, they can be expected to be larger in policy scenarios. In this context, the framework presented in this paper can be a useful tool to understand the economic benefits of integrated policy action on air pollution and climate change.

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Annex A. Description of the ENV-LINKAGES model

General description of ENV-Linkages

The OECD's in-house dynamic CGE model - ENV-Linkages - is used as the basis for the assessment of the economic consequences of climate impacts until 2060. The advantage of using a CGE framework to model climate impacts is that the sectoral details of the model can be exploited. Contrary to aggregated IAMs, where monetised impacts are directly subtracted from GDP, in a CGE model the various types of impacts can be modelled as directly linked to the relevant sectors and economic activities.

ENV-Linkages is a multi-sectoral, multi-regional model that links economic activities to energy and environmental issues. The ENV-Linkages model is the successor to the OECD GREEN model for environmental studies (Burniaux et al., 1992[33]). A more comprehensive model description is given in Chateau, Dellink and Lanzi (2014[10]); whereas a description of the baseline construction is given in Chateau, Rebolledo and Dellink (2011[34]).

Production in ENV-Linkages is assumed to operate under cost minimisation with perfect markets and constant return to scale technology. The production technology is specified as nested Constant Elasticity of Substitution (CES) production functions in a branching hierarchy. This structure is replicated for each output, while the parameterisation of the CES functions may differ across sectors. The nesting of the production function for the agricultural sectors is further re-arranged to reflect substitution between intensification (e.g. more fertiliser use) and extensification (more land use) of crop production; or between intensive and extensive livestock production. The structure of electricity production assumes that a representative electricity producer maximizes its profit by using the different available technologies to generate electricity using a CES specification with a large degree of substitution. The structure of non-fossil electricity technologies is similar to that of other sectors, except for a top nest combining a sector-specific resource with a sub-nest of all other inputs. This specification acts as a capacity constraint on the supply of the electricity technologies.

The model adopts a putty/semi-putty technology specification, where substitution possibilities among factors are assumed to be higher with new vintage capital than with old vintage capital. In the short run this ensures inertia in the economic system, with limited possibilities to substitute away from more expensive inputs, but in the longer run this implies relatively smooth adjustment of quantities to price changes. Capital accumulation is modelled as in the traditional Solow/Swan neo-classical growth model.

The energy bundle is of particular interest for analysis of climate change issues. Energy is a composite of fossil fuels and electricity. In turn, fossil fuel is a composite of coal and a bundle of the "other fossil fuels". At the lowest nest, the composite "other fossil fuels" commodity consists of crude oil, refined oil products and natural gas. The value of the substitution elasticities are chosen as to imply a higher degree of substitution among the other fuels than with electricity and coal.

Household consumption demand is the result of static maximization behaviour which is formally implemented as an "Extended Linear Expenditure System". A representative consumer in each region– who takes prices as given– optimally allocates disposal income among the full set of consumption commodities and savings. Saving is considered as a standard good in the utility function and does not rely on forward-looking behaviour by the consumer. The government in each region collects various kinds of taxes in order to finance government expenditures. Assuming fixed public savings (or deficits), the government budget is balanced through the adjustment of the income tax on consumer income. In each period, investment net-of-economic depreciation is equal to the sum of government savings, consumer savings and net capital flows from abroad.

International trade is based on a set of regional bilateral flows. The model adopts the Armington specification, assuming that domestic and imported products are not perfectly substitutable. Moreover, total imports are also imperfectly substitutable between regions of origin. Allocation of trade between partners then responds to relative prices at the equilibrium.

Market goods equilibria imply that, on the one side, the total production of any good or service is equal to the demand addressed to domestic producers plus exports; and, on the other side, the total demand is allocated between the demands (both final and intermediary) addressed to domestic producers and the import demand.

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 in a way similar to Hyman et al. (2003[35]). 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 (SF_6, PFCs and HFCs) from chemicals industry (foams, adipic acid, solvents), aluminium, magnesium and semi-conductors production. Over time, there is, however, some relative decoupling of emissions from the underlying economic activity through autonomous technical progress, implying that emissions grow less rapidly than economic activity.

Emissions can be abated through three channels: (i) reductions in emission intensity of economic activity; (ii) changes in structure of the associated sectors away from the ‘dirty’ input to cleaner inputs, and (iii) changes in economic structure away from relatively emission-intensive sectors to cleaner sectors. The first channel, which is not available for emissions from combustion of fossil fuels, entails end-of-pipe measures that reduce emissions per unit of the relevant input. The second channel includes for instance substitution from fossil fuels to renewable in electricity production, or investing in more energy-efficient machinery (which is represented through higher capital inputs but lower energy inputs in production). An example of the third channel is a substitution from consumption of energy-intensive industrial goods to services. In the model, the choice between these three channels is endogenous and driven by the price on emissions.

ENV-Linkages is fully homogeneous in prices and only relative prices matter. All prices are expressed relative to the numéraire of the price system that is arbitrarily chosen as the index of OECD manufacturing exports prices. Each region runs a current account balance, which is fixed in terms of the numéraire. One important implication from this assumption in the context of this paper is that real exchange rates immediately adjust to restore current account balance when countries start exporting/importing emission permits.

As ENV-Linkages is recursive-dynamic and does not incorporate forward-looking behaviour, price-induced changes in innovation patterns are not represented in the model. The model does, however, entail technological progress through an annual adjustment of the various productivity parameters in the model, including e.g. autonomous energy efficiency and labour productivity improvements. Furthermore, as production with new capital has a relatively large degree of flexibility in choice of inputs, existing technologies can diffuse to other firms. Thus, within the CGE framework, firms choose the least-cost combination of inputs, given the existing state of technology. The capital vintage structure also ensures that such flexibilities are large in the long-run than in the short run.

The sectoral and regional aggregation of the model, as used in the analysis for this paper, are given in Tables A.1 and A2, respectively.

Table A.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 (incl. 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 A.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)

Modelling emissions in ENV-Linkages

The regional and sectoral structure of the ENV-Linkages model, as well as the energy details, can be exploited to produce projections of GHG emissions. CO_2 emissions from fossil-fuel combustion are directly linked to the use of different fuels in production or the consumption by final demand. 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 (CH_4) 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 (NO_X) 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 from ENV-Linkages, the MAGICC (Meinshausen, Raper and Wigley, 2011[14]) model 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 ENV-Linkages by linking them to production activities in different key sectors. The main emission sources are similar to those of GHGs emissions: 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. The air pollutants tracked in the model are the following: 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 Particulate Matter (PM) and ground level ozone (O_3), the concentration levels of which are the main causes of impact on human 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, Klimont and Wagner, 2013[26]; Wagner, Amann and Schoepp, 2007[36]). The emissions per unit of the related economic activity (i.e. the emission coefficients) are time-, 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.[15]

Emission projections of precursor gases are used to calculate the associated concentrations of $PM_{2.5}$ and O_3. These concentrations have been calculated using the EC-JRC's TM5-FASST model (Van Dingenen et al., 2018[15]).[16] As impacts on human health are related to individuals' exposure, the concentrations are calculated as population-weighted mean concentrations, rather than average concentrations across areas with widely varying population densities.

Main trends used for the calibration of ENV-Linkages

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.[17] 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 the OECD Economic Outlook (OECD, 2014[37]). 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.

15 For more details see (OECD, 2016[9]).

16 Concentrations of $PM_{2.5}$ that are used for the calculations of the health impacts are quantified as population-weighted annual average $PM_{2.5}$ 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 the accumulated hourly ozone above 40 parts per billion (ppb) during a 3-monthly growing season (i.e. AOT40); 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.

17 Demographic projections, including effects of changes in fertility, death rates, life expectancy and international migration, are taken from the UN population prospects (2015[66]). The labour force database (participation rates and employment rates by cohort and gender) is extracted from ILO (2011[65]) active population prospects (up to 2020) and OECD Labour Force Statistics and Projections (2011[67]).

Projections of sectoral energy intensities until 2035 are in line with the IEA's World Energy Outlook "Current Policy Scenario" (CPS) (IEA, 2013[38]). 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 (Robinson et al., 2015[42]) 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[43]). 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 (e.g. fruits and vegetables). 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.

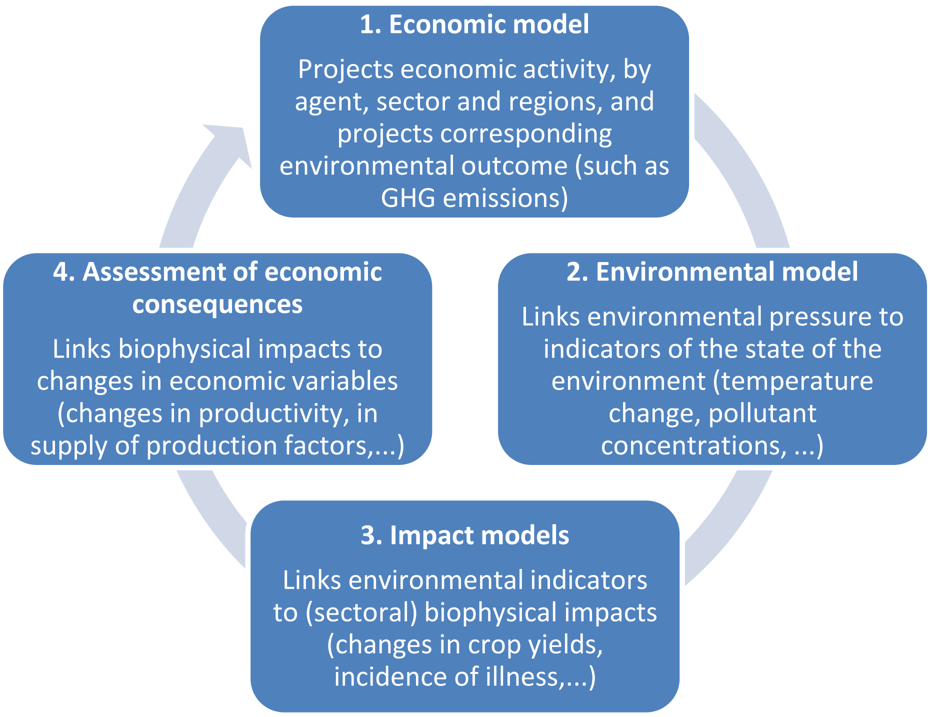
Annex B. Description of the modelling framework to assess environmental damages

Overview of the modelling framework

The modelling approach used in this report was previously used for the assessment of the economic consequences of climate change (OECD, 2015[8]) and of air pollution (OECD, 2016[9]) separately, and it is now used for the joint assessment of the two environmental issues.

Figure B.1 illustrates the modelling framework used for the analysis. First, a baseline socioeconomic projection that excludes environmental damages ("no-damage projection") is used to calculate environmental pressures (1). Second, using external models, the resulting concentrations of GHGs and air pollutants, temperature change and other environmental indicators such as carbon stocks are calculated (2). Third, based on these environmental indicators, impact models are used to a set of biophysical impacts, such as changes in crop yields or labour productivity losses (3). Finally, the resulting biophysical impacts are implemented as shocks in specific variables of the economic model to calculate the economic consequences of the environmental damages (4).

Figure B.1. The modelling framework



In step 4, ENV-Linkages is used to quantify the economic consequences of environmental damages with a production function approach. The effects of a selected set of environmental impacts are linked directly to the drivers of economic growth and structural changes of the production function underlying the model. Some of the impacts of climate change and air pollution directly affect the volume of use of labour, capital and intermediate inputs; an example is loss of coastal land, buildings and infrastructure due to inundation as a result of sea level rise. Other impacts affect the efficiency of these same inputs to production, necessitating the use of more inputs to generate a given level of output; labour productivity impacts from heat stress fall in this category. Finally, there are demand-driven impacts, such as those on health care and energy, which directly affect consumption patterns.

The damages are included in the model using a production function approach. In this approach damages can also affect capital stocks, and thus limit the extent to which capital accumulates over time. In this sense, climate change and air pollution damages can limit growth in the long term not just through the direct damages, but also by diminishing the available capital and thus affecting the growth rate of the economy. Compared to 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.

Climate change impacts included in the analysis

The quantification of climate change impacts in ENV-Linkages relies on available information on how climate impacts affect different economic sectors. Different information sources are used to find out what climate change impacts correspond to the temperature increases of the ENV-Linkages "no-damage projection". 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 (Van Vuuren et al., 2011[39]; IPCC, 2013[12]; IPCC, 2014[40]; IPCC, 2014[41]).[18] Where estimates for RCP 8.5 are not available, the impact data used is related to the A1B SRES scenario, which describes a similar future temperature trend (Nakicenovic et al., 2000[42]), at least until 2060. Both scenarios are similar to the ENV-Linkages model "no-damage projection" with respect to GHG concentration levels.

The information sources are used mostly derived from various dedicated studies using quantitative methods: bottom-up partial-equilibrium models, climate impact models and econometric studies.[19] Table B.1 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[8]).

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

[18] Wherever possible, the central projection uses results from the HadGEM3 model (Hewitt et al., 2011[61]) from the Hadley Centre of the UK Met Office, for the specification of the climate system variables.

[19] 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.

source studies specified impact data with a regional aggregation tailored for other CGE models, including the ICES model (Eboli, Parrado and Roson, 2010[43]; Bosello, Eboli and Pierfederici, 2012[44]; Bosello and Parrado, 2014[45]), which was used as a reference for several climate impacts.

Table B.1. 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[46])	AgMIP	2050
	Changes in fisheries catches	(Cheung et al., 2010[47])	SESAME	2060
Coastal zones	Loss of land and capital from sea level rise	DIVA model - (Vafeidis et al., 2008[48])	ClimateCost	2100
Extreme events	Capital damages from hurricanes	(Mendelsohn et al., 2012[49])		2100
Health	Mortality and morbidity from infectious diseases, cardiovascular and respiratory diseases[20]	(Tol, 2002[50])		2060
	Morbidity from heat and cold exposure	(Roson and Mensbrugghe, 2012[51])and (Ciscar et al., 2014[52])for Europe	World Bank ENVISAGE model & Peseta II (Europe)	2060
	Mortality from heat stress	Not covered in the modelling exercise		
Energy demand	Changes in energy demand for cooling and heating	(IEA, 2013[32])	WEO	2050
Tourism demand	Changes in tourism flows and services	HTM - (Bigano, Hamilton and Tol, 2007[53])	ClimateCost	2100

Some important impacts that could not be included in the analysis are effects on ecosystems, effects on water stress outside agriculture, major tipping points and other non-linearities and large-scale singular events such as collapse of the West-Antarctic ice sheet. These impacts are discussed in more detail in (OECD, 2015[8]).

Outdoor air pollution impacts included in the analysis

Analogous to the specification of the climate change impacts, the impacts of outdoor air pollution stem from integrating state-of-the-art assessments from detailed models into the economic modelling framework. A detailed description of how these impacts are quantified is given in (OECD, 2016[9]).

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

[20] The inclusion of mortality effects from diseases is not in line with the way other mortality effects (heat stress, air pollution) are treated, but this particular mortality effect could not be teased out of the total costs of climate-induced diseases. The effect on total damages is relatively small.

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).

Crop yield changes have been incorporated in the model using the methodology of (Van Dingenen et al., 2009[31]). Crop losses for rice, wheat, maize and soybean are calculated in TM5-FASST based on concentrations of ozone during the growing season.[21] 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[54]), following the methodology of (Chuwah et al., 2015[55]).

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. Premature deaths from air pollution are calculated in ENV-Linkages and presented in OECD (2016[9]) but not included in the modelling of economic feedbacks exercise. Table B.2 summarises the impacts modelled and the data sources.

Table B.2. Outdoor air pollution impacts calculated 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[56]) and on results from the Global Burden of Disease studies.[22]
Health - mortality	Not covered in the modelling exercise on economic feedbacks	
Agriculture	Changes in crop yields	Calculations by the EC-JRC Ispra with the TM5-FASST model (Van Dingenen et al., 2009[31]).

Changes in health expenditures are implemented in the model as a change in demand for the aggregate other 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[9]). It is assumed that the additional health expenditures affect both households and government expenditures on healthcare.[23] The extent to which households or governments are affected

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

[22] 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 (GBD) studies as described in (Forouzanfar and et al., 2015[20]; Brauer et al., 2016[21]). Effects of ozone on mortality in 2010 are based on the earlier Global Burden of Disease results of (Lim et al., 2012[22]) and (Burnett et al., 2014[23]). Note that recently, the GBD have revised their estimates of current premature deaths upwards; this revision could not be taken on board for the analysis in this paper.

[23] 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

depends on regional characteristics of the health system in terms of their relative contribution to healthcare.

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[57]), using assumptions on the average number of work days per year in each region (World Bank, 2014[58]). 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, and not the 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 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.

Other impacts, such as direct health impacts from NO_2, damages to cultural heritage, ecosystems, biodiversity and forestry, have also been discarded due to lack of data.

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.

Annex C. Detailed results of the "no-damage projection"

Projected changes in economic activities and economic structures

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 C.1 shows that GDP levels in the no-damage projection 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 C.1. Trend in real GDP, no-damage baseline projection

Billions of USD, 2010 PPP exchange rates

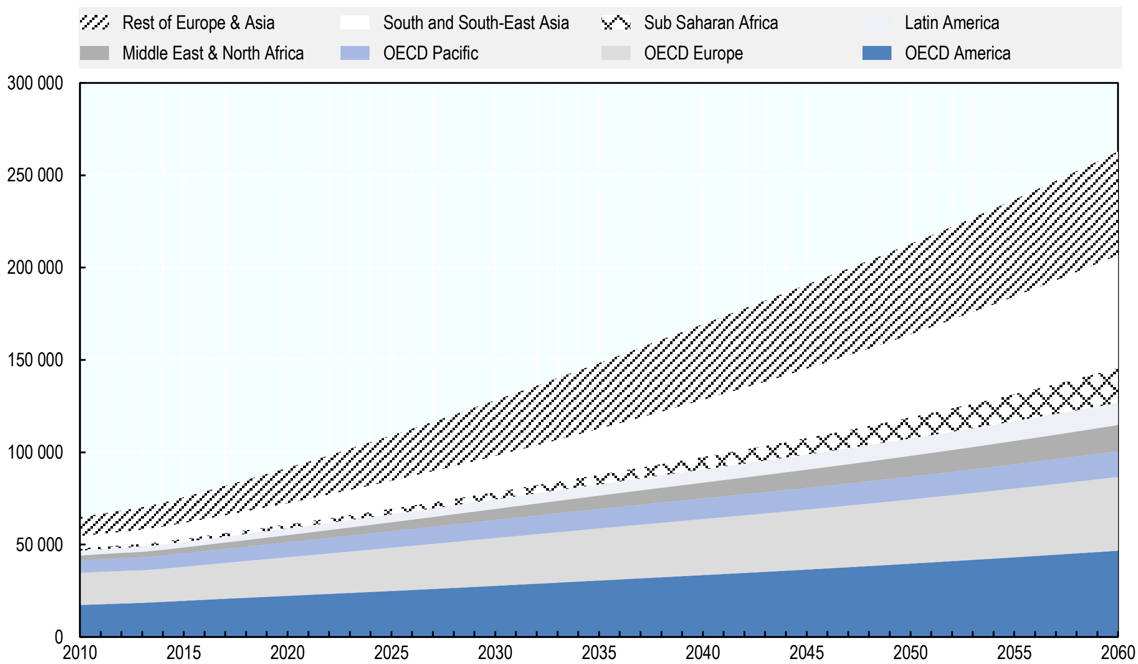
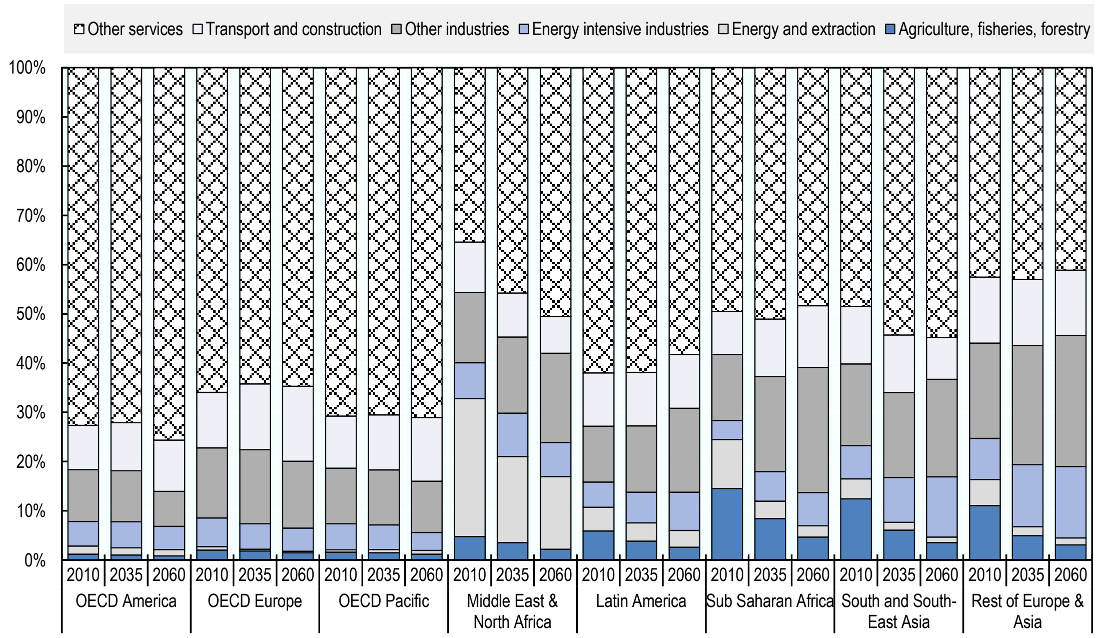


Figure C.2 shows how the sectoral structure evolves in the regional economies. The shares of the various sectors in OECD economies tend to be relatively stable, with the services sectors accounting for almost 2/3 of GDP (i.e. value added). However, there are undoubtedly many fundamental changes at the 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 C.2. Sectoral composition of GDP by region, no-damage projection

Percentage of GDP, 2010, 2035 and 2060



Resulting projection of climate change[24]

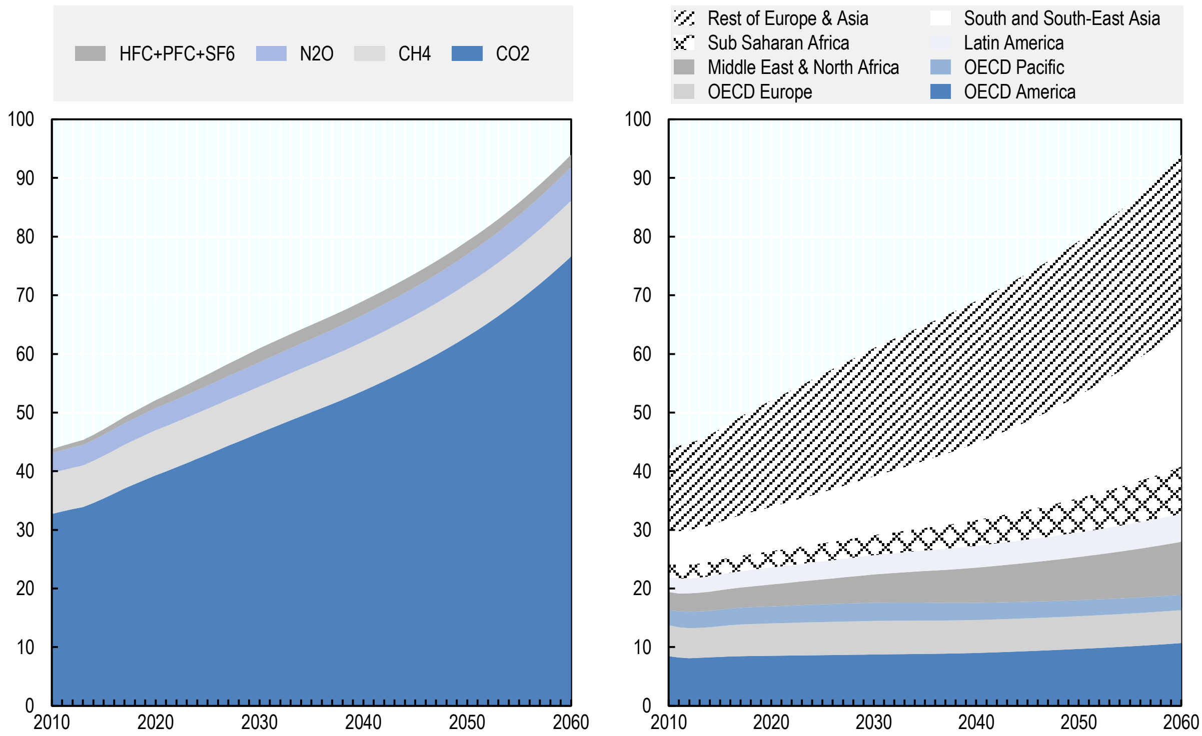
Figure C.3 illustrates how baseline economic activities lead to a steady increase in regional and global emissions. Global anthropogenic GHG emissions (excl. emissions from land use, land-use change and forestry, which are treated exogenously) are projected to rise from around 45 Gigatonnes (Gt) of CO_2 equivalent (CO_2-e) 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 and increased economic activity that lead to 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

[24] This section summarises the results of the "no-damage projection" for climate change, as presented in detail in (OECD, 2015[8]).

increased consumption of coal accelerates increases in emissions. Nonetheless, there is some relative decoupling: emissions grow less rapidly than production.

Figure C.3. Evolution of greenhouse gas emissions, no-damage baseline projection

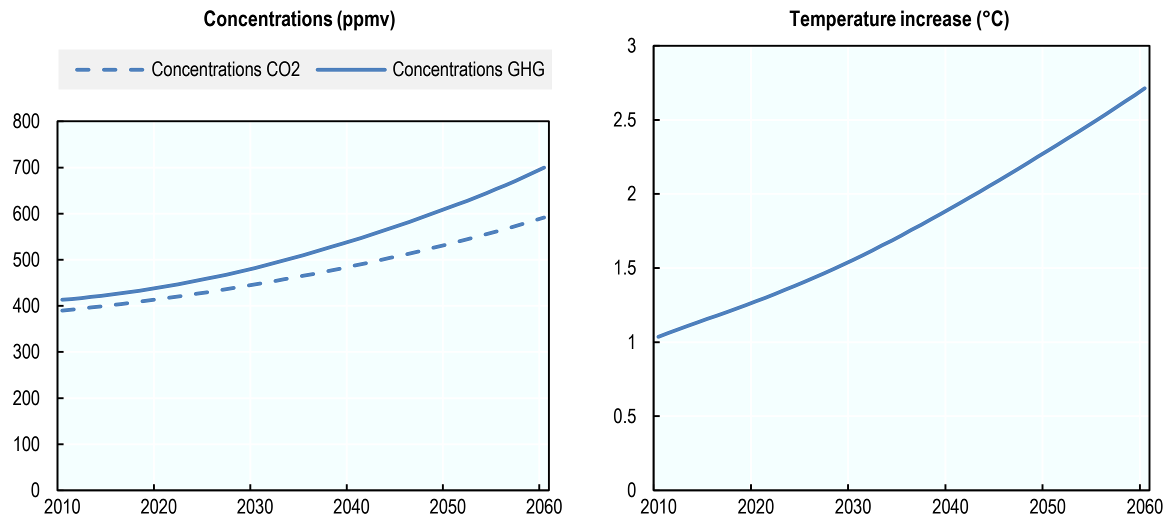
Gigatonnes of CO_2 equivalent



The rapid increase in GHG emissions accelerates climate change. For sake of simplicity 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 C.4, left panel), and global average temperature increases above pre-industrial levels (Figure C.4, right panel). Concentrations of CO_2 in the atmosphere rise from 390 parts per million (ppm) to 590 ppm between 2010 and 2060. The central projection delivers temperature increases of more than 2.5°C by 2060. This global temperature increase by 2060 is affected by the uncertainty on the equilibrium climate sensitivity (ECS); the likely range equals 1.6 to 3.6°C, while the larger range is 1.1 to 4.3°C.[25]

[25] According to IPCC (2013[12]), "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, Meinshausen and Knutti, 2012[64]; IPCC, 2013[12]).

Figure C.4. Key climate indicators, no-damage baseline projection



The regional impacts of climate change that are quantified in this study are based on more detailed projections of regional changes in temperatures and precipitation patterns.

Projected changes in outdoor air pollution[26]

For most air pollutants, emissions are projected to increase in the coming decades, as illustrated in Figure C.5. 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.[27] 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 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,

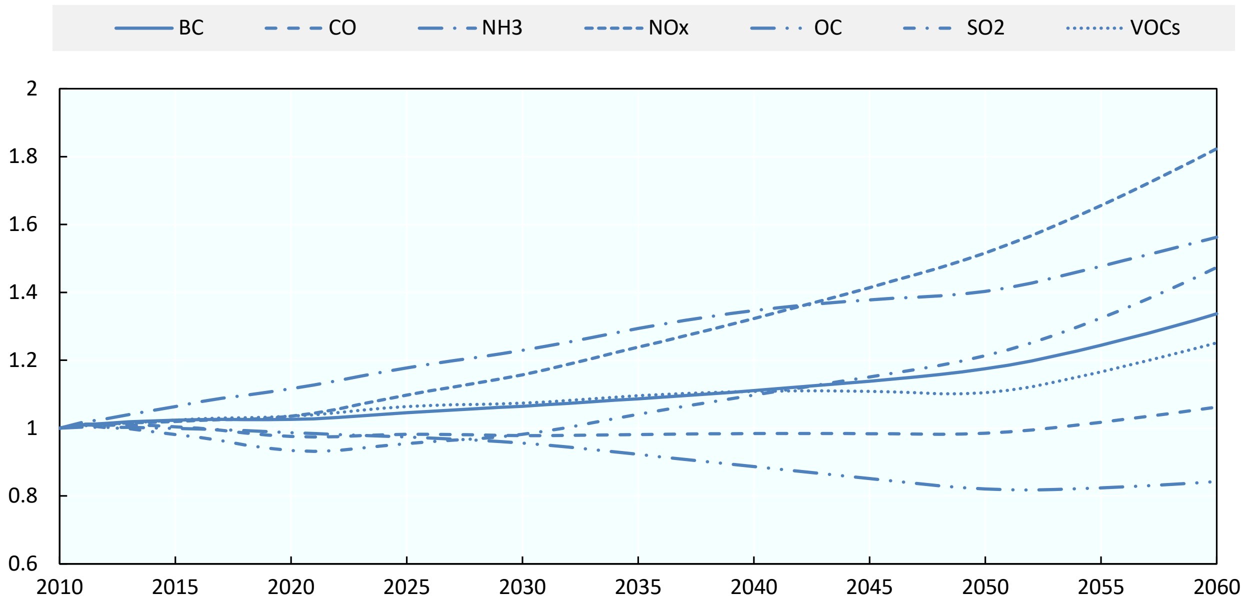
26 This section summarises the results of the "no-damage projection" for climate change, as presented in detail in (OECD, 2016[9]).

27 The projections in this report reflect a cost of inaction scenario that could be used as a reference to study policy scenarios. In this sense the recent policy developments to reduce air pollution in China have not been taken into consideration.

although the projections show a small increase in emissions of all gases but NO_x and SO_2 in the OECD America region.

Figure C.5. Air pollutant emission projections over time, no-damage projection

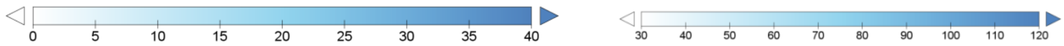
Index with respect to 2010



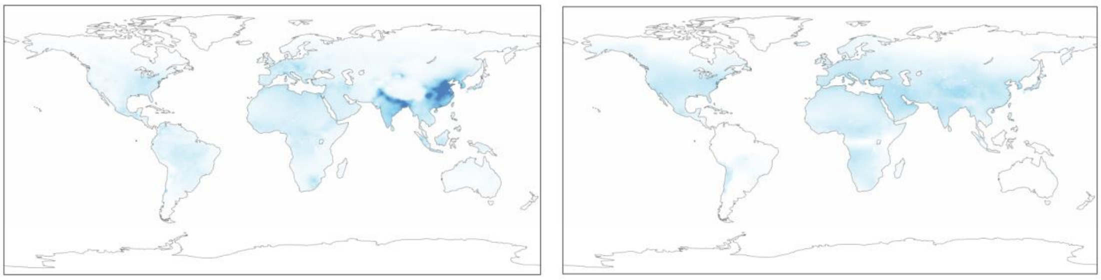
With emissions of air pollutants generally rising over time, the concentrations of $PM_{2.5}$ and ozone are also projected to increase in most regions, although, climatic conditions and several other factors influence concentrations. The maps in Figure C.6 illustrate the annual average of anthropogenic $PM_{2.5}$ 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 C.6, 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 C.6 show lighter colours for OECD regions, these levels are above the recommended WHO (2006[59]) guidelines in most areas, implying that there are still strong impacts on human health and the environment.

Figure C.6. Particulate matter and ozone concentrations, no-damage baseline projection

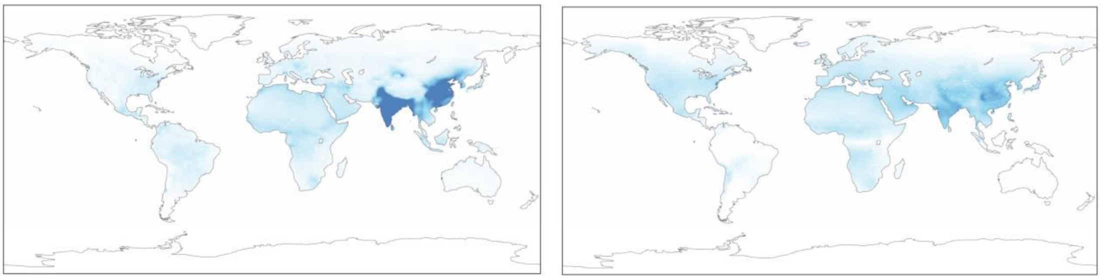
Annual average anthropogenic PM2.5, µg/m3, on left panel and
Maximal 6-month mean of daily maximal hourly ozone, M6M, in ppb, on right panels



Panel A. Concentrations in 2010



Panel B. Concentrations in 2060



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