The (uncertain) future of air quality

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The assessment of the future evolution of air quality requires accounting for both climate projections and the development of environmental policies. In the context of climate change adaptation, the geophysical changes to be expected in the decades to come will have an impact on chronic and extreme air pollution events (Jacob and Winner, 2009). But air quality is also sensitive to climate mitigation strategies: the social and technological changes required to reduce greenhouse gases emissions will also be accompanied by changes in the emission of air pollutants and precursors thereof. There are potentially large co-benefits between air quality and climate change mitigation that could help in leveraging efforts to engage in win-win strategies. But mitigating climate change can also potentially induce collateral damages to air quality. It is thus very important to precisely identify what are the co-benefits and the possible collateral damages in order to maximize the former while minimizing the later. Here we briefly review recent results on climate change impacts on Mediterranean regional air quality in terms of ozone and particles, and list identified positive and negative feedbacks of climate change on air quality.

1 Adaptation: The impact of climate change on air quality

1.1 Surface Ozone

Ozone concentrations in the troposphere are driven by many chemical and dynamical processes including emissions of ozone precursors and meteorological variables. Climate change has an impact on the tropospheric ozone through effects on biogenic emissions of ozone precursors (mainly volatile organic compounds - VOCs), meteorological parameters (temperature, precipitations, humidity) and atmospheric chemistry (chemical budget, photochemical regimes). Climate change will be accompanied by a decrease in rainfall over southern Europe, creating wintertime deficits that lowers soil water content contributing to increase average temperature and heat waves frequency and severity (Fiore *et al.*, 2012; Vautard *et al.*, 2013) with important consequences for summertime ozone pollution in Europe and the Mediterranean that were pointed out by (Langner *et al.*, 2005; Meleux *et al.*, 2007). A meta-analysis of the 25 projections of ozone pollution in Europe in the context of climate change that were published between 2007 and 2015 was performed by Colette *et al.*, (2015a) in order to explore the robustness of the climate change impact on surface ozone (Figure 1). The corresponding climate ozone penalty is defined as the incremental change in ozone that can be attributed to climate change alone, in the absence of evolution of anthropogenic emissions of ozone or other drivers. The penalty is confirmed over most continental Europe, especially in European countries of the Mediterranean basin where such a penalty is robust, i.e. consistent over two-third of the models in the ensemble (diamond signs in Figure 1).

The main climate effect responsible for this increase in surface ozone pollution in Europe is the increase in temperature and solar radiation leading to an increase in biogenic isoprene emissions even if a possible inhibition of these emissions with increasing CO_2 concentration could occur over the long run, thereby yielding important uncertainties (Lathière *et al.*, 2010; Langner *et al.*, 2012).

The other pathways of climate impacts on surface ozone are the direct impact of temperature rises on the kinetics of atmospheric chemistry and the direct impact of solar radiation on photochemistry resulting from changes in cloud cover. They both lead to enhanced photolysis rates, particularly for nitrogen dioxide which favours ozone formation. In both cases, the increased temperature and solar radiation can result from gradual changes in the average climate, but they are exacerbated in the case of extreme heat wave events. Besides meteorological factors, it should also be pointed out that heat waves are favourable to the accumulation of pollution in the absence of atmospheric dispersion.

In the context of the MISTRALS/ChArMEX project, the global model outputs from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) are being analysed to assess the future evolution of surface ozone over the euro-Mediterranean region (Jaidan *et al.*, in prep.). Under the pessimistic Representative Concentration Pathway (RCP8.5), the mean temperature will increase by about 5.4K by 2100 compared to 2000 accompanied by a small increase in surface ozone of about 2%.

Over European land surfaces, the 95% confidence interval of summertime mean ozone change is [0.44; 0.64] and [0.99; 1.50] ppbv for the 2041–2070 and 2071–2100 time periods, respectively. Such a change could appear limited, but it is of the same order as the observed ozone trends reported over Europe for the past couple of decades despite the implementation of ambitious policies (Monks *et al.*, 2015; Colette *et al.*, 2016). This yields important concerns about our ability to compensate for the climate change penalty by controlling the emissions of ozone precursors.

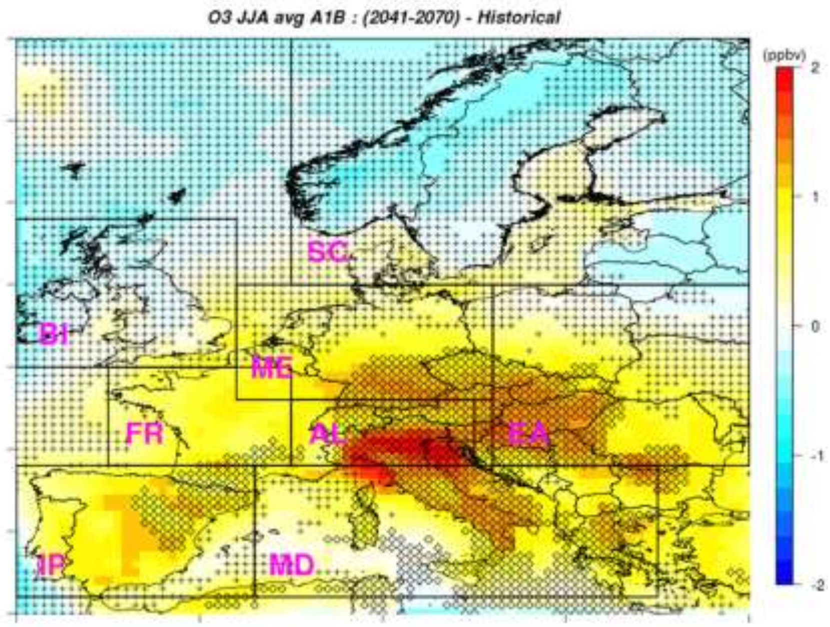

Figure 1 : Increase in surface summertime ozone concentrations (ppbv) by the middle of the century in the moderate climate change scenario A1B in an ensemble of all the published European model projections, [NB. Augustin Colette can make an adapted version if the figure is ultimately selected] (adapted from Colette et al.*, 2015a)*

1.2 Particulate Matter

The largest detrimental sanitary impacts of air pollution are presently attributed to atmospheric aerosols from various sources (WHO, 2013). Also called particulate matter (PM), they can originate from anthropogenic or biogenic gaseous precursors (it is the case, e.g., for sulphate, nitrate, ammonium, but also secondary organic aerosols), from primary emissions of particulate matter (e.g. elemental carbon (EC), but also heavy metals and persistent organic pollutants (POPs) such as polycyclic aromatic hydrocarbons (PAHs)), or from natural sources (desert dust, sea salt, volanic ash).

The future evolution of PM pollution in the context of climate change adapation is more ambiguous than that of ozone because of the complexity of processes, often competitive, involved (Fuzzi *et al.*, 2015). Recent evidences point toward a climate change benefit (with a reduction of PM loads, in particular because of an increased volatility with increasing temperature) Lecœur and Seigneur, 2013; Colette *et al.*, 2013; (Lacressonnière *et al.*, 2016; Lemaire *et al.*, 2016) but increases have been reported for the southern parts of Europe (Manders *et al.*, 2012; Hedegaard *et al.*, 2013). Change in biogenic precursor emission of secondary aerosol (SOA), likely to increase substantially in a warmer climate, could lead to an increase of PM concentrations (Megaritis *et al.*, 2013). Change in scavenging by precipitations, transport patterns and persistence of anticyclonic conditions leading to PM accumulation can also play a role in shaping future aerosol concentrations (Pausata *et al.*, 2013). Frequency of precipitation is more likely to affect PM scavenging than intensity of precipitation. Simulating accurate frequencies is very challenging for climate models, and large uncertainties exist in projections.Extreme heat events, associated with stagnation of air masses, are projected to increase, but the relative contribution of changes in the frequency and duration versus changes in the intensity of heat waves is unclear (Clark and Brown, 2013). PM pollution is likely to be more sensitive to increased duration of the events.

The potential change of PM loads in southern Europe is largely determined by the mineral dust fraction. Both advection from the Saharan and North African deserts and local mobilisation e.g. from agricultural lands during dry conditions (Bessagnet *et al.*, 2008) are contributing to this fraction. Global and regional climate changes as well as land use changes might have significant impacts on dust emission and transport. African dust activity has shown to be correlated to various aspects of climate variability including the El Niño/Southern Oscillation, the North Atlantic Oscillation, the meridional position of the intertropical convergence zone, Sahelian rainfall and surface temperatures over the Sahara Desert which can impact to diverse degree surface wind activity (Evan *et al.*, 2016). The same authors conclude that the likely tendency for African dust activity would be to decrease in a warmer climate. However, change in PM_{10} exceedances due to dust over Europe are more likely to be sensitive to change in the frequency and transport pathways of dust storms rather than variation of the mean emission and concentrations. As of now, there is no current consensus on the sign and magnitude of future regional change in dust concentrations affecting Mediterranean regions and southern Europe.

As another source of natural aerosol, sea sprays can constitue a major fraction of PM in the coastal regions of Europe. Beside sea salts, a significant part of the submicron fraction of sea sprays is organic and related to biogenic sources. Existing studies show that sea sprays activity has not shown any significant trend in the North Atlantic for the last decades (Korhonen *et al.*, 2011) and is not likely to change significantly with climate change (Jacobson and Streets, 2009).

Wildfire activity is another important source of aerosol and ozone precursors that can severely impact air quality (Hodzic *et al.*, 2007; Miranda *et al.*, 2008) and for which climate and land use change might be determining factors. A dryer climate would tend to increase fire activity but man-driven land use evolution has also a very strong impact, especially in Europe where the population density is high. Landscape management and fragmentation and fire suppression tend to decrease fire activity (Knorr *et al.*, 2014). For these reasons, an increase of fire frequency with climate change will not necessarily translate into a net increase in PM emissions which are not only determined by the number of fires but also by their duration, extent and intensity.

1.3 Mitigation: towards win/win solution to limit global warming and improve air quality

The evolution towards a low carbon economy will be accompanied by reductions of air pollutant emissions. There is a vast array of mitigation measures that shall have beneficial impacts on both air pollution and climate mitigation, several of them belong to the category of energy efficiency measures which constitute a very substantial pathway for win/win solutions (Colette *et al.*, 2015b), even if some strategies favorable for climate mitigation can be detrimental for air quality (for instance diesel and residential wood burning with outdated appliances).

The sanitary benefits that can be expected with the future evolution of climate and air quality policies were quantified for instance in IIASA (2013) or Likhvar *et al.* (2015) who demonstrate that it is in European countries along the Mediterranean coasts that the sanitary benefits related to ozone exposure were the most important.

A quantitative assessment of the costs and benefits associated to climate mitigation in Europe was proposed by Schucht *et al.* (2015). They found that the very substantial costs of migrating to an energy mix that would comply with the 2°C warming target would be compensated by the positive externality constituted by air pollution improvement. That is because the low-carbon scenario also yield (i) reduced cost of end of pipe technologies and (ii) direct sanitary benefits (Figure 2).

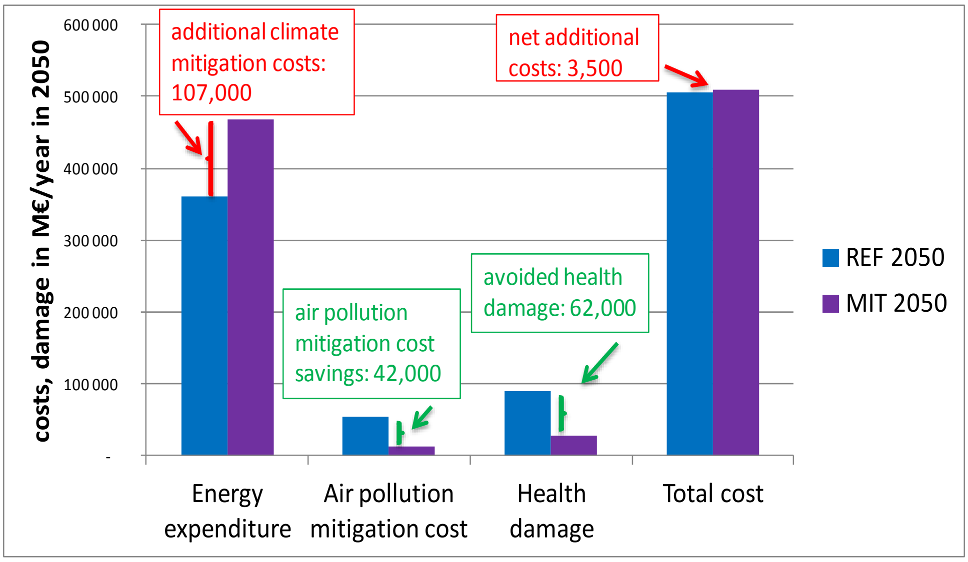

Figure 2 : Win-win strategies: cost benefit analyses at the scale of Europe demonstrate that the additional costs related to climate mitigation (MIT) scenario aiming at a 2°C warming at the end of the century compared to the business as usual scenario (REF) could largely be compensated by savings in end of pipe air pollution mitigation costs and avoided health damages in Europe. Adapted from Schucht et al.*, (2015).*

1.4 Way forward

Recent evidences demonstrate the link between climate change and air pollution both regarding adaptation and mitigation strategies. It should be emphasized that, at present, most of the work was performed at the continental scale, through Europe-wide assessment, in addition to a few global studies (Anenberg *et al.*, 2010; West *et al.*, 2013;; Lelieveld *et al.*, 2015). There has been little focus on dedicated assessment of such impacts over the Mediterranean area, thereby offering new research perspectives, where the contribution of the MISTRALS/ChArMEx Programme should be instrumental.

Overall important uncertainties remain on the likely evolution of aerosols, especially over southern Europe and the Mediterranean basin. Beside process studies, ensemble of high resolution modelling approaches coupling climate, aerosols and including land use change/management scenarios could be a way to characterizing key mechanisms and quantifying and reducing these uncertainties.

As far as climate adaptation is concerned, the role of climate change on land-use and, in turn, in dust resuspension and dispersion constitute a key uncertainty. The role of biogenic emissions, as precursor of ozone but also secondary organic aerosol is also an important topic.

There are important win/win strategies to be developed in the years to come to improve air quality and engage towards a low carbon economy. Such benefits have been pointed out in several European studies, but the specific situation of Mediterranean countries would deserve a closer look to tailor the most efficient sustainable strategies.

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