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ÉCLAIRE

Effects of Climate Change on Air Pollution Impacts and Response Strategies for European Ecosystems

Seventh Framework Programme

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D7.2 Improved EMEP model with climate-change and canopy-chemistry capabilities

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CO	Confidential, only for members of the consortium (including the Commission Services)	

Improved EMEP model with climate-change and canopy-chemistry capabilities

Executive Summary

The EMEP model has been modified in order to take account of physical/chemical changes expected in the future. The main modifications are:

- CO_2 inhibition of isoprene emissions
- CO_2 inhibition of stomatal conductance, modelled using either a photosynthesis module or a semi-empirical approach
- Increased NH_3 emissions in a warmer climate
- Inclusion of ammonium-nitrate evaporation effect
- Addition of stress-induced BVOC to the model
- Improved growing season estimates, sensitive to temperature change
- Development of the ECLAIRE Ecosystem Surface Exchange (ESX) model, for offline running from EMEP, in order to evaluate canopy-chemistry issues.
- Technical changes, which now enable the EMEP model using climate-scenario meteorologies from a from several types of global and regional climate model.

1 Objectives

The objective of D7.2 is to improve the EMEP model with climate change and canopy-chemistry capabilities, so that it is better able to make predictions of future air pollution acrosss Europe.

2 Activities

The EMEP MSC-W model is a well verified chemical transport model, designed for the prediction of pollutants such as ozone and acidifying and eutrophying compounds (Simpson et al. 2006, 2012, Fagerli and Aas 2008)

In this work, the EMEP model has been enhanced so that it can take account of a number of changes which are expected in a future climate. These changes can be summarised in two main themes:

- The model has been adapted in a technical way, so that it can now be driven by a number of meteorological drivers, in particular from global and regional climate models. This work allowed the use of the regional climate model (RCM; we used SMHI's RCA3 model Samuelsson et al. 2011, Kjellstrom et al. 2011) itself driven by global simulations of ECHAM5. Other climate-model drivers which have been enabled are the Norwegian Earth System Model (Kirkevåg et al. 2013), downscaled with the WRF model (Skamarock and Klemp 2008), and also the Hadley Centre ESM via the HIRHAM system (Haugen and Iversen 2008).

- The EMEP model has been modified in order to take account of physical/chemical changes expected in the future. The main modifications are:

  1. CO_2 inhibition of isoprene emissions
  2. CO_2 inhibition of stomatal conductance
  3. Increased NH_3 emissions in a warmer climate
  4. Inclusion of ammonium-nitrate evaporation effect
  5. Addition of stress-induced BVOC to the model
  6. Improved growing season estimates, sensitive to temperature change

The impact of the meteorological driver on EMEP and other CTMs has been presented in deliverable D7.4, and in two published papers (Langner et al. 2012b, Simpson et al. 2014b), and further on the Swedish MATCH model in the comlementary study (Langner et al. 2012a). The basic conclusion from these and other studies is that the main driver of future air pollution (AP) will be emissions changes rather than climate-induced changes. For ozone the impacts of non-European emissions sources are substantial, but their development very uncertain.

However, these studies did not consider the impact of the physical/chemical changes mentioned above, and in the report we therefore concentrate on these. We first describe briefly the background to the model changes in sections 2.1-2.2, then in Section 3 we present results for ozone and nitrogen deposition metrics.

The inclusion of the ammonium-nitrate evaporation is reported in D4.4. The addition of stress-induced emissions has been described in detail in Bergström et al. (2014) and reported in D7.4.

In addition, we have developed the ECLAIRE Ecosystem Surface Exchange model in order to evaluate canopy-chemistry issues. The ESX model is run offline from EMEP, but driven by EMEP meteorology and calculated concentrations. This work is reported in Deliverable D7.3.

2.1 CO_2 - Isoprene inhibition

Globally, emissions of biogenic volatile organic compounds (BVOC) far exceed anthropogenic emissions (Guenther et al. 2012). In Europe, BVOC emissions play an important role for ozone production (Simpson 1995, Simpson et al. 1999), and for secondary organic aerosol (Kanakidou et al. 2000, Simpson et al. 2007, Bergström et al. 2012, Zhang et al. 2013).

Th direct temperature effect of climate change should of course promote increases in BVOC emissions in future (Lathiere et al. 2005, Arneth et al. 2011), and this increase has indeed been assumed in most modelling studies to date. However, increasing CO_2 can inhibit isoprene metabolism, and a number of studies suggest that higher CO_2 levels will reduce BVOC emission rates (e.g. Arneth et al. 2007, Wilkinson et al. 2009, Possell et al. 2005, Possell and Hewit 2011).

For this work, we have implemented the isoprene-CO2 inhibition function of Wilkinson et al. (2009) into the EMEP model. For a CO_2 concentration of ca. 500 ppm (ca. 2050 levels consistent with the 2050 scenarios used in ECLAIRE), this produces a reduction in emission rates of 9%.

2.2 Stomatal sensitivity

Rising CO_2 concentrations are likely to reduce stomatal conductance (g_{sto}) and have been expected to reduce ozone impacts by restricting stomatal uptake of ozone (Ainsworth et al. 2012). In this work, we have implemented two different approaches to stomatal conductance in the EMEP model:

Photosynthesis module (An-method) We implemented the photosynthesis module from the DO3SE model of the Stockholm Environmental Institute into the EMEP chemical transport model. This model is a development of the Büker et al. (2007), extended in C1 with parameters for the different land-cover classes used in the EMEP model (see Deliverable D4.3). The use of this An model provides a completely different methodology for the calculation of g_{sto}, one which is more mechanistic and sensitive to CO_2.

'Klingberg' algorithm Klingberg et al. (2011) modelled the effect of CO_2 on g_{sto} with a much simpler algorithm. They assumed that the influence of increasing CO_2 on g_{sto} was a linear decrease between 360 and 560 ppm CO_2 concentration from 1 to 0.66 for a generic crop and to 0.8 for a generic deciduous tree, with no further reductions in gs above 560 ppm CO_2.

2.3 Increased NH_3 emissions

Two papers arising from the ECLAIRE project drew drawn attention to the possibility of quite significant increases in NH_3 emissions in the future as a result of increasing evaporation from sources such as animal manure (Sutton et al. 2013, Skjøth and Geels 2013). NH_3 emissions are a function of both water availability and temperature with, in principle, a doubling of the emission for each 5 °C increase. Sutton et al. (2013), using empirical models and measurements, estimated a potential 42 % increase in the global NH_3 emissions following a 5 °C increase towards 2100. Skjøth and Geels (2013) used a dynamic NH_3 emission model to study the temporal and geographical variations in ammonia emissions across the northern part of Europe arising from a 'typical' pig-stable. They found increases towards the 2050s of 15–30 % (relative to 2007) in the emissions in central to northern Europe, increasing to ca. 20–40 % by the end of the century.

The projected increase will of course depend heavily on the projected temperature change and hence on the applied climate model, as well as assumptions concerning NH_3 emission factors. However, based on the above studies, Simpson et al. (2014b) explored the potential impact of a 20 and 30 % increase in NH_3 emissions for the future (2050s) scenarios. Here we illustrate some changes arising from an assumed NH_3 emission increase of 20%.

2.4 Growing seasons - evaluation and development of new methods

Chemical transport models (CTMs) such as EMEP, require estimates of the growing season of plants for a number of reasons - e.g. to control the uptake properties of the surface, or to define emission properties of BVOC. Typically, the growing seasons are defined in a very simplified way in CTMs, using e.g. fixed dates or simple functions, and in the EMEP model the European runs make use of the simple latitude function defined in the UN-ECE Mapping Manual (LRTAP 2009). Of course, in order to enable EMEP model calculations for future years (when climate will likely change growing seasons), a more realistic system is needed. Sakalli and Simpson (2012) explored a number of ways to obtain more realistic methods, and developed a new and simple method (the 'T5' method) for calculating the start of the growing season (SGS) of birch (which we use as a surrogate for deciduous trees), suitable for use in CTMs and other modelling systems. They showed that with just two parameters 'T5' captures well the spatial variation in SGS across Europe. Some examples are given below.

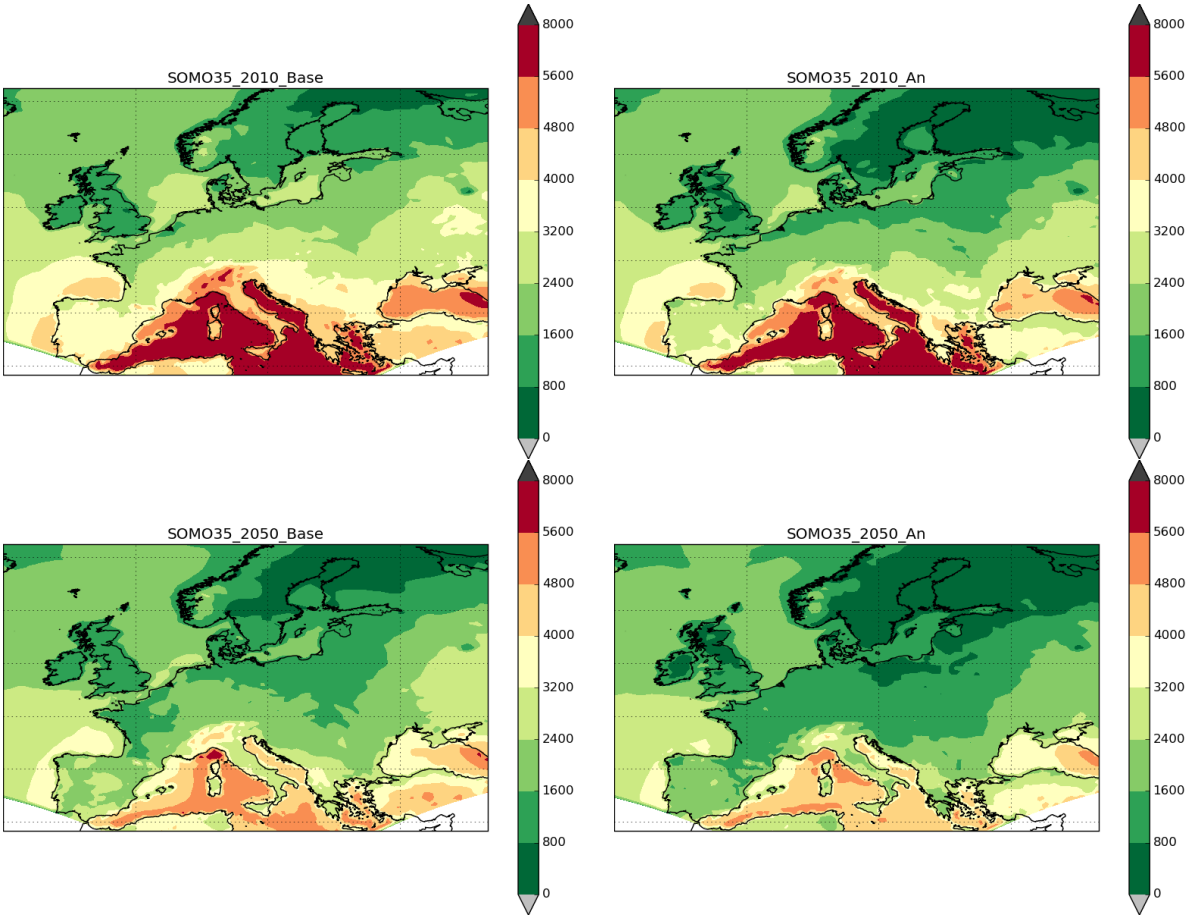


Figure 1: Base-case calculations of SOMO35 for 2010 (top) and 2050 (bottom). Left column gives results with standard EMEP g_{sto}, right column with photosynthesis-based ($An-$) g_{sto}. Units: ppb.day

3 Results

The climate-modifications discussed above have quite different effects for ozone and nitrogen metrics. Detailed analysis of the impacts of these changes will be presented in a future article, but here We provide examples of the changes for the human health-risk metric SOMO35 (Amann et al. 2008), and both oxidised and reduced nitrogen depositions.

3.1 Ozone

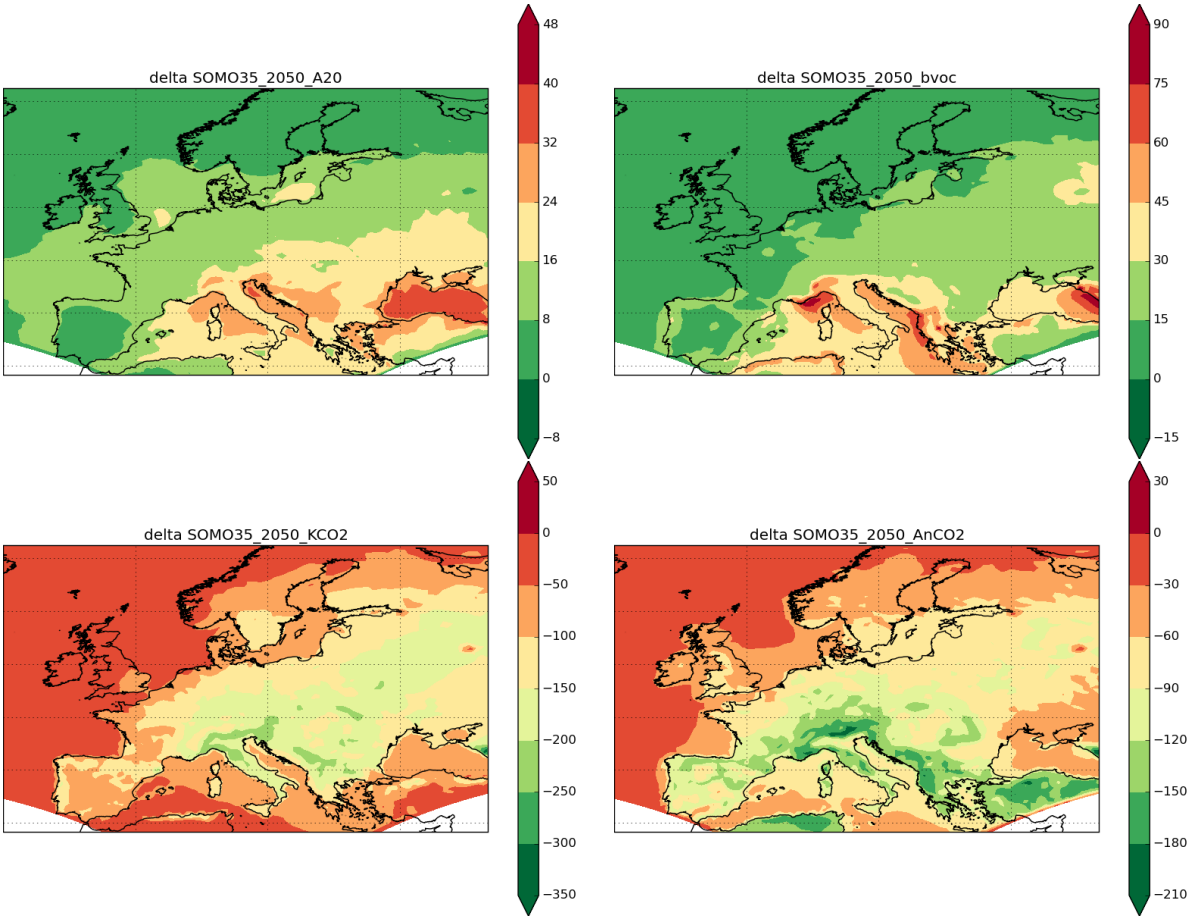


Figure 2: Differences between of SOMO35 in 2050 between climate-test cases and base-calculation of Fig. 1. Cases (a-c) should be compared to the standard EMEP run for 2050, and case (d) against the $An - gsto$ EMEP run for 2050. Test-cases are (a, top-left) Increased NH_3 emissions, (b, top-right) CO_2-inhibition on isoprene emissions (top-right), (c, bottom-left) CO_2-inhibition on stomatal conductance, Klingerg method. (d, bottom-right) CO_2-inhibition on stomatal conductance, DO3SE-Photosynthesis method. Note - plots have different colour-scales. Same units as Fig. 1

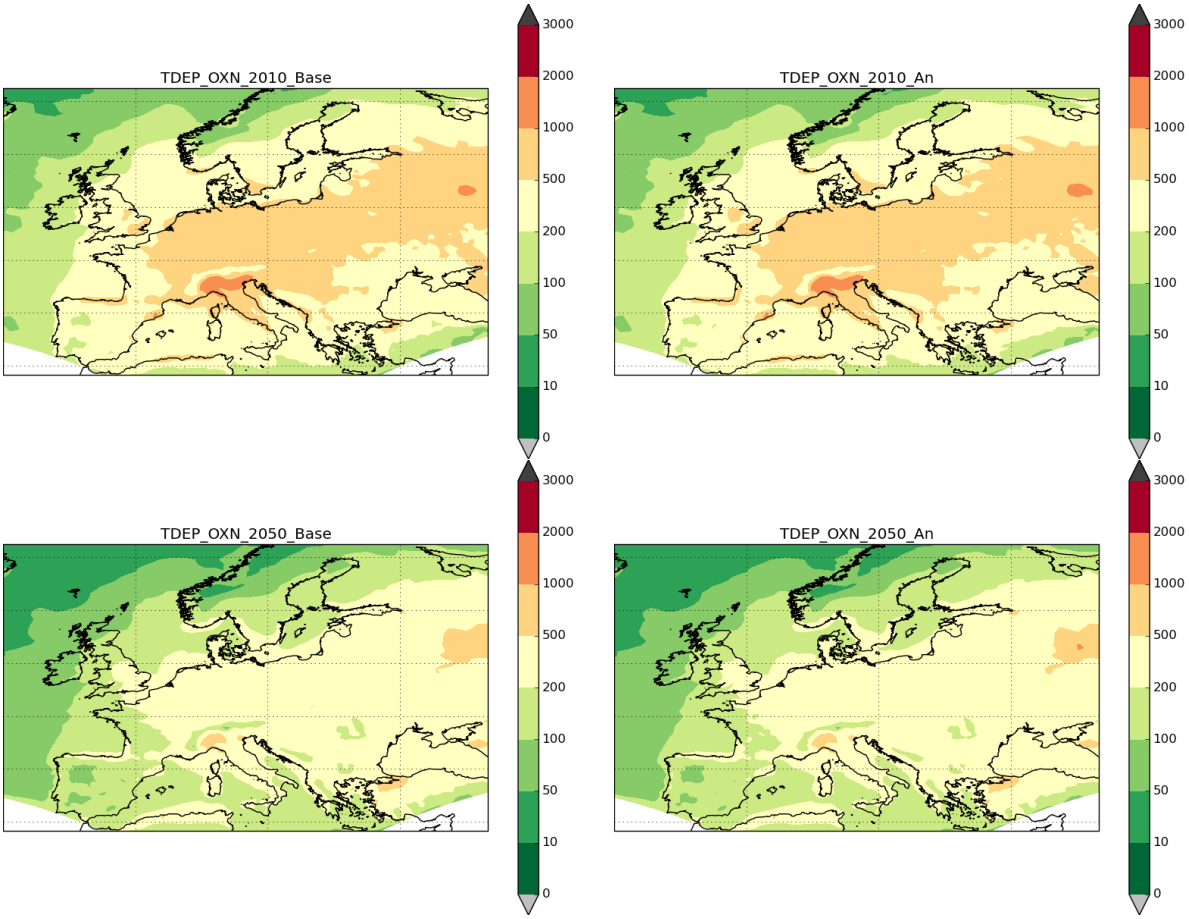


Figure 3: Base-case calculations of TDEP-OXN for 2010 (top) and 2050 (bottom). Left column gives results with standard EMEP g_{sto}, right column with photosynthesis-based ($An-$) g_{sto}. Units: mg (N) m^{-2}

Fig.1 illustrates calculated SOMO35 for both 2010 and 2050 calculations, and with standard g_{sto} and the DO3SE photosynthesis (An)-method g_{sto}. The overall values and patterns are similar, but the An method produces somewhat lower values, especially in the 2050 scenario. Figure 2 illustrates the differences between the different climate tests and the appropriate base-2050 case. The largest changes are clearly associated with the two g_{sto}-inhibition algorithms, with the BVOC-inhibuition and especially the NH_3 emission scenario being substantially less important.

3.2 Nitrogen deposition

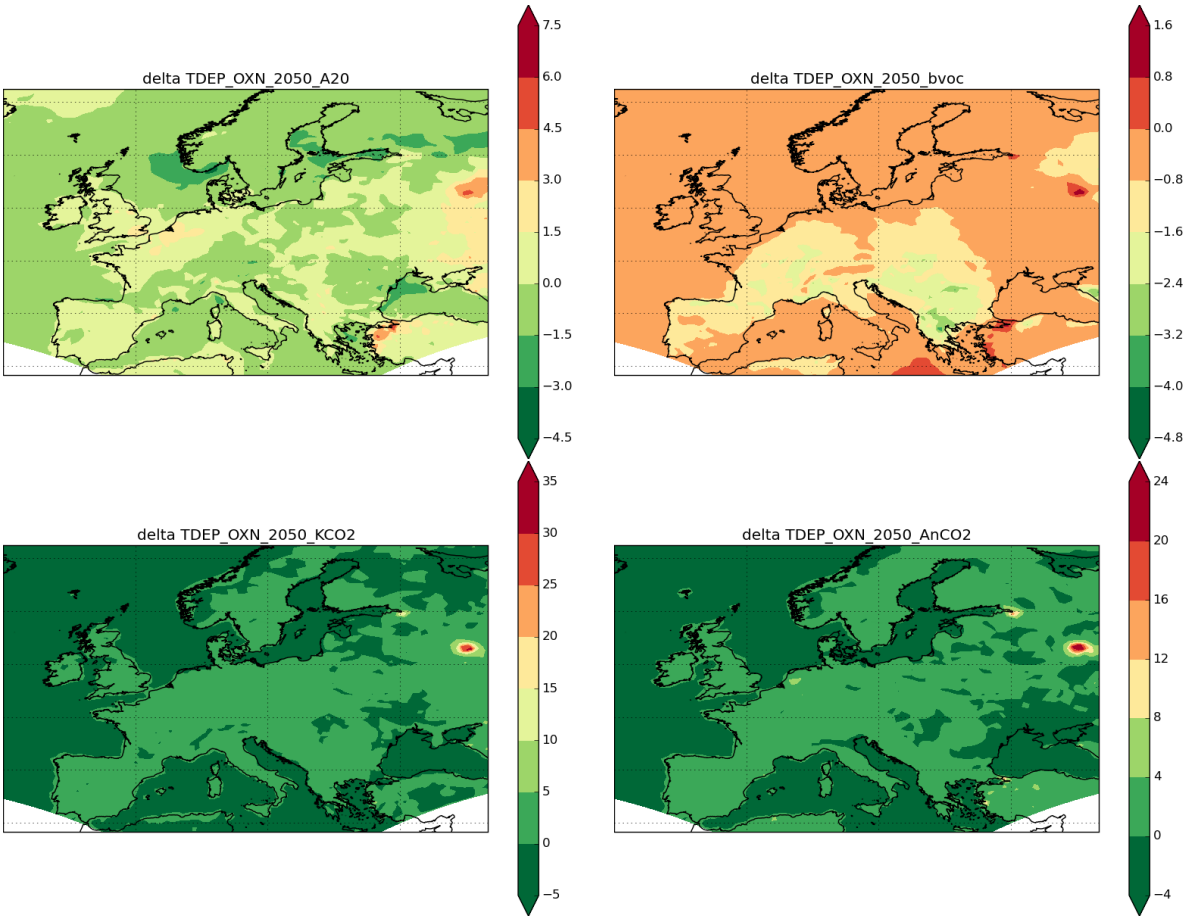


Figure 4: Differences between of TDEP-OXN in 2050 between climate-test cases and base-calculation of Fig. 3. Cases (a-c) should be compared to the standard EMEP run for 2050, and case (d) against the $An - gsto$ EMEP run for 2050. Test-cases are (a, top-left) Increased NH_3 emissions, (b, top-right) CO_2-inhibition on isoprene emissions (top-right), (c, bottom-left) CO_2-inhibition on stomatal conductance, Klingerg method. (d, bottom-right) CO_2-inhibition on stomatal conductance, DO3SE-Photosynthesis method. Note - plots have different colour-scales. Same units as Fig. 3

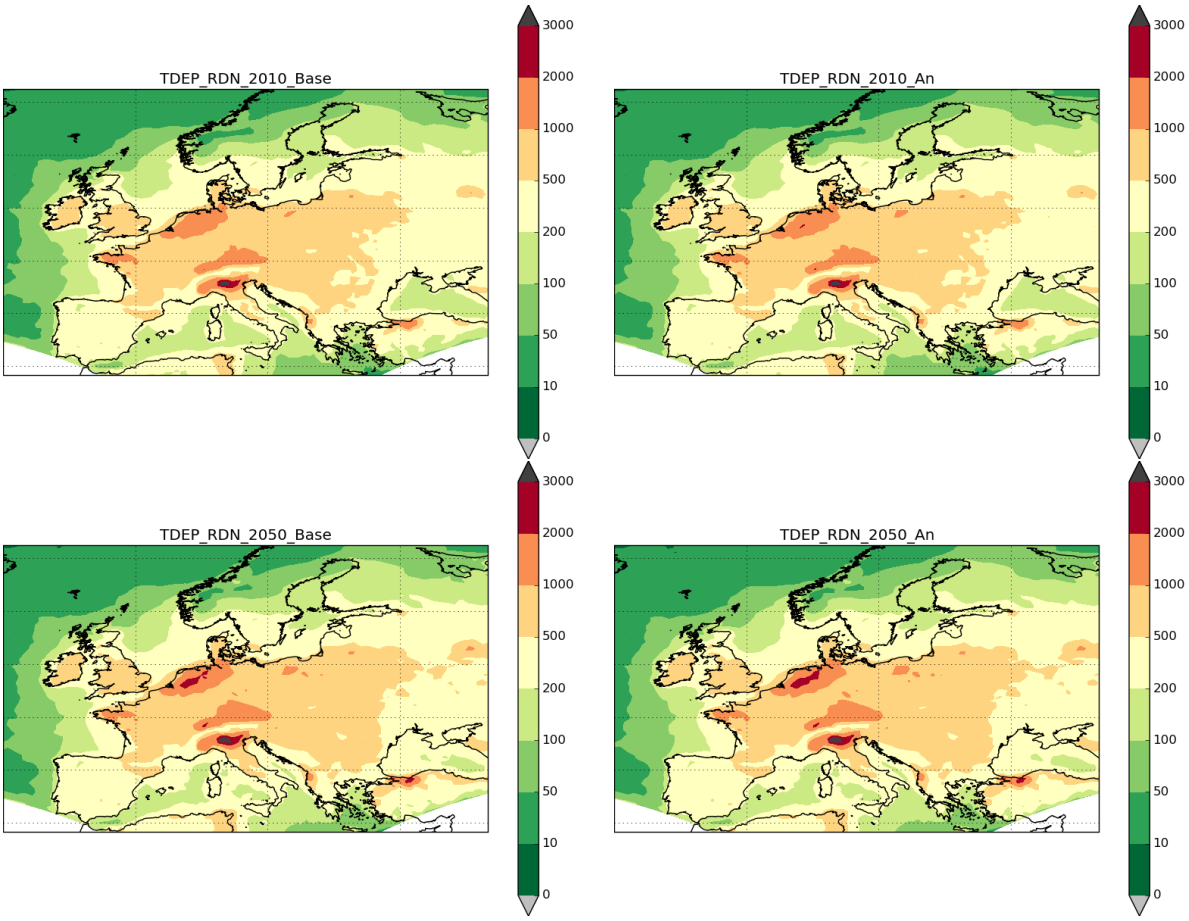


Figure 5: Base-case calculations of TDEP-RDN for 2010 (top) and 2050 (bottom). Left column gives results with standard EMEP g_{sto}, right column with photosynthesis-based ($An-$) g_{sto}. Units: mg (N) m^{-2}

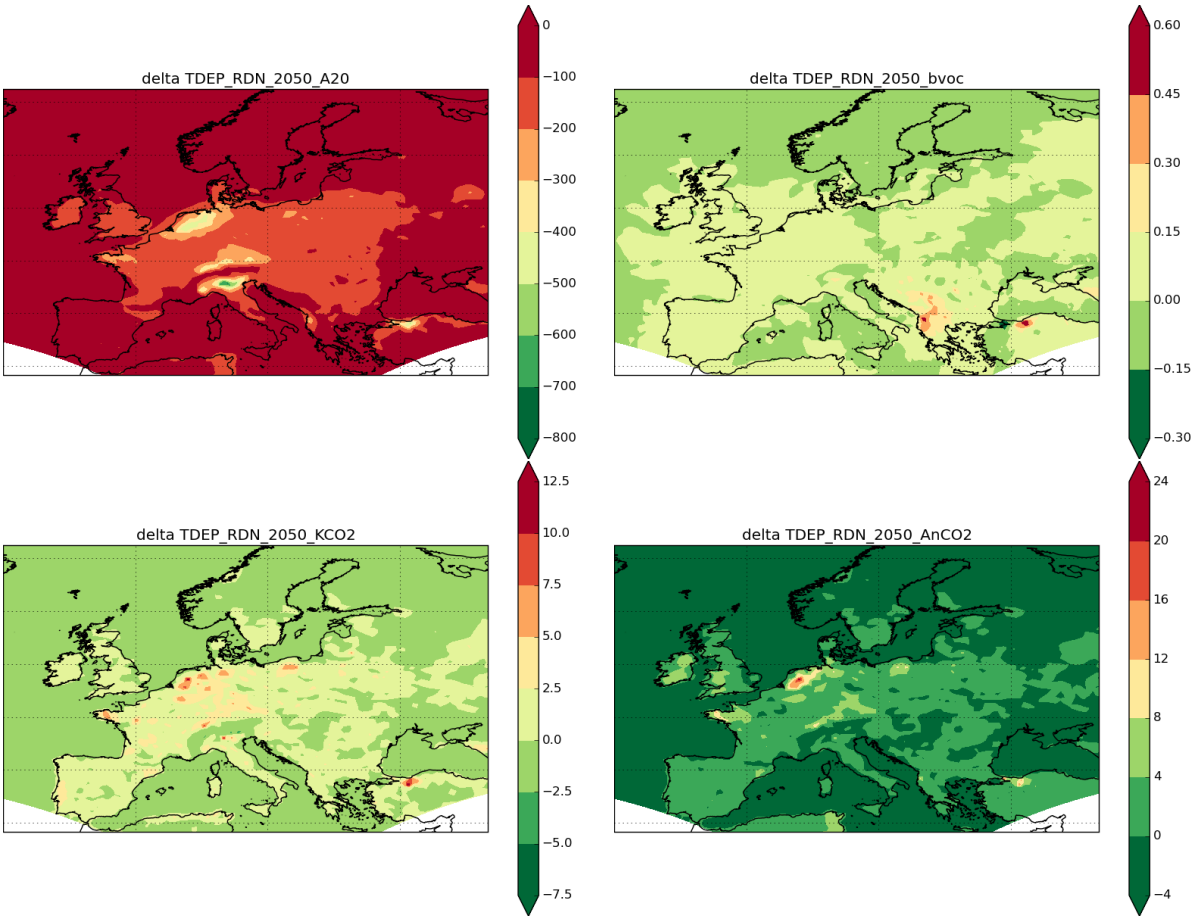


Figure 6: Differences between of TDEP-RDN in 2050 between climate-test cases and base-calculation of Fig. 5. Cases (a-c) should be compared to the standard EMEP run for 2050, and case (d) against the $An - gsto$ EMEP run for 2050. Test-cases are (a, top-left) Increased NH_3 emissions, (b, top-right) CO_2-inhibition on isoprene emissions (top-right), (c, bottom-left) CO_2-inhibition on stomatal conductance, Klingerg method. (d, bottom-right) CO_2-inhibition on stomatal conductance, DO3SE-Photosynthesis method. Note - plots have different colour-scales. Same units as Fig. 5

Figures 3-4 gives the equivalent plots for total deposition of oxidised nitrogen (TDEP-OXN), and Figures 5-6 for total deposition of reduced nitrogen (TDEP-RDN). Concerning oxidised nitrogen, the standard and $An - g_{sto}$ methods show quite similar patterns and levels in 2010 and 2050 base-cases. This simply reflects that deposition levels are closely related to emissions, at least on larger scales. Concerning the differences due to climate-enhancements, then these are of course limited for the same reason. Changes are small on the European scale, although some local changes can be seen, especially around the Moscow area.

For reduced nitrogen the ECLAIRE scenarios predict higher emissions in 2050 than in 2010 in many countries (see Simpson et al. 2014b for more details), and so deposition levels in 2050 are comparable to and sometimes higher than for the 2010 runs. Again, the $An - g_{sto}$ method shows similar levels to the standard EMEP model.

Concerning the differences due to climate-enhancements, then here the increased NH_3 case (Fig5a) stands out, simply because of the large emission change in this scenario. The changes seen here, of order 100 mg (N) m^{-2}, are a factor 100 or 1000 greater than changes due to g_{sto}-inhibition or especially isoprene-inhibition.

3.3 Growing seasons

As noted above, Sakalli and Simpson (2012) compared the predictions of the five methods for the start and end of the growing season (SGS, EGS, respectively). Figure 7 compares the SGS predictions of these five SGS methods against observed values from an observational database (PAN). The results are shown in Figure 7. The regression line, 1:1 line, correlation coefficients (r^2) and index of agreement are also given on these plots.

The r^2 values range between 68% to 87%, indicating quite good performance for all methods. The very simple 'LAT' method correlates quite well with the observations (r^2=0.76), but the regression line has a slope of just 0.48, and large intercept of 51 days. The modelled SGS with the 'LAT' method covers a much smaller range of values than the observed. The poorest correlation and index of agreement are found for the LPJ-CRU method (r^2=0.68, d=0.56), which uses monthly average temperature. The LPJ-NWP method, which uses daily temperature, is significantly better (r^2=0.85, d=0.68), confirming that the availability and use of daily temperature data leads to superior SGS predictions compared to the use of monthly data. The LPJ-NWP method shows a slope of almost 1:1, but with some bias; the modelled SGS starts typically 24 days before the observations. The TTM method performs well with this dataset, with r^2=0.87 d=0.93, although with a slope of 1.34 and quite large (42 day) intercept.

Finally, the 'T5' method developed by Sakalli and Simpson (2012) performed very well, with best index of agreement (d=0.95) and a regression line which is almost coincident with the 1:1 line. Of course, much of this good agreement stems from the fact that the parameters of the 'T5' method were obtained by fitting this data-set (optimising

for r^2 and slope), but the fact that all three statistical measures fit so well suggests that the underlying model has a good structure.

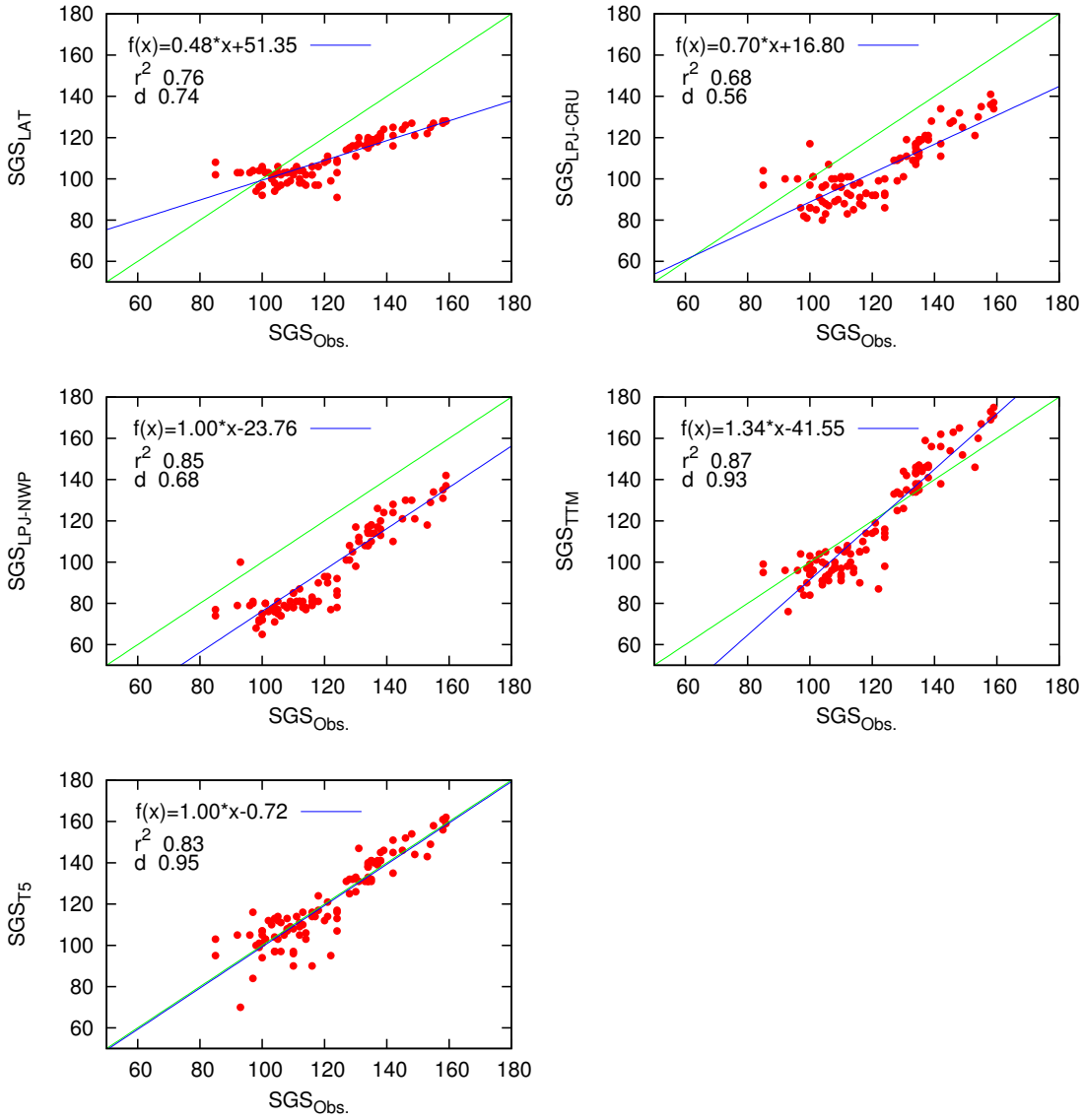
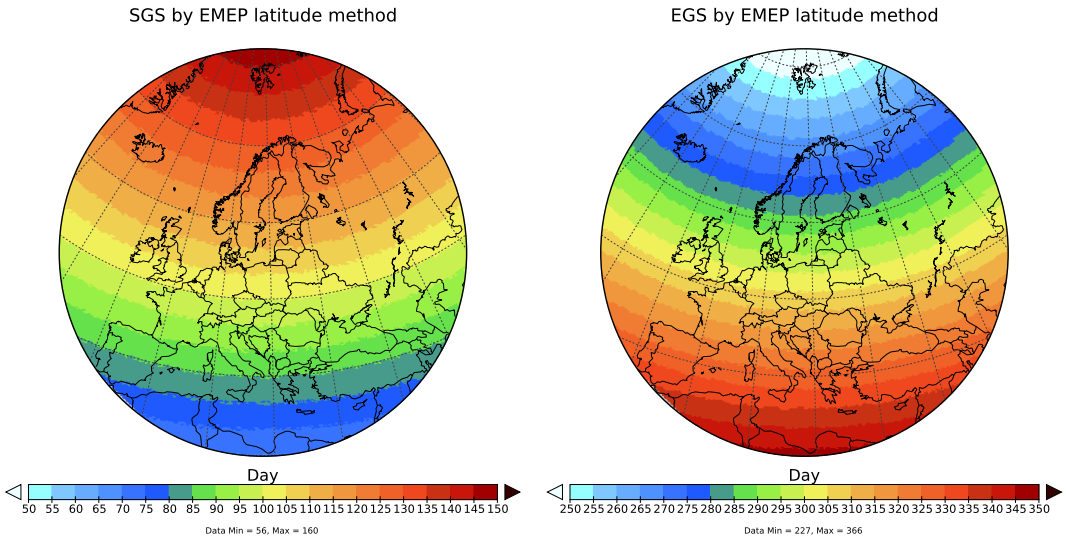


Figure 7: Comparison of estimated and observed SGS (day number) using the methods 'T5', 'LPJ-CRU', 'LPJ-NWP', 'TTM' and 'LAT' at 100 stations. From Sakalli and Simpson 2012, where further details can be found

Figures 8 and 9 illustrate the estimated distribution of SGS and EGS obtained using the standard EMEP 'LAT' method, and SGS as estimated by the new 'T5' method.



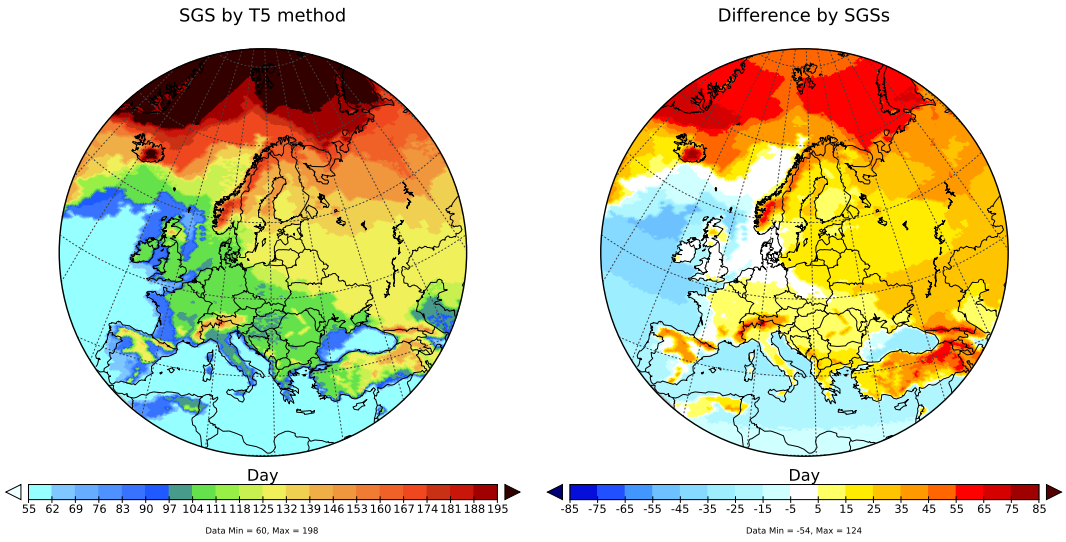
(a) $d_{\mathrm{SGS,\,EMEP}}$ (b) $d_{\mathrm{EGS,\,EMEP}}$

Figure 8: Estimated start and end of growing season in Eurasia, using the standard EMEP 'LAT' method.

The 'T5' SGS values are obviously much more complex than those obtained with the 'LAT' method, reflecting both climate differences across Europe and topographic effects. Fig. 9(b) shows significant differences between the two methods, with 'T5' SGS values frequently more than a month later than the 'LAT' values (e.g. in the Alps, western Norway, Turkey).

As an example of the impact of this change, Figure 10 shows the modelled POD1 for deciduous forest, $\mathrm{POD}_{1,DF}$, across Eurasia when using the 'LAT' method for the year 2009. Highest values, of around 30 mmole O_3 m^{-2} yr^{-1} are found in southern Europe, but values exceed 10 mmole O_3 m^{-2} yr^{-1} over much of the continent. (These values are all well in excess of the recommended critical levels of 4 mmole O_3 m^{-2} yr^{-1} for deciduous forests, c.f. Mills et al. 2011). Fig. 10(b) shows the difference in modelled $\mathrm{POD}_{1,DF}$ when using the 'T5' methodology. The effect of the different SGS methods is seen mainly in the Mediterranean area, where $\mathrm{POD}_{1,DF}$ using the 'T5' method is significantly lower than in the base-case run ('LAT').

Sakalli and Simpson (2012) give another example to illustrate the importance that the use of improved SGS estimates can have for ozone and two metrics associated with ozone-damage to vegetation. This study showed that although inclusion of more realistic growing seasons had only small effects on annual average concentrations of pollutants such as ozone, the metrics associated with vegetation-risk from ozone were significantly affected.



(a) $d_{\text{SGS, T5}}$

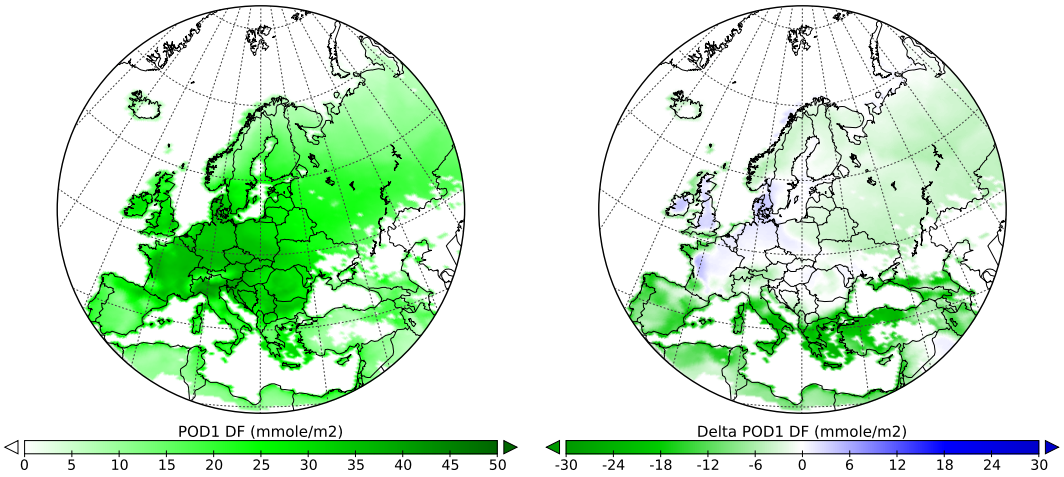
Figure 9: (a) Estimated start of the growing season using the 'T5' method, and (b) the difference between this and the LAT method ($d_{\text{SGS, LAT}}$ minus $d_{\text{SGS, T5}}$)

This work demonstrates a strong need to include more realistic treatments of growing seasons in CTMs. The method used here could also be suitable for other types of models which require information on vegetation cover, such as meteorological and regional climate models. In future work, the 'T5' method will also be further evaluated for use with agricultural and grassland land-covers, which are important for emissions and deposition of reactive nitrogen compounds.

3.4 Final Remarks

The EMEP model has been significantly enhanced in the ECLAIRE project with respect to its ability to simulate climiate change scenarios. Not least, the model can now be driven by meteorology from different global or regional climate models, enabling the kind of studies presented in Langner et al. (2012b) and Simpson et al. (2014b), or as part of the EU FP7 IMPACT2C project.

In this deliverable we have demonstrated new features such as the inclusion of CO_2 inhibition effects on isoprene emissions or stomatal conductance calculations. It is important to realise however that the basic science underlying such algorithms is still rather speculative. With respect to BVOC emissions, the experimental basis for predictions concerning future BVOC emissions is at present too limited to draw firm conclusions Also with regard to the stomatal conductance changes, there is a large uncertainty with



(a) $POD_{1,DF}$ - 'LAT'

(b) Change in $POD_{1,DF}$

Figure 10: Modelled values of (a) $POD_{1,DF}$ (mmole O_3 m^{-2} yr^{-1}) using the EMEP 'LAT' method, and (b) the difference (LAT minus T5) between the modelled $POD_{1,DF}$ when using the 'T5' method.

respect to the effect of elevated CO_2 on g_s in closed forest stands (Uddling et al. 2010, Simpson et al. 2014a, and references within). This evidence, together with new results showing that ozone exposure can uncouple the critically important leaf processes of stomatal conductance and photosynthesis in the field (e.g. Fares et al. 2013), is leading to a re-think over how ozone effects in a future changing climate should be modelled.

Thus, for both BVOC and g_{sto}, there is a strong need for new experimental studies before we can reliably predict the sign of changes in BVOC emissions and hence changes in ozone and BSOA. For further discussion and some recent references on these issues, see Simpson et al. (2014a).

Land cover changes may also have significant impacts on BVOC emissions, with local and potentially global implications for O_3 and BSOA (Ashworth et al. 2012, Lathiere et al. 2010), and changes in growing season will impact emissions and calculation metrics such as POD (Sakalli and Simpson 2012, Klingberg et al. 2011).

One further problem concerns the chemistry of isoprene degradation. In a recent study, Squire et al. (2015) compared a number of chemical mechanisms, and concluded that the choice of reduced isoprene mechanism may alter both the magnitude and sign of the ozone response. Here again, more measurements and laboratory studies are needed to validate these reduced mechanisms especially under high-volatile-organic-compound, low-NOx conditions (*ibid*).

In conclusion, although models can be used to exlore possible consequences of changes associated with climate change, much experimental work is needed before consequences for air pollution metrics are really understood. On the other hand, most modelling studies to date suggest that the most important driver of changes will be emissions and anthropogenic land-cover changes. This remains the main policy message regardless of factors such as CO_2 inhibitions.

4 Milestones achieved

MS28 Implementation and initial testing of coupled model system

This milestone was achieved, although later than planned. The EMEP model is now coupled to the DO3SE Photosynthesis model from C1, and through one-way nesting to the 1-D canopy-chemistry ESX model of C1. The model was further developed to read boundary conditions and landcover changes from WP5 and WP5 partners.

5 Deviations and reasons

Early in the project it was agreed that the canopy-chemistry work was best tackled with a new 1-D model, the ECLAIRE Ecosystem Surface Exchange (ESX) model. The development of this model is reported under C1, D4.4 and C2, D7.3. This ESX model is currently being run with offline-coupling to EMEP, but much testing and optimisation remains before online coupling is a realistic alternative. Examples of the offline coupled calculations are given in D7.3. Finally, there is still a need to upgrade the treatment of bi-directional NH_3 in the EMEP model, but the algorithms from Component 1 (WP3,WP4) which will enable this are only just becoming available at the end of ECLAIRE, too late for inclusion in this report. The work will be continued however within the EMEP framework, and reported in scientific publications.

6 Publications

Bergström, R., Hallquist, M., Simpson, D., Wildt, J. & Mentel, T. F. Biotic stress: a significant contributor to organic aerosol in Europe? Atmospheric Chemistry and Physics, 2014, 14, 13643-13660

Bergström, R.B., Carbonaceous Aerosol in Europe. Out of the woods and into the blue?, PhD Thesis, Dept. Chemistry & Molec. Biology, University of Gothenburg, Sweden, ISBN 978-91-628- 9505-1, Sept. 2015

Colette, A., Granier, C., Hodnebrog, ., Jakobs, H., Maurizi, A., Nyiri, A., Rao, S., Amann, M., Bessagnet, B., D'Angiola, A., Gauss, M., Heyes, C., Klimont, Z., Meleux, F., Memmesheimer, M., Mieville, A., Roul, L., Russo, F., Schucht, S., Simpson, D., Stordal, F., Tampieri, F. & Vrac, M. Future air quality in Europe: a multi-model assessment of projected exposure to ozone Atmos. Chem. Physics, 2012, 12, 10613-10630

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Langner, J., Engardt, M. & Andersson, C. European summer surface ozone 1990–2100 Atmos. Chem. Physics, 2012, 12, 10097-10105

Sakalli, A. & Simpson, D. Towards the use of dynamic growing seasons in a chemical transport model Biogeosciences, 2012, 9, 5161-5179

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7 Meetings

Participation in ECLAIRE annual meetings, plus several WP7 meetings to organise and analyse the model ensemble results.

- 21-22.05.2013, Copenhagen,

  Meeting with other ECLAIRE/EnsClim modellers to discuss the N-deposition runs.

- 16-20.09.2013, Urbino,

  ACCENT Conference, DS and other ECLAIRE modellers presented results.

- 28-29.09.2013, Amsterdam,

  Work-meeting for ECLAIRE ESX model development

- 11-12.11.2013, Oslo, internal meeting

  Meeting with colleagues in Oslo to discuss EMEP model development and climate adaptations.

- 18-19.11.2013, Oslo, internal meeting

  EMEP informal group meeting on model development. Presentation and discussion of the ECLAIRE ESX work.

- 02-06.02.2014, Paris,

  ECLAIRE Winter school on biosphere-atmosphere exchange. David Simpson was one of the teachers.

- 19-22.05.2014, Edinburgh,

  Meeting with CEH and colleagues from Garmisch (KIT) to discuss approaches to link ecosystem modelling with EMEP. Focus on Landscape DNDC model.

- 25-28.05.2014, Edinburgh,

  Meeting with ECLAIRE ESX+DEWS development group, CEH and University of Manchester colleagues

8 List of Documents/Annexes:

n.a.

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