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ENHANCEMENTS TO THE UK PHOTOCHEMICAL TRAJECTORY MODEL FOR SIMULATION OF SECONDARY INORGANIC AEROSOL

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26 **Abstract**

27 Particulate matter remains a challenging pollutant for air pollution control in the UK
28 and across much of Europe. Particulate matter is a complex mixture of which secondary
29 inorganic compounds (sulphates, nitrates) are a major component. This paper is
30 concerned with taking a basic version of the UK Photochemical Trajectory Model and
31 enhancing a number of features in the model in order to better represent boundary layer
32 processes and to improve the description of secondary inorganic aerosol formation. The
33 enhancements include an improved treatment of the boundary layer, deposition processes
34 (both wet and dry), attenuation of photolysis rates by cloud cover, and inclusion of the
35 aerosol thermodynamic model ISORROPIA II to account both for chemistry within the
36 aerosol and between the particles and gas phase. Emissions inventories have been
37 updated and are adjusted according to season, day of the week and hour of the day.
38 Stack emissions from high level sources are now adjusted according to the height of the
39 boundary layer and a scheme for generating marine aerosol has been included. The skill
40 of the improved model has been evaluated through predictions of the concentrations of
41 particulate chloride, nitrate and sulphate and the results show increased accuracy and
42 lower mean bias. There is a much higher proportion of the values lying within a factor of 2
43 of the observed values compared to the basic model and Normalised Mean Bias has
44 reduced by at least 89% for nitrate and sulphate. Similarly, the Index of Agreement
45 between calculated and measured values has improved by ~10%. Considering the
46 contribution of each enhancement to the improvement in the performance metrics, the
47 most significant enhancement was the replacement of the parameterisation of the
48 boundary layer height, relative humidity and temperature by HYSPLIT values calculated
49 for each trajectory. The second most significant enhancement was the parameterisation of
50 the photolysis rates by values calculated by an off line database accounting for the
51 dependence of photolysis rates on zenith angle, cloud cover, land surface type and column
52 ozone. The inclusion of initial conditions which were dependent on the starting point of the
53 trajectory and the modulation of stack emissions made the most significant improvement to
54 sulphate. Furthermore, in order to assess the model's response to abatement scenarios,
55 30% abatements of either NH₃, NO_x or SO₂ showed a reduction in the sum of chloride,
56 nitrate and sulphate of between 3.1 % to 8.5 % (with a corresponding estimated reduction
57 of 1.6 – 3.7% reduction in PM₁₀). The largest reduction in this contribution is due to the
58 abatement of NO_x.

59 **Keywords:** Lagrangian model; sulphate; nitrate; chloride; Master Chemical Mechanism

60 Introduction

61 The United Kingdom, along with other European countries, is required to meet
62 stringent air quality standards for PM₁₀ and PM_{2.5}, as well as exposure reduction targets
63 for PM_{2.5} set by the European Union (EC, 2008). Abatement strategies to improve air
64 quality with respect to particulate matter (PM) pollution have considerable economic cost.
65 The Directive on “Ambient Air Quality and Cleaner Air for Europe” for example estimates
66 the cost of the ‘Maximum Technically Feasible Reduction’ scenario, abating SO₂, NO_x,
67 VOC, NH₃, and PM_{2.5}, to be € 39.7 billion per year in the year 2020. Additional measures
68 may be needed as there has been little change in annual mean concentrations of PM₁₀
69 since the year 2000 across considerable parts of Europe (Harrison et al., 2008, UN ECE
70 report on PM, 2007: <http://tarantula.nilu.no/projects/cccr/reports/cccr8-2007.pdf>).

71 Airborne particulate matter, be it expressed as PM_{2.5} or PM₁₀ mass, is a complex
72 mixture of chemical constituents. In the UK, the predominant individual constituents are
73 sulphates, nitrates and organic matter. Campaign data was collected in the months of May
74 and November of the years 2004 and 2005, in central Birmingham (Yin and Harrison,
75 2008), showing that sulphates and nitrates account on average for 34.5% of PM₁₀ and
76 45.2% of PM_{2.5} mass with the rest comprising of organics (PM₁₀; PM_{2.5} = 23.7%; 26.1%),
77 iron rich dust (PM₁₀; PM_{2.5} = 13.4%; 5.9%), elemental carbon (PM₁₀; PM_{2.5} = 8%; 11.2%),
78 sodium chloride (PM₁₀; PM_{2.5} = 9.3; 4%) and calcium salts (PM₁₀; PM_{2.5} = 7.4%; 2.5%).
79 During episodes of elevated PM concentrations exceeding the daily European Limit Value
80 of 50 µg m⁻³, the contribution of sulphates and nitrates increased to 57.2% of PM₁₀ and
81 68.5% of PM_{2.5} (Yin and Harrison, 2008) and were associated with transport of secondary
82 pollutants. Consequently, abatement of these components is potentially an attractive
83 policy option focussing on their precursor gases emitted by traffic, industry and domestic
84 sources (Erisman and Schaap, 2004, AQEG, 2005, Jones and Harrison, 2011).

85 Numerical models have an important part to play in predicting the impact of
86 abatement strategies and a number of such models have been used to predict
87 concentrations of particulate matter components within the European atmosphere. These
88 include Eulerian models such as LOTOS-EUROS (Schaap et al., 2008), CHIMERE
89 (Bessagnet et al., 2009), REM-CALGRID model (RCG) (Beekmann et al., 2007), and the
90 Unified EMEP model (Simpson et al. 2011) to name but a few. The unified EMEP model
91 has been used for policy development in Europe (Aas et al., 2007) to address regional
92 scale impacts of NO_x and SO₂ emission reductions on PM mass concentrations (despite
93 having uncertainties of about ± 40% for nitrate).

94 In the UK, the Photochemical Trajectory Model (PTM) has often been used to
95 understand boundary-layer pollution. For example, Walker et al. (2009) and Baker (2010)
96 simulated concentrations of ozone, and Derwent et al. (2009b) modelled concentrations of
97 sulphate and nitrate. The PTM is a boundary-layer Lagrangian model whose main
98 advantage over the Eulerian modelling approach is its ability to run highly comprehensive
99 chemical schemes without simplifications and parameterisations that may compromise the
100 performance of the chemical reaction scheme. The PTM is therefore suited to the
101 examination of abatement policies aimed at targeting emissions of individual precursors
102 (e.g. NH₃, NO_x, SO₂). A number of studies have modelled particulate matter in Europe.
103 Most notably, the CityDelta project compared the ability of several models to predict the
104 impact of emissions reductions upon concentrations in European cities (Cuvelier et al.,
105 2007), specifically Berlin, Milan, Paris and Prague (Thunis et al., 2007). A subsequent
106 study (Stern et al., 2008) examined the ability of five chemical transport models to
107 reproduce PM₁₀ episode conditions in central Europe. Model specific studies, such as
108 those with CHIMERE, have sought to simulate particulate matter concentrations in specific
109 parts of Europe, e.g. Portugal (Monteiro et al., 2007) and northern Italy (de Meij et al.,
110 2009). Air quality models used for calculating aerosol species over the UK include the
111 Community Multiscale Air Quality model (CMAQ), Chemel et al., 2010) and the Hull Acid
112 Rain Model (HARM), (Metcalf et al., 2005). CMAQ over-predicted O₃ and under-
113 predicted aerosol species with the exception of sulphate (Chemel et al., 2010). The
114 HARM and ELMO models (Whyatt et al., 2007) underestimated sulphate, nitrate and
115 ammonium by a large margin, and chloride massively. In the work of Redington and
116 Derwent (2002), the NAME model slightly under-predicted measured sulphate values
117 although the annual average values of nitrate compared well.

118 We have previously used the UK Photochemical Trajectory Model (a version of the
119 Derwent et al. (2009b) UK-PTM) to model concentrations of particulate sulphate and
120 nitrate in southern England and Northern Ireland in 2002 (Abdalmogith et al., 2006). While
121 our study was quite successful in modelling monthly mean concentrations and trends in
122 both nitrate and sulphate, it performed poorly in modelling daily concentration data,
123 especially during nitrate and sulphate episodes which were observed during easterly
124 transport trajectory events that brought high levels of particulate matter from Europe. It
125 was concluded that this was unlikely to be due to errors in the back trajectory alone and
126 that inclusion of a more sophisticated treatment of emissions and meteorology would
127 probably be required to address the issue adequately. It was also recognised that it would
128 be advantageous to: (i) use more than one photochemical back trajectory calculation for

129 each daily measurement, (ii) update emissions inventories and injection parameters to
130 account for daily and seasonal variation; (ii) add wet deposition processes; (iii) replace the
131 dynamic approach which treated the chemistry of the NH_4NO_3 – HNO_3 – NH_3 system as a
132 bimolecular gas phase reaction with a more sophisticated thermodynamic algorithm,
133 ISORROPIA II and (iii) and replace the clear-sky photolysis rates with ones which
134 accounted for cloud cover.

135 Numerous amendments have been applied to the original model to form an
136 enhanced UK-PTM with a view to providing an improved model aimed at addressing
137 policymaking decisions. In this paper, we assess the changes resulting from the
138 enhancements by using observed gas- and aerosol-phase data collected at the Harwell
139 observatory in Oxfordshire, UK in 2007.

140

141 **TECHNICAL DESCRIPTION OF THE MODIFICATIONS TO THE UK-PTM**

142 The UK-PTM is a boundary-layer trajectory model originally assembled to simulate
143 photochemical ozone production and subsequently used to derive Photochemical Ozone
144 Creation Potentials (POCPs) (Derwent et al., 1998, Derwent et al., 2005). The model was
145 initially set up to represent an idealised summertime photochemical episode occurring over
146 the UK and used linear air mass trajectories. More recent studies have used air mass
147 back trajectories calculated from meteorological wind velocity vector fields and a
148 parameterised boundary layer height (Abdalmogith et al., 2006; Derwent et al., 2009b;
149 Walker et al., 2009 and Baker, 2010). The changes made by these authors have
150 improved the PTM. Here, we have modified the PTM further to include a new treatment of
151 aerosol processes and of emissions from tall stacks, the effect of cloud cover on photolysis
152 values, wet deposition, and a revised treatment of the emissions, amongst others. A
153 complete list of changes made to the emissions inventories, chemical mechanism and
154 back trajectory calculation is presented in Table 1.

155

156 **Initial Conditions**

157 An implicit assumption made in the original model (Abdalmogith et al., 2006) was that
158 all trajectories, if they were extrapolated far enough back in time, would start over the
159 Atlantic. The initial conditions were fixed to one set of values derived from a remote
160 marine location off the west coast of the Republic of Ireland. In practice, 3-5 day back
161 trajectories with arrival points in the UK do not all start over the Atlantic but may start over
162 continental Europe. Stohl (1998) recommends that these trajectories are not further
163 lengthened in order to maintain a reasonable level of certainty of their position. The

164 amended model uses 5 starting regions, namely Western, Northern, Eastern, Southern
165 and Central (Figure 1) to which initial concentrations of HCl, NO, NO₂, NO₃, HNO₃, SO₂,
166 SO₄, CO, CO₂, CH₄, HCHO, O₃, NH₃, NH₄⁺, NO₃⁻ and SO₄²⁻ were assigned (see Table S1
167 in Supplementary Information). These initial concentrations were derived from data
168 measured at Birkenes, Braganca, Campisabolos, Glashaboy, Hohenpeissenberg, Ispra,
169 Melpitz, Montelibretti, Norway Ocean Station, and S. Pietro Capofiume between 2000 and
170 2007. The initial concentrations were averaged over the measurements taken at a site
171 which best represented the conditions within the initial zone, e.g. for the Western or
172 Northern initial conditions, the most representative measurements are those collected at
173 Birkenes with back-trajectories crossing only over the ocean or the polar ice cap. There is
174 scope in the future to increase the number of starting zones and to make seasonal
175 adjustments to these values or to use concentration fields provided from larger domain
176 models.

177

178 **Meteorology**

179 The majority of studies use back trajectories with a timescale of 3-5 days. This is
180 generally a compromise between having sufficient time to describe the long-range
181 transport and the decreasing accuracy of individual back trajectories the further they are
182 projected backward in time (Stohl, 1998). In this work, four-day back trajectories were
183 calculated using the NOAA Hybrid Single Particle Lagrangian Integrated Trajectory
184 (HYSPLIT-4) model (Draxler and Hess, 1998) and the archived NCEP/NCAR global data
185 assimilation system data (GDAS). The original UK PTM was simply based on three day
186 ECMWF back trajectories consisting of latitude/longitude values calculated online by
187 BADC.

188 An improvement in accuracy can also be achieved by averaging over the values
189 obtained from the output of more than one photochemical back trajectory for each daily
190 PM measurement. Instead of using a single trajectory with a specific arrival time e.g.
191 during the mid-afternoon at 15:00 h (as in the case of Baker (2010) who considered air
192 parcel trajectories arriving in Birmingham, UK), our model was adapted to run
193 photochemical calculations along trajectories for air masses arriving every hour of the day.
194 This implied that for each daily PM₁₀ filter measurement, an average calculated value was
195 determined based on meteorological conditions which were liable to change significantly
196 over the course of a day. Other multiple trajectory sampling schemes can potentially use
197 trajectories arriving at different heights and/or at many nodes of a gridded zone placed
198 symmetrically around the receptor site (private communication with R. Derwent, 2008).

199 In addition to latitude and longitude, other parameters are included in the back
200 trajectory data, namely the boundary layer height, relative humidity and temperature. The
201 HYSPLIT boundary layer heights give a more realistic description of the boundary-layer
202 (BL) and replace the “clipped saw-tooth” function used in the earlier model of Abdalmogith
203 et al. (2006) and shown in Figure S4 which is based on an idealised summertime episode.
204 In particular, in HYSPLIT, the height of the mixing layer is taken as the height at which the
205 potential temperature is at least two degrees greater than the minimum potential
206 temperature. When plotted, the temporal boundary layer height profiles are no longer
207 angular, they change more progressively and they are correctly synchronised to the rising
208 and falling of the sun no matter at what latitude the air mass is located at. As the boundary
209 layer expands, the constituents in the supra layer are mixed into the boundary layer and at
210 dusk the supra layer concentrations are made equal to the boundary layer concentrations
211 at dusk. However, as the boundary layer depth decreases, the constituents in the
212 boundary layer are mixed back into the supra layer. There is no chemical evolution of the
213 upper box.

214 Further auxiliary values in the back trajectory data included the 10 m wind velocity
215 U_{10} and hourly rain rates f which were inputted into the parameterisation of sea salt flux
216 and PM deposition respectively. Cloud cover and time/date data are also included so that
217 the clear-sky assumption could be removed from the model and the emission flux
218 corrections could be correctly synchronised to the hour of the day, day of the week and
219 month of the year.

220

221 **Chemistry**

222 In order to include a more sophisticated treatment of aerosol properties (e.g.
223 inclusion of ISORROPIA II) and to speed up the calculation, the Master Chemical
224 Mechanism (MCM 3.1) was replaced with the Common Reactive Intermediate (CRI)
225 mechanism (version CRI v02) developed by Jenkin et al. (2008). Jenkin et al. (2008) have
226 shown that the CRI mechanism is virtually equivalent to the full MCM. This reduction in
227 the number of species and reactions reduced the calculation time for one trajectory from
228 one hour to approximately one minute. Watson et al. (2008) have made further reductions
229 in the CRI mechanism by removing specific VOCs and reallocating the emissions to
230 retained VOCs, but these reduced mechanisms were not included.

231 The VOC speciation used in this study is based on the speciated VOC emission
232 inventory for 2000 compiled by Passant (2002) as part of the UK National Atmospheric
233 Emission Inventory (NAEI) programme for the 2002 inventory year (the latest available at

234 the time of the original model development). This speciated emission inventory comprised
235 664 VOCs emitted from 249 source sectors with a total annual emission of 1543.7
236 ktonnes, including natural VOC emissions of 178 ktonnes per annum. The emissions from
237 the 249 source sectors were aggregated to the relevant SNAP-1 sector. As many of the
238 VOCs in the UK inventory were isomers or related to the model VOCs, the assignments
239 were relatively straightforward.

240 In the original model, a clear sky scenario was always in place generally limiting the
241 application of the model to summer conditions. The photolysis values J were
242 parameterised to the solar zenith angle Z , using equation 1, where l , m , n , are constants
243 available from the MCM website (<http://mcm.leeds.ac.uk/MCM>).

$$J = l(\cos Z)^m \exp(-n \sec Z) \quad (1)$$

244 In the enhancement, the photodissociation rates were calculated off line using the
245 PHOTOL code (Hough, 1988). This has been updated to account for changes to
246 spectroscopic and photochemical parameters, most notably the quantum yield of ozone
247 (Atkinson et al., 1997). The input database contains the dependence of photolysis rates
248 for 21 species on zenith angle, cloud cover, land surface type and column ozone. The
249 local photolysis rates were derived during the model run by identifying the nearest element
250 in the database. The aerosol and ozone columns were initially fixed, the latter at ~300 DU,
251 but could be varied subsequently. The tabular values not only accounted for the solar
252 zenith angle at a given time of the day, latitude and longitude, but also account for the
253 surface over which the air mass travels (surface albedo of land, sea or ice) and the
254 fractional cloud cover which was included as a field within the back trajectory data.
255 Fractional cloud cover values were extracted, for each step of the trajectory, from Global
256 Data Assimilation System (GDAS) forecast data generated by the National Weather
257 Service's National Centers for Environmental Prediction (NCEP)
258 (<http://ready.arl.noaa.gov/gdas1.php>). Using this system, values of photosynthetically
259 active radiation (PAR) are also derived for the calculation of an environmental correction
260 factor for monoterpenes and isoprenes calculated in the biogenic emission inventories
261 (Figure S5).

262

263 **Aerosol Processes**

264 In the original UK-PTM, the aerosol chemistry was accounted for by a very simple
265 process to represent the establishment of thermodynamic equilibrium in the NH_4NO_3 –
266 HNO_3 – NH_3 system. Ammonia was rapidly combined with available aerosol sulphate to

267 form ammonium sulphate and any ammonia that remained was assumed to form a
 268 thermodynamic equilibrium with nitric acid and ammonium nitrate. No account was taken
 269 of hygroscopic water uptake which substantially affects the equilibrium. Furthermore, the
 270 formation of coarse mode aerosol nitrate was parameterised by the reaction of N₂O₅ and
 271 nitric acid with natural dusts and sea salt. Abdalmogith et al. (2006) and Derwent et al.
 272 (2009b) provide more details. The parameterisations based on the concentrations of the
 273 trace gases NH₃, N₂O₅, HNO₃, and SO₃ have been replaced in the enhanced model by the
 274 aerosol thermodynamic equilibrium model for K⁺, Ca²⁺, Mg²⁺, NH₄⁺, Na⁺, SO₄²⁻, NO₃⁻, Cl⁻,
 275 H₂O aerosols and associated gases, called ISORROPIA II (Fountoukis et al., 2009). In
 276 this work, it was compiled from FORTRAN code into a dynamic link library accessible by
 277 the FACSIMILE model. The complete theory of ISORROPIA II, together with a detailed
 278 description of the equations solved, the activity coefficient calculation methods and the
 279 computational algorithms used can be found in Nenes et al. (1998a,b) and Fountoukis and
 280 Nenes (2007).

281

282 **Aqueous Phase Processes**

283 The aqueous phase oxidation of SO₂ to H₂SO₄ in clouds is treated using a pseudo
 284 first-order process with a reaction constant R_k. The original value for R_k based on an
 285 assumed conversion of 1-2% / hour was replaced by a parameterisation based on relative
 286 humidity and cloud cover ε, (see equation 2 and Schaap et al. (2004)).

$$R_k = \begin{cases} 5.8 \times 10^{-5}(1 + 2\varepsilon), & RH < 90 \% \\ 5.8 \times 10^{-5}(1 + 2\varepsilon)[1.0 + 0.1 * (RH - 90.0)], & RH \geq 90 \% \end{cases} \quad (2)$$

287

288 **Deposition Values**

289 The conventional resistance approach - reviewed by Wesely and Hicks (2000) - of
 290 representing dry deposition processes was used in the model. The rate of dry deposition
 291 of the chemical species *i*, of concentration C_{*i*}, was given by,

$$\frac{d}{dt}[C_i] = -\frac{v_g}{H}[C_i] \quad (3)$$

292 where the boundary layer height and deposition velocity are represented by *H* and *v_g*
 293 respectively. For gases, tabulated dry deposition values were subdivided in the model to
 294 account for whether the air mass was over land or sea (see Table S2). For ozone, a
 295 more developed representation was used which accounted for the diurnal and seasonal
 296 variation induced by stomatal opening and closing. In the model, the approximation of the
 297 half sinusoidal function described by Hayman et al. (2010) was used. Further

298 improvements could be made by accounting for the opening and closing of stomata in
 299 response to the availability of moisture and the meteorological conditions. This adjusts the
 300 deposition value of ozone between a night time and winter constant value of 2 mm s^{-1} and
 301 a seasonal maximum ranging from 4 to 7 mm s^{-1} (Hayman, 2010).

302 For particulate matter (in this case for chloride, nitrate and sulphate particles) dry-
 303 deposition was accounted for by an expression developed by Smith et al. (1993) primarily
 304 for air masses as they move over the sea (equation 4),

$$V_d = \frac{V_t}{1 - \exp\left\{-\left(\frac{V_t}{CD \cdot U_{10}}\right)\right\}} \quad (4)$$

305 This is a function of the 10 m wind speed U_{10} , the gravitational sedimentation velocity
 306 V_t and the Drag Coefficient CD , between the atmosphere and ocean (equation 5).

$$CD(U_{10}) = \begin{cases} 1.14 \times 10^{-3}, & U_{10} \leq 10 \text{ ms}^{-1} \\ (0.49 + 0.065U_{10}) \times 10^{-3}, & U_{10} > 10 \text{ ms}^{-1} \end{cases} \quad (5)$$

307 This expression (eq. 4) was used for land multiplied by a ratio of typical fixed
 308 land/sea values for $1 \mu\text{m}$ particles.

309 An additional loss term Λ_g , was added to represent removal by wet deposition using
 310 the parameterisation given by McMahon et al. (1979). This is a function of hourly rainfall f
 311 which was taken from the HYSPLIT back trajectory data (equation 6). The expression for
 312 SO_2 appears in equation 6, where f is the rainfall rate (mm h^{-1})

$$\Lambda_g = 17 \times 10^{-5} f^{0.6} \quad (6)$$

313

314 **Emission Inventories**

315 Emission fluxes were calculated using one of two sets of SO_2 , NO_x , NMVOC, CO and
 316 NH_3 emission inventories. For the UK land mass, NAEI emission data were used
 317 (<http://naei.defra.gov.uk/>). The NAEI inventory programme produces annual emission
 318 maps at $1 \text{ km} \times 1 \text{ km}$ spatial resolution for the major emission source sectors. These were
 319 aggregated to $10 \text{ km} \times 10 \text{ km}$ for each pollutant and major source sector. Emission data
 320 were taken from EMEP (<http://www.emep.int/>) for the remaining model domain. These
 321 were available on a $50 \text{ km} \times 50 \text{ km}$ grid for the same pollutants and major emission source
 322 sectors. The base year for the emissions was 2005 (the latest available at the time of the
 323 work), which were scaled to 2007 using the ratio of the national sector emission totals for
 324 2005 and 2007 for each country. In a similar manner to that adopted by Hayman et al.
 325 (2010), a separate term was added to represent the emissions of VOCs from natural
 326 sources (taken to be trees), This is described further below.

327

328 *Emission fluxes*

329 Instantaneous emission fluxes were derived from the annual average emission
330 inventories for SO₂, NO_x, CO, NH₃, VOCs and NMVOCs and updated every 30 minute
331 trajectory step within the calculation as the air mass moved across the model domain. The
332 emissions were calculated from the annual emissions of NH₃, NO_x, VOCs, biogenic VOCs,
333 EC, and OC, scaled by factors describing diurnal, day-of-week, and monthly variations
334 which were published as part of the City-Delta European Modelling Exercise
335 (http://aqm.jrc.ec.europa.eu/citydelta/temp_factors_gh.txt)

336 *Biogenic emission fluxes*

337 Additional emission terms are added to the emission rate of isoprene and terpenes to
338 represent the natural biogenic emissions from European forests and agricultural crops.
339 The emission inventory used was that derived in the PELCOM project (PELCOM, 2000).
340 The inventory was aggregated to the EMEP 50 km x 50 km grid and gives emission
341 potentials for isoprene (from deciduous and evergreen trees: temperature and light-
342 sensitive), monoterpenes (from deciduous and evergreen trees: temperature or
343 temperature and light-sensitive) and other VOCs (OVOCs, from deciduous and evergreen
344 trees: temperature sensitive). The emission potentials were converted to local emission
345 rates using environmental correction factors (Guenther, 1997), derived from the
346 meteorological datasets. Hayman et al. (2010) compared the PELCOM emission
347 inventory with other estimates and discussed the implications of using this inventory.

348

349 *Sea salt emission flux*

350 In order to use ISORROPIA II, a sodium and chloride concentration were required
351 and this was derived from a sea-salt parameterisation developed by Gong (2003). Figure
352 S1 shows the flux distribution (equation 7) used to derive an injection term in the model
353 which was dependent on the wind speed at 10 m (U₁₀). This term was integrated into a
354 mass flux (using particle density to mass density relationship, $\frac{dm}{dr} = m_p \frac{dF}{dr}$) for all particle
355 radii r, reducing the parameterisation to a term involving just U₁₀,

$$\frac{dF}{dr} = 1.373u_{10}r^{-A}(1 + 0.057r^{3.45}) \times 10^{1.607e^{-B^2}} \quad (7)$$

356 For values of particle radius r and an adjustable parameter $\Theta = 30$, which controls the
357 shape of the sub-micron size distributions, the constants A and B are given by equations 8
358 and 9.

$$A = 4.7(1 + \Theta r)^{-0.017r^{-1.44}} \quad (8)$$

$$B = (0.433 - \log r)/0.43 \quad (9)$$

361 *Treatment of emissions from large stacks*

362 As the modelled air mass tracks along a trajectory, the emissions are entered
 363 independently of any height constraint into the boundary layer, suggesting a possible
 364 reason for the initially high SO₂ values (c.a. 2.5 times the expected value). Redington and
 365 Derwent (2002) also reported a similar problem with SO₂ concentrations calculated by
 366 their NAME model. The highest emissions of SO₂ on the emission maps were attributable
 367 to coal- and oil-fired power stations, together with other heavy industries (illustrated for the
 368 UK in Figure S3). Given that major industrial emissions are made via tall chimney stacks
 369 (100-300 m), there will be times of the day when the emissions are not made into the
 370 boundary layer but above it. Compared to state-of-the art 3-D models, where the
 371 emissions can be injected into the relevant model layer, this is a limitation of the boundary-
 372 layer model.

373 Bieser et al. (2011) calculated the vertical emission profiles of point-source emissions
 374 over Europe, evaluating an average effective emission height from plume rise calculations
 375 applied to various meteorological fields, seasons, times of the day and emission stack
 376 characteristics. In this work, an empirical equation (10) - approximating the findings of
 377 Bieser et al. (2011) - was derived by re-aggregating the calculated fractional values for the
 378 binned emission heights.

$$AFV(h) = \begin{cases} 0, & h < 144 \text{ m} \\ 0.45 + \tan^{-1}(1.02 * h - 310.6)/2.49, & 144 \text{ m} < h < 724 \text{ m} \\ 1, & h \geq 724 \text{ m} \end{cases} \quad (10)$$

379 where AFV(h) represents the mixing height (h)-dependent average fractional value of the
 380 emissions.

381 Using equation 10, the chimney code cuts the SNAP 1 NO_x and SO₂ emission fluxes
 382 by the fractional value AFV(h), if (i) the air mass passes over an emission square
 383 containing a major point source and (ii) the boundary layer height is less than 724 m, when
 384 it starts to slice the average emission plume.

385 The locations of emitting stacks were identified in the model using positional data
 386 published by the European Environment Agency's European Pollutant Release and
 387 Transfer Register (E-PRTR). (<http://prtr.ec.europa.eu/>) In total, 417 UK and 5171
 388 European NO_x and SO₂ emitters are accounted for in this way within the model. The
 389 inclusion of a "chimney code" attempts to overcome the limitation of a single box to

390 describe the boundary layer. As a result, the relatively high NO_x and SO₂ concentrations
391 are reduced by 69% and 91% on average respectively relative to the base case of 11.18
392 ppb and 2.43 ppb without the “chimney code”. Future model enhancements may well
393 seek to account for the seasonal and daily activity of the power stations according to
394 expected output.

395 The main local source of SO₂ and NO_x within the vicinity of the Harwell site is Didcot
396 power station which is an 1.9 GW coal fired station used to meet peak demand. This is
397 located 7 km downwind of Harwell for the prevailing south-westerly air masses, and it has
398 been shown in a past study (Jones and Harrison, 2011) that Didcot power station has
399 virtually no influence on the measurements at Harwell, and thus the SO₂ and NO_x
400 emissions are reduced to zero for Didcot Power station in the model. This conclusion was
401 drawn from data collected at Harwell from 2001 to 2008 and is thought to be due primarily
402 to the lofting of the chimney emissions above the air sampled at Harwell.

403

404 **Computation**

405 The model was coded using the FACSIMILE numerical integration package (Curtis
406 and Sweetenham, 1988). For each species *i* within the air parcel, its concentration within
407 the boundary-layer C_i is governed by the differential equation (11)

$$\frac{d}{dt}[C_i] = P_i + \frac{E_i}{H} - L_i[C_i] - \frac{v_g}{H}[C_i] - ([C_i] - [B_i])\frac{1}{H}\frac{dH}{dt} \quad (11)$$

408 The source terms include the local emission rate from pollution sources E_i and the
409 production rate of the species from photochemistry P_i . Similarly, the loss terms include the
410 loss rate by photochemistry $L_i C_i$ and dry deposition rate $\frac{v_g}{H}[C_i]$. The effect of boundary
411 layer height changes is represented by the time-dependent variable H . B_i is the
412 concentration of the species in the supra boundary layer. The differential equations were
413 solved using the variable order GEAR solver in the FACSIMILE software package.

414

415 **Model Validation**

416 The model was used to simulate a wide range of PM concentrations measured at the
417 Harwell site in southern England (latitude = 51.571°N and longitude = 1.325°W). The
418 primary test of the model was against daily concentrations of chloride, nitrate and sulphate
419 collected at the Harwell site as part of the Airborne Particle Concentrations and Numbers
420 Network (Hayman, 2008). The daily samples were collected using a Partisol 2025 sampler
421 fitted with a PM₁₀ inlet. In addition hourly concentrations of NO, NO_x, CO and O₃ data were
422 measured using chemiluminescence, IR Absorption and UV absorption respectively. The

423 data are verified and ratified every quarter using the results from independent QA/QC site
424 audits (see link for more details
425 http://www.airquality.co.uk/verification_and_ratification.php).

426 Other analytes were taken from other networks offering either a monthly or an hourly
427 resolution. Monthly measured data was taken from the Acid Gas and Aerosol Network
428 (AGANET) and the National Ammonia Monitoring Network (NAMN). These are two of the
429 four components of the UK Eutrophying and Acidifying Atmospheric Pollutants (UKEAP)
430 network (<http://pollutantdeposition.defra.gov.uk/aganet>). The UKEAP measurements were
431 carried out using the CEH DELTA (DENuder for Long-Term Atmospheric sampling) system
432 which is a low-cost diffusion denuder system that was originally developed for long-term
433 sampling of ammonia and ammonium (Sutton et al., 2001), and which has also been
434 tested for long-term sampling of acid gases (HNO_3 , HONO, HCl, SO_2) and aerosols (NO_3^-
435 NO_2^- , Cl^- , SO_4^{2-}) (Tang et al., 2008). Quality Assurance is maintained through the
436 implementation of established sampling protocols, and monitoring of laboratory
437 performance through participation in the EMEP and WMO-GAW inter-comparison
438 schemes for analytical laboratories. The data quality is assessed using set Quality Control
439 criteria: a) based on the capture efficiency using two denuders in the DELTA systems and
440 b) involving the coefficient of variation for ammonia concentrations with the triplicate
441 ALPHA samplers. Further details of the measurements and verification/ratification
442 procedures are given in the annual reports to DEFRA (see link [http://www.uk-](http://www.uk-pollutantdeposition.ceh.ac.uk/reports)
443 [pollutantdeposition.ceh.ac.uk/reports](http://www.uk-pollutantdeposition.ceh.ac.uk/reports)).

444

445 **RESULTS**

446 **Generalisation of the Patterns Observed in the Daily Back Trajectories**

447 Data from the period 19 March 2007 to 18 May 2007 were used for the validation
448 capturing a large range of PM_{10} values to model. The patterns observed in the measured
449 daily PM values can be accounted for by how the 24 hourly back trajectories (for the
450 measurement day) spread across the emission map (see Figure S6). At the start of the
451 sampling period (19th March) an increase – from relatively small concentrations - in the
452 nitrate and sulphate values - was observed after the third day (Figure 2). This is
453 accounted for by the air mass trajectories switching their origins from over the North Pole
454 (passing directly down through Scotland and Northern England to the receptor site on
455 20/03/2007) to an origin in Eastern Europe on 25th March (25/03/2007 in Figure S6). The
456 air masses continued to originate from eastern Europe up until 2nd April (03/04/2007) after
457 which the starting points of the trajectories move towards the North Sea and then towards

458 the Atlantic off the coast of Republic of Ireland and France between 3rd and 14th April
459 (09/04/2007). From 15th April to 5th May the trajectories start at locations close to the west
460 and east coast of the UK, crossing over France, Germany and Denmark periodically
461 (15/04/2007). Then in the final phase of the sampling period 6-19th May, the air masses
462 have their origin firmly in the middle of the Atlantic Ocean (18/05/2007). In general, when
463 the air mass spends most of its time over the sea, the chloride measurements are high
464 and the nitrate and sulphate are low (see Figure 2). Conversely, when the air mass
465 originates over land and passes mainly over land, then the chloride measurements are low
466 and the nitrate and sulphate measurements are high, consistent with the clustered back
467 trajectory measurements of Abdalmogith and Harrison (2005). When considering the time
468 series of predicted and modelled chloride, nitrate and sulphate, the model output
469 impressively tracks the measured nitrate values. Similarly, the modelled sulphate values
470 satisfactorily track the measured values but with a high degree of scatter shown by the
471 plotted hinges. The performance of chloride is not as impressive but is acceptable when
472 considered in the context of the range of modelled values with nitrate and sulphate.

473

474 **Model Verification and Validation**

475 Table 2 compares the simple statistical values calculated for the gases $\text{NH}_{3(g)}$, HNO_3 ,
476 SO_2 , HCl , CO , NO , NO_2 and O_3 and the aerosol components NH_4^+ , Cl^- , NO_3^- , SO_4^{2-} , for the
477 period 02/04/2007 to 30/04/2007, across which the average temperature and relative
478 humidity were 11°C and 72 % respectively. This period corresponds to the monthly
479 denuder and aerosol filter measurement for April made on the Acid, Gases and Aerosol
480 Network (AGANET). Considering the core functionality of the enhanced-PTM in
481 predicting ozone, the model under-predicts O_3 , NO and NO_2 by 20%, 64% and 46%
482 although the ratio of NO_2 to NO is similar for both modelled and measured values.

483 The enhanced model under-predicts mean values of ammonia gas, ammonium, nitric
484 acid and hydrochloric acid by 12 %, 0 %, 88 % and 96 % respectively. In the original
485 model, there was an overestimation of sulphur dioxide as also reported by Redington and
486 Derwent (2002). By using the height dependent emission of SO_2 , prescribed in the
487 chimney code, we have brought this prediction down from a mean value of 2.43 ppb to a
488 mean value of 0.27 ppb. With regards to the particulate matter concentrations, the model
489 over-predicts the measured value of chloride, nitrate and sulphate by 20 %, 8.1 % and
490 18% respectively. Although these discrepancies appear large, the model results appear
491 more reasonable when comparing with the full time series (Figure 2 & 3).

492 The improvement in the capability of the enhanced PTM to model nitrate and
493 sulphate can be judged from Figure 2 where a comparison with the original model output is
494 presented. Both original and enhanced modelled values of nitrate and sulphate do indeed
495 span the range of measured values for the sampling period considered but the original
496 model fails to account for specific scenarios thus leading to a short-fall in the calculated
497 nitrate and sulphate values. The original model did not calculate chloride but the
498 comparison shows that the enhancements made to the model address the general under
499 prediction of nitrate and sulphate. The original PTM was capable of modelling the more
500 significant nitrate and sulphate episodes associated with easterly back trajectories but
501 failed to account for the smaller episodes resulting from westerly trajectories. This led to
502 sharp increases in nitrate and sulphate when the air masses switched from westerly to
503 easterly (14/04/2007-15/04/2007). The enhanced model accounts better for the high
504 values observed during the nitrate episodes, especially the episode between 25th and 27th
505 March where the nitrate value reached 36 $\mu\text{g m}^{-3}$. This episode was initially thought to be
506 due to the presence of fog, although the meteorology measured at the nearby met-station
507 of Benson did not indicate this to be the case. However, weather diaries for these three
508 days record the UK weather as being generally dry by day due to an anticyclonic ridge,
509 which can be associated with overnight fog. (see link:
510 <http://www.met.rdg.ac.uk/~brugge/diary2007.html>). The trajectories for this period
511 originated over central and eastern Europe thus leading to the observed sulphate episode.
512 The enhanced model also reflected, but over-predicted, later sulphate episodes
513 (12/04/2007-18/04/2007 and (20/04/2007-24/04/2007). Whereas the original model
514 represented this episode by a brief spike in the sulphate values, the new model, which is
515 able to model episodes due to westerly air masses, shows a longer episode better
516 matching the measured data.

517 A direct comparison of the calculated and measured data is shown in Figure 3 where
518 the time-series data has been replotted. The poor performance of the model to account
519 for chloride can be immediately seen by the large fraction of points which are respectively
520 either above or below the marked 2:1 or 1:2 boundary. Although the general trend is
521 correct, there is a significant amount of scatter about the fitted and 1:1 line showing that
522 there is a weakness in the modelling of chloride to be accounted for. The plots for nitrate
523 and sulphate are much better with the majority of points within the 2:1 and 1:2 boundary.
524 The over-prediction of sulphate results in a larger than unity gradient for sulphate, and the
525 less than unity gradient of nitrate suggest the model is still slightly under-estimating the

526 higher values seen during the episodes.

527 Even though some of the higher measured chloride values are under-predicted, the
528 temporal trends predicted by the model reflect the measured values fairly well as seen in
529 Figure 2. This gives confidence in the ability of the Gong parameterisation and
530 ISORROPIA II parameterisation to model the correct magnitude of sea salt, although the
531 measured value was in general within or just outside of the max/min modelled values.
532 This large discrepancy may be accounted for by uncertainties in the trajectory values of 10
533 m wind speed. Good results are obtained for nitrate for which the median daily value was
534 much closer to the PM value. With regards to sulphate, the PTM was able to model
535 correctly both high and low sulphate episodes although with a very high scatter of values
536 as depicted by the max/min point of the plotted hinges. Also, there were periods where
537 sulphate was significantly over-predicted.

538 Table 3 considers the effect of the model enhancements - measured against the daily
539 observed PM measured values - using performance metrics calculated separately for the
540 original and enhanced UK-PTM. The complete 61 day measurement period was
541 considered for this comparison and the enhanced model improves considerably the
542 average calculated values for the period. Both nitrate and sulphate were under-predicted
543 relative to the observed values by 56% using the original model. The enhancements
544 reduced this discrepancy for nitrate and sulphate to within 1.5% and 3.3% of the measured
545 mean values and the calculated chloride value was within 13% of the measured value.
546 Furthermore, improvements in how well the calculated values track with the measured
547 values are reflected in the values of Spearman's correlation coefficient r which increase
548 from approximately 0.5 to 0.83 and 0.65 for nitrate and sulphate respectively. As Figure 3
549 also indicates, the correlation coefficient of 0.5 for the chloride values shows that the
550 model does not estimate chloride as well as it calculates nitrate and sulphate.

551 The Root Mean Square Error, RMSE provides information on the short term
552 performance and has a possible range from 0 to $+\infty$ (Derwent 2009a). Again, the closer
553 this value is to zero the better is the short term performance and although fractional values
554 are not achieved using the enhanced model and we do not better the values of Derwent et
555 al. (2009b) modelling longer time series measurements at Harwell with a UK-PTM, a
556 considerable improvement in the short term performance of the PTM can be seen in our
557 enhanced model. The Index of Agreement, IA, reflects the improvement in performance.
558 IA is a statistical measure of the correlation of the predicted and measured concentration;
559 the closer this is to 1 the better the correlation. For nitrate and sulphate an increase in the

560 value of IA is observed from 0.88 and 0.86 to 0.96 and 0.95 respectively. The value of IA
561 for chloride is also unexpectedly high considering the values of Spearman correlation
562 coefficient (r). As argued by Nath and Patil (2006) the value of r is often misleading as it
563 may be unrelated to the size of difference between observed and predicted values, and
564 that IA is better measure of how two values track each other over a period of time.

565 The improvement in the calculation of nitrate and sulphate is reflected also in the
566 improved value of the mean bias error MB. The Mean Bias, MB provides information on
567 the long term performance and has a range between the negative of the mean observed
568 value to $+\infty$. The closer this value is towards zero the better the long term performance.
569 For both nitrate and sulphate the MB value is reduced to fractional values implying that the
570 model's long term performance is improved. The fractional MB value for chloride also
571 indicates that the model's long term performance in calculating chloride is comparable to
572 that of nitrate and sulphate. Considering the Normalised Mean Bias (NMB) values, if these
573 lie between -0.2 and 0.2 then the model is acceptable according to the recommendation of
574 Derwent et al. (2009a). For the case of the nitrate and sulphate values respectively, the
575 values decrease in magnitude from -0.59 and -0.58 respectively using the original model to
576 0.05 and -0.07 for the enhanced model (cf the average values of Derwent et al. (2009a) of
577 0.05 and 0.14 for the whole year). The NMB value of -0.1 for chloride indicates that the
578 model's performance is acceptable but far from ideal. This is also reflected by the fraction
579 of the calculated chloride concentrations FAC2, within a factor of two of the observed
580 values, being just less than 50 %. For nitrate and sulphate this FAC2 value is 77 % and 81
581 % respectively. Using the original model the fraction of calculated nitrate and sulphate
582 values within a factor of 2 of the observed values was 18% and 11% respectively.

583 The contribution of each enhancement can be judged in Table 4. In this, the results
584 from the enhanced model are compared with the chloride, nitrate and sulphate values
585 when each enhancement is restored to its original setting. For each case, the decrease in
586 performance is represented by each percentage. Considering the percentage change in
587 the arithmetic means, the significance of the enhancements has been ranked from top to
588 bottom in the table. The most significant enhancement for chloride, nitrate and sulphate is
589 observed when the replacement of parameterisation of temperature, relative humidity and
590 the boundary layer height by values modelled by HYSPLIT. This is closely followed by the
591 enhanced photolysis values for just chloride and nitrate and then by the inclusion of
592 ISORROPIA II and cloud cover in the model for nitrate. The enhancement of the liquid
593 phase oxidation of SO_2 to H_2SO_4 in clouds by equation 2, inclusion of stack height
594 dependent emissions and the improvement in the initial conditions contribute most to the

595 sulphate enhancement. These trends are also observed with the percentage change of
596 the NMB values and in the context of a limit of acceptability of ± 0.2 , the largest changes
597 were seen for sulphate. Similar comparisons were made for FAC2 and r^2 and although the
598 changes were not as significant, again, the maximum changes were observed for
599 sulphate.

600 For policymaking decisions, Derwent et al. (2009b) showed that a 30% abatement of
601 either NH_3 , NO_x or SO_2 led to at least 3.5% reduction of either nitrate or sulphate.
602 Reducing NH_3 by 30% reduced nitrate and sulphate by 12.2% and 0% respectively
603 compared to a 14.8% and 2.3% reduction when abating NO_2 (Derwent et al., 2009b). The
604 abatement of SO_2 yielded the highest reduction (of 14.8%) of the contribution of sulphate
605 to the PM value. The abatement of CO had no effect on the PM contribution from
606 ammonium, nitrate or sulphate. Likewise, the abatement of VOCs reduced the
607 contribution to PM from ammonium, nitrate and sulphate by 0 %, 2.1 % and 0.6 %
608 respectively. Referring to Table 5, our model shows comparable findings. Abating NH_3 by
609 30 % reduced nitrate and sulphate by 5.1 % and 0.1 % respectively. Similarly, lowering
610 NO_x by 30 % reduced nitrate and sulphate by 17.7 % and 1.9 % respectively. The 30 %
611 abatement of SO_2 yielded the highest reduction (by 20.8 %) of the contribution to the PM
612 value via sulphate and 2.5% of nitrate. For NO_x and SO_2 , our enhanced model predicts a
613 larger reduction of nitrate and sulphate respectively, compared to Derwent et al. (2009b)
614 suggesting that our enhancements are potentially accounting for additional sensitivity to
615 the abatement of these precursors. The model suggests that the abatement of any of NH_3 ,
616 NO_x , or SO_2 by 30% will lead to a reduction in the sum of SO_4^{2-} , NO_3^- and Cl^- of between
617 3.1 % to 8.5 %, with the largest reduction due to NO_x abatement.

618

619 **SUMMARY**

620 Modifications to the UK Photochemical Trajectory model have been made in order to
621 make the chemical and meteorological processes more representative of the actual
622 conditions leading to the composition of the air masses sampled. The principal aim of this
623 work has been to model values of chloride, nitrate and sulphate over a fixed period of time
624 where a varied range of hourly nitrate values have been encountered resulting from air
625 mass trajectories with origins both over sea and continental Europe. Although the full
626 episodic trends of nitrate have not been totally accounted for by the enhancement, the
627 nitrate, sulphate and chloride have been modelled far more satisfactorily in comparison to
628 the original model.

629 When the original and enhanced UK-PTM are evaluated against the criteria
630 established by Derwent et al. (2009a) for deciding the adequacy of models for policy
631 relevant queries, we observe a general improvement in the performance metrics. The
632 largest improvement is seen for the nitrate concentration with the mean bias falling to well
633 below 0.05 with 77 % of the values lying within a factor of two of the observed values. The
634 calculations of sulphate had a mean bias of 0.07, and 88 % of the values lay within a factor
635 of two of the observed values. The calculation of chloride however needs improvement
636 having a normalised mean bias of -0.1 with 42 % of the calculated values lying within a
637 factor of two of the observed values. In general, the original model under predicted the
638 average observed values by 55% and using the enhancements the model calculates
639 nitrate and sulphate to within 1.5% and 3.3% of the mean measured values. Furthermore,
640 the enhancements have improved the correlation between the calculated and measured
641 values reflected by the increase in the Index of Agreement from 0.88 and 0.86 to 0.96 and
642 0.95 for nitrate and sulphate respectively. Similarly, improvements in the model's ability to
643 represent the long and short term trends in both nitrate and sulphate have been
644 demonstrated by the lowering of the values of the normalised mean bias and root mean
645 square error towards the preferred values of zero. Our model indicates that a 30%
646 abatement of either NH₃, NO_x or SO₂, will lead to a reduction in the sum of chloride, nitrate
647 and sulphate of between 3.1 % to 8.5 % (with a corresponding estimated reduction of 1.6 –
648 3.7% reduction in PM₁₀). The largest reduction in this contribution is due to the abatement
649 of NO_x.

650

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873 **TABLES LEGENDS**

874 Table 1. Summary of changes made to the UK-Photochemical Trajectory Model.

875

876 Table 2. Simple statistics calculated using modeled and measured concentrations
877 collected over the period from 02/04/2007 to 30/04/2007. Mean temperature
878 $284.3 \pm 2.3\text{K}$ and relative humidity of $71.8 \pm 6.7\%$. [* Values represent the
879 measured monthly value only. ** The O₃ values represent the period when
880 measured values were available, from 26/04/2007 to 19/05/2007.]

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882 Table 3. Model performance metrics for the period from 19/03/2007 to 19/05/2007 using
883 full days data. [N = number of complete pairs of measured and calculated
884 values; MB = mean bias ($\mu\text{g}/\text{m}^3$); NMB = Normalised mean bias; MGE = mean
885 gross error; NMGE = normalised mean gross error; FAC2 = A count fraction of
886 points within 0.5 and 2 times the observation; RMSE = root mean square error
887 ($\mu\text{g}/\text{m}^3$); r = Spearman's correlation; r² = correlation coefficient; and IA = Index
888 of Agreement.]

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890 Table 4. Observed changes in values of the Performance Metrics when each
891 enhancement in the model is restored to its original setting.

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893 Table 5. Change of calculated species concentrations (%) resulting from precursor
894 abatement (by 30%) on the calculated chloride, nitrate and sulphate
895 concentrations. A comparison is made with the study of Derwent et al. (2009) –
896 abatement figures shown in italics.

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FIGURE LEGENDS

900 Figure 1. Boundaries separating the Northern, Eastern, Southern, Western and Central
901 Regions of Europe. Initial concentrations are specified for each region and are
902 used as initial conditions in each calculation depending on which region the
903 trajectory starts.

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905 Figure 2. Comparison between calculated and measured PM₁₀ chloride, nitrate and
906 sulphate. Measurements (black line) were made with a Rupprecht and
907 Patashnick Partisol 2025 sampler with PM₁₀ sampling inlet. The calculated data
908 is depicted by the blue whisker plots derived from the statistics of each group of
909 24 hourly calculated values. The middle horizontal line represents the median;
910 the two hinges represent the first and third quartile; and the two whiskers
911 represent the maximum and minimum values. Also included are the results
912 shown by the brown line from the initial PTM model. (Referring to Figure 1, the
913 coloured ribbon at the bottom of each plot shows the zone from which the
914 trajectory used in the calculation started.)

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916 Figure 3. Comparison between calculated and measured PM₁₀ chloride, nitrate and
917 sulphate. Measurements made with a Rupprecht and Patashnick Partisol 2025
918 sampler with PM₁₀ sampling inlet. The data is fitted using the Reduced Major
919 Axis method (Ayers, 2001), indicated by the solid black line and equation. Also
920 included on these correlation plots is the ideal case of a 1:1 correlation marked
921 out by the blue line and the boundaries where the calculated values are twice or
922 half the value of the measured values (dashed lines).

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Table 1. Summary of changes made to the UK-Photochemical Trajectory Model.

	Enhancement of	TO	FROM
Emissions	Continental VOC/NOx/CO/SO2/ Biogenics/NH3	EMEP, base year 2005 (50×50 km)	CORINAIR, base year 1985 (150×150 km)
	United Kingdom VOC/NOx/CO/SO2/ Biogenics/NH3	NAEI, base year 2005, (10×10 km)	CORINAIR, base year 1985 (10×10 km)
	Sea Salt flux	Gong (2003) parameterisation	None present
	Boundary layer / free troposphere injection	B.L. height determines input of SO ₂ and NO _x .	None present
	Initial Conditions	Dependent on initial lat/long position being in either a N/E/S/W or Central Region.	Westerly Clean conditions for all trajectories
	Chemical Mechanism	Gas phase	cri-v02
Aqueous phase		ISORROPIA II	None present
Aqueous oxidation of SO ₂ ,		Schaap et al. (2004)	None present
Photolysis Rates		Dependent of lat/long, cloud cover and surface.	Based on a parameterisation.
Gaseous dry deposition Rates		Dependent on surface (land/sea)	Fixed values
NO ₂ & SO ₂ wet deposition Rates		McMahon et al. (1979) parameterisation	None Present
PM deposition rates	Smith et al. (1993) parameterisation	None present	
Back Trajectory Calculation	Lat/Long	Calculated using HYSPLIT	Calculated using BADC
	Mixing Depth	Calculated using HYSPLIT	Saw tooth fn
	Temperature	Calculated using HYSPLIT	Sinusoidal fn
	RH	Calculated using HYSPLIT	Sinusoidal fn
	Cloud Cover	Calculated using HYSPLIT	None present
	U10	Calculated using HYSPLIT	None present
	Rain (YY/MM/DD/HH/MM)	Calculated using HYSPLIT	None present

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Table 2. Simple statistics calculated using modeled and measured concentrations collected over the period from 02/04/2007 to 30/04/2007. Mean temperature 284.3 ± 2.3K and relative humidity of 71.8 ± 6.7 %. [* Values represent the measured monthly value only. ** The O₃ values represent the period when measured values were available, from 26/04/2007 to 19/05/2007].

Const- ituent	Unit	Field Values					PTM Values				
		<i>Min.</i>	<i>Lower quartile</i>	Geo. Mean	<i>Upper quartile</i>	<i>Max.</i>	<i>Min.</i>	<i>Lower quartile</i>	Geo. Mean	<i>Upper quartile</i>	<i>Max.</i>
NH_{3(g)}	ppb	-	-	6.95	-	-	0.14	3.95	6.11	9.8	22.1
NH₄⁺	μg/m ³	-	-	2.80	-	-	0	0	2.80	5.05	16.9
HNO₃	ppb	-	-	0.59	-	-	0	0.02	0.07	0.28	2.3
SO₂	ppb	-	-	0.99	-	-	0.02	0.12	0.27	0.63	15.9
HCl	ppb	-	-	0.26	-	-	0	0	0.01	0.04	0.99
Cl⁻	μg/m ³	0.13	0.26	0.56	1.10	3.40	0	0.43	0.67	1.42	4.16
NO₃⁻	μg/m ³	2.17	4.56	6.89	10.7	16.4	0.05	4.62	7.45	13.9	35.7
SO₄²⁻	μg/m ³	1.21	2.42	3.62	5.33	9.92	0.48	1.59	4.27	9.39	67.8
CO	ppb	-	-	-	-	-	123.6	150	177.1	200.8	528.5
NO	ppb	0.00	0.00	1.20	2.20	18.8	0.0	0.03	0.43	2.64	115.0
NO₂	ppb	0.00	3.67	7.03	9.98	37.1	0.47	2.46	3.78	5.93	20.2
O₃^{**}	ppb	7.6	24.4	28.7	36.7	62.1	0	15.8	23.0	28.4	46.3

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Table 3. Model performance metrics for the period from 19/03/2007 to 19/05/2007 using full days data. [N = number of complete pairs of measured and calculated values; MB = mean bias ($\mu\text{g}/\text{m}^3$); NMB = Normalised mean bias; MGE = mean gross error; NMGE = normalised mean gross error; FAC2 = A count fraction of points within 0.5 and 2 times the observation; RMSE = root mean square error ($\mu\text{g}/\text{m}^3$); r = Spearman's correlation coefficient; and IA = Index of Agreement.]

	<i>Chloride</i>	<i>Nitrate</i>	<i>Sulphate</i>
Observed Values			
<i>Arithmetic Mean</i>	1.10	6.75	3.90
<i>St dev</i>	1.02	6.23	2.60
Original Model Values			
<i>Arithmetic Mean</i>	-	2.96	1.73
<i>St dev</i>	-	4.99	4.11
<i>N</i>		58	58
<i>MB</i>	-	-3.93	-2.24
<i>MGE</i>	-	5.10	3.33
<i>NMB</i>	-	-0.59	-0.58
<i>NMGE</i>	-	0.76	0.86
<i>RMSE</i>	-	6.80	4.43
<i>FAC2</i>		0.18	0.11
<i>r (Spearman)</i>	-	0.57	0.55
<i>IoA</i>	-	0.88	0.86
Enhanced Model Values			
<i>Arithmetic Mean</i>	0.96	6.85	4.03
<i>St dev</i>	0.52	5.10	3.33
<i>N</i>	57	57	57
<i>MB</i>	-0.11	0.32	0.28
<i>MGE</i>	0.78	2.47	1.82
<i>NMB</i>	-0.10	0.05	0.07
<i>NMGE</i>	0.71	0.36	0.47
<i>RMSE</i>	1.06	3.94	2.51
<i>FAC2</i>	0.42	0.77	0.81
<i>r (Spearman)</i>	0.27	0.83	0.65
<i>IA</i>	0.9	0.96	0.95

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944 **Table 4. Observed changes in values of the Performance Metrics when each enhancement**
 945 **in the model is restored to its original setting.**
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<i>Enhanced Model Values minus...</i>	Δ (Arithmetic Mean)			Δ NMB		
	<i>Cl⁻</i>	<i>NO₃⁻</i>	<i>SO₄²⁻</i>	<i>Cl⁻</i>	<i>NO₃⁻</i>	<i>SO₄²⁻</i>
<i>HYSPLIT temp, RH, BLH values</i>	14%	10.0%	-8.2%	-0.08	-0.18	0.00
<i>Enhanced photolysis rates</i>	-7.4%	-17%	-0.5%	0.15	0.12	-0.09
<i>ISORROPIA II</i>	-	8.0%	0.9%	0.11	0.09	0.01
<i>Aqueous oxidation of SO₂,</i>	2.1%	2.7%	-30%	0.01	0.03	-0.33
<i>Trajectory dependent initial conditions</i>	4.3%	-0.3%	-26%	-0.02	-0.01	0.22
<i>NO₂ and SO₂ Stack height dependent emissions</i>	-2.1%	-1.9%	14%	0.03	0.00	-0.29
<i>Cloud cover dependent photolysis rates (sunny day scenario)</i>	-1.1%	6.4%	0.9%	-0.01	0.07	0.01

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950 **Table 5. Change of calculated species concentrations (%) resulting from precursor**
 951 **abatement (by 30%) on the calculated chloride, nitrate and sulphate concentrations. A**
 952 **comparison is made with the study of abatement figures shown in italics.**
 953

Precursor Abated	<i>Chloride</i>	<i>Nitrate</i>	<i>Sulphate</i>	Σ (chloride + nitrate + sulphate)	<i>PM₁₀</i>
<i>NH3</i>	-2.2	-5.1 (-12.2)	0.1 (0)	-3.1	-1.6
<i>NOx</i>	-0.6	-17.7 (-14.8)	1.9 (2.3)	-8.5	-3.7
<i>SO2</i>	0.8	2.5 (3.5)	-20.8 (-14.8)	-6.1	-2.3

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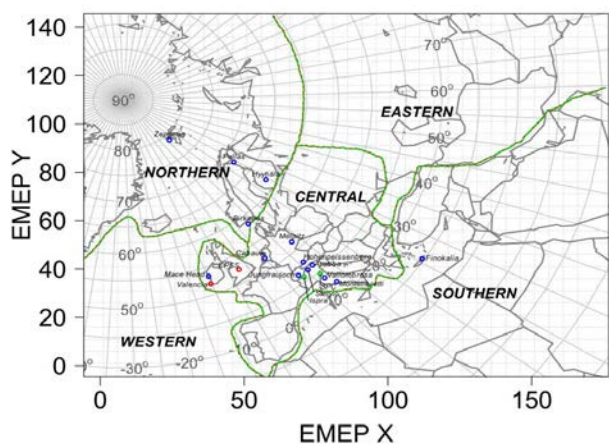
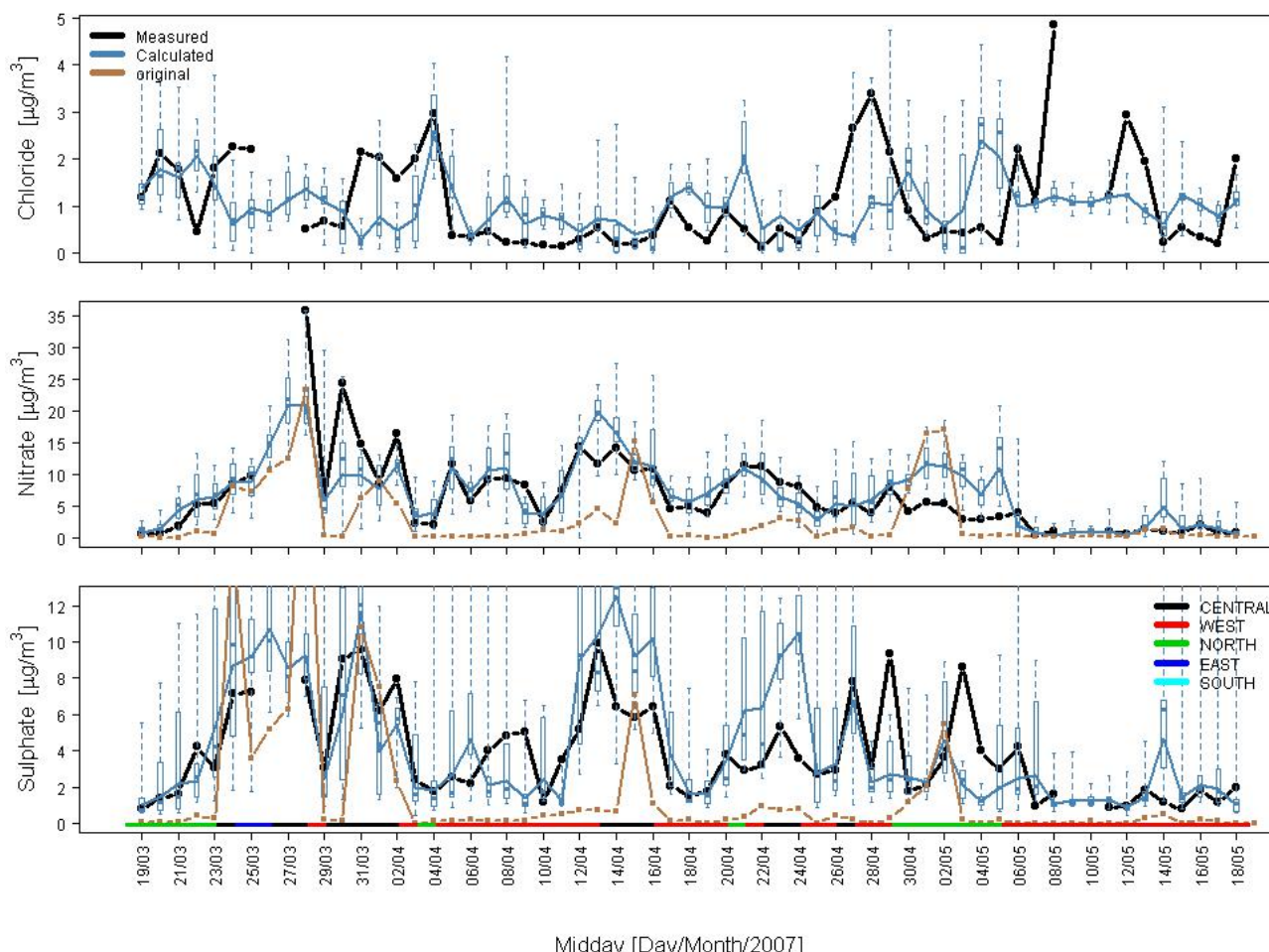


Figure 1. Boundaries separating the Northern, Eastern, Southern, Western and Central Regions of Europe. Initial concentrations are specified for each region and are used as initial conditions in each calculation depending on which region the trajectory starts.

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Figure 2. Comparison between calculated and measured PM₁₀ chloride, nitrate and sulphate. Measurements (black line) were made with a Rupprecht and Patashnick Partisol 2025 sampler with PM₁₀ sampling inlet. The calculated data is depicted by the blue whisker plots derived from the statistics of each group of 24 hourly calculated values. The middle horizontal line represents the median; the two hinges represent the first and third quartile; and the two whiskers represent the maximum and minimum values. Also included are the results shown by the brown line from the initial PTM model. (Referring to Figure 1, the coloured ribbon at the bottom of each plot shows the zone from which the trajectory used in the calculation started.)

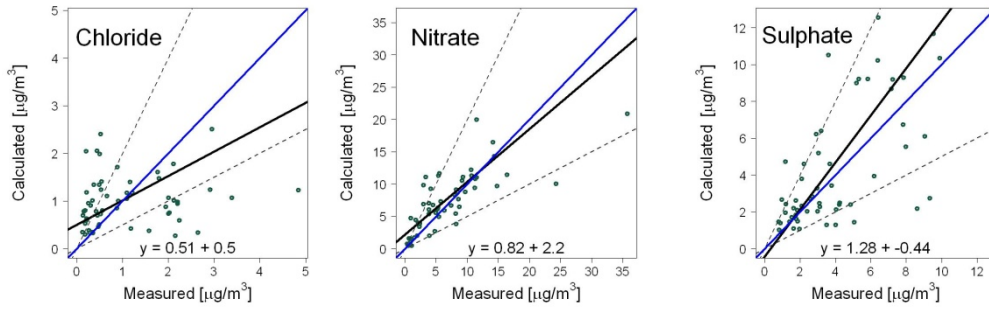


Figure 3. Comparison between calculated and measured PM₁₀ chloride, nitrate and sulphate. Measurements made with a Rupprecht and Patashnick Partisol 2025 sampler with PM₁₀ sampling inlet. The data is fitted using the Reduced Major Axis method (Ayers, 2001), indicated by the solid black line and equation. Also included on these correlation plots is the ideal case of a 1:1 correlation marked out by the blue line and the boundaries where the calculated values are twice or half the value of the measured values (dashed lines).