AIRPACTS

EQUATIONS FOR IMPACT AND DAMAGE COST ASSESSMENTS

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For the:

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Addendum to the AirPacts manual
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CONTENTS

IMPACT ASSESSMENT MODELS IN AIRPACTS

Introduction

The AirPacts suite of programs enables the user to obtain a preliminary estimate of the physical impacts and associated damage costs to human health, agricultural crops and man-made materials arising from exposure to atmospheric emissions of the following pollutants: particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NOx), carbon monoxide (CO), and secondary species such as nitrate and sulfate aerosols. *Primary* pollutants are those emitted at the source, meanwhile *secondary* pollutants are those created downstream of the source location as a result of chemical reactions involving species resident in the surrounding atmosphere. The assessment methodology that is employed is based on the Impact Pathways Analysis (IPA), also known as the Damage Function Approach (DFA).

Impacts are characterized in physical terms (e.g., number of asthma attacks) by using Exposure Response Functions (ERF). For public health impacts, the ERF is linear without thresholds. Meanwhile, for damages to crops and materials, the ERF is non-linear. For agricultural products, it is even possible to have a "benefit" (negative impact estimates and damage costs) from increasing the background concentration of certain pollutants, like sulfur dioxide (SO_2). Impacts are monetized by multiplying the number of cases by the unit costs (e.g., US$ per asthma attack). Damages are aggregated over all downstream receptors affected by a pollutant.

In the Simple Uniform World Model (SUWM) assessment, the local details are ignored in the analysis. But, the local impact may account for 75% or more of the total damage if the source happens to be located close to a large city. In the current version of AirPacts, different adjustments to the SUWM have been implemented to improve the modeling of the local impact. The level of input information has been kept to a minimum, consistent with the simplified impact assessment philosophy. A brief description of the four models included in the AirPacts package is provided below.

QUERI Model

Model assesses the respiratory impacts to *human health* and their associated damage costs due to primary (particles, SO_2, NOx, CO) and secondary (nitrate and sulfate aerosols) pollutants present in the air. The model uses a semi-empirical approach in which correlations derived from existing IPA studies are used to approximate the impacts.

RUWM Model

Model approximates the physical impacts and costs to *human health* from exposure to primary and secondary atmospheric species. By contrast to QUERI, the RUWM model uses different simplifying assumptions to solve analytically the damage function equation. In the assessment, it is assumed that the local and regional populations are uniformly distributed throughout the appropriate impact domain. The meteorological data for the local scale refer to average or typical conditions and assume a uniform windrose.

URBAN Model

Model estimates the *human health* impacts and monetary costs due to air emissions from a source located near a city. Damages associated with primary and secondary pollutants can be assessed. Weather data for the local scale correspond to mean conditions and assume a uniform windrose. Local population data can be specified using actual values (5 by 5 km^2 resolution) or the distribution can be approximated using a Gaussian-shaped function.

AGRIMAT Model

Assesses the impacts to *crops* and *materials* and the resulting economic costs from exposure to SO_2 (excluding wet deposition). Currently, the model can approximate the damages to the following receptor types:

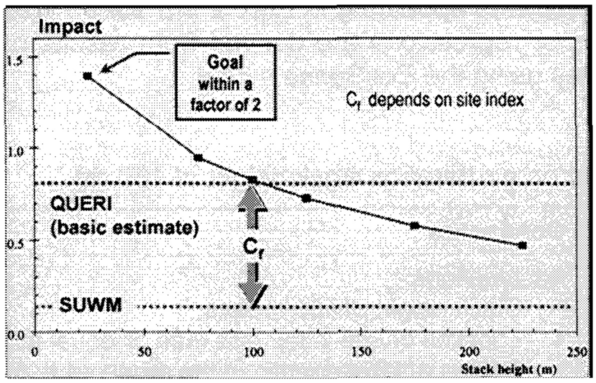
Agricultural crops: Barley, Oats, Potatoes, Rye, Sugar Beets and Wheat

Building materials: Galvanized steel, Limestone, Natural stone, Paint, Sandstone, Zinc.

QUERI MODEL

Basic estimate – Primary pollutants

Impact assessment models in AirPacts – QUERI
Impact assessment approaches for "primary" pollutants
Basic estimate



Objective

The goal is to multiply the Simple Uniform World Model (SUWM) impact estimate by a scaling factor that depends only on source location so that the deviation between the predicted impact using a complex analysis (the solid curve in the above figure) and the *adjusted* SUWM impact estimate is less than a factor of two over the entire stack height range of interest (25 to 300 m). Source location is characterized by the Location or Site index parameter (see below).

Impact equations

The SUWM impact estimate is scaled using the factor C_f so that the adjusted estimate (empirical solution) matches exactly the complex analysis impact curve shown in the above figure at a stack height of 100 meters. The impact curve has been calculated using the following input reference (Ref) data:

Regional population density ($\rho_{Regional\_Ref}$):	80 persons/km^2;
Pollutant depletion velocity (k_{Ref}):	0.67 cm/s;
Exhaust flue gas temperature (T_{Ref}):	413 K;
Exhaust flue gas flow (F_{Ref}):	61.126 Nm^3/s.

The Basic estimate is the product $C_f \times$ SUWM. The expression for the (SUWM) is:

$$SUWM = \frac{Q\,\rho_{Regional}\,f_{ERF}}{k} \quad . \qquad (1)$$

Q being the pollutant emission rate, $\rho_{Regional}$ is the regional population density, f_{ERF} is the slope of the exposure-response function (ERF) and k is the pollutant depletion velocity, which includes pollutant removal by deposition (dry and wet) and chemical transformation.

The coefficient C_f is calculated using the equation:

$$C_f = C_h \times C_t \times C_g \times C_p \times C_k \; . \qquad (2)$$

The expressions for the various coefficients appearing in Eqn. 2 are summarized in the tables that follow. Individual values or regressions are derived from results based on actual case studies for European sites using the EcoSense model.

Table 1: *Coefficient C_h* (estimate based on a reference stack height of 100 m)

Expression or value	Comments
$C_h = 0.7972 \times \left(\frac{\rho_{Local}}{\rho_{Regional}} \right)^{0.7912}$	*Assumptions*: ▪ Stack height of 100 meters; ▪ Location or site index less than or equal to 3; ▪ Radius of local domain in the range 44 to 56 km; ▪ Range of applicability: ρ_{Local} to $\rho_{Regional}$ = 0.5 to 15. *Input information*: User must enter either the local population distribution (5 by 5 km resolution) or the local population density ρ_{Local}. AirPacts will calculate the value ρ_{Local} if the population distribution is specified.
C_h = 0.62 (Site index = 0) C_h = 2.44 (Site index = 1) C_h = 4.29 (Site index = 2) C_h = 6.10 (Site index = 3) C_h = 4.14 (Site index = 4) C_h = 2.22 (Site index = 5) C_h = 1.69 (Site index = 6)	*Assumptions*: ▪ Stack height of 100 meters. *Input information*: No local population statistics are available.

Table 2: *Coefficient C_t* (adjust reference estimate for differences in flue gas temperature)

Expression or value	Comments
$C_t = a \times \left(\frac{Exhaust\ Temperature}{T_{Ref}} \right)^{b}$ Site index = 0 a = 1.02; b = -0.2446 Site index = 1, 2, 4, 5 or 6 a = 1.02; b = -0.4288 Site index = 3 a = 1.05; b = -0.6	*Assumptions*: ▪ Stack height of 100 meters; ▪ Reference flue gas exhaust temperature is 413K; ▪ Range of applicability: 300-600 K. *Input information*: User must enter a value for the exhaust temperature otherwise C_t is assigned a value of 1.

Table 3: *Coefficient C_g* (adjust reference estimate for differences in exhaust flue gas flow)

Expression or value	Comments
$$C_g = \left(\frac{Exhaust\ Flow}{F_{Ref}} \right)^b$$ Site index = 0 b = -0.0568 Site index = 1, 2, 4, 5 or 6 b = -0.1034 Site index = 3 b = -0.1507	*Assumptions*: ▪ Stack height of 100 meters; ▪ Reference flue gas exhaust flow is 61.126 Nm^3/s; ▪ Range of applicability: 30-120 Nm^3/s. *Input information*: User must enter a value for the exhaust flue gas speed and temperature, the inner stack diameter at the height of release (these variables are used to calculate the normal flue gas flow rate). If these values are not available, C_g is assigned a value of 1.

Table 4: *Coefficient C_p* (adjust reference value for regional population density differences)

Expression or value	Comments
$$C_p = \left(\frac{\rho_{Regional\_Ref}}{\rho_{Regional}} \right) \times \left[\gamma_{Local} + (1-\gamma_{Local}) \times \left(\frac{\rho_{Regional}}{\rho_{Regional\_Ref}} \right) \right]$$ γ_{Local} is the local impact as a fraction of the overall impact estimate.	*Assumptions*: ▪ Stack height of 100 meters; ▪ Reference regional population: 80 pers/km^2. *Input information*: If the value of ρ_{Local} or the local population distribution is available, the parameter γ_{Local} is estimated using the relationship: $$\gamma_{Local} = 0.2574 \times \left(\frac{\rho_{Local}}{\rho_{Regional}} \right)^{0.4715}.$$ This equation assumes a radius of 44 to 56 km for the local domain, and has a range of applicability ρ_{Local} to $\rho_{Regional}$ = 0.5 to 15. If local population statistics are not available, γ_{Local} is approximated using the Site index parameter as summarized below: γ_{Local} = 0.22 (Site index = 0) γ_{Local} = 0.50 (Site index = 1) γ_{Local} = 0.73 (Site index = 2) γ_{Local} = 0.84 (Site index = 3) γ_{Local} = 0.76 (Site index = 4) γ_{Local} = 0.54 (Site index = 5) γ_{Local} = 0.41 (Site index = 6).

Table 5: *Coefficient C_k* (adjust reference value for depletion velocity differences)

Expression or value	Comments
$$C_p = \left(\frac{k}{k_{Ref}} \right) \times \left[\gamma_{Local} + (1-\gamma_{Local}) \times \left(\frac{k_{Ref}}{k} \right) \right]$$ γ_{Local} represents the fraction of the overall impact allocated to the local domain.	*Assumptions*: ▪ Stack height of 100 meters; ▪ Reference depletion velocity is 0.67 cm/s. *Input information*: See Table 4 comments.

Damage cost equation

The damage cost is the product of the unit cost per incidence U_v and the impact estimate calculated from the previous section (annual number of cases), namely

$$\text{Damage} = U_v \times \text{Impact} . \tag{3}$$

Uncertainty range

The 68% confidence interval of the damage cost assessment is estimated using Eqn. 4, which refers to a lognormal distribution. In applying this relationship, it is assumed that the geometric median is equal to the damage cost result calculated in Eqn. 3. Values for the geometric standard deviation parameter σ_G are, respectively, 3, 6, 4 and 6 for health morbidity cases, short-term or acute mortality, long-term or chronic mortality and incidences of fatal cancer.

$$Uncertainty\ interval = \left[\frac{Damage\ cost}{\sigma_G},\ Damage\ cost \times \sigma_G\right] \tag{4}$$

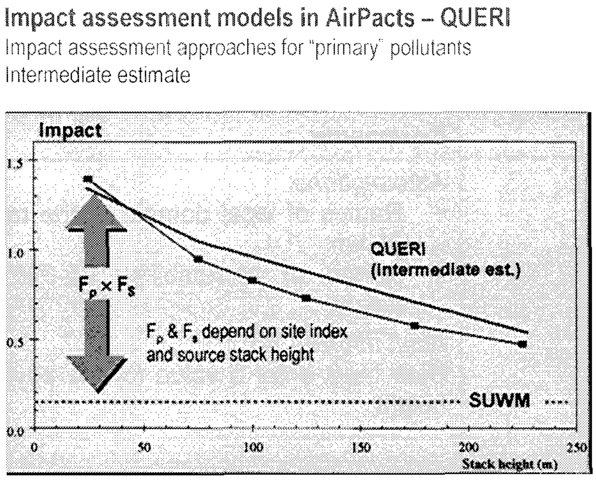
Additional notes

- The slopes of the exposure response functions f_{ERF} are summarized in Table 1 to 3 in the document InputDataERF.pdf; depletion velocities k for different locations around the world are reported in Table 2.3 in the document ImpactMethodology.pdf, and unit costs U_v are given in Table 1 in the document InputDataMonetary.pdf.
- A procedure for estimating depletion velocities is discussed in the report ImpactMethodology.pdf, Section 2.2 – The Simplified Approach.
- Below is a table of definitions of the Location or Site indices mentioned in the previous tables.

Site index	**Comments**
0	Source located in a rural area or country site (ratio of local to regional population density less than 2)
1	Source within a few km of a small-sized city, ex. Stuttgart in Germany (ratio of local to regional population density less than 6)
2	Source within a few km of a medium-sized city, ex. Milano in Italy (ratio of local to regional population density less than 10)
3	Source within a few km of a large city, ex. Paris in France (ratio of local to regional population density greater than 10)
4	Source lies between 15 and 25 km distant from a large city
5	Source lies between 25 and 40 km distant from a large city
6	Source located more than 40 km distant from a large city
0 or 1	Source located on a small island, ex. Crete in Greece, or near a large water body (ocean or lake), or close to a city surrounded by unpopulated areas, ex. Finland in Europe

NB, The receptor densities for the local (typically, less than 50 km from the source) and regional (beyond 50 km) domains are the number of persons at risk from exposure to air pollution divided by the appropriate land and water surface area. The source is always located at the origin. The regional domain size can be estimated using Eqn. (18) on page 30 in ImpactMethodology.pdf.

Intermediate estimate – Primary pollutants



Objective

The objective of the Intermediate approach is to include the influence of the physical stack height on the impact result.

Impact equations

For the Intermediate estimate, the product $F_s \times F_p$ replaces the coefficient C_h. The factor F_s takes into account the variability of the impact for changes in stack height when the local and regional population densities are maintained at the same level. The influence of population density, on the other hand, is included in the parameter F_p. Coefficients F_s and F_p are determined by regression analysis using as input data the results from detailed impact assessments calculated with the EcoSense model for various European sites. The reference conditions assumed for the Basic case are also employed for the Intermediate estimate.

The Intermediate estimate is calculated as follows:

$$\text{Intermediate impact estimate} = (F_s \times F_p \times C_t \times C_g \times C_p \times C_k) \times \text{SUWM} . \qquad (5)$$

The coefficients C_t, C_g, C_p and C_k were defined in Tables 2 through 5; and the mathematical expression for the Simple Uniform World Model was given in Eqn. 1. Expressions for the parameters F_s and F_p are listed in Tables 6 and 7, respectively.

Table 6: *Coefficient F_s*

<table>
<tr><th>Expression or value</th><th>Comments</th></tr>
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$F_s = a \times (stack\ height)^b$

Site index	a	b
0	2.94	-0.206
1	1.52	-0.076
2	1.38	-0.560
3	1.47	-0.071
4	1.40	-0.060
5	1.50	-0.074
6	1.52	-0.076

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Assumptions:
- Radius of local domain in the range 44 to 56 km;
- Range of applicability: 25-300 m stack height.

Input information:
User must enter a value for the physical stack height.

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Table 7: *Coefficient F_ρ*

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$F_\rho = a \times (stack\ height)^b \times C_{ST}$

$$C_{ST} = \frac{\left[\gamma_{Local} \times \rho_{Local} + (1-\gamma_{Local}) \times \rho_{Regional}\right]_{New\ location}}{\left[\gamma_{Local} \times \rho_{Local} + (1-\gamma_{Local}) \times \rho_{Regional}\right]_{Reference\ location}}$$

The coefficient C_{ST} is the ratio of population-weighted densities over the local and regional domains at the user specified location and at a reference site located in Europe. C_{ST} is a "site-transfer" coefficient that permits the impacts at *Reference location* to be transferred to *New location* after adjusting for differences in the local and regional population densities between the two sites. The value for $\rho_{Regional\_Ref}$ is 80 persons/km^2. Values of a, b and *Reference* coefficients of γ_{Local} and ρ_{Local} are indicated below:

Site index	a	b	γ_{Local_Ref}	ρ_{Local_Ref}
0, 1, 2, 6	4.35	-0.153	0.50	424
3	30.40	-0.374	0.84	1013
4	11.90	-0.248	0.76	993
5	3.93	-0.141	0.54	692

The coefficient γ_{Local} at the New location is calculated according to the rules specified in Table 4.

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Assumptions:
- Radius of local domain is in the range of 44 to 56 km;
- Range of applicability: 25-300 m stack height.

Input information:
User must enter a value for the physical stack height. If no local population statistics are available (ρ_{Local}), AirPacts will approximate the local population density ($\rho_{Local\_assumed}$) using the Site index specified by the user and a reference local population density for a European location having the same Site index. Specifically, with $\rho_{Regional\_Ref}$ = 80 persons/km^2:

$$\rho_{Local} = \rho_{Local\_assumed} = \rho_{Local\_Ref} \times \left(\frac{\rho_{Regional}}{\rho_{Regional\_Ref}}\right).$$

Site index	ρ_{Local_Ref}
0	56 persons/km^2
1	424
2	559
3	1013
4	993
5	692
6	362

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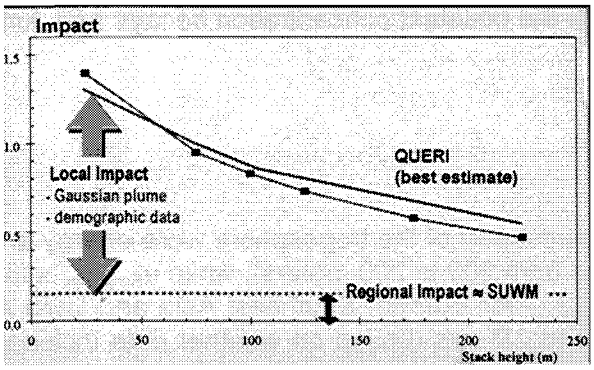
</table>

Best estimate – Primary pollutants

Impact assessment models in AirPacts – QUERI
Impact assessment approaches for "primary" pollutants
Best estimate



Objective

The purpose in the Best estimate approach is to improve the assessment of the local impact by carrying out a detailed Gaussian model dispersion of the pollutant locally. This necessitates complete information on local weather conditions and of stack characteristics, including stack height and exit diameter, exhaust flue gas temperature and flow rate.

Impact equations

The local impact is estimated using a Gaussian plume model for calculating the local concentration profile and a detailed local population distribution having a resolution of 5 by 5 km covering a square surface area of 10,000 km^2. AirPacts uses the US EPA Industrial Source Complex (ISC) Long-Term Gaussian model (version 3). The emitting source is located in the center of the domain, where the origin of the coordinate system is fixed. Concentrations are calculated at the centroids of each 5 by 5 km cell. Detailed meteorological data are needed, preferably hourly values, for ambient temperature, wind speed and wind direction. If known, atmospheric stability class (Pasquill class) and mixing height data should be included as part of the input meteorological datafile. In the present version of AirPacts, for simplicity sake, it is assumed that the surrounding topography is mostly flat terrain and pollutant removal by deposition and chemical transformation events are negligible. However, correction factors for including the influence of complex terrain or local pollutant removal are available and may be applied outside of the AirPacts program to adjust the local impact estimate (see the file AirPactsSlideShow.pdf).

Eqn. 6 shows how AirPacts calculates the local impact.

$$Local\ impact = \sum_{j=1}^{400} (Population\ 5x5\ km\ cell)_j \times f_{ERF} \times (Concentration)_j \tag{6}$$

Across the regional domain, pollutant removal by deposition (dry and wet removal) and chemical activity is characterized by the pollutant depletion velocity k. Values for various locations or areas are summarized in Table 2.3 in the documentation file ImpactMethodology.pdf. The pollutant decay constant is defined in Eqn. 7. This coefficient specifies the rate at which the pollutant concentration decays as a function of downwind distance (km).

$$Decay\ constant = \frac{k}{u_{Regional} \times h_{mix}} \tag{7}$$

h_{mix} is the mixing layer height, the lowest part of the troposphere were energy and mass transfer occurs (typically, h_{mix} ranges from 200 to 200 meters), while $u_{Regional}$ is the mean regional wind speed. Values of $u_{Regional}$ for Europe, Southeast Asia and Latin America are, respectively, 5.5 m/s, 3.7 m/s and 2.7 m/s (based on weather data included in the EcoSense model). For other areas, AirPacts assumes a value of 3.8 m/s.

The regional impact estimate is obtained by integrating the SUWM cumulative impact distribution curve for a uniform windrose from R_{Local}, the effective circular radius of the local domain (56 km), to infinity. The cumulative impact distribution curve and the regional impact estimate are shown below in Eqn. 8.

$$\begin{aligned} &SUWM\ Cumulative\ impact\ distribution = 1 - Exp\left(-Decay\ constant \times Downwind\ distance\right) \\ &Regional\ impact = SUWM \times Exp\ (\,-Decay\ constant \times Radius_{Local}) \end{aligned} \tag{8}$$

The total impact is the sum of local and regional impact estimates.

Impact estimate – Secondary pollutants

Secondary pollutants are those species created in the atmosphere by chemical transformation involving contaminants emitted directly into the air at the source location and reactants present in the atmosphere (see ImpactMethodology.pdf). Creation of secondary pollutants usually occurs a few tens of kilometers downwind of the source, consequently near-source weather conditions, demographic distribution and stack parameters have a much smaller influence on the total impact assessment. In fact, most of the damage attributable to secondary species is distributed across the regional domain, where the mean population density is $\rho_{Regional}$.

Pollutant removal is characterized by the *effective* depletion velocity k_{eff}, which includes atmospheric removal by dry and wet deposition of the secondary pollutant and chemical transformation from primary or precursor to secondary species. A list of effective depletion velocities for nitrate and sulfate aerosols is available in Table 2.3 in the document ImpactMethodology.pdf. NOx and SO_2 are the precursors of nitrate and sulfate species, respectively.

AirPacts approximates the impact on human health from exposure to secondary species by using the SUWM relationship presented in Eqn. 9.

$$Impact\ secondary\ species = \frac{Q_{Precursor}\ \rho_{Regional}\ f_{ERF}}{k_{eff}} \tag{9}$$

$Q_{Precursor}$ is the precursor pollutant emission rate.

RUWM MODEL

Basic estimate – Primary pollutants

The Basic impact estimate in RUWM is calculated in the same way as done for the QUERI model (Eqns. 1 through 4; and Tables 1 through 5).

Intermediate estimate – Primary pollutants

WORK IN PROGRESS

(for further information, see AirPactsSlideShow.ppt and ImpactMethodology.pdf)

Best estimate – Primary pollutants

WORK IN PROGRESS

(for further information, see AirPactsSlideShow.ppt and ImpactMethodology.pdf)

Impact estimate – Secondary pollutants

Health impacts from exposure to secondary pollutants are calculated using the same procedure as outlined for the QUERI model (Eqn. 9).

URBAN MODEL

Basic estimate – Primary pollutants

The Basic impact estimate in URBAN is calculated in the same way as done for the QUERI model (Eqns. 1 through 4; and Tables 1 through 5).

Best estimate – Primary pollutants

WORK IN PROGRESS

(for further information, see AirPactsSlideShow.ppt)

Impact estimate – Secondary pollutants

Health impacts from exposure to secondary pollutants are calculated using the same procedure as outlined for the QUERI model (Eqn. 9).

AGRIMAT MODEL

WORK IN PROGRESS

(for clearer presentation, click on Help button in AGRIMAT.xls)

INTRODUCTION

The AGRIMAT model assesses the impacts to agricultural crops and to building materials (man-made environments) and the resulting economic costs from atmospheric exposure to SO_2, not including wet deposition. Currently, the model can approximate the damages to the following type of receptors.

Agricultural crops → Barley, Oats, Potatoes, Rye, Sugar Beets and Wheat;
Building materials → Galvanized steel, Limestone, Natural stone, Paint, Sandstone and Zinc.

Damage assessments may be carried out separately for crops and materials.

Input data requirements

* Background SO_2 concentrations in $\mu g/m^3$ (**mandatory data**);
* Background ambient temperature in Kelvins (mandatory data for material damage assessment);
* Background relative humidity in % (mandatory data for material damage assessment);
* SO_2 emission rate in tons/year and depletion velocity in cm/s (**mandatory data**);
* Receptor distributions across the impact domain:
  Crops as annual production in tons (mandatory data for crop assessment);
  Materials as m^2 of exposed surface (mandatory data for material assessment);
* Monetary unit costs in US$ per ton of crop (market losses) or US$ per m^2 of damaged surface (repair costs); **these data are optional;**
* **User case study comments are optional.**

NB. (a) Input data can be specified for the entire impact domain (2000 x 2000 km area about the source) or for any portion(s) thereof.
(b) For materials, one may assume that the stock at risk is proportional to the population density for the area in question.

REGIONAL CONCENTRATIONS

Incremental concentrations at the regional scale $C_{Regional}$ are calculated using the equation displayed below

$$C_{Regional} = \frac{Q}{2\pi u\, h_{mix}\, r}\ exp\left(-\frac{k}{u\, h_{mix}}\, r\right) \qquad \textbf{(1)}$$

Here, Q is the pollutant's annual emission rate (kg/s), u the mean wind speed at stack height (m/s), h_{mix} the mixing layer height (m), r the downwind distance from source (m) and k the pollutant's depletion velocity (m/s). In the SI base unit system, $C_{Regional}$ is expressed in kg/m^3. In AGRIMAT, u and h_{mix} have the default values of 4 m/s and 560 m (corresponding to neutral atmospheric dispersion conditions or Pasquill D class), respectively. The grid resolution for calculating the incremental concentrations is 100 by 100 km, with the emission source located at the origin. Concentrations are calculated at the centroid of each cell. For SO_2, the depletion velocity range for selected sites around the world is 0.7 to 2.1 cm/s (see Table 2.3, page 24 in ImpactMethodology.pdf). **User input data include the variables Q and k.**

EXPOSURE RESPONSE FUNCTIONS

Exposure Response Functions (ERFs) relate the impact to a receptor at risk (in this case, different crops or building materials) to a change in the atmospheric concentration of a particular pollutant (in this case, SO_2). For both crops and building materials, the ERFs are non-linear relationships, whcih depend on the background SO_2 concentration at the location of exposure and other meteorological parameters, including background temperature, relative humidity, precipitation and ambient pH level. For crops, a benefit (negative damages) is possible when the background SO_2 concentration is sufficiently low ($< 19\ \mu g/m^3$).

Agricultural Crops

Impacts to agricultural crops from exposure to particulates

None observed.

Impacts to agricultural crops from exposure to NOx

NOx acts as a fertilizer up to high doses.

Impacts to agricultural crops from exposure to Ozone

Exposure to tropospheric ozone (O_3) levels has by far the greatest impact to agricultural crops. For more information, double click on the files below. To read these documents, you must have installec the Adobe Acrobat Reader.

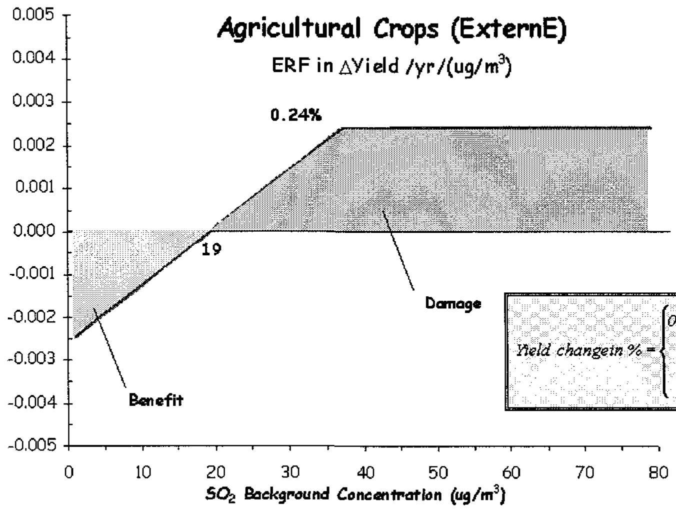
Mauzerall et al., (2001) | ExternE 1998 Ozone Damages | Rabl and Eyre (1998)

Impacts to agricultural crops from exposure to SO_2

The exposure response function (ERF) that has been implemented in the AGRIMAT Model is the relationship recommended by the specialists of the ExternE Study of the European Commission (ExternE 1998). The ERF has been widely used in Europe to assess the impacts to crops from exposure to sulphur dioxide (SO_2). The function (see graph below) has been applied to the following agricultural crops: Barley, Oats, Potatoes, Rye, Sugar beets and Wheat. For other types of crop and other pollutants (such as Ozone, for example), different ERFs apply.

In the figure, the impact to crops is measured as a change in annual yield (or production) per change in SO2 background concentration (measured in ug/m^3). The ERF is non-linear (i.e., the slope is not constant over the entire SO_2 interval). In fact, below 19 ug/m^3, the slope increases steadily from -0.0025 (a benefit!) to a value of 0 (which represents no change in yield) with increasing SO_2 background concentration. Above 19 ug/m^3, the slope remains constant at a value of +0.0024 loss in annual yield for each ug/m^3 increment in SO_2 concentration in the atmosphere. In contrast to crops, the potential of a benefit from increased airborne pollution has not been observed for other receptors, such as human health, building materials and forests. To learn more, double click on the file below.

ExternE 1998 Ecosystem Damage



Source: Based on ExternE 1998

$$\text{Yield change in } \% = \begin{cases} 0.0067\,C_{SO2,back}^2 - 0.259\,C_{SO2,back} & \text{for } C_{SO2,back} \le 39\ \mu g/m^3 \\ 0.241\,C_{SO2,back} - 9.35 & \text{for } C_{SO2,back} > 39\ \mu g/m^3 \end{cases} \quad (2)$$

where,

$C_{SO2,back}$ = Background SO_2 concentration in $\mu g/m^3$

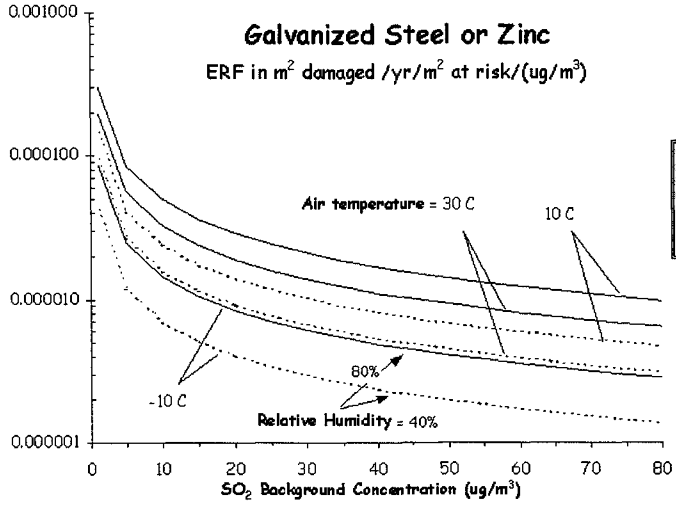
NB, a positive value means a damage, whereas negative numbers correspond to a benefit (*fertilizer effect*).

Building Materials

The 'Simplified' ERFs for several types of building materials (also referred to as man-made environments) are illustrated below. The relationships have been derived from data collected in Europe in the mid 1990s by Tidblad and colleagues at the Swedish Corrosion Institute in Sweden (Tidblad et al., 1998), and have been extensively used in the latest ExternE Study (ExternE 1998). **The 'Simplified' functions allow for the quantification of the impacts from direct ambient exposure to SO_2.** The impacts from wet deposition are typically greater than those calculated from direct exposure only, but simplification of the relevant ERF is not so simple, and has not been considered here for the moment.

As can be observed in the various figures, the relationships are non-linear, with strong dependence on background ambient temperature (measured in Celsius degrees), local relative humidity (%) and SO_2 concentration (in $\mu g/m^3$). The ERFs have units of m^2 of damaged surface area per year per m^2 of stock at risk and per unit change in SO_2 concentration ($\mu g/m^3$). The slope of the ERF is also a function of the maintenance time period between repairs, which can vary greatly depending on the type material, meteorological conditions and local cleaning practices. Typical values in Europe for galvanized steel (or zinc), limestone and sandstone (or natural stone) are 10, 15 and 12 years, respectively. To learn more, double click on the file to the right.

ExternE 1998 Material Damage



$$ERF\ slope = \frac{10^{-4}\, C_{SO_2,back}^{-0.78}\, exp\,[0.018\, RH_{back} + b\,(T_{back} - 10)]}{\tau^{0.15}}$$

$$b = 0.062\ (T_{back} \leq 10\ C)\ \text{or}\ -0.021\ (T_{back} > 10\ C); \quad \tau \sim 10\ \text{years}$$

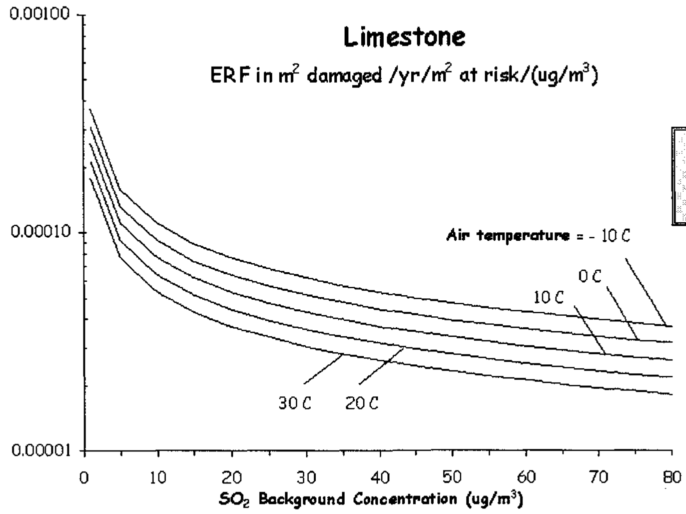
where, (3)

$C_{SO2,back}$ = Background SO_2 concentration in $\mu g/m^3$

RH_{back} = Background relative humidity in %

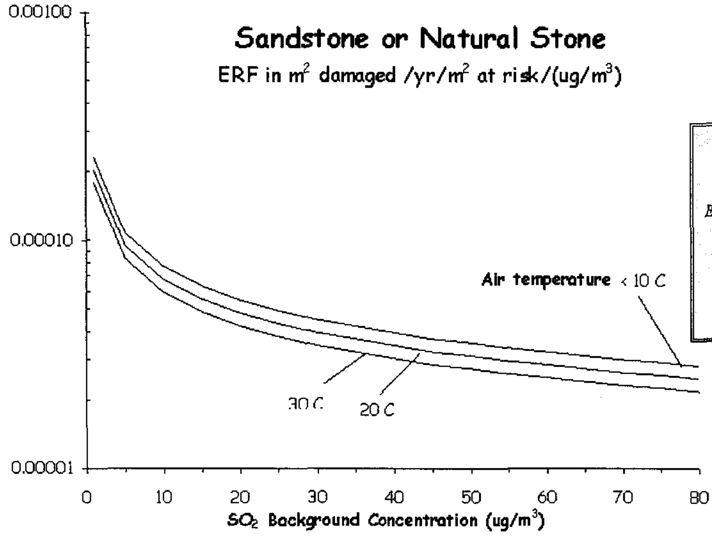
T_{back} = Background ambient temperature in °C

τ = Maintenance time period in years



$$ERF\ slope = \frac{3.4 \times 10^{-4}\, C_{SO_2,back}^{-0.52}\, exp\,[-0.018\, T_{back}]}{\tau^{0.04}}; \quad \tau \sim 15\ \text{years}$$

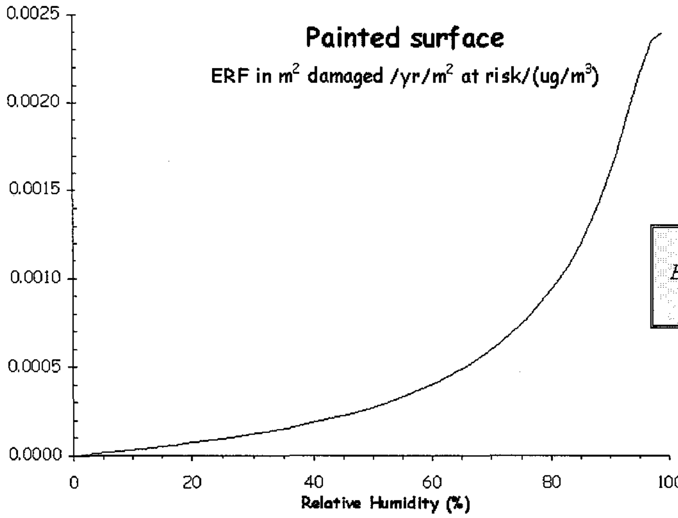
(4)



$$ERF\ slope = \begin{cases} \dfrac{2.9\times10^{-4}\ C_{SO_2,back}^{-0.48}}{\tau^{0.09}} & T_{back} \le 10\ C \\ \dfrac{2.9\times10^{-4}\ C_{SO_2,back}^{-0.48}\ exp\,[-0.013\,(T_{back}-10)]}{\tau^{0.09}} & T_{back} > 10\ C \end{cases}$$

$\tau \sim 12$ years

(5)



Source: Based on Tidblad et al., (1998)

$$ERF\ \ slope = 24\times10^{-4}\left(1 - exp\left[-\frac{0.121\,RH_{back}}{100 - RH_{back}}\right]\right)$$

(6)

IMPACTS AND DAMAGE COSTS

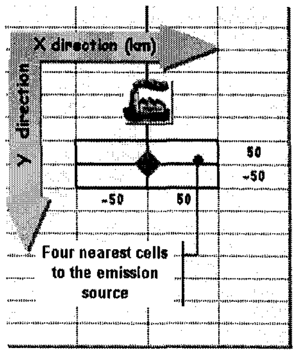
Impacts and damage costs are evaluated using Eqns. (7) and (8).

$$Impact = \sum_{domain} C_{Regional} \times ERF\ slope(SO_{2,back}\,;T_{back}\,;RH_{back}\,;\tau) \times Receptors\ at\ risk \qquad (7)$$

$$Damage\ cost = Impact \times Monetary\ unit\ cost \qquad (8)$$

For a more detailed local assessment (nearest four cells about the emission source; corresponding roughly to a circular area of radius 100 km), the incremental air concentrations C_{Local} for an emission source located at the origin and emitting at an annual rate equal to Q can be estimated using a Gaussian plume model:

$$C_{Local} = \frac{Q}{\sqrt{2}\,\sqrt[3]{\pi}\,u\,\sigma_Z}\ \frac{1}{r}\ exp\left(-\frac{h_E^2}{2\,\sigma_Z^2}\right) \qquad (9)$$



h_E is the effective stack height (actual stack + plume rise) and σ_z is the vertical dispersion coefficient. For the details, read:
For additional details, read: ImpactMethodology.pdf (starting on p. 34) or SensitivityAnalyses.pdf (Section 3)

The improved impact estimate $Impact_{Improved}$ is given by:

$$Impact_{Improved} = Eqn(7) - Impact\ results\ from\ four\ nearest\ cells\ about\ source$$

$$+ \sum_{local\ domain} C_{Local} \times ERF\ slope(SO_{2,back}\,;T_{back}\,;RH_{back}\,;\tau) \times Receptors\ at\ risk$$

$$= Regional + Local\ impact \qquad (10)$$

Differences between Eqns. (7) and (10) are greatest when the local receptor distribution is rather high compared to the regional values. For example, when calculating impacts to building materials for a city close the to the emission source location.

Monetary Unit Costs

Below are summarized the unit values for crops and materials as recommended by the ExternE project of the EC.

Agricultural crops
(market costs in US$$_{2000}$ per ton of produce)

Barley	66
Oats	69
Potatoes	101
Rye	192
Sugar beets	59
Wheat	119

Building materials
(maintenance costs in US$$_{2000}$ per m^2 of surface)

Galvanized steel	34
Limestone	314
Natural stone	314
Paint	14
Sandstone	314
Zinc	28

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SUMMARY OF INPUT DATA REQUIREMENTS

Parameter	SUWM	QUERI			RUWM		URBAN
		Basic[a]	Intermediate	Best	Intermediate	Best	Best
Local characteristics							Applies to urban sites only
o Urban or rural location		✓	✓	✓	✓	✓	
o Receptor density		‡	✓		✓	✓	
o Receptor data (5 by 5 km^2)		†	†	✓	†	†	✓
Regional characteristics							
o Receptor density	✓	✓	✓	✓	✓	✓	✓
Local weather data							
o Mean wind speed						✓	✓
o Mean ambient temperature						✓	✓
o Pasquill class distribution						✓	✓
o Detailed hourly data				✓		§	§
Stack data							
o Height			✓	✓		✓	✓
o Exit diameter				✓		✓	✓
o Exhaust gas temperature		‡	‡	✓		✓	✓
o Exhaust gas velocity		‡	‡	✓		✓	✓
o Pollutant emissions	✓	✓	✓	✓	✓	✓	✓
o Pollutant depletion velocity	✓	✓	✓	✓	✓	✓	✓
Other							
o ER functions	✓	✓	✓	✓	✓	✓	✓

[a] **NB**, *Basic* estimate input data for QUERI, RUWM and URBAN models are the same.
✓ mandatory input datum
† can be substituted for the local receptor density
§ can be substituted for mean weather statistics
‡ if known an improved impact estimate will be calculated

Input data for the AGRIMAT model include:

- Background SO_2 concentration;
- Background ambient temperature;
- Background relative humidity;
- Agricultural crop distribution;
- Material distribution;
- SO_2 emission rate and depletion velocity;
- Monetary unit costs.

Input data can be specified for the entire impact domain (2000 x 2000 km area about the source) or for any portion(s) thereof.