

Brief presentation of the TIMES Integrated Assessment Model (TIAM)

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| I | i n t e g r a t e d |
| A | a s s e s s m e n t |
| M | m o d e l |



1. The model

The TIMES **Integrated Assessment Model (TIAM)** is a global partial equilibrium model based on the TIMES paradigm, and developed under the sponsorship of ETSAP from 2004. The TIMES model generator was also developed through ETSAP from 1997 to 2003. A complete description of the TIMES equations appears in www.etsap.org/documentation. The TIAM incarnation of TIMES is described in Loulou (2007) and in Loulou and Labriet (2007).

TIAM includes the following distinct **15 regions**: Africa, Australia, Canada, Central and South America, China, Eastern Europe, Former Soviet Union, India, Japan, Middle-East, Mexico, Other Developing Asia, South Korea, USA, Western Europe. For this research, the model is run **from 2005 to 2100**.

The model is driven by a set of **42 demands for energy services in all sectors**: Agriculture, Residential, Commercial, Industry, (for and Transportation services. Examples of energy services are: lighting, water heating, space cooling, etc. (residential and commercial sectors), tons of aluminium, of iron&steel, etc. to produce (industry), vehicle-km to drive by cars, by bus, etc. (transport). Demands for energy services are exogenously specified only for the Reference scenario, and have each a user-defined own-price elasticity. Therefore, each demand may endogenously vary in alternate scenarios, in response to endogenous price changes. Although TIMES does not encompass all macroeconomic variables beyond the energy sector, accounting for price elasticity of demands captures a major element of feedback effects between the energy system and the economy. The model thus computes a partial equilibrium on world-wide energy and emissions markets that **maximizes the discounted present value of global surplus**, representing the surplus of all consumers and producers (practically, the LP minimizes the negative of the surplus, which is then called the system cost). As described in its general form by Takayama and Judge (1971) and, in the case of Bottom-Up energy models, in Loulou and Lavigne (1996), the computation of the supply-demand partial equilibrium is equivalent to the maximization of the total surplus, which is a concave maximization problem. In TIAM, all non linear expressions possess the required concavity or convexity property, and all are approximated by piece-wise linear expressions before treatment via Linear Programming.

The **cost portion of the surplus objective** is constructed as follows: first, each period's investment and dismantling costs are annualized, using hurdle rates that are sector dependent. These annualized investment costs are then added to annual costs (fixed and variables), to form the total annual costs. The stream of annual costs is then discounted to year 2005 using the general discount rate of 5% (the interest rate). All costs are expressed in USD₂₀₀₅. Hurdle rates are important in influencing the competition between technologies in each subsector (a large hurdle rate favors technologies with small investment expenditures). The hurdle rates range from 6% to 9% per year for large utilities and heavy industries, to more than 25% per year for investments in the residential, commercial, and private transportation sectors. The hurdle rates were obtained from the work done in the European Union integrated project NEEDS (Cosmi et al, 2006). A salvage value term is subtracted from the cost objective in order to account for the residual value of technologies still extant after the end of the horizon, and thus attenuate the end-of-horizon bias. TIAM, as all TIMES models, tracks all financial flows in much detail in order to account for the time lags and lead-times existing between the investment decisions, the actual commissioning, decommissioning, and dismantling of technologies.

The **model's variables** include the investments, capacities, activity levels of all technologies at each period of time, plus the amounts of energy, material, and emission flows in and out of each technology. Trade links are also represented as technologies between two regions, with their own costs and efficiencies; such endogenous trade of crude oil, petroleum products, gas, liquefied natural gas, coal, as well as greenhouse gas permits, if wanted, is included in TIAM.

ETSAP-TIAM contains explicit descriptions of more **than one thousand technologies and one hundred commodities (energy forms, materials, emissions) in each region**, logically interrelated in a Reference Energy System (Figure 1). Each technology has its own technical and economic parameters. Such technological detail allows precise tracking of capital turnover, and provides a precise description of technological competition. The model's scope covers extraction, processing, conversion, trading, and end-uses of all energy forms. Primary resources are disaggregated by type (e.g. proven vs. future natural gas reserves, connected vs. not, frontier gas, CBM, associated gas, etc). Each type of non renewable resource is described in each region by means of a step-wise supply curve (3 steps) for the cumulative amounts in the ground, technical annual extraction limits, and fixed and variable costs, thus constituting a compound step-wise supply curve for each primary energy form (coal, oil, gas). All renewable energy forms have annual potentials in each region, also with multiple steps.

The TIMES model generator contains **more than 30 types of standard constraints**, ranging from flow balance equations to capacity transfer equations, to bounds on the utilization rate of technologies, to technical equations that simulate the utilization regime of some electricity generation plants, etc. In addition, there are a number of **user-defined constraints** that express specific regional, sectoral, and technological conditions. For example, in many cases, the penetration of new technologies or of new fuels is partially controlled by upper bounds that are progressively relaxed as time goes on. In some end-use sectors, there are also fuel share constraints that impose certain bounds on the market shares of some fuels (e.g. natural gas use is often unavailable in parts of non urban residences, and thus can never conquer the entire end-use sector). These additional constraints confer additional realism to the technological competition.

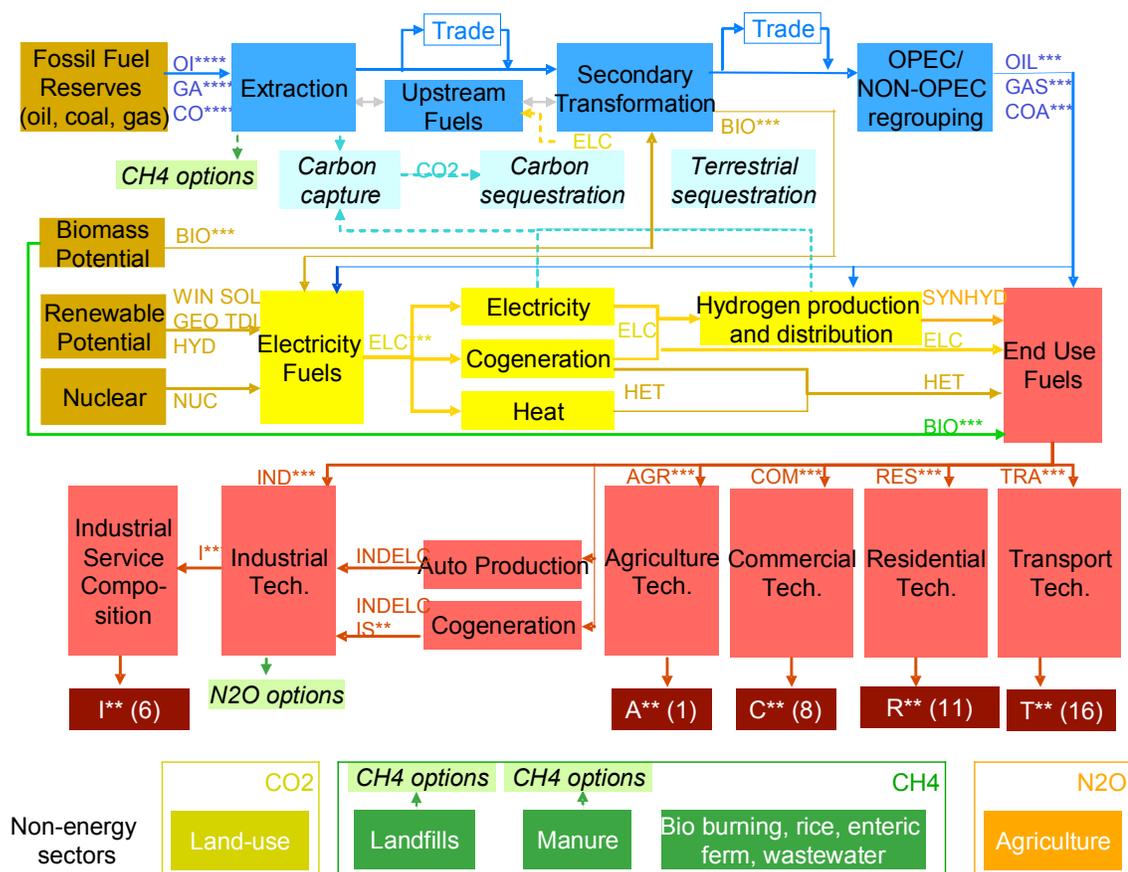


Figure 1. The Reference Energy System of TIAM

2. Emissions explicitly represented

ETSAP-TIAM explicitly models emissions of CO₂, N₂O and CH₄ from all anthropic sources (energy, industrial processes, land, agriculture, waste) directly related to energy consumption but also to processes themselves (eg. N₂O from nitric and adipic acid industry; CH₄ from landfills, etc.).

The CO₂, CH₄ and N₂O emissions related to the energy sector are explicitly represented by the energy technologies included in the model. Each technology includes the appropriate emission coefficients. In addition, there are measures to destroy N₂O, others to burn methane (by flaring or electric power plants), and still others to capture CO₂ and store in underground or undersea in a variety of reservoirs (deep saline aquifers, exhausted wells, enhanced oil recovery, coal seams, ocean). Capture and geological storage of CO₂ is available at electric power plants, at oil wells, at plants that produce synthetic fuels, and at hydrogen plants. In each case, the capture is not complete (around 9-11% of the CO₂ escapes to the atmosphere). Regarding non-energy N₂O and CH₄, only about 40-45% of the emissions can be destroyed or burned, the rest, mainly from the agricultural sector (see Figure 1), have no abatement measures.

Although no mitigation measures are available in the model for the non-energy CO₂, CH₄ and N₂O emissions (except for CH₄ from landfills and manure, where options are available), these emissions are included in order to correctly represent the radiative forcing induced by them. These emissions are:

- CH₄ from landfills, manure, rice paddies, enteric fermentation, wastewater, based on the EMF-22 data;
- N₂O from agriculture, based on the EMF-22 data;
- CO₂ from land-use, based on the Reference scenario of the United States Climate Change Science Program (MIT) presented in Prinn *et al.* (2008), which shows a quasi linear decline from 2.7 GtCO₂ in 2010 to 0.1 GtCO₂ in 2100.

The representation of Land-use CO₂ emissions is quite simplified: first there is a fixed, exogenous trajectory of CO₂ emissions from Land Use, derived from the Climate Change Science Program estimates (see Prinn *et al.* 2008), which shows a quasi linear decline from 3.3 GtCO₂ in 2010 to 0.1 GtCO₂ in 2100.

Emissions from some Kyoto gases (CFC's, HFC's, SF₆) are not explicitly modeled, but a special forcing term is added as described in the next paragraph. **Emissions of chemically active gases** such as NO_x, CO, VOC's are not modeled either. Their influence on the life cycles of GHG gases is *implicitly* accounted for in the concentration equations for the three main GHG's (IPCC AR4, 2007, vol.1, ch. 2), but only through the calibration phase of the equations (Nordhaus and Boyer, 1999).

3. Climate

3.1. Presentation

The climate module is directly inspired by the Nordhaus-Boyer (1999) model, but underwent several changes in order to a) represent the three gases separately, b) use more precise forcing expressions based on the non controversial equations provided by the IPCC (2001, WG1), c) be linearized, and d) accommodate the variable-length periods of TIAM. The module allows the user to simulate climate targets either in terms of concentrations, of forcing, or of temperature change.

The climate module also uses the most recent information provided by the IPCC, such as the Global Warming Potentials (298 for N₂O and 25 for CH₄) and the radiative forcing sensitivity to atmospheric CO₂ concentration doubling (3.7 W/m²).

The climate model proposed by Nordhaus and Boyer and used in ETSAP-TIAM has been compared to more sophisticated climate models and found quite accurate within the range of emissions usually considered (Nordhaus and Boyer, 1999).

It includes a complete consists of three sets of equations, detailed below.

- The first set accepts as inputs the emissions of three Greenhouse gases, CO₂, CH₄, and N₂O, from all sources (energy, industrial, land-use), net of geological capture and storage or destruction and calculate the atmospheric concentrations of the three gases using recursive dynamic equations. The CO₂ life cycle includes three layers (atmosphere, upper ocean, deep ocean, Nordhaus and Boyer, 1999). The CH₄ and N₂O atmospheric concentrations are each governed by a one-box exponential decay model, as used for example in Monni *et al.* (2003) and Manne and Richels (2004).
- The second set of equations accepts as inputs the atmospheric concentrations and calculates the atmospheric radiative forcings of these three gases via their three specific functional forms (IPCC AR4, 2007, vol. 1, ch. 2). The total forcing is then computed by adding up these three forcings plus a fourth (exogenous) forcing due to Kyoto GHG's that are not explicitly modeled in TIAM, so as to account for the totality of the Kyoto gases. The exogenous

forcing trajectory was established from the values indicated in the AR4 (IPCC 2007, vol 1, ch 2) and extended to 2100 using the assumptions from Prinn et al (2008). The forcing expressions for the three gases CO₂, CH₄ and N₂O are non linear and non convex, but have been linearized in the TIAM module. The linear approximation was tested within the range of interest of concentrations (i.e. from 400 to 700 ppmv CO₂-equivalent). The maximum error thus incurred is less than 3%, which is well within the range of uncertainty attached to climate equations. The approximations are used only to compute the constraints on forcing, but the exact expressions are used when reporting the results. Note that the reference case emissions do exceed the 700 ppmv level, but this is of no consequence, as this scenario does not involve upper bounding.

- The third set of equations accepts as inputs the total radiative forcing and recursively calculates the yearly change in mean global temperature in two layers. The first layer consists of the atmosphere and the ocean surface, the second layer is the deep ocean. Heat transfer equations between these layers are represented in the equations. The transition from forcing to temperature change involves a crucial parameter, the climate sensitivity C_s , which is subject to much uncertainty. In section 3.3, we indicate how this uncertainty is explicitly taken into account in this research.

3.2. Concentrations (accumulation of CO₂, CH₄, N₂O)

a) **CO₂ accumulation** is represented as the linear three-reservoir model below¹: the atmosphere, the quickly mixing upper ocean + biosphere, and the deep ocean. CO₂ flows in both directions between adjacent reservoirs. The 3-reservoir model is represented by the following 3 equations when the step of the recursion is equal to one year:

$$M_{atm}(y) = E(y-1) + (1 - \varphi_{atm-up}) M_{atm}(y-1) + \varphi_{up-atm} M_{up}(y-1) \quad (1)$$

$$M_{up}(y) = (1 - \varphi_{up-atm} - \varphi_{up-lo}) M_{up}(y-1) + \varphi_{atm-up} M_{atm}(y-1) + \varphi_{lo-up} M_{lo}(y-1) \quad (2)$$

$$M_{lo}(y) = (1 - \varphi_{lo-up}) M_{lo}(y-1) + \varphi_{up-lo} M_{up}(y-1) \quad (3)$$

With:

- $M_{atm}(y)$, $M_{up}(y)$, $M_{lo}(y)$: masses of CO₂ in atmosphere, in a quickly mixing reservoir representing the upper level of the ocean and the biosphere, and in deep oceans (GtC), respectively, at period t (GtC)
- $E(y-1)$ = CO₂ emissions in previous year (GtC)
- φ_{ij} , transport rate from reservoir i to reservoir j ($i, j = atm, up, lo$) from year $y-1$ to y

b) **CH₄ accumulation** is represented by a so-called single-box model in which the atmospheric methane concentration obeys the following equation:

$$CH4_{atm}(y) = \Phi_{CH4} \cdot \left(CH4_{atm}(y-1) + \frac{1}{d} (EN_{CH4}(y-1) + EA_{CH4}(y-1)) \right) \quad (1a)$$

where

- $CH4_{atm}$, EN_{CH4} , and EA_{CH4} , are respectively: the atmospheric concentration, the natural emission and the anthropogenic emission of CH₄ for year y , expressed in ppbv
- d is the density of CH₄, expressed in Gt/ppbv ($d=2.84$)
- Φ_{CH4} is the one-year retention rate of CH₄ in the atmosphere.

c) **N₂O accumulation** is also represented by a single-box model in which the atmospheric N₂O concentration obeys the following equation:

$$N2O_{atm}(y) = \Phi_{N2O} \cdot \left(N2O_{atm}(y-1) + \frac{1}{d} (EN_{N2O}(y-1) + EA_{N2O}(y-1)) \right) \quad (1b)$$

¹ There exists another representation of CO₂ accumulation equations, using a five-box model and also programmed in TIMES.

where

- N_{2O} , EN_{2O} , and $EA_{N_{2O}}$, are respectively: the atmospheric concentration, the natural emission and the anthropogenic emission of N_{2O} for year y , expressed in ppbv
- d is the density of N_{2O} , expressed in $Gt/ppbv$ ($d=7.81$)
- $\Phi_{N_{2O}}$ is the one-year retention rate of N_{2O} in the atmosphere.

3.3. Radiative forcing

As already mentioned we assume that the forcings due to the various gases are additive (IPCC, 2007). Thus:

$$\Delta F(y) = \Delta F_{CO_2}(y) + \Delta F_{CH_4}(y) + \Delta F_{N_{2O}}(y) + O(y)$$

a) The relationship between CO_2 accumulation and increased radiative forcing, $\Delta F_{CO_2}(y)$, is derived from empirical measurements and climate models (IPCC 2007).

$$\Delta F_{CO_2}(y) = \gamma * \frac{\ln(M_{atm}(y)/M_0)}{\ln 2} \quad (4a)$$

where:

- M_0 (i.e. $CO_2ATM_PRE_IND$) is the pre-industrial (circa 1750) reference atmospheric concentration of $CO_2 = 596.4$ GtC
- γ is the radiative forcing sensitivity to atmospheric CO_2 concentration doubling = 3.7 W/m² (IPCC, 2007)

b) The radiative forcing due to atmospheric CH_4 is given by the following expression (IPCC, 2001, ch.2)

$$\Delta F_{CH_4}(y) = 0.036 \cdot (\sqrt{CH_{4,y}} - \sqrt{CH_{4,0}}) \cdot [f(CH_{4,y}, N_{2O_0}) - f(CH_{4,0}, N_{2O_0})] \quad (4b)$$

c) The radiative forcing due to atmospheric N_{2O} is given by the following expression (IPCC, 2001, ch.2)

$$\Delta F_{N_{2O}}(y) = 0.12 \cdot (\sqrt{N_{2O,y}} - \sqrt{N_{2O,0}}) \cdot [f(CH_{4,0}, N_{2O,y}) - f(CH_{4,0}, N_{2O,0})] \quad (4c)$$

where:

$$f(x, y) = 0.47 \cdot \ln \left[1 + 2.01 \cdot 10^{-5} \cdot (xy)^{0.75} + 5.31 \cdot 10^{-15} \cdot x(xy)^{1.52} \right] \quad (4d)$$

Note that the $f(x,y)$ function, which quantifies the cross-effects on forcing of the presence in the atmosphere of both gases (CH_4 and N_{2O}), is not quite symmetrical in the two gases. As usual, the 0 subscript indicates the pre-industrial times (1750)

d) $O(y)$ is the increase in total radiative forcing at period t relative to pre-industrial level due to anthropogenic GHG's not represented explicitly in the model. Units = W/m². In Nordhaus and Boyer (1999), only emissions of CO_2 were explicitly modeled, and therefore $O(y)$ accounted for all other GHG's. In TIMES, N_{2O} and CH_4 are fully accounted for, but some are not. Therefore, our values for $O(y)$ will differ from those in Nordhaus and Boyer. It is the modeler's responsibility to include in the calculation of $O(y)$ only the forcings from those gases that are not modelled, but that are used in any forcing target. When the target is on temperature change, then the forcing from *all* no modelled GHG's must be accounted for.

The parameterization of the three forcing equations (4a, 4b, 4c) is not controversial and relies on the results reported by Working Group I in the IPCC. IPCC (2001, Table 6.2, p.358) provides a value of 3.7 for γ , smaller than the one used by

Nordhaus and Boyer ($\gamma=4.1$). We adopt this lower value of 3.7 W/m^2 as default in TIMES. Users are free to experiment with other values of the γ parameter. That same table provides the entire expressions for all three forcing equations.

In TIMES, each of the three forcing expressions is replaced by a linear approximation, in order to preserve linearity of the entire TIMES model. All three forcing expressions (4a, 4b, 4c) happen to be concave functions. Therefore, two linear approximations are obvious candidates. The first one is an approximation from below, consisting of the chord of the graph between two selected points. The second one has the same slope as the chord and is tangent to the graph, thus approximating the function from above. The final approximation is taken to be the arithmetic average of the two approximations. These linear expressions are easily derived once a range of interest is defined by the user.

As an example, we derive below the linear approximation for the CO2 forcing expression. The other approximations are obtained in a similar manner.

First, an interval of interest for M must be selected by the user. The interval should be wide enough to accommodate the anticipated values of the concentrations, but not so wide as to make the approximation inaccurate. We denote the interval (M_1, M_2) .

Next, the linear forcing equation is taken as the half sum of two linear expressions, which respectively underestimate and overestimate the exact forcing value. The underestimate consists of the chord of the logarithmic curve, whereas the overestimate consists of the tangent to the logarithmic curve that is parallel to the chord. These two estimates are illustrated in Figure A2, where the interval (M_1, M_2) is from 375 ppm to 550 ppm.

By denoting the pre-industrial concentration level as M_0 , the general formulas for the two estimates are as follows:

$$\text{Overestimate:} \quad F_1(M) = \frac{\gamma}{\ln 2} \cdot \left[\ln\left(\frac{\gamma}{\text{slope} \cdot \ln(2) \cdot M_0}\right) - 1 \right] + \text{slope} \cdot M \quad (5)$$

$$\text{Underestimate:} \quad F_2(M) = \gamma \cdot \ln(M_1 / M_0) / \ln 2 + \text{slope} \cdot (M - M_1) \quad (6)$$

$$\text{Final approximation:} \quad F_3(M) = \frac{F_1(M) + F_2(M)}{2} \quad (7)$$

$$\text{where:} \quad \text{slope} = \gamma \cdot \frac{\ln(M_2 / M_1) / \ln 2}{(M_2 - M_1)}$$

The linearized forcing function implemented in TIMES is based on the final approximation, which takes the average of the two linear estimates.

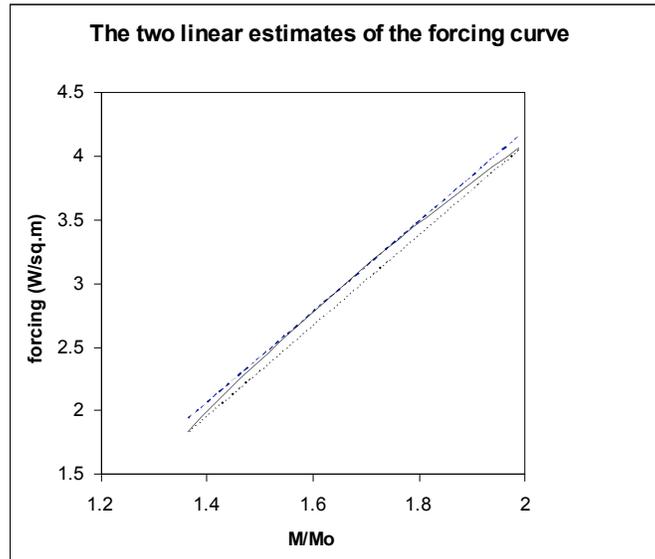


Figure. Illustration of the linearization of the radiative forcing function.

3.4. Temperature increase

In the TIMES Climate Module as in many other integrated models, climate change is represented by the global mean surface temperature. The idea behind the two-reservoir model is that a higher radiative forcing warms the atmospheric layer, which then quickly warms the upper ocean. In this model, the atmosphere and upper ocean form a single layer, which slowly warms the second layer consisting of the deep ocean.

$$\Delta T_{up}(y) = \Delta T_{up}(y-1) + \sigma_1 \{ F(y) - \lambda \Delta T_{up}(y-1) - \sigma_2 [\Delta T_{up}(y-1) - \Delta T_{low}(y-1)] \} \quad (8)$$

$$\Delta T_{low}(y) = \Delta T_{low}(y-1) + \sigma_3 [\Delta T_{up}(y-1) - \Delta T_{low}(y-1)] \quad (9)$$

with

- ΔT_{up} = globally averaged surface temperature increase above pre-industrial level,
- ΔT_{low} = deep-ocean temperature increase above pre-industrial level,
- σ_1 = 1-year speed of adjustment parameter for atmospheric temperature (also known as the *lag* parameter),
- σ_2 = coefficient of heat loss from atmosphere to deep oceans,
- σ_3 = 1-year coefficient of heat gain by deep oceans,
- λ = feedback parameter (climatic retroaction). It is customary to write λ as $\lambda = \gamma / C_s$, C_s being the *climate sensitivity* parameter, defined as the change in equilibrium atmospheric temperature induced by a doubling of CO_2 concentration.

Remark: in contrast with most other parameters, the value of C_s is highly uncertain, with a possible range of values from $1^\circ C$ to $10^\circ C$. This parameter is therefore a prime candidate for sensitivity analysis, or for treatment by probabilistic