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Fossil fuel reserves and depletion: can they comply with CO2-emission pledges and targets?

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1. Introduction

Future greenhouse gas (GHG) emissions are the subject of extensive research, related with to the international pledges about net zero 2050 emissions.

Since 1990, the Inter-govermnental Panel on Climate Change (IPCC) has developed long-term emission scenarios up to 2100.

These different scenarios have been widely used in the analysis of possible climate change, impact and options to mitigate climate change.

In 2000 IPCC issued a Special report on Emissions Scenarios, focusing on complex driving forces such as demographic and socio-economic development, and technological change.

Surprisingly, all the above scenarios do not include as a limiting factor for the emissions the reserves of the main fossil fuels, coal, oil and natural gas.

The limit to growth for the fossil resource exploitation was introduced by M.K. Hubbert in 1956. He proposed that fossil fuel production in a given region over time would follow a bell-shaped curve without a precise formula. He later suggested the derivative of the logistic curve for estimating future production from past observed discoveries.

While a description of the different resource decay curves is given in [1] and [2], here the Meixner distribution [10] is employed for describing the per capita production of CO2 (CD for short, Carbon Dioxide) in the years to come. The goal of the paper is to predict the future

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CD emissions per capita, based on historical data as in Figure 2, and the 2020 estimate of the fossil-fuel reserves, which are reported in Table 1, for coal, oil and gas.

2. Population growth, CD emissions and fossil fuel reserves

The Population Division of United Nations (UN) has published accurate growth predictions until 2100 of the global population [3], to be denoted by *p(t),* with unit written as [GVol] and meaning one billion people. The time *t* is expressed as a fraction of year starting from *t0=1855.5,* the time unit being one year [y]. Population predictions are divided according to different criteria, like high-medium-low variant, constant fertility and others. We have chosen the medium-variant which converges to a stationary value around 2100. The different variant curves are shown in Figure 1 together with the worldwide CD emission by fossil-fuel combustion up to 2020 inclusive, from [4]. Let us remark that the emission curve does not include emissions from methane and nitrous oxide and those referred to land-use change and forestry, as they do not depend on fossil fuel combustion.

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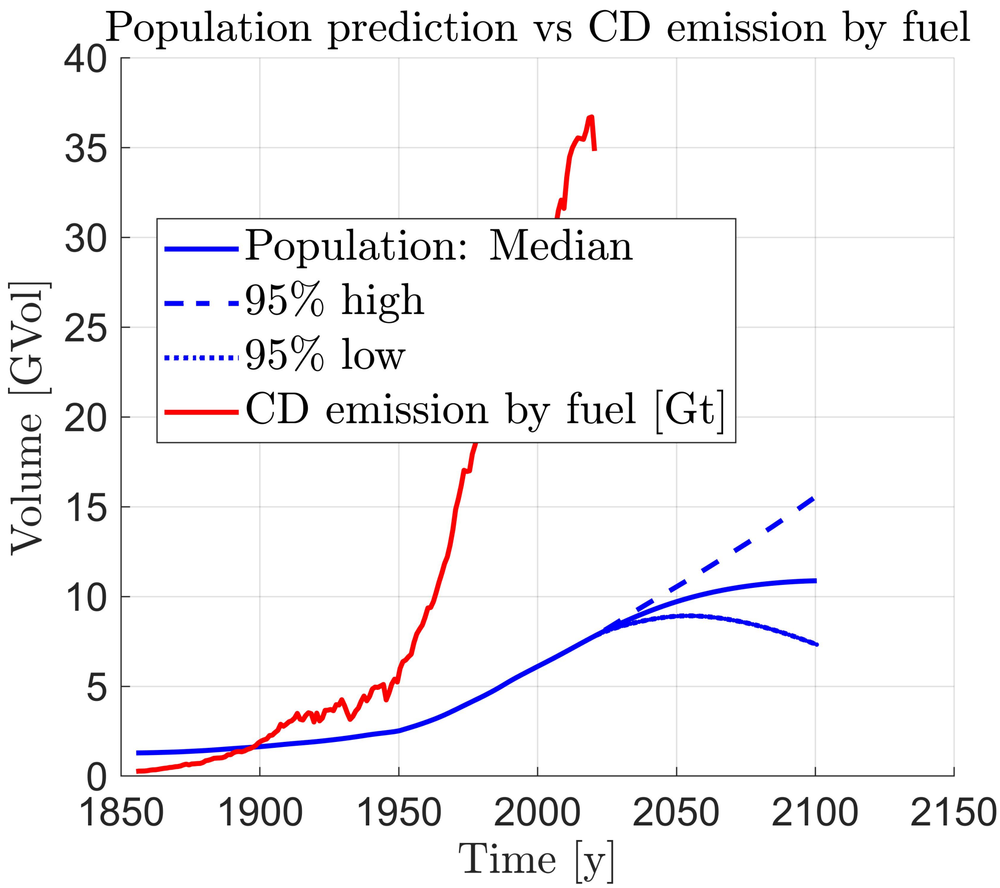

Figure 1. UN worldwide population prediction and CD emissions by fuel combustion.

The same source [4] allows us to subdivide, as in Figure 2, the CD emissions by fuel into the three major fossil fuels, coal, oil and (natural) gas. Fuel types will be denoted by the subscript f=1(coal), 2(oil), 3(gas). The subdivision is the key for the estimated predictions of the paper.

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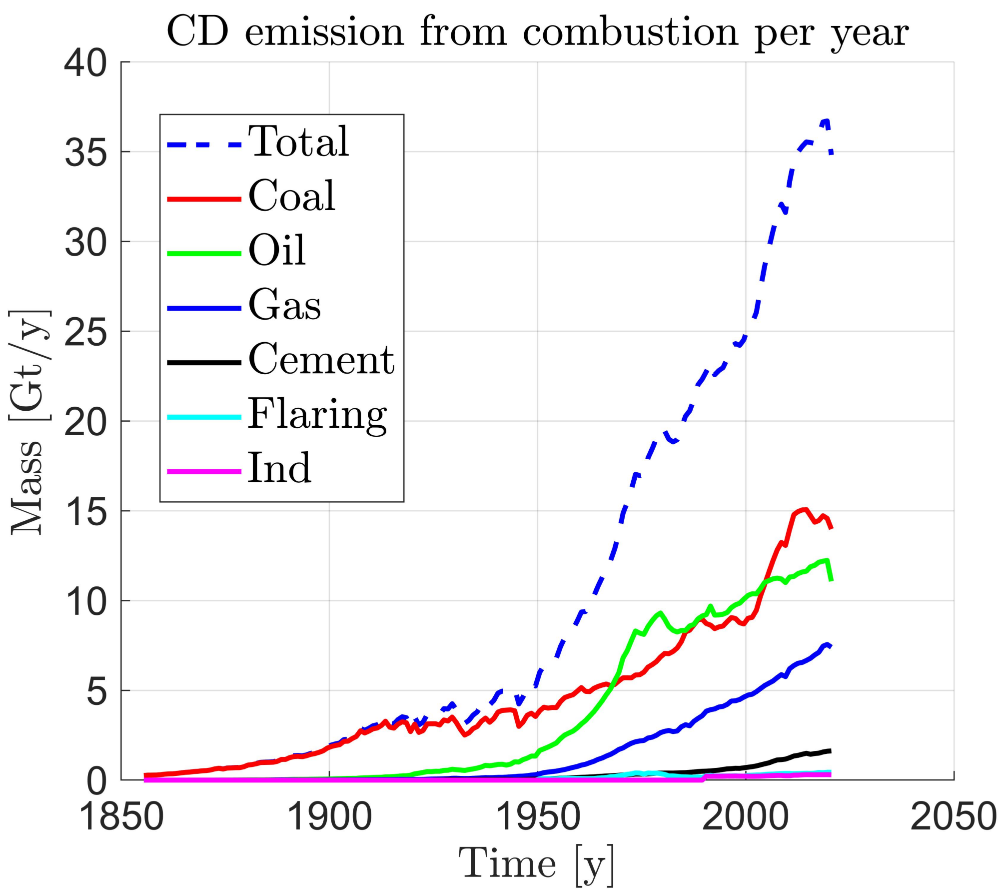

Figure 2. Wordwide CD emissions by fuel combustion (Ind=Industry).

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Before reporting in Table 1 fossil fuel reserves, the distinction between natural reserves and resources is briefly recalled [5]. Resource is that amount of a natural commodity (in this case fossil fuels) that exists in both discovered and undiscovered deposits. Reserves are the subgroup of a resource that have been discovered, have known size, and can be technically recovered at a cost that is financially feasible at the present price of that feedstock. Hence reserves will change with the price, unlike resources, which include all the amount of that stuff that can be technically recovered at any price. For example, the world's estimated oil reserves are about a third of the resource amount.

Fossil fuel reserves denoted by *Cfinf,f=1,2,3* are reported as the equivalent mass [Gt] of CD emissions in rows 7 to 9 of Table 1. They have been estimated as the product *Cfinf=kf*Rfinf* of the reserve mass *Rfinf*, found through the web, free of uncertainty (rows 1 to 3 of Table 1), and the conversion factor *kf* whose range has been derived from a table in [8]. The range (min,max) expresses the different kinds of combusted coal and oil.

Table 1 Fuel reserves at 31 december 2020 and equivalent CD emission

No	Fuel	Symbol	Unit	Value	Comment
2020 reserves in unit of mass					
1	Coal	$R_{1\infty}$	Gt	1047	From Google, 1156 billions of short tons
2	Oil	$R_{2\infty}$	Gt	246.5	From Google, 1732 billions of barrels
3	Natural gas	$R_{3\infty}$	Gt	141	From OWID [7]
Conversion from fuel mass to CD equivalent mass emitted by combustion					
4	Coal (min, max)	K_1	Gt/Gt	2.08, 2.72	From [8], mixed coal
5	Oil (min, max)	K_2	Gt/Gt	2.59, 3.23	From [8], distillate fuel oil
6	Gas (min, max)	K_3	Gt/Gt	2.56	From [8]
Fuel reserves (min,max) in equivalent Gt of CD emissions,					
7	Coal (min, max)	$C_{1\infty}$	Gt	2180, 2850	
8	Oil (min, max)	$C_{2\infty}$	Gt	639,787	
9	Gas (min, max)	$C_{3\infty}$	Gt	362	

Table 1.

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3. Prediction of per-capita CD emissions under finite fuel reserves

3.1 The variables and the reserve constraint

Given the historical fossil-fuel consumption, we aim to predict the future consumption a s to predict the per-capita fuel consumption *gf(t)* of each fuel type *f* (1=coal, 2=oil and 3=gas) by constraining the total future consumption (per-capita consumption *gf(t)* multiplied by the predicted population *p(t)*) with the relevant fuel reserve. In doing this, fuel consumption will be measured in mass units [Gt] of equivalent CD emissions.

Let us denote the cumulative consumption of the fossil fuel *f* at time *t*, in equivalent CD mass [Gt], by *cf(t), t0<=t<tc*, where *tc* is the current time, and assume that the future consumption *cf(t), tc<=t<tinf* is bounded by the available reserve *Cfinf*. The limit time *tinf* , though an unknown of the problem, is fixed in advance as *tinf>=2100.5* , not smaller than the upper limit of the population prediction. The cumulative consumption of the fuel *f* is written as the integral of the consumption rate *dcf(t)/dt=gf(t)p(t)*, product of the per capita consumption *gf* and the population *p*, as in Eq. (1), Section 5.

The initial consumption *cf(t0)=cf0* is set to zero, and the future consumption for *tc<=t<tinf* is assumed to be equal to the fuel reserve *Cfinf* as in Eq. (2), Section 5.

The total (all the fuels) cumulative consumption is denoted by *c(t)* and the rate by *rc(t)* as in Eq.(3), Section 5.

3.2 Regression model and results

The goal is to predict the per-capita consumption *gf* from *tc* to *tinf,* based on historical data and the reserve constraint in Eq. (2), Section 5. To this end *gf(t;**pf**)*, is approximated by an analytic function depending on the parameter vector ***pf*** to be estimated from experimental data. The adopted analytic function is the skewed Meixner distribution (MD, or skewed hyperbolic secant distribution) [10], which can be written as in Eq. (4), Section 5. In Eq. (4), *a* is the scale factor, *s* denotes location (the peak time) and the pair *b,c* defines shape and skewness.

Let *yg(tk), k=0,1, ..,N-1* denote the historical samples of a generic per-capita consumption, let *yp(tk), k=0,1,…,N+M* denote historical and predicted population and *y(Cinf)* the reserve datum. Least squares fit of the historical samples with the function *gf(t;**pf**)*, and the reserve constraint requires the minimization of the functional in Eq. (5), Section 5.

The historical data employed by the nonlinear regression run from *t0* (to be selected) until *t(N-1)=2020.5* , and the time *tk* corresponds the the mid of a solar year.

Figure 3 shows the regression results for each fuel and the total of the fuels. The starting time was selected as *t0=1970.5* and min and max fuel reserves in Table 1 have been consid-

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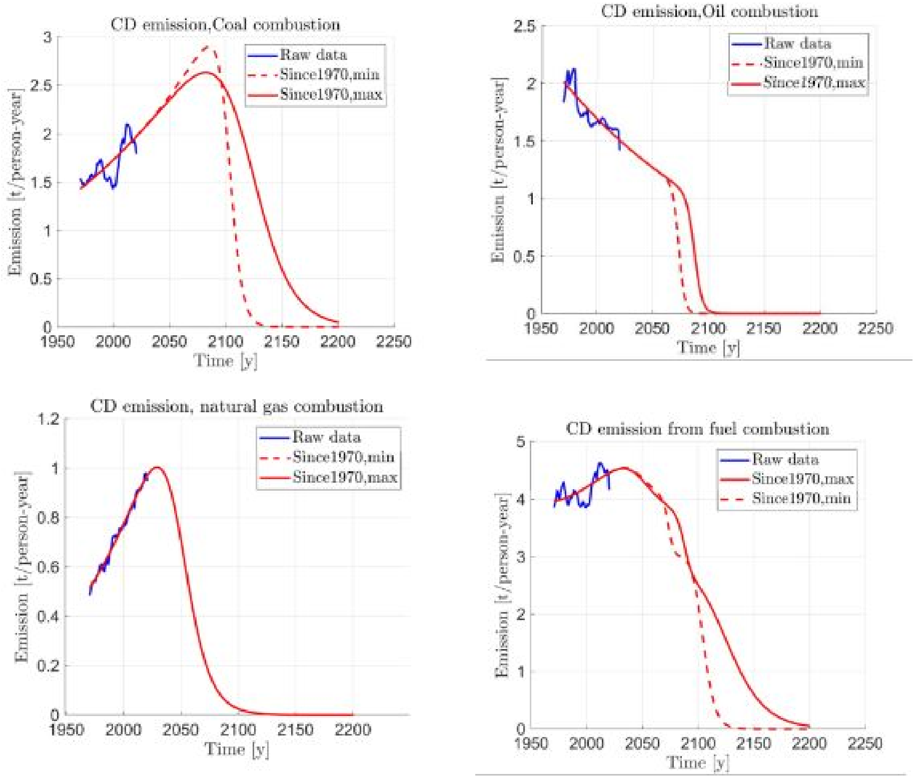

Figure 3. Raw data and prediction of per capita emissions bounded by min and max fuel reserves.

ered. The limit time *t(N+M)=tinf* has been selected as 2200.5, which requires the extrapolation of the predicted population in Figure 1. By restricting to the median profile, a constant population volume has been assumed. Figure 3 shows that only coal consumption requires a time extension until 2200.5, because of the largest reserve as in Table 1. Prediction can be repeated by selecting *t0<1970.5.* As a rule of thumb, such predictions are such to anticipate the zero-consumption date. Space restrictions prevents further discussions.

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The estimated coefficients are reported in Table 2:

Table 2 Coefficients of the estimated Meixner distribution under minimal reserves						
No	Fuel	$a[t(p-y)^{-1}]$	$b[y^{-1}]$	$c[y^{-1}]$	$s[y]$	Comment
1	Coal	1.69	0.176	0.00647	2103.3	
2	Oil	0.553	0.387	-0.0058	2073.7	
3	Gas	0.769	0.0790	0.0142	2047.6	

Table 2.

4. Prediction comparison of finite-reserve emissions by fuel with those in the literature

As mentioned in the introduction, future GHG emissions have been the subject of extensive research. Here we refer to the projections (and relevant data) as reported by the Climate 01Action Tracker [9]. Emissions studied in this article are limited to carbon dioxide. Emissions of other greenhouse gases, like methane, are linked to fossil fuel usage, to some extent, as described in [11].

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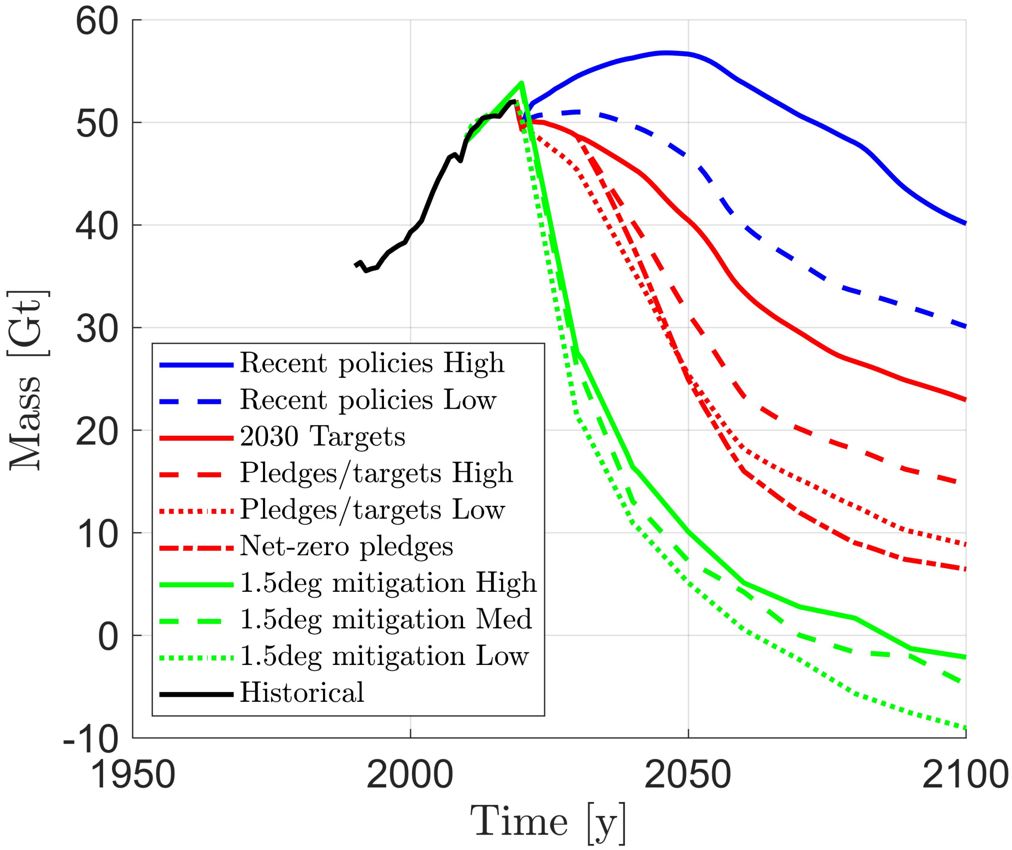

Figure 4. Projections of greenhouse gas emissions from [9].

Roughly, three groups of projections are reported in [9], their profiles being in Figure 4. They can be summarized as follows.

1. *Recent policies* (in blue color): the projections assume current mitigation policies and actions against global warming and are organized into two levels of confidence, high and low.

2. *Pledges and targets* (in red color): the projections assume fulfillment of National Determined Contributions to warming mitigations on the basis of pledges and/or international targets. They split into four levels.

3. *1.5 degree mitigation policies* (in green color), based on optimistic policies.

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The black increasing profile in Figure 4, left, corresponds to the emissions of the total of greenhouse gases, inclusive of methane and nitrous oxides, and other minor gases. Let us recall that the paper goal only concerns emissions by fossil fuels as they only are constrained by finite natural reserves.

Comparison with the finite-reserve projections of this paper (magenta color), in Figure 5 top and bottom, is restricted to recent policies (blue color, solid and dashed lines) and 2030 targets (solid line, red color).

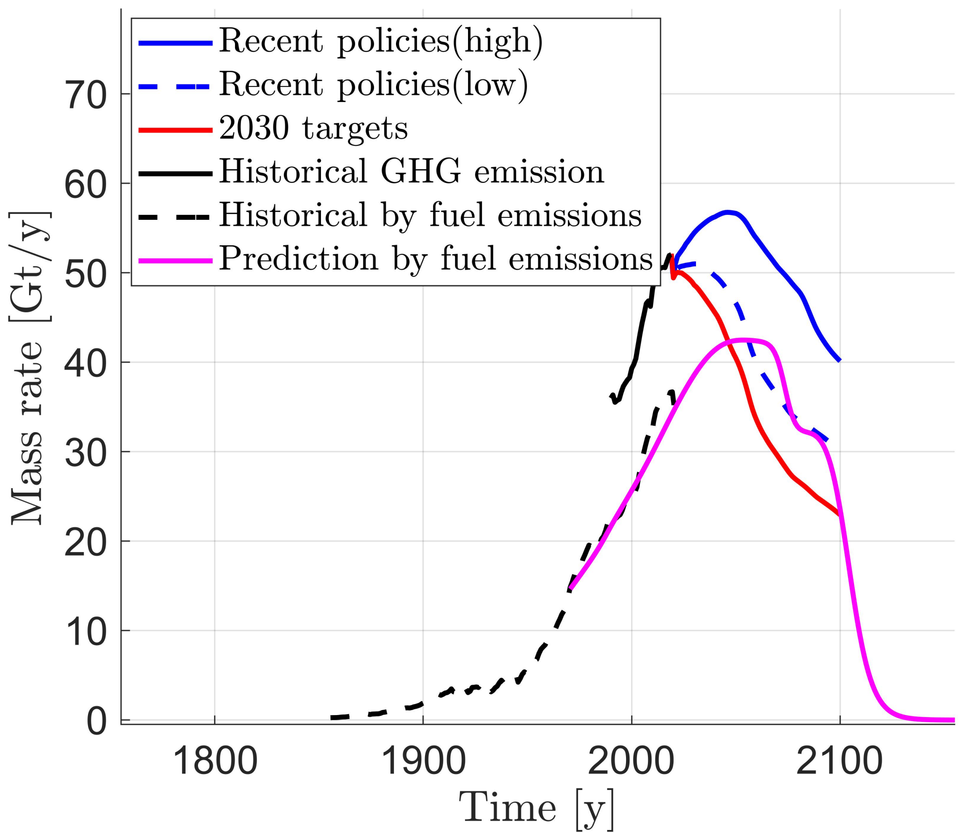

Figure 5. Comparison between literature projections of GHG emissions and finite-reserve emission projections by fuel (since 1970.5). Minimal reserves.

The difference between GHG projections and finite-reserve projections in Figure 5, about 10 Gt, is due, as already mentioned, to the difference between total GHG and fossil-fuel com-

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bustion emissions. GHG emissions are limited to 2100 whereas fossil-fuel emissions have been extended beyond 2100 under the assumption of constant population since 2100. Having justified the difference, recent-policies and finite-reserve projections look rather comparable, which implies that the question of the title looks positive at least for what concerns the cited policies.

5. Equations

$cf(t)=cf0+\int_{t0}^{t} gf(\tau)p(\tau)d\tau$.	(1)
$\int_{tc}^{tinf} gf(\tau)p(\tau)d\tau=Cf\text{inf}$.	(2)
$c(t)=\sum_{f=1}^{3} cf(t), rc(t)=\sum_{f=1}^{3} gf(t)p(t)$	(3)
$g(t,\boldsymbol{p})=\frac{2a}{\exp(b(t-s))+\exp(-c(t-s))}, \boldsymbol{p}=[a,b,c,s]$ $a=max(g(t)), arg\,max(g(t))=s$.	(4)
$J(\boldsymbol{p})=\sqrt{\frac{1}{N}\sum_{k=0}^{N-1}(yg(tk)-g(tk,\boldsymbol{p}))^2+\left(\frac{\sum_{k=N}^{N+M}(g(tk,\boldsymbol{p})yp(t_k))-y(C\text{inf})}{\sum_{k=N}^{N+M} yp(tk)}\right)^2}$	(5)

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