Emissions and climate change: a module of the DEFINE model

R code

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Module equations

Output: $Y = Y_{-1}(1+g_y)$	(1)
Total energy: $E = \varepsilon Y$	(2)
Non-renewable energy: $EN = (1-\theta)E$	(3)
Industrial CO_2 emissions: $EMIS_{IN} = \omega EN$	(4)
Land-use CO_2 emissions: $EMIS_L = EMIS_{L-1}(1-lr)$	(5)
Total emissions: $EMIS = EMIS_{IN} + EMIS_L$	(6)
Atmospheric CO_2 concentration: $CO2_{AT} = EMIS + \phi_{11}CO2_{AT-1} + \phi_{21}CO2_{UP-1}$	(7)
Upper ocean/biosphere CO_2 concentration: $CO2_{UP} = \phi_{12}CO2_{AT-1} + \phi_{22}CO2_{UP-1} + \phi_{32}CO2_{LO-1}$	(8)
Lower ocean CO_2 concentration: $CO2_{LO} = \phi_{23}CO2_{UP-1} + \phi_{33}CO2_{LO-1}$	(9)
Radiative forcing: $F = F_{2\times CO2}\, log_2 \frac{CO2_{AT}}{CO2_{AT-PRE}} + F_{EX}$	(10)
Radiative forcing due to non-CO_2 greenhouse gas emissions: $F_{EX} = F_{EX-1} + fex$	(11)
Atmospheric temperature: $T_{AT} = T_{AT-1} + t_1\left(F - \frac{F_{2\times CO2}}{S}T_{AT-1} - t_2(T_{AT-1} - T_{LO-1})\right)$	(12)
Temperature of the lower ocean: $T_{LO} = T_{LO-1} + t_3(T_{AT-1} - T_{LO-1})$	(13)

Module symbols and values

Variable	Description	Value/calculation
$CO2_{AT}$	Atmospheric CO_2 concentration (Gt)	3,120.0
$CO2_{AT\text{-}PRE}$	Pre-industrial atmospheric CO_2 concentration (Gt)	2,156.2
$CO2_{LO}$	Lower ocean CO_2 concentration (Gt)	6,381.0
$CO2_{LO\text{-}PRE}$	Pre-industrial CO_2 concentration in upper ocean/biosphere (Gt)	6,307.2
$CO2_{UP}$	Upper ocean/biosphere CO_2 concentration (Gt)	1,687.0
$CO2_{UP\text{-}PRE}$	Pre-industrial CO_2 concentration in lower ocean (Gt)	1,320.1
E	Energy used for the production of GDP (EJ)	580.0
$EMIS$	Total CO_2 emissions (Gt)	Calculated from equation (6)
$EMIS_{IN}$	Industrial CO_2 emissions (Gt)	36.3
$EMIS_{L}$	Land-use CO_2 emissions (Gt)	2.6
EN	Non-renewable energy (EJ)	Calculated from equation (3)
F	Radiative forcing over pre-industrial levels (W/m^2)	Calculated from equation (10)
F_{EX}	Radiative forcing, over pre-industrial levels, due to non-CO_2 greenhouse gases (W/m^2)	0.5
F_{2xCO2}	Increase in radiative forcing (since the pre-industrial period) due to doubling of CO_2 concentration from pre-industrial levels (W/m^2)	3.7
fex	Annual increase in radiative forcing (since the pre-industrial period) due to non-CO_2 agents (W/m^2)	0.006
g_y	Growth rate of GDP	0.027
lr	Rate of decline of land-use CO_2 emissions	0.024
S	Equilibrium climate sensitivity, i.e. increase in equilibrium temperature due to doubling of CO_2 concentration from pre-industrial levels (°C)	3.1
T_{AT}	Atmospheric temperature over pre-industrial levels (°C)	1
T_{LO}	Lower ocean temperature over pre-industrial levels (°C)	0.0068
t_1	Speed of adjustment parameter in the atmospheric temperature equation	0.021
t_2	Coefficient of heat loss from the atmosphere to the lower ocean (atmospheric temperature equation)	0.018
t_3	Coefficient of heat loss from the atmosphere to the lower ocean (lower ocean temperature equation)	0.005
Y	GDP (trillion dollars)	74.2
ε	Energy intensity, i.e. energy use per unit of GDP (EJ/trillion US$)	7.8
θ	Share of renewable energy in total energy	0.14
φ_{11}	Transfer coefficient for carbon from the atmosphere to the atmosphere	0.976
φ_{12}	Transfer coefficient for carbon from the atmosphere to the upper ocean/biosphere	0.024
φ_{21}	Transfer coefficient for carbon from the upper ocean/biosphere to the atmosphere	0.0392
φ_{22}	Transfer coefficient for carbon from the upper ocean/biosphere to the upper ocean/biosphere	0.9595
φ_{23}	Transfer coefficient for carbon from the upper ocean/biosphere to the lower ocean	0.0013
φ_{32}	Transfer coefficient for carbon from the lower ocean to the upper ocean/biosphere	0.0003
φ_{33}	Transfer coefficient for carbon from the lower ocean to the lower ocean	0.9997
ω	CO_2 intensity, i.e. CO2 emissions per unit of non-renewable energy use (Gt/EJ)	Calculated from equation (4)

Steps in simulating the module in R

#Open R and create a new R script (File->New file->R script). Save this file as 'Climate' (File->Save as).

#Clear the workspace and identify how many time periods (T) you wish your model to run (once you write the commands, press 'Source')

```
rm(list=ls(all=TRUE))
T<-101
```

#STEP 1: Identify the endogenous variables of the model (as well as some auxiliary variables). For each of them create a vector that has a length equal to the time periods. (Once you have written the commands, press 'Source'.)

```
#Endogenous variables
Y<- vector(length=T)
E<- vector(length=T)
EN<- vector(length=T)
EMIS_IN<- vector(length=T)
EMIS_L<- vector(length=T)
EMIS<- vector(length=T)
CO2_AT<- vector(length=T)
CO2_UP<- vector(length=T)
CO2_LO<- vector(length=T)
Forc<- vector(length=T)
F_EX<- vector(length=T)
T_AT<- vector(length=T)
T_LO<- vector(length=T)
```

#STEP 2: Identify the baseline scenario and select the parameter values (use the values reported in the table on p. 1)

```
#Parameters
for (i in 1:T) {

gy<-0.027
theta<-0.14
epsilon <-7.8 #EJ/trillion US$
S<-3.1 #oC; this value can be modified in the web interface


if ( i>5){
gy<- 0.027 #this value can be modified in the web interface
theta<- 0.14 #this value can be modified in the web interface
epsilon <- 7.8 #this value can be modified in the web interface

}

if (i == 1) {
  for (iterations in 1:10){

lr<-0.024
CO2_AT_PRE<-2156.2 #Gt of CO2
CO2_UP_PRE<-1320.1 #Gt of CO2
```

```
CO2_LO_PRE<-6307.2 #Gt of CO2
phi11<-0.976
phi12<-0.024
phi21<-0.0392
phi22<-0.9595
phi23<-0.0013
phi32<-0.0003
phi33<-0.9997
F2CO2<-3.7 #W/m^2
fex<-0.006
t1<- 0.021
t2<-0.018
t3<-0.005
omega<-EMIS_IN[i]/EN[i] #Gt/EJ
```

#STEP 3: Identify the initial values for the endogenous variables (use the values in Table 1)

```
#Initial values
Y[i] <- 74.2 #trillion US$
E[i]<-580 #EJ
EN[i]<-(1-theta)*E[i] #EJ
EMIS_IN[i]<-36.3 #Gt
EMIS_L[i] <-2.6 #Gt
EMIS[i] <- EMIS_IN[i]+EMIS_L[i] #Gt
CO2_AT[i]<-3120 #Gt
CO2_UP[i]<-1687 # Gt
CO2_LO[i]<-6381  # Gt
Forc[i]<-F2CO2*log2(CO2_AT[i]/CO2_AT_PRE)+F_EX[i] #W/m^2
F_EX[i]<-0.5 #W/m^2
T_AT[i] <-1 #ºC
T_LO[i] <-0.0068 #ºC
  }
 }
```

#STEP 4: Write down the equations and run the model. (Once you have written the commands, press 'Source'.)

```
#Equations
else {

for (iterations in 1:10){

Y[i] <- Y[i-1]*(1+gy)
E[i] <- epsilon*Y[i]
EN[i] <- (1-theta)*E[i]
EMIS_IN[i] <- omega*EN[i]
EMIS_L[i] <- EMIS_L[i-1]*(1-lr)
EMIS[i] <- EMIS_IN[i]+EMIS_L[i]
CO2_AT[i] <- EMIS[i]+phi11*CO2_AT[i-1]+phi21*CO2_UP[i-1]
CO2_UP[i] <- phi12*CO2_AT[i-1]+phi22*CO2_UP[i-1]+phi32*CO2_LO[i-1]
CO2_LO[i] <- phi23*CO2_UP[i-1]+phi33*CO2_LO[i-1]
Forc[i] <- F2CO2*log2(CO2_AT[i]/CO2_AT_PRE)+F_EX[i]
F_EX[i] <- F_EX[i-1]+fex
T_AT[i] <- T_AT[i-1]+t1*(Forc[i]-(F2CO2/S)*T_AT[i-1]-t2*(T_AT[i-1]-T_LO[i-1]))
```

```
T_LO[i] <- T_LO[i-1]+t3*(T_AT[i-1]-T_LO[i-1])

    }
  }
}
```

#STEP 5: Report your results by using tables and graphs. (Once you have written the commands, press 'Source'.)

```
#Table
matrixname<-paste("Table")
assign (matrixname, (round(cbind(Y, EN, EMIS_IN, EMIS, CO2_AT, T_AT), digits=4)))

par(mar = c(3,3.3,1,1)+0.1,mgp=c(1.8,0.5,0), family="Georgia")
plot(Table[1:101,c("T_AT")], col="blue",  type="l", lwd=1.5, xlab= "Year", ylab=expression("Temperature ("^{o}*"C above pre-industrial)"), xaxt="n", cex.lab=1.1)
axis(side=1, at=c(1,21,41,61,81, 101), labels=c("2015","2035","2055", "2075","2095","2015"))

par(mar = c(3,3.3,1,1)+0.1,mgp=c(1.8,0.5,0), family="Georgia")
plot(Table[1:101,c("EMIS")], col="firebrick4", type="l", lwd=1.5, xlab= "Year", ylab=expression("CO"[2]*" emissions (Gt)"),xaxt="n", cex.lab=1.1)
axis(side=1, at=c(1,21,41,61,81, 101), labels=c("2015","2035","2055", "2075","2095","2015"))

par(mar = c(3,3.3,1,1)+0.1,mgp=c(1.8,0.5,0), family="Georgia")
plot(Table[1:101,c("Y")], col="darkgreen",  type="l", lwd=1.5, xlab= "Year", ylab="GDP (trillion US$)", xaxt="n", cex.lab=1.1)
axis(side=1, at=c(1,21,41,61,81, 101), labels=c("2015","2035","2055", "2075","2095","2015"))
```