DEFINE-CLIMATE

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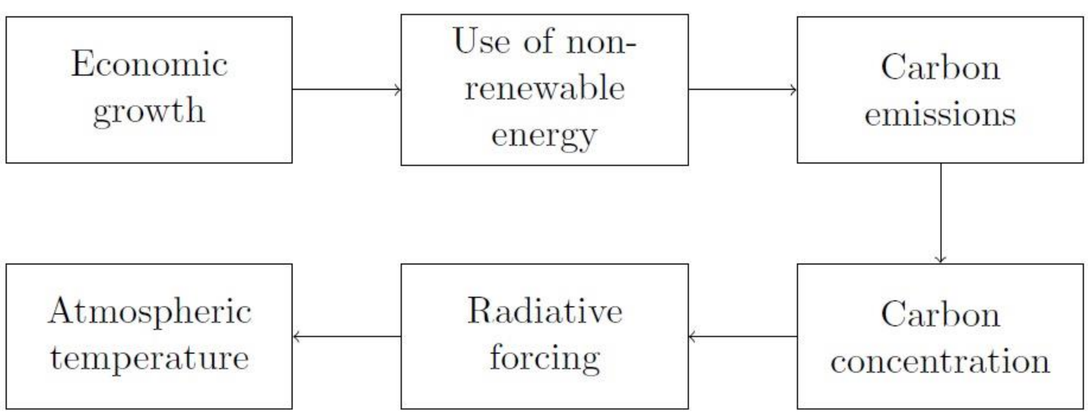
1. Brief description

DEFINE-CLIMATE is a simplified module of DEFINE, which shows how climate change is affected by economic activity. The way that the module works is outlined in Figure 1. Higher economic growth leads to higher carbon emissions (for a given level of energy intensity and share of renewables). These carbon emissions affect the amount of carbon that is concentrated in the atmosphere, after taking into account the amount of carbon that is absorbed by the upper and the lower ocean.

Figure 1: The link between economic growth and atmospheric temperature



An increase in carbon concentration affects radiative forcing, i.e. the difference between the sunlight absorbed by the Earth and the energy radiated back to the space. The overall result is an increase in atmospheric temperature.

2. 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 CO₂ concentration: $CO2_{AT} = EMIS + \phi_{11}CO2_{AT-1} + \phi_{21}CO2_{UP-1}$ (7)

Upper ocean/biosphere CO₂ concentration: $CO2_{UP} = \phi_{12}CO2_{AT-1} + \phi_{22}CO2_{UP-1} + \phi_{32}CO2_{LO-1}$ (8)

Lower ocean CO₂ 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-CO₂ 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)

3. Symbols and values

Symbol	Description	Value/calculation
	Parameters	
g_Y	Growth rate of GDP	0.027
θ	Share of renewable energy in total energy	0.14
ε	Energy intensity, i.e. energy use per unit of GDP (EJ/trillion US$)	Calculated from equation (2)
S	Equilibrium climate sensitivity, i.e. increase in equilibrium temperature due to doubling of CO_2 concentration from pre-industrial levels (°C)	3.1
lr	Rate of decline of land-use CO_2 emissions	0.024
$CO2_{AT\text{-}PRE}$	Pre-industrial atmospheric CO_2 concentration (Gt)	2,156.2
$CO2_{UP\text{-}PRE}$	Pre-industrial CO_2 concentration in lower ocean (Gt)	1,320.1
$CO2_{LO\text{-}PRE}$	Pre-industrial CO_2 concentration in upper ocean/biosphere (Gt)	6,307.2
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
F_{2xCO2}	Increase in radiative forcing (since the pre-industrial period) due to doubling of CO_2 concentration from pre-industrial levels (W/m²)	3.7
fex	Annual increase in radiative forcing (since the pre-industrial period) due to non-CO_2 agents (W/m²)	0.006
t_1	Speed of adjustment parameter in the atmospheric temperature equation	0.020301
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
ω	CO_2 intensity, i.e. CO2 emissions per unit of non-renewable energy use (Gt/EJ)	Calculated from equation (4)
	Endogenous variables	
Y	GDP (trillion dollars)	80.7
E	Energy used for the production of GDP (EJ)	580.0
EN	Non-renewable energy (EJ)	Calculated from equation (3)
$EMIS_{IN}$	Industrial CO_2 emissions (Gt)	36.2
$EMIS_L$	Land-use CO_2 emissions (Gt)	2.5
$EMIS$	Total CO_2 emissions (Gt)	Calculated from equation (6)
$CO2_{AT}$	Atmospheric CO_2 concentration (Gt)	3,164.0
$CO2_{UP}$	Upper ocean/biosphere CO_2 concentration (Gt)	1,694.2
$CO2_{LO}$	Lower ocean CO_2 concentration (Gt)	6,380.6
F	Radiative forcing over pre-industrial levels (W/m²)	Calculated from equation (10)
F_{EX}	Radiative forcing, over pre-industrial levels, due to non-CO_2 greenhouse gases (W/m²)	0.51
T_{AT}	Atmospheric temperature over pre-industrial levels (°C)	1.1
T_{LO}	Lower ocean temperature over pre-industrial levels (°C)	0.0112

4. Steps for simulating the model 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<-104
```

#STEP 1: For each endogenous variable, 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: Give values to the parameters (use the values reported in the table in Section 3).

```
#Parameters
for (i in 1:T) {
if (i == 1) {
  for (iterations in 1:10){
g_Y<-0.027
theta<-0.14
epsilon <- E[i]/Y[i] #EJ/trillion US$
S<-3.1 #oC
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<- 0.020301
t2<-0.018
t3<-0.005
```

```
omega<-EMIS_IN[i]/EN[i] #Gt/EJ
```

#STEP 3: Give values to your initial variables (use the values reported in the table in Section 3).

```
#Initial values
Y[i] <- 80.7 #trillion US$
E[i]<-580 #EJ
EN[i]<-(1-theta)*E[i] #EJ
EMIS_IN[i]<-36.2 #Gt
EMIS_L[i] <-2.5 #Gt
EMIS[i] <- EMIS_IN[i]+EMIS_L[i] #Gt
CO2_AT[i]<-3164 #Gt
CO2_UP[i]<-1694.2 # Gt
CO2_LO[i]<-6380.6  # Gt
Forc[i]<-F2CO2*log2(CO2_AT[i]/CO2_AT_PRE)+F_EX[i] #W/m^2
F_EX[i]<-0.51 #W/m^2
T_AT[i] <-1.1 #ºC
T_LO[i] <-0.0112 #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+g_Y)
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: Create a table to report the following variables: Y, EN, EMIS_IN, EMIS, CO2_AT, T_AT. Create also 3 graphs for the variables Y, EMIS and T_AT. (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)))
```

```
plot(Table[1:101,c("Y")], type="l", xlab= "Year", ylab="Output (trillion US$)", xaxt="n")
axis(side=1, at=c(1,24,44,64,84, 104), labels=c("2017","2040","2060", "2080","2100","2120"))

plot(Table[1:101,c("EMIS")], type="l", xlab= "Year", ylab=expression("CO" [2]*" emissions
(Gt)"),xaxt="n")
axis(side=1, at=c(1,24,44,64,84, 104), labels=c("2017","2040","2060", "2080","2100","2120"))

plot(Table[1:101,c("T_AT")], type="l", xlab= "Year", ylab=expression("Temperature ("^{o}*"C above pre-
industrial)"), xaxt="n")
axis(side=1, at=c(1,24,44,64,84, 104), labels=c("2017","2040","2060", "2080","2100","2120"))
```

 # Re-run the simulations by changing some parameters.

#First, assume that there is a decrease in energy intensity (ε) from 7.19 to 7.19/2 in 2022.

Put the command below after '**(**i **in** 1:T**) {**'
```
if ( i<6){epsilon<-7.19} else {epsilon<-7.19/2}
```

Delete the command:
```
epsilon <- E[i]/Y[i] #EJ/trillion US$
```

(Once you have have done the above, press 'Source'.)

#Second, assume that there is a decrease in the growth rate of output (g_Y) from 0.027 to 0.01 in 2022; keep the energy intensity (ε) equal to 7.19

Put the command below after '**(**i **in** 1:T**) {**'
```
if ( i<6){g_Y<-0.027} else {g_Y<-0.01}
```

Delete the command:
```
g_Y<-0.027
```

(Once you have have done the above, press 'Source'.)