Radiative-convection climate model

The model source code is available at:
http://www.pku-atmos-acm.org/static/other/radiation_convection.zip

Model source: http://vpl.astro.washington.edu/sci/AntiModels/models.html

Note: This is the low-CO_2 version (VMR of CO_2 < 3.55%)

Deadline: 12/21/2020. Please email to Ni Lu (luni@pku.edu.cn)

This problem aims to improve understanding of the energy balance for the Earth surface and the atmosphere, as governed by radiation and convection processes. A 1-D (i.e., vertical) radiative-convection model is used here. Clouds and aerosols are treated as an implicit factor affecting the planetary albedo. Key elements influencing the climate equilibrium include:

1. the amount of incident solar radiation, as determined by solar constant and solar zenith angle (latitude-dependent)
2. The planetary albedo of the Earth, as affected by the ground conditions, clouds, aerosols, air molecules, etc.
3. The greenhouse effects, as determined by the amounts of CO2, H2O, O3 and other GHGs
4. The dry adiabatic lapse rate, as determined by the specific heat capacity of the atmosphere at fixed pressure (Cp) and the gravity acceleration
5. The water vapor content (that has a strong greenhouse effect and affects latent heat transfer)

Several questions are designed below to provoke students' thoughts on climate and climate equilibrium. Some questions require more thoughts and model modifications than others. Please try your best to answer some or all of them. The scoring (评分) will depend on to what the extent and depth a student presents the analysis.

Total scoring (评分): 100% + 20% bonus. Max = 100%

Q1. (Required. 30%) Derive the vertical distributions of temperature, solar flux, thermal flux and heating/cooling rates under radiative equilibrium (i.e., no convection adjustment is considered), for the mid latitude for the present day Earth atmosphere. BRIEFLY comment on the vertical distributions.

*** Use the main program   clima.f_radiation (i.e., cp clima.f_radiation clima.f)

Q2. (Required. 30%) Repeat Q1 but consider the convective adjustment. In addition, demonstrate and discuss how would temperature change if solar zenith angle or albedo changes?

*** Use the main program clima.f_radiation_convection (i.e., cp clima.f_radiation_convection clima.f)

For questions below, please only consider the case with **convective adjustment**.

Q3. (Bonus. 20%) Please demonstrate the dependence on latitude of the temperature and radiation flux profiles. Consider the effects of solar zenith angle and albedo. Please try to show the vertical-meridional distribution of temperature, radiative fluxes, heating rates, etc. It will be nice to show 2-D contour-type plots (e.g., T = f(SZA, ALB)).

Q4_1. (Choose one and only one of Q4_1, Q4_2 and Q4_3. 20%) Demonstrate what could happen if the Earth is closer or further from the Sun. Please take into account the phase (gaseous, liquid, and solid) of water. Can we see a frozen ground? Can we see boiling ocean water (i.e., $T_g \geqslant 100^{\circ}C$). Comment on the runaway greenhouse effect.

*** Runaway greenhouse effect: http://en.wikipedia.org/wiki/Runaway_greenhouse_effect

Q4_2. (Choose one and only one of Q4_1, Q4_2 and Q4_3. 20%) Demonstrate what could happen to the temperature profile if the Earth gravity changes (i.e., because the Earth gets heavier or lighter with a fixed volume). Note that the air density at the same height is changed. Show both pressure and height in the y-axis of the plot.

Q4_3: (Choose one and only one of Q4_1, Q4_2 and Q4_3. 20%) Demonstrate what could happen to the temperature profile if all molecules of O2 and N2 in the atmosphere are replaced by Argon. Note that the air density, the atmospheric absorption and the specific heat capacity are all changed. Show both pressure and height in the y-axis of the plot.

*** Adjust the file IO/mixing_ratio.dat

Q5_1. (Choose one and only one of Q5_1 and Q5_2. 20%) The atmospheric CO2 content is increasing rapidly due to anthropogenic emissions. This will have significant impacts on future climate. Please demonstrate the effects on ground temperature, atmospheric temperature and atmospheric heating/cooling rates when the CO2 mixing ratio decreases to the pre-industrial value of 280 ppm or increases to 2 times, 4 times and 8 times the pre-industrial value. Calculate the climate sensitivity (i.e., increase in the ground temperature when CO2 is doubled from 280 ppm). Does the climate sensitivity remain constant when the amount of CO2 continues to increase, and why? Compare the greenhouse effect of CO2 and CH4.

*** Adjust the file IO/mixing_ratio.dat

Q5_2. (Choose one and only one of Q5_1 and Q5_2. 20%) So far, the relative humidity for each vertical layer is fixed in the model using the Manabe/Wetherald scheme. (This assumption is based on observations, and it implies, among other atmospheric characteristics, a water vapor feedback on anthropogenic warming due to increased GHG emissions.) What would happen to the vertical temperature profile if the Earth atmosphere were much drier/wetter than the present, or if the vertical distribution of relative humidity is changed?

*** Edit the file CONVEC/relhum.f

Reference: Thermal equilibrium of the atmosphere with a given distribution of relative humidity. S Manabe, RT Wetherald – 1967

Quick user guide for the radiative-convection model:

There are two models in separate directories. ATMCHEM (for atmospheric chemistry, e.g., ozone related stuff) and CLIMA (a radiative-convection model. It reads some inputs from ATMCHEM). For this problem, we only have to work on CLIMA.

1. Go to the directory CLIMA/
2. To compile and run, see readme
3. Main program: clima.f
4. Main input setup: IO/input_clima.dat and IO/mixing_ratios.dat
5. Main output file: IO/clima_allout.dat.
   Please edit clima.f (around Line 712-780) to change the output structure, format, etc.
   As default, detailed results are given for the first two and the last three iterations. For intermediate iterations, results are given with fewer details.
6. Default output variables in clima_allout.dat:
   F_CH4: volume fraction of CH_4
   F_CO2: volume fraction of CO_2
   F_O2: volume fraction of O_2
   F_N2: volume fraction of N_2
   IO3: indicator for O_3 (0 = with no ozone, 1 = with ozone)
   IUP: indicator for initialization type (see IO/input_clima.dat)
   NST: indicator for the iteration time (迭代次数)
   dt0: time step (that is varying from one iteration to another)
   TIME: passed simulation time (模拟时间)
   ND: vertical level (same as J below)
   DT(ND): see below

T(ND): see below
DIVF(1): see below
Ftot(ND-1): see FTOTAL below
FtIR(ND-1): see FTIR below
FtSol: see FTSOL below
J: vertical layer (J = 1 for the top layer)
P: pressure in atm
ALT: altitude in km
T: temperature in K
CONVEC: indicator for convection (0 = no convection, 1 = convection, 2 = dry convection)
DT: temperature change from last to the present model iteration, in K
TOLD: temperature from last model iteration, in K
FH2O: volume fraction of H_2O
TCOOL: (longwave) radiative cooling rate in K/day
THEAT: (shortwave) radiative heating rate in K/day
FTOTAL: Net radiative flux (positive for downward flux) in erg/s/cm2 = 0.001 w/m2
FTIR: Net longwave radiative flux (positive for downward flux) in erg/s/cm2 = 0.001 w/m2
FDNIR: Downward longwave radiative flux (defined as a positive value) in erg/s/cm2 = 0.001 w/m2
FUPIR: Upward longwave radiative flux (defined as a positive value) in erg/s/cm2 = 0.001 w/m2
FTSOL: Net shortwave radiative flux (positive for downward flux) in erg/s/cm2 = 0.001 w/m2
FDNSOL: Downward shortwave radiative flux (defined as a positive value) in erg/s/cm2 = 0.001 w/m2
FUPSOL: Upward shortwave radiative flux (defined as a positive value) in erg/s/cm2 = 0.001 w/m2
DIVF: the FTOTAL/FTIR ratio (used to determine when to reach equilibrium and quit the iteration)

Note: At equilibrium, DIVF(1) should be a very small number (e.g., with a magnitude below 1e-3), that is, the outgoing radiation and incoming radiation are approximately in balance at the top of atmosphere. To achieve equilibrium, adjust the parameter NST and TIME (only for ICONSERV = 1) in IO/input_clima.dat

赵洲峤同学的建议（2018/07/24）：

1） 编译时需要保持 ATMCHEM 和 CLIMA 两个文件夹的相对位置，因为编译 CLIMA 的 clima.f 需要读取 ATMCHEM 下面的文件（会自动读取里面的文件，只要别把 ATMCHEM 删了就行了）

2） 编译时需要确保 CLIMA 目录下有 CLIMA.o 和 RRTM.o 这两个文件夹。可以是空文件夹，但不能没有。

3）mixing_ratio.dat 在 ATMCHEM/IO 下面，拷过来就行。四行数字分别代表 Ar、CH4、CO2、O2 的体积分数（详见 ATMCHEM/README.firsttime）

4） 运行前需要将 CLIMA/IO/input_clima.dat 中 ICONSERV 设为 1。

5） ZY 为太阳的天顶角（入射光与垂直方向的夹角），默认值 89.5 相当于水平入射，所以地表温度极低。应当改为 40 左右。

6） SRFALB 为地表反照率，默认值 0.9 相当于雪面，应该改小一些。

7） 这个模式有两个自动终止条件：DIVF<1e-4 或者 DIVF 的正负符号与前一个时次相反。所以它常常会早早地停掉而运行不到预设的步数。尽量检查保证最后一个时次的 DIVF<1e-4。这在 clima.f_radiation_convection 下比较容易实现，但在 clima.f_radiation 下基本无法实现。

8） 在无对流纯辐射（clima.f_radiation）下很难收敛（事实上我就没调收敛过，因为他跳过了许多重要步骤），不过它通常会停在一个差不多的结果上。别太离谱就行。除了 Q1 尽量别用 clima.f_radiation。