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: 11/27. Please email to Jintai Lin (linjt@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 irradiance, 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 CO_2, H_2O, CH_4, O_3 and other GHGs
4. The dry adiabatic lapse rate, as determined by the specific heat capacity of the atmosphere at fixed pressure (C_p) and the gravity acceleration (g)
5. The water vapor content and vertical profile (that has a strong greenhouse effect and affects latent heat transfer)

Several questions are designed below to stimulate thinking on climate equilibrium and climate change. Some questions require more intensive thinking and model modifications than others. 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. Be BRIEF.

*** 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 plots for 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 becomes closer or further from the Sun. Please take into account the phase (gaseous, liquid, and solid) of water and the magnitude of surface albedo. Can we see a frozen ground? Can we see boiling ocean water (i.e., $T_g \geqslant 100^{o}C$). 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 a given height (above ground) 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 O_2 and N_2 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 CO_2 content is increasing rapidly due to anthropogenic emissions. This has significant impacts on climate. Please demonstrate the effects on ground temperature, atmospheric temperature and atmospheric heating/cooling rates when the CO_2 mixing ratio increases from the pre-industrial value of 280 ppm to 2 times, 4 times and 8 times the pre-industrial value. Calculate the equilibrium climate sensitivity (i.e., increase in the ground temperature when CO_2 mixing ratio is doubled from 280 ppm). Does the equilibrium climate sensitivity remain constant when the amount of CO_2 continues to increase, and why? Compare the greenhouse effect of CO_2 and CH_4.

*** 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 information from ATMCHEM as input). For this problem, we only have to work on CLIMA; no changes to ATMCHEM are needed.

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/cm^2 = 0.001 w/m^2
FTIR: Net longwave radiative flux (positive for downward flux) in erg/s/cm^2 = 0.001 w/m^2
FDNIR: Downward longwave radiative flux (defined as a positive value) in erg/s/cm^2 = 0.001 w/m^2
FUPIR: Upward longwave radiative flux (defined as a positive value) in erg/s/cm^2 = 0.001 w/m^2
FTSOL: Net shortwave radiative flux (positive for downward flux) in erg/s/cm^2 = 0.001 w/m^2
FDNSOL: Downward shortwave radiative flux (defined as a positive value) in erg/s/cm^2 = 0.001 w/m^2
FUPSOL: Upward shortwave radiative flux (defined as a positive value) in erg/s/cm^2 = 0.001 w/m^2
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 0.001), 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、CH_4、CO_2、O_2 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。对于中纬度，应当改为 40 左右。

6) SRFALB 为地表反照率，默认值 0.9 相当于新雪表面，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，因为它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。