A flexible tool for diagnosing water, energy and entropy budgets in climate models

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Abstract

We have developed a new flexible software for studying the global energy budget, the hydrological cycle, and the material entropy production of global climate models and reanalyses. The program receives as input 2-D gridded data at the surface, near-surface and TOA, with the requirement that the variable names are in agreement with the Climate and Forecast (CF) conventions for the production of NetCDF datasets. Annual mean maps, meridional sections, time series and global mean values are computed. If a land-sea mask is provided, the program also computes the required quantities separately on the continents and oceans. Depending on the user's choice, the program computes the entropy production from radiative fluxes alone or comparing results with those obtained explicitly resolving the hydrological cycle and its contributions. If required by the user, it also calls the MATLAB software to compute meridional heat transports and location and intensities of the peaks in the two hemispheres. We are currently adapting the program in order to be included in the Earth System Model eValuation Tool (ESMValTool) community diagnostics.

Introduction

Thermodynamics analysis is a useful way to synthetize key properties of the climate system. Based on previous works on Carnot efficiency [4, 1], energy budgets and enthalpy transport [2], material entropy production [3, 1], we propose a diagnostic tool for evaluation of thermodynamics, as reproduced in CMIP climate models or reanalyses. The tool allows for computation of the long-term averaged global scale energy budgets at Top-of-Atmosphere (TOA), at the surface and within the atmosphere as a residual. The meridional energy transports are computed from zonal-mean budgets. The hydrological cycle is diagnosed in terms of latent energy balance. Two methods are used and compared in order to compute the material entropy production, i.e. the production of entropy related to irreversible processes.

Input data

The tool relies on 2-D global scale gridded fields, in principle at any time resolution. Variables are among those usually provided by climate model outputs (cfr. CMIP or ECMWF Reanalysis). Fluxes are usually vertically integrated at the surface and at TOA.

Energy budgets

Top-of-Atmosphere
- Incident SW radiation (S_t^u)
- Upward SW radiation (S_t^d)
- Outgoing LW radiation (L_t)

Surface
- Surface LW radiation (L_s^d, L_s^u)
- Surface SW radiation (S_s^d, S_s^u)
- Turbulent sensible heat flux (H_L)
- Turbulent latent heat flux (H_S)

Hydrological cycle

- Total precipitation (P)
- Snowfall precipitation (Ps)

Rainfall precipitation: $Pr = P - Ps$

Material entropy production

Near-surface
- Humidity (q_s)
- Wind speed (u_s,v_s)
- Pressure (p_s)
- Temperature (T)
- Downward stress (τ_u,τ_v)

Surface
- Evapo-transpiration (e)
- Temperature (T_s)

Methods

Energy budgets

Internal energy budgets

$$\begin{cases} B_t = S_t^d - S_t^u - L_t \\ B_s = S_s^d + L_s^d + H_L + H_S - S_s^u - L_s^u \\ B_a = B_t - B_s \end{cases} ,$$

Meridional heat transports:

$$F_i(\phi) = \int_{-\frac{\pi}{2}}^{\phi} 2\pi R^2 \cos(\phi) < B_i(\phi) > d\phi \, , \qquad (1)$$

where ϕ is the latitude and F_i denotes the total transport (using B_t), the atmospheric transport (using B_a), and the oceanic transport (using B_s). <> denotes zonal means. The Carissimo imbalance correction (cfr. [2]) is applied.

Hydrological cycle

Latent energy:

$$B_l = H_L + L_v Pr + (L_v + L_s) Ps \, ,$$

where L_v and L_s denote the latent heat of vaporization and solidification respectively. The meridional latent energy transport is also computed, according to equation 1.

Material entropy production

Direct method

$$\begin{aligned} \dot{\mathbf{\Sigma}}_{dir}^{mat} &= \dot{\mathbf{\Sigma}}_k + \dot{\mathbf{\Sigma}}_{hs} + \dot{\mathbf{\Sigma}}_e + \dot{\mathbf{\Sigma}}_{pr} + \dot{\mathbf{\Sigma}}_{ps} + \dot{\mathbf{\Sigma}}_{crs} + \dot{\mathbf{\Sigma}}_{csr} \\ &= \int_A \frac{\epsilon_s^2}{T_d} dA - \int_A F_s \left(\frac{1}{T_s} - \frac{1}{T_{BL}} \right) dA - \int_A \frac{L_v e}{T_s} dA + \\ & \left[\int_{A_r} \left(\frac{L_v Pr}{T_C} + g \frac{Prz}{T_p} \right) dA_r + \int_{A_s} \left(\frac{(L_v + L_s) Ps}{T_C} + g \frac{Psz}{T_p} \right) dA_s \right] - \int A_{cs} \frac{L_s Ps}{T_C} dA_{cs} + \int A_{cr} \frac{L_s Pr}{T_C} dA_{cr} \end{aligned}$$

where ($\dot{\mathbf{\Sigma}}$) denote the changes in material entropy production because of: kinetic energy dissipation ($\dot{\mathbf{\Sigma}}_k$), sensible heat fluxes ($\dot{\mathbf{\Sigma}}_{hs}$), evaporation ($\dot{\mathbf{\Sigma}}_e$), rainfall/snowfall precipitation ($\dot{\mathbf{\Sigma}}_{pr}$,$\dot{\mathbf{\Sigma}}_{ps}$), droplet phase changes ($\dot{\mathbf{\Sigma}}_{crs}$); snow->rain, $\dot{\mathbf{\Sigma}}_{crs}$; rain-> snow). ϵ_s denotes the kinetic energy dissipation, z the vertical distance covered by the droplet. T_d, T_{BL}, T_C, T_p are temperatures representative of the boundary layer interior, of the boundary layer top, of the condensation of moist particles in the cloud, of the potential energy associated with the droplets. A_r, A_s, A_{cs} and A_{cr} denote the sub-domains of the global A domain where rainfall and snowfall precipitation, phase changes of the droplets respectively occur.

Indirect method

$$\dot{\mathbf{\Sigma}}_{ind}^{mat} = \dot{\mathbf{\Sigma}}_{ver} + \dot{\mathbf{\Sigma}}_{hor} = \int_A (S_s + L_s) \left(\frac{1}{T_s} - \frac{1}{T_E} \right) dA + \int_A \frac{S_t + L_t}{T_E} dA \, ,$$

where $\dot{\mathbf{\Sigma}}_{ver}$ and $\dot{\mathbf{\Sigma}}_{hor}$ denote the material entropy production by vertical transport of radiation between surface and TOA, and by large-scale horizontal enthalpy transports. S_s, L_s, S_t and L_t denote the net LW and SW radiative fluxes at TOA and at the surface respectively. T_E is the emission temperature, computed from L_t by means of Stephan-Boltzmann law.

Comments

- When averaging over long-term periods (>1yr) $\dot{\mathbf{\Sigma}}_{ind}$ is expected to equal $\dot{\mathbf{\Sigma}}_{dir}$ (the radiative fluxes have to be well balanced in the vertical column);
- $\dot{\mathbf{\Sigma}}_k$ is the minimal entropy produced in the system by irreversible processes, which is equal to the intensity of the Lorenz Energy Cycle ($\overline{W}$);
- $\dot{\mathbf{\Sigma}}_k$ is bounded from below by the horizontal enthalpy divergence (i.e. $\dot{\mathbf{\Sigma}}_{hor}$);

Metrics

The program provides further metrics describing the thermodynamic state of the climate system:

- The degree of irreversibility of the system can be defined [1] as the ratio

$$\alpha = \frac{\dot{\mathbf{\Sigma}}_{ex}}{\dot{\mathbf{\Sigma}}_k} \, ,$$

where $\dot{\mathbf{\Sigma}}_{ex}$ denotes the sum of all other contributions exceeding the kinetic energy dissipation term in the direct method equation;

- A measure of the baroclinic efficiency [4] is given dividing the domain in a subdomain of TOA net energy gain ($A_>$) and net energy loss ($A_<$), and averaging the emission temperature over these sub-domains:

$$\eta = \frac{T_E^{>} - T_E^{<}}{T_E^{>}}$$

References

[1] Knietzsch M-A, Schröder A, Lucarini V, Lunkeit F (2015) The impact of oceanic heat transport on the atmospheric circulation. Earth Syst Dyn 6:591–615. doi: 10.5194/esd-6-591-2015

[2] Lucarini V, Ragone F (2009) Energetics of PCMDI/CMIP3 Climate Models: Energy Budget and Meridional Enthalpy Transport. 57. doi: 10.1029/2009RG000323.1

[3] Pascale S, Gregory JM, Ambaum M, Tailleux R (2011) Climate entropy budget of the HadCM3 atmosphere–ocean general circulation model and of FAMOUS, its low-resolution version. Clim Dyn 36:1189–1206. doi: 10.1007/s00382-009-0718-1

[4] Pauluis O (2011) Water Vapor and Mechanical Work: A Comparison of Carnot and Steam Cycles. J Atmos Sci 68:91–102. doi: 10.1175/2010JAS3530.1

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