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Time and space scale analysis of the climate entropy budget

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Nonequilibrium thermodynamics is becoming increasingly important for studying complex systems such as Earth's climate. In particular, material entropy production is a key quantity which gives insights into the strengths of the irreversible processes taking place within it. Whether it be in models or measurements, entropy production is generally estimated starting from the ratio between diabatic heating and temperature. However its dependence on time and space resolution involved in data processing has not been extensively explored so far. It is therefore relevant for both observational and theoretical purposes to know how the climate entropy budget is affected by different coarse graining with respect to time and space and what are the errors involved when certain time means (e.g. annual) are used in place of others (e.g. daily). Here we study the effect of the combined space and time averaging of the material entropy production (direct and indirect formula), entropy production due to kinetic energy dissipation, hydrological cycle and ocean turbulence. Time coarse graining shows that material entropy production decreases as the averaging period is increased. Daily cycle and seasonal cycle are the main signals which can be observed. The indirect formula (Goody, 2000) gives an underestimate of 4% and 10%, which is found to be connected to neglecting the correlations associated with the daily and seasonal cycles. The direct formula is less sensitive and shows errors of 2% and 4% respectively which are mainly due to the response of the hydrological cycle. The material entropy production due to small-scale ocean turbulence shows a sharp decrease ($\sim 45\%$) linked to the variations in the seasonal thermocline. We then take into account a spatial coarse graining in which diabatic heatings and temperature are systematically re-gridded at coarser horizontal and vertical resolutions, from the models maximum resolution, down to a zero-dimensional space. It is found that entropy budget terms decrease when the spacial resolution is decreased as would be expected from general coarse-graining theory. In particular when the horizontal resolution is completely reduced (column model), the remaining material entropy production if found to be about 40 mW m^2 K^{-1}, thereby losing nearly 10 mW m^2 K^{-1}. Additionally, when the vertical resolution is reduced to one layer, a value of about 10 mW m^2 K^{-1} is obtained so that 40 mW m^2,$^{-1}$ is lost in the collapse of the vertical dimension. These results are in agreement and reinforce the entropy budget partition associated with horizontal and vertical processes as proposed by Lucarini et al. (2011) and suggest that the model in consideration, although not designed for dealing with entropy production, behaves fairly consistently with the second law of thermodynamics.