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THE GLOBAL AVAILABLE ENERGY AND ITS TRENDS

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1. INTRODUCTION

Lorenz (1955) introduced the theory of available potential energy (APE) and defined it as the difference in the total potential energy (i.e. the sum of internal and gravitational potential energies) of the observed state of the atmosphere and the total potential energy of a reference atmosphere that can be achieved by an adiabatic and reversible redistribution of mass in which the entropy of a parcel is conserved. This reference state is one for which the enthalpy is minimized. The original theory accounted only for a dry atmosphere, but Lorenz (1978, 1979) extended the theory to include moisture as well.

The available energy of a thermodynamic system represents the amount of useful energy that can be extracted and is also known as the exergy or the free energy. Unlike Lorenz' APE, these quantities are usually defined with respect to a reference state that is isothermal. Using this same approach, Bannon (2012) used a generalized Gibbs' function to determine the available energy of geophysical systems. An availability function is defined as the difference between the observed atmospheric state and a reference atmosphere that is isothermal and hydrostatic. The temperature at which the availability function is minimized uniquely defines an equilibrium atmosphere. Like Lorenz' theory, this is the difference between the total potential energy of the system and the total potential energy of a reference system, but the specification of the reference state is different here. Instead of the entropy of each parcel being conserved, the entropy of the entire system is conserved. This approach is more general than that of Lorenz and includes contributions from water vapor, hydrometeors, terrain, as well as baroclinic and convective contributions.

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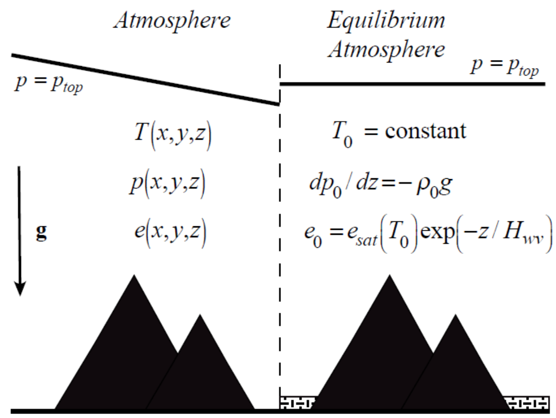

Fig. 1: A schematic of the observed (left) and equilibrium (right) atmospheres. The equilibrium atmosphere is isothermal and hydrostatic and contains an "ice rink" at the surface.

Because the available energy represents a maximum amount of energy in a system that can be converted into kinetic energy, it is of interest to determine what this value is globally as well as locally, and whether global reanalysis data is showing any trends in the available energy.

2. BACKGROUND THEORY

a. The Availability Function

As shown in Bannon (2012), the available energy is given by,

$$\delta a_j = \delta h_j - T_0 \delta s_j - \alpha_j \delta p_j \qquad (1)$$

where h_j is the specific enthalpy, T_0 is the equilibrium temperature that minimizes the function, s_j is the specific enthalpy, α_j is the specific volume, and p_j is the partial pressure. The *j* subscript can be equal to *d*, *v*, *l* or *i*, which refer to dry air, water vapor, liquid water, and ice, respectively. Here, the δ symbol indicates a finite difference between the atmosphere and its reference state. By integrating (1) over all grid points and for each component, the available energy of the global atmosphere can be calculated by determining the temperature for which it is minimized.

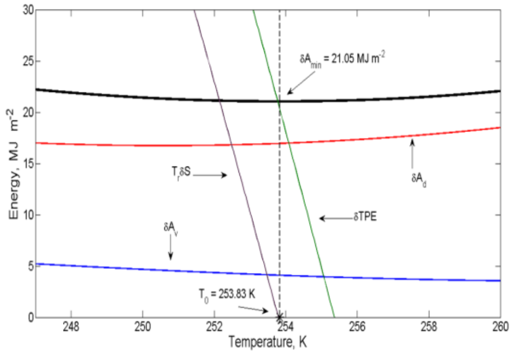

Fig. 2: The availability functions for a climatological atmosphere. The black, red and blue curves represent the total, dry and water vapor available energies, respectively. The equilibrium temperature is indicated by the dashed line, while the green and purple lines are the change in total potential energy and change in total entropy, respectively.

b. The Equilibrium atmosphere

The observed state of the atmosphere is given as in the left hand side of Figure 1. Temperature, pressure and moisture all vary spatially, the top of the atmosphere is a sloping pressure surface, and the surface of the planet contains varying terrain. In contrast, the equilibrium atmosphere, which must contain the same total mass as the observed atmosphere, is isothermal and hydrostatic, and so moisture and pressure vary only in the vertical, and temperature is constant. This results in a flat top to the atmosphere. In practice, the equilibrium temperature is always below freezing and this would result in a supersaturated equilibrium state. To account for this, any vapor in excess is condensed into an “ice rink” of equal depth everywhere, laying on the surface of the planet.

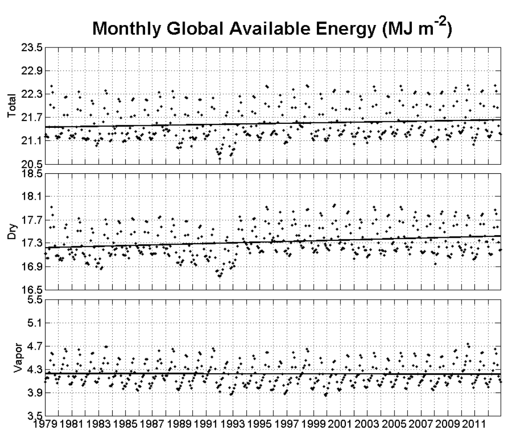

Fig. 3: The global available energy as calculated for each of the 408 months. The total and dry global available energies are increasing while the available energy of water vapor is decreasing slightly.

3. DATA

Using 34 years of monthly mea Era-Interim reanalysis data at a 1.5 by 1.5 degree resolution at all 37 pressure levels from 1000 up to 1 hPa, the availability function was computed and minimized to determine the equilibrium atmosphere for each month.

To examine trends, the available energy at every grid point for the 408 months in the 1979-2012 period is fit with a linear least squares curve. The significance of the fit is determined by using a Student’s t-test.

4. RESULTS

a. Minimization of the Availability Function

In Figure 2, the minimization of the availability function for the 34 year mean climatological atmosphere is shown. The thick black line is the sum the dry air and water vapor available energies, the red line is the dry air component alone and the blue line is the water vapor component alone. The dashed black line shows the equilibrium temperature of 253.83 K. Additionally, the green line shows the change in total potential energy and the purple line shows the change in total entropy multiplied by the reference temperature. Note that this vanishes exactly at the equilibrium temperature and that the availability function and the change in total potential energy are equal here.

Globally, the dry available energy accounts for 17.25 of the 21.05 MJ m^{-2} total while the water vapor contributes the bulk of the rest, with the hydrometeors having a negligible contribution. These global values are about 5 times as large as those found using the APE of Lorenz.

b. The Global Available Energy

The global available energy is plotted in Figure 3 for each of the months in the analysis period. This figure also breaks it down into the contributions from dry air and water vapor. A clear seasonal cycle is evident in all three plots with the maximum values coming in boreal summer.

The linear trend for each is plotted as a solid black line. Both the total available energy and that due to dry air show a positive trend (total change of 0.188 and 0.200 MJ m^{-2}, respectively), while the available energy due to water vapor shows a small negative trend of an order of magnitude smaller (-0.015 MJ m^{-2}.) All trends are significant at the 95% confidence level.

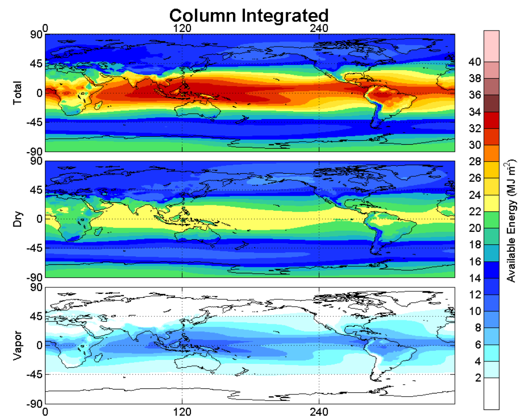

Fig. 4: The column integrated values of available energy. The upper panel is the sum of dry and vapor components, and the lower two are the dry and vapor contributions alone, respectively.

c. The Geographical Distribution

Figure 4 shows the column integrated 34 year mean values of available energy for dry air, water vapor, and their sum. The available energy of water vapor contributes only in the tropics, but even there it is the lesser contributor to the total available energy. The most available energy is over the tropical Pacific Ocean as well as over the tropical rainforest regions of the Amazon and the Congo.

A second maximum is seen coming from the dry air component over the Antarctic continent. As it turns out, this is coming from the tropopause of the South Pole, as seen in Figure 5. This figure shows the zonal mean values of available energy. There are two areas from which the large values of available energy are coming from in the tropics: the tropopause and the surface. Relative minima exist through much of the troposphere north and south of about 45 degrees, as well as above approximately 500 hPa.

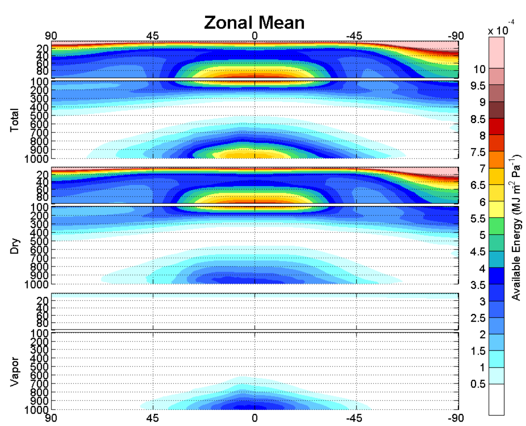

Fig. 5: The zonal mean available energy of total, dry air and water vapor. Note that the values are MJ m^{-2} Pa^{-1}.

d. The Geographical Distribution of Trends

In Figure 6, the trends in column integrated values are plotted as a total change over the period analyzed. Despite the vapor contribution being smaller than that of dry air, it almost completely dominates the total trend in the tropics. There is a large region of decreasing available energy over the central and eastern Pacific and a smaller region of increase over the western Pacific. The dry air contribution also indicates an increase in available energy over most of the northern hemisphere land masses.

A closer look at what is occurring in the tropics is plotted in Figure 7 which shows the mean over ±10 degrees. Figures 6 and 7 appear to indicate that the Walker circulation is increasing in strength, or equivalently that the atmosphere is trending toward a more La Nina-type structure.

Lastly, Figure 8 shows the trends in the zonal mean of the available energy. A small region of decrease appears in the vapor contribution near the surface here. The increasing available energy of dry air near the surface in the northern hemisphere is once again evident. More strikingly, the stratosphere is showing large trends with high confidence. Decreasing available energy near 100 hPa and increases just above appear to be indicative of an upward shift in the pressure level of the tropopause. This is, however, not the case over the North Pole as it is over the rest of the atmosphere.

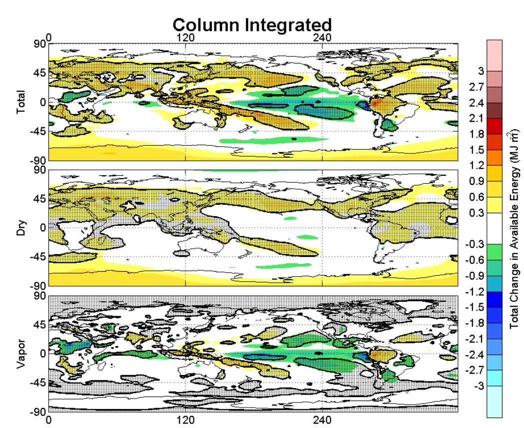

Fig. 6: A linear least-squares fit is used to determine the total change in the column integrated available energy. Stippled contours represent regions where the trend is significant at the 95% confidence level.

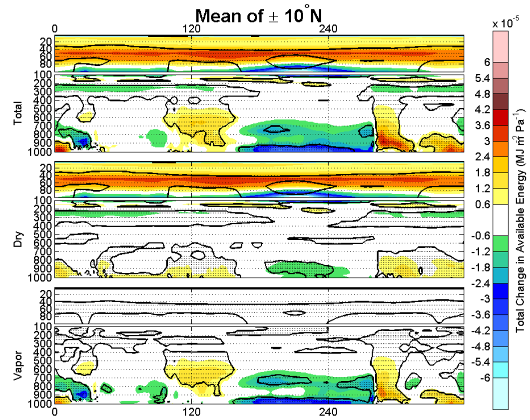

Fig. 7: The total change in available energy over the equatorial region. Stippled contour represent regions where the trend is significant at the 95% confidence level.

5. SUMMARY AND CONCLUSIONS

The available energy is a measure of the maximum kinetic energy. It is more general than the APE of Lorenz because it includes contributions from dry air, water vapor, hydrometeors, convective and baroclinic redistributions of mass and simply incorporates real topography. For these reasons, the available energy is about 5 times as large at the APE, globally. Globally, the available energy is dominated by dry air contributions, but the contributions from water vapor are important in the tropics.

Over the period analyzed, the global available energy was decreasing in ERA-Interim Reanalysis data. In particular, a pattern in the Pacific appears to show an increase in the strength of the Walker circulation. The northern hemisphere land masses are also showing increases in available energy. Lastly, the tropopause is shifting upward toward lower pressure over most of the planet, with the North Polar region being the notable exception.

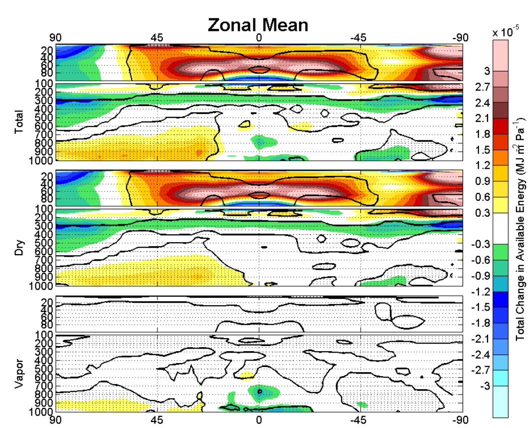

Fig. 8: Total change in the zonal mean available energy. Stippled contour represent regions where the trend is significant at the 95% confidence level.

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