

Observed changes in surface atmospheric energy over land

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[1] The temperature of the surface atmosphere over land has been rising during recent decades. But surface temperature, or, more accurately, enthalpy which can be calculated from temperature, is only one component of the energy content of the surface atmosphere. The other parts include kinetic energy and latent heat. It has been advocated in certain quarters that ignoring additional terms somehow calls into question global surface temperature analyses. Examination of all three of these components of atmospheric energetics reveals a significant increase in global surface atmospheric energy since the 1970s. Kinetic energy has decreased but by over two orders of magnitude less than the increases in both enthalpy and latent heat which provide approximately equal contributions to the global increases in heat content. Regionally, the enthalpy or the latent heat component can dominate the change in heat content. Although generally changes in latent heat and enthalpy act in concert, in some regions they can have the opposite signs. **Citation:** Peterson, T. C., K. M. Willett, and P. W. Thorne (2011), Observed changes in surface atmospheric energy over land, *Geophys. Res. Lett.*, *38*, L16707, doi:10.1029/2011GL048442.

1. Introduction

[2] The total energy content of a parcel of air at any pressure level is given by the sum of the kinetic energy, latent heat, enthalpy, and gravitational potential energy. This can be written as:

$$\text{Total Energy} = \frac{1}{2} m v^2 + L q m + m C_p T + m g z \quad (1)$$

where m is the mass of the parcel of air (kg), v is the velocity or speed of the air in m s^{-1} , L is the latent heat of evaporation (J kg^{-1}), q is the specific humidity (kg kg^{-1} though usually given in g kg^{-1}), C_p is the specific heat of air at constant pressure ($\text{J K}^{-1} \text{kg}^{-1}$), T denotes the absolute temperature in Kelvin, g is the acceleration of gravity (m s^{-2}), and z is the geometric height (m) [*Hastenrath*, 1969; *Lorenz*, 1955]. To simplify the following analysis, we will consider a 1 kg parcel of air. Since we are discussing atmospheric energetics near the surface of the earth, we can ignore gravitational potential energy. The remaining terms of the equation can be divided into kinetic energy:

$$\text{KE} = \frac{1}{2} v^2 \quad (2)$$

and heat content which is the sum of the enthalpy and latent heat:

$$H = C_p T + L q \quad (3)$$

Heat content, H , [*Pielke et al.*, 2004] has also been referred to as moist static energy [*Pielke et al.*, 2004] and moist enthalpy [*Davey et al.*, 2006].

2. Data

[3] The bane of long-term in situ data analysis is inhomogeneities due to changes in the observing systems such as station moves or installation of a new hygrometer [*Peterson et al.*, 1998]. While observations of temperature, humidity and winds may be hourly or even more frequent, assessments and adjustments to account for inhomogeneities, at least to date, have generally been applied to means averaged over multiple days [e.g., *Aguilar et al.*, 2003]. Therefore, we use monthly and five day mean (pentad) data that have undergone quantitative quality control and homogeneity analysis.

2.1. Analysis of Global Averages

[4] The monthly global-mean specific humidity data are based on the HadCRUH land dataset [*Willett et al.*, 2008]. Although the spatial station coverage is quite good, humidity data for the majority of the stations were not internationally exchanged until the advent of the Global Telecommunications System in the early 1970s. Therefore global analysis does not start until 1973 and ends in 2003 because HadCRUH is not yet regularly updated.

[5] The monthly temperature data come from the Global Historical Climatology Network Monthly (GHCN-M) Version 3 [*Lawrimore et al.*, 2011]. These data are updated through 2010 and have adequate global coverage to go back to 1880, but in keeping with the humidity data we consider 1973 onwards.

[6] Global land surface wind data come from hourly or synoptic observations taken at meteorological stations [*Lott et al.*, 2008]. The homogeneity assessed data start in 1979 and come from two analyses, *Vautard et al.* [2010] and *McVicar et al.* [2008]. These data were combined, updated through 2010 and analyzed globally by *Peterson et al.* [2011].

2.2. Analysis of Spatial Variations

[7] Pentad anomaly and climatology (1974–2003) specific humidity station data are obtained from the HadCRUH dataset. For consistency of spatio-temporal sampling, rather than using GHCN-M temperature data, simultaneous pentad mean anomaly temperature observations from the source data used in HadCRUH (extracted in 2003) [*Lott et al.*, 2008], are used to calculate the enthalpy term. The tem-

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Table 1. Summary of Changes in Atmospheric and Oceanic Energy^a

	Unit
Kinetic Energy	$-0.63 \text{ J kg}^{-1} \text{ decade}^{-1}$
Latent Heat	$270 \text{ J kg}^{-1} \text{ decade}^{-1}$
Enthalpy	$300 \text{ J kg}^{-1} \text{ decade}^{-1}$
Total Heat Content	$570 \text{ J kg}^{-1} \text{ decade}^{-1}$
Total Energy	$570 \text{ J kg}^{-1} \text{ decade}^{-1}$
Heat Content of bottom 2 m of the global atmosphere over land	$1.9 \times 10^{17} \text{ J decade}^{-1}$
Heat Content of the top 2 m of the global ocean	$3.7 \times 10^{20} \text{ J decade}^{-1}$
Heat Content of top 700 m of the global ocean	$\sim 4.2 \times 10^{22} \text{ J decade}^{-1}$

^aAs documented in the paper, the period of record differs depending on the data source, but all start in the 1970s and end in the 2000s.

perature data have undergone quality control as part of HadCRUH development. The locations of breakpoints found for the specific humidity data were used to apply adjustments to the temperature data also [Willett *et al.*, 2008]. This will capture the majority of inhomogeneities but will not take into account changes that impact solely dry-bulb temperature measurements. Equally, it is possible that adjustments may have been made to the temperature data when in fact an inhomogeneity only occurred in the wet-bulb or humidity sensor. This is not ideal as clearly some biases will remain in the data at a few stations but the errors are unlikely to alter the broad conclusions drawn from the results. However, as temperature adjustments are calculated using the temperature candidate minus neighbor difference series, where differences are small, these adjustments will be negligible.

[8] Climatological pentad mean temperatures are obtained from a 2010 extraction of Lott *et al.* [2008] stations in HadCRUH. Due to data updates, a more rigorous quality control procedure, and a strict missing data criterion, there are fewer stations than in HadCRUH (2496 as opposed to 3236). These data have not undergone homogenization but this is unnecessary given that they are only providing a climatology.

3. Changes in Global Average Energy

3.1. Latent Heat: L q

[9] The specific humidity, q , over land has increased between 1973 and 2003 at an average rate of $0.11 \text{ g kg}^{-1} \text{ decade}^{-1}$ [Willett *et al.*, 2008]. Based on New *et al.* [1999], the NOAA's National Climatic Data Center (NCDC) calculated the global average annual land surface mean temperature to be 8.5°C (www.ncdc.noaa.gov/cmb-faq/anomalies.html). At 8.5°C , the value of L , which varies with temperature, is calculated to be 2480 J g^{-1} of water vapor [Henderson-Sellers, 1984]. On average then, a parcel of air containing 1 kg of dry air near the surface gained latent heat at a rate of $270 \text{ J decade}^{-1}$ (note that given the uncertainties involved in this and other calculations, we retain only two significant figures). Accounting for temperature-dependent variations of L would not change this result by more than a few percent at individual stations and would tend to cancel in the global mean (Section 4).

3.2. Enthalpy: C_p T

[10] C_p , the specific heat of dry air at constant pressure is $1005.7 \text{ J K}^{-1} \text{ kg}^{-1}$ [Glickman, 2000]. The specific heat of

the moisture in the air at constant pressure is $1952 \text{ J K}^{-1} \text{ kg}^{-1}$ [Wallace and Hobbs, 1977]. Using data from Willett *et al.* [2008] global average specific humidity was calculated to be 9.6 g kg^{-1} . This level of humidity would mean an average parcel of moist air would have a specific heat of $1015 \text{ J K}^{-1} \text{ kg}^{-1}$. The change in average temperature over land surfaces during the period 1973 through 2010 is $0.291 \text{ K decade}^{-1}$ (the trend is the same to three significant digits should we limit the analysis to end in 2003) according to area-averaged analysis of GHCN-M land surface data available from NCDC (<http://www.ncdc.noaa.gov/cmb-faq/anomalies.html>). Therefore, the enthalpy of an average 1 kg parcel of air has been increasing at a rate of $300 \text{ J decade}^{-1}$.

3.3. Kinetic Energy: $\frac{1}{2} v^2$

[11] Observations of homogeneous subsets of surface winds indicate that wind speeds have been decreasing since the start of the global analysis in 1979 [Peterson *et al.*, 2011]. Because reanalyses do not show similar decreases, the cause for the decrease in observed wind speed is hypothesized to be at least partly due to increases in surface roughness associated with enhanced vegetation growth, partly in response to increasing air temperatures and CO_2 at many of the locations with adequate long-term wind speed observations [Vautard *et al.*, 2010; McVicar and Roderick, 2010]. Whatever the cause, the average rate of decrease across the sampled regions of the globe is $0.093 \text{ m s}^{-1} \text{ decade}^{-1}$ [Peterson *et al.*, 2011].

[12] Since kinetic energy is proportional to the square of the wind speed, a decrease of $0.093 \text{ m s}^{-1} \text{ decade}^{-1}$ represents a larger decrease in kinetic energy in high wind areas than low wind areas or for a particular station during windier as opposed to calmer times of the year. However, for purposes of this simple estimate, we will use the change in mean wind speed averaged over the 11,853 stations which have at least 5 years of observations by Lott *et al.* [2008], rather than the change at each individual station. The locations of these stations are given by Peterson *et al.* [2011]. The average observed wind speed at these sites is 3.39 m s^{-1} .

[13] A $0.093 \text{ m s}^{-1} \text{ decade}^{-1}$ decrease in wind speed for a 1 kg parcel of air with an average speed of 3.39 m s^{-1} represents a change in kinetic energy of $-0.63 \text{ J decade}^{-1}$ between 1979 and 2010. The neglect of inter-station or even intra station variation has negligible impact on the final results; even if the mean wind speed was three times faster (10.17 m s^{-1}) the calculated change in kinetic energy would still only be $-0.95 \text{ J decade}^{-1}$, which is over two orders of magnitude smaller than either of the thermal components (see Table 1). A direct assessment of observed changes in kinetic energy in Northern Hemisphere surface winds also indicated that, on average, it has been decreasing (R. Vautard, unpublished data, 2010).

3.4. Ocean Heat Content for Comparisons

[14] Seven different time series of global ocean heat content from 0 to 700 m depth are presented by Kennedy *et al.* [2010]. The average of the four of these time series with data from 1973 to near present indicate an increase in ocean heat content of $\sim 4.2 \times 10^{22} \text{ J decade}^{-1}$. For a more direct comparison to the surface atmosphere it is possible to calculate the change in ocean surface heat content using sea surface temperature (SST) data. Smith *et al.* [2008] data, available from <http://www.ncdc.noaa.gov/cmb-faq/anomalies.html>, indicate that the global ocean surface temperature from 1973

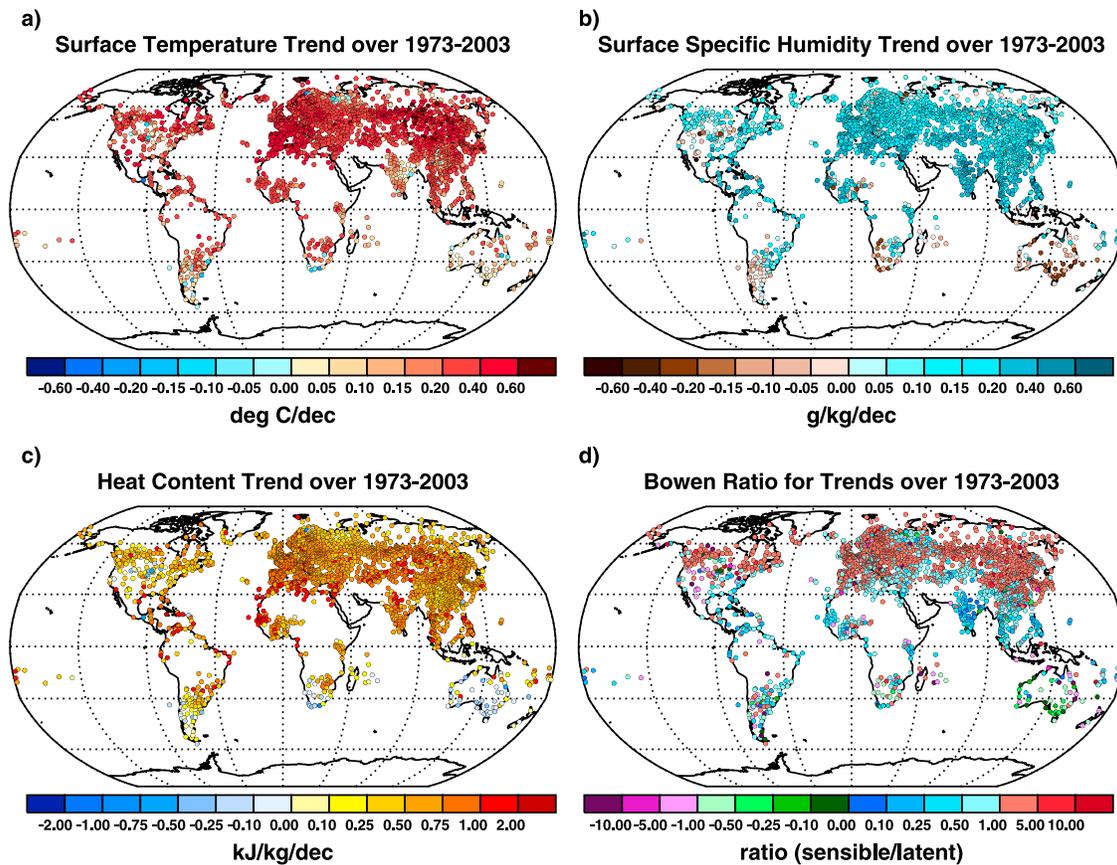


Figure 1. (a–d) Decadal trends (1973–2003) calculated for HadCRUH stations using pentad anomaly specific humidity and temperature and pentad climatologies (1974–2003) from *Lott et al.* [2008]. A heat content equation was used where L varies with temperature as provided by the climatological pentad mean $(1.0057 \cdot T) + (q \cdot (1918.46 \cdot ((T + 273.15)/(T + 273.15) - 33.91))^2)$ where T is in $^{\circ}\text{C}$ and q is in kg kg^{-1} .

through 2010 has been increasing at a rate of $0.125 \text{ K decade}^{-1}$. That same web page indicates that the global average SST is 16.1°C which, according to Appendix 3 of *Gill* [1982], corresponds to an average density of sea water of $1025.7 \text{ J kg}^{-1} \text{ K}^{-1}$ and a heat capacity of 3991 J kg^{-1} . The area of the global ocean is $3.61 \times 10^8 \text{ km}^2$ [*Barnes-Svarney*, 1995]. Therefore, the top two meters of the ocean has been gaining heat content at a rate of $3.7 \times 10^{20} \text{ J decade}^{-1}$.

4. Spatial Analysis

[15] Almost the entire world is experiencing increases in surface temperature (Figure 1a). While specific humidity is, on average, increasing, Figure 1b shows large regions, particularly in the Southern Hemisphere sub-tropics, where it is decreasing from 1973 to 2003. Heat content also shows regional decreases in the Southern Hemisphere, although not always concurrent with drying alone (Figure 1c). Figure 1d of the Bowen ratio for the heat content trends, that is, the change in sensible heat divided by the change in latent heat, provides additional insight into the relative influence of these factors. Generally speaking, the high northern latitudes tend to have larger Bowen ratios, where a ratio greater than one implies that changes are dominated by sensible heat. In the lower latitudes the Bowen ratio tends to be less than one indicating that the latent heat component is dominant. The Bowen ratio helps to identify regions where temperature and

humidity are acting in concert and where they are not – which is unclear from the heat content analysis alone.

[16] To examine these factors more closely, examination of Figure 2 reveals that the trends in specific humidity tend to be higher in warmer annual mean temperatures. Also, the higher the annual mean specific humidity, the lower the temperature trend tends to be. This makes physical sense based on the Clausius-Clapeyron relationship. For example, where the annual mean temperature is warmest, (i.e., the tropics) it tends to be easier for inputs of additional energy to go into latent heat. The same is true for regions with high annual mean specific humidity which indicate not only availability of water but also high temperatures. This partitioning of energy between moist and dry terms likely helps to partially explain why temperature trends are greatest in high latitudes and humidity trends, in absolute terms, are greatest in low latitudes.

5. Discussion

[17] Increasing heat content of the surface atmosphere does not necessarily increase moist available enthalpy [*Marquet*, 1993] let alone the probable release of that enthalpy. For moist available enthalpy is dependent not only on the heat content or moist enthalpy within a parcel of air but also of the conditions in the atmosphere above that parcel which may also have changed over time. While numerous studies

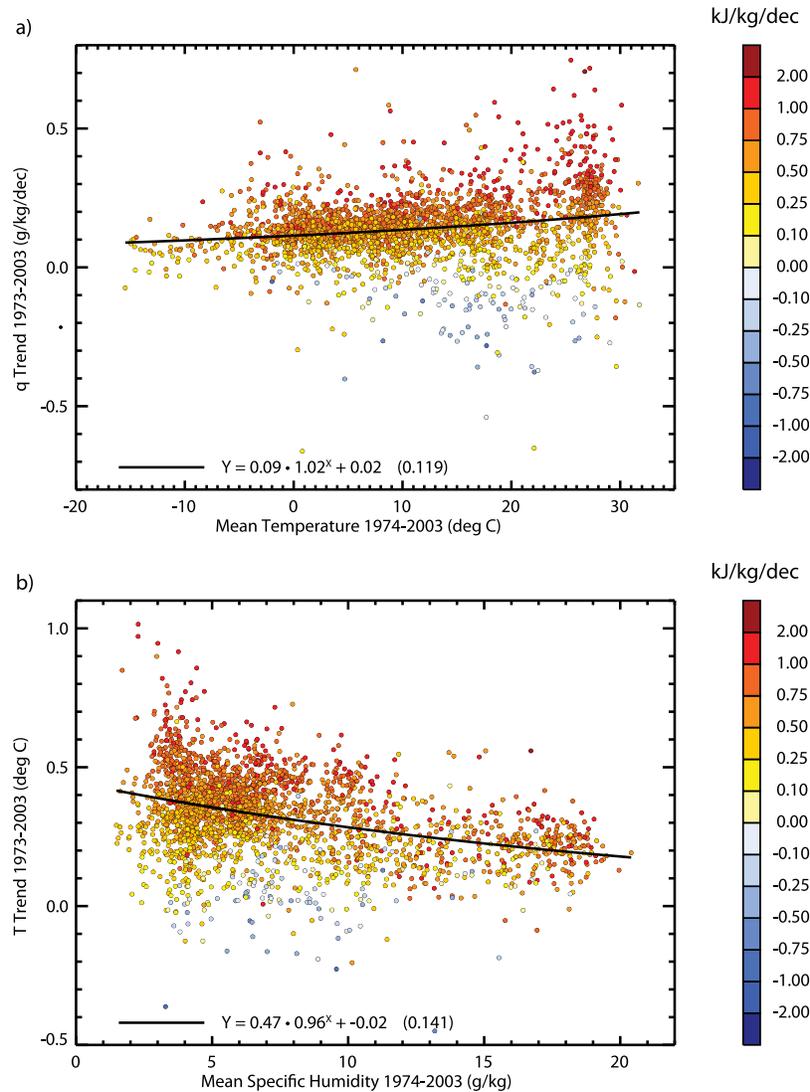


Figure 2. The relationship between temperature and specific humidity for global land surface stations. The dot colors represents the heat content trend as in Figure 1. (a) Generally the warmer the annual mean temperature, the higher the increases in humidity. (b) Conversely, examination reveals that the greater the annual mean specific humidity, the lower the temperature trend. Figures 2a and 2b have a line showing an exponential fit to the data with the best fit equation shown along with the RMS error of the residuals given in brackets.

identified increases in heavy precipitation events [e.g., *Karl et al.*, 2009], a phenomenon which has been causally linked to human activities [*Min et al.*, 2011], the results of this study do not necessarily imply that moist available enthalpy has increased as we did not assess atmospheric energy above the surface level.

[18] This analysis intentionally excluded certain considerations that would not have significantly impacted the results. Observed decreases in wind speed may be disproportionately greater in light wind conditions or during strong winds which would impact the assessed change in kinetic energy. However, even if the changes primarily occurred during the strongest winds, the change in kinetic energy would still be orders of magnitude less than the changes in heat content. Also, increases in humidity may primarily occur in warm seasons or places, or cold seasons or places. Despite the temperature dependence of the latent heat of evaporation value, at 20°C this is only 1% less than that at

8.5°C [*Henderson-Sellers*, 1984]. Hence, this refinement would also have produced similar results. So in terms of the total energetics of the surface atmosphere, the results with or without these additional considerations are essentially the same: in recent decades the lower atmosphere has been gaining energy with the increase in temperature and water vapor providing approximately equal contributions while the observed reduction in kinetic energy is more than two orders of magnitude less.

[19] The heat content of the upper ocean has become a heavily utilized metric of global climate change [e.g., *Palmer et al.*, 2010]. Some authors argue that the heat content of the surface atmosphere should also be a key metric. Indeed, the “concept of ‘global warming’ requires assessments of units of heat (that is, Joules)” according to *Pielke et al.* [2004]. *Davey et al.* [2006] argue that global surface temperature is not a “proper” measure of the heat content of the Earth’s climate system; which is true as it is just a measure of

temperature. But *Pielke et al.* [2007] go even further to claim that “ignoring concurrent trends in surface air absolute humidity therefore introduces a bias in the analysis of surface air temperature trends” and that we “need to include absolute humidity in order to describe observed temperature trends.”

[20] Temperature and humidity are distinctly different physical parameters as implied by their units of K and g kg^{-1} , and they are measured by different instrumentation. Therefore, we do not understand how ignoring humidity could bias an analysis of temperature trends or why an assessment of humidity would be required in order to describe trends in temperature. We do, however, have concerns about the potential for the general public to misinterpret heat content analysis. Figure 1 shows that heat content tends to be decreasing in Australia despite increases in surface temperature. Presenting heat content as the primary metric for global warming could lead lay readers to erroneously perceive Australia as cooling – after all, its heat (content) is decreasing. Our concern is not just nomenclature. Heat content by any other name if used as a global warming metric has the potential to imply cooling even in places with increasing temperature simply because the location is becoming dryer.

[21] Atmospheric temperature is a much less complex concept. Additionally global analysis of heat content using surface data cannot, at this point, extend farther back in time than the early 1970s, being limited by the lack global digitized humidity observations. Therefore, whilst herein presenting global changes in heat content over land surfaces, the authors’ view is that global temperatures with their greater coverage, heritage and longer period of record remains the preferred metric. Furthermore, we note that broadly relative humidity has remained constant at the largest spatial scales [*Willett et al.*, 2008], with a possible recent decrease [*Simmons et al.*, 2010]. This implies widespread absolute moistening that scales for the most part with temperature as expected based on the Clausius–Clapeyron equation and demonstrated over land by *Willett et al.* [2010]. Coupling this with the results that total heat content went up at approximately twice that of enthalpy, implies that changes in global temperatures can provide a reasonable estimate of total heat content changes.

6. Concluding Remarks

[22] The change in energetics of the surface atmosphere over the last 40 years is dominated by heat content as changes in kinetic energy were small. Increases in both the temperature and the humidity components are consistent with theory and expectations of anthropogenic climate change [*Solomon et al.*, 2007]. However, it can be helpful to put this amount of energy into perspective, such as determining its conversion into gravitational potential energy. The density of the atmosphere in low-lying land areas is approximately 1.2 kg m^{-3} [*Committee on Extension to the Standard Atmosphere*, 1976]. So a cylinder of air 100 m in diameter and two m high holds approximately 18,800 kg of air. Our analysis indicates that on average, this amount of air is gaining energy at a rate of $1.1 \times 10^7 \text{ J decade}^{-1}$. The Gravitational Potential Energy (in joules) of an object held above the earth equals the mass of the object, times gravity, times the distance it is above the earth (see equation 1). The

heaviest car we own, Dr. Thorne’s SUV, weighs 1,535 kg and our lightest vehicle, Dr. Willett’s bicycle, weighs 9.5 kg. For these objects to gain the equivalent amount of gravitational potential energy as this two m tall by 100 m diameter cylinder of air gained in heat content, the car would have to rise $700 \text{ m decade}^{-1}$ while after 10 years the bicycle would be just above the mesosphere at an elevation of 110 km.

[23] The global land surface covers approximately $1.49 \times 10^8 \text{ sq km}$ [*Barnes-Svarney*, 1995]. Using the Standard Atmosphere [*Committee on Extension to the Standard Atmosphere*, 1976] for an elevation of 840 m which is the average land elevation [*Sverdrup et al.*, 1942], and adjusting for a temperature of 8.5°C which is $\sim 1^\circ\text{C}$ colder than the standard atmosphere’s value, the mean density of surface air is approximately 1.13 kg m^{-3} . Therefore, a two meter high layer of the atmosphere covering the global land surface would contain $3.37 \times 10^{14} \text{ kg}$ of air and be gaining heat content at a rate of $1.9 \times 10^{17} \text{ J decade}^{-1}$. This seems like a tremendous amount of energy and it is. Yet it is a drop in the bucket, three orders of magnitude less than the concurrent increase in heat content of the top two meters of the ocean and five orders of magnitude less than the concurrent increases in ocean heat content from 0 to 700 m depth.

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