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Moist Enthalpy Climatology and Long Term Anomaly Trends

Abstract

Moist enthalpy hereafter referred to as equivalent temperature *(TE)*, expresses the atmospheric heat content by combining into a single variable air temperature *(T)* and atmospheric moisture. As a result, *TE*, rather than *T* alone, is an alternative metric for assessing atmospheric warming, which depicts heat content. Over the mid-latitudes, *TE* and *T* generally present similar magnitudes during winter and early spring, in contrast with large differences observed during the growing season in conjunction with increases in summer humidity. *TE* has generally increased during the recent decades, especially during summer months. Large trend differences between *T* and *TE* occur at the surface and lower troposphere, decrease with altitude and then fade in the upper troposphere. *TE* is linked to the large scale climate variability and helps better understand the general circulation of the atmosphere and the differences between surface and upper air thermal discrepancies. Moreover, when compared to *T* alone, *TE* is larger in areas with higher physical evaporation and transpiration rates and is more correlated to biomass seasonal variability.

Keywords: heat content; enthalpy; temperature; equivalent temperature

Introduction

Presently, air temperature is the key metric for assessing climate change and more specifically global warming over land. A huge body of studies dealing with surface air temperature trends suggest that at global scale, an increase took place over the last century (e.g. 1-5). This widely scrutinized warming observed at the surface and in the troposphere is associated with anthropogenic greenhouse forcing of the climate system (6-8), although natural effects have also been suggested as being important (e.g. 9)

However, warming is related to atmospheric energy content and temperature is only one of its components, as emphasized in some studies (10-13). Another component which plays an important role in the warming process is atmospheric moisture content, which has been reported to have increased during the past decades (14-20), although recent studies suggest that this increase has stopped (e.g. 21) and even reversed (e.g. 22). A broader assessment of warming could, therefore, take into consideration moist enthalpy, which includes both temperature and moisture and denotes the heat content of air.

Although this study is limited to the atmospheric heat content, it is worth mentioning that that at global scale, ocean heat content (i) is the major contributor of the increase of heat content of the whole Earth system; (ii) is found to be well correlated with the global net radiation flux; and (iii) is the main driver of the variability of the Earth's climate system (23-28).

So far, few studies relatively few studies have simultaneously quantified temperature and moisture by combining them into a single variable. Steadman (29,30) utilized a scale of apparent temperature (*A*), which expresses levels of human comfort. His method has been employed by the National Oceanic and Atmospheric Administration (NOAA) as a heat stress index. To investigate summertime heat stress over the United States, Gaffen and Ross (31) used a simplified version of Steadman's *A* and derived thresholds defined by the 85th percentile values of July and August daily temperature and *A* averages. They found that the annual frequency of days exceeding the thresholds as well as the number of high heat-stress nights did increase at most stations. Using observed temperature and humidity datasets from 188 first-order weather stations for the period 1961–90, Gaffen and Ross (32) found upward trends in *A* over the United States, in accordance with upward temperature and humidity trends. More recent studies focus on moist enthalpy, which combines both air temperature and humidity in a single variable, to assess surface heating trends. At a global scale, Ribera et al. (33) used the NCEP/NCAR re-analysis temperature to study the relationships between equivalent temperature and modes of climate variability. Although an increase of the globally averaged equivalent temperature was found, significant differences were observed between oceanic and continental areas. Pielke et al. (10) compared values of year 2002 daily temperature and moist enthalpy for the city of Fort Collins (Colorado) and the Central Plains Experimental Range of the U.S. Department of Agriculture's Agricultural Research Service located 60 km northeast of the city. Their results show that temperature and moist enthalpy are nearly equal when absolute humidity is low, but as humidity increases during the growing season, moist enthalpy values become much larger. Davey et al (11) examined 1982–1997 temperature and moist enthalpy trend differences for surface sites in the Eastern U.S. They found that moist enthalpy trends are warmer than temperature trends during the winter season, but relatively cooler in the fall. Rogers et al (34) analyzed 124-year records of summer moist enthalpy for Columbus (Ohio) and found that the highest values of moist enthalpy occurred during the summer of 1995 when both temperature and moisture were very high, in contrast with the hot summers of 1930–1936 which, despite high temperatures, experienced lower moist enthalpy because of relatively low or negative anomalies of absolute humidity. More recently, Fall et al (12) used National Centers for Environmental Prediction North American Regional Reanalysis data to investigate temperature and moist enthalpy at near-surface and various upper-air standard levels. They noted that the moisture component induces larger trends and variability of moist enthalpy relative to temperature. Their results indicated that, while moist enthalpy values and trend were much larger than temperature ones at near-surface level, there was almost no difference at 300–200 mb. Peterson et al. (13) examined the energy content of the surface atmosphere, which is composed of temperature (enthalpy), kinetic energy and latent heat. They found that the global surface atmospheric energy has increased since the 1970s, mainly because of increases in both enthalpy and latent heat which equally contribute to the global increases in heat content. At regional scale, the two components were in some cases found to be of opposite signs.

Definition of Moist Enthalpy

Moist enthalpy, also referred to as moist static energy (10) or equivalent temperature (11, 12, 33, 34) refers to surface air heat content (H) by taking into account air temperature and moisture in the same variable. A previous variant of moist enthalpy, namely A, was developed by Steadman (29, 30) by combining four variables: summer temperature, humidity (vapor pressure), wind speed and extra-radiation. Gaffen and Ross (31, 32) simplified Steadman's *A* by ignoring the effects of wind and radiation and computing it from ambient temperature (*T*, in degree Celsius) and water vapor-pressure (*e*, in kilopascals)

$$A = -1.3 + 0.92\, T + 2.2\, e \tag{1}$$

Recent studies have mainly focused on moist enthalpy (10), which is written as:

$$H = CpT + Lvq \tag{2}$$

where *Cp* is the specific heat of air at constant pressure, *T* is the air temperature, *Lv* is the latent heat of vaporization and *q* is the specific humidity. Thus, it can be seen that, as described by Peterson et al. (13), moist enthalpy is the sum of two terms: enthalpy (calculated from *T*) and latent heat.

The approximate value of *Lv* (30°C) has been used in most of the studies. Recently, Fall et al. (12), following the Priestley-Taylor method, estimated *L*v (J/kg) with the temperature function:

$$L\mathrm{v} = 2.5 - 0.0022 \times T \tag{3}$$

Such an estimate accounts for the variation of *Lv* with temperature.

The specific humidity *q* can be computed from the dewpoint temperature and surface pressure using Bolton's empirical relationship (35):

$$q = \frac{0.62197e}{p - 0.37803e}, \text{ where } \mathrm{e} = 6.112 \exp\left[\frac{17.67Td}{Td + 243.5}\right] \tag{4}$$

e is the saturated vapor pressure in hPa, *p* is the surface pressure in hPa, and *Td* is the dewpoint temperature in °C (34, 36).

H is the heat in units of Joule and must be scaled into degree units in order to obtain equivalent temperature (TE) for easy comparison to air temperature

$$TE = H/Cp \tag{5}$$

Equation (4) can be also written as

$$TE = T + (L\text{v}q / Cp) \tag{6}$$

where Lv is in units of Joules per kilogram and Cp is in units of Joules per kilogram per degree K. As q is dimensionless (i.e. kg per kg), the ratio has units of degree K.

The above equations show that both sensible and latent heat contribute to the magnitude of TE. Pielke et al (37) have shown that for example at 1000 mb, an increase of 2.5°C in air temperature will produce the same change in TE as a 1°C increase in dew point temperature. TE becomes larger as both T and q increase. Conversely, when T is abnormally high but out of phase with a low q, TE exhibits modest to low values (34). However, in the long term, the combination of the two terms seems to result in larger trend and variability of TE, regardless of the magnitude of q. For example, in their comparison between T and TE over the United States (1979 – 2005), Fall et al. (12) found larger trends and variability of TE (relative to T), even though in terms of contribution to the magnitude of TE, the moisture component (Lvq) was much smaller than the enthalpy (or sensible heat: CpT).

Climatology

In general, moist enthalpy increases progressively from winter to summer and then decreases, thus exhibiting patterns that are similar to surface temperature annual cycle. A comparison between monthly mean T and TE over the United States shows that in winter and early spring there is almost no difference between the two variables. However, with increasing humidity from late spring to early fall, *TE* increases much more than *T*, in particular during summer (Figure 1). Therefore, large differences are observed during the growing season (up to 22.74 °C in July according to results from Fall et al. (12)). The same patterns are noted at daily time scale and for both maximum and minimum *T* and *TE* (10).

Moist Enthalpy Variability and Anomaly Trends

In general, at global scale, there is scientific consensus on an increase of the heat content of the ocean, especially during the latter half of the past century (e.g. 25). Findings from Levitus et al. (26) show that from 1955 to 1998, approximately 85% of this warming occurred in the world's oceans. With the ocean, only the temperature is required to diagnose moist enthalpy. However, in the atmosphere, the humidity also must be included.

As shown in recent studies (13, 33), over the past decades moist enthalpy anomalies at global scale have generally exhibited warmer trends. Ribera et al. (33) found *TE* increments between +0.05 and +0.29ºK decade^{-1} during the 1958-1998 period, with most of this increase occurring during the 1958-1978 period over densely populated coastal areas (e.g. Eastern Asia, Northern Europe, southeastern North America and South Africa) and oceanic zones, in contrast with dry continental areas which generally are characterized by negative trends (e.g. Sahara).

Positive *TE* trends are also found at regional and local scales, although Peterson et al (13) indicate that the two terms can be of opposite signs in some regions (e.g. Southern Hemisphere sub-tropics, as shown in Figure 2). Results from Gaffen and Ross studies (31, 32) indicate that the occurrence of hot and humid days increased in the United States during the past decades (1961-1995). As a result, extreme heat-stress events became more frequent, and because of a pronounced increase in atmospheric moisture content, summertime T_E trends were positive and higher than summertime *T* ones. In more recent studies, comparisons between near-surface *T* and *TE* have confirmed that *TE* trends are generally warmer and significantly different from *T* (11, 12). However, differences between *T* and *TE* trends decrease gradually with altitude and almost disappear at 300 - 200 mb [about 9,000 - 12,000 meters). For example, results from Fall et al (12) who computed trend differences (*TE* minus *T*) at various levels for the United States during the period 1979-2005 (Figure 3) show not only the decreasing trend differences with altitude (e.g. 0.211ºC/decade at near-surface and 0.005ºC/decade at 300 mb), but also a shift to an opposite trend sign (-0.003ºC/decade for both *T* and *TE* at 200 mb).

Seasonally, at global scale during the 1958-1998 period, Ribera et al. (33) found that *TE* trends remained positive for all seasons and most of the increase generally took place during the summer season; the largest trends were found over the continental southern hemisphere and oceanic areas. Over the United States, surface *TE* trends are found to be warmer in winter and cooler in fall and summer (11, 12). These seasonal patterns persist up to 700 mb and above that level, most of *TE* increase occurs during the fall season; at 200 mb, *TE* trends are negative, with the most substantial cooling taking place in winter (12).

Conclusion: On the Importance of Heat Content

The significance of considering heat content for a broader understanding of the Earth system climate variability has been demonstrated by various studies. The assessment of warming rates at global and regional scales requires considering the variability of ocean, atmosphere and cryosphere heat content (25-27). In particular, ocean heat content varies in conjunction with the annual cycle of the Earth net radiation balance and has been found to be a major source of variability of the global heat balance (23, 25, 27, 28, 38). The observed ocean heat content variations also appear to be correlated with simulated variations in greenhouse gases, sulfate aerosols, solar irradiance, and volcanic aerosols (27).

Several studies have highlighted the importance of atmospheric heat content (alternatively moist enthalpy or equivalent temperature- *TE*) in climate variability and change assessments. The relevance of *TE* includes, but is not limited to the following:

- Moist enthalpy, which expresses the combined effects of temperature and humidity, represents an important forcing of the general circulation of the atmosphere through different transport mechanisms and provides a better understanding of the large-scale dynamics in the atmospheric heat balance (39, 40). Ribera et al. (33) found a close relationship between *TE* and large scale modes of climate variability (the North Atlantic Oscillation and the Arctic Oscillation).
- Apparent Temperature (*A*), a variant of *TE*, is closely related to human comfort. The *A* climatology developed by Gaffen and Ross (31, 32) has been extended and adopted by NOAA as a useful index for heat stress and is periodically updated.
- Pielke et al (10) stated that… "*The difference in temporal trends in surface and tropospheric temperatures [National Research Council,2000],which has not yet been explained, could be due to the incomplete analysis of the surface and troposphere for temperature, and not the more appropriate metric of heat content*". In a subsequent study, Fall et al. (12) compared *TE* and *T* at different atmospheric levels (up to 200 mb) and investigated the vertical structure of the combined effects of temperature and moisture. They analyzed the climatology, time series and decadal trends of the two variables and found a contrast between (i) pronounced temporal and spatial differences at the near- surface level, and (ii) almost no difference at 300 – 200 mb. More specifically, the thermal discrepancies between surface and upper air are much larger when *TE* is used instead of *T* alone. Fall et al (12) concluded that the use of to assess tropospheric heating trends may "*help obtain an improved estimate of the impacts of surface properties on heating trends*".
- Observation and reanalysis-based studies have shown that moist enthalpy (*TE)* is more sensitive to surface vegetation properties than is air temperature (*T*). Davey et al. (11) found that over the eastern United States from 1982 to 1997, *TE* trends were similar or slightly cooler than *T* trends at predominantly forested and agricultural sites, and significantly warmer at predominantly grassland and shrubland sites. Results from Fall et al. (12) indicate that *TE* (i) is larger than *T* in

areas with higher physical evaporation and transpiration rates (e.g. deciduous broadleaf forests and croplands) and (ii) shows a stronger relationship than *T* to vegetation cover, especially during the growing season (biomass increase). These moist enthalpy-related studies confirm previous results showing that changes in vegetation cover, surface moisture and energy fluxes generally lead to significant climatic changes (e.g. 41-43) and responses which can be of a similar magnitude to that projected for future greenhouse gas concentrations (44, 45). Therefore, it is not surprising that *TE*, which includes both sensible and latent heat, more accurately depicts surface and near-surface heating trends than *T* does.

In general, studies dealing with heat content have suggested that despite its undeniable relevance and popularity, temperature needs to be supplemented with additional metrics for assessing global warming. For this purpose, moist enthalpy, which includes both temperature and atmospheric moisture content, is a useful variable (e.g. 10-12). Using the Bowen ratio (ratio of sensible heat to latent heat) is another efficient way for analyzing the combined effects of temperature and moisture and their co-variation (13, 46).

Overall, a large majority of studies still use temperature as the key-metric for assessing global warming. Relatively few studies have addressed the importance of moist enthalpy which actually represents a robust measure of heat (Joules) and have recommended the use of both variables in climate change assessments.

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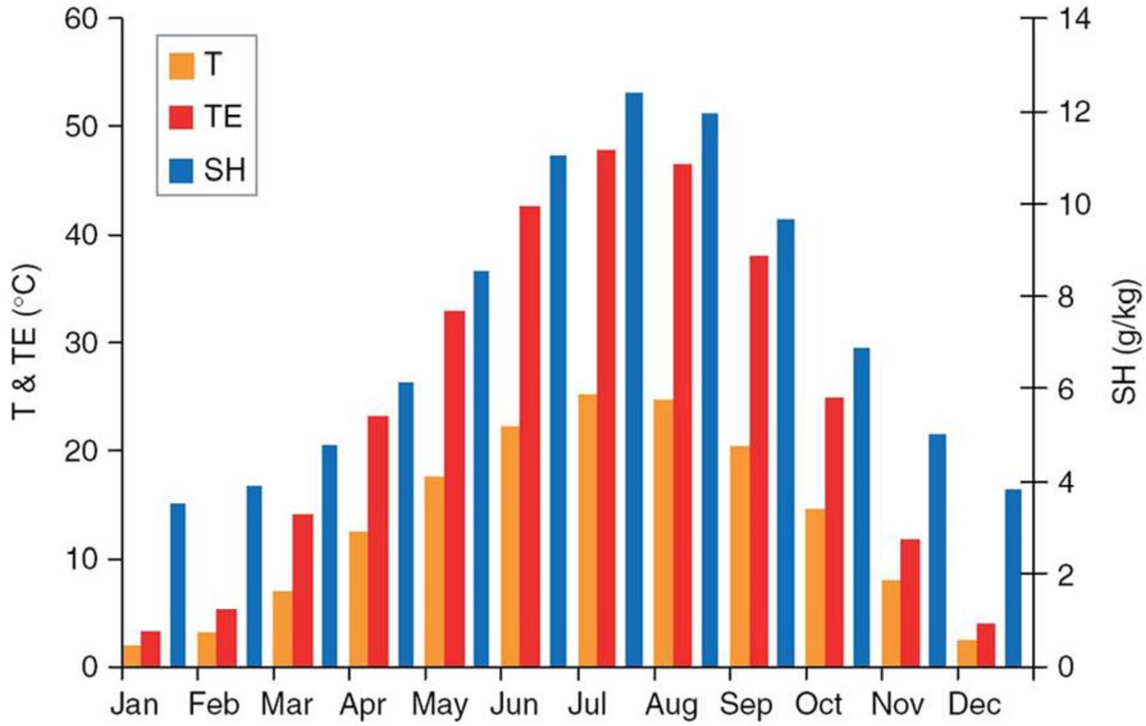
Figure Captions

Figure 1. Monthly climatology of temperature (*T)*, equivalent temperature (*TE*) and specific humidity (SH) at 2 m (average 1979–2005) over the United States. The ordinate scale on the right pertains to values of specific humidity. *(Reprinted with permission from Ref 12: Fall et al., 2010).*

Figure 2. 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) surface temperature trends (deg. C/decade); b) heat content trends (kJ/kg/decade). *(Reprinted with permission from Ref 13: Peterson et al., 2011).*

Figure 3. Decadal anomaly trends computed from monthly *T* and *TE* at different pressure levels (1979–2005; units: °C/10 years). Italicized values denote the differences *TE* minus *T*. All trends are significant at the 5% level (p-value <0.05). *(Reprinted with permission from Ref 12: Fall et al., 2010)*



T
TE
SH
T & TE (°C)
SH (g/kg)
0
10
20
30
40
50
60
0
2
4
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12
14
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Mar
Apr
May
Jun
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Sep
Oct
Nov
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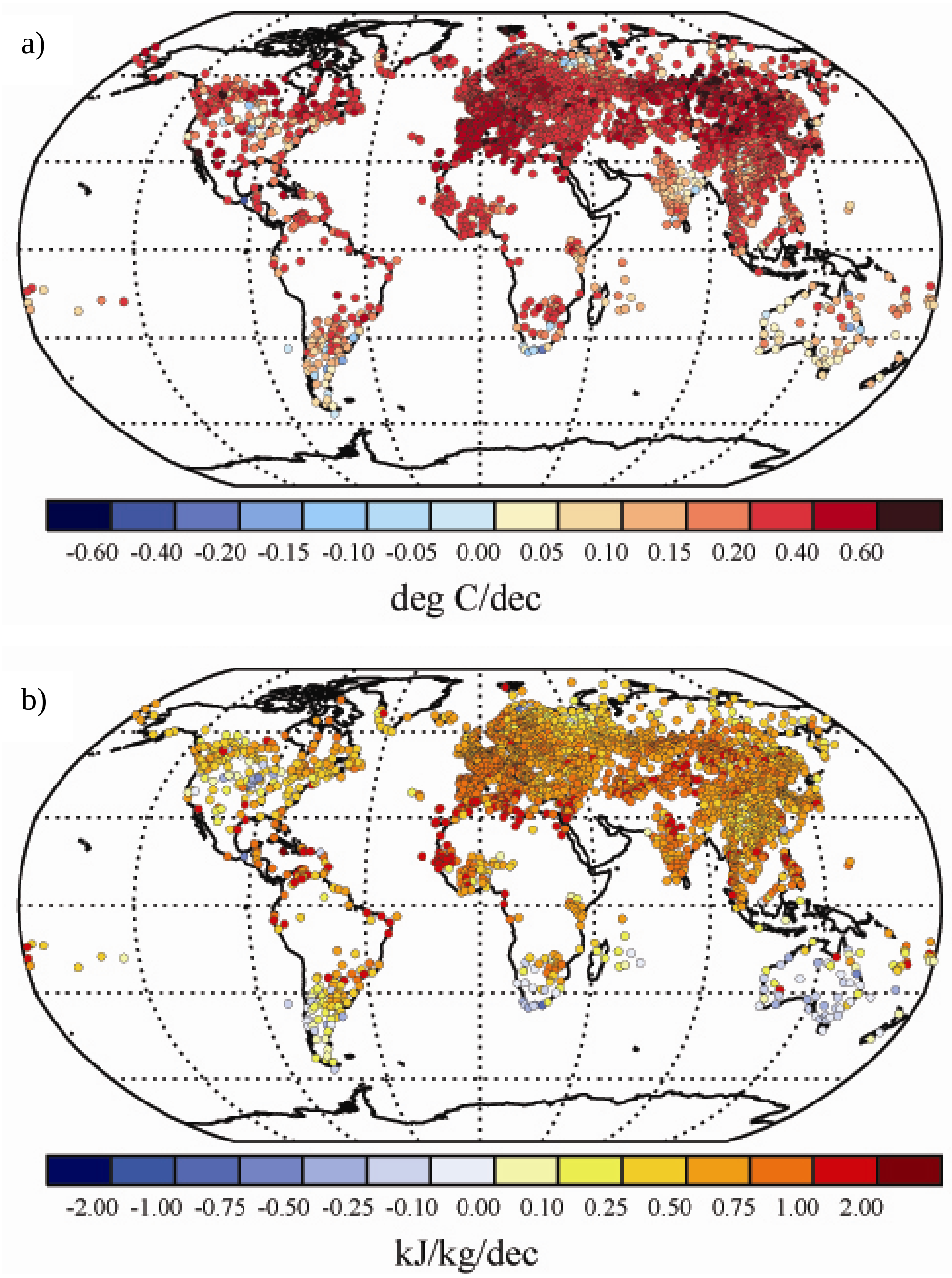
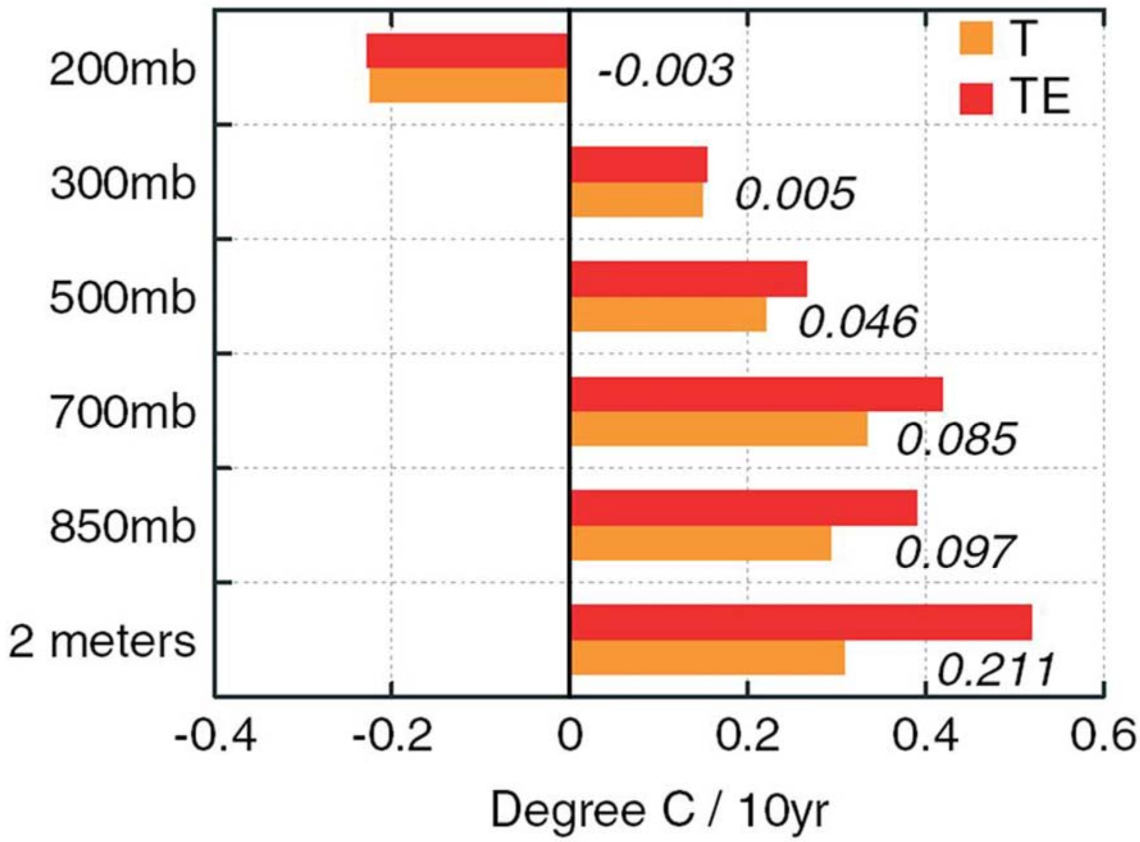

a)
-0.60 -0.40 -0.20 -0.15 -0.10 -0.05 0.00 0.05 0.10 0.15 0.20 0.40 0.60
deg C/dec
b)
-2.00 -1.00 -0.75 -0.50 -0.25 -0.10 0.00 0.10 0.25 0.50 0.75 1.00 2.00
kJ/kg/dec



T
TE
200mb
300mb
500mb
700mb
850mb
2 meters
-0.003
0.005
0.046
0.085
0.097
0.211
-0.4
-0.2
0
0.2
0.4
0.6
Degree C / 10yr