TROPICAL TEMPERATURE ALTITUDE AMPLIFICATION IN THE HIATUS PERIOD (1998-2012)

by

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There was a stagnation in temperature rise in the period 1998-2012, despite increase in greenhouse gases radiation forcing (hiatus period). According to Global Circulation Models simulations, expected response on the rise of greenhouse gases forcing is tropical temperature altitude amplification – temperature increases faster in higher troposphere than in lower troposphere. In this paper, two satellite data sets – University of Alabama in Huntsville, Microvawe Sounding Units (UAH MSU) and Remote Sensing Systems (RSS), were used to test altitude temperature amplification in tropics in the hiatus period. We compared satellite data sets both for the temperature of the lower troposphere and the temperature of the middle troposphere, in general and particularly for land and ocean (for UAH MSU). The results from both satellite measurements showed the presence of hiatus, i. e. slowdown of the temperature rise in the period 1998-2012 compared to period 1979-2012 (UAH MSU) and temperature fall for RSS. Smaller increase, i. e. temperature fall over ocean showed that hiatus is an ocean phenomenon above all. Data from UAH MSU showed that temperature altitude amplification in tropics was not present either for period 1979-2012, or 1998-2012. RSS data set also does not show temperature altitude amplification for these periods. RSS data for successive 15-year periods from 1979-1993 till 1998-2012 does not show tropical temperature altitude amplification and in one case negative trend is registered in lower troposphere and in two cases in middle troposphere. In general, our results do not show presence of temperature altitude amplification in tropics in the hiatus period.

Key words: *hiatus, tropical temperature altitude amplification, greenhouse gases, satellite data*

Introduction

There is a growing attention of climate science community to the observed stagnation in global surface temperature rise during last decade. The trend of global averaged annual mean surface temperatures has been nearly flat since the late 1990s [1] and this period which has now lasted for more than a decade with no warming trend is frequently referred as *warming pause* or *hiatus* contrary to decades with rapid increases of temperatures usually called *accelerated warming decades* [2]. Disagreement between observed temperatures and climate model predic-

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tions under different greenhouse forcing scenarios during *pause* yields many partial explanations of potential causes, but still does not exist a unique driving mechanism.

Global warming issue and thermal features of the atmosphere are the main topics of numerous climate studies in past years. Various data sets and observations for the Earth's surface and different altitudes make enable the trend analysis of physical parameters of the atmosphere, especially air temperature. Recently, human caused emission of greenhouse gases (GHG) is recognized as a leading driver of climate change and global warming. According to Intergovernmental Panel on Climate Change (IPCC) 4th assessment report (AR4), as results of Global Circulation Models (GCM) simulations, expected responses on the rise of CO_2 concentration and GHG forcing are warming in the troposphere and cooling in stratosphere in tropics [3]. Also, there is related warming amplification which means that temperature trend increases with increasing altitude in troposphere and reaching maximum at ≈200 hPa and decreasing to the zero near the tropical tropopause.

In this study we tried to test altitude temperature amplification in tropics in global warming pause period 1998-2012. The analyzed hiatus period in this research coincides with the period with the highest anthropogenic GHG emissions in human history [1]. The global emission of CO_2 is increased for 41.13% [4] and the measurement of CO_2 concentration at Mauna Loa (Hi, USA) showed rise for 7.4% in the period 1998-2012 [5]. The total CO_2 radiation forcing is increased from 1.47 to 1.85 Wm^{-2} and total radiation forcing of GHG (CO_2, CH_4, N_2O, CFC12, CFC11 and 15-minor) is increased from 2.41 to 2.86 Wm^{-2} in the same period [6].

Methods

In this paper satellite data from the Earth System Science Center of the University of Alabama in Huntsville, Microvawe Sounding Units (UAH MSU) – version 5.6 [7, 8] were used, as well as data from Remote Sensing Systems (RSS) [9, 10], obtained from microwave measuring of thermal emission of oxygen molecules in the atmosphere (in different frequencies). Compared with the Earth surface meteorological stations or radiosonde measurements, the main advantage of such measurement is good spatial coverage of obtained data. The UAH MSU data set covers latitudes between 85 °N-85 °S from lower troposphere. The RSS data set covered latitudes between 82.5°N and 70°S for lower troposphere and 82.5°N and 82.5°S for middle troposphere. Data are presented as anomalies in temperature of the lower troposphere (TLT) and temperature of the middle troposphere (TMT). The reference periods are 1981-2010 for UAH MSU and 1979-1998 for RSS.

The UAH MSU TLT data are represented by the average value of the surface and up to approximately 10 km altitude. The TMT data are represented by surface and up to approximately 17 km altitude. The TMT gives more weight to the region between 500 hPa (≈5.5 km) and 200 hPa (≈12 km) where the tropical warming is expected to be the most pronounced according to models [11].

In this paper monthly values of TLT and TMT are analyzed in the periods 1979-2012 and 1998-2012, obtained from both satellite data sets for the tropics (20°N and 20°S according to UAH MSU and 25°N – 25°S according to RSS), in general and particularly for land and ocean (for UAH MSU). For testing the differences in mean values of TLT and TMT, the t test was used. The Mann-Kendall test was used for testing the significance of trend. This test is considered to be powerful non-parametric alternative (less sensitive to disruptions of assumptions about normal distribution). The reason for the use of this non-parametric test was also relatively short time series. To evaluate the slope of trend line was used the Sen's method. Sen's slope rating was used in monotonical (linear) trends and it was insensitive to outlayers, because median of all possible values was used.

Results

Based on the results from the t test for UAH MSU data set, it can be concluded that the anomalies of TLT in the tropics generally (both land and ocean) are higher than for TMT. However, there is not statistically significant difference between mean values and variances in lower and middle troposphere, either for land or ocean part of the tropics.

In the period 1979-2012 in lower troposphere (based on UAH MSU data set) is registered statistically significant rise of global temperature of 0.014 °C per year. In the tropics, this increase is 0.007 °C per year, whereby it is higher over land (0.012 °C per year) than over ocean (0.005 °C per year). For tropical TMT, the rise is less than in lower layer, and the highest value is registered over the land (0.008 °C per year). Temperature trends in the tropics (in general, over land and ocean), are higher in lower troposphere, which means the temperature altitude amplification is not present.

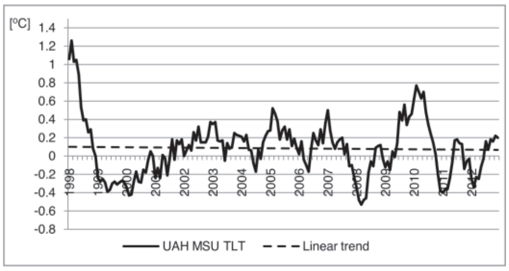

Figure 1. TLT trend for the tropics (20°N and 20°S) on the basis of UAH MSU satellite data set

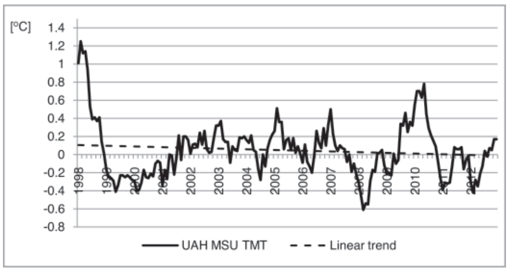

Figure 2. TMT trend for the tropics (20°N and 20°S) on the basis of UAH MSU satellite data set

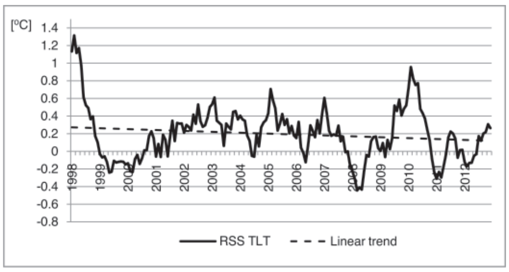

Figure 3. TLT trend for the tropics (25°N and 25°S) on the basis of RSS satellite data set

The UAH MSU data in the period 1998-2012 in lower troposphere (fig. 1) show smaller rise of global temperature (0.005 °C per year) compared with the period 1979-2012 (0.014 °C per year), which is in accordance with statement of IPCC [1] that there has been a slowdown in temperature rise on the Earth. Rise of 0.005 °C per year in the tropics is registered, where the rise over land is statistically significant and it is 0.024 °C per year. Trend is negative over ocean in the tropics, and it is (–0.008 °C per year). The TMT trend in the tropics is flat (fig. 2). The biggest fall is registered over tropical ocean (–0.012 °C per year). So, there is no tropical temperature altitude amplification in the period 1998-2012.

The results of the t test for RSS data network are similar to those for UAH MSU, with difference that values for TLT are higher than for TMT. Also, the difference between mean values and variances in TLT and TMT is not statistically significant.

Regarding the trends of global TLT in period 1979-2012 (RSS) it is noticed that there is statistically significant rise (0.013 °C per year). However, there is a negative trend of air temperature (–0.006 °C per year) in the period 1998-2012. In the tropics in this period (1998-2012)

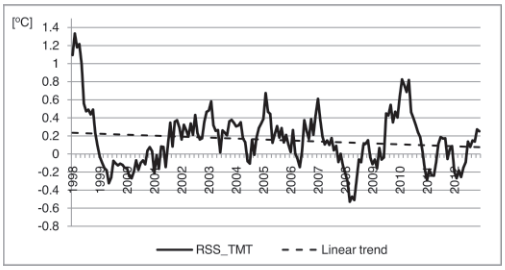

Figure 4. TMT trend for the tropics (25°N and 25°S) on the basis of RSS satellite data set

both in lower and middle troposphere (fig. 3 and fig. 4) is registered fall of air temperature of –0.008 °C per year, respectively –0.009 °C per year, while in period 1979-2012, the rise of 0.012 °C per year in lower and 0.009 °C per year in middle troposphere are registered.

It is clear that RSS data set confirms the presence of hiatus and does not show temperature altitude amplification either for longer (1979-2012), or for shorter period (1998-2012) in the tropics. Moreover, trends in period 1998-2012 are negative.

Concerning the fact that 15-year series is shorter than standard 30-year, and that there is a possibility that absence of temperature altitude amplification in period 1998-2012 can be a coincidence, we observed 15-year successive periods from 1979-1993 to 1998-2012 (tab. 1).

Table 1. Sen's slope tropical TLT and TMT trend line values (Q) for successive 15-year periods (based on RSS satellite data sets). Significance: p = 0.05 (*), p = 0.01 (**) and p = 0.1 (+)

Period	Data set	*Q*	Significance	Data set	*Q*	Significance
1979/1993	TLT	0,002		TMT	0,001	
1980/1994	TLT	0,008		TMT	0,002	
1981/1995	TLT	0,018		TMT	0,011	
1982/1996	TLT	0,019		TMT	0,005	
1983/1997	TLT	0,024		TMT	0,020	
1984/1998	TLT	0,041	**	TMT	0,036	+
1985/1999	TLT	0,028	+	TMT	0,024	
1986/2000	TLT	0,016		TMT	0,000	
1987/2001	TLT	0,009		TMT	–0,005	
1988/2002	TLT	0,024	+	TMT	0,017	
1989/2003	TLT	0,030	*	TMT	0,025	
1990/2004	TLT	0,023	+	TMT	0,018	
1991/2005	TLT	0,024	*	TMT	0,019	
1992/2006	TLT	0,023	*	TMT	0,019	+
1993/2007	TLT	0,017	+	TMT	0,017	
1994/2008	TLT	0,005		TMT	0,001	
1995/2009	TLT	0,005		TMT	0,001	
1996/2010	TLT	0,013		TMT	0,013	
1997/2011	TLT	0,005		TMT	0,001	
1998/2012	TLT	–0,008		TMT	–0,009	

Not one of the twenty observed successive series showed the presence of tropical temperature altitude amplification and in one case negative trend is registered in TLT and in two cases in TMT.

Discussion

Fu *et al.* [12] analyzed temperature differences between tropical upper and lower-middle troposphere based on satellite measurements and simulated outputs of GCM used in AR4 in the period 1979-2010. They found that observational data showed little trends on contrary to the AR4 GCM which overestimated warming in the tropics. Also, models overestimate tropical surface temperature trend for 60% compared to observations. After running 22 GCM simulations, with atmospheric parameters from various surface, radiosonde and satellite data sets, Douglass *et al.* [13] showed disagreement between model results and observed data for the most of tropical troposphere in period 1979-1999 and concluded that modeled trend is 100-300% higher than observed in layers near 5 km and modeled and observed trends have opposite signs above 8 km. Paltridge *et al.* [14] stressed that understanding the water vapor feedback in climate models had a huge importance in predicting how air temperature respond to increase of CO_2 concentration. These authors showed that the trend in zonal average annual specific humidity was significantly negative at all altitudes above 850 hPa in the tropics in 35-years long records and the water vapor feedback in negative. They also said this fact could be reflected in reducing rather than magnifying the response of climate system to external forcing as GHG effect. Using historical sea surface temperatures (SST) as boundary conditions in GCM and coupled atmosphere-ocean GCM, and comparing model simulations with satellite measurements, Po-Chedley and Fu [15] found that most models showed excessive tropical upper tropospheric warming relative to the lower-middle troposphere. Santer *et al.* [16] also found model's overestimations in tropospheric warming. Klotzbach *et al.* [17] compared global linear temperature trends for surface and lower troposphere data, separately for land and ocean, over the 1979-2008 period, and found larger trends in surface data compared with satellite data. Also, they found that differences between these two kind observations were larger over land areas and pointed out possible warm bias in surface temperature trend analyses. Using scaling ration as the ratio of atmosphere temperature trends to surface temperature trends, Christy *et al.* [18] found significant difference between measured data (0.8 ± 0.3) and models simulations (1.38 ± 0.08). Seidel *et al.* [19] confirmed that models overestimated vertical amplification of tropospheric warming during 1979-2010 and emphasized many problems of using imperfect tropical tropospheric temperature observations which affected climate model performances. According to Mitchell *et al.* [20], the poor simulation of surface temperature data is seen as a major reason for discrepancy between model and observations, and this could be avoided with examination of atmosphere only and if the trends are considered as an amplification of the surface temperature trend with height. Also, it is shown that high horizontal resolution models have good agreement with observations because they consider convective processes at suitable resolution what could be fundamental for correct simulation of tropical tropospheric temperature trends. Comparing climate models and weather balloon series in tropical troposphere for period 1958-2012, McKitrick and Vogelsang [21] found inconsistency and concluded that models showed smooth upward trend in analyzed period, while observations showed a single jump in late 1970s (coinciding with the Pacific Climate Shift) without statistically significant trend. The IPCC Fifth Assessment Report [1] states that *CMIP3 and CMIP5 models overestimate the observed warming trend in the tropical troposphere during the satellite period 1979-2012* and this is due *overestimation of the SST trend, which is propagated upward because models attempt to maintain static stability*.

Fyfe *et al.* [22] analyzed the inconsistency between observed and simulated global warming reproduced by models participated in phase 5 of the Coupled Model Intercomparison Project (CMIP5) and found that for the period 1998-2012 the observed trend was 0.05 ± 0.08 °C per decade, what was four times lower than the average simulated trend of 0.21 ± 0.03 °C per decade. In the first of three reports dedicated to causes and implications of *hiatus* published by Met Office Hadley Centre [23] it is shown that much of the recent pause in global mean surface warming is associated with the SST (particularly in the Eastern Pacific) and that many land areas have continued to warm for at least part of the most recent period. The fact that ocean showed slower warming trend, compared to land areas in last decade, leads to the conclusion that the reason for changes in global surface temperature can be found in decadal pattern of ocean circulation and its influences all around world due to teleconnection processes. Sillmann *et al.* [24] analyzed the trends in global warm and cold temperature extremes and showed that a coherent cooling pattern across the northern hemisphere mid-latitudes could be a reason for discrepancy between observed and simulated temperature trends in global mean surface temperature and observed warming pause.

So far, most studies highlight the role of the ocean in recently observed decline of global surface temperature. This implies that most of excess heat in climate system is stored in the ocean and the reasons for hiatus can be found in variations of ocean heat content by depth and respect decadal mode of variability. Significant progress in the research of the ocean temperature, especially down to 2000 m depth, is made by measurements within Argo project [25]. Several studies are focused on the research of the Pacific tropical regions in explanation the *warming pause*. Meehl *et al.* [26] suggested that the net energy imbalance at the top of the atmosphere of about 1 Wm^{-2} was associated with greater increases of deep ocean heat content below 300 m during the hiatus decade, while there was little globally averaged surface temperature increase or warming in the upper ocean layers. Furthermore, the authors indicated that hiatus periods were relatively common climate phenomenon in observations and climate model simulation and might be linked to La Nina-like conditions. In subsequent work, Meehl *et al.* [2] showed that decades of *accelerated warming* and *hiatus* were a natural product of interactions of internally generated decadal variability associated with interdecadal Pacific oscillation (IPO) and external forcing from increasing GHG. This study suggests that *accelerated warming* decades are characterized by *rapid warming of globally averaged surface air temperature, greater increases of heat content in the upper ocean layers and less heat content increase in the deep ocean, opposite to the hiatus decades*. Accelerated warming decades are observed with positive phase of IPO and hiatus decades typically occur with the negative phase of the IPO and the transition of IPO from positive to negative phase occurred in late 1990s. Balmaseda *et al.* [27] showed that ocean depths below 700 m became much more strongly involved in the heat uptake after 1998, and subsequently accounted for about 30% of the ocean warming. Also, it is shown that surface wind variability is largely responsible for the changing ocean heat vertical distribution. They concluded that *detecting, understanding and modeling the processes that lead to the vertical distribution of heat within the ocean is a key for the correct initialization of decadal predictions, because the trends in forecasts of the SST will likely depend on whether the ocean is in a recharge (low stratification) or discharge (high stratification) mode*. Kosaka and Xie [28] showed that the current hiatus was part of natural climate variability caused by decadal cooling tropical Pacific with propagation effect all around globe. According to England *et al*. [29], Pacific trade winds showed pronounced strengthening in past two decades causing increased subsurface ocean heat uptake and slowdown in surface warming. They calculated that *the net effect of these anomalous winds is a cooling in the 2012 global average surface air temperature of*

0.1-0.2 °C, which can account for much of the hiatus in surface warming observed since 2001. Even most of aforementioned studies predict similar hiatus events in the future, they also stated that the global warming trend is very likely to continue in future according to GHG effect.

The ocean circulation in North Atlantic region is also detected as a source of decadal climate variability. According to Tung and Zhou [30], many historical episodes of warming and cooling can be explained by a natural multidecadal oscillation related to the Atlantic multidecadal oscillation (AMO), possibly caused by the thermohaline circulation variability and with average period of 70 years. Their analysis showed that this large multidecadal variability accounted for 40% of the observed warming since the mid 20th century. They concluded that *without AMO into account in predictions of future warming under various forcing scenarios may run the risk of overestimating the warming for the next two to three decades, when the AMO is likely in its down phase*.

The newest studies explain the *warming pause* by the combination of internal and external forcing. According to Schmidt *et al*. [31], a coincidence caused by combination of factors such as solar activity, volcanic aerosol, and El Nino Southern Oscillation (ENSO) fluctuations is the main reason for gap between climate model projections and observed temperatures in the past 15 years and damped warming trends. With corrections of these variables according their values during 2000s, the difference between climate model which is a part of the CMIP5 and observed temperatures is much smaller for the period 1997-2013. These authors concluded that further warming could be expected in the future due to dominant long-term warming effect of GHG if forcing shift back to values from earlier periods. Similarly, Huber and Knutti [32] used their own methods with corrections in CMIP5 in order to estimate contribution of natural variability to the global temperature evolution during past 15 years and found that ENSO variability led to a cooling trend of about –0.06 °C in the research period. Also, it is estimated that solar forcing led to reduction in global temperature increase since 1998 by –0.04 °C and stratospheric aerosol by –0.035 °C.

Conclusions

According to IPCC, GHG contributed a global mean surface warming likely to be between 0.5 °C and 1.3 °C over the period 1951-2010, with the contributions from other anthropogenic forcing likely to be between –0.6 °C and 0.1 °C, from natural forcing likely to be between –0.1 °C and 0.1 °C, and from internal variability likely to be between –0.1 °C and 0.1 °C. Together these assessed contributions are consistent with the observed warming of approximately 0.6 °C over this period [1]. Still, in the period 1998-2012 there was a stagnation in temperature rise, despite increase of the total CO_2 radiation forcing from 1.47 to 1.85 Wm^{-2} and increase of total radiation forcing of GHG (CO_2, CH_4, N_2O, CFC12, CFC11, and 15-minor) from 2.41 to 2.86 Wm^{-2} in the same period.

The starting point in our research was that temperature increase in conditions of GHG concentration growth should be higher in upper troposphere compared with lower layers, primarily in the tropics (tropical altitude amplification). In this regard, monthly values of TLT and TMT for the tropics were analyzed in periods 1979-2012 and 1998-2012, obtained from satellite data sets UAH MSU and RSS, both in general and particularly for land and ocean (for UAH MSU).

The results from both satellite measurements showed the presence of hiatus, *i. e.* slowdown of the temperature rise in the period 1998-2012 compared to the period 1979-2012 (UAH MSU) and temperature fall for RSS data. Smaller increase, *i. e.* temperature fall over ocean showed that hiatus is an ocean phenomenon above all, what is in accordance with other studies [2, 26-29].

Data for UAH MSU showed that temperature altitude amplification in tropic was not present either for period 1979-2012, or 1998-2012. The RSS data set also does not show temperature altitude amplification either for longer (1979-2012), or for shorter period (1998-2012). Moreover, trend sign in period 1998-2012 is negative. The RSS data for successive 15-year periods from 1979-1993 till 1998-2012 does not show tropical temperature altitude amplification and in one case negative trend is registered in TLT and in two cases in TMT.

In general, our results do not show presence of temperature altitude amplification in tropics in hiatus period. However, there are still many open questions, and the answers so far are limited by length of instrumental observations, weaknesses of the climate models, and also by assessment of the impact of natural variability (*i. e.* El Nino) on Earth's climate system. These are all research tasks for future investigations.

Acknowledgments

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