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Research Article

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Earth Infrared Radiation Spectra During Global Warming Hiatus

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Keywords

Greenhouse gases (GHG): an atmospheric heating phenomenon, caused by short-wave solar radiation being readily transmitted inward through the earth's atmosphere

Outgoing longwave radiation (OLR): the energy leaving the earth to space as infrared radiation

Stratosphere: the layer of the upper atmosphere extending upward from the tropopause to about 50 km above the earth, characterized by increasing temperature with altitude

Troposphere: lowest layer of the atmosphere, characterized by a steady drop in temperature with increasing altitude and is where nearly all cloud formations occur

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Abstract

Background: Since 1997–98, observations of annual mean surface temperature have shown a slowdown of global temperature increases, suggesting a hiatus in global warming. Given this finding, we are interested in diagnosing trends in the Earth's outgoing longwave radiation (OLR) spectrum throughout the last decade.

Methods: We calculated the trend in OLR measured by the Atmospheric Infrared Sounder (AIRS) aboard NASA's Aqua satellite between 2003 and 2013, and compared these results with the trend in atmospheric and surface temperature and tropospheric absolute humidity, obtained from AIRS retrieval product and from the ECMWF (European Center for Medium range Weather Forecasting) Re-Analysis (ERA) interim product. We also isolated the greenhouse effect from the OLR trend by subtracting the amount of surface radiation emitted from the total radiation received by the sounder.

Results: The OLR trend is negative in the CO_2 absorption band, negative in the window spectral region, and positive in the water vapor band. The trend in surface and tropospheric temperature is negative, as is the trend in tropospheric absolute humidity. The greenhouse effect is increasing in the CO_2 band, generally slightly increasing in the window region, and decreasing in the H_2O band.

Conclusion: Our results show that the CO_2 forcing was still present globally through the last decade, with steadily increasing effects. Contributors to the negative trend in OLR in the window region are a small decrease in surface temperature and a strong decrease in tropospheric temperature, where tropospheric H_2O emit radiation to space. The decreasing effect of water vapor in the H_2O band is due to decreasing tropospheric humidity. This analysis will allow us to detect the changes in greenhouse gas forcing, to examine the correlated surface temperature response, and to study changes and effects in tropospheric water vapor concentration.

Introduction

Hiatus in global warming

Global surface temperature has increased the last century. This increase is a result of an increase in greenhouse gases concentrations, which causes an imbalance between ingoing and outgoing radiation at the top of the atmosphere (TOA). Currently, there exists an energy imbalance at the TOA, estimated to be 0.5–1 Wm−2 over the 2000s. (1-6) There has been a hiatus in global warming – that is to say, a period of no or negative trend in surface temperature – over the past 15 years, triggering discussions about climate change. This phenomenon is not unique; global surface temperature has in the past exhibited periods of neutral or negative trends amid a longer period characterized by warming. (7) Hunt et al. (2011) have demonstrated that decade-long episodes of subaverage surface temperature can be sustained solely by internal variability, i.e. without external forcing, showing that the hiatus in global warming can be explained by a natural decadal cooling period. (8) Others argue that these decades of hiatus in warming result from stronger deep oceans heat uptake. (4, 6, 9, 10) It is also possible that the observed decrease in stratopheric water vapor concentration after 2000 has contributed to the cooling of the troposphere in the last decade. (11) Solomon et al. (2011) suggest that the observed increase in stratospheric aerosols in the 2010s have partly canceled out the radiative forcing from greenhouse effect by scattering solar radiation back to space. (12) To get a clearer picture of the true cause behind atmospheric changes, we look to outgoing longwave radiation (OLR) spectrum of the past decade, which provides information about both the infrared radiation emitted by the earth's surface and the composition of the atmosphere.

Spectrum analysis of the outgoing longwave radiationshuang

A change in OLR can be caused by many factors, including changes in temperature at surface or gas emission levels, or changes in specific greenhouse gas concentrations. (13, 14) Earth's surface emitted infrared radiation (wavenumbers 0 to 3000 cm-1) is proportional to the planet's temperature. As upwelling radiation crosses the atmosphere, it is absorbed by atmospheric particles and molecules that in return re-emit energy at specific wavelengths as a function of their temperature. If a greenhouse gas layer in the atmosphere increases in density and width, the layer becomes more opaque to infrared radiations coming from Earth's surface and consequently re-emits energy from higher, colder levels in the atmosphere. According to Stefan-Boltzmann's law, a colder greenhouse gas layer emits less radiation. Thus, the energy emitted to space decreases, resulting in a temporary imbalance between the incoming radiation from the sun and heat emission transmitted from the atmosphere to outer space. This can result in Earth's surface warming, increasing the upwelling flux of energy until the planetary energy balance is restored.

In order to analyze changes in atmospheric composition and in tropospheric and surface temperatures, we investigated spectral trends in

Earth's OLR. We studied changes in radiation in the CO_2 absorption bands ranging between wavenumbers 580 to 750 cm-1 and 2200 to 2400 cm-1. The spectral regions where the absorption of infrared radiation by CO_2 in the troposphere is the strongest are at wavenumbers 600 to 640 and 690 to 800 cm-1. The radiative cooling of CO_2 in stratosphere is dominated by the 640-690 cm-1 band. (8, 9)
In order to analyze the effects of changes in tropospheric humidity and in surface temperature, we studied the radiation trend of the water vapor absorption bands (wavenumbers 1400 to 1800 cm-1) as well as in the OLR spectrum in the window region (wavenumbers 800 to 1300 cm-1). In parallel with our analysis of the OLR trend, we analysed the trends in tropospheric and surface temperature and in tropospheric humidity through the same decade. We also isolated the effect of greenhouse gases in the OLR spectrum trend.

Methods

Data Download

We analyzed OLR data collected by the Atmospheric Infrared Sounder (AIRS) aboard satellite Aqua part of the NASA Earth Observing System. (17) Aqua has a polar sun-synchronous orbit and a repeat cycle period of 233 orbits (16 days). Its AIRS instrument is a continuously operating cross-track scanning sounder. We also retrieved calibrated and geolocated radiance data collected by the AIRS Version 5 Level 1B Infrared Radiance Products (AIR1BRAD).

We also analyzed tropospheric temperature and humidity data collected by Aqua Level 2 retrieval product (AIRX2RET) to be put in parallel with our previous results. (18)

The surface temperature used in our calculations of the temperature profile trend and in the greenhouse effect calculation was downloaded from the ERA-interim reanalysis product of the European Center for Medium range Weather Forecasting (ECMWF). (19)

All collected data represented the same time period: January 1st, 2003 to December 31st , 2013.

Data Processing

We averaged daily OLR measurements to calculate the 16-day mean. We then spatially averaged the data set over the world. We converted the radiances to equivalent brightness temperatures using the Planck function, the relationship between the radiance emitted by a body and its temperature. After, we filtered the 16-day mean data by deleting all wavenumbers at which the time series had more than 10 missing data points, which corresponds to less than 5% of the length of the time series. We then de-noised the 16-day mean of brightness temperature measurements. To do so, we set the maximum noise level to the 25th and 75th percentile of a normal function with mean 0 and variance 0.5, with precision 10-9. We removed spectra with points at one maximum noise level away from the 25th or the 75th percentile. Then, the de-noised 16 day mean data were averaged over years 2003 to 2013.

A similar method of processing was used to analyze the geophysical variables from AIRX2RET and ERA-interim.

Trend Calculation

To calculate the trend and standard deviation in observed OLR spectrum from the yearly mean data, we used the AR(1) method. (20) This method of calculation assumes that noise is autoregressive of the order of 1 (AR(1)). The confidence level is 95%.
We used the same method to analyze the geophysical variables from AIRX2RET, ERA-interim and simulated OLR spectrum.
Greenhouse Effect Calculation

We defined the greenhouse effect as the difference between the upward longwave radiation at the surface and the outgoing longwave radiation at the TOA. To calculate the greenhouse effect, we subtracted the annual mean OLR spectrum from the annual mean surface radiation spectrum. The mean surface radiation spectrum was computed using the ERA-interim surface temperature and the Planck function, assuming that Earth is a black body. We then calculated the trend in greenhouse effect using the AR(1) method.

Results

In Fig. 1, we see the trend in OLR spectrum from 2003 to 2013 over the world. There is a negative trend in radiation in the CO_2 absorption bands. This reduced emission is signatory of increasing CO_2 concentration. (13, 15, 21) In fact, increasing concentration of CO_2 causes a rise in altitude of the levels of effective emission of CO_2 to space as well as emission of thermal infrared radiation. Because temperature decreases with height and radiation emissions is a function of the body temperature, the OLR is decreased. Therefore, the decreasing trend in equivalent brightness temperature at the CO_2 bands suggests that the CO_2 concentrations have been increasing in the last decade.

To compensate for this loss of energy to space, we expect the thermal infrared radiation from Earth to increase – in other words, a global warming in terms of surface temperatures. We can study surface emissions by looking at the OLR over the window region (wavenumbers 800 to 1300 cm-1). At these wavenumbers, the changes in signal are dominated by the changes in surface temperature and are also affected by the changes in lower troposphere humidity in clouds and in aerosols. The results in Fig. 1 show a negative trend in equivalent brightness temperature over the window region. If it is caused by a decreasing surface temperature, then the data are consistent with the observed hiatus in global warming. (7)

The H_2O absorption band (wavenumbers 1400 to 1600 cm-1) exhibits a positive trend in radiation. For equivalent brightness temperature to increase at these wavenumbers, the concentration in water vapor has to decrease such that the level of emission of water vapor is at lower altitude and warmer level. This positive trend could be also caused by increasing temperatures at the level of effective emission of water vapor.

Fig. 2 presents the trend in surface and atmospheric temperatures and in tropospheric humidity at different pressure levels (atmospheric pressure is here used as a measure of altitude) for the same time period. Note that pressure at the tropopause is around 200-100 hPa. The trend in surface temperature less than one standard deviation away from zero, which is consistent with the hiatus in global warming reported by the literature. (7) However, the trend in the lower tropospheric temperature (900-1000 hPa) is significantly above zero (more than one standard deviation away from zero). Part of this difference in trends can be a result of sampling biases (given the fact that the geographic region and altitude covered by a surface temperature sample will not be the same as, by example, a 1000 hPa level sample) – however, the 1000-900 hPa trend is consistent with the trend at the next higher level. Therefore, the trends in atmospheric temperature calculated from AIRS is ambiguous.

The slightly negative trend in surface temperature in Fig. 2.a is consistent with the negative trend in OLR over the window region (see Fig. 1), but is too weak to completely explain the decrease in OLR. The negative trend in tropospheric water vapor in Fig. 2.b is in agreement with the positive trend in OLR over the H_2O absorption band. Because tropospheric temperature is strongly decreasing, this last observation implies that in the H_2O band, the change in tropospheric water vapor concentration had more impact than tropospheric temperature change on the OLR trend in the H_2O band. Moreover, a decrease in tropospheric humidity causes an increase in OLR not only in the water vapor band but also in the window region (water vapor continuum). (14) However, OLR in the window region is decreasing, so there should exist a stronger contributor that cancels this effect from water vapor. We suspect the important decreasing tropospheric temperature to cause cooling at altitudes at which water vapor emit radiation to space, provoking a decrease in OLR. These results suggest that a decrease in tropospheric temperature contributes to the negative trend in OLR in the window region (Fig. 1).

Greenhouse Effect

By isolating the greenhouse effect (GHE) from the surface radiation in the OLR spectrum, we can identify more clearly the contributors to the change in OLR, especially in the window region. In Fig. 3, we compare the average OLR spectrum with the average surface radiation over the world from 2003 to 2012. The difference between the two spectra is mainly due to the GHE. The CO_2, O_3, and H_2O absorption bands are clearly noticeable at the 650-800, 980-1080 and 1400-1600 cm-1 spectral ranges, respectively, where the OLR spectrum is particularly lower than the surface upward IR spectrum.
Fig. 4 presents the trend in the greenhouse effect from 2003 to 2012. The greenhouse effect increased in the CO_2 band (wavenumbers 650 to 800 cm-1) and decreased in the water vapor band (wavenumbers 1400 to 1600 cm-1). These trends in the GHE could be caused by changes in greenhouse gas concentration or by changes in temperature at the level of the gas emission. There are also several significantly positive trends, namely in GHE over the window region (wavenumbers 800 to 1300 cm-1), and at the O_3 band (at the center of the window region). These positive trends in GHE in the window region suggest that water vapor has increasing greenhouse effect in this spectral range.

Discussion

In this study, we analyze the trend in observed Earth thermal infrared In this study, we analyze the trend in observed Earth thermal infrared radiation between 2003 and 2013 over the world, in particular through the window region, as well as the H_2O and CO_2 absorption bands.

In the CO_2 absorption band of the OLR spectrum, we are able to observe an evident decreasing trend in radiation. Moreover, following the greenhouse effect, there was increasing GHE over the CO_2 band. These results imply that the trend in CO_2 forcing was present worldwide during the hiatus in global warming of the last decade. According to literature, the OLR in the CO_2 band was also decreasing in the previous decades. (15, 16)
We also looked at the trend in equivalent brightness temperature (emission temperature) in the window region, where the emission is dominated by changes in surface temperatures, but also affected by water vapor concentration and clouds. We compared the observed trend in radiation with the observed trends in surface temperature, tropospheric temperature, and humidity to determine which one could be responsible for the change in radiation. Globally, from 2003 to 2013, there was a small negative trend in OLR through the window region. We propose that the main contributors to this reduced emission were a slight negative trend in surface temperature and changes in water vapor emission, particularly due to cooling at altitudes at which H_2O emits to space. In previous decades, the trend in OLR in the window region was positive (11,12).

In the water vapor absorption band, the trend in OLR over the world between 2003 and 2013 is positive. Coupling this observation with our other results, such as the negative trend in greenhouse effect at the same wavelength and the decrease in tropospheric humidity, we can conclude that humidity decreased globally in the last decade, along with its effect in the water vapor absorption band. Moreover, considering that tropospheric temperature was mainly decreasing, we can propose that changes in gas concentration had more effect on the OLR trend than did change in temperature of the layer of emission.

It would be relevant to use global climate model simulations to further identify key atmospheric contributors to this global cooling of the lower troposphere and clarify the impacts of the change in humidity on these observed trends in the OLR spectrum. This study does not take into account cloud cover, which can be addressed in future studies. In fact, cloud cover can mask OLR emitted by the surface below and emit OLR at higher altitude, further lowering measured temperatures. As a result, in cloud-covered skies, the OLR measured in the window region is a function of the clouds temperature instead of the surface temperature, which biases our analysis.

In the broader context of climate change, this study shows that although if global warming has paused in the last decade, the greenhouse effect of CO_2 is still increasing. Therefore, the source of the problem of climate change is not solved. Considering that this hiatus in global warming is caused by a natural decadal cooling period, we expect that the global warming will resume with renewed strength in the next decade.

Figures

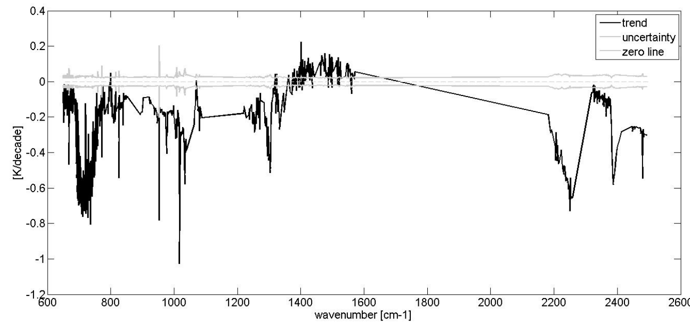

Figure 1. Trend in equivalent brightness temperature measured from OLR at different wavenumber from 2003 to 2013 over the global Earth (all latitudes and all longitudes). The spectrum was taken from 650 cm−1 to 2500 cm−1.

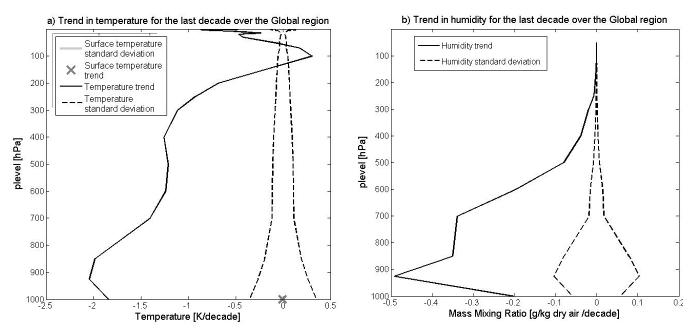

Figure 2. Trend in a) temperature and in b) humidity in function of plevel (1000 to 0.1hPa) from 2003 to 2013 over global Earth.

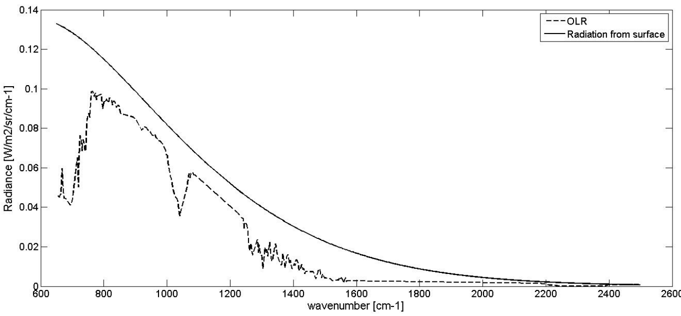

Figure 3. Comparison between climatology of OLR spectrum and surface radiation spectrum from 2003 to 2012 over global Earth. The spectrum was taken from 650 cm−1 to 2500 cm−1.

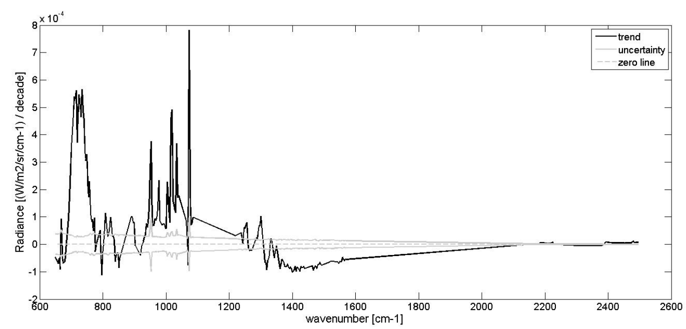

Figure.4. Trend in greenhouse effect trough longwave spectrum, from 2003 to 2012 over global Earth. The spectrum was taken from 650 cm−1 to 2500 cm−1.

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