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Key Points:

- Negative greenhouse effect occurs only over central Antarctica on yearly average
- Rising CO_2 can induce slightly negative instantaneous radiative forcing in central Antarctica

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How increasing CO_2 leads to an increased negative greenhouse effect in Antarctica

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Abstract CO_2 is the strongest anthropogenic forcing agent for climate change since preindustrial times. Like other greenhouse gases, CO_2 absorbs terrestrial surface radiation and causes emission from the atmosphere to space. As the surface is generally warmer than the atmosphere, the total long-wave emission to space is commonly less than the surface emission. However, this does not hold true for the high elevated areas of central Antarctica. For this region, the emission to space is higher than the surface emission; and the greenhouse effect of CO_2 is around zero or even negative, which has not been discussed so far. We investigated this in detail and show that for central Antarctica an increase in CO_2 concentration leads to an increased long-wave energy loss to space, which cools the Earth-atmosphere system. These findings for central Antarctica are in contrast to the general warming effect of increasing CO_2.

1. Introduction

Throughout the last years, several ideas have been discussed describing the lack of warming of central Antarctica [*Chapman and Walsh*, 2007; *Steig et al.*, 2009; *Thompson et al.*, 2011; *Langematz et al.*, 2003; *Shindell and Schmidt*, 2004; *Shine and Forster*, 1999]. The global warming observed is to a large extent caused by anthropogenic emission of greenhouse gases [*Intergovernmental Panel on Climate Change (IPCC)*, 2013]. Greenhouse gases (GHGs) act on the climate by absorbing terrestrial surface radiation and provoking long-wave (LW) emission from the atmosphere. This is radiated in two directions, back toward the surface and out into space. Generally, the surface is warmer than the atmosphere. Thus, radiation emitted from the surface through the atmospheric window is higher compared to radiation from the stratosphere. This is clearly visible looking at the CO_2 band around 15 μm, where the emission originates mostly from the stratosphere [*Elachi and Zyl*, 2006, Figure 11–10]. The spectra give an emission minimum in the CO_2 band [*Thomas and Stamnes*, 1999, Figures 1.2a and 1.2b].

However, above Antarctica the top-of-atmosphere (TOA) spectra look different; the spectra yield a maximum in the CO_2 band [*Thomas and Stamnes*, 1999, Figure 1.2c]. This observation is consistent with the finding that in the interior of the Antarctic continent the surface is often colder than the stratosphere; therefore, the emission from the stratospheric CO_2 is higher than the emission from the surface.

The intensity maximum in the CO_2 band above Antarctica has been observed in satellite spectra [*Thomas and Stamnes*, 1999, Figure 1.2c], but its implication for the climate has not been discussed so far. The aim of this paper is to see where and how often this negative surface-stratosphere temperature differences occurs and to study for these situations the impact of CO_2 and its long-term increase on the radiative budget on Antarctica. Our results might help to understand the specific conditions of the Antarctic climate and its sensitivity to changes in CO_2 concentration.

In our paper we first present two different model studies which show that increasing atmospheric CO_2 causes an increase in the LW cooling in central Antarctica. Satellite observations presented demonstrate that over central Antarctica a negative greenhouse effect (see next chapter) occurs frequently and that Antarctica is the only place on Earth where the greenhouse effect is below zero on yearly average. Calculations with the ECMWF forecast model demonstrate that an increase in CO_2 increases the LW cooling above the Antarctic Plateau.

2. Two-Layer Model Considerations

The emitted LW flux at the top-of-atmosphere F_{TOA} as measured by satellites can be estimated from the transmitted surface radiation $(1-\varepsilon_{atm})\ \sigma\ T_{surf}^4$ (with σ as Stefan-Boltzmann constant and assuming the emissivity of the surface to be 1) and the emission of the atmosphere $\varepsilon_{atm}\ \sigma\ T_{atm}{}^4$:

$$F_{TOA} = (1 - \varepsilon_{atm})\sigma\ T^4{}_{surf} + \varepsilon_{atm}\ \sigma\ T^4{}_{atm} \\ = \sigma\ T^4{}_{surf} - \varepsilon_{atm}\sigma\left(T^4{}_{surf} - T^4{}_{atm}\right) \quad (1)$$

This two-layer model consideration simply features a surface layer at temperature T_{surf} and one atmospheric layer at temperature T_{atm} with LW emissivity ε_{atm} which includes the radiative effects of all trace gases. ε_{atm} depends on the concentration c and increases with increasing c in certain absorption bands.

In order to investigate the absorption and reemission of the LW radiation within the atmosphere, the greenhouse effect (GHE) can be defined as the difference between the surface emission and F_{TOA}: GHE = σ $T^4_{surf} - F_{TOA}$. With equation (1) we then get

$$\text{GHE} = \varepsilon_{atm}\ \sigma\left(T^4{}_{surf} - T^4{}_{atm}\right) \quad (2)$$

This corresponds to the definition of the GHE by Thomas and Stamnes [1999, equation 12.19]. The quantity denotes the effect of trapping the radiation emitted from the surface. According to Thomas and Stamnes, it is also the downward flux impinging on the surface, the "backwarming" by the atmosphere [*Thomas and Stamnes*, 1999, equation 12.15].

Equations (1) and (2) do not distinguish between the different greenhouse gases and do not describe the dependency of wavelength and altitude. But the two simple equations allow us to provide some insight into the combined emission of a surface and the atmosphere above as a function of temperature difference and trace gas concentrations. A detailed line-by-line calculation is presented in the next chapter.

As the surface in most regions on Earth is warmer than the atmosphere, ${T_{surf}}^4 - {T_{atm}}^4$ in equation (1) is commonly positive; hence, the presence of the atmosphere reduces the TOA emission F_{TOA}. Therefore, both the GHE and the instantaneous radiative forcing ($-\partial F_{TOA}/\partial\varepsilon_c$) are usually positive. However, if the surface is colder than the atmosphere, the sign of the second term in equation (1) is negative. Consequently, the system loses more energy to space due to the presence of greenhouse gases. The GHE and the instantaneous radiative forcing turn negative. Furthermore, the energy loss to space F_{TOA} then increases with increasing ε_{atm}.

For the high elevated areas of Antarctica, T_{surf} is frequently lower than T_{atm} (shown below), which is a unique feature on Earth. The observation of an intensity maximum in the CO_2 band above Antarctica corresponds to a negative GHE, in agreement with the negative surface-stratosphere temperature differences. This implies that increasing CO_2 causes the emission maximum in the TOA spectra to increase slightly, which instantaneously enhances the LW cooling in this region, strengthening the cooling of the planet. This is in contrast to the generally warming associated with rising CO_2 level [*Shine and Forster*, 1999; *Ramaswamy et al.*, 2001; *Hansen et al.*, 2005].

3. Radiative Transfer Calculations

3.1. Methodology

In addition to the two-layer model considerations the negative greenhouse effect of CO_2 has also been studied by employing a line-by-line radiative transfer model, which allowed us to investigate the spectral dependence in detail and compare the spectra to observations. Instead of the definition for the GHE above, we applied the integral version for the GHE:

$$\text{GHE} = \int\left(\pi B_\lambda(T_{surf}) - F_{\lambda,TOA}\right)d\lambda \quad (3)$$

with B_λ being the spectral radiance according to Planck's law. From radiative transfer calculations, it is easy to determine what would have been emitted to space, if there was no CO_2, which is $F_{\lambda,TOA}(c = 0)$. Therefore, we replaced $\pi B_\lambda(T_{surf})$ in equation (3) by $F_{TOA}(c) = 0$, resulting in

$$\text{GHE}_{CO_2}(c) = \int_{5\ \mu m}^{200\ \mu m}\left(F_{\lambda,TOA}(c = 0) - F_{\lambda,TOA}(c)\right)d\lambda \quad (4)$$

with $F_{\lambda,TOA}(c)$ being the calculated spectral radiance emitted to space for a CO_2 concentration *c*. Equation (4) is consistent with the "single factor removal" metric described by *Schmidt et al.* [2010], which they regard as the minimum effect that a GHG has. As the temperature profile is fixed in all experiments, and therefore no feedback mechanism is included in the model, the derivative $\partial GHE_{CO2}/\partial CO_2$ can be interpreted as direct radiative forcing of CO_2.

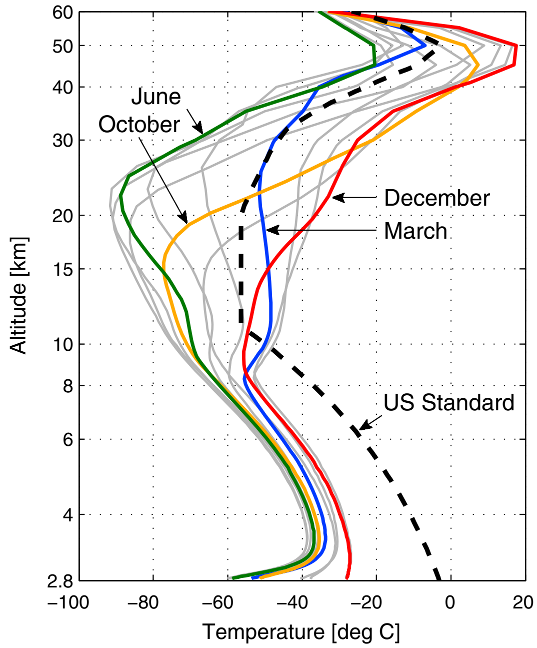

Figure 1. Monthly averaged temperature profiles from South Pole station (solid lines) together with the U.S. standard atmosphere 1976 [*National Oceanic and Atmospheric Administration et al.*, 1976] (dashed line). One typical month for each season is accentuated by the color coding. The lowest point of each profile was calculated from BSRN surface measurements [*Dutton et al.*, 2015] for the period 1994 to 2012. Above that, mostly daily radiosoundings from the same period were used up to 25–38 km, where data becomes too sparse. ECMWF ERA interim reanalysis data, again for the same period, complement the profiles up to some 60 km. Beyond this, the U.S. standard atmosphere 1976 was used in the calculations.

Calculations were performed using the line-by-line radiative transfer model ALFIP [*Notholt et al.*, 2006]. Figure 1 shows the temperature profiles used in this work: monthly averages from South Pole station (data from 1994 to 2012) and the U. S. standard 1976 atmosphere for comparison. All calculations were performed for clear sky conditions necessary to address the question at hand.

3.2. Results

Figure 2 shows examples of simulated emission spectra at TOA. The simulated spectra for midlatitudes and Antarctica for 380 ppm CO_2 qualitatively agree with the satellite observations [*Thomas and Stamnes*, 1999, Figure 1.2]. Figure 2 shows that while for the U.S. standard atmosphere an increase in CO_2 concentration results in an instantaneous decrease of terrestrial emission, the effect for central Antarctic conditions is opposite; here increased CO_2 causes increased terrestrial emission. Calculating GHE_{CO2} using equation (4) results in an increased direct radiative cooling of $GHE_{CO2} = -2.9\ W/m^2$ (comparing $c = 380$ ppm to $c = 0$ ppm) for Antarctica. For the U.S. standard atmosphere we calculate $GHE_{CO2} = +28.0\ W/m^2$.

Figure 3 shows the greenhouse effect of CO_2 as a function of CO_2 concentration, calculated using ALFIP. Generally, (as for the U.S. standard atmosphere) GHE_{CO2} is positive and increases with increasing CO_2. However, for conditions typical for the Antarctic Plateau GHE_{CO2} can be negative and commonly decreases with increasing CO_2. This can also be seen from Table 1; only winter conditions (May till August) show positive values for the direct radiative forcing. During the rest of the year, the forcing is slightly negative.

4. Satellite Measurements of GHE

Model calculations will be no better than the input data, which are potentially quite poor over remote regions like Antarctica. Observations are not subject to such error of specification. Therefore, in addition to our model studies, we included satellite observations to demonstrate the negative greenhouse effect for the specific conditions in Antarctica.

4.1. Methodology

In order to depict a global overview of the occurrence of the phenomenon of negative GHE and investigate its climatic relevance, 1 year of measurements taken by the Tropospheric Emission Spectrometer (TES) [*Beer et al.*, 2001] on board the AURA spacecraft have been analyzed. The TES satellite observations in the infrared region allow studying the radiative contribution of CO_2 and its GHE in detail, by focusing on spectral regions where CO_2 is the dominant absorber. The greenhouse effect of CO_2 was determined similar to equation (3) by

$$GHE_{TES} = \int_{12.58\ \mu m}^{15.34\ \mu m} \left(\pi B_\lambda(T_{eff}) - F_{\lambda,TES}\right) d\lambda \quad (5)$$

where the effective emission temperature T_{eff} was determined from the atmospheric window between 10.88 and 12.03 μm and $F_{\lambda,TES}$ being the spectral radiance observed by the satellite sensor. The limits of the integral correspond to the measurement channel width of the TES instrument, a region spectral where CO_2 is the main absorber.

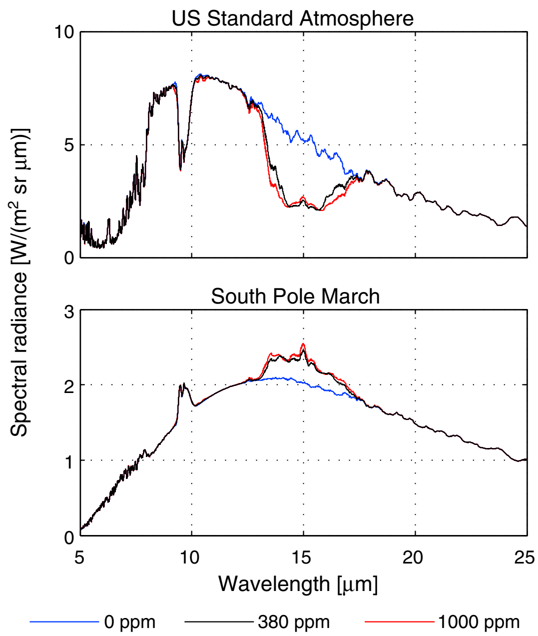

Figure 2. Extraterrestrial emission spectra calculated with ALFIP, using temperature profiles shown in Figure 1. The simulated South Pole spectrum for $c = 380$ ppm replicates the intensity maximum in the CO_2 band around 15 µm, which corresponds to the negative greenhouse effect of CO_2 as observed by satellite over Antarctica (Figure 4).

The definition of GHE_{TES} used here certainly has disadvantages; e.g., it generally underestimates the greenhouse effect, as it uses T_{eff} from the atmospheric window rather than the actual surface temperature. However, this is considered a fair assumption, as the emissivity of a snow or firn surface is close to one. Additionally, it does not account for spectral overlaps: for the 15 µm CO_2 band, this mainly concerns water vapor, which is of minor importance for the extremely cold atmosphere of central Antarctica. Nevertheless, the definition sharply distinguishes whether the emission in the CO_2 band is lower or higher than in the adjacent atmospheric window, and GHE_{TES} is a good measure to study the exceptional conditions in Antarctica.

4.2. Results

Figure 4 shows the global distribution of the greenhouse effect of CO_2 in 2006, averaged for the whole year, as measured from satellite. For most of the Antarctic Plateau, GHE_{TES} is close to zero or even slightly negative; i.e., the presence of CO_2 increases radiative cooling. Over Greenland, the greenhouse effect of CO_2 is also comparatively weak but invariably positive. An evaluation of monthly averages of GHE_{TES} shows that the increased cooling due to CO_2 of Antarctica is strongest during austral spring and autumn; seasons when the stratosphere above 20 km is mostly warmer than the surface. Even though the surface is coldest in austral winter, the temperature difference between the surface and stratosphere is not at its maximum then. Consequently, GHE_{TES} does not reach its minimum in austral winter. The TES results demonstrate that the yearly averages of GHE_{TES} being negative are unique to the Antarctic Plateau and nowhere else observed on the planet. This is due to the fact that Antarctica is the only region on Earth where the surface is frequently colder than the stratosphere.

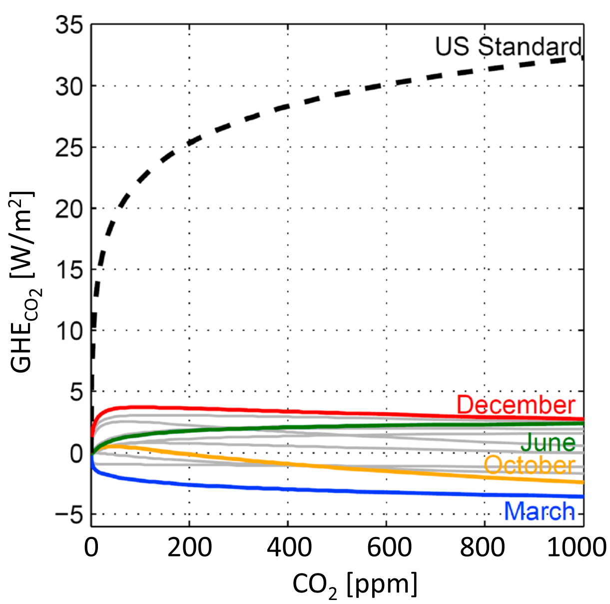

Figure 3. Greenhouse effect of CO_2 as a function of CO_2 concentration (equation (4)) for temperature profiles shown in Figure 1. For each season at South Pole one typical month is highlighted by color coding. The slope of the curves can be interpreted as direct radiative forcing of CO_2 (see also Table 1).

T_{eff}, as used in equation (3), represents the temperature of the emitting surface, which is for cloudy conditions the clouds' top. Therefore, individual negative values of GHE_{TES} are also observed above high reaching clouds, especially over the tropics. However, as the clouds are not stationary, the yearly averages remain positive for all regions, except Antarctica.

Table 1. Greenhouse Effect GHE_{CO2} and Direct Radiative Forcing $\partial GHE_{CO2}/\partial CO_2$ for $c = 380$ ppm[a]

Atmosphere	GHE_{CO2} (Wm^{-2})	$\partial GHE_{CO2}/\partial CO_2$ (Wm^{-2}/100 ppm)
U.S. Standard Atmosphere	28.07	1.15
South Pole January	2.95	−0.07
South Pole February	−0.99	−0.16
South Pole March	−2.94	−0.15
South Pole April	−1.03	−0.02
South Pole May	1.34	0.08
South Pole June	2.05	0.10
South Pole July	2.12	0.08
South Pole August	1.95	0.02
South Pole September	0.57	−0.11
South Pole October	−0.83	−0.34
South Pole November	1.74	−0.25
South Pole December	3.39	−0.13

[a] All values were calculated with ALFIP using the temperature profiles shown in Figure 1. Positive direct radiative forcing is seen only during winter from May till August. The rest of the year the forcing is slightly negative (see also Figure 3).

5. ECMWF Model Experiments With Quadrupled CO_2

To evaluate the spatial distribution of the influence of increased CO_2 concentrations, experiments with the atmospheric model of the European Centre for Medium-Range Weather Forecast (ECMWF) [*Jung et al.*, 2010] were performed. Four 15 day forecasts with present-day and quadrupled CO_2 concentrations were run for each month of the period 1989–2010. Each forecast was initialised with ECMWF reanalysis data (ERA interim) and then run freely for the 15 days in both CO_2 configurations. The forecast period was chosen to evaluate the local response to the forcing. While very fast responses of the system can take place (e.g., cloud formation), the integration period is not long enough to allow global transport processes and teleconnections to obscure the local influence [*Rodwell and Jung*, 2008]. Longer integration times would conflate radiative tendencies with nonradiative effects.

Figure 5 gives the difference in the LW radiation emitted to space, F_{TOA}, for a quadrupled CO_2 relative to present-day CO_2 concentrations after letting the model run for 15 days. Central Antarctica is the only place on the planet where increased CO_2 concentrations lead to an increased LW energy loss to space. In the Northern Hemisphere the lowest, but invariably positive, forcing values are seen over Greenland and Eastern Siberia.

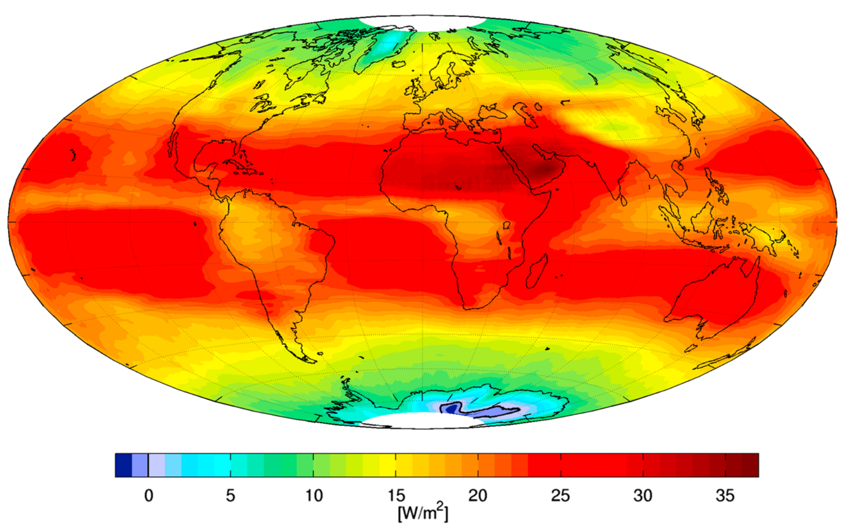

Figure 4. Yearly averaged greenhouse effect of CO_2 (equation (5)) derived from 2006 TES thermal IR spectra [*Beer et al.*, 2001]. The data shown comprises 586.860 observed spectra from 173 global surveys, each consisting of 16 orbits. The calculations do not cover the entire 15 μm CO_2 band, due to the spectral limitations of the TES instrument. The orbit of the satellite does not allow data acquisition right at the poles.

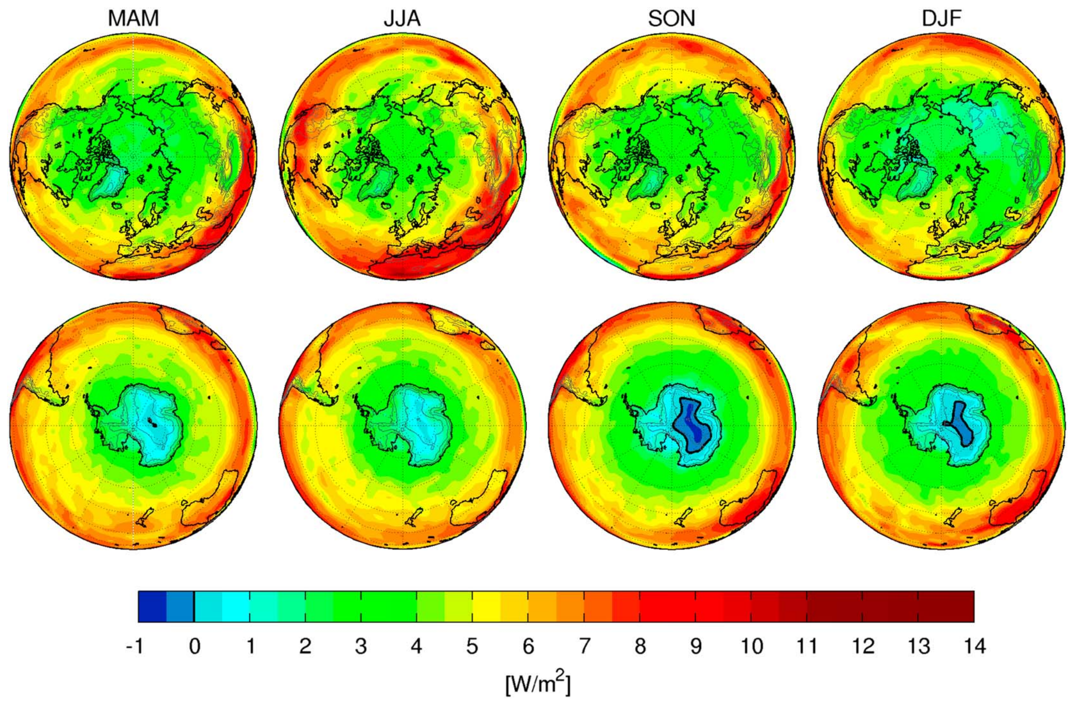

Figure 5. Mean difference in outgoing LW radiation at TOA for 15 day forecast with the ECMWF model for experiments with quadrupled to present-day CO_2 concentrations. The black contour line denotes 0 W/m^2. Surface elevation contour lines are shown in 1000 m intervals. The high elevated areas of central Antarctica stand out as the only region on Earth where increased CO_2 concentrations lead to increased LW energy loss into space.

The numbers shown in Figure 5 will be offset when the outgoing short-wave flux contribution is included. Short-wave radiation is affected by changes in humidity, cloud cover, and also by the weak absorption of solar radiation by CO_2. Over Antarctica, this sums up to 0.5 W/m^2 for autumn, winter, and spring and up to 1 W/m^2 in summer.

The surface temperature in the ECMWF reanalysis above the Antarctic Plateau is typically around 3 K higher compared to what is measured by the Baseline Surface Radiation Network (BSRN) station at South Pole, which could be due to inaccuracies in the parametrization of the turbulent heat flux or inaccuracies in the radiation scheme. This indicates an underestimation of the LW cooling effect of increasing CO_2 over central Antarctica. Nevertheless, with our ECMWF model experiments we determined the yearly averaged TOA net forcing above the Antarctic Plateau to be on the order of 1 W/m^2 for a quadrupled CO_2 concentration, which is the lowest warming on Earth.

6. Discussion and Conclusion

We can conclude that the role of CO_2 in the Antarctic climate is somewhat different to the rest of the planet: Increasing CO_2 has a rather small direct effect on the Antarctic climate; it even tends to cool the Earth-atmosphere system of the Antarctic Plateau. The analysis carried out by *Chapman and Walsh* [2007] and *Steig et al.* [2009] did not result in any statistically significant surface temperature trend on the East Antarctic Plateau during the last decades. They even found a slight (but statistically not significant) cooling trend for the centre of Antarctica. Our findings cannot be understood as explanation of this phenomena but show remarkable similarities with the observations.

It is important to note that these results do not contradict the key statements of the Intergovernmental Panel on Climate Change (IPCC) [*Solomon et al.*, 2007; *Ramaswamy et al.*, 2001; *IPCC*, 2013], namely, the well-known warming effect that CO_2 has on the Earth's climate. Yet we showed that for the cold Antarctic continent some care needs to be taken when discussing the direct warming effect of CO_2.

Earlier studies with general circulation models (GCMs) have also shown the comparably small effect of increasing CO_2 on the LW flux at the top of atmosphere emitted to space above Antarctica [*Shine and Forster*, 1999; *Hansen et al.*, 2005], but they neither show a cooling effect nor give an explanation for this and its climatic relevance. We have compared BSRN surface measurements of broadband LW upward fluxes from South Pole with model estimates of this quantity compiled for the fifth IPCC assessment report (fifth phase of the Coupled Model Intercomparison Project), analogue to the comparisons reported by *Wild et al.* [2012]. This comparison shows that GCMs tend to overestimate the surface temperature. Specifically, 18 of the 21 GCMs report a higher (0.8 to 25.8 W/m^2) LW emission from the surface than the BSRN measurements, whereas the other three models report a lower (1.3 to 7.2 W/m^2) surface emission. This suggests that current GCMs tend to overestimate the surface temperature at South Pole, due to their difficulties in describing the strong temperature inversion in the boundary layer. Therefore, GCMs might underestimate a cooling effect from increased CO_2, due to a bias in the surface temperature.

Acknowledgments

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