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Author(s):
Petrus, Ana; Lohmann, Ulrike; Storelvmo, Trude

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Bacteria in the ECHAM5-HAM global climate model

A. Sesartic[1], **U. Lohmann**[1], **and T. Storelvmo**[2]

[1]ETH Zurich, Institute for Atmospheric and Climate Science, 8092 Zurich, Switzerland
[2]Department of Geology and Geophysics, Yale University, New Haven, CT, USA

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Correspondence to: A. Sesartic (ana.sesartic@env.ethz.ch)

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Abstract

Bacteria are the most active naturally occuring ice nuclei (IN) due to the ice nucleation active proteins on their surface, which serve as active sites for ice nucleation. Their potential impact on clouds and precipitation is not well known and needs to be investigated. Bacteria as a new aerosol species were introduced into the global climate model (GCM) ECHAM5-HAM. The inclusion of bacteria acting as IN in a GCM leads to only minor changes in cloud formation and precipitation on a global level, however, changes in the liquid water path and ice water path can be observed, specifically in the boreal regions where tundra and forests act as sources of bacteria.

1 Introduction

Primary biological aerosol particles (PBAP, also called bioaerosols) are airborne particles that are either alive, carry living organisms or are released by them (Ariya and Amyot, 2004). A prominent example of PBAP are bacteria, on which we focus our research.

The presence of bacteria in the troposphere and even in the stratosphere has long been established by a variety of aerobiological research (Wainwright et al., 2003; Morris et al., 2011). Most of that research however, has focused on issues related to health hazards, while ignoring their impacts on cloud formation and the hydrological cycle.

Bacteria have been shown in laboratory studies to be efficient ice nuclei (IN) and it has been suggested from different sides that bacteria which act as IN or cloud condensation nuclei (CCN) in the atmosphere could impact the global distribution of clouds and precipitation (Schnell and Vali, 1972, 1973; Yankofsky et al., 1981a,b; Levin and Yankofsky, 1988; Sands et al., 1982; Bauer et al., 2003; Diehl et al., 2006; Morris et al., 2004, 2011; Sun and Ariya, 2006).

Bacteria are ubiquitous and can enter the atmosphere as aerosol particles from almost all surfaces (Jones and Harrison, 2004). Once in the air, they are carried upward by vertical updraughts. They have relatively long atmospheric residence times on the order of several days (Morris et al., 2011). They can be transported by wind over long distances (Bovallius et al., 1978b; Prospero et al., 2005) before being removed by precipitation and/or scavenging, or dry deposition onto surfaces due to gravitational settling. Burrows et al. (2009b) summarised that mean concentrations in ambient air are likely to be at least 1×10^4 cells m^{-3} over land, while concentrations over ocean may be lower than over land by a factor of about 100 to 1000.

It is estimated that on a global average in the lower troposphere or near the surface, 25% of the total mass concentration of atmospheric aerosols is provided by primary bioaerosols (Jaenicke et al., 2007). Over biomes with high vegetation density such as the Amazon rainforest, bioaerosols account for as much as 74% of the total aerosol number concentration, with fungal spores contributing 30–50% (Matthias-Maser and Jaenicke, 1995). Even in remote marine air masses, the contribution of bioaerosols by both number concentration and volume amounts to 10–20% (Gruber et al., 1998).

The highest number concentration of bacteria in the atmosphere is reached during summer, as this is the season with most abundant vegetation coverage that provides a habitat for leaf-dwelling bacteria (Amato et al., 2006; Tong and Lighthart, 2000; Burch and Levetin, 2002). Most bacteria which act as IN are gram-negative, which means that they have an outer membrane containing lipopolysaccharide chains on which lipoproteins are attached (Brock et al., 2000). Their surface area is therefore substantially enlarged and provides more potential active sites where ice nucleation is expected to take place. Ice nucleation active bacteria can catalyse the immersion freezing of supercooled water at temperatures as warm as -2°C due to the ice nucleation activating protein InaZ (Schnell and Vali, 1972; Maki et al., 1974; Yankofsky et al., 1981a).

In particular, *Pseudomonas syringae* is a bacterium which is an excellent CCN/IN. It is commonly associated with plants as a pathogen living on the leaf surface. Its ice nucleation activity is conferred by a single gene (inaZ) that encodes the outer membrane InaZ protein. Individual InaZ proteins cannot serve as IN, but form large, homogeneous aggregates that collectively orient water molecules into a conformation mimicking the crystalline structure of ice, thereby catalysing ice formation (Baertlein et al., 1992). It has also been shown that there are ice nucleation active fungi (Pouleur et al., 1992; Iannone et al., 2010) and pollen (Diehl et al., 2001, 2002; von Blohn et al., 2005), though they initiate freezing at colder temperatures than bacteria do. Šantl Temkiv et al. (2009) found 9% of bacteria in rain samples to be IN active.

Aircraft observations from the campaign Ice in Clouds Experiment-Layer-clouds (ICE-L) conducted in Wyoming in 2007 showed that biological particles were present in the residual material from heterogeneously nucleated ice crystals (Pratt et al., 2009). Furthermore, bacteria were found to be present at concentrations of up to about 500 particles per litre of freshly fallen snow (Christner et al., 2008).

Diehl et al. (2006) and Diehl and Wurzler (2004) provide parameterisations for the contact and immersion freezing efficiencies of bacteria compared to those of other bioaerosol and mineral dust. Based on their experimental data, Fig. 1 shows the fraction of frozen droplets for different temperatures and IN. Ice formation due to contact freezing starts at similar temperatures for bacteria and montmorillonite mineral dust particles, but then proceeds most rapidly for bacteria. For the case of immersion freezing, bacteria initiated freezing at approximately 10 °C higher temperatures than mineral dust (montmorillonite and kaolinite) does. As bacteria nucleate ice already at such high temperatures, the ice particles forming on them have the longest possible growth times in a cloud and the greatest chance to grow to precipitation sizes, which makes them interesting to investigate.

The interaction between aerosols and mixed-phase clouds is still uncertain, as reviewed by Lohmann and Feichter (2005). Recently there have been various modelling studies on potential impacts from biological aerosols on clouds, which have reached different conclusions (Möhler et al., 2008; Phillips et al., 2009; Burrows et al., 2009a; Hoose et al., 2010). While Hoose et al. (2010) do not find any significant impact of bioaerosols on clouds and precipitation, e.g. Phillips et al. (2009) state that cloud properties are altered by boosted bacterial concentrations. They agree however, that there is no impact to be observed with realistic bacterial concentrations.

The overall aim of the present study is to examine the influence of bacteria on microphysical properties of stratiform clouds and precipitation on a global scale.

In the following section, the global climate model and experimental design are described. Results from sensitivity tests are shown and discussed in the subsequent section.

2 Model setup

ECHAM5 is the fifth generation atmospheric general circulation model (GCM) that evolved from the model of the European Centre for Medium Range Weather Forecasting (ECMWF) and was further developed at the Max-Planck Institute for Meteorology (Roeckner et al., 2003). The model solves prognostic equations for vorticity, divergence, temperature and surface pressure using spherical harmonics with triangular truncation. Water vapour, cloud liquid water and ice, as well as trace components, are transported using a semi-Lagrangian scheme (Lin and Rood, 1996) on a Gaussian grid. Prognostic equations for cloud water and ice follow Lohmann et al. (2007). The model includes the cirrus scheme of Kärcher and Lohmann (2002). Convective clouds and transport are based on the mass-flux scheme of Tiedtke (1989) with modifications following Nordeng (1994). The solar radiation scheme has 6 spectral bands (Cagnazzo et al., 2007) and the infrared has 16 spectral bands (Mlawer et al., 1997; Morcrette et al., 1998).

The GCM is coupled to the Hamburg Aerosol Model (HAM), which is described in detail by Stier et al. (2005) and most recently adapted by Lohmann and Hoose (2009). The aerosols are represented by seven log-normal modes, 4 internally mixed/soluble modes (nucleation (NS), Aitken (KS), accumulation (AS), and coarse (CS)) and 3 insoluble modes (Aitken (KI), accumulation (AI), and coarse (CI)). The median radius for each mode is calculated from the aerosol mass and number distributions in each mode. Aerosol mass and number are transferred between the modes by the processes of sulphuric acid condensation, and coagulation between aerosols.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

The natural emissions of sea salt, dust, and dimethyl sulphate (DMS) from the oceans are calculated on-line, based on the meteorology of the model. Emissions for all other aerosol species are taken from the AEROCOM emission inventory, and are representative for the year 2000 (Dentener et al., 2006). The aerosol emissions and the removal processes of in-cloud scavenging, sedimentation, and dry deposition are described in detail in Stier et al. (2005).

All results presented in this study are from simulations which have been integrated for one year, following a three months spin-up period. All simulations are nudged to the ECMWF ERA40 reanalysis data for the year 2000 (Simmons and Gibson, 2000), according to the nudging technique described by Timmreck and Schulz (2004). The spectral resolution of all simulations is T42 which corresponds to $2.8125^\circ \times 2.8125^\circ$ horizontally, with 19 vertical levels from the surface up to 10 hPa and a 30-min time step.

All simulations conducted in this study are summarised in Table 1.

2.1 Bacteria in ECHAM5-HAM

Bacteria in general and those with ice nucleating abilities in particular are commonly found on plant leaves (Lindemann et al., 1982; Hirano and Upper, 2000). Their concentration depends on the plant functional types. Plant functional types and their seasonally changing leaf area index from the JSBACH dynamic vegetation model (Raddatz et al., 2007) were combined with observed near surface bacteria fluxes (Burrows et al., 2009b) and used as an input for ECHAM5.

The emission flux F of bacteria is calculated in ECHAM5 according to

$$F = \sum_{i=5}^{5} f_i F_i \tag{1}$$

with F_i being the number emission flux [$\mathrm{m}^{-2}\mathrm{s}^{-1}$] over a particular ecosystem, f_i denoting the fractional coverage of a gridbox with a certain ecosystem, and i standing for crops, grass, shrubs, forests and land ice.

Due to the limited available data on emissions of bacteria in the air, the ecosystem types available in JSBACH which are based on the Olson World Ecosystems dataset (Olson, 1992) were lumped into the aforementioned five groups. *Crops* and *land ice* are ecosystem types on their own, *grass* is comprised by C3 and C4 grasslands, while *shrubs* contains both raingreen and deciduous shrubs. The *forest* category is made of tropical broadleaf evergreen and deciduous trees, temperate broadleaf evergreen and deciduous trees, as well as coniferous evergreen and deciduous trees.

In order for bacteria to be incorporated into HAM (Stier et al., 2005) the number of aerosol modes was increased from 7 to 9. Bacteria are emitted initially in the bioaerosol insoluble mode. They can transfer to the mixed mode by coating with H_2SO_4 and coagulation with sulfate, black carbon and organic carbon. Bacteria are additionally allowed to coagulate with dust, as this has been observed in nature (Griffin, 2007). The parameterisation for contact freezing of bacteria stems from Diehl et al. (2006) and that for immersion freezing from Diehl and Wurzler (2004). Deposition nucleation on bacteria is not considered, because the observational data are missing. As there were no data available about shortwave and longwave radiative properties of bacteria, but they have a similar refractive index as sea salt (Wyatt, 1970; Ebert et al., 2002), the identical data as for sea salt (Fenn et al., 1981) were assumed for bacterial shortwave and longwave radiative properties. The standard deviation of the bacterial distribution was set to 2, equal to that of dust. The mean mass scavenging coefficient for bacteria scavenged by rain was set to $1\,\mathrm{kg\,m^{-2}}$ and to $5\times10^{-3}\,\mathrm{kg\,m^{-2}}$ for bacteria scavenged by snow, as estimated from Seinfeld and Pandis (2006). The mass of a bacterium in ECHAM was set on the average value 1^{-15} kg and its average density was calculated as being $1.2\,\mathrm{g\,cm^{-3}}$ from data available in Baron and Willeke (2001) and Hinds (1999).

3 Results and discussion

In the reference simulation (CTL) bacteria act only as passive tracer, i.e. bacteria are emitted and transported around the globe, but have no effects on the radiation budget, cloud microphysics and precipitation. In all the other simulations (cf. Table 1) the bacteria are allowed to act as IN. In the simulations BT-1, BT-10 and BT-100 bacteria best estimate emissions from Burrows et al. (2009a) are used and the fraction of bacteria acting as IN is varied from 1% to 10% and 100%, respectively. The simulation 100BT-100 represents an extreme case where all bacteria are assumed to be IN active, and their emission flux is increased by a factor of 100. This factor of 100 is plausible for natural fluctuations of bacteria emissions due to seasonality, vegetation periods and micro-climatic effects. Phillips et al. (2009) also conducted simulations with bacteria numbers boosted up by two orders of magnitude in their research. Additionally, this allows us to investigate what would happen if their number concentration was assumed to be on the same order of magnitude as that of the dust aerosol.

The annual zonal mean vertical profiles of dust and bacteria number concentrations, as depicted in Fig. 2 show that there is transport of bacteria to the middle and upper troposphere. However, their number in the troposphere is two to three orders of magnitude lower than that for dust. By increasing bacteria emission a hundredfold, their number concentrations become comparable to those of dust, with average values of $1\,\text{cm}^{-3}$.

The bacteria emissions and burdens calculated with ECHAM (cf. Table 2) are comparable to the ones calculated by Burrows et al. (2009a) and Jacobson and Streets (2009). A hundredfold increase in emissions leads to the according increase of bacterial burden as well.

The results from the BT-10 simulation in Fig. 3 show the emission, deposition and burden of bacteria compared to dust. It is evident from Fig. 3d that the bacteria are transported over quite large distances. Their deposition is enhanced over areas which show both plenty of vegetation and high precipitation, e.g. the Amazon, the Congo basin, or South-East Asia. Their burden is enhanced over North-West Africa as there are high emissions from the grasslands as well as a relatively dry climate.

Furthermore, as can be seen in Table 3, the model results for BT-10 are on the same order of magnitude as the few observational data available. While the modelled dry deposition is on the higher end of the observations, the modelled wet deposition of bacteria is even larger than observed. However, as the observational data relies only on single measurements, it does not reproduce the observed variability.

The simulated bacterial number concentrations were compared to observations at various locations in Fig. 4. As the comparability of point measurements to global model data which are mean values for a $2.8^\circ \times 2.8^\circ$ gridbox is limited, the gridbox values were extrapolated to the coordinates of the measurement location. The standard deviation of observational data is rather large, as the measurement methods differ for each location and the variability of bacteria concentrations is high. While the mean observed bacteria concentrations are captured by the model, it greatly underestimates the variability in the bacteria concentrations. Standardised long-term observations with world-wide coverage are necessary for a more precise model evaluation.

Bacteria produce ice faster and earlier than dust, as can be seen from Fig. 1, thus depleting moisture available for the formation of ice on dust. At the same time, there are much fewer bacteria than dust available as IN. Consequently, the changes from CTL to BT-1, BT-10 and BT-100 in the cloud droplet number concentration (CDNC), ice crystal number concentration (ICNC), precipitation, cloud cover, relative humidity, short-wave (SCF) and long-wave cloud forcing (LCF), as well as the aerosol optical depth (AOD) remain small (cf. Table 4). However, one can see from the vertical profiles in Figures 5 and 6 that this is partly the result of averaging. While the values vary considerably over height, they average in the mean.

There is a slight reduction in LWC and increase in IWC, which is expected, as bacteria are efficient IN. The IWC is slightly higher in the heterogeneous freezing regime, while the LWC is lower, as can be seen in Fig. 5. The maximum in ICNC seen around 238 K is very likely due to homogeneous freezing.

The area of large changes in IWC in the Arctic visible in Fig. 5 is due to the fact that temperatures there are in the range of mixed-phase clouds (0 °C to −35 °C) for large parts of the year even at the surface, so the bacteria do not have to be transported high up into the atmosphere to have an impact in this region. Around the Arctic circle there are vast areas of tundra and boreal forests which are providing relatively high bacteria concentrations to the Arctic, which is also evident in the zonal mean bacteria concentration in Fig. 2.

We consider the simulation BT-10 to be the best estimate, according to observations by Šantl Temkiv et al. (2009) which found 9% of bacteria in rain samples to be IN active. Even in this simulation, the change in LWP and IWP is small but non-negligible and a feature consistent throughout the simulations. As expected, the IWP increases while the LWP decreases due to the earlier onset of the Bergeron-Findeisen process, if bacteria as additional IN are available. As evident from Figure 6, the change is especially pronounced on the northern hemisphere, where forests contribute to higher bacteria concentrations. Looking at global maps of LWP and IWP in Figs. 7 and 8, respectively, LWP is generally lower over the continents, and especially over North America and Asia. Corresponding to the LWP decrease the IWP is increased over continents, specifically in the boreal regions where tundra and forests act as sources of bacteria.

If we look at the extreme assumption of a 100-fold increase in bacteria emissions in the 100BT-100 simulation, a considerable change can be observed (Table 4). There is a 7% reduction in LWP between the CTL and 100BT-100 case (cf. Fig. 6). As a result there is also significantly less solar radiation reflected back to space by clouds (Δ SCF 1.65 $\mathrm{W m^2}$). This change in cloud radiative forcing is almost exactly the same as the entire increase in the greenhouse effect due to anthropogenic CO_2 (Forster et al., 2007). There is also more longwave radiation escaping to space (Δ LCF 0.58 $\mathrm{W m^2}$) because of the reduced LWP so that the net change is slightly more than 1 $\mathrm{W m^2}$, which is still a rather strong effect. Additionally, bacteria seem to have an immense effect on the AOD in the 100BT-100 simulation, leading to a 59% increase by direct reflection of solar radiation.

At this point we do not know enough about bacteria emissions to rule that simulation out as unrealistic. Standardised observations of bacteria fluxes in all regions are necessary to gain a better understanding of actual emissions. However, to the best of our current knowledge, the influence of bacteria on the global climate appears small. There is virtually no effect on the shortwave and longwave cloud forcing, or on the precipitation. What changes is the size of crystals, as well as the region where the crystals/droplets form and remain.

4 Conclusions

Bacteria as a new aerosol particle mode were introduced to ECHAM5-HAM. The inclusion of bacteria acting as ice nuclei in a GCM leads to only minor changes in cloud formation and precipitation on a global level. Nevertheless, changes in the liquid water path and ice water path can be observed, specifically in the boreal regions where tundra and forests act as sources of bacteria. More observational data about bacterial emissions and deposition, as well as in-situ measurements inside clouds and vertical profiles are needed for a better comparison of model results with the observations. There are currently several uncertainties constraining the modelling of the impact of bacteria on climate and precipitation, for example their exact emissions, size distributions, ice nucleation active fractions etc. Further research should focus on regional and local effects of bioaerosols, as a potential impact of bacteria on local climate might be expected.

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Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

References

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Table 1. Simulations

Simulation	Description
CTL	Control simulation. Bacteria are not IN active.
BT-1	Bacteria best-estimate emissions Burrows et al. (2009b), 1% of bacteria IN active
BT-10	Bacteria best-estimate emissions Burrows et al. (2009b), 10% of bacteria IN active
BT-100	Bacteria best-estimate emissions Burrows et al. (2009b), 100% of bacteria IN active
100BT-100	Same as BT-100 but with a hundredfold increase of bacteria emissions

Table 2. Global bacteria emissions and burden calculated with ECHAM5 compared to the model results by Burrows et al. (2009a) and Jacobson and Streets (2009).

Emissions	Burden	Source
[Tg yr^{-1}]	[Tg]	[Tg yr^{-1}]
2.58	1.11	ECHAM5 best estimate bacteria emissions
258	116	ECHAM5 hundredfold bacteria emissions
0.7–3.5	0.04–1.8	Burrows et al. (2009a)
8.0	n/a	Jacobson and Streets (2009)

Table 3. Modelled global annual means of emissions and deposition of bacteria and mineral dust. Observational estimates from single measurements of bacterial emissions and deposition are included for reference. (Lindemann et al., 1982)*, (Jones et al., 2008)**, (Lindow and Andersen, 1996)***, (Lindemann and Upper, 1985)****.

	BT-10 Dust [$kgm^{-2}yr^{-1}$]	BT-10 Bacteria [$kgm^{-2}yr^{-1}$]	100BT-100 Bacteria [$kgm^{-2}yr^{-1}$]	OBS Bacteria [$kgm^{-2}yr^{-1}$]
Emission	4.55×10^{-11}	5.49×10^{-13}	5.49×10^{-11}	1.02×10^{-13}*
Dry Deposition	2.35×10^{-11}	1.70×10^{-13}	1.02×10^{-11}	2.0×10^{-11}** 1.4–5.6×10^{-14}***
Wet Deposition	2.19×10^{-11}	3.80×10^{-13}	3.89×10^{-11}	1.69×9^{-13}** $6.9°\,E\times10^{-12}$****
Total Deposition	4.55×10^{-11}	5.49×10^{-13}	5.49×10^{-11}	n/a

Table 4. Yearly average values for the simulations CTL, BT-1, BT-10 and BT-100 compared to observations (OBS). The table displays liquid water path (LWP), ice water path (IWP), total cloud cover (TCC), cloud droplet number concentration (N_l), ice crystal number concentration (N_i), total precipitation (P), shortwave cloud forcing (SCF), longwave cloud forcing (LCF), radiation budget at the top of the atmosphere F_{net} and aerosol optical depth (AOD). See Table 1 for the description of the simulation acronyms. Global averaged annual estimates and zonal mean estimated observational data are taken from the Global Precipitation Climatology Project (GPCP) for total precipitation P_{tot} (Huffman et al., 1997; Adler et al., 2003). LWP stem from satellite (SSM/I) retrievals by Wentz (1997), Greenwald et al. (1993) and Weng and Grody (1994). IWP is derived from the International Satellite Cloud Climatology Project ISCCP data (Storelvmo et al., 2008). Cloud droplet number concentration N_l retrievals are from Han et al. (1998). The ISCCP dataset is available for a temperature range of −50 °C to 50 °C based on four months from the year 1987. Shortwave and longwave cloud forcing (SCF and LCF) are deduced from Kiehl and Trenberth (1997). The data of aerosol optical depth AOD are provided by (Schulz et al., 2006) and S. Kinne (personal communication). Cloud cover observations are derived from observations of ISCCP (Rossow and Schiffer, 1999), surface observations collected by Hahn et al. (1995) and satellite observations estimated by Stubenrauch and Kinne (2009).

ECHAM5.5-	CTL	BT-1	BT-10	BT-100	100BT-100	OBS
LWP [$\mathrm{g\,m^{-2}}$]	56.61	56.24	56.09	55.78	52.80	48–83
IWP [$\mathrm{g\,m^{-2}}$]	6.965	6.976	6.990	7.007	7.019	29
TCC [%]	60.14	60.16	60.21	60.18	60.12	65–75
N_l [$10^{10}\,\mathrm{m^{-2}}$]	3.415	3.397	3.401	3.403	3.192	4
N_i [$10^{10}\,\mathrm{m^{-2}}$]	0.124	0.123	0.122	0.121	0.096	–
P [$\mathrm{mm\,day^{-1}}$]	2.839	2.840	2.840	2.841	2.856	2.74
SCF [$\mathrm{W\,m^{-2}}$]	−48.81	−48.76	−48.77	−48.71	−47.16	−47 to −50
LCF [$\mathrm{W\,m^{-2}}$]	26.33	26.33	26.33	26.29	25.75	2-30
AOD	0.117	0.117	0.117	0.117	0.187	0.15–0.18

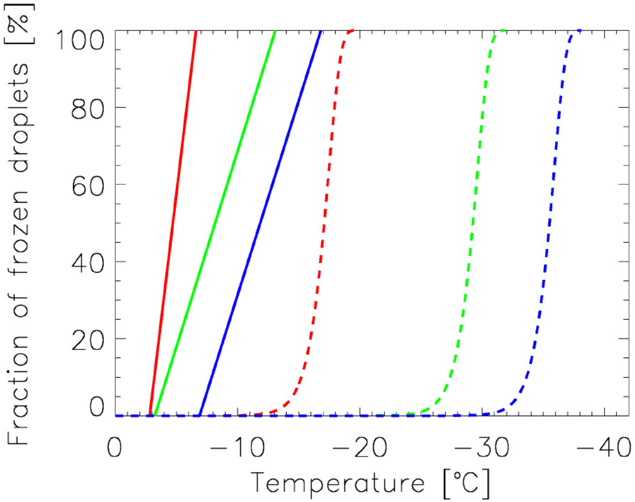

Fig. 1. Contact freezing frozen fractions (full lines) and immersion freezing frozen fractions (dashed lines) of bacteria (red), montmorillonite (green) and kaolinite (blue); from experimental data. Adapted from Lohmann and Diehl (2006).

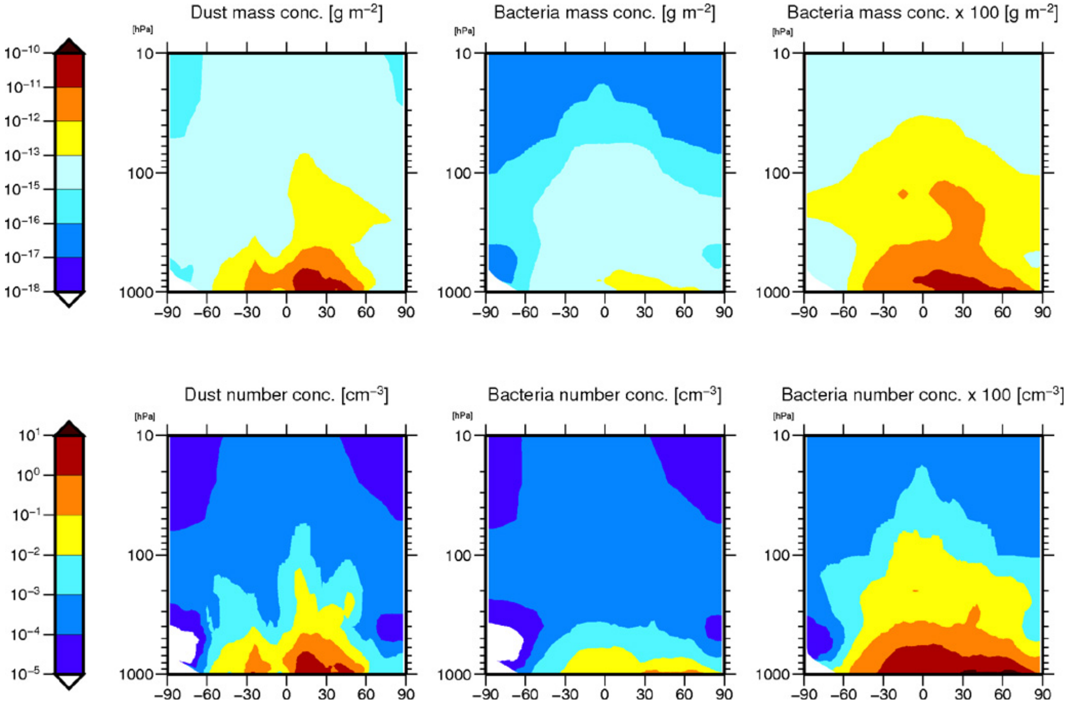

Fig. 2. Modelled (CTL and 100BT-100, see Table 1 for description) annual zonal mean vertical profiles of dust and bacteria mass and number concentrations in [m^{-3}].

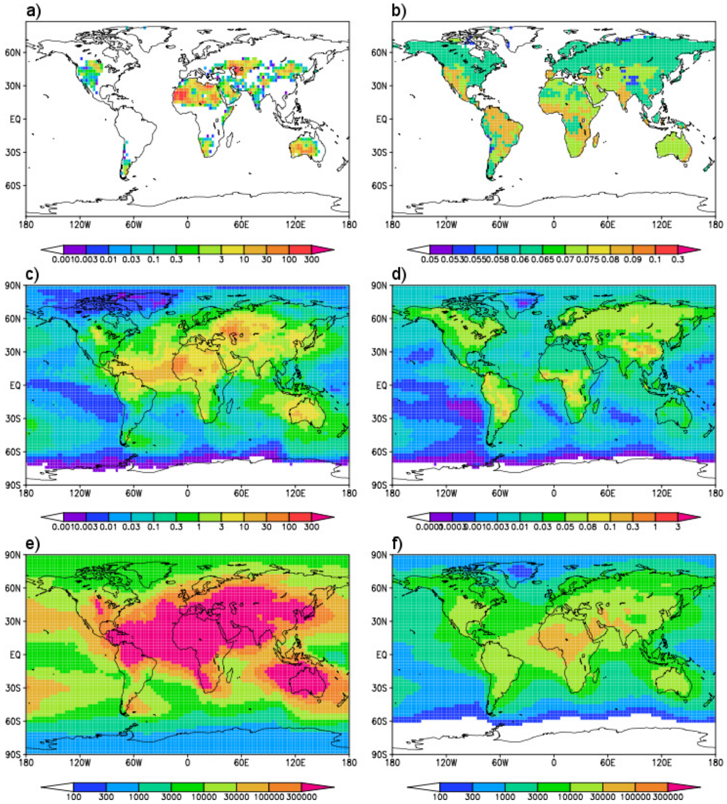

Fig. 3. Modelled (BT-10, see Table 1 for description) global annual means of emission, deposition and burden of bacteria and mineral dust. **(a)** dust emission [$\mathrm{g\,m^{-2}\,yr^{-1}}$] **(b)** bacteria emission [$\mathrm{g\,m^{-2}\,yr^{-1}}$] **(c)** dust deposition [$\mathrm{g\,m^{-2}\,yr^{-1}}$] **(d)** bacteria deposition [$\mathrm{g\,m^{-2}\,yr^{-1}}$] **(e)** dust burden [$\mathrm{g\,m^{-2}}$] **(f)** bacteria burden [$\mathrm{g\,m^{-2}}$].

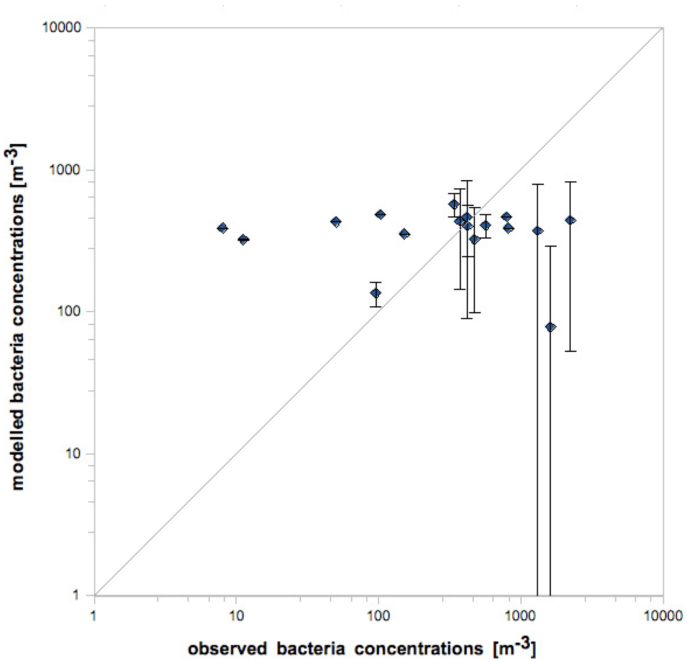

Fig. 4. Simulated bacteria concentrations at ground level compared to observations. Observations are averages over different time periods, and the simulated data are taken for the gridboxes containing the measurement location. The vertical bars indicate the standard deviation for all measurements at one location. Observations are taken from Bauer et al. (2002), Bovallius et al. (1978a), Bovallius et al. (1978b), Borodulin et al. (2005), Chen et al. (2001), DiGiorgio et al. (1996), Fang et al. (2007), Kelly and Pady (1954), Lindemann et al. (1982), Mouli et al. (2005), Negrin et al. (2007), Pastuszka et al. (2000), Rosas et al. (1994), Rüden et al. (1978), Schlesinger et al. (2006), Shaffer and Lighart (1997), Tilley et al. (2001), and Vlodavets and Mats (1958).

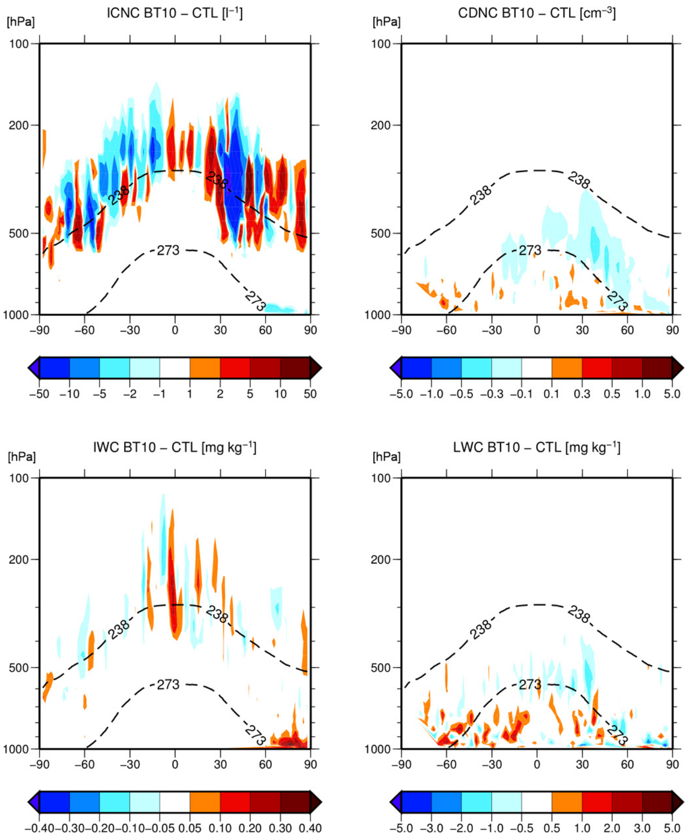

Fig. 5. Modelled annual zonal mean vertical profiles of the difference between the simulations with 10% of bacteria acting as IN (simulation BT-10) and no bacteria acting as IN (simulation CTL), for the ice water content (IWC), ice crystal number concentration (ICNC), liquid water content (LWC) and cloud droplet number concentration (CDNC).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◂◂
▸▸
◂
▸
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

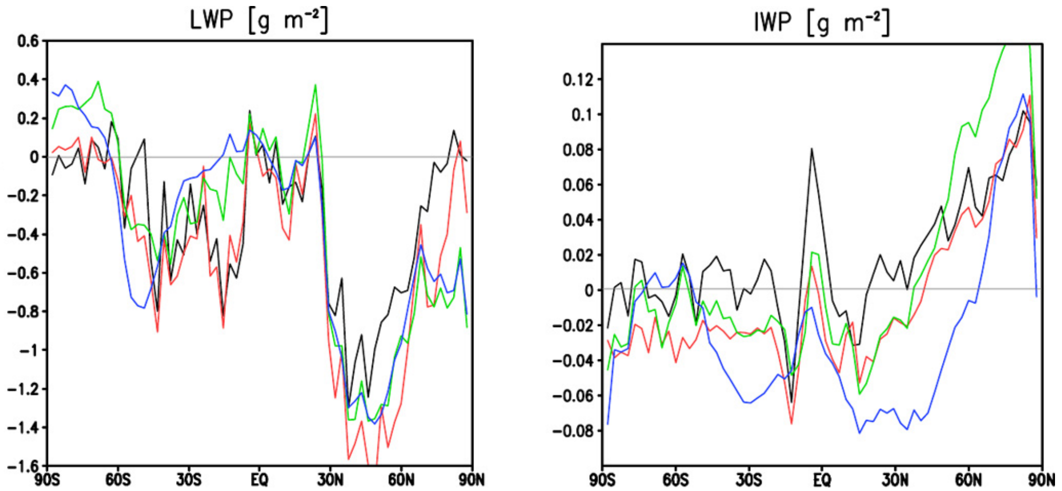

Fig. 6. Modelled annual zonal mean vertically integrated difference between the simulations with 1% of bacteria acting as IN (simulation BT-1, black line), 10% of bacteria acting as IN (simulation BT-10, red line), 100% of bacteria acting as IN (simulation BT-100, green line), 100% of hundredfold bacteria acting as IN (simulation 100BT-100, blue line) and no bacteria acting as IN (simulation CTL), for the ice water path (IWP) and liquid water path (LWP), respectively.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀|
|▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
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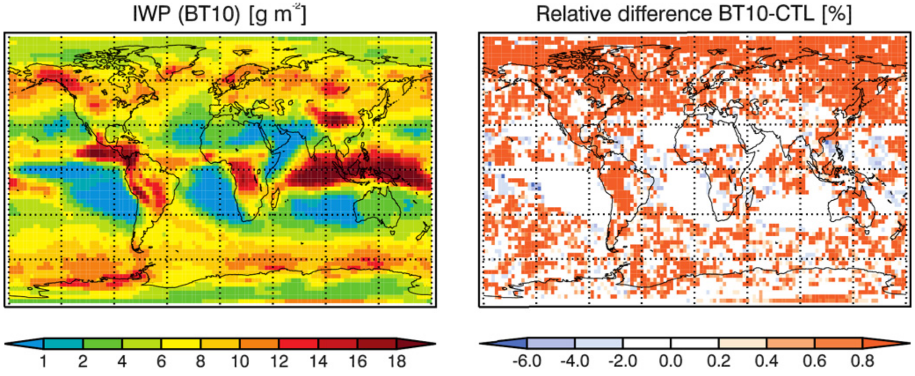

Fig. 7. Modelled annual global mean ice water path (IWP), and the difference between BT-10 and CTL.

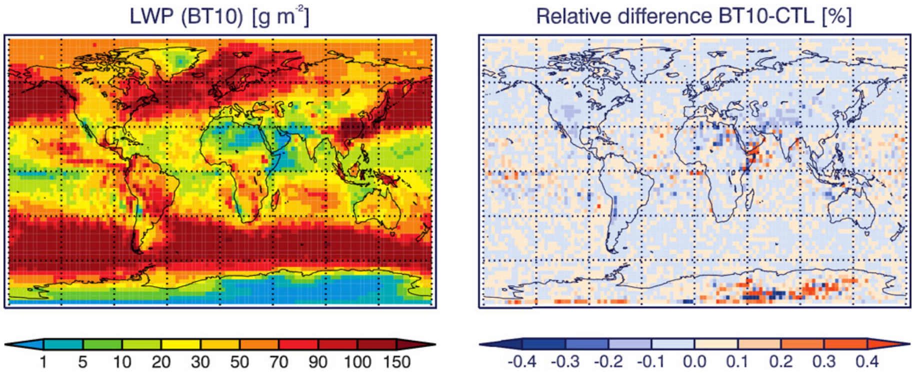

Fig. 8. Modelled annual global mean liquid water path (LWP), and the difference between BT-10 and CTL.