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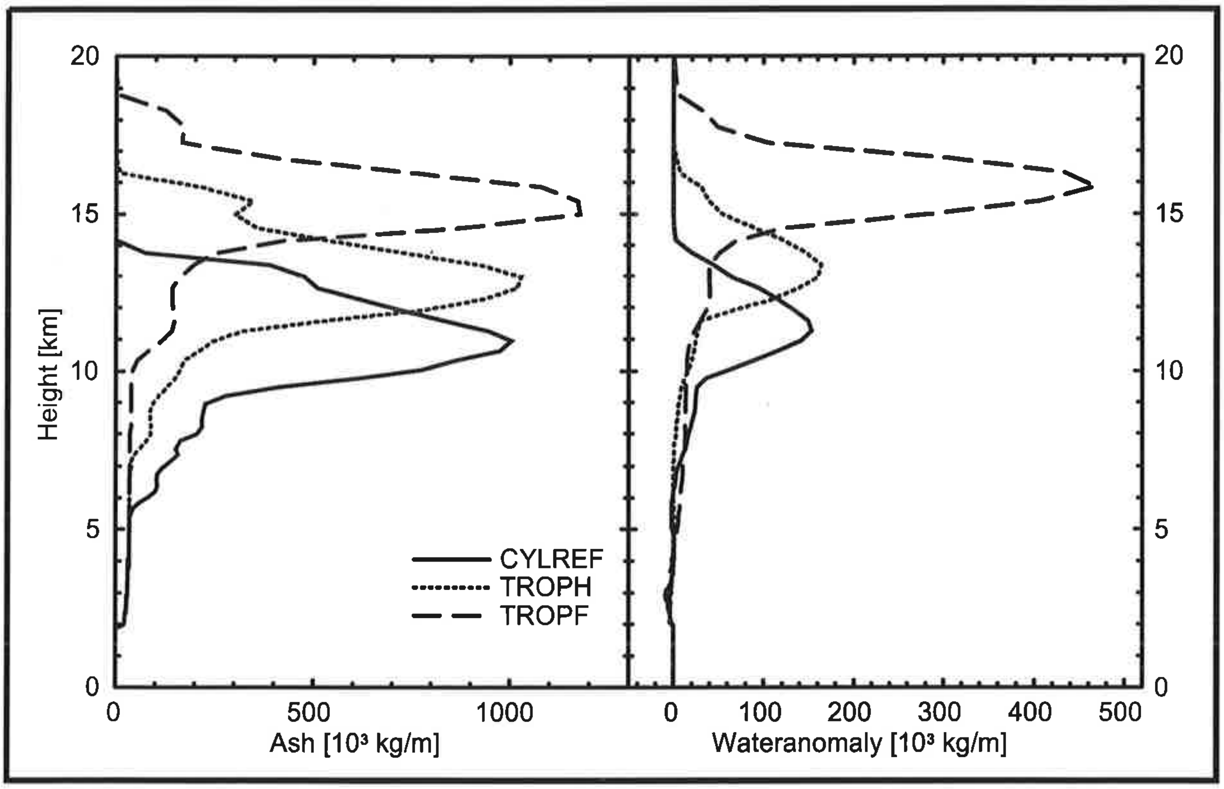

THE EFFECT OF ENVIRONMENTAL CONDITIONS ON VOLCANIC PLUME RISE

by

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The Effect of Environmental Conditions on Volcanic Plume Rise

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Abstract

Sensitivity studies were performed with a complex nonhydrostatic volcano plume model that explicitely treats turbulence and microphysics. The impact of environmental conditions like wind-, temperature- and humidity-profiles was studied for standard observational data. To investigate the wind effects, a 2d cartesian formulation of the model was used, while for the temperature and humidity effects a cylindrical coordinate system had to be applied since this treats the entrainment process more realistically. It was found that horizontal wind generally reduces the height of the ash plume. The gaseous part of the plume sometimes may rise higher than without wind due to the more effective separation between gas and solid material. Besides reduced static stability also the absolute temperature and humidity increase the plume height. All environmental impacts strongly depend on the strength of entrainment and thus on the quality of the prognostic turbulence.

1 Introduction

Volcanic plumes, consisting of a hot mixture of silicate particles (ash and the larger lapilli), volcanic and environmental gases and condensed water are one of the most fascinating natural phenomena. The development of the plume is important for the vertical transport of particles and gases. Internal processes like phase transitions, adhesion of gases to particles and dissolution into droplets determine the efficiency of the lithospheric source for the atmosphere. Tropopause penetrating plumes can inject large amounts of sulfurous gases into the stratosphere, where they may persist for years and lead to climatic anomalies. The airborne volcanic ashes are hazardous for aviation and deposited ashes can destroy houses and agricultural properties. Heights of eruption columns still are the most important factors to estimate the explosive strength of an eruption. The distribution of proximal and distal fallouts serves as a means to estimate the column height of historic and prehistoric eruptions.

In the 70ties volcanologists began to study the physics and dynamics of eruption columns with the focus being laid on sedimentation of ashes. Wilson (1976) and Sparks and Wilson (1976) experimented with one dimensional top-hat models to study the transport of particles and their sedimentation in eruptive clouds. Microphysical and chemical aspects were not treated in these models. The role of condensational heat of water vapour was considered by Woods (1988),Woods (1993) and Glaze et al. (1997) only with respect to increased updraft due to latent heat release. Water vapour is one of the most abundant volcanic gases and its influence on the plume behaviour was discussed in detail based on complex microphysics and diagnostic entrainment by Herzog et al. (1998).

The only complex (i.e. including particle dynamics) 2d dynamic plume models used for the simulation of volcanic eruptions so far have been those of Wohletz et al. (1984) and later of Valentine and Wohletz (1989), Dobran and Neri (1993) and Neri and Macedonio (1996). These models are conceptually very similar and treat in a relatively small model domain a short term high resolution in space and time. They predict the time evolution of the flow, momentum and heat for each constituent, and explicitly parameterize the interaction of the components due to exchange of momentum and heat. For this purpose a model concept is needed that resolves time scales of micro-seconds. In brief, complete sets of Navier-Stokes equations for each component are solved, which have been only gas and ash in the above mentioned models.

However, a difficulty arises when this model concept is applied to longer time scales, namely if one is interested not in the explicit resolution of phenomena inside a volcano vent on the scale of a meter, but - as we intend to do - in the link to the large-scale atmospheric flow and chemistry. At larger space and time scales interactions in the meter scale can be neglected, but many different components have to be treated. The goal to simulate larger spatial scales implies also the need of simulating longer temporal scales. The model concept published by Valentine and Wohletz (1989) consumes enormous amounts of computer resources when applied to more than only two components, solved in a bigger domain than of the order of 5km box size and run over more than 10 minutes, which is the time scale of dynamic feedbacks due to cloud-physics. So their model concept cannot be applied very well with a growing number of components and a coverage of larger spatial and longer temporal scales. This is because each additional component, e.g. like water vapor, results in an increase of five more prognostic variables in the 3-dimensional case. Therefore, a simulation over longer time scales and the need to add a larger number of components to describe the cloud-physics immediately results in an impracticable computer code due to its intense use of memory and CPU-time without necessarily bearing higher quality results because of the immense increase in degrees of freedom and of numerical uncertainties.

In order to circumvent that problem a concept was developed in which each additional component requires only one additional prognostic variable. Based on the assumption that particles are small, i.e. particles approach their stationary fall-out velocity in the order of a second, and not trying to resolve spatial scales down to the meter scale, the explicit description of the components by separate sets of Navier-Stokes equations can be replaced by one set of Navier-Stokes equations for the volume mean of momentum and heat, while the mass of each component is treated by a separate mass continuity equation. The equation of state connects volume mean quantities with the dynamics of single components. This allows to apply a more elaborate microphysical-package or chemistry.

After a short introduction of the model concept, we will show results from sensitivity studies for different environmental conditions, like vertical profiles of horizontal wind, temperature and humidity.

2 Model Concept

The plume model ATHAM (**A**ctive **T**racer **H**igh Resolution **A**tmospheric **M**odel) is originally designed to simulate explosive volcanic eruptions for a given forcing as lower boundary condition.

In the present version the model ATHAM consists of four modules: The dynamic part solves the Navier-Stokes equation for a gas particle mixture including the transport of active tracers (Oberhuber et al., 1998). The turbulence closure scheme computes turbulent exchange coefficients for each dynamic quantity (Oberhuber et al., 1998; Herzog, 1998; Herzog and Oberhuber, 1998). The microphysics is based on a Kessler type parameterization and describes condensation and formation of precipitation. The connected changes in internal energy can have a strong impact on the plume dynamics. All phases of water are included: vapour, liquid, solid (Herzog et al., 1998). The soil module computes the amount of deposed particles, ashes as well as water and provides a model consistent lower boundary condition for temperature and humidity. This means the atmosphere can be heated from the ground and water can evaporate into the atmosphere from the soil. A physico-chemical module treats the interaction of gases and condensed matter in the plume (Textor et al., 1998). The model is written in a modular structure. It is easy to couple to it modules of different levels of sophistication for special processes. The coupling is organized via defined interfaces.

ATHAM is fully three dimensionally formulated with an implicit time step scheme. The flux form of the transport equations is employed for all tracers. For sensitivity studies and to test the model two different types of 2d versions are implemented: One cartesian 2d version computes on a vertical slice of the 3d model and allows for the study of cross wind effects. The 3d counterpart is a fissure eruption with infinite length. The second 2d version represents cylindrical coordinates. No cross wind effects can be studied, but the dilution of the mixture corresponds to the 3d case in an atmosphere at rest.

2d (3d) simulations are performed on a stretched grid with $127 \times 127 \times 4$ (127) grid points. The horizontal domain is typically 250 km, the vertical 50 km. In the center of the model area we use a spatial resolution of 100 m or, in some special cases, 50 or even 20 m. At the fringes of the model domain the horizontal resolution is in the order of several kilometers. The simulation time is typically one hour with time steps being dynamically adjusted to the CFL criterion. Time steps are normally smaller than one second during the active eruption phase.

Dynamical and Thermal Equilibrium

The special feature of ATHAM is its ability to treat active tracers. In contrast to passive tracers normally used in atmospheric models, active tracers can occur in any concentration, affect the equation of state and can therefore have a strong influence on the dynamics of the system. In case of a volcanic eruption, the mass fraction of silicate particles close to the vent is often higher than 90%. Active tracers like silicate particles influence the dynamics of the system in two ways: First, in the presence of solid or liquid particles the density of the mixture is in general greater compared to the density of the gas phase alone. As a consequence the buoyancy force can be strongly reduced. Second, silicate particles can act as a source of heat and thereby change the temperature distribution and the dynamics of the system towards increased buoyancy.

Without additional assumptions the description of a multi-component system of active tracers requires one set of dynamic and thermodynamic equations for each component with interactions between them. This requires enormous computer ressources for a large number of active tracers. Wohletz et al. (1984) and Neri and Macedonio (1996) therefore only use one or two particle classes. Our goal is to describe the plume during its whole lifetime, including the thermodynamics and microphysics of water and a large number of other chemical species. Therefore we need another level of abstraction which allows to parameterize the total effect of the active tracers without treating each component with a separate set of prognostic equations.

The main assumption of ATHAM is only a minor restriction in the case of a plinian eruption plume: All particles are small. This has two consequences in physical terms: First, the system is at all times in dynamic equilibrium. That means, we assume an instantaneous momentum exchange between particles and gas. All particles move with their terminal velocity relative to the mixture, which simplifies the description of sedimentation. The assumption of dynamic equilibrium is, for the given resolution of ATHAM and typical densities and accelerations, valid for ash (particles smaller than 2 mm) and also for lapilli (particles of 2-64 mm) consisting of rough and gas rich material, as long as their terminal velocity remains small. If the terminal velocity of the particles is larger than about 10 m/s, their deviation from the concept of dynamical equilibrium is no longer negligible within the frame of our problem of simulating strong volcanic eruption plumes (Oberhuber et al., 1998).

The second assumption requests that the system is at all times in thermal equilibrium. Tracers can act as a source of heat, but the temperature exchange is instantaneous. Thermal equilibrium can be accepted only for particles of diameters not larger than one millimeter which have adjustment times smaller than one second. These include practically all ashes. For larger particles a prognostic temperature equation would be necessary, which, if needed, is easy to be included in the model.

The assumption of small particles strongly reduces the number of prognostic quantities and allows for the treatment of a multi component system with many active tracers. The dynamic behaviour of the gas particle mixture is described by five prognostic equations for the three momentum components, the pressure and the temperature. For each tracer one additional transport equation has to be solved. Apart from two types of silicate particles (ash and lapilli) five types of tracers for the microphysics of the system are implemented in the present version: water vapour, cloud water, precipitable water, ice and graupel. Additional tracers can be included. Active tracers and dynamic variables are coupled due to bulk density and heat capacity of the mixture.

Turbulence

Generally the plume of a plinian eruption is described as a jet regime close to the vent and a convective regime above. The jet regime is characterized by the consumption of initial momentum and laminar character of the flow. The plume regime is dominated by buoyancy forces. Initially, the bulk density of the erupted hot gas particle mixture is higher than the density of the surrounding atmosphere. Without entrainment, followed by sedimentation of heavier material and separation between the gas and solid and liquid phases, no plume could develop. The amount of entrainment determines the large scale behavior of the plume. Microphysical processes are dominated by entrained water vapour. Except in very dry environments the water vapour released by the volcano is of secondary importance. Hence, the correct treatment of entrainment, which is a function of turbulence, is essential.

In atmospheric problems one usually assumes an equilibrium of turbulent quantities and a local isotropy of turbulence. Turbulent exchange is locally the same in all directions. This is not valid for an eruption plume: The time scales of the physical problem are smaller or in the same range as the time scales of turbulence. The conditions under which turbulence develops change faster than the turbulent quantities can adapt. This requires that the history of the development of turbulent quantities must be taken into account. Transport processes and the existence of a mean density gradient cannot be neglected. The dominant influence of buoyancy leads to an asymmetry between horizontal and vertical components of turbulent quantities.

Following the formulations of Kolmogorov-Prandtl the turbulent exchange coefficient for momentum is given by a turbulent length scale and the turbulent kinetic energy. This formulation (Oberhuber et al., 1998; Herzog, 1998; Herzog and Oberhuber, 1998) is based on the imagination that turbulent processes are illustrated through eddies of different size. The turbulent energy is a measure for the intensity of turbulent eddies, the turbulent length scale for the averaged size of turbulent eddies, the exchange coefficient for the efficiency of turbulent eddies.

To take into account the anisotropy of horizontal and vertical components the original formulation of Kolmogorov-Prandtl is extended under the assumption that the anisotropy of the exchange coefficients is only expressed in the anisotropy of the turbulent energy. The turbulent length scale is assumed to be isotropic. The chosen formulation guarantees the original formulation in the isotropic case. The horizontal and vertical component of the turbulent kinetic energy as well as the turbulent length scale are simulated by a set of three coupled prognostic equations and solved numerically.

To describe buoyancy effects in turbulent processes we have to use the potential density: This is the density of a gas particle mixture if it is brought to a reference pressure. In case of no active tracers this leads to a formulation, which is equivalent to the standard formulation with the potential temperature. There are two types of compressibility effects: density and Mach number effects. In the present version of the turbulence scheme we have added a simple correction term for the Mach number effects. Particle gas interaction as well as particle particle interaction is neglected at the moment.

Coordinate Systems

Performing simulations on a vertical slice of the 3d model the behaviour of typical volcanic eruptions can be simulated reasonably (Oberhuber et al., 1998; Herzog et al., 1998; Textor et al., 1998). At the beginning of the simulation the model is initialized with horizontally homogeneous profiles for temperature, relative humidity and wind with the assumption of a hydrostatic initial state. The flow over a 3000 m high volcano leads to the development of turbulence mostly concentrated at the top of the volcano. It shows the formation of a boundary layer, an orographic cloud and a lee wave (Figure 1).

The use of cylindrical coordinates allows for the investigation of the first period of a volcanic eruption under realistic boundary conditions not only for the temperature and exit velocity, but also for the composition of the erupted material and the mass eruption rate. The entrainment and mixing of the plume with ambient air is treated better in cylindrical coordinates than in 2d cartesian coordinates, which underestimate entrainment due to the missing third dimension.

Results from simulations with finer grid resolution can be used to estimate a forcing for a coarser model grid. This simple nesting technique combines processes of smaller scales close to the vent and the large scale behaviour of the plume.

Plume Chemistry

A plume chemistry model has been developed to treat the relevant heavy metal reactions and the chemistry of oxygen, hydrogen, nitrogen, sulfur, chlorine and methane species in the gaseous as well as in the liquid phase. A special emphasis is put on the chemistry of chlorine and sulfur species which are the most important gases in volcanic emissions (Textor et al., 1998).

Constraints and Advantages

The constraints and advantages of our model concept can be summarized as follows: Constraint for ATHAM: Our model concept assumes an instantaneous exchange of momentum and heat between the components of the mixture of gas, liquid and solid particles. Thus, the time resolution of applications with ATHAM is not much less than a second. Advantages of ATHAM: The computer code is cheap in memory and CPU-time. This is due to the use of only one set of Navier-Stokes equations for the volume mean momentum and heat content and due to the use of efficient solution techniques for the implicit time stepping scheme. Additional modules - already realized are cloud-physics, turbulence closure, soil and chemistry - are easy to add. Additional tracers cost only the memory and CPU-time for one prognostic equation. Due to the memory-saving programming - currently the 127x127 grid-size version requires only 6 Mwords of memory - there is enough potential to add a large number of additional tracers which are allowed to feedback dynamically due to their high mass concentration. The model domain can be extended to scales appropriate for the plume development in the first hours even of larger eruptions.

Within the constraint to solve only one set of Navier-Stoke equations the additional assumption to predict only the volume mean heat content can be removed easily. If particles are allowed to be bigger, the thermal equilibrium between particles and gas is no more valid within time scales of seconds. By adding further prognostic equations for bigger particles as lapilli and a prognostic treatment of the heat exchange at least the assumption of thermal equilibrium can be removed without losing the efficiency of ATHAM.

Our model domain has normally 250 km horizontally and 50 km vertically and typically predicts one hour. The earlier models cover a model domain of 10 km horizontally and 5 km vertically. This limits the simulation time to few minutes since then border effects dominate the solution. Because we integrate over longer time scales, water vapour and all processes to gain latent heat, i.e. micro-physical processes, are needed. The same argument applies for turbulence as its length scale and thus its efficiency to mix properties within scales resolved by the model grid grows in time and thus becomes non-negligible. In addition we can apply a mean background state, i.e. geostrophic flow, and temperature and humidity profiles, which allows us to study the link between the large-scale weather and the volcanic plume.

3 The Background Experiment

The ATHAM model is a complete non-hydrostatic limited area circulation model. Therefore, a first test of its performance will be an orographic overflow simulation. The model is used in 2-d cartesian coordinates over a horizontal domain of 250 km and 50 km in the vertical.The horizontal and vertical resolution of the model grid is different with the highest resolution of 100 m just above the mountain peak and about 5 km at the model boundaries. The vertical and horizontal resolution can be seen from the steplike contour of the model mountain (painted black in all figures). This is the standard configuration. In the center of the model area a mountain ridge exists with a height of 3000 m above the surrounding flatlands. The peak has a 2 km wide depression of 700 m (a caldera). A background vertical pressure, temperature, humidity (mean tropical conditions, McClatchey et al. (1972) in the standard case) and a typical wind profile derived from ECMWF reanalysis data is prescribed at the edges of the model domain. The wind blows from the left. The initial state of the atmosphere is found by letting the model run with these boundary conditions without any volcanic forcing until a quasi stationary circulation is reached (Figure 1). All the typical features of orographic flow can be found. There is enhanced flow above the mountain and a lee-wave develops to the right of the obstacle. Cooling occurs on the windward side leading to condensation of atmospheric water vapour and the formation of a mountain cloud. Leewards typical warming by sinking of dry air leads to larger temperature anomalies than at the upstream side of the mountain. Turbulent energy is increased in the peak region and especially at the leeward peak. Having seen that the model is able to describe basic features of observed atmospheric behaviour in a simplified terrain and also in other similarily simple experiments in addition to several sensitivity studies (Oberhuber et al., 1998; Herzog et al., 1998; Textor et al., 1998), we believe in the model's ability to also simulate volcanic plumes at least qualitatively correct.

4 Impact of the Enviroment on Volcanic Plume Rise

Before our studies, volcanic plume simulations always were performed in an environmental atmosphere that was specified quite simplistic using standard atmospheric profiles. The influence of horizontal wind shear was not studied systematically since this is impossible in radial symmetric models. Here we want to study such effects in more detail.

4.1 Wind Effects

For the estimation of the effect of horizontal wind on the plume behaviour we again use cartesian coordinates in a geometry like in the standard background experiment described before. We performed four simulations of a standard volcanic eruption in an atmosphere at rest, with a mean wind profile and with modifications of the wind such that once the wind was increased in the lower troposphere and another when the wind was reduced in the middle and upper troposphere. The profiles are tropical ones with the tropopause at 17 km. The relative humidity has a second maximum just below the tropopause due to temperature effects (Figure 2). The standard volcanic eruption parameters (Table 1) had to be scaled to the resolution of the model as described in Herzog (1998).

The study of horizontal wind effects on the development of the plume in 2-d cartesian coordinates will overestimate the effect to a certain degree because of the unlimited extension of the mountain ridge in the third dimension.This leads to stronger acceleration of the wind over the obstacle and thus to a stronger bentover of the plume than has to be expected for a single mountain in a 3-d model. This means that the dynamical effects are stronger in the model than in nature. On the other hand, thermodynamic effects based on the microphysical transformations will be underestimated due to the neglect of entrainment from the third direction. However, the wind induced differences, mainly for ash and water vertical distribution are dramatic and will have to be considered even when they are somewhat reduced. Figure 3 shows the horizontally integrated vertical distributions of ash, lapilli and total water for the four experiments with idealized atmospheric profiles from Figure 2 for the time of 25 minutes after the begin of the eruption. Very clearly, the introduction of horizontal wind leads to a strong reduction of the height of the ash and water plume, which for the standard wind is 4000 m lower than in an initially resting atmosphere. Important is also that the maximum of the ash load is at 15 km in the no-wind case, but at 9 km in the standard wind case. The stratospheric injection of ash is reduced from 30% in the no-wind case to 3% of the total emitted ash in the standard wind case. The effects on the vertical ash distribution between different wind profiles are not as important. Generally a weaker wind leads to higher plume rise.

In case of the vertical distribution of lapilli, which have a significantly higher fall velocity than ash particles, the shape of the vertical wind profile is very important. While the maximum load of lapilli in all cases is at 3000 m above surface (after 25 minutes a significant amount of all ejected lapilli has been transported to altitudes well below the peak of the volcano) in the case of intensified lower tropospheric winds from this height the lapilli concentration decreases sharply, while for the other wind profiles only minor differences exist up to the upper troposphere. Again in the windless case lapilli can reach the highest altitudes. In Figure 4 the reason for these differences is shown at the example of the distribution of ash in a subdomain of our computing area 25 minutes after the begin of the eruption. The increased wind in the lower troposphere leads to a strong bentover of the plume, which, due to contact with the rim of the caldera, loses kinetic energy. This strengthens the bentover and leads to an increased deposition of particles and a decrease of the plume density. While in the standard wind experiment 25 minutes after the begin of the eruption not more than 10% of all lapilli are deposited at the ground, in the case of stronger lower tropospheric winds already 65% reached the ground. The bentover of the plume reduces the residence time of lapilli in the strong updraft region and thus enhances their effective sedimentation velocity. The effect on ashes is less strong since their terminal velocity is much smaller. In the strong wind system only 5% of all ashes reached the ground after 25 minutes compared with practically no deposition in all other cases.

The consideration of horizontal wind increases the rate of entrainment of ambient air by increased turbulence. 10% more water vapour is entrained into the plume in the standard wind case compared with the atmosphere initially at rest. Nevertheless, the amount of released latent heat is reduced by about one third due to the lower plume with higher temperatures leading to reduced condensation in the case with horizontal wind. Generally wind leads to a lower altitude of the condensation height and to less transport of water into the stratosphere. A strengthened wind in the lower troposphere leading to bentover at the caldera rim can overcompensate the negative effect of decreased condensation by enhanced entrainment in the humid lower layers of the troposphere. In our strong wind simulation we found 60% more latent heat production than in the standard wind regime.

Even though the plume loses energy by increased turbulence and friction when wind is considered, this does not affect the transport of gases in the same direction. The deceleration of the vertical velocity component due to the bentover in low altitudes leads to a more rapid separation of hot rising gases and heavy sedimenting solid particles. Even when the horizontal winds induced by a violent eruption are stronger than those in the preeruptive atmosphere, the background winds lead to distinct changes of the horizontal distribution of ashes (Figure 5) besides the above mentioned influence on the vertical distributions.

In contrast to earlier simulations with simpler models there is only a minor upwind transport of ashes. The ash distribution is highly asymmetric, the area of significant ash loading is reduced drastically, and the gradient of the vertically integrated load at the downwind and at the upwind edge of the ash plume is much sharper than in the case of missing background wind. Much of these differences are determined by the circumstances in the umbrella region, where in our simulation the maximum wind from the left blows between 9 and 14 km (Figure 2), just the height of the biggest ash concentration, i.e. in the umbrella region (Figure 3). In the no-wind case the umbrella region is higher, and the maximum horizontal wind only influences the lower part of the umbrella region. Thus, it is not only the superposition of wind, plume dynamics and fall speed that determines the deposition of volcanic ashes, but rather the interaction of all these quantities during the whole process of plume development.

4.2 Environmental Temperature and Humidity

The fact that thermal stability, as measured e.g. by the vertical temperature gradient, must have an impact on a buoyant volcanic plume is obvious and was shown long ago with simple models (Woods, 1988; Glaze et al., 1997). However, there is another effect apart from the vertical temperature gradient which may be important. That is the initial entrainment of ambient air and moisture which leads to a decrease in density and, after condensation of water vapour, to the release of latent heat and further vertical acceleration. The entrainment rate is dependent on the evolving turbulent energy, which in older models has been chosen arbitrarily and constant in a way that the final result of the model (i.e. maximum plume height or sedimentation fan) is in accordance with observations. However, the conditions supposed to exist during the plume development are not always very realistic. While the importance of a realistic treatment of turbulent processes and of microphysical processes for the plume energetics was discussed already in Herzog et al. (1998), here we will focus on the effect of environmental conditions. These conditions influence plume development primarily via entrainment.

In order to treat the process quantitatively as appropriate as possible we have to apply cylindrical coordinates. This means that we can not account for any effects of a vertically changing wind field. This may lead to an underestimation of the entrainment as discussed above. Besides the change in the coordinate system, the model geometry remains. Our reference experiment is, with the exception of the neglection of horizontal wind, the same as the one we discussed in section 4.1. It is a tropical atmosphere corresponding to McClatchey et al. (1972). In addition to this we used data from the same authors to describe typical mid-latitude vertical profiles for summer and winter (Figures 6 and 7). The main difference between the experiments lies in the tropopause height, which is at 17 km in the tropics and at 13 (10) km in the midlatitude summer (winter). In winter in addition the temperature at the surface and up to the tropopause is reduced in the order of 20 K. The maximum in relative humidity that occurs in the tropics at the tropopause is much smaller in midlatitudes. For the tropics two more experiments were performed such that the temperature profile was changed towards a 10 K higher temperature at the elevation of the crater of the volcano. This may e.g. be an effect of the daily cycle of temperature. A stable vertical temperature gradient was assumed. Above 11 km height there is no difference between the temperature profiles of the two tropical cases. The relative humidity was determined under the assumption of identic specific humidity. This is a reasonable assumption for air mass internal diurnal changes. In a third tropical experiment (humid tropics) the same temperature profile was used as in the warm tropical case, but the specific humidity was changed to a value about twice that in the warm tropical case. The characteristics of the volcanic eruption again are those from Table 1. Thus we have now one reference experiment CYLREF, one tropical warm TROPW and one tropical warm and humid TROPWH, as well as one midlatitude summer MIDSUM and one mid-latitude winter MIDWIN experiment. The results of the respective simulations are given in Figures 8 and 9 for the time of 25 minutes after the begin of the eruption. The vertical distributions of horizontally integrated ash concentration and of water exceeding the ambient concentration (water anomaly) for the midlatitude simulations (Figure 8) show that the mean meteorological condition significantly influences the plume behaviour. Under midlatitude summer (MIDSUM) conditions the ash plume rises 1000 m less than in the tropics. It is being stopped at the tropopause at 13 km height. Only a small amount of cloud ice and water vapour (about 1% of the total plume water) reaches the stratosphere. This value will be typical also for other gases that are not dissolved in the condensated water or adhere at the ashes, like SO_2. Even more clear is this effect under midlatitude winter conditions. The total plume height is reduced by another 1000 m. But due to the lower tropopause height (10 km) nearly one third of the erupted ash particles reaches the lower stratosphere, and of the plume water even more than 50% enter the stratosphere. Most of it (90%) is in the form of ice crystals, the remainder as gas.

As shown for the tropics, the actual weather condition also plays an important role for the plume development. The results of the experiments TROPW and TROPWH are given in Figure 9. In comparison to the standard experiment CYLREF warming and moistening of the lower troposphere both lead to increased height of the ash and water plumes. Even the higher temperature alone, which may develop in the daily course leads to 2300 m higher plumes. The water plume already reaches the tropopause at 17 km. The ash plume stops about 500 m below. After 25 minutes water vapour entrainment is in TROPW about 10% above the reference value and 90% of the water is condensed, while in CYLREF it is only 75%. Hence, the effect of latent heat release is enhanced.

The vertical temperature profile has a bigger effect on the final plume height than have the slightly enhanced microphysical processes. Simulations with and without microphysics revealed that due to phase changes of water the total thermal energy is increased by 13% in CYLREF and by 17% in TROPW, resulting in a difference in plume height due to the microphysical effects of only 300 m.

The doubling of the water vapour content in the lower troposphere (TROPWH) results in a strongly enhanced influence of the microphysics on plume behaviour. Compared with only higher temperature effects of TROPW the increased humidity leads to a 2200 m higher plume. Changed atmospheric conditions alone increase the plume height in TROPWH by 4500 m (30% more than the height in the reference experiment). This is enough to rise into the stratosphere. The plume spreads below the tropopause level and therefore only 10% of the total ash and 14% of total water (99% as ice crystals) are found in the stratosphere 25 minutes after the begin of the eruption. The amount of entrained water vapour is by nearly one order of magnitude larger than in the reference experiment. Hence, microphysics become more important. They contribute with 4000 m (CYLREF only 1500, TROPW 1800 m) to the total plume height, as was computed with simulations excluding microphysics.

5 Conclusions and Discussion

Applying a new complex non-hydrostatic model to a standard violent volcanic eruption we performed a series of sensitivity studies to investigate the influence of environmental conditions on the plume development. In our discussion we concentrate on ash and water plumes which most clearly indicate the strong impact of the environment even in case of a strong volcanic eruption.

Generally we found that the horizontal wind field can dramatically change the shape and height of the volcanic plume. The stronger the wind the lower the top of the plume will be.

Under special circumstances, the bentover of the plume may induce early separation of gas and particles, thereby leading to a higher gas plume and more gas being injected into the stratosphere. Thus, the climatic consequences of a volcanic eruption, which mainly are determined by the amount of sulfurous gases (SO_2, H_2S) injected into the stratosphere, are strongly dependent on the environmental conditions during the time of the eruption.

The standard treatment of deposition of volcanic ashes as based on Sparks and

Wilson (1976) and recently discussed by Woods and Bursik (1991) supposes that all ashes are transported to the umbrella of the volcanic plume, which then is shifted by the horizontal wind and the deposition can be calculated by vector addition of the vertical wind profile and the sedimentation velocity of the solid particles. The vertical transport of ash is normally computed by simple top-hat or axisymmetric models which, during the plume development, do not allow to consider horizontal wind. As our simulations show this leads to an overestimation of the height of the ash and lapilli plume. And, in addition to this, it leads to an overestimation of the horizontal extension of the ash plume. Further, if the wind drift of the whole plume is not accounted for, the distribution of the total load of ashes is overestimated to the windward side and underestimated to the leeward side of the source. This may lead to misinterpretations of the sediment fan in terms of plume height, of volcanic and environmental conditions for events for which direct observations of these parameters are not available.

Not only the wind, but also the temperature and humidity stratification are important factors for the volcanic plume evolution. If only vertical stability of the atmosphere is considered, important effects of entrainment of ambient air (including water vapour) are neglected. Even due to temperature changes which may develop during the course of the day, significant changes in plume top height can be expected. Further more important seems to be the humidity in low altitudes, which in the tropics may be determined by tropical weather systems. High water vapour content of ambient air may lead to one third and more higher plumes. Therefore it is important to include environmental conditions into the computation of volcanic plume rise. Environmental conditions also determine the internal structure (concentration of ash, lapilli, water etc.) and thus the potential of the climate impact.

Our results may be considered only qualitatively. More quantitative results are expected from a full 3-d simulation of the series of Mt. Spurr (Crater Peak) eruptions in 1982, which we plan for the future. Only then we will also have a chance to directly compare our simulated results with real observations.

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Tables

vent diameter	[m]	60
exit velocity	[m/s]	250
temperature at the vent	[K]	1200
gasfraction	[weight %]	3
water vapor fraction	[weight %]	67
bulk density at the vent	[kg/m^3]	5.52
mass eruption rate	[10^6 kg/s]	3.90

Table 1: Volcanic forcing

Figures

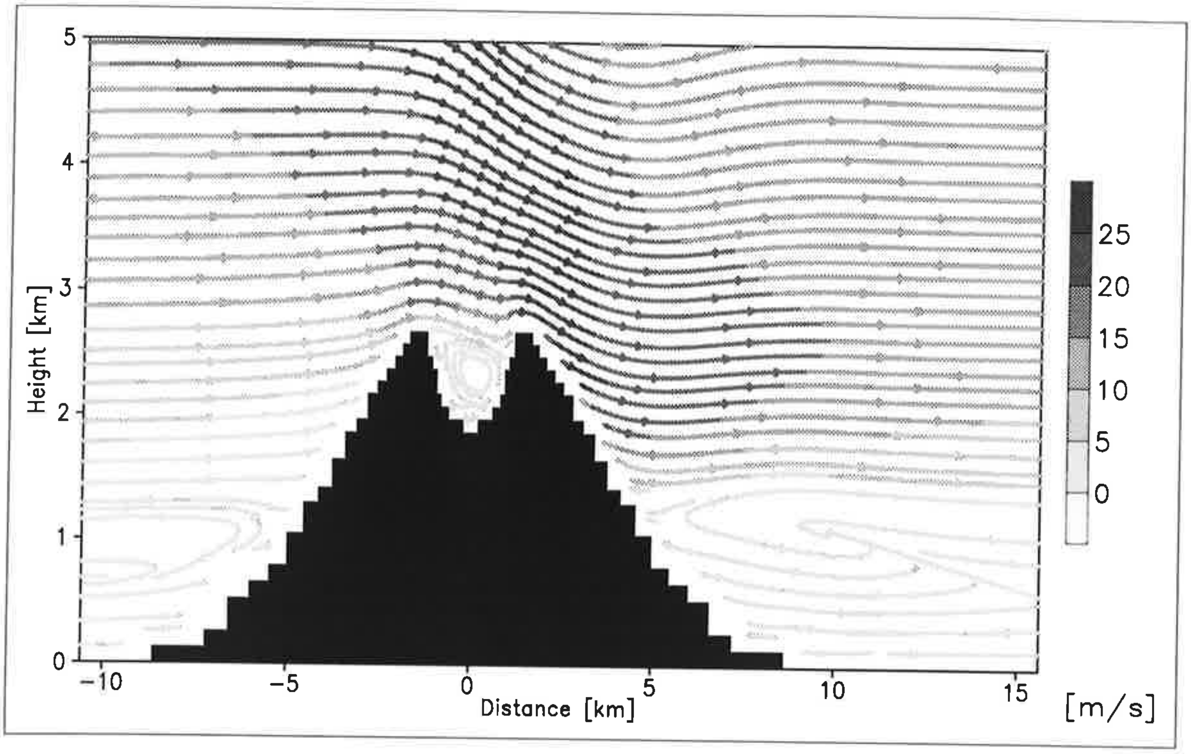

Figure 1a: Wind after 15 min spinup

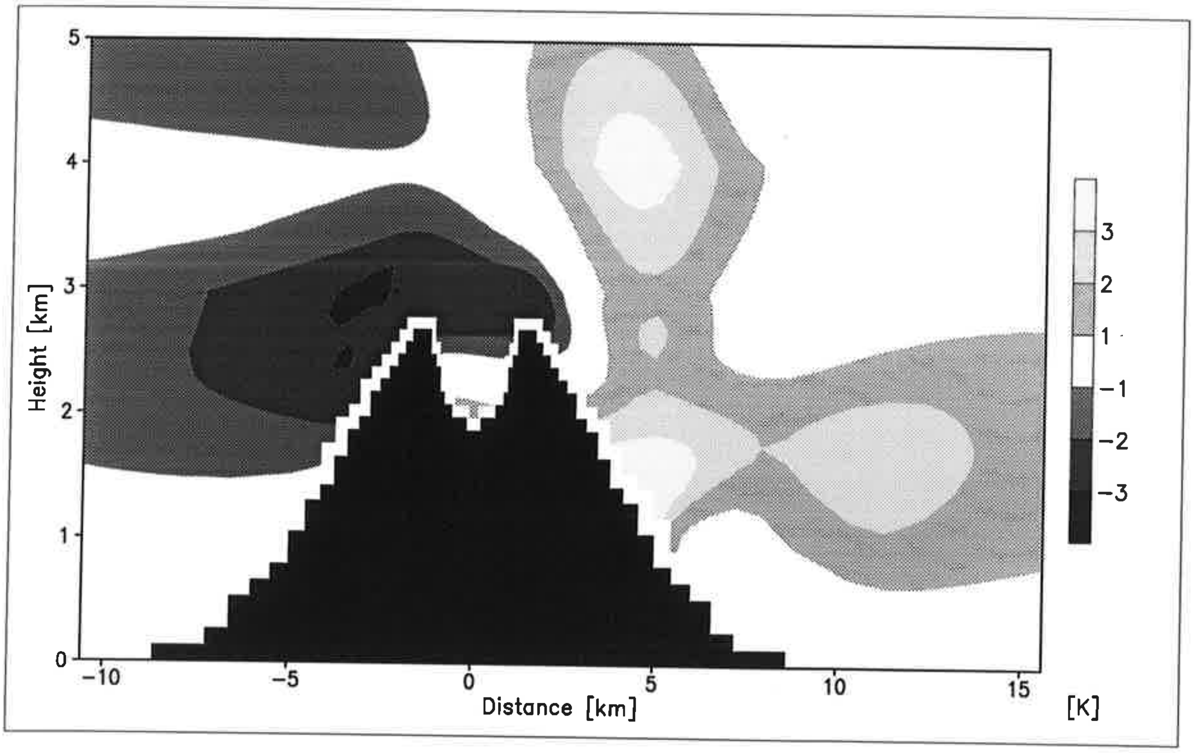

Figure 1b: Temperature anomaly after 15 min spinup

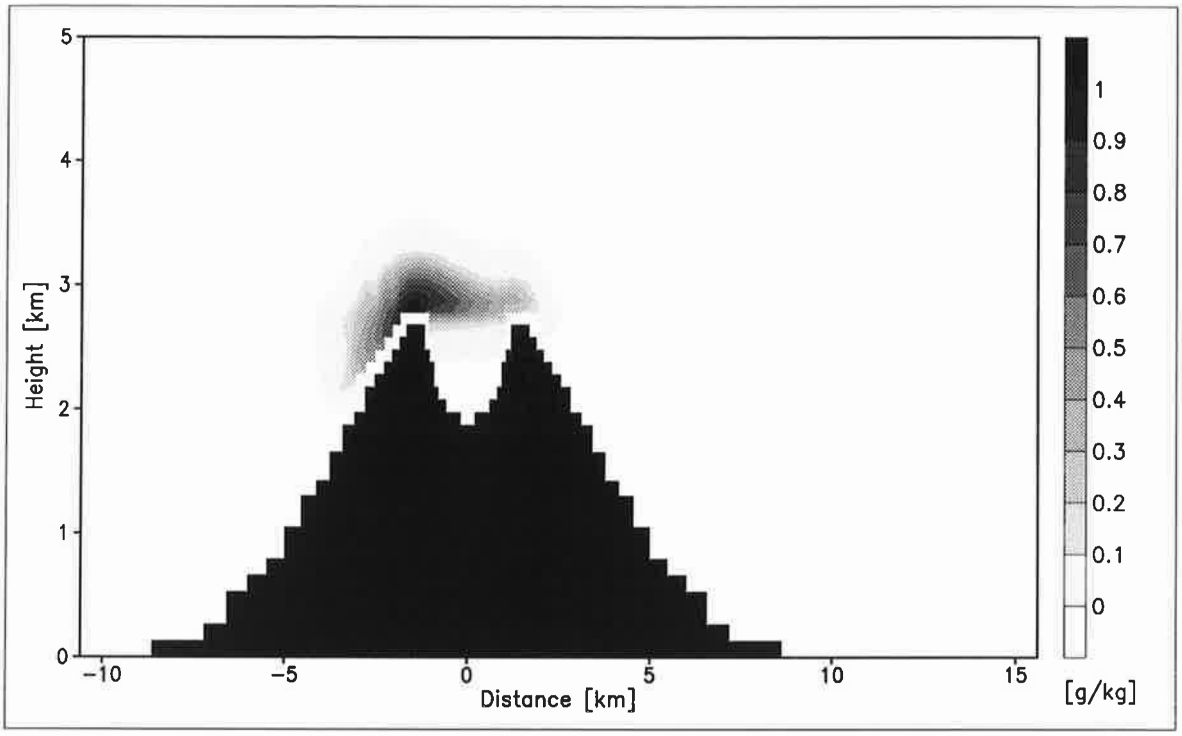

Figure 1c: Cloud water after 15 min spinup

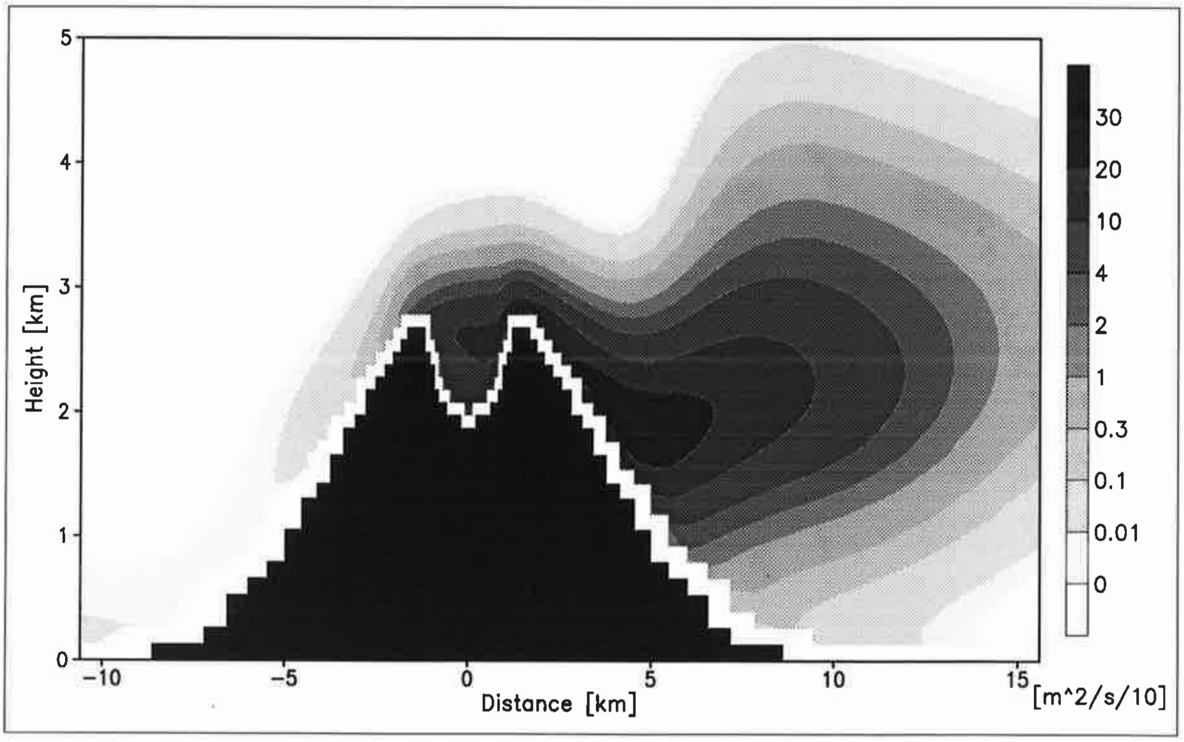

Figure 1d: Turbulent exchange coefficient after 15 min spinup

Figure 1: Quasi stationary solution of ATHAM for wind (1a), temperature anomaly(1b), condensed water (1c) and turbulent exchange for the boundary conditions from Figure 2.

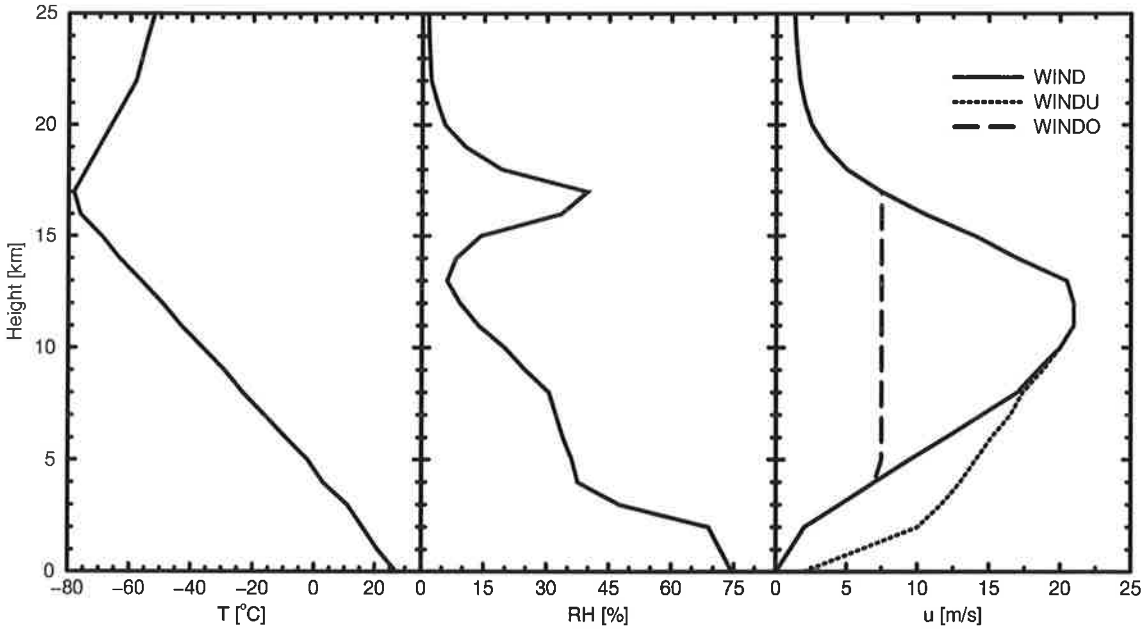

Figure 2: Meteorological boundary conditions for the reference experiment: The vertical profiles of temperature (T) and relative humidity (RH) correspond to tropical conditions (McClatchey et al. 1972), the standard wind profile (u, WIND solid line) is taken from ECMWF reanalysis data (Gibson et al., 1997). The other windprofiles are for strengthened lower tropospheric (WINDU) and reduced wind (WINDO), respectively. The wind blows from the left.

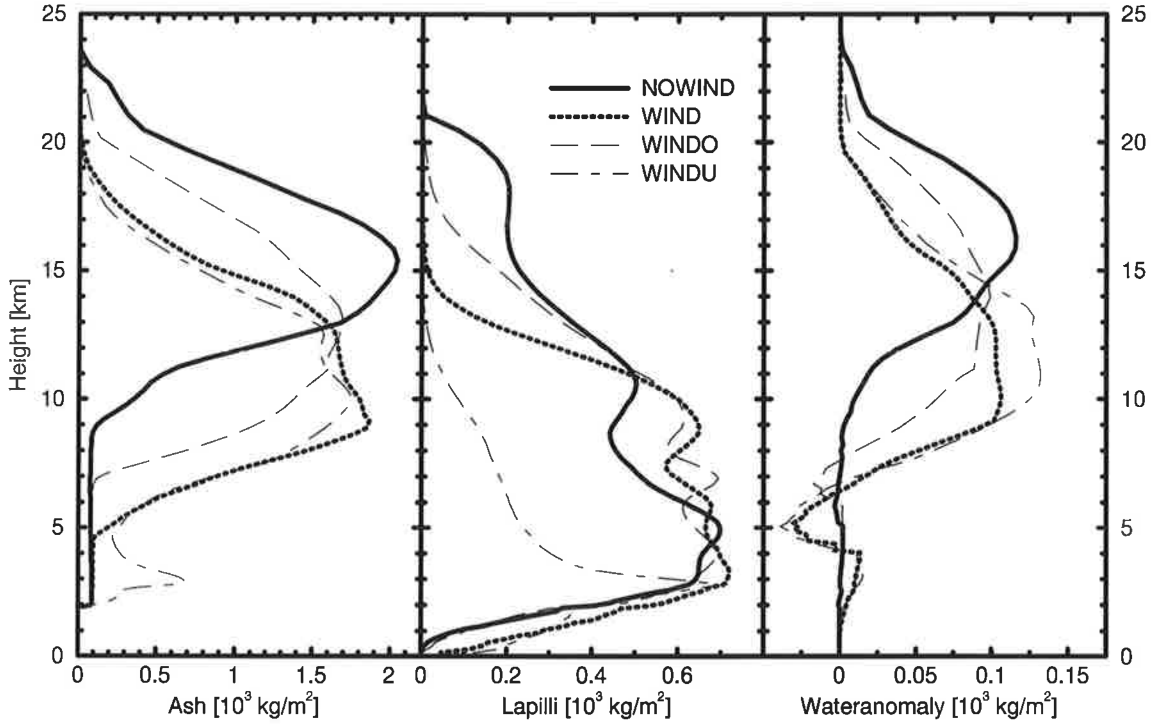

Figure 3: Vertical distribution of ash,lapilli and water for the experiments with different horizontal wind at 25 minutes after the begin of the eruption.

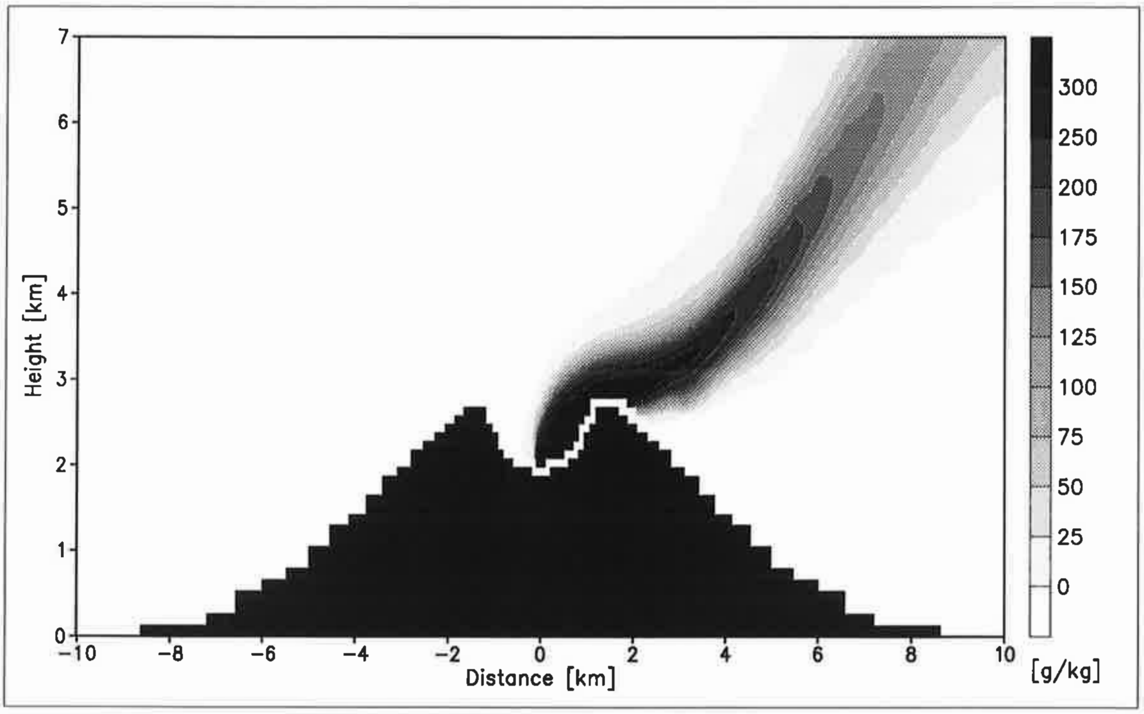

Figure 4: Specific concentration of ash particles in the experiment WINDU at 25 minutes after the begin of the eruption.

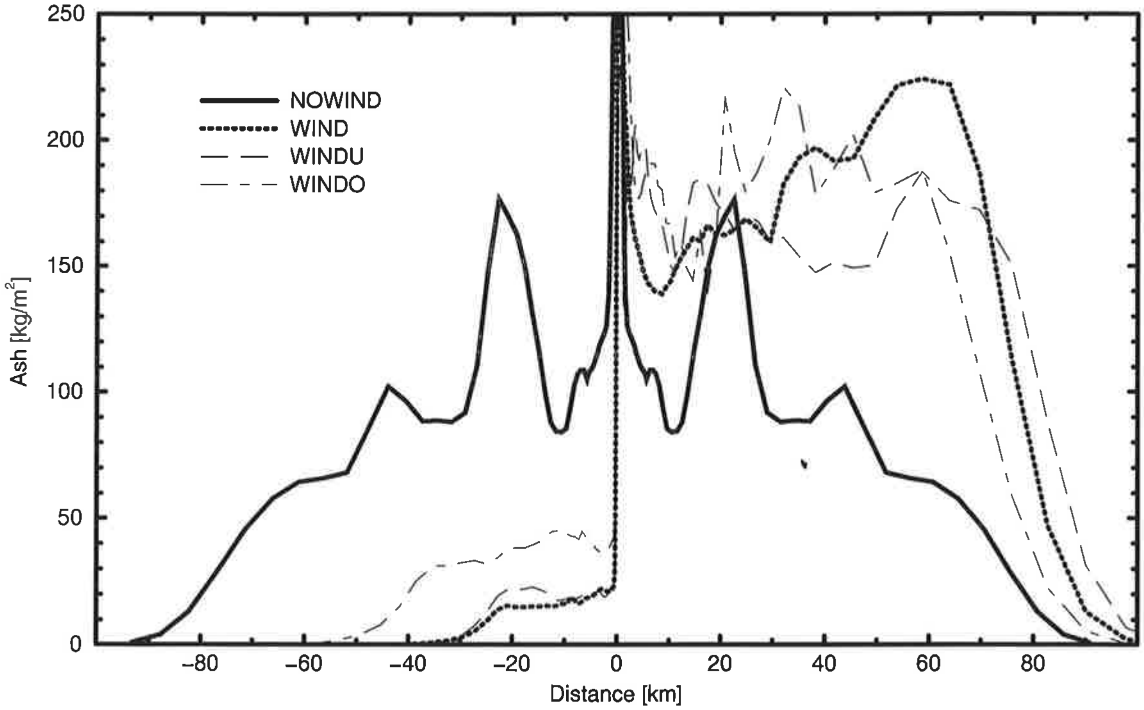

Figure 5: Horizontal distribution of the vertically integrated mass of ash for different wind regimes 25 minutes after the begin of the eruption.

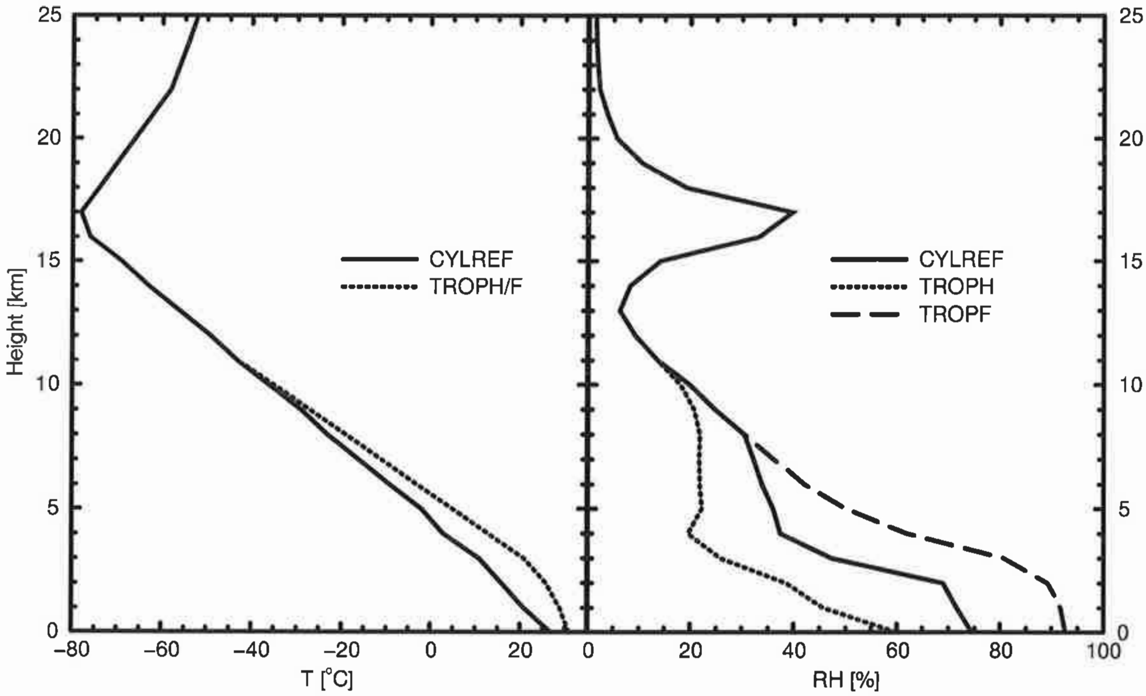

Figure 6: Meteorological conditions (temperature T and relative humidity RH) for a tropical eruption. Besides the standard (CYLREF, solid line) distribution a warmer (TROPH) and a warm/moist case (TROPF) are also shown.

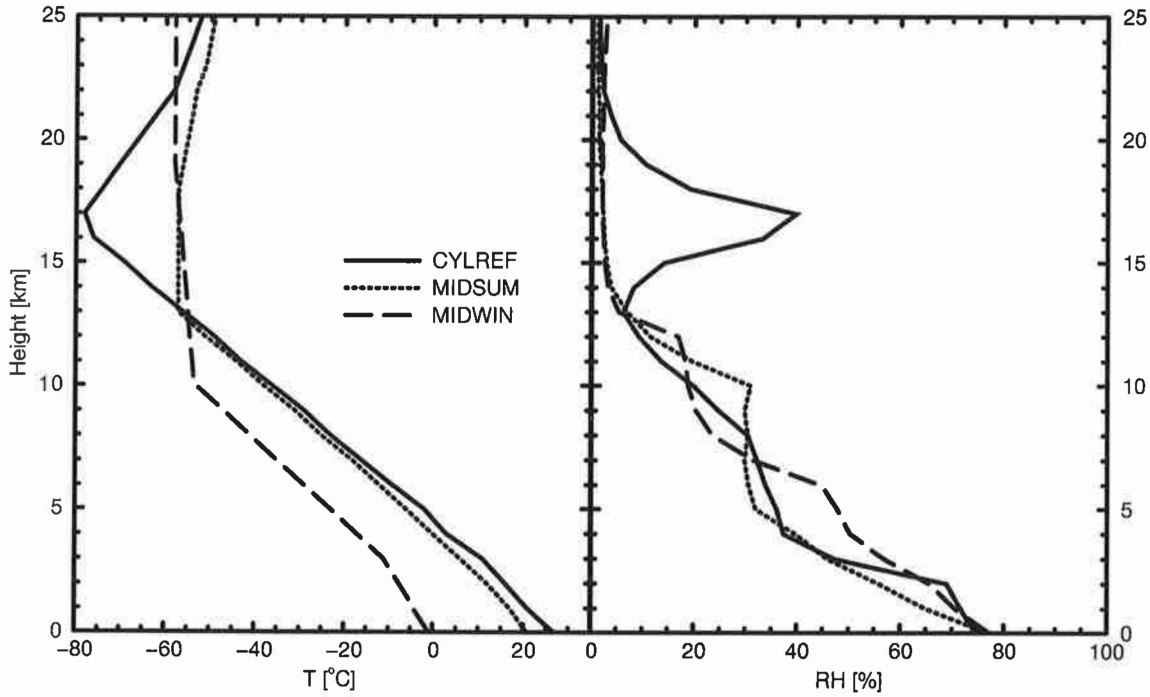

Figure 7: Like Figure 6, but for midlatitude midwinter (MIDWIN) and midsummer (MIDSUM).

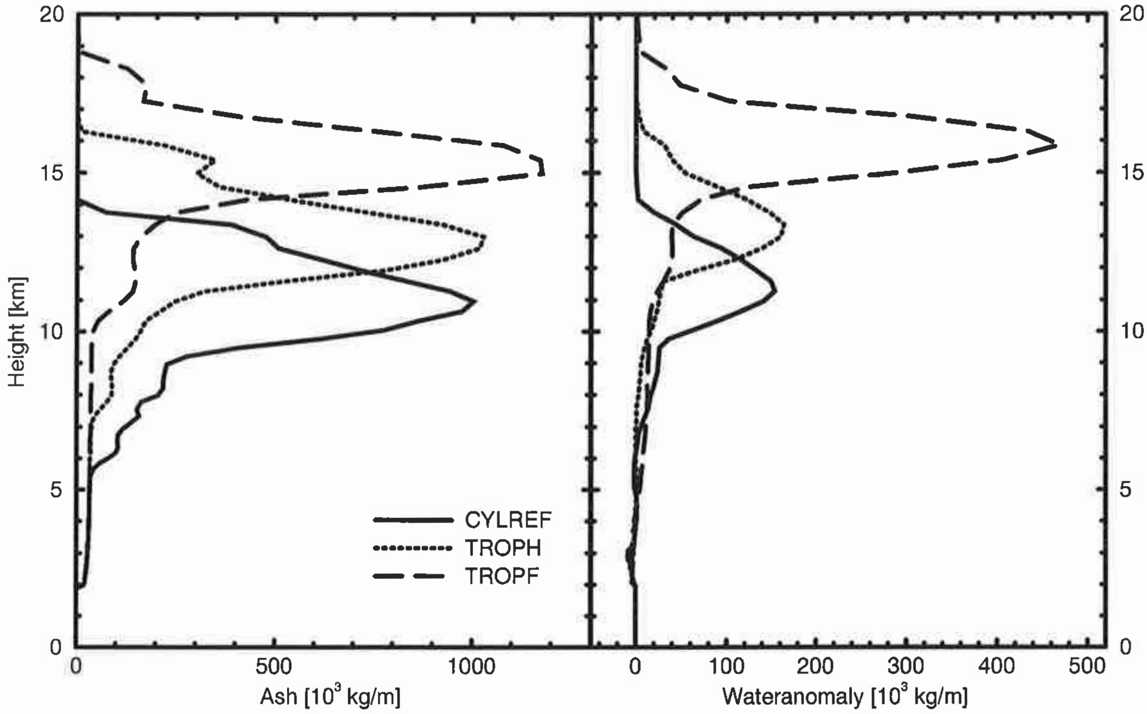

Figure 8: Vertical distribution of ash (left) and wateranomaly (right) per 1m vertical column for the different tropical experiments as defined by the T and RH profiles in Figure 6. 25 minutes after the begin of the eruption.

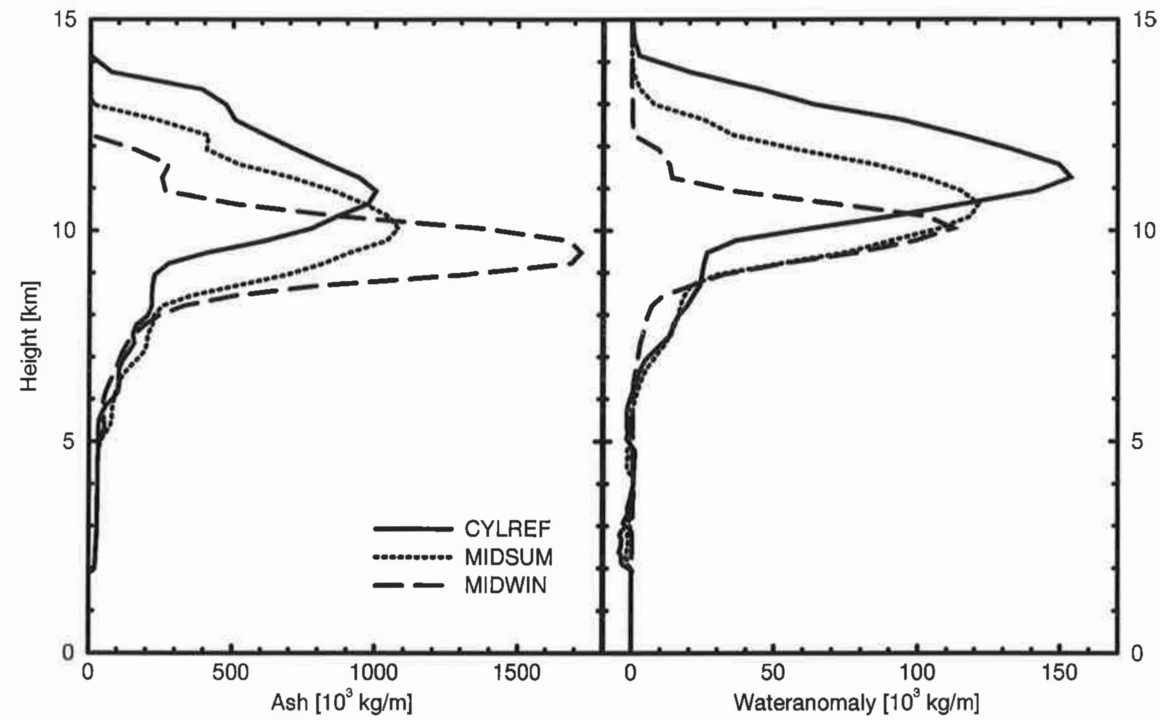

Figure 9: Vertical distribution of ash (left) and wateranomaly (right) per 1m vertical column for the different midlatitude experiments as defined by the T and RH profiles in Figure 7. 25 minutes after the begin of the eruption.