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Modeling of Orographic Precipitation Events in South America to couple Hydrological and Atmospheric Models

Part I:

The simulation of rain with the Mesoscale Model GESIMA

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Zusammenfassung

Globalmodelle sind aufgrund ihres groben Gitters (60 x 60 km) nur unzureichend in der Lage kleinskalige Prozesse (orographische Niederschlagsverstärkung) in der Atmosphäre aufzulösen. Mit Mesoskalenmodellen z.B. dem GESIMA (5 x 5 km) können deshalb die physikalische Grundlagen der Atmosphäre (Wolken- und Niederschlagsbildung) besser studiert und eine Kopplung mit hydrologischen Abflussmodellen erprobt werden. Zukünftig sieht dieses Projekt genau das vor, wobei der erste Teil, die Arbeit mit dem meteorologische Modell hier vorgestellt werden soll.

Starkniederschlagserreignisse sind vielerorts auf der Welt mit charakteristischen Wetterlagen verbunden, die quasi über Tage unverändert ergiebigen Regen produzieren. Initialisiert mit den lokalen Vertikalprofilen aus Radiosondendaten, produzieren das prognostische Mesoskalenmodell GESIMA und das diagnostische Niederschlagsberechungsverfahren (MAXRR) maximale Regenmengen vergleichbarer Größenordnung.

Abstract

Global models are insufficient to solve small scale atmospheric processes (e.g. orographic precipitation) due to their gross resolution (60 x 60 km). With mesoscale models e.g. the GESIMA (5 x 5 km), the physical fundamentals of the atmosphere (formation of precipitation and clouds) can better be studied and a coupling with hydrological models be tested through. This project plans exactly, as a first step, the work with the cited meteorological model.

Heavy rainfall events are connected with characteristic weather conditions in many places in the world which produce invariably rain quasi over days. Initialized with the local vertical profiles from radiosonde data, the prediction model GESIMA and the diagnostic model MAXRR produced rain quantities of comparable order of magnitude.

1. Introduction

Storm and flooding events cause serious damages to economic and social activities in many regions worldwide. Thus, reliable weather forecasts are necessary to reduce damages caused by these extreme events. Warning systems can offer alerts to provide local inhabitants enough time to perform security actions. Some forecasts of natural disasters are based on numerical methods. Previous studies (Chang, 2004) have shown that a coupled atmosphere-streamflow modeling system is able of capturing short- and longterm quantitative precipitation and streamflow that are important for flood forecasting and water resources management.

Model linkage is a challenging task due to model designs and problems of incompatible units, spatial scales, and temporal scales (Yu et al., 1999). While atmospheric models work from few to hundreds of kilometers, hydrological models work with smaller scales, from a few meters to hundreds of meters.

Coupled systems can be used in regions where monitoring is sparse. It is economically unfeasible to build an observation network dense enough to accurately monitor climate variables. Atmospheric model forecasts can be used as input to the hydrological models (Kite and Haberlandt, 1999). This application requires incorporation of the spatial heterogeneity present in sub-grid scale.

Another application of coupled systems is the use of the hydrological information in validating and improving atmospheric models. The discrete nature of precipitation observations, coupled with the high variability of the atmospheric events and model errors complicate the use of precipitation data for model validation (Benoit et al., 2000). Hence, hydrological models are an important complementary tool for atmospheric model validation. The accuracy of atmospheric model in predicting watershed precipitation can be evaluated by ignoring internal spatial variability and by comparing simulated flow with observations.

It is also possible to optimize the management of the reservoirs, for water supply as much as for the energy production, by predicting basin outflows.

The Institute for Meteorology – University Leipzig – carried out a study within framework of coupling a mesoscale atmospheric models with a hydrological grid point model for closed description of water cycle.

A two-way-coupling of a meso-β-scale meteorological model with a runoff model was developed and tested in short time scale. The hydrological processes of river catchment are considered in the atmospheric model, which itself drives the hydrological model (Mölders and Raabe, 1997). It means that precipitation and evapotranspiration predicted by meteorological model serve as input for hydrological model, while runoff and lateral water flows determined by hydrological model are considered in calculation of soil wetness by the meteorological model.

The Leipzig's version of non-hydrostatic model GESIMA (Geesthacht's Simulation Model of the Atmosphere) was used in that study. The hydrological model NASMO (Niederschlag-Abflußβ-Simulations-Modell, i.e., precipitation runoff model, Beckmann, 1998) is a physically based model. It distinguishes surface runoff from subsurface flow and groundwater flow.

NASMO is bounded by drainage basin and has grid cells of 100 m side length. GESIMA encompasses a 225 km x 150 km region and its horizontal resolution is 5 x 5 km^2.

In the meteorological model, an explicit subgrid scheme was adapted for meso-β-scale to downscale the hydrologically relevant quantities (Mölders et. al., 1996, 1997; Mölders and Raabe, 1996). Herein, a higher resolution grid (1 x 1 km^2) consisting of $N=25$ subgrid cells per grid cell (5 x 5 km^2) was defined.

Hydrological characteristics such as flow direction, flow length, retention, initial abstraction, etc., may significantly vary within 1 x 1 km^2 as a consequence of terrain irregularity. Therefore, they are considered on a 100-m grid resolution. These 100-m grid cells are superimposed on 1 x 1 km^2 areas, which correspond to GESIMA's subgrid cells, by forming area weighted means (Mölders and Raabe, 1997). Results confirmed that there is a significant impact of surface-hydrology on cloud and precipitation formation.

Recent research is concentrated in analyzing the meteorological conditions for extreme floods. Especially, the organization of orographic rain in the low mountain regions of Germany and the resulting distribution of rain fall necessary for hydrological predictions are investigated (Zimmer, 2005). Hoffmann (2005) constructed an idealized mountain profile and

a simulation with the Lokal-Model (LM, DWD) carried out to compare with the results of the GESIMA outputs and both are close together in a kind of ensemble prediction for a heavy precipitation event.
That is the basis for the work presented here. It is planned to couple a meteorological mesoscale model with a hydrologic model in comparable form like the former tested combination GESIMA – NASMO including very intensive rainfall events. These works are carried aut during a DAAD supported project between ITA, São José dos Campos – SP, Brazil an LIM Leipzig.

2. Study area

Ubatuba catchment is part of Serra do Mar and covers an area of around 64 km^2 in northeast São Paulo. This region presents a complex orography and frequently is reached by extreme events like intensive rainfall, floods and torrents or landslides that results serious economical and social damages. Figure 1 presents the study area localization and its steep topography.

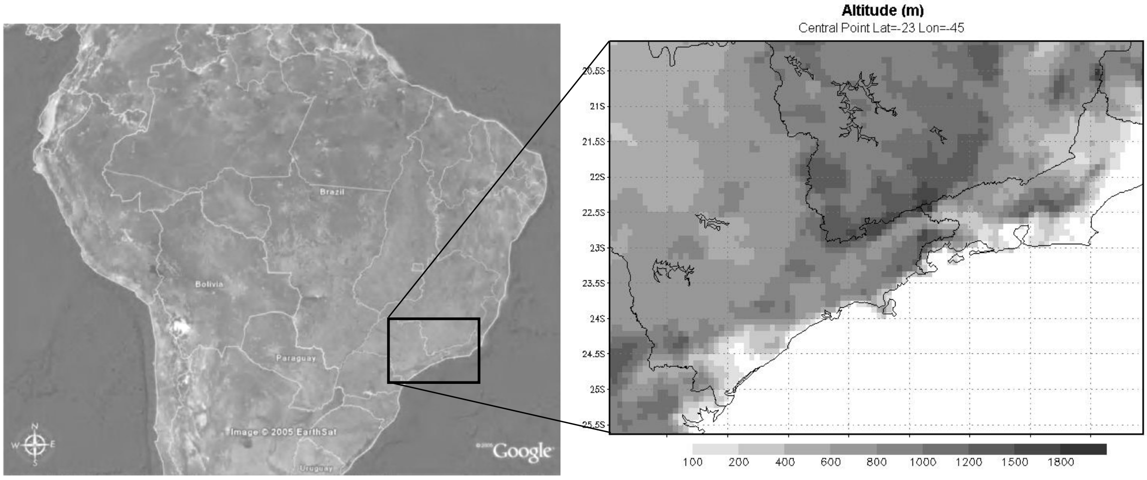

Figure 1: Ubatuba basin - Study area.

Its area is predominantly covered by tropical forest, called Mata Atlântica, and presents a significant human interference.

2.1 Time series of precipitation

The scarce numbers of stations in the studied area limits the investigations. There is just one station inside basin with recent data, named E2-009 at 220 m altitude. The annual mean precipitation at this station is 3040 mm. Another station inside the basin, E2-052 at sea level, has data from 1945 to 2000 and was not used, because we looked for a recent case. The station E2-135 at 815 m, situated outside basin, has data from 1972 to 2004 and was used to choose an event that enclosed a bigger region and was not only a local phenomenon. This station has an annual mean precipitation of 1785 mm.

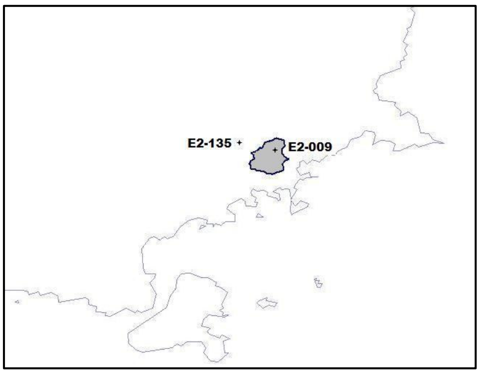

Figure 2: The station localization.

Figure 2 depicts the localization of these stations and Figure 3 presents the monthly mean precipitation (right) and the 2004 daily rainfall for station E2-009 and E2-135 (left). The selected cases were 17.07.2004 until 20.07.2004 and 22.02.2204 until 24.02.2204 due to the expressive rainfall quantity in both stations along four and three consecutive days, respectively. This way, short single events like convective rain are filtered and precipitation events of longer duration become more relevant. In the left graph in Figure 3, the two selected events have the greatest peak near 150 to 200 mm. One event is during the southern hemispheric winter (July), generally less wet with about 100 mm per month and the other one is during the summer season (February) with a monthly mean of almost 400 mm.

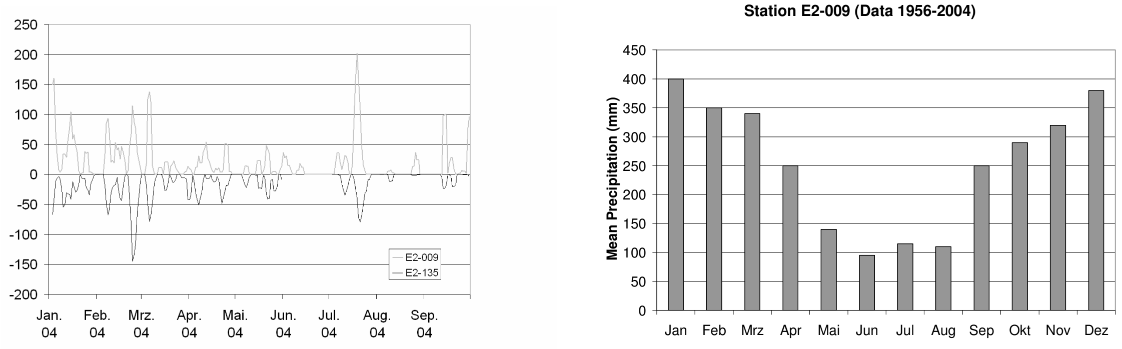

Figure 3: Three day mean of precipitation [mm] for two observatories (left) one inside the study area E2-009 (220 m) and the other E2-135 (815 m) outside. One might see two significant peaks, one in the end of February and another in the middle of July 2004, with more than 150 mm. A half century mean of monthly rain at station E2-009 (right) with heavy summer rain events (Jan.-Feb.) about 400 mm and less wet winter month (Jun.-Aug.) near 100 mm.

2.2 Synoptic situation

The synoptic conditions for the two selected cases were observed by the NCEP/NCAR global reanalyzes. Whereas the goal was to study orographic effects on the precipitation, the 20.07.2004 00h was selected due to southeast winds over the study area. Figure 4 depicts the 850 hPa topography with the geopotential height (gpm) shaded and wind vectors (m/s) to the referred case. The synoptic situation is determined by two cyclones, one in the south at 40°S and 48°W and another at northern of the study area. The streamlines on the southern hemisphere are directed counter clockwise. Near the meteorological station (black box) the flow shows a convergent character. The study area at southern is determined by a steady wind from the seaside almost orthogonal to the mountain direction.

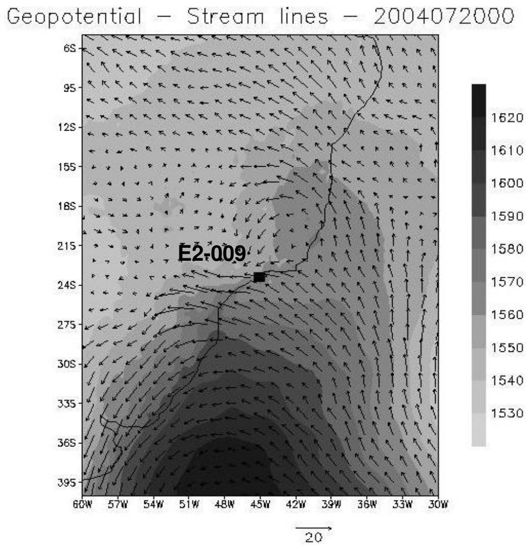

Figure 4: 850 hPa topography with the geopotential height (gpm) shaded and wind vectors (m/s). NCPE/NCAR reanalyze data from 20.07.2004 00h.

The black point indicates E2-009 station position, from where vertical profiles are taken (Figure 5). The temperature profile shows a gradient of about -5.4 K/km, the air is almost saturated (~95 %) up to 3000 m and the meridional component of velocity rotates from 10 m/s east at ground levels to 30 m/s west at upper tropospheric levels.

The 20.07.2004 00h reanalyzed global data (without a figure) presents no large scale precipitation to the study area although there is rain measured at both meteorological observatories of about 150 mm/3d. It can be explained as global models which can not solve precipitation caused by orographic effects or local phenomena, like convective precipitation, due to small resolution.

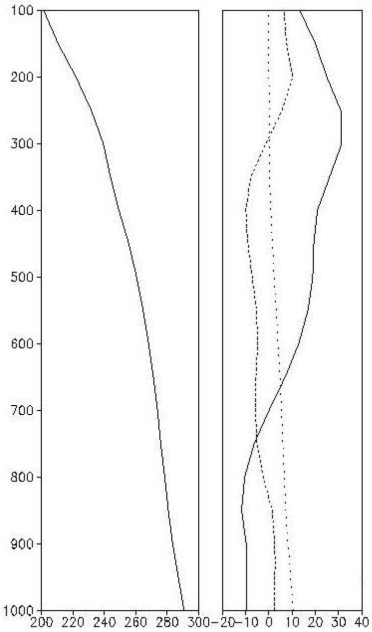

Figure 5: Absolute temperature [K] (left panel), zonal wind [m/s] (solid line, right), meridional wind [m/s] (dashed line, right panel) and specific humidity [g/kg] (dotted line, right) profile at E2-009 station at 20.07.2004 00:00UTC.

2.3 Sounding data

Soundings data are available just at the São Paulo (23.52° S; 46.63° W) and Rio de Janeiro (22.81° S; 43.25° W) airports, situated about 200 and 300 km far from Ubatuba catchment, respectively. Due to similar topographic characteristics, Rio de Janeiro sounding data were chosen for the present study. Data from 20.07.2004 00h are present in Table 1.

Altitude (m)	0	50	150	300	600	900	1200	1500	2000	2500
Theta (K)	288.2	288.1	287.5	287.5	288.7	289.9	291.2	294.0	296.4	298.9
RH (%)	98.0	97.9	96.7	95.9	95.4	95.0	94.4	94.0	94.0	94.0
U (m/s)	-2.6	-2.7	-3.9	-5.2	-7.2	-8.8	-8.2	-7.7	-6.0	-4.1
V (m/s)	0.0	0.0	0.5	1.4	3.4	5.1	4.7	4.5	1.8	-1.1
Altitude (m)	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000
Theta (K)	301.3	308.7	314.9	319.7	324.3	327.0	330.0	340.0	345.4	349.4
RH (%)	94.0	82.2	71.2	66.7	65.1	56.9	54.8	48.0	46.4	43.7
U (m/s)	-2.2	2.8	9.5	19.0	25.0	30.0	34.4	36.0	33.1	27.1
V (m/s)	-4.0	-8.1	-10.4	-7.6	-4.6	-1.7	-0.5	6.3	7.0	11.0

Table 1: Rio de Janeiro sounding data – 20/07/2004 00h.

2.4 Landuse

A sensitivity analyze was carried out to study the impact of landuse over the results. In the first simulations a homogeneous deciduous forest was used. Whereas there was not appropriated landuse map to our study area, we created an arbitrary map which was dependent on the topography. This was meant to present its impacts over the precipitation results. The used criteria are summarized in Tab. 2.

Altitude	Landuse	GESIMA landuse number
0	Open water	1
$0 < h \leq 150$ m	Sandbank (usually)	12
150 m $< h \leq$ 700 m	Agricultural area (loam, knick)	10
$h > 700$ m	Tropical forest	-

Tab. 2: The simplified land use data orientated at topographic height.

GESIMA model has no tropical forest classification. Therefore a new class was created with the following parameters that either was found in literature or taken from GESIMA (Tab. 3).

Soil diffusion coefficient	0.70×10^{-6} m^2/s
Heat capacity	3.0×10^{6} J/K m^3
Emissivity	0.97
Albedo	0.15
Roughness length	2.0 m
Field capacity	0.01 m
Capillarity	8×10^{-2} kg/m^{3}s
Switch for characteristic of roughness elements	0.0
Maximum evaporative conductivity	3.0×10^{-2} m/s
Particle resistance	2.50×10^{2} s/m

Tab. 3: Characteristic values to describe land use classification ‘tropocal forest’.

3. GESIMA Model

The GESIMA model is developed by Kapitza and Eppel (1992) to study regional weather phenomena like the baltic heat cyclone (Devantier, 1995) or orographic precipitation (Hoffmann, 2005) in the mesoscale. After the heavy rainfall event (~ 300 mm/d) in August 2002 caused by a quasi steady flow of saturated air against the „Erzgebirge“ (~ 1000 m) in east Germany. Meteorological models were used to simulate such precipitation events (Hoffmann 2005, Zimmer 2005).

These events are underdetermined by global operating models so that such mesoscale models with a larger time and space resolution (5 x 5 km) were used to investigate microphysical processes in clouds, for example, while a wet air parcel passes structured topography. From reanalyzed sounding data, the vertical structure of the local air in parameters of relative humidity (rH), potential temperature (Φ) and the wind components (u, v) are described. In the model source code, the dynamic non-hydrostatic equations numerically are solved by the Mac Cormack scheme (Kapitza and Eppel 1995). These are based on the fundamental laws of the classical physics: the conservation of mass, energy, momentum and their continuities. Microphysical processes like the genese of clouds and other turbulent interactions are parameterized.

The GESIMA model includes three different cloud modules (Jacob 1991, Levkov et al. 1992, Devantier 1995, Mölders et al., 1997, see Fig. 6). All of them a cloud is described as a composition of 4-6 different water classes (water vapor, cloud water, cloud ice, graupel, rainwater, snow), every with a characteristically size distribution (bulk). The production of rainwater for example is the positive balance of coalescence (collision of raindrops with different size), autoconversion and melting ice as well as the evaporation of rain water to water vapor as Figure 6. With the prognostically determined variables, the mass mixing ratio, the concentration number and the rain rate per hour can be calculated.

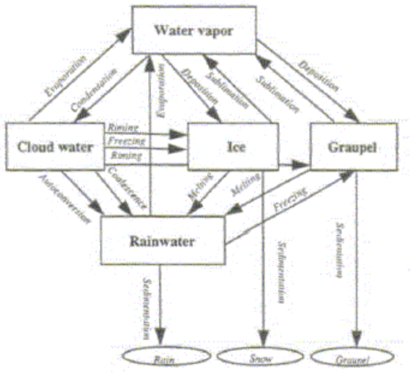

Figure 6: A cloud parameterize scheme taken from Mölders (1997). This classifies water into 5 different groups. One gas phase (WV), two liquid phases (CW & RW) as well as two ice phases (I & G). In it, 18 microphysical processes are parameterized. They describe the conversion rate from one class to another.

5. Results and Discussion

5.1 GESIMA domain and creation of an idealized topography (bellshape)

The meteorological model domain encompasses a 300 km x 300 km region around the studied basin with a horizontal resolution of 5 x 5 km (Figure 7). The big cities São Paulo and Rio de Janeiro are situated outside the model area. The vertical resolution varies from 50 m close to the ground to 1 km at the top of the model, with 11 levels below 3 km and 12 km above that height. Figure 9 depicts the respective meridional profiles at each 10 grid cells, where the high slopes can be observed. There are three characteristical areas in dependence to the height of the topography (0 m -, 1000 m -, 2000m - level). All three are separated by steep slopes directed from northeast to southwest, the first near coast and the second about 200 km into the area.

Due to the high terrain irregularity, an idealized topography based in bell-shaped form was created to evaluate the orographic effects about precipitation generation without secondary interferences. The analytically constructed topography consists of two mountain ridges with 150 km length, 1000 m height and a half-wide of 20 km. The shape is showed later overlying with the results.

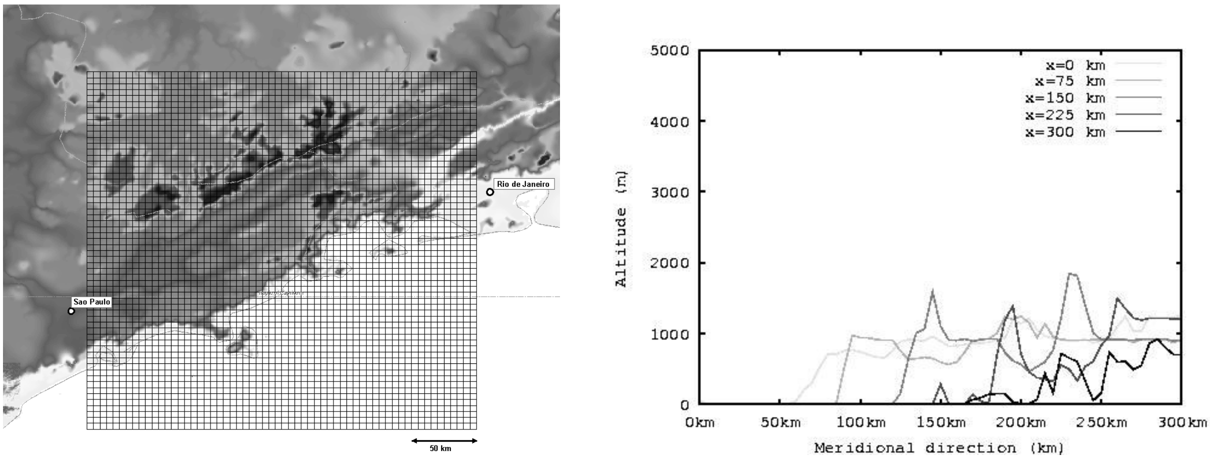

Figure 7: The topographic data are taken from ArcGis world map data with a horizontal grid of 1 km. The model area arranged to the meteorological model with a resolution of 5 x 5 km and 60 x 60 grid points (left). On the right some selected vertical cross section of the topography data for different meridional grid points starting in the east (left, sea-side, 0 m) going west (right, land-side, 1000 m – 2000m) .

5.2 3D-Gesima study on idealized simulation

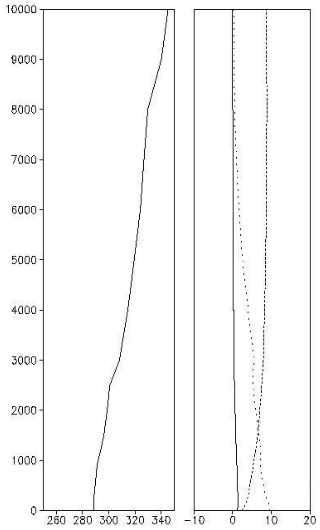

Figure 8: Initial conditions. Potential temperature [K] (left), zonal wind [m/s] (solid line, right), meridional wind [m/s] (dashed line, right) and specific humidity [g/kg] (dotted line, right) profile.

The initial conditions used in GESIMA simulations are depicted in Figure 8. These data were taken from 20.07.2004 00h Rio de Janeiro sounding data with some modifications (see Fig. 5). The zonal wind was taken around zero (solid), and the meridional wind (dashed) above the shear point was taken constant (right plot). The GESIMA- initialization demands a constant geostrophic wind, here 8.8 m/s. The air is up to 3000 m almost saturated with water vapor (95%) and the vertical potential temperature profile (left plot) shows a gradient of 3.7 K/km (< 2000 m) and 5.1 K/km (> 2000 m). That means a Brunt-Vaisälä-Frequency (N) of 0.0112 s^{-1}.

With U = 5 m/s at 300 m height and the given slope geometry the Froude-number amounts 0.79. The flow tends to block and converging luv-side (A description of the influence of flow stratification, using N are given in Zimmer, 2005 and Hoffmann, 2005).

Figure 9 presents the results obtained with 3D GESIMA simulation. For comparison, simulations with 2D GESIMA and MAXRR models were executed. Three cloud modules were submitted to 2D GESIMA: Jacob, Levkov and Devantier. As final 2D result, average value attained with different models was adopted. The diagnostically model MAXRR calculates the maximal instant rain of an air column caused by the topographically induced vertical velocity $w=U_0(dh/dz)$ parallel to the direction of flow using a humidity and temeperature profile describing the observed atmospheric conditions (Zimmer, 2005).

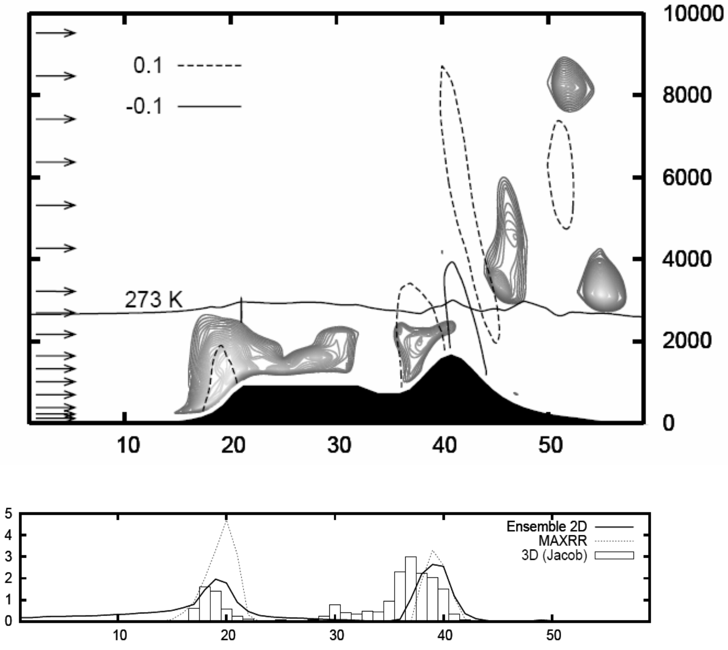

Figure 9: Results with idealized topography: Upper, the vertical cross section of the 3D GESIMA (Jacob) with topography (filled), 0°C line (horizontal, solid), upward (solid) and downward (dashed) directed velocity as well as cloud water and cloud ice (gray scaled). Below is compared the horizontal rain rate [mm/h] distribution for a 3d-simulation (boxes), 2d-simulation (solid) and MAXRR-simulation (dotted).

Figure 10 depicts the horizontal wind vectors and the rainfall rate results obtained with 3D GESIMA simulation using Jacob cloud module at 50 m in height for the idealized topography. Some streamlines are passing on the left and right border of the mountain ridge and converge toward the lee-side. This causes irregularities in precipitation rates. The orographic induced rain on the first slope (south) amounts near 2 mm/h and on the second slope (north), 3 mm/h.

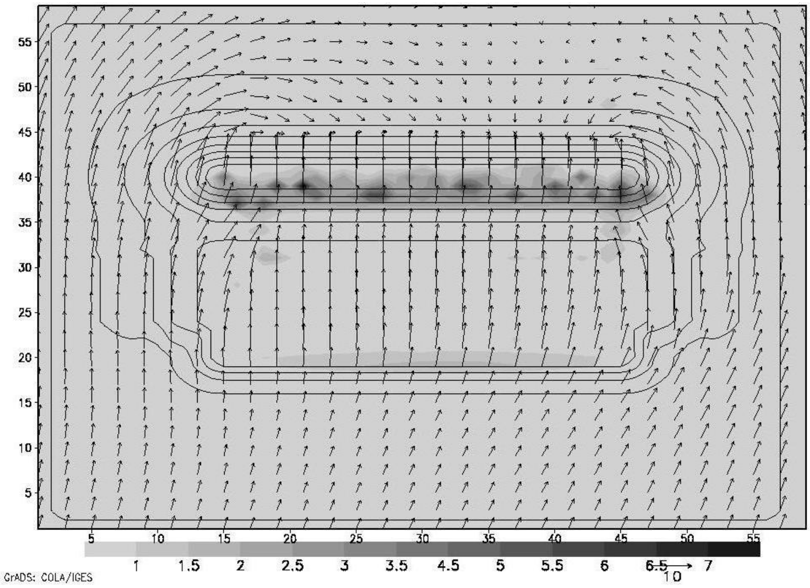

Figure 10: Results with idealized topography 3D GESIMA (Jacob). Horizontal view at 50 m in height with wind vector and rainfall rate [mm/h] (gray scaled). The isolines of constant topographic height are plotted solid every 250 m.

5.3 3D-Gesima study on quasi real topography

Finally a 3d-GESIMA simulation with the Jacob cloud module on a real topography is made and Figure 11 and 12 depicts the results for the given initialized vertical profiles but the meridional wind velocity component is used like the values in table 1. One simulation was carried out with a homogeneous landuse type (mixed forest) and the other one with a constructed landuse data dependent on the topography (see section 2.4). On the horizontal view at 50 m height (Figure 11, left panel) two precipitation areas were identified. The first, along near coast line, produces about 3 mm/h orographic rain, and the second, 200 km inside, almost 4 mm/h more.

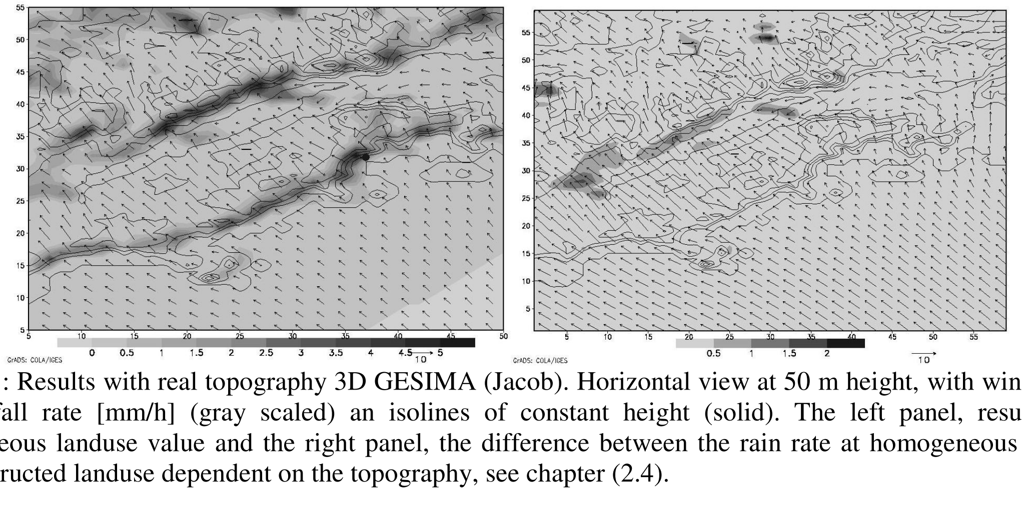

Figure 11: Results with real topography 3D GESIMA (Jacob). Horizontal view at 50 m height, with wind vector and rainfall rate [mm/h] (gray scaled) an isolines of constant height (solid). The left panel, results with homogeneous landuse value and the right panel, the difference between the rain rate at homogeneous landuse and constructed landuse dependent on the topography, see chapter (2.4).

Through the variation in landuse there are some differences on the second slope which can be seen in Figure 11 (right). The roughness length parameter is very important in this view. For the mixed forest, used as homogeneous landuse, the roughness length was 0.50 m. For the constructed landuse, the roughness lengths were 0.0001, 0.01 and 2.0 m to the sandbank, agricultural area and tropical forest, respectively.

Figure 12 depicts results obtained with 3D GESIMA simulation as vertical cross section in parameters of positive and negative vertical velocity, cloud water and cloud ice above 273 K isotherm line. The real topography is overlaid and the arrows indicate the stream direction. The second plot shows the horizontal rain distribution produced by the Jacob cloud module.

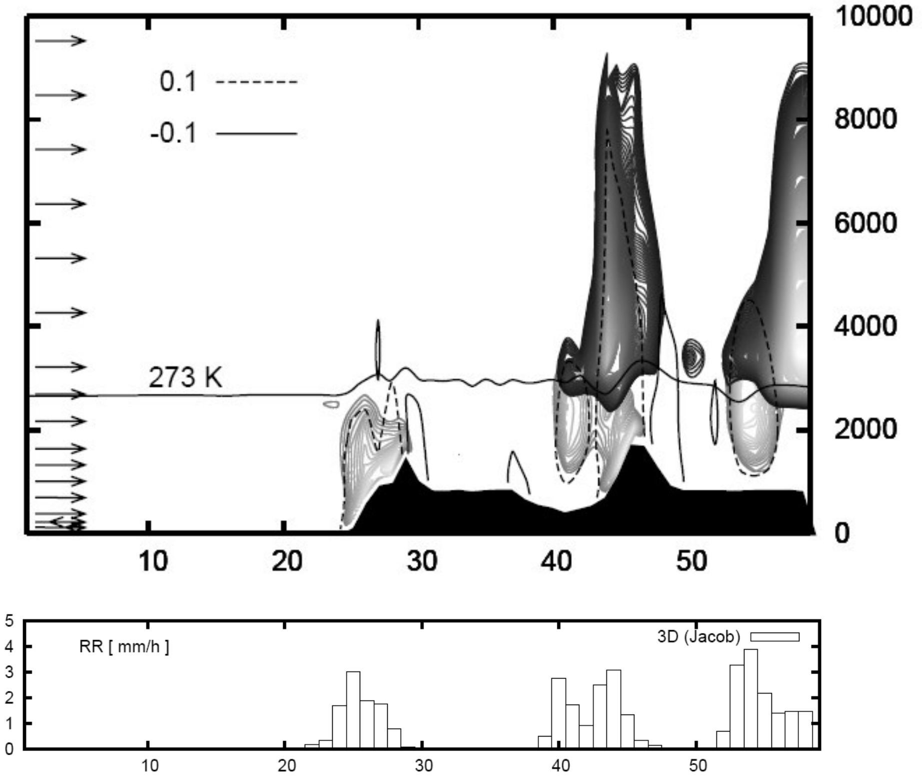

Figure 12: Results with real topography: Upper, the vertical cross section of the 3D GESIMA (Jacob) with topography (filled), 0°C line (horizontial, solid), up (solid) and downward (dashed) directed velocity as well as cloud water and cloud ice (gray scaled). Down, the horizontal rain rate [mm/h] distribution for a 3d-simulation (boxes).

6. Summary and Conclusions

With the GESIMA model we are able to simulate quasi stationary weather phenomena. Heavy orographic rain events was studied by Hoffmann (2005) with the GESIMA and Zimmer (2005) with the LM-model. The calculated precipitation rate per grid pointed every 5 km is the input data set for any hydrological model to modulate the water budget of basins in general but also river overflows, erosion hazards and sediment transport on the surface. The next step will be the downscaling to a higher resolution using an explicit subgrid scheme based on Mölders and Raabe (1997).

In this work, a orographic rain is researched for an orographic rain event in Brazil. There are rain observations of 150 – 200 mm during 3 days in the study area. From NCEP/NCAR global reanalysis data and soundings data of Rio de Janeiro, the synoptic situation discussed and the mesoscale model are initialized. On 20.07.2004, the stream direction southeast is normal to the mountain ridge. Simulations are carried out with idealized and real topography.

Rain rates of 3 mm/h were attained. Thus, a total value of about 216 mm, for a quasi steady duration of 72 h, was reached. The model results show a good agreement with the observations.

Acknowledgements

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