Journal of Geology & Geosciences
ISSN: 2381-8719
Enyew and Steeneveld, J Geol Geosci 2014, 3:6
DOI: 10.4172/2329-6755.1000173
Research Article Open Access

Analysing the Impact of Topography on Precipitation and Flooding on the Ethiopian Highlands

Enyew BD[1] and Steeneveld GJ[2]*

[1]Department of Meteorology and Hydrology, Arbaminch University, P.O. Box 21, Ethiopia
[2]Meteorology and Air Quality, Wageningen University, The Netherlands

Abstract

This study used MM5 mesoscale modeling to analyze the influence of regional atmospheric circulation on flooding of the Ethiopian highlands from 26th-28th of July 2006. It had been found that the northern, south western and the central highlands of the country had showed large amount of precipitation and cloud cover in comparison to the lowland parts of the country, in the East and South east, due to the effect of topography and regional weather systems. Investigating the effect of topography on precipitation reveals that there was a clear reduction in the amount of precipitation and a shift in the pattern of precipitation, when topography height was reduced by 50%. While topography had increased by 50%, no clear pattern of precipitation had been revealed. In general topography and regional weather systems play a great role in the amount and spatial pattern of precipitation in the region.

Keywords: MM5; Topography; Ethiopia; Precipitation; Cloud cover

Introduction

Precipitation patterns vary widely throughout the country due to elevation, atmospheric pressure patterns, and local features. In the lowlands, rainfall is typically quite meager, whereas the southwest, central, and northwest regions receive quite appreciable quantities, but in varying patterns. In the southwest, a relatively even month-to-month distribution may be observed, while the dominant pattern in the northwest and western regions, containing the Blue Nile basin, is generally associated with tropical monsoon-type behavior, delivering significant June-September rainfall. Other regions throughout the country, not necessarily adjacent, demonstrate a distinct bimodal pattern. Topography can affect global climate in at least three important ways. First, it can intensify the solar heating over land by providing an elevated heat source. This magnifies the regional-scale land-sea temperature contrast and facilitates the onset and maintenance of monsoon regimes that produce convective rainfall and latent heating. Variations of this heating can affect weather and climate in other tropical areas, as well as in the extra tropics via atmospheric teleconnections. Second, topography can contribute to orographic rainfall and additional latent heating. That is, as moist air is forced up a slope, the air cools, moisture condenses and rainfall and latent heating occur with consequences similar to those associated with convective heating. Third, topographic barriers in the tropics obstruct the large-scale air flow and force some air to go around rather than over topography. This mechanical effect disturbs the flow downstream and sets up large-scale circulation patterns that extend into the extra tropics via planetary long waves [1]. Two main rainy seasons exist within Ethiopia: the Belg ("small rains" in March-May) and the Kiremt("big rains"). The Kiremtseason is part of a larger east African monsoon season spurred on by the shifting of the Intertropical Convergence Zone (ITCZ) northward [2,3]. During the pre-monsoon season (March-May) the Tropical North African and South Asian land is predominantly dry, resulting in a general warming of the regional land and atmosphere. The ITCZ is formed where the wet southeasterly winds meet the dry northeasterly winds. The shifting of the ITCZ is a direct result of solar heating and warming of the surface [2,3], following the migration of the sun. This creates a low pressure, and pulls the ITCZ to the north from the equatorial region. The northern reach of the ITCZ is one of the dominant factors in controlling the timeliness and quantity of Kiremtrains. Simultaneous to the shifting of the ITCZ, high-pressure systems in the South Atlantic and Indian Oceans, coupled with the Arabian and the Sudan thermal lows, allow for the influx of moisture into the upper Blue Nile basin [4,5]. In addition to atmospheric systems affecting temporal and spatial variation of rainfall in Ethiopia, topography and geographical location of the country could be another factor for this variation [6]. According to Bekele [6], the main weather systems affecting the main rainy period (known as 'kiremet' locally which extends from June to September) are the Inter Tropical Convergence Zone (ITCZ), the South Indian Ocean anticyclone (Mascarin High), the low level jet (LLJ), the South Atlantic anticyclone (St. Helena). The tropical easterly jet (TEJ) and the Tibetan anticyclone are another two important upper-level atmospheric feature affecting the rainfall activity in the region. The highlands and Blue Nile basin are predominantly fed by moisture advected over the Congo basin, transported via a southwesterly flow, and released due to orographic effects. This pattern persists until September or October, when the north-easterly continental airstream is re-established, and the ITCZ shifts south [7]. Seasonal and annual rainfall variations in Ethiopia as well as the neighboring areas of the region are associated with the macro-scale pressure systems and monsoon flows [8,9]. A pressure drop in India provokes an increase in the southwest–northeast pressure gradient between Africa and India, and thus a reinforcement of the southwester lies north of the equator, as well as the occurrence of anomalous moist wester lies above the East African highlands [10]. Orographic lifting, enhanced moisture content in the lower levels, and convergence with the Indian monsoon southerly flow all favor an enhancement of rain-producing convective activity in the Kenya and Ethiopia highlands. This is also the rare occasion on which convective showers can develop in the dry lowlands near Lake Turkana, as moist westerlies replace the usually dry and divergent southeasterly Turkana jet.

Although Ethiopia is often plagued by drought, heavy rainfall in 2006 and 2007 over the Ethiopian highlands (6–14°N, 35–40°E; Figure

***Corresponding author:** Steeneveld GJ, Meteorology and Air Quality, Wageningen University, The Netherlands, Tel: 31 317 483839; E-mail: Gert-Jan.Steeneveld@wur.nl

Received July 28, 2014; **Accepted** August 18, 2014; **Published** August 22, 2014

Citation: Enyew BD, Steeneveld GJ (2014) Analysing the Impact of Topography on Precipitation and Flooding on the Ethiopian Highlands. J Geol Geosci 3: 173. doi: 10.4172/2329-6755.1000173

Citation: Enyew BD, Steeneveld GJ (2014) Analysing the Impact of Topography on Precipitation and Flooding on the Ethiopian Highlands. J Geol Geosci 3: 173. doi: 10.4172/2329-6755.1000173

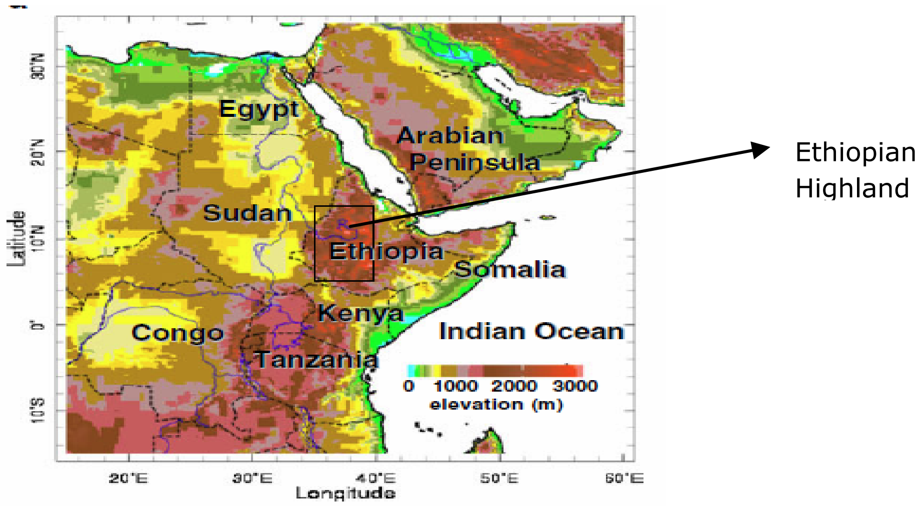


Figure 1: Map of the region considered for the study.

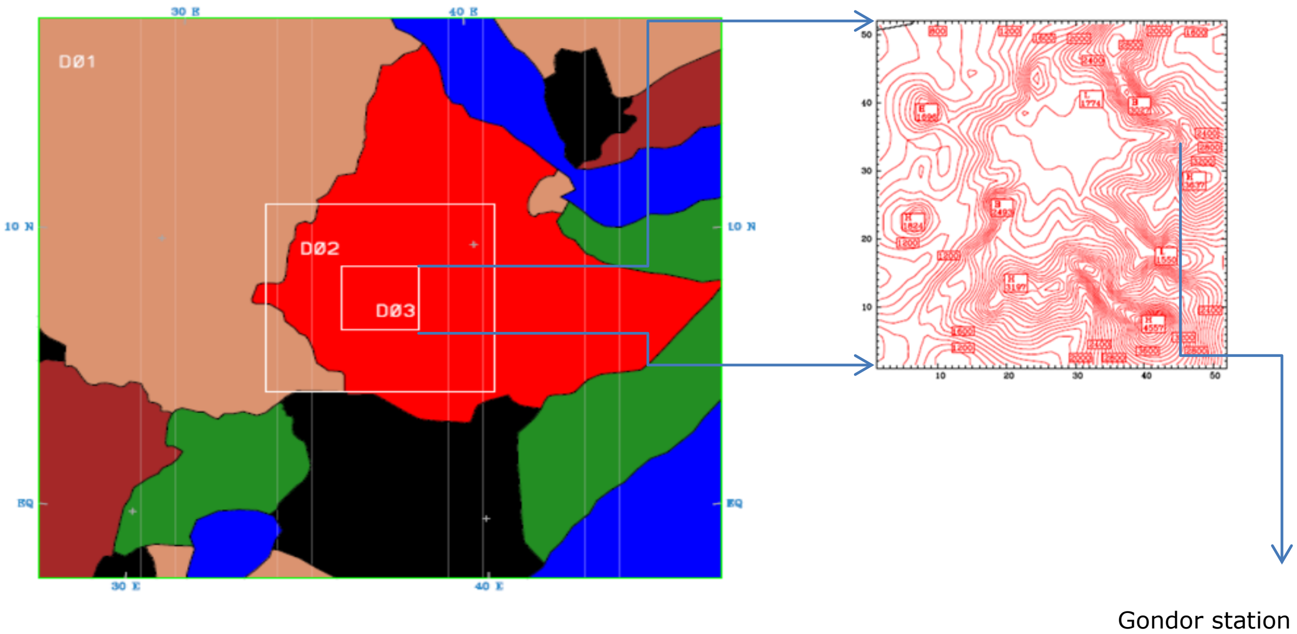


Figure 2: Domains of MM5 model simulations used for this study.

1) caused flooding of the Blue Nile River. The Ethiopian Meteorological Service reported July totals >400 mm across western districts, with daily totals >100 mm and seasonal totals up to 2,000 mm. The United Nations reported 620 fatalities, ~35,000 displaced and ~118,000 people 'affected' by flooding in 2006. Since late July 2006, unusually heavy rains resulted in flash floods and overflow of rivers and dams which affects 199, 000 people in eight regions of Ethiopia, resulting in loss of life. Damage to property, and destruction of livelihoods for tens of thousands of people [11].

The country experiences two types of floods; flash and river floods from excess rains falling on the central highlands that makes their way down to the outlying lowlands with high concentration, speed and force that causes devastating damages both in infrastructure and human life (e.g. the 2006 incident that Dire-Dawa city experiences is the most typical of flash flooding). The other flood disaster in Ethiopia related to rivers that overflow and burst their banks is occurred in South Omo zone (South West Ethiopia) and other parts of the country (e.g. Lake Tana Region in North West Ethiopian) in 2006 (Early Warning Special Report 02, 2007). The objective of this paper is to analyze the regional atmospheric circulation and thermodynamic conditions that modulated the 2006 Ethiopian flood events through analysis of meteorological patterns on flood days for a period 26-28 July 2006 that had greatest rainfall and assessing the effect of topography on precipitation.

Methodology

Study area description

Ethiopia is located in the horn of Africa (Figure 1) with an area

Citation: Enyew BD, Steeneveld GJ (2014) Analysing the Impact of Topography on Precipitation and Flooding on the Ethiopian Highlands. J Geol Geosci 3: 173. doi: 10.4172/2329-6755.1000173

Model elements	Components	Specification
Domain	Horizontal	Domain-1, 54 kmx54 km Domain-2, 18 kmx18 km Domain-3, 6 kmx6 km
	Vertical	27 half sigma level
	Output time steps	1hr, all domains
	Topography	USGS
	Vegetation / Land use	USGS
Dynamics		Non hydrostatic
	Nesting	One- way nesting –Domain 1 Two-way nesting –Domain 2 &3
	Time integration	Semi-implicit
	Boundary condition	Fixed
		Time dependent .nest
	Horizontal diffusion	Fourth order for all domain
Physics	Cumulus Parameterization	Betts-Miller
	PBL Parameterization	MRF PBL
	Explicit moisture schemes	Mixed phase
	Radiation schemes	cloud

Table 1: Configuration of MM5 used for this study.

of 1 127 127 sq km, of which, 7444 sq km is water (CIA world Fact book, 2006). The topography of Ethiopia is highly divers, with elevation ranging from -125 m at the Danakil Depression to 4620 m at RasDejen. More than 45% of the country is dominated by high plateau with a chain of mountain ranges that is divided by the East African Rift Valley [12].

Ethiopia is both a highland/mountainous (with elevation greater than 1500 m) and lowland (with elevation less than 1500 m) country. It is composed of some nine major river basins, the drainage systems of which originate from the centrally situated highlands and make their way down to the peripheral or outlying lowlands.

The climate in Ethiopia is geographically quite diverse, due to its equatorial positioning and varied topography. Three general temperature zones are apparent–cool, temperate, and hot–categorized predominantly by elevation. The cool zone incorporates parts of the north-western plateau, at elevations above 2,400 meters; the temperate zone lies between 1,500 and 2,400 meters, and supports most of the population. The hot zone, at elevations below 1,500 meters, constitutes much of the eastern and southern portions of the country, as well as the tropical valleys in the west and north.

Methodology

The non-hydrostatic version of the MM5 modeling system developed at Penn State University/ National Centre for Atmospheric Research (PSU/NCAR) has been used for this study. It is a limited area, non-hydrostatic model with vertical levels as the terrain following sigma co-ordinate. It has been designed to simulate both meso-scale and regional-scale atmospheric circulations. Simulations of Regional phenomena or processes that affect precipitation in the Ethiopian highlands are performed using MM5 model with three domains (Figure 2). Simulations are performed using a horizontal grid spacing of 54 km, 18 km, and 6 km for the first, second and third domain respectively and 27 half vertical sigma levels. Initial conditions and boundary conditions are derived from ECMWF reanalysis interpolated on to the MM5 model grid. Simulations are initialized on 26th of July and run for 3 days updated every 1 hour. These days were selected because, higher precipitation were over northwest parts of the country. The boundary and surface–layer processes are represented by the medium Range Forecast (MRF) boundary layer scheme. Convection is parameterized by Betts-Miller and moisture by mixed phase schemes. In Table 1 is a short description the configuration of MM5 used for this study.

Data for validation of the MM5 model were obtained from National Meteorological Agency (NMA) of Ethiopia for daily precipitation. In addition to precipitation data, three hourly temperature data have been also obtained from National Climatic Data Centre (NCDN), USA. MM5 model has been integrated in one way nested with a resolution 54 km by 54 km for the outer domain, in two way nested with a resolution of 18 km by 18 km and 6 km by 6 k for the second and third domain respectively.

Results and Discussions

Model validation

The validation of the MM5 model output had performed for two variables; temperature and precipitation against ground observation data collected at Gondor Station found at the centre domain. Figure 3 reveals the time series of the three hourly temperature data. It depicts that the model slightly underestimated temperature in most of the time. Figure 4 shows the bar graph of precipitation data from both model output and ground observation data in the same station. The result reveals that in this case, the model overestimated precipitation in the station. The overestimation could be the sensitivity of the complex terrain or topography of the region.

Sensitivity analysis

The atmospheric flow modeled by MM5 can be strongly dependent on the settings of physical parameterizations and initial or boundary conditions. To investigate the sensitivity of MM5, we have changed the boundary conditions, specifically topography and re-run model with the new conditions. Then we have compared the results of the

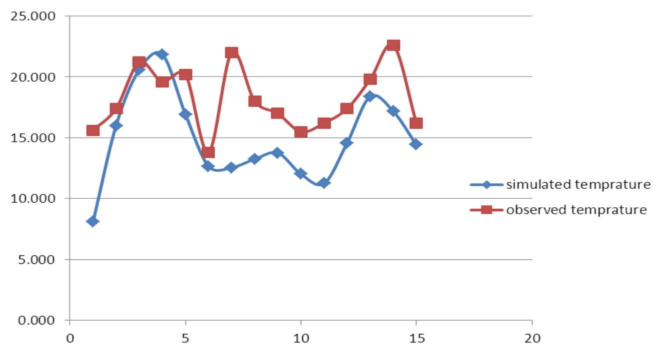


Figure 3: Time series of the three hourly model simulated and observation temperature °C data at Gondor station.

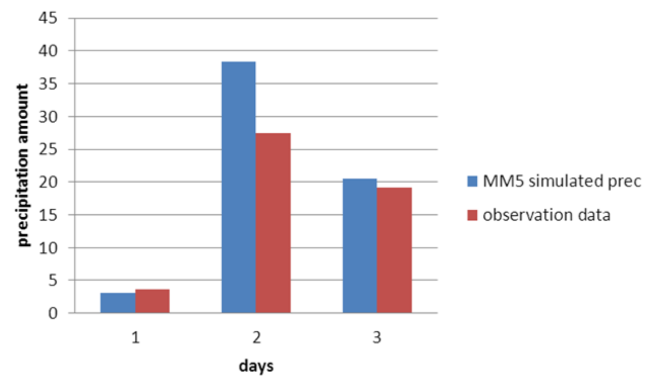
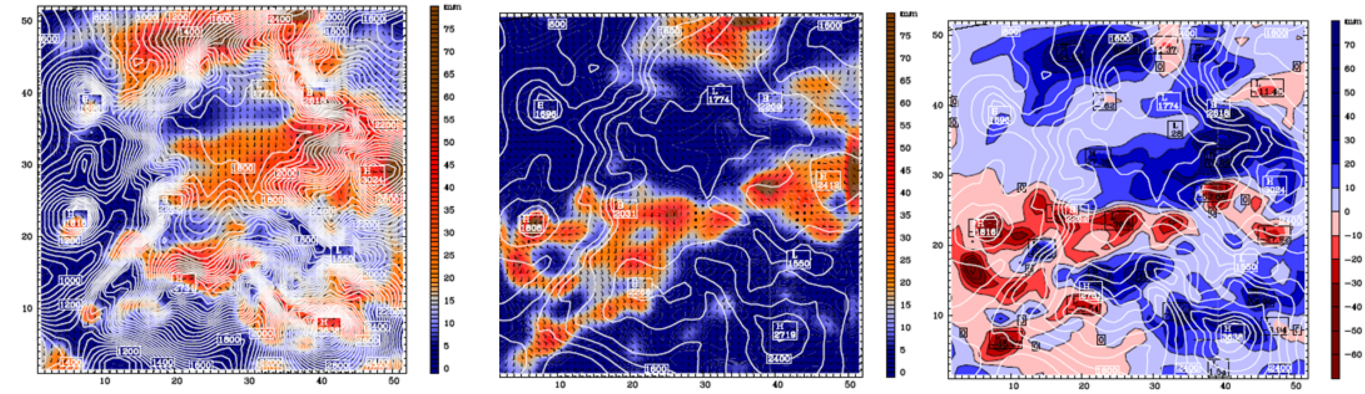


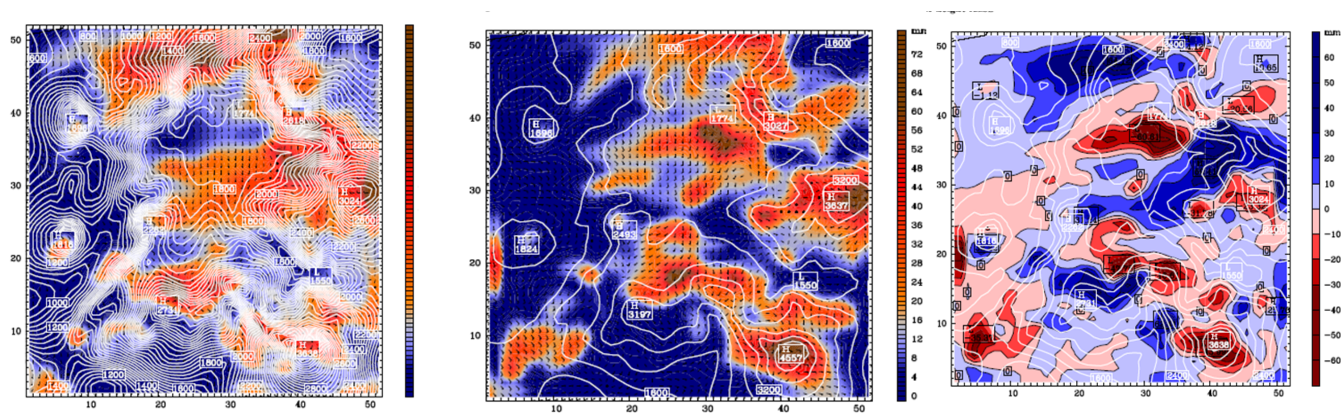
Figure 4: Comparison of MM5 simulated and observation precipitation (mm).

Citation: Enyew BD, Steeneveld GJ (2014) Analysing the Impact of Topography on Precipitation and Flooding on the Ethiopian Highlands. J Geol Geosci 3: 173. doi: 10.4172/2329-6755.1000173



a) for control run b) after terrain is lowered by 50% c)

Figure 5: The spatial distribution of precipitation on 27th of July, 2006 for the inner domain; (a) , (b), and c) the difference between run (a) and (b).

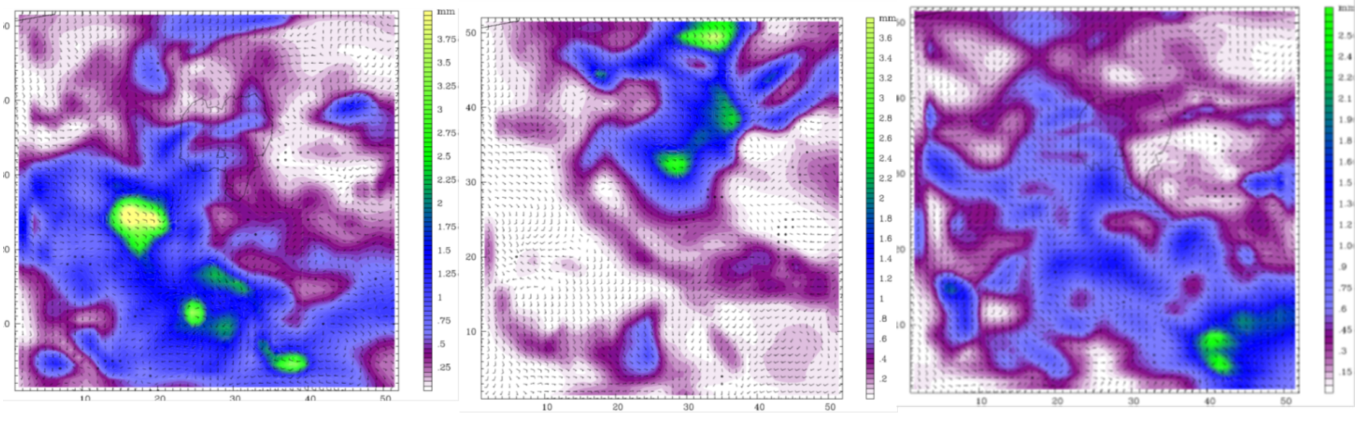


a) for control run b) after terrain is lowered by 50% c)

Figure 6: The spatial distribution of precipitation on 27th of July, 2006 for the inner domain; (a) for control run , (b) after terrain is raised by 50%, and c) the difference between run (a) and (b).

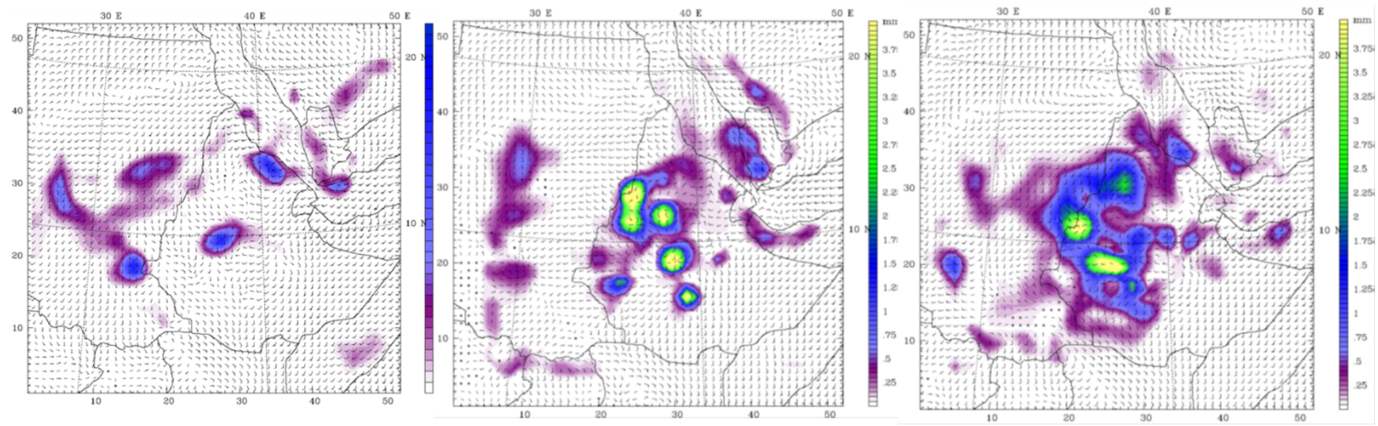
new runs with the control simulation. We have discussed the results mainly for the inner domain-3 (6 km resolution) for rainfall, and outer domain-1 for regional cloud cover and wind vectors. Topography leads to a diverse range of modifications to the large (or macro-scale) wind patterns of the Earth's atmosphere. These modifications, in the form of topographically-induced mesoscale circulations, can modify cloud and precipitation-producing micro-scale processes. Figure 5 reveals the spatial pattern of precipitation on 27th of July, 2006 for the control run, after terrain is reduced by 50% and the difference between runs respectively. There is a clear reduction in the amount of precipitation in the areas where they have already high precipitation in the control run. For instance in Figure 5a, areas in the northern, central and eastern part of the region get considerably higher precipitation amount and the areas in the west, and south western parts get only small amount of precipitation or no precipitation. The blue shaded areas in Figure 5c show a reduction in the amount of precipitation in most parts of the region and there is an increase in the south west section of the region. This shifting in the precipitation pattern could be because, we have made a change in terrain height for those grids whose topographic height is less than or equal to 1800 m, this could change the regional wind patterns and atmospheric circulations which in turn could result a change in precipitation amount or pattern. The net effect of the topography is to redistribute and modify the amount of precipitation that would have occurred in the absence of topography and, in some cases, to cause rainfall which would otherwise not have occurred at all. This is witnessed when, after terrain is reduced by 50% (Figure 5b), the precipitation pattern also has changed or shifted to South western parts of the region. Figure 6, shows the spatial distribution of precipitation for control run, after terrain is raised by 50% and the difference between these runs. Unlike the results in the case of lowering terrain, there is no clear pattern of reduction or increase in the amount of precipitation in this case. The blue shades in Figure 6c, shows areas with a decrease in the amount precipitation and red shades shows areas with an increase in the amount of precipitation. The reduction in amount of precipitation in some of the areas could be, the topography heights in their adjust areas are high enough to disrupt the regional wind pattern and atmospheric circulations, which in turn induces a micro-scale wind patterns in the peaks, as air rises, it also cools and the water vapor is then forced to condense, depositing rain on windward slopes. Figure 7, shows spatial patterns of the amount of column-integrated cloud hydrometeor and wind vector for control run, after terrain is reduced and after terrain is raised by 50% respectively. The cloud covered has

Citation: Enyew BD, Steeneveld GJ (2014) Analysing the Impact of Topography on Precipitation and Flooding on the Ethiopian Highlands. J Geol Geosci 3: 173. doi: 10.4172/2329-6755.1000173



a) b) c)

Figure 7: The amount of column-integrated cloud hydrometeors and wind vector on 27th, July 2006 for the inner domain; (a) for the control run, (b) after terrain is reduced by 50% , (c) after terrain increased by 50%.



a) b) c)

Figure 8: The amount of column-integrated cloud hydrometeors and wind vector on 26th, July 2006 for the outer domain and control run; (a) for 3 UTC, (b) 15 UTC and (c) 23 UTC.

been reduced significantly when the terrain is reduced (Figure 7b), and there is also a shift in the spatial pattern of cloud cover from south and west portion of the region to the small northern portion of the region. Therefore topography also plays role for cumulus generation and has a strong effect on the heat and water vapor exchange [13]. Comparing and contrasting the control run (Figure 7a) and the run after terrain is raised (Figure 7c) depicts a decrease in the amount of cloud cover in contradiction to expected increase in cloud cover due to the heating effect of high topographic height which could enhance convection. There is also a shift in the position of the maximum cloud cover to the far south east parts of the region. Unlike the case of the reduced terrain run (Figure 7b), there is no clear pattern of how increase in terrain could affect cloud cover and also precipitation.

Impact of regional weather systems

Generally speaking the amount of rain fall over the mountainous areas in western and north-west parts of Ethiopia is higher than the low lands in the eastern and south eastern parts of the country. Topography is a major trigger for rainfall, through orographic lifting or more generally convective development initiated by the heating of the plateaus [9]. In addition to topographic effect of rainfall on the highlands Ethiopia there are some regional weather systems influencing precipitation on the region. Among the systems that control the weather activity in the region are: Inter-tropical Convergence Zone (ITCZ), Tropical Easterly Jet (TEJ), East African Low Level Jet (EALLJ), El Niño-Southern Oscillation (ENSO) as well as Mascarene, St. Helena, Azores and Arabian High pressure systems [11]. Figure 8, reveals the time evolution of the amount of column–integrated cloud hydrometeors and wind vector 3 UTC, 15UTC, 23UTC on the 26th, of July 2006 for the outer domain and control run. There is an intensification of cloud cover over time due to the influx of moisture from the west and south west.

The main rains of Ethiopia are said to be rely on moisture advection from the south-westerly monsoon. Moisture influx from the Arabian and red sea regions play a significant role on the intensification of the cloud cover over the highlands, as among weather systems that control the region are the Arabian high [14].

Conclusion and Recommendations

In this paper MM5 is employed to analyze the impact of topography and regional weather systems on flooding in the Ethiopian highlands. It has been found that the northern, south western and the central highlands of the country has showed large amount of precipitation and cloud cover in comparison to the lowland parts of the country in the east and south east. To investigate the sensitivity of MM5, we have changed the boundary conditions, specifically topography and re-run model with the new conditions. The results have shown the precipitation pattern and amount simulated by MM5 has shown a substantial change when topography is also changed. The spatial precipitation pattern have shown a clear reduction and shift when terrain is reduced but no clear pattern have been observed in precipitation when terrain in increased by 50%. Generally the results have shown that topographic barriers such as mountains play an important role in the pattern and amount of precipitation in the region. This study has only attempted to analyze the effect of topography and regional atmospheric circulations on precipitation in the Ethiopian highlands. To get a better picture of the effect regional atmospheric circulations or weather systems, the domains should be as wide as possible to include the South east Atlantic ocean and South west Indian ocean, the high pressure systems over this ocean plays a vital role on precipitation in the region. There are no hourly quality data available for validation of the model output. The results for the study could have been better if there had been data available for validation. MM5 couldn't reproduce observation data for precipitation very well at station level. There should be further efforts to improve simulation of precipitation.

Acknowledgement

The authors thank feedback from prof. Bert Holtslag, and Marina Sterk MSc. Moreover we acknowledge ECMWF for providing the operational analysis data used in this study.

References

1. Meehl GA (1992) Effect of Tropical Topography on Global Climate. Annu Rev Earth Planet Sci 20: 85-112.
2. Griffiths J (1972) Ethiopian Highlands. World Survey of Climatology, Landsberg H (ed) Climates of Africa 10 Elsevier: Amsterdam 369-388.
3. Gamachu D (1977) Aspects of climate and water budget in Ethiopia. Addis Ababa, University Press: Addis Ababa.
4. NMSA (1996) Climatic and agroclimatic resources of Ethiopia. National Meteorological Services Agency of Ethiopia, Meteorological Research Report Series 1: 1-137.
5. Seleshi Y, Zanke U (2004) Recent Changes in Rainfall and Rain days in Ethiopia. Int J Clim 24: 973-983.
6. Bekele F (1997) Ethiopian use of ENSO information in its seasonal forecasts.
7. Block P, Balaji R (2008) Interannual Variability and Ensembles Forcast of Upper Blue Nile Basin Kiremt Season Precipitation. American Meteorological Society.
8. Haile T (1987) A case study of seasonal forecasts in Ethiopia. In: WMO RAI (Africa) Seminar on Modern Weather Forecasting (Part II), 30 November-4 December 1987, Addis Ababa, Ethiopia 53-83.
9. Hastenrath S (1991) Climate Dynamics of the Tropics. Kluwer Academic Publishers 488.
10. Camberlin P (1996) Rainfall Anomalies in the Source Region of the Nile and Their Connection with the Indian Summer Monsoon. AMS Journal Online.
11. Jury MR (2010) Meteorological scenario of Ethiopian floods in 2006–2007. Theory Applied Climatology 104: 209-219.
12. Cheung WH, Senay GB, Singh A (2008) Trends and spatial distribution of annual and seasonal rainfall in Ethiopia. Int. J. Climatol. 28: 1723-1734.
13. Nishikawa M, Hiyama T, Tsuboki K, Fukushima Y (2009) Numerical Simulations of Local Circulation and Cumulus Generation over the Loess Plateau, China. Journal of Applied Meteorology and Climatology 48: 849-862.
14. Gebru JE (2007) Changes in the frequency and intensity of extremes over Northeast Africa. Scientific report; WR 2007-02.