

Environmental Simulator Application to the Analysis of the Tropical Cyclone Gonu in 2007

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Abstract

Asia Environment Simulator (AES) is a coupled system of computer simulation for meteorology, physical oceanography, land surface, vegetation, hydrology, coastal dynamics, and urban environment. The atmosphere, land surface, and hydrology models of AES have been applied to the analysis of the cyclone Gonu that had a landfall in Oman in June 2007. Gonu considered the strongest tropical cyclone ever recorded in the northern Indian Ocean, and the first fifth-category cyclone to enter the Arabian Sea. AES is applied to study the hydroclimatological features followed the landfall of the Cyclone Gonu in Oman. The significant discrepancy between the rainfall records at the ground rainfall gauges in Oman and the remote sensing estimates is clarified by using AES in simulating the cyclone Gonu hydroclimatological characteristics. Direct and indirect assessment methods show that the cumulative simulated rainfall depth is relevant to those estimated by satellites, whereas there is a considerable difference with the records at the ground rain gauges. By performing hydrological simulation of Wadi Hayafdh in Oman, it is found that the computed peak discharge and the runoff volume based on the ground rain gauges records are significantly higher than the corresponding observed peak discharge and runoff volume at the watershed outlet. Whereas, the computed peak discharge and the runoff volume based on computed rainfall depth are representing the observed values with high accuracy. Results from AES recommend instant assessment and evaluation of the ground rain gauges network such that it can be used safely in various future developing projects in the Omani area.

1. Introduction

The entire Asian region is characterized by monsoons that are stretching from Japan in the east to the Arabian Peninsula in the west and Indonesia region in near equatorial to Tibetan & Mongolian region in the north. Asian region is impacted by a variety of hydrometeorological disasters like monsoon heavy rainfall, urban and riverine floods, droughts, landslides, avalanches, tropical storms land fall and storm surges. Asian economics and societies are strongly affected by the above hydrometeorological disasters and suffer great losses. This article is about one of those hydrometeorological disasters that struck the Asian countries causing many losses and casualties (Tropical Cyclone Gonu in 2007). Mobery (2001) introduced the idea of 'monsoon tropical cyclones' in the Arabian Sea-cyclones that form preferentially during the four-week period from mid-May to mid-June as a response to changes imposed on the region by the developing Asian monsoon. Cyclones affect both the Bay of Bengal and rarely affect the Arabian Sea. Cyclones do not form in Arabian Sea during the months of January, February and March and are rare in April, July, August and September. They generally form in the southeast Arabian Sea and adjoining central Arabian Sea in the months of May, October, November and December and in east central Arabian Sea in the month of June. Most of the storms in Arabian Sea move in westerly direction towards Arabian coast in the month of May and in a northerly direction towards Gujarat coast, India, in the month of June. In other months, they generally move northwest north and then recurve northeast affecting Gujarat-Maharashtra coasts; a few, however, also move west north westwards towards Arabian coast.

In June 2007, cyclone Gonu, also known as Super Cyclonic Storm Gonu was an unusual strong tropical cyclone that showed up in an unusual place for hurricanes and cyclones. Cyclone Gonu developed in the eastern part of the Arabian Sea in June 1 in 2007. The cyclone passed very close to Oman in June 6 with maximum sustained winds near 148 km/hr. It was approaching the northeastern shore of Oman, a region better known for hot desert conditions. Cyclone Gonu is the strongest tropical cyclone on record in the Arabian Sea, and ties for the strongest tropical cyclone on record in the northern Indian Ocean. Cyclones seldom make landfall in Oman or reach the Gulf of Oman due to the surrounding environmental factors, and there are very few historical parallels to Gonu. Despite the very warm sea surface temperatures, this region is characterized by very low humidity and dry descending air that inhibits deep convection required to sustain tropical cyclones. As the risk of tropical cyclones is perceived to be very low in the Middle East, onshore facilities are generally not constructed to withstand the associated strong winds, heavy rains and storm surges. As a result, Oman sustained widespread floods and wind damages from Gonu. Fortunately, Oman's oil industry was spared, with minimal damage and disruption. According to the Oman News Agency, the cyclone killed 49 people in the country, around 20,000 people were affected, and damage was estimated in the billions of USD. In Iran, throughout the country, the cyclone caused 23 deaths, including 20 from drowning; damage in Iran was estimated at 216 million USD.

Despite of the rareness and the vast damage resulted by Gonu, this event was not documented or considered for analysis among hydrometeorologists. The significant discrepancies between the recorded rainfall intensities at the ground rain gauges in Oman and satellite remote sensing estimates of rainfall have started an argument about the accuracy of ground rain gauges network records under severe storm conditions and has raised questions about the safety of the ongoing large-scale development plans in the Arabian peninsula countries, and mainly the safety of the hydraulic structures such as dams and do we need to be more conservative in our design. The problem of wind effect on rain gauge measurements has been recognized and investigated for many years (e.g. Biswas 1967; Warnick 1953). Methods to evaluate this include field measurements (e.g. Strangeways 2004; Duchon and Essenberg 2001; Yang et al. 1998), wind tunnel experiments (Folland 1988), and numerical approaches (e.g. Habib and Krajewski 2001; Nešpor and Sevruk 1999; Folland 1988). Field measurements have several drawbacks, as they

require both a considerable budget and time, while numerical approaches based methods seem to be the most economical way to estimate the accuracy of rainfall measuring devices.

This paper describes the development and application of Asia Environment Simulator (AES)—a dynamically coupled atmosphere, land surface hydrology model (Haggag et al. 2008; Haggag 2007; Yamashita et al. 2007)—to the analysis of hydrological features resulted from cyclone Gonu. The models incorporated in AES are the fifth generation mesoscale non-hydrostatic atmosphere model (MM5) (Grell et al. 1996), and the new multi-layer atmosphere vegetation soil model (SOLVEG) (Nagai 2002, 2003, 2005), and the Hydrological Simulation Program-FORTRAN (HSPF) (Bicknell et al. 1997). The coupling of the models has been originally carried out to study the atmosphere land surface interaction processes. The main objective of the study is to judge the accuracy of ground rain gauge records in Oman after the passage of cyclone Gonu. AES computations, remote sensing data, and recorded data at surface weather station are used altogether to analyze Gonu event. The paper is organized as follows: section 2 briefly describes the characteristics of the AES models and the coupling scheme. In section 3, a description of the case study and the different types of datasets are presented. The results of the test case compared with available observations are shown in section 4. Finally, section 5 concludes and summarizes the contents of the paper.

2. Methods

This study uses the atmosphere, land surface and hydrology models of the AES of which framework is explained by Haggag et al. (2008), Haggag (2007) and Yamashita (2007), Fig. 1-a. A brief description of each of the models is given below.

2.1. Overview of models

MM5 (Grell 1996) is a regional, non-hydrostatic model designed to simulate or predict mesoscale and regional-scale weather. The MM5 uses a terrain-following, or sigma-pressure, vertical coordinate. The MM5 uses an efficient split/semi-implicit temporal integration scheme and has a nested-grid capability. Reanalysis data from the Global Final (FNL) analyses on 1.0x1.0 degree grids covering the entire globe every six hours are used for the initial and lateral boundary conditions on the outermost grid mesh. These data are operationally prepared by the National Center for Environmental Prediction (NCEP). The analyses are available on the surface, 26 mandatory levels from 1000 mb to 10 mb. Parameters include surface pressure, sea level pressure, geopotential height, air temperature, sea surface temperature, soil values, ice cover, relative humidity, u-winds and v-winds, vertical motion, vorticity and ozone. Land surface processes in MM5 model has been represented by several Land Surface Models (LSM) among them the simple LSM (Blackadar, 1976) and the NOAA LSM (Chen and Dudhia 2001a, b). Because of the extensive prior validation of the MM5, we use it directly to provide the best available representation of the atmosphere and have not made modifications to the MM5 other than those associated with the flux transfer calls through the developed model coupler.

SOLVEG is developed at the Japan Atomic Energy Research Institute. It is a multilayered model, therefore, it can aid in clarifying the heat and water exchanges in each layer of the atmosphere-soil-vegetation system. The model considers interactions between the CO₂ exchange and the heat/moisture exchanges by the stomatal resistance scheme based on photosynthesis. Nagai (2002, 2003, 2005) have tested the performance of SOLVEG using observed data in the Cooperative Atmosphere–Surface Exchange Study (LeMone et al., 2000). A comparison with Oregon State University LSM (Chen et al., 1996) and the National Center for Atmospheric Research LSM (Bonan, 1995) was also made (Chen et al., 2003; Yates et al., 2003), and the performance of SOLVEG was

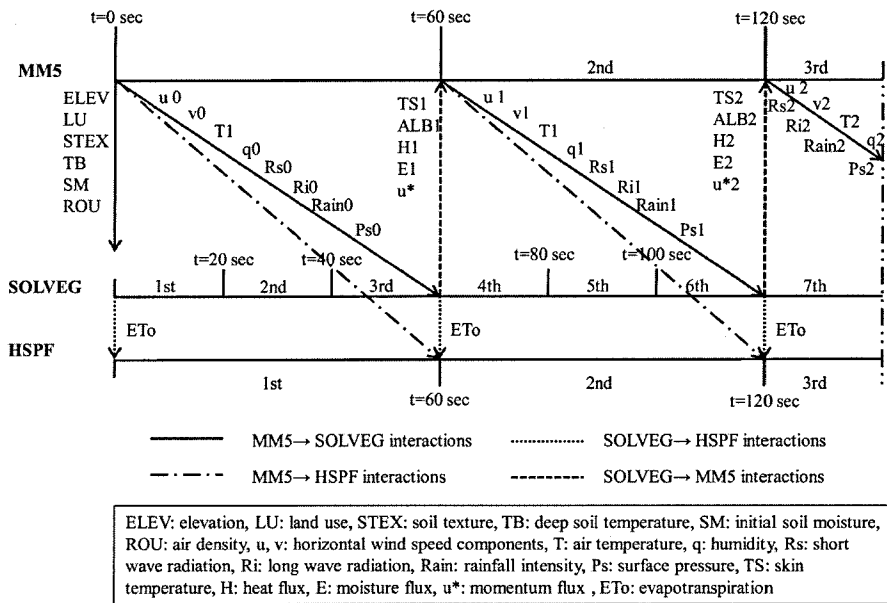
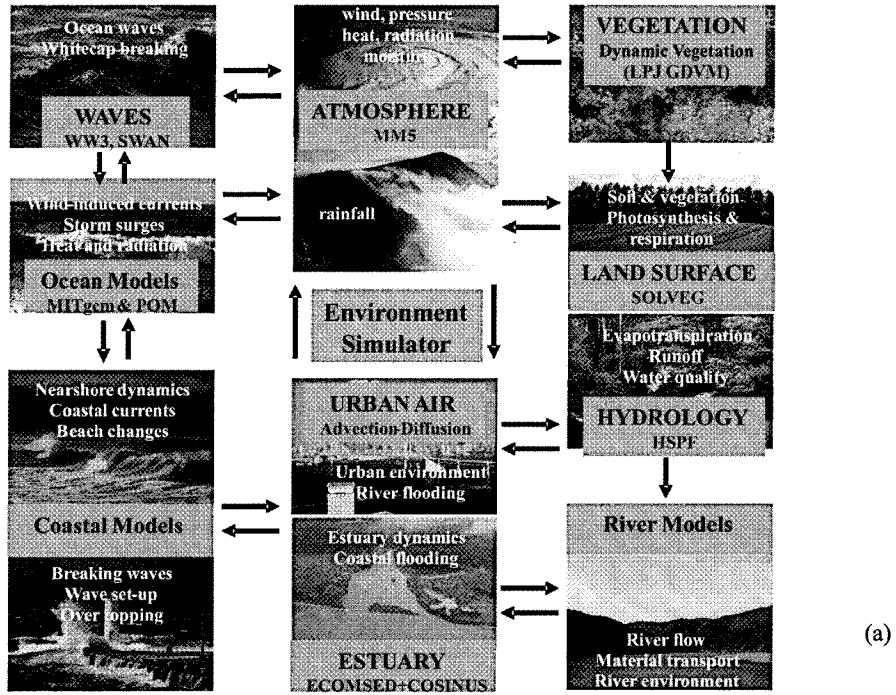


Figure 1: (a) AES model structure, (b) coupling method and data exchange in the coupled atmosphere-land surface-hydrology model for mesoscale water and heat circulation.

comparable to those of the other models.

HSPF is a U.S. EPA model for simulation of watershed hydrology (Bicknell et al., 1997). The hydrological processes of HSPF are constructed on the basis of algorithms of the Stanford Watershed Model IV (Crawford and Linsley 1966). The soil is vertically divided into three storage zones (the upper-zone, the lower-zone, and the active groundwater zone) in each land segment, which is developed by dividing the watershed into homogeneous hydrological land segments. Each flux of runoff water and the volume of evapotranspiration are calculated from the moisture condition in each zone. Three types of runoff components (surface runoff, interflow runoff, and active groundwater runoff) are considered in the hydrologic processes. Flow components from each land segment along a given stream reach and physical data on the stream reach are then used to route flows through the basin. HSPF simulates hydraulic processes that occur in a single reach of stream based on the one-dimensional kinematic wave theory.

2.2. Coupling method and models interaction

Calculations of the three models (MM5, SOLVEG and HSPF) are carried out as independent tasks at different processors and a model coupling program (coupler) controls these processes and data exchanges between the models using Message Passing Interface (MPI). All models and the coupler start together, and the coupler invokes and controls calculation processes. It receives 2D data from one model and distributes them to the other models in arbitrary time intervals. Figure 1-b shows the data exchange between the MM5-SOLVEG-HSPF coupled system. At the first time step, MM5 sends the initialization parameters and variables to SOLVEG: elevation (ELEV), land use (LU), soil texture (STEX), soil bottom temperature (TB), initial soil moisture (SM), initial air density (ROU), air pressure (P_s), radiation (solar: R_s , long-wave: R_l), precipitation (Rain), wind speed (u , v), temperature (T), humidity (q). SOLVEG calculation proceeds for the same time interval as MM5 and sends its results to MM5: skin temperature (T_s), albedo, momentum flux (u^*), heat flux (H), and vapor flux (E). MM5 receives these values in the next time step and uses them as the surface boundary condition in the Planetary Boundary Layer (PBL) processes. HSPF receive the necessary meteorological parameters from MM5 and evapotranspiration (ET_0) from SOLVEG without further feedback from HSPF neither to MM5 nor to SOLVEG. The time step of SOLVEG calculation is usually smaller than that of MM5 and HSPF, and several time steps are carried out for SOLVEG calculation during a single time step of MM5 or HSPF calculation. For following time steps, this process of data exchange repeats between the models through the coupler for complete consideration of the interaction between the land surface and the atmosphere.

3. Materials

3.1. Case Study: Cyclone Gonu

In June 2007, the Middle East was taken by surprise by a rare tropical cyclone that skirted the coast of Oman and made landfall in Iran. Gonu formed in the Arabian Sea and travelled northwest towards Oman, intensifying as it tracked across the open waters. Gonu is the strongest tropical cyclone in the Arabian Sea. It weakened as it approached the Arabian Peninsula, and then declined over the Gulf of Oman to tropical storm status before making landfall in Iran. Figure 2 shows the Gonu's track based on advisories from Joint Tropical Weather Center (JTWC). Tropical cyclones usually form in the Bay of Bengal, to the east of India. Those that form to the west of India, in the Arabian Sea, tend to remain small systems with a limited lifespan, so they very rarely become as large and powerful as the cyclone Gonu.

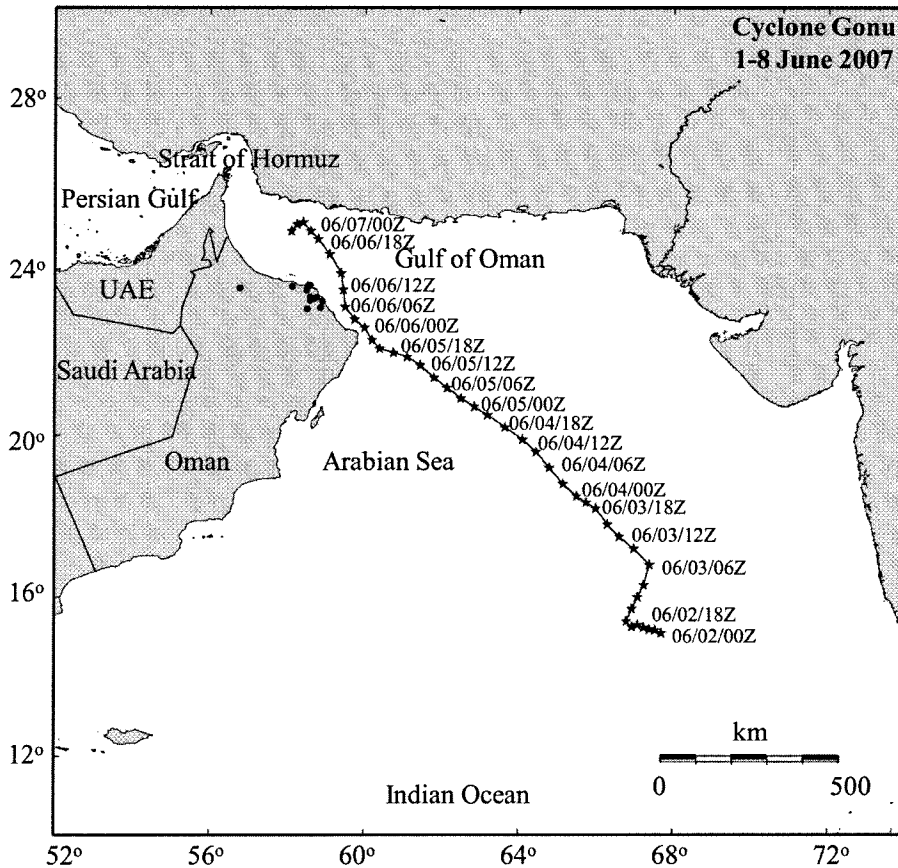


Figure 2: The computation domain showing the track of Cyclone Gonu (black star with lines) and the location of the available ground rain gauges (black dots) in the East of Oman.

3.2. Data sources

Six different types of datasets employed in this study; meteorological reanalysis data, Sea Surface Temperature (SST) data, ocean surface wind (QSCAT) data, Tropical Rainfall Measuring Mission (TRMM) data, surface gauges data, and Shuttle Radar Topography Mission (SRTM) data. MM5 initialized and laterally bounded using the large-scale analysis data from the National Center for Environmental Prediction (NCEP) at the National Center for Atmospheric Research (NCAR) of the U.S. The reanalysis data archived at NCAR exists every 6 hours at a spatial resolution of $1^\circ \times 1^\circ$ at 21 standard pressure levels below 100hPa. SST is a dominant factor in controlling the evaporation, moisture and precipitation distribution. SST data is available from RTG_SST analysis ($0.5^\circ \times 0.5^\circ$) (Thiebaut et al. 2003) provided by the U.S. National Oceanic and Atmospheric Administration (NOAA). A daily real-time global SST data has been implemented in the modeling system to provide the daily ocean SST for the MM5 model. The Microwave Scatterometer Sea Winds (QSCAT) launched on the QuickBird satellite in June 1999. The primary mission of this sea winds scatterometer is to measure winds near the ocean surface. Sea winds scatterometers are essentially radars that transmit microwave pulses down to the earth's surface and then measure the power that is scattered back to the instrument. The QSCAT during the lifetime of cyclone Gonu distributed over

the entire Arabian Sea. QSCAT works as an independent dataset useful in validating the simulation results. TRMM is the first space-borne satellite precipitation radar designed to provide 3D-maps of storm structure. TRMM provides systematic, multi-layer measurements of rainfall in the tropics as key inputs to weather and climate research. TRMM covers almost the whole globe and its estimates provided on a global $0.25^{\circ} \times 0.25^{\circ}$ grid over the latitude band 50°S to 50°N . Since the number of the available ground rain gauges is limited and the gauges are sparse with large distances in between, the use of other sources of rainfall data renders to be important. TRMM data from 1 to 8 June in 2007 used as an additional rainfall dataset to help in the accuracy assessment of the simulated and observed rainfall intensities.

Oman covered with more than 4,000 monitoring stations for climate, rainfall, watershed flow, sediments, groundwater levels and groundwater quality that comply broadly with World Meteorological Organization Standards (Al-barwani and Al-khatri 2005). Table 1 presents a list of the available ground rain gauge stations with their recorded cumulative rainfall depth received during Cyclone Gonu. Outflow observations from several watersheds in Oman are also included in the analysis; these stations provide peak discharges and the daily runoff volume for severe meteorological event that took place at their locations. The SRTM obtained elevation data on a near-global scale to generate the most complete high-resolution (90m) digital topographic database of earth (Farr et al 2007). The SRTM data used for the automatic delineation of the watershed selected in this study.

3.3. Model configuration

The area that severely affected by the cyclone Gonu is located in the eastern part of Oman including its capital city of Masqat. The geographical location of the simulation domain is shown in Figure 2. The total area of the domain is $4.05 \times 10^5 \text{ km}^2$ with a grid spacing of 18 km that was selected to cover the whole Arabian Sea. In Oman, the eastern part is the mostly affected part by the cyclone; this area is characterized by its large extended mountain ranges with steep slopes toward the Gulf of Oman with barren land, mainly desert, is the dominant land use category in the area. The numerical experiments performed using 23 vertical levels (with the model top at 100hpa). Data from the NCAR used for experiments initialization and provided with 6-hourly boundary conditions

Table 1: List of Available ground rainfall gauges data in Eastern Oman during the lifetime of Cyclone Gonu.

St. Name	Longitude	Latitude	Total rainfall (mm)
AI KHOUDH	58.121	23.578	118.8
AMRAT	58.500	23.488	438.4
BUEI NEAR BUEI	58.590	23.253	384.6
FUWAD 2 AT FUWAD	58.581	23.340	374.8
HAYFADH AT HAYFADH	58.741	23.326	625.6
JABAL ABYADH	56.780	23.550	687.6
JABAL ASFER	58.516	23.050	938.0
MAZARA 3 AT MAZARA	58.856	23.091	363.8
MUSCAT NEAR MUSCAT	58.591	23.612	139.8
QURAYAT NEAR QURAYAT	58.903	23.232	232.2
RUWI AT MWR	58.539	23.598	224.4
TABA AT TABA	58.672	23.295	519.0
YITI	58.665	23.526	289.2

on the simulation domain. The model physics in all runs reported here are the Reisner graupel mixed phase explicit moisture scheme (Reisner et al. 1998), the Grell cumulus parameterization scheme (Grell et al. 1996), the cloud radiation scheme, and among various PBL schemes available in MM5, we choose MRF's PBL scheme (Hong and Pan 1996). We selected the above options from the various other physics options in MM5 because they are used in several operational MM5 applications. Soil parameters used in SOLVEG are the saturated volumetric soil water content, the saturated hydraulic conductivity, the exponent in the Clapp and Hornberger equations (Clab and Hornberger 1978), the wilting volumetric soil water content, and the dry soil heat capacity. Vegetation leaf surface properties and vegetation structure are given values from global survey of leaf area index of land use classes (Asner et al. 2003).

4. Results and Discussion

4.1. Storm development

An organized tropical disturbance developed over the southeastern Arabian Sea, with cyclonic convection and a well-defined mid-level circulation in May 31 in 2007 (JTWC, 2007). By late in June 1, the system developed to the extent that the India Meteorological Department (IMD) classified it as a depression (IMD, 2007).

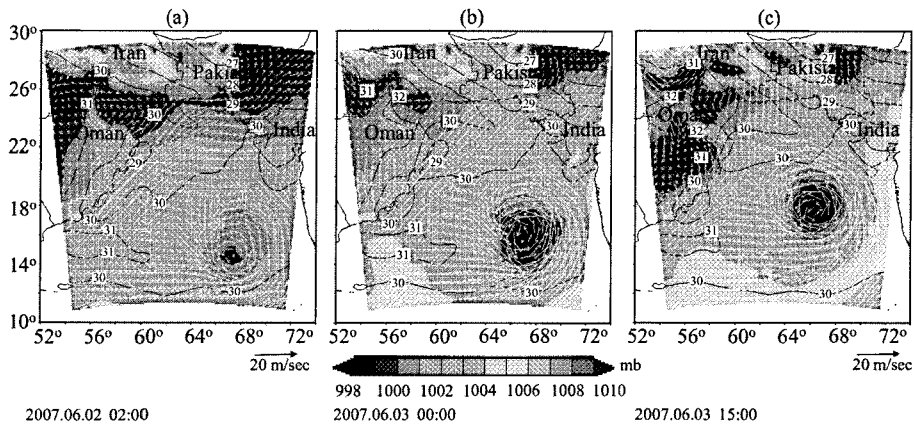


Figure 3. Wind vectors (m/sec), sea surface temperature contours ($^{\circ}\text{C}$) and shaded sea level pressure (hPa) at the surface level for cyclone Gonu at several times.

Figure 2 shows the storm track based on advisories from JTWC. Figures 2 and 3 show the early stages of the storm, it tracked westward along the south-western periphery of a mid-level ridge over southern India. As a mid-latitude trough developed over Pakistan, the track of Gonu turned to the north and northeast, Fig. 3-b, though resumed a westward track after ridging built to the north of the storm and several trough developed over Iran and Oman to the north-west of the storm, Fig.3-c. Gonu rapidly deepened and developed a well-defined eye in the center of convection. Late in June 3, the IMD classified the storm as Very Severe Cyclonic Storm Gonu, upon which it became the most intense cyclone on record in the Arabian Sea.

The QSCAT during the lifetime of cyclone Gonu distributed over the entire Arabian Sea, but it is only one level wind almost at 10m heights. QSCAT data is helpful in getting a reliable independent view of Gonu's development stages compared with simulation results. Figure 4 shows the QSCAT wind vectors, from June 2-7 in 2007, representing the ascending and descending paths of the satellite covering the entire vortex area. The figure

shows the size of Gonu and its associated wind field. A cyclonic circulation around the centre of Gonu is apparent. According to the JTWC, the maximum wind speed observed in June 4 in the afternoon, then after encountering dry air and cooler waters, the degree of severity decreased. The closest point of Gonu to Omani coasts occurred at the evening of June 5 and at the early morning of June 6. According to the QSCAT, Cyclone Gonu crossed the eastern-most tip of Oman, making it the strongest tropical cyclone to strike the Arabian Peninsula. As Gonu continued tracking north-west over cooler Oman gulf water temperatures and through drier air, it started to dissipate with gradual decrease of wind speed as it interacted with land.

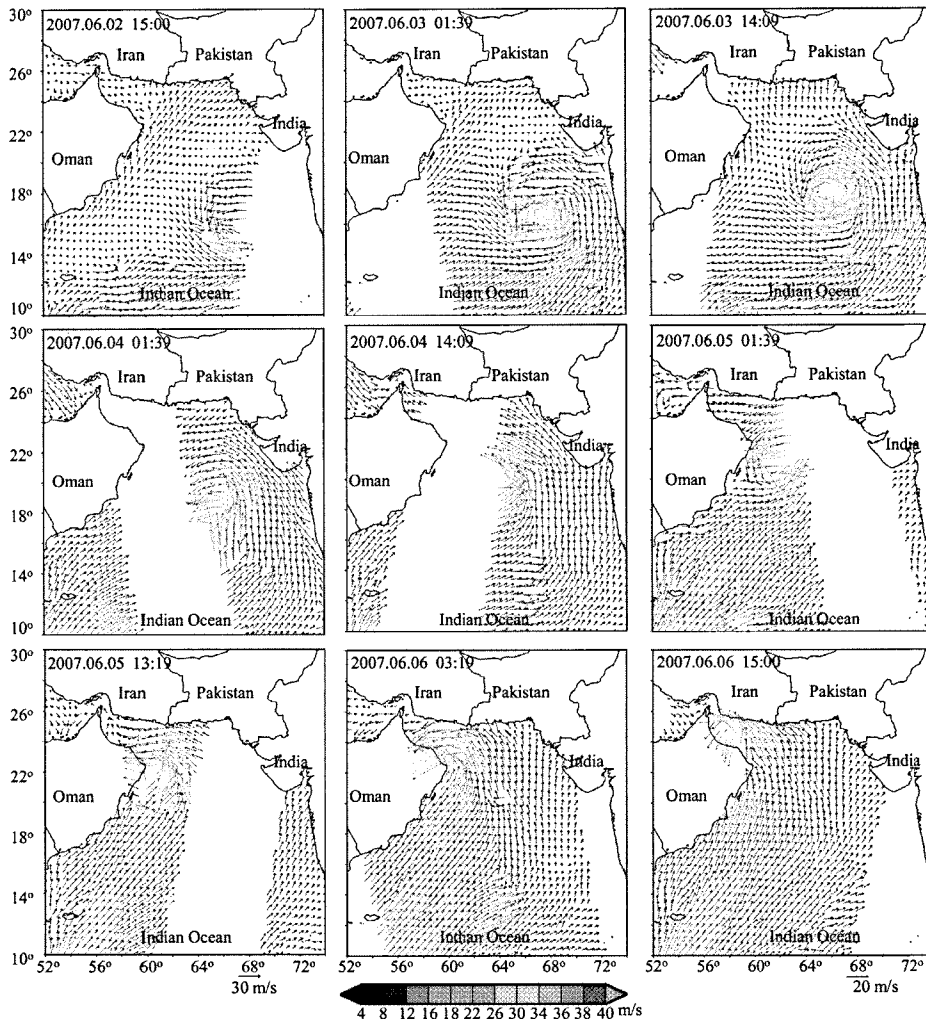


Figure 4: QSCAT wind vectors from 3 to 7 June in 2007 showing the ascending and descending paths of the satellite over the Arabian Sea area.

4.2. Rainfall analysis

Three rainfall datasets are used in the analysis of areal rainfall distribution and rainfall intensity at the surface rain gauges. The datasets are the surface rain gauge records at the station stated in Table 1, TRMM's, and the simulated rainfall intensity. Figure 5 shows a comparison among the simulated cumulative rainfall depth and the TRMM rainfall depths in the period from 1-8 June. Both simulated rainfall and TRMM's shows a similar pattern with respect to areal distribution, although the simulations seem to be higher than the TRMM's along the eye track of Gonu. The maximum cumulative simulated rainfall depth is 450 mm whereas the maximum TRMM cumulative rainfall depth is about 300 mm. Figure 6 focuses in the Omani area; both simulated rainfall and TRMM's cumulative rainfall depths show a comparable areal distribution and intensity pattern. The north-eastern part of Oman is the only area affected by the rainfall of Gonu. This area is characterized by its large extended mountain ranges with steep slopes toward the Gulf of Oman. The mountainous terrain near the coast of Oman and Iran posed an additional hazard to coastal regions. Heavy rain falling on the steep mountains sent torrents of fast-moving floodwater down to the coastal areas. Both datasets shows a maximum cumulative rainfall depth of about 300mm.

It has been found that there are 4 rain gauges among those listed in Table 1 where the recorded maximum total rainfall depth exceeded 400 mm. It is shown that the station at Jabal Asfer recoded a total rainfall depth of 930 mm. Figure 7 shows a comparison among the three types of values for the cumulative rainfall depth (mm) at Hayfadh, Taba, Jabal Asfer, and Jabal Abyadh, respectively, in the period from 1 to 8 June in 2007. There are significant differences among the ground rainfall gauges' recorded rainfall intensities and the corresponding rainfall intensities from TRMM and AES. There is a little variation between the TRMM-based values and the simulated values. The order of the cumulative rainfall is on the range of 200-300mm except for the case of Jabal Abyadh station where the estimated rainfall depth was too small. On the other hand, the recorded cumulative rainfall depth at the ground rain gauges shows strange values that reached 938 mm at Jabal Asfer station. NASA's natural hazard website (<http://earthobservatory.nasa.gov>) presented an updated visualization for the total rainfall corresponding to Gonu (from 1-8 June in 2007) based on a multi-satellite precipitation analysis (not shown), the visualization indicated that the total rainfall depth is of the order of 250 mm which is significantly small compared with

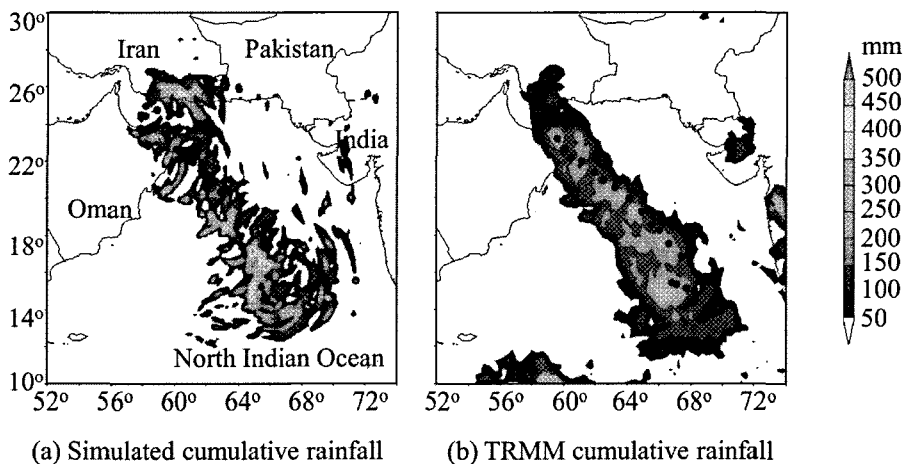


Figure 5: Accumulated rainfall depth (AES and TRMM) from 1 to 8 June in 2007 with the cyclone eye track represented by black dots.

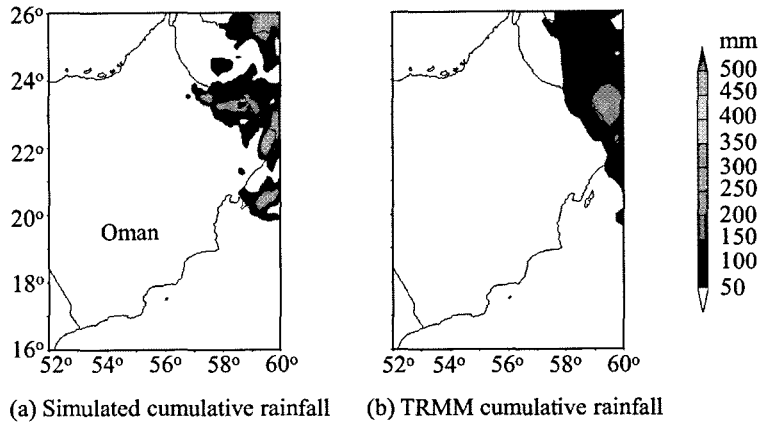


Figure 6: Accumulated rainfall depth (AES and TRMM) from 1 to 8 June in 2007 over Oman during the tropical cyclone Gonu, the black dots show the locations of the available rain gauges in the area.

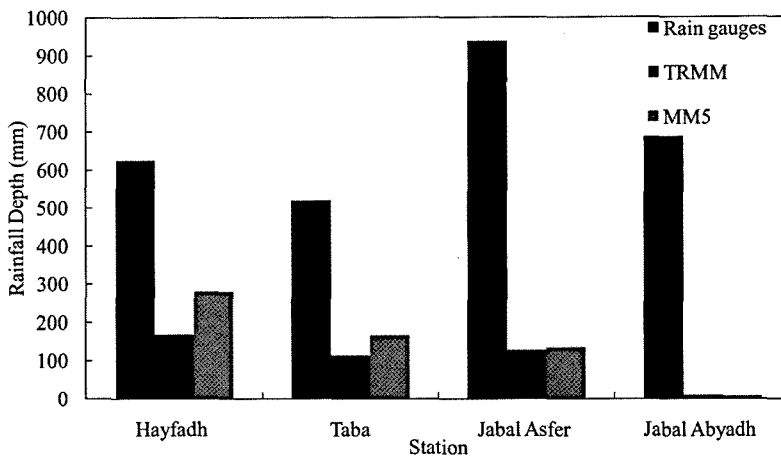


Figure 7: Comparison of cumulative rainfall depths at Hayfadh, Taba, Jabal Asfer, and Jabal Abyadh rain fall stations among the recorded, TRMM, and MM5 computation during the Gonu event.

the recorded surface rain gauge records listed in Table 1. Moreover, NOAA website (<http://www.nnvl.noaa.gov>) presented visualization images (not shown) during Gonu for the rainfall depth using Advanced Microwave Sounding Unit (AMSU) that shows a total rainfall depth over Oman of the order of 300 mm.

It is apparent that there is a significant difference between the ground rain gauges measurements and the corresponding TRMM data and the rainfall simulation results. This raises a question mark about the accuracy of the different rainfall datasets used in the analysis. Before judging which dataset is more accurate to be considered for the planning and design purposes, the following should be mentioned:

- The surface rain gauges measure directly the rainfall rates, whereas the TRMM and the model simulation indirectly estimate the rainfall rate; therefore, it needs calibration that is usually done using a number of trusted surface rain gauges.

- Rain gauges have their limitations. Attempting to collect rain data in a hurricane can be nearly impossible and unreliable (even if the equipment survives) due to wind extremes.
- Data from ground rain gauges are prone to errors from different sources.
- Ground rain gauge stations present point rain data rather than areal rainfall depth that is provided by TRMM and MM5.
- The TRMM and MM5 application proved a large success and capability in capturing the structure of a large number of tropical storms in different places.

Another indirect method to judge the accuracy of the rainfall datasets performed through selecting one of the gauged watersheds in the area and performing the hydrological simulation to estimate the runoff volume and hydrograph. The dataset that results in a comparable runoff volume and peak discharge to the observations will gain extra points toward its accuracy. This procedure is explained in the following section.

4.3. Hydrological simulation in Wadi Hayfadh watershed

Wadi Hayfadh is a small watershed located in the eastern part of Oman. It is 22 km to the west of Wilayat (prefecture) Quriyat. Figure 8 shows the location of Wadi Hayfadh on Omani land use map (USGS 24 categories), the barren land, mainly desert, is the dominant land use category in the area. Wadi Hayfadh drains a 573.8 km² watershed along 58.2 km stream to the Gulf of Oman at Quriyat. Table 2 summarizes the hydrological characteristics of Wadi Hayfadh. The watershed is dry most of the year; normally the annual amount of rainfall over the watershed does not exceed 100 mm yr⁻¹. Four rain gauges are located inside the watershed (Hayfadh, Taba, and Buei, and Fuwad 2). The watershed has no control structures; the only observation record for the watershed runoff is available at the exit of Wadi Hayfadh (58.884°E, 23.262°N). Figure 9 shows the history of the Hayfadh's runoff volume in the period from 1980 to 2007. Figure 9 shows that the Hayfadh watershed was almost dry in the past 26 years until the coming of cyclone Gonu in June 2007. The recorded runoff during June 2007 was 37.5×10⁶ cubic meters which is considered a huge runoff in this dry area. Different datasets are needed for the application of HSPF model (e.g. watershed topography, land use, soil type, field measurements, and meteorological data). To apply HSPF to the Wadi Hayfadh watershed, the area was delineated to create sub-watersheds for the modelling purpose. A hypothetical single land use category (barren land) was assumed to

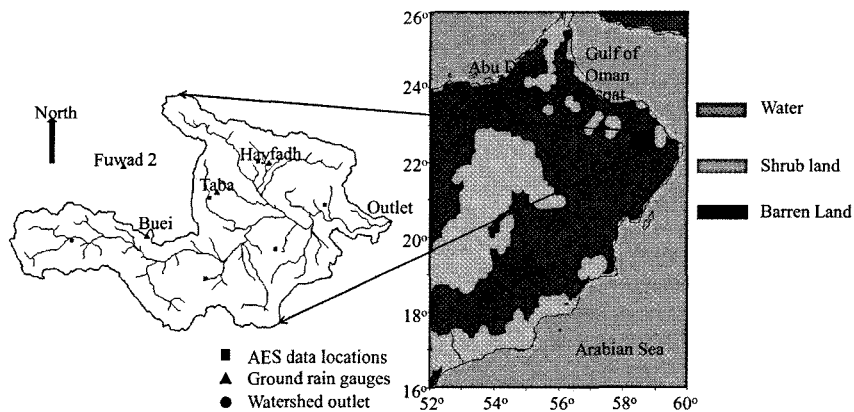


Figure 8: Right: land use distribution over Oman with barren land (desert) covering most of the area, Left: Wadi-Hayfadh watershed delineated for the hydrological simulation.

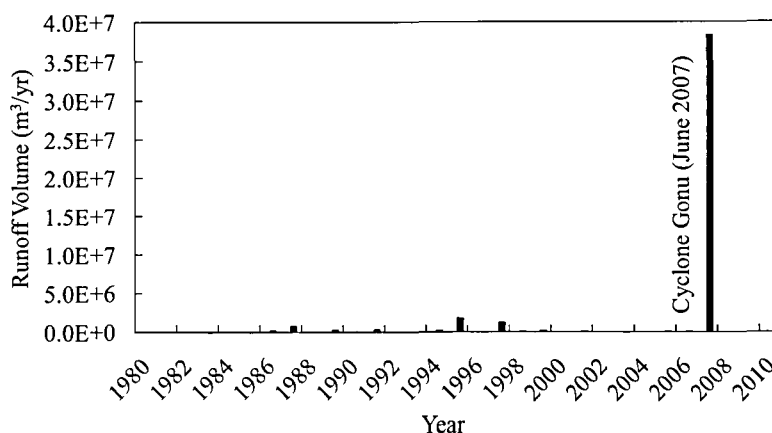


Figure 9: Wadi Hayfadh (Oman) history of runoff volume.

Table 2: Geographical Characteristics of Wadi Hayfadh, Oman.

Item	Value	Unit
Catchment area	573.8	km ²
Max. stream length	58.2	Km
Max. stream slope	1.15	m/m
Average basin elevation	536.4	M
Centroid to stream distance	27.1	Km
Shape factor	3.6	km ² /km ²
Sinuosity	1.28	m/m

cover the whole area. Most of the model parameters were estimated from information given in HSPF reference materials (Bicknell et al. 1997). Runoff processes were simulated at an hourly time step to suit the steep topography in the area. Hourly precipitation computed using the coupled model and those recorded at the surface rain gauges were used for the HSPF input data for two different scenarios. A single rainfall station was assigned for each sub-watershed. Hourly computed air temperature, relative humidity, wind speed, and sunshine hours from each station were used to compute a time series of reference evapotranspiration for each sub-watershed.

4.4. Hydrograph in Wadi Hayfadh

Figure 10 shows the computed hydrographs at the outlet of Wadi Hayfadh after the passage of cyclone Gonu close to Oman in 6-7 June in 2007. Two cases were computed: the first case is computed with rainfall intensity records at three surface rain gauges (Hayfadh, Taba, and Buei). Since there are no other available observed meteorological parameters, the wind, radiation, temperature were extracted from the model computations. The peak computed discharge in this case was 6620 m³/sec that took place at 7.00 in the morning of 6 of June. The second case is computed with rainfall intensities and other meteorological parameters computed using AES at six points, each of which is located in the centre of each sub-watershed. The peak computed discharge in this case was 1509 m³/sec that took place at 3.00 in the morning of 6 of June. The peak observed discharge at the outlet of Wadi

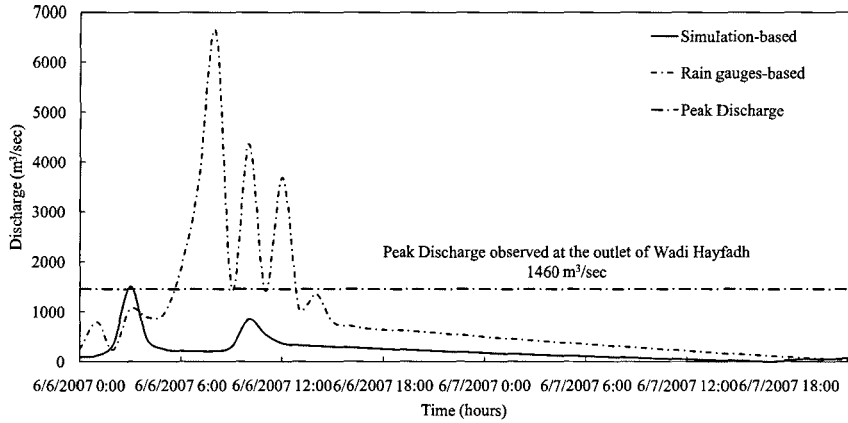


Figure 10: Computed hydrographs at the outlet of Wadi Hayfadh in 5-6 June in 2007. The dashed line is based on rainfall records at the rain gauges, and the solid line is based on computed rainfall intensities using the coupled model.

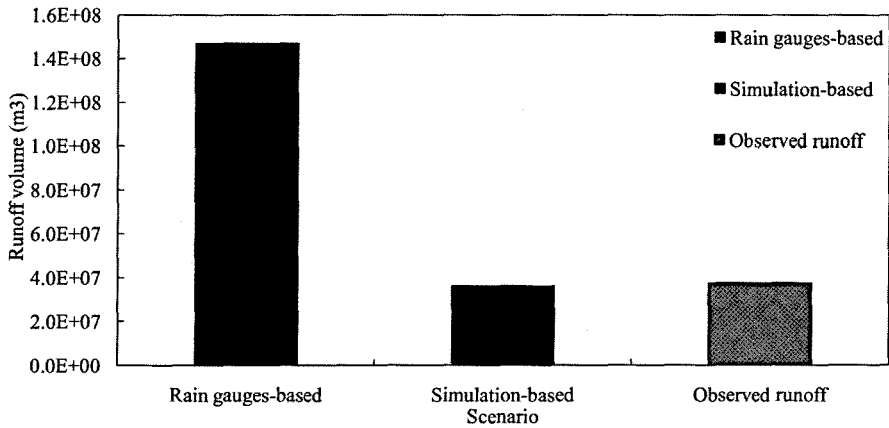


Figure 11: Comparison of observed and computed runoff volumes at Wadi Hayfadh after the landfall of cyclone Gonu in June 2007.

Hayfadh during cyclone Gonu is $1460 \text{ m}^3/\text{sec}$ which is relevant to the peak discharge computed using simulated rainfall intensities. Figure 11 shows a comparison of the total runoff volume at the outlet of Wadi Hayfadh during the cyclone Gonu among the computed runoff based on rainfall records at the surface rain gauges, the computed runoff based on computed rainfall intensities, and the observed runoff volume at the outlet of Wadi Hayfadh. The computed runoff volume for the three cases was found to be 147×10^6 , 36.2×10^6 , and $37.5 \times 10^6 \text{ m}^3$, respectively. Based on the above results, the computed peak discharge and runoff volume based on the rain gauge records are significantly higher than the corresponding observed values at the Hayfadh outlet: 4.5, and 4 times the observed values, respectively. Whereas, the computed peak discharge and runoff volume based on simulated rainfall intensities are representing the observed values with high accuracy.

5. Summary and conclusions

This paper described the application of Asia Environmental Simulator (AES) that is a dynamically coupled atmosphere-land-surface-hydrology model. The models incorporated in AES for this study are the non-hydrostatic atmospheric model (MM5), multi-layer atmosphere vegetation soil model (SOLVEG), and Hydrological Simulation Program-FORTRAN (HSPF) model. In this coupling, the models are two-way coupled with full consideration of momentum, energy, and water exchanges between the atmosphere and land-surface. AES showed a talent in studying the development and the hydrometeorological features accompanied the tropical cyclone Gonu that hit the Arabian Peninsula in June 2007. Cyclone Gonu is a rare event, most cyclones that form in the region form over the Bay of Bengal, east of India. Those that take shape over the Arabian Sea, west of the Indian peninsula, tend to be small and fizzle out before coming ashore. Oman and Iran were severely affected by the passage of Gonu with more than 72 deaths and damage estimated in the billions of dollars.

The coupled model is used to assess the accuracy of the surface rain gauges in Oman. There was a significant difference between the ground rain gauge measurements and the corresponding Tropical Rainfall Measuring Mission (TRMM) data and AES computation results. AES computed rainfall depths are relevant to those estimated by the TRMM satellite data, whereas there were big differences with the records at the ground rain gauges. Another indirect method to judge the accuracy of the rainfall datasets was followed through performing hydrological simulation of Wadi Hayfadh to estimate the runoff volumes and hydrograph. The computed peak discharge and runoff volume based on the ground rain gauge records were significantly higher than the corresponding observed values at Wadi Hayfadh outlet. Whereas, the computed peak discharge and runoff volume based on computed rainfall intensities were representing the observed values with high accuracy.

As a final conclusion, one can claim that the surface rainfall gauges measurement in Oman could probably be significantly higher than the actual measurement due to any mal-function in the measuring system (such as pseudo tipping problem, data acquisition problem, etc...). The measurement of the surface rainfall gauges in Oman should not be used to represent the surrounding site precipitation for planning and design purposes without using significant assessment and evaluation criteria. It is also of interest to realize that the TRMM seems to give much better and reasonable rainfall estimates that results in reasonable runoff results.

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