UNIVERSITÀ DELLA CALABRIA
Dipartimento di Ingegneria per l'Ambiente e il Territorio e Ingegneria Chimica

CeSMMA

KIT Karlsruhe Institute of Technology
Institute for Meteorology and Climate Research
IMK-IFU

NCAR

International Workshop

1st European Fully Coupled Atmospheric-Hydrological Modeling and WRF-Hydro Users workshop

Book of Abstracts

University of Calabria
Italy
June 11-13, 2014

Edited by

Benjamin Fersch - KIT, Campus Alpin, Germany

David J. Gochis - National Center for Atmospheric Research, USA

Harald Kunstmann - KIT & University of Augsburg, Germany

Giuseppe Mendicino - DIATIC, University of Calabria, Italy

Alfonso Senatore - DIATIC, University of Calabria, Italy

1st European Fully Coupled Atmospheric-Hydrological Modeling and WRF-Hydro Users workshop

First publication by:
Dept. of Environmental and Chemical Engineering, University of Calabria, Italy
June 2014

Layout:
Andrea Luci

Contents

1st Session

Fully coupled atmo-hydro modeling approaches: State of Art

Integrated Climate and Hydrology Modelling – catchment scale coupling of the HIRHAM regional climate model and the MIKE SHE hydrological Model

M.A.D. Larsen[1], M. Drews.[1], J.C. Refsgaard[2], K.H. Jensen[3], M.B. Butts[4], J.H. Christensen[5] and O.B. Christensen[5]

[1] *Technical University of Denmark, Denmark*
[2] *Geological Survey of Denmark and Greenland, Denmark*
[3] *University of Copenhagen, Denmark*
[4] *DHI, Denmark*
[5] *Danish Meteorological Institute, Denmark*
madla@dtu.dk

Applying regional climate models (RCM) at finer scales, down to even a few kilometres, representing the complex atmosphere/land-surface/subsurface hydrology interactions is crucial for understanding climate feedbacks. The ability of many current climate models to fully represent the terrestrial water cycle is however limited and particular true for surface and subsurface processes.
We here present a dynamically coupled version of the MIKE SHE hydrology model nested inside the DMI-HIRHAM RCM. A major challenge in the coupling resides in the vastly different philosophies between such model codes as RCM's generally implement primary physical equations while hydrological models typically require substantial calibration. Further challenges include differences in spatial and temporal resolutions and computational platform differences (Windows and Linux based codes) necessitating the use of the OpenMI cross-platform model interface.
The coupled model is evaluated for a groundwater-dominated catchment in Denmark (2500 km^2 – 500 m resolution) embedded within the RCM domain (4000 x 2800 km – 11 km resolution). Inside the shared model domains the coupled model enables two-way atmosphere/land-surface interactions via the energy-based land-surface model (SWET) embedded in MIKE SHE in the current configuration. In this manner the simpler DMI-HIRHAM land-surface scheme is effectively replaced by the superior land-surface component of the combined MIKE SHE/SWET model, which includes a wider range of processes at the land-surface and 3D subsurface flows as well as higher temporal and spatial resolution. The setup has proven stable and has been used for simulations of several years.

Integrated Hydrometeorological Predictions: A case study of the Colorado Front Range Flood of 2013

D. Gochis, W. Yu, K. Ikeda, K. Sampson

National Center for Atmospheric Research, Boulder, Colorado, U.S

During the second week of September 2013 an uncharacteristic weather pattern stalled over the Rocky Mountain Front Range region of northern Colorado bringing with it copious amounts of moisture from the Caribbean Sea and the tropical Eastern Pacific Ocean. This feed of moisture was funneled into the mountain front by a series of mesoscale circulation features resulting in several days of rainfall over steep mountainous terrain. Catastrophic flooding ensued within several Front Range river systems that washed away highways, destroyed towns, isolated communities, necessitated days of airborne evacuations and resulted in 10 fatalities. The impacts from heavy rainfall and flooding was felt over a broad region of northern Colorado leading to 18 counties being designated as federal disaster areas and caused an estimated cost in excess $3B in damages. In this talk the basic climatic, meteorological and hydrological conditions contributing to this event are described. Following a basic diagnostic description of the event, the performance of several quantitative precipitation estimate, quantitative precipitation forecast and hydrological forecast products available prior to and during the event are analyzed. A set of emerging research tools that have been used to perform post-event analyses and hindcasts are also presented with the intention of identifying where some of the biggest opportunities lie with respect to improving hydrometeorological predictions and where further improvements are needed.

Coupling WRF and HMS: a model system allowing simulations of the full atmospheric and terrestrial water balance at regional spatial and climate relevant temporal scales

S. Wagner[1 2], B. Fersch[2], H. Kunstmann[1 2], F. Yuan[3], Z. Yu[3 4]

[1] *Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research (IMK-IFU), Garmisch-Partenkirchen, Germany*

[2] *Institute of Geography, University of Augsburg, Germany,*

[3] *State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China*

[4] *D*epartment of Geoscience, University of Nevada, Las Vegas, NV, USA

sven.wagner@kit.edu

Feedback among the atmosphere, land surface and subsurface is important to understanding the nonlinear connections in the hydrological cycle caused by climate and land-use change. The quantification of such feedback mechanisms calls for coupled modelling systems describing both the atmosphere and terrestrial hydrosphere.

Our approach combines the regional atmospheric model WRF-ARW with the distributed hydrological model HMS. Both models are bound to the Noah land surface model (Noah-LSM) and share compatible water and energy flux formulations. Due to the suitability of HMS for medium and large scale hydrological applications, this model system allows to study hydrometeorological fluxes with respect to climate and land use change at regional spatial and climate relevant temporal scales. In addition to the coupling of the atmospheric and hydrological models we implemented methods to represent the interaction between groundwater and soil moisture of the LSM.

The model system is applied for the Poyang Lake basin, China. The region is characterized by tremendous land use changes in the last decades. Its catchment size is approximately 160,000 km^2 and our coupled model system simulates the full regional water cycle with a spatial resolution of $10x10km^2$.

The application of the developed coupled model system consists of three main steps: First, uncoupled simulations of the advanced weather research and forecast model WRF-ARW to identify a suited setup for the target region. Second, the setup and calibration of the hydrological model HMS with a standalone version driven by meteorological observation data. Third, the performance of fully coupled WRF-HMS simulations combining the identified stand-alone WRF and HMS setups for the Poyang Lake catchment.

We will present the integration of the hydrological model HMS into WRF-ARW and simulation results of all three steps which are required to investigate the full regional water cycle for the Poyang Lake basin with the newly developed coupled modelling system.

Evaluating Coupled Atmospheric-Hydrological Model Systems: Design and Operation of Hydrometeorological Testbeds

H. Kunstmann[1 2], B. Fersch[1], L. Hingerl[2], T. Rummler[2], J. Arnault[2], J. Bliefernicht[2]

[1]*Karlsruhe Institute of Technology*
[2]*University of Augsburg*
harald.kunstmann@kit.edu

Traditionally, hydrological models are evaluated by comparison to streamflow observations. This is still appropriate for lumped model systems that aim at describing river runoff only. With the increasing complexity of physically based hydrological model systems, that allow to describe the complex interaction of the regional water cycle on different spatial and temporal scales, the reliability and predictability of model simulations can only be shown, if a variety of hydrological variables is considered for evaluation and validation. Beside streamflow, soil moisture plays a crucial role in distributed model systems. As, at every phase transition of water, the water- and energy cycle are interlinked inextricably, also energy flux observations play an increasingly important role in complex model evaluation. This is particularly valid for coupled atmospheric-hydrological model systems, as the land surface energy balance is the crucial link between the atmospheric and the terrestrial part.
We will show current activities in the establishment and operation of comprehensive hydrometeorological testbeds that allow extensive evaluation of complex model systems, and in particular the evaluation of both water- and energy fluxes. The first test site is the TERENO-prealpine test site in southern Bavaria, consisting of soil moisture devices, lysimeters, and various Eddy-Covariance stations and full land surface energy balance measurements. The test site covers the region of the Ammer catchment, an area of around 700 km^2. The second hydrometeorological test bed is being established in the Savanna region of Southern Burkina Faso and Northern Ghana. Here, also three Eddy-Covariance stations and full energy balance measurements are performed in three different land use intensification regions (natural Savanna, partly agriculturally impacted Savanna, and agriculturally degraded Savanna). In all cases, automatic data transmission is realized allowing to detect failures in time.
We apply the WRF-Hydro model system to both the Ammer catchment in southern Germany and the Sissili catchment in West Africa and show first evaluation of results.

Performance of WRF-Hydro in complex terrain

T. Rummler[1], H. Kunstmann[1 2], D. J. Gochis[3]

[1] *University of Augsburg*
[2] *Karlsruhe Institute of Technology*
[3] *National Center for Atmospheric Research, Boulder, Colorado, U.S*
thomas.rummler@geo.uni-augsburg.de

Limitations in the adequate representation of terrestrial hydrologic processes controlling the land-atmosphere coupling are assumed to be a significant factor currently limiting the model prediction skill of warm season precipitation. Especially the so-called ‘zones of transition’ - which are located between the wet and dry climates - are assumed to be the regions that will most likely exhibit a strong link between soil moisture and precipitation.
To address this issue, recent developments in hydrometeorological model development tend towards a more sophisticated representation of terrestrial hydrologic processes, accounting for the interdependencies of the water and energy fluxes between the compartmental interfaces.
We will present first results from two multi-month simulations using the Weather Research and Forecasting Model (WRF) and the hydrologically-enhanced version WRF-Hydro in a high resolution configuration (Δx=3 km) over the German pre-alpine region and the southerly adjoining Eastern Alps. A comparison between both model runs will be made to evaluate how sensitive model simulations and predictions of precipitation are to including lateral soil water movements and re-infiltration.

Fully coupled WRF-Hydro atmospheric-hydrological modeling in a Mediterranean catchment

G. Mendicino, A. Senatore

Dept. of Environmental and Chemical Engineering, University of Calabria, Italy
alfonso.senatore@unical.it

Fully coupled modeling of land-atmosphere water transfer processes is an increasingly attractive topic for both weather/climate modelers and hydrologists because, on the one hand, the opportunity of taking into account lateral moisture redistribution in the land-surface boundary portends to improve land-atmosphere water fluxes modeling, on the other hand, fully coupled models candidate themselves as unique powerful tools for assessing water distribution and space-time variations from the atmosphere up to a given stream outlet.
With the aim of evaluating potential of fully coupled modeling in a typical Mediterranean catchment, where also sea-atmosphere interactions play a relevant role, WRF-Hydro modeling system is applied in a southern Italian basin, the Crati River Basin closed at the S. Sofia d'Epiro section (1281 km^2). The procedure followed for comparing fully-coupled and uncoupled simulations is made up of several steps: a) the stand-alone WRF-Hydro hydrological model with hourly time step and a 250 m resolution is calibrated and validated for the period December 2002 – September 2003, using distributed meteorological forcing derived from ground-based observations of meteorological variables; b) for the same period, observed meteorological forcing is replaced by WRF-derived meteorological fields (one-way coupling of the hydrological model with WRF). WRF parameterization is taken from a detailed analysis performed over both dry and wet periods in the analyzed region, where two nested domains were used (12.5 and 2.5 km resolution, respectively); c) finally, a fully-coupled WRF-Hydro simulation is performed.
From preliminary results it seems that fully coupled modeling provides better rainfall estimates for convective events, while precipitation events generated by frontal systems coming from surrounding sea don't show relevant differences. Also spatial distributions of hydrometeorological fluxes show interesting differences.

Evaluation of a fully coupled atmospheric-hydrological modeling system for the Sissili watershed in the West African Sudanian Savannah

J. Arnault[1 2], L. Hingerl[1], A. Aduna[3], S. Andresen[1 2], T. Rummler[1], H. Kunstmann[1 2]

[1]*Institüt für Geographie, Universität Augsburg, Alter Postweg 118, 86159 Augsburg, Germany,*
[2]*Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Germany*
[3]*WASCAL Competence Center, Ouagadougou, Burkina Faso*
joel.arnault@geo.uni-augsburg.de

The land atmosphere exchange processes in regional climate models are usually described by a one-dimensional land-surface model, so that hydrological feedbacks on climate can only be partially taken into account. The aim of this presentation is to investigate whether a detailed representation of the fully 3-dimensional terrestrial hydrological processes would make a difference in the modeled climate. To address this topic the Weather Research and Forecasting (WRF) model, stand-alone or coupled with the NCAR Distributed Hydrological Modeling System (NDHMS), has been used to simulate the land-atmospheric system in the Sissili watershed, a sub-catchment of the White Volta catchment located in South Burkina Faso - North Ghana. The selected WRF configuration includes one domain at 10 km resolution forced by ERA-Interim data at its lateral boundaries, and covering a sufficiently large area for resolving the dynamical processes involved in the West African climate. In the WRF-Hydro configuration, i.e. WRF coupled with NDHMS, surface and river runoff are computed on a 2km resolution grid coupled with the WRF domain. In this presentation two WRF and WRF-Hydro one-year simulations for 2013 are compared with observations at three Eddy-Covariance (EC) stations operating in the Sissili watershed and neighboring catchments, installed in October 2012 during a field campaign of the West African Science Service Center on Climate Change and Adaptive Land Use (WASCAL). The WRF-Hydro simulation is further validated with river gauge measurements provided by the Hydrological Services Department of the Ministry of Water Resources, Works and Housing of Ghana, at two locations along the Sissili river. A comparison between the WRF and WRF-Hydro simulations finally shows to which extent the lateral land surface water fluxes taken into account in WRF-Hydro modify the simulated soil moisture, evapotranspiration, precipitation and surface temperature in the Sissili watershed.

2nd Session

Enhancing process representation in fully coupled modeling systems

Coupled modeling of groundwater/surface water interactions: successes and challenges from recent applications

C. Paniconi

INRS-ETE (Institut National de la Recherche Scientifique, Centre Eau Terre Environnement), Université du Québec, Quebec City, Canada
claudio.paniconi@ete.inrs.ca

The boundary condition-based coupling scheme used in the CATHY (CATchment HYdrology) model will be presented. The model is based on a three-dimensional Richards equation solver for subsurface flow and a path-based diffusion wave representation of overland and channel flow. The coupling scheme automatically partitions potential fluxes (rainfall and evapotranspiration) into actual fluxes across the land surface and calculates changes in surface storage. This procedure, which is performed at every subsurface time step, determines whether a surface node is ponded, saturated, unsaturated, or air dry, and it ensures that pressure and flux continuity is enforced at the surface/subsurface interface. Recent CATHY model developments (e.g., coupling with the land surface model NoahMP, incorporating solute transport phenomena) and applications (from hillslope to catchment scales, and including intercomparison with other models) will be examined. The impacts of heterogeneity, grid resolution, surface flow paradigms, hysteresis, boundary conditions, and other factors on hydrologic state variables such as streamflow, soil water storage, groundwater recharge, and evaporation will be addressed.

Saturated zone interaction within WRF-Hydro: from the bucket approach to a physically-based distributed groundwater representation

B. Fersch[1], S. Wagner[2], T. Rummler[2], D. Gochis[3], H. Kunstmann[1 2]
[1]*Karlsruhe Institute of Technology, Campus Alpin, Germany*
[2]*Institute of Geography, University of Augsburg, Germany*
[3] *National Center for Atmospheric Research, Boulder, Colorado, U.S*
fersch@kit.edu

Shallow groundwater bodies typically affect the vertical moisture transport within the vadose zone and are in close interaction with river channels. Their inert response to high frequency input signals provides slowly varying baseline contributions to channel baseflow and dampens the dynamic of moisture variation of the deeper soil. Moreover, lateral groundwater movement connects the sink (recharge) and source (depletion) regions.
Currently, WRF-Hydro uses a conceptual bucket approach for storing and redistributing the bottom drainage of the land surface model's lowest soil layer. The percolation water is collected in a linear storage body and equally distributed in a lumped way to generate the baseflow component for the channel routing. In such a configuration the hydraulic head has no impact on the vertical distribution of moisture in the soil column and intra-basin redistribution of groundwater is not possible.
For an enhanced representation of the saturated zone in WRF-Hydro, including storage, lateral redistribution and interaction with other compartments of the hydrological cycle, a two-dimensional distributed groundwater model is coupled to the system. The augmented functionality includes non-linear groundwater unsaturated zone interaction using a parametrized Darcy flux approach and a groundwater channel exchange method which is based on the potential gradient between groundwater and channel head.
Moreover, the enhanced model is applied for the Ammer catchment of southern Germany. The Ammer drains an area of approximately 900km² with alpine to pre-alpine orography, largely covered by grassland and forests. It will be shown, how the distributed groundwater approach impacts the model's water budgets with respect to the conceptual bucket method.

Using the WRF-Hydro model for flood forecasting of 100 years flood event in Israel

A. Givati[1], E. Fredj[2], T. Rummler[3], D. Gochis[4], W. Yu[4], H. Kunstmann[5]

[1] *Israeli Hydrological Service, Water Authority, Israel*
[2] *The Jerusalem College of Technology, Israel*
[3] *University of Augsburg, Germany*
[4] *National Center for Atmospheric Research, Boulder, Colorado, U.S*
[5] *Karlsruhe Institute of Technology, Germany*
amirg@water.gov.il

The WRF-Hydro model was employed to provide precipitation forecasts during 3 flood events at the 2012-2013 and 2013-2014 winters (wet season) for Israel and the surrounding region. This period was characterized with unique climate and hydrologic conditions: severe drought on one hand and extreme floods events on the other hand.
The WRF model has been coupled with the NCAR distribute Hydrological model system (WRF-Hydro) to simulate stream flow at several locations at the Ayalon basin in central Israel for deferent types of floods: relatively small, high magnetite and 1%, extreme flood event. The WRF-Hydro forecasts were verified against measurements from rain gauges and hydrometric stations in the basin. The simulation results indicated a good agreement with the actual measurements also for the rare events. The total storms simulated precipitations were close to the actual measurements and the peak discharges were at same level of exceedance probability as the observed peak flow. However, the timing of the simulated peak discharges and the hydrograph shape showed significant bias in some cases. Using observed precipitation as an input to the hydrological model in exchange to the simulate precipitation lead to a much accurate hydrograph simulations which mean that much of the WRF-Hydro bias was due to the WRF input and not the hydrology.
The hydro-meteorological modeling system that ingests the high-resolution gridded WRF forecasts coupled with the hydrological components was prove to be a useful tool for flood forecasting and warning proposes, and improved upon the current operational stream flow forecast method for this region. The modeling tools presented in this study are used to support the water-drainage and resource-assessment process, and can be applied for studies of seasonal hydro-climate forecasting and climate change future scenarios.

WRF-Hydro simulation of the Himalayan Beas river basin

L. Li[1 2], David J. Gochis[3], Michel d. S. Mesquita[1 2]

[1] *Uni Climate, Uni Research AS, Allégaten 55, 5007 Bergen, Norway*
[2] *Bjerknes Centre for Climate Research, Bergen, Norway*
[3] *National Center for Atmospheric Research, Boulder, Colorado, U.S*
lu.li@uni.no

Evidence is showing that climate change has a direct influence on changes in precipitation and the hydrological cycle. The regional Hydrometeorological system model (WRF-Hydro) that couples the atmosphere with physical and gridded-based surface hydrology provides efficient predictions for hydrological events. This modeling system has been successfully used for some cases of flood forecasting and headwaters simulations. In this study, we examine the performance of WRF-Hydro model system for a longer period hydrological simulation in a mountainous basin at high spatial resolution, i.e. 3 km for atmosphere and land surface grid and down to 300 meters for the hydrological routing sub-grids.
In the study region, three nested domains (with spatial resolution of 27 km, 9 km and 3 km) were set-up using the Weather and Forecasting Model (WRF, version 3.5.1). The largest domain covers 3375 * 3375 km^2, including part of the Indian Ocean, the Bay of Bengal and the whole Himalaya region. This setup is used to capture large-scale processes and to avoid model bias near the lateral boundaries. The medium and small domains cover an area of 900 * 900 km^2 and 354 * 354 km^2 respectively. Since the precipitation is the most important input data within the hydrological modeling for the success of the hydrological simulation, the high-resolution precipitation results from two microphysical parameterization schemes (MP) (i.e. WRF Single-Moment 3-class (WSM3) Scheme and the Thompson Scheme) are presented and discussed in the study. The five years (1997-2001) precipitation from the two MP methods are compared to reveal how differently these two methods influence orographic-related precipitation at high resolution simulations for this glacier fed basin over the Himalayas using the WRF model with its associated hydrological modeling extension ('WRF-Hydro'). The focus is on the utility of high resolution precipitation downscaling for the discharge simulation. Five years precipitation and stream flows are evaluated with gauge and satellite-based precipitation and measured stream flow values. The Stream flow prediction skill from the WRF-Hydro modeling system, using the two MP schemes, was accessed against observations of basin outlet. The calibrated modeling results are compared and assessed based on Nash-Sutcliffe efficiency (NS) and absolute value of the volume error (VE). The modeling system shows skills in capturing the spatial and temporal structure of high-resolution precipitation and resulted stream flow hydrographs.

The ENKI Hydrologic Modeling Framework: A preprocessor for WRF-Hydro?

J.F. Burkhart[1 2], S. Kolberg[3], S. Helset[2]

[1] *Department of Geosciences, University of Oslo*
[2] *Statkraft AS*
[3] *Sintef*
john.burkhart@geo.uio.no

ENKI is a modular framework for building hydrological or other environmental models. A model consists of a set of user-defined subroutines, and operates on GIS data within a geographical region. A region contains geographical elements such as topography, lakes, land use, and other variables. Through a coupled interface, the ENKI framework recognizes the number, types, and names of each variable that are in use in the model and linked to the region. The framework then exposes the variables to the user within the proper context, ensuring that:

- The model is completely and consistently set up
- Distributed maps coincide spatially where necessary
- Time series exist for input variables
- State variables are initialized for the correct date/time
- GIS data sets exist for static map data.

ENKI is written in C++ and has Python wrappers developed for easy access to model subroutines. The code is developed such that the modules that make up a model are easy to modify and customize with limited programming knowledge, allowing one to create new methods and test them rapidly. Due to the simple architecture and ease of access to the module routines, we see ENKI as an optimal choice of models to evaluate new routines in a research environment. Furthermore, as different types of modules are readily available (Bayesian Kriging, Gaussian Random Field, etc.) input data for WRF-Hydro could be preprocessed in the framework prior to being used as input data for more complex hydrologic simulations.

The software is Open Source and released under a LGPL license.

OpenMI 2.0 based WRF - SWAT models integration.

A. Bugaets[1], L. Gonchukov[2]

[1] *Federal State Budget Institution the Far Eastern Regional Hydrometeorological Research Institute (FERHRI), 24, Fontannaya St., Vladivostok 690600, Russian Federation (www.ferhri.ru)*
[2] *Federal State Budgetary Institution Primorskoe administration for hydrometeorology and environmental monitoring (Primgidromet), 3, Mordovtseva St., Vladivostok 690600, Russian Federation (www.primgidromet.ru)*
andreybugaets@yandex.ru

The objective of this study is development of end-to-end workflow that executes, in a loosely coupled mode, an integrated modeling system comprised of Weather Research and Forecast (WRF) atmospheric model and Soil and Water Assessment Tool (SWAT 2012 v.622) hydrological model using OpenMI 2.0 and web-service technologies. Migration SWAT into OpenMI compliant involves reorganization of the model into a separate initialization, performing timestep and finalization functions that can be accessed from outside. To save SWAT normal behavior, the source code was separated from OpenMI-specific implementation into the static library. Modified code was assembled into dynamic library and wrapped into C# class implemented the OpenMI ILinkableComponent interface. Development of WRF OpenMI-compliant component based on the idea of the wrapping web-service clients into a linkable component and seamlessly access to output netCDF files without actual models connection. The weather state variables (precipitation, wind, solar radiation, air temperature and relative humidity) are processed by automatic input selection algorithm to single out the most relevant values used by SWAT model to yield climatic data at the subbasin scale. Spatial interpolation between the WRF regular grid and SWAT subbasins centroid (which are coinciding as virtual weather stations) realized as OpenMI AdaptedOutput.
Numerical experiments were carried out for the period of 2012-2013 on the Komarovka river watershed located in the small mountains landscapes in the western part of the Khankaiskaya plain. The watershed outlet is equipped with the automatic water level and rain gauging stations of Primorie Hydrometeorological Agency (Prigidromet http://primgidromet.ru) observation network. Spatial structure of SWAT simulation realized by ArcSWAT 2012 based on 10x10m DEM resolution and 1:50000 soils and landuse cover. WRF-SWAT composition is assembled in the GUI OpenMI.
For the test basin in most cases the simulation results show that the predicted and measured water levels demonstrate acceptable agreement. Enforcing SWAT with WRF output avoids some semi-empirical model approximation, replaces a native weather generator for WRF forecast interval and improved upon the operational streamflow forecast.

Simulation of a Flood event occurred in Istanbul in September 2009 by using the WRF-Hydro Model

E. Tan

Istanbul Technical University, Aeronautics and Astronautics Faculty, Department of Meteorological Engineering, Maslak, 34469, Istanbul, Turkey
elcin.tan@itu.edu.tr

According to the IPCC (AR5), it is most likely that intensity and frequency of the flood events tend to increase with climate change. On the other hand, it is still a challenge to simulate location and timing of extreme precipitation events that cause floods, accurately. Although numerical weather prediction models such as the WRF Model capture the event with some shift in both space and time, we need more reliable simulations to take preventive precautions. In this study, a flood occurred in Istanbul on September 8 and 9 of 2009 is chosen as a case study for which 31 people died and total property damage was estimated at $70 million. WRF-ARW Model is used to perform a sensitivity analyses to predict this extreme precipitation event precisely. ECMWF and NNRP global datasets are used for the initial and boundary conditions of the WRF Model, which has horizontal domain resolutions of 9km, 3km, and 1km covering northwestern part of Turkey, Marmara region, and Istanbul area, respectively. All microphysics parameterizations of the WRF Model were tested for these sensitivity analyses. Results show that although some microphysics parameterizations have advantageous on others, all schemes are considered as inefficient in terms of both timing and local representation of the event. Therefore, an advanced approach is needed to capture the event as much as possible both in space and time. WRF-Hydro model is activated to overcome this problem. The results will be compared in detail with the consideration of amount, timing and spatial distribution of the extreme precipitation. The best physical parameterization options will be presented as a combination of microphysics, boundary layer, and land-atmosphere parameterizations. Our preliminary results show that as well as the choice of physical parameterizations, resolution of the model and the accuracy of initial and boundary conditions data set have major effect on accuracy of the results as expected. Moreover, the effects in inclusion of hydrological processes to the WRF Model will be emphasized.

3rd Session

The forecasting chain and other aspects of land-atmosphere coupling

Use of a fully distributed triangulated irregular network hydrologic model in climate change and ecohydrological studies

G. Mascaro

School of Sustainable Engineering and the Built Environment,
Arizona State University, Tempe, AZ, USA
gmascaro@asu.edu

The Triangulated Irregular Network (TIN)-based Real-Time Integrated Basin Simulator (tRIBS) is a fully-distributed and physically-based model of the coupled water and energy balance. Its structure and domain representation via TINs have been designed to feasibly conduct high-resolution (10-100 m; sub-hourly) simulations up to regional scales of a range of hydrologic processes, including evapotranspiration and its partitioning, rainfall interception, vertical and lateral moisture movement in the vadose and saturated zones, snowmelt, and overland and channel flow routing. In this talk, the model capabilities are presented through two recent applications. The first has the goal of quantifying the climate change impacts on water resources in a mid-sized (~470 km^2) basin in Sardinia, Italy. Outputs of four regional climate models were disaggregated in space and time with statistical methods and used to force the tRIBS model in a reference (1971-2000) and a future (2041-2070) period. Results indicate that decreasing annual precipitation (-13% averaged across the four RCMs) and increasing mean temperature (+3° C) predicted in future climate would lead to decreasing runoff (-32%), soil moisture (-4%) and actual evapotranspiration (-3%). tRIBS outputs, including time series and spatial maps, have been also used to evaluate the potential variations in the dominant hydrologic processes. The second application is focused on an ecohydrological study in a semiarid region in northwest Mexico. Here, tRIBS has been applied in a small basin (~100 km^2) with complex terrain to investigate the evolution of land surface temperature (LST) patterns in the transition from the drier spring to the wetter North American monsoon. For this purpose, the model was forced with time-varying vegetation parameters, derived from remote sensing products, and it was calibrated and validated against ground, aircraft and satellite observations of LST and soil moisture. Distributed simulations reveal how LST varies with topographic features and the role played by the seasonal vegetation canopy in cooling the land surface and increasing the spatial variability in LST.

DRIHM and DRIHM2US: e-Infrastructures for hydro-meteo research

F. Delogu

CIMA Research Foundation
fabio.delogu@cimafoundation.org

Predicting weather and climate and its impacts on the environment, including hazards such as floods and landslides, is a big challenge, that can be efficiently supported by a distributed and heterogeneous infrastructure, exploiting several kind of computational resources: HPC, grid and cloud. This can help researcher in speed-up experiments, improve resolution and accuracy, simulate with different models and model chains. Such simulation models are complex, with heavy computational requirements, tons of parameters to tune and not fully standardized interfaces, so each research entity is usually focusing on a limited set of tools, customized to interact. DRIHM approach is based on strong standardization, well defined interfaces, and an easy to use web interface for model configuration and experiment definition. A researcher can easily compare different hydrologic models forced by its meteo model of choice, or compare a different meteo model to validate or improve its research. Along these lines DRIHM2US will promote international cooperation between Europe and the USA for the development of a common infrastructure to be used for a more comprehensive cooperation between Europe and USA in the study of severe hydro meteorological events and climate changes effects.
Then, this work presents how the interoperability between meteorological and hydrological models can improve the evaluation of the uncertainty and lead to an accurate prediction of flood events by the use of the DRIHM and DRIHM2US e-Infrastructures.

The POLIMI forecasting chain for flood and drought predictions

A. Ceppi[1], G. Ravazzani[1], C. Corbari[1], R. Salerno[2], M. Mancini[1]

[1] *Department of Civil and Environmental Engineering (D.I.C.A.), Politecnico di Milano, Italy*
[2] *Epson Meteo Centre, Cinisello Balsamo (Mi), Italy*
alessandro.ceppi@polimi.it

Nowadays coupling meteorological and hydrological models, it is recognized by scientific community as a necessary way to forecast extreme hydrological phenomena, in order to active useful mitigation measurements and alert systems in advance.
The development and implementation of a real-time forecasting chain with a hydro-meteorological operational alert procedure for flood and drought events is described in this study.
As far as concerning drought predictions, a real-time forecasting system called Pre.G.I., an Italian acronym that stands for "Hydro-Meteorological forecast for irrigation management", is shown in this study. The system is based on ensemble predictions at medium-range (30 days) with hydrological simulations of water balance to forecast the soil water content in the experimental test-site of a maize field in Livraga (northern Italy).
The hydrological ensemble forecasts are based on 20 meteorological members of the non-hydrostatic WRF model, provided by Epson Meteo Centre, while the hydrological model used to generate the soil moisture and water table simulations is the rainfall-runoff distributed FEST-WB model, developed at Polytechnic of Milan. The hydrological model was validated against measurements of latent heat flux and soil moisture acquired by an eddy-covariance station and TDR probes, respectively. Reliability of the forecasting system and its benefits was assessed on some cases-study occurred in the recent years.
Regarding flood forecasts, a real time flood forecasting system based on online simulation of discharge time series in Milan urban area is shown.
Since the complex flood protection system of Milan and surrounding urban area, developed in the last 60 years, has not been able to protect the Milan urban area, which flooded frequently in the last 25 years, the improvement of the Milan flood control system needs a synergism between structural and nonstructural engineering approaches.
Therefore, the same hydrological model FEST-WB is coupled with high resolution (1 km) deterministic weather forecasts provided by the WRF model. Studies on three catchments located northern than Milan (the Olona, Seveso and Lambro River basins) show how early warning systems are an effective complement to structural measures for flood control in Milan city.

Evaluation of hydrometeorological extremes using WRF-Hydro system

I. Yucel and A. Onen

Middle East Technichal University, Civil Engineering Department, Water Resources Lab, 06800 Ankara Turkey
iyucel@metu.edu.tr

Evidence is showing that global warming or climate change has a direct influence on changes in precipitation and the hydrological cycle. Extreme weather events such as heavy rainfall and flooding are projected to become much more frequent as climate warms. Regional hydrometeorological system model which couples the atmosphere with physical and gridded based surface hydrology provide efficient predictions for extreme hydrological events. This modeling system can be used for flood forecasting and warning issues as they provide continuous monitoring of precipitation over large areas at high spatial resolution. This study examines the performance of the Weather Research and Forecasting (WRF-Hydro) model that is operated in one-way for case studies. The modeling system performs the terrain, sub-terrain, and channel routing in producing streamflow from WRF-derived forcing of extreme precipitation events. The capability of the system with different options such as data assimilation is tested for number of flood events observed in basins of western Black Sea Region in Turkey. Rainfall event structures and associated flood responses are evaluated with gauge and satellite-derived precipitation and measured streamflow values. The modeling system shows skills in capturing the spatial and temporal structure of extreme rainfall events and resulted flood hydrographs. High-resolution routing modules activated in the model enhance the simulated discharges.

Towards a WRF-Hydro application for the Tana River basin of East Africa

N. Kerandi[1 2], H. Kunstmann[1 2], P. Laux[1], S. Wagner[1 2], J. Arnault[1 2]

[1]*Institute of Meteorology and Climate Research (IMK-IFU), Garmisch-Partenkirchen, Germany*
[2]*Institute of Geography, University of Augsburg, Augsburg, Germany*
noah.kerandi@kit.edu

The WRF-Hydro model is designed to provide more information of terrestrial hydrological processes than the stand alone WRF model. This is significant for analyzing land-atmospheric interactions of regional watersheds in climate and water sensitive environments like the Tana River basin of East Africa. The basin is a region of complex terrain with a catchment area of 126,026 km². The basin lies between the latitudes 0.0147° and 2.014° S and longitudes 37° and 40.25° E. The basin is important for Kenya's economy because of its contribution to the agricultural sector and its supply of about 70% of the country's hydro-power. Understanding its water balance will be fundamental in addressing water challenges in this region which might be exacerbated by climate change and land-use practices.

In this study, as a first step towards coupled WRF-Hydro simulation, we have carried seventeen stand alone WRF sensitivity experiments based on different physical parameterization combinations, i.e. cumulus, micro-physics, planetary boundary layer and radiation scheme, to identify a suitable setup for the study area. The simulations were performed for a 5-year period (2005-2009) for the coarse nest of 50 km and a fine nest of 10 km. The coarse nest covered the whole of East Africa whereas the finer nest covered the Tana River basin and surrounding areas. The precipitation and temperature simulation results were compared to various gridded observation datasets at monthly resolution. For precipitation CRU, CPC, GPCC, and GPCP, and for temperature CRU and UDEL (University of Delaware) were used to assess their performance in capturing the spatial and temporal distribution. From this WRF configuration experiments we found diverse performances with the vast majority of them being wetter than the observations. In general, the WRF model was able to capture the intra-annual distribution of precipitation in the Tana River basin. For temperature, all the model configurations generally showed a good performance in capturing the annual cycle across the Tana River basin. However, the WRF temperatures were slightly colder than the observations showing a mean absolute error of less than 2°C.

With the best WRF set-up we have included a third domain at 2 km horizontal resolution, covering a sub-catchment of the Tana River basin for the envisaged fully coupled WRF-Hydro simulations.

High resolution numerical modeling of an idealized daytime Urban Heat Island circulation

S. Falasca[1], F. Catalano[2], M. Moroni[1]

[1] *Sapienza University of Rome, Rome, Italy*
[2] *ENEA, Rome, Italy*
serena.falasca@uniroma1.it

The urbanization produces alterations to the land-surface properties inducing a modification of the surface energy balance which originates the Urban Heat Island (UHI) phenomenon. The UHI influences local weather patterns and the hydrological cycle and, interacting with larger scale phenomena may contribute to natural hazards. In this work Large Eddy Simulations of the idealized diurnal UHI are performed using the Weather Research and Forecasting model. The phenomenon is reproduced through the surface energy balance scheme in the model. A new option that allows to differentiate the soil properties between urban and rural areas and to add the anthropogenic heat in correspondence of the urban area is introduced in the land-surface scheme of the model. The domain is characterized by a constant horizontal resolution of 50m and a vertical parabolic stretching (from ~2m close to the ground to ~90m at domain top). A modified subgrid-scale model is used to consider the effect of the grid's anisotropy in the calculation of the filter width. High resolution modeling can provide useful information to improve the hydrometeorological forecasting in the presence of the UHI, including knowledge of the turbulent Planetary Boundary Layer (PBL) features as a function of the UHI characteristics. Twelve cases are simulated, considering different values of the control parameters: albedo, thermal inertia, roughness length, anthropogenic heat, geostrophic wind intensity. First- and second- moment statistics and the turbulent kinetic energy (TKE) budget analysis are analyzed. The influence of the different control parameters on the turbulence intensity and distribution is discussed. The structure of the PBL over the UHI is similar to that of a convective BL and the presence of the geostrophic wind of increasing velocity introduces features similar to those of a shear driven PBL. The geostrophic wind determines a deep redistribution of the TKE. Data from present study and literature are used to seek scaling relationships for the UHI phenomenon, depending on the control parameters. Since the UHI phenomenon strongly depends on the partitioning between latent and sensible heat fluxes, the inclusion of reliable hydro-meteorological information in the framework of a coupled multiscale model (as WRF-hydro) is expected to significantly improve UHI modeling and the development of appropriate mitigation strategies.

Enhancement of Mercury emissions at the sea water – atmosphere interface driven by regional climate changes

C. N. Gencarelli, F. De Simone, I. M. Hedgecock, F. Sprovieri, N. Pirrone
CNR – Institute of Atmospheric Pollution Research
c.gencarelli@iia.cnr.it

Mercury (Hg) is a global pollutant that is known to have adverse effects on human health. Globally Hg is mainly distributed via the atmosphere but its environmental impact is not directly related to its atmospheric concentration. In fact while the major redistribution of Hg is via the atmosphere, its primary environmental and health impact occurs when oxidized Hg is deposited to aquatic systems, where it is methylated to form neurotoxic monomethylmercury, which enters the food chain and bioaccumulates to such an extent that its concentrations in predatory fish can be harmful if consumed.

Hg can be emitted to the atmosphere both from anthropogenic and from natural sources, most anthropogenic and almost all natural sources emit elemental Hg. Elemental Hg is relatively unreactive and remains in the atmosphere for between 8 month and a year. It is eventually oxidised in the atmosphere and the $Hg^{(II)}$ formed, being less volatile and more soluble than $Hg^{(0)}$ is relatively rapidly deposited via dry or wet deposition processes.

The oceans play an important role in the biogeochemical cycle of mercury, as they are the places where Hg can be methylated in the water column, but photolytic and biological processes in the surface waters can reduce $Hg^{(II)}$ to $Hg^{(0)}$ which can be re-emitted to the atmosphere. The rate at which $Hg^{(0)}$ is emitted from oceans and seas is a function of its relative concentrations in the atmospheric boundary layer and the surface waters, but it is also highly dependent on meteorological parameters such as wind speed and the air and water temperature. The re-emission of previously deposited Hg is important as it effectively prolongs the length of time which anthropogenic Hg emissions perturb the global Hg biogeochemical cycle, because the eventual removal of Hg from the cycle occurs when it is buried with deep sea sediments.

Mediterranean area Hg cycle has been studied using a modified version of the WRF/Chem model. This model version has been developed specifically with the aim to simulate the atmospheric processes determining atmospheric Hg emissions, concentrations and deposition at high spatial resolution.

The Hg emission flux from the Mediterranean Sea has been estimated for present day conditions and for different climatological scenarios, to estimate the contribution of this source to the regional Hg air concentrations and deposition fluxes.

Influences of shipping emissions on Mediterranean air quality and radiative forcing

C. N. Gencarelli, F. De Simone, I. M. Hedgecock, F. Sprovieri, N. Pirrone
CNR – Institute of Atmospheric Pollution Research
c.gencarelli@iia.cnr.it

Tropospheric ozone (O_3) and Black Carbon (BC) as well as being hazardous to health are short-lived climate forcers. Approximately 90% of ozone present in the atmosphere is located in the stratosphere where conditions favour its production, but it is present also in the troposphere where even levels of 60 ppb can have negative impacts on health and also agricultural production. The relationship between climate change and air quality has been under scrutiny in recent years: in the Mediterranean a summer time temperature increase will have repercussions on the hydrological cycle but also on the atmospheric composition, and it is estimated that the O_3 concentration will increase by 1 ppb with each 1 K rise in temperature.

The Mediterranean area is one of the busiest shipping routes in the world, and emissions from shipping have been increasingly studied over the last several years. The impact of shipping emissions is expected to increase in magnitude as global maritime traffic increases. Thus shipping emissions have an impact on regional air quality, and this has been examined using the WRF/Chem model to estimate the magnitude of the influences of these emissions on the O_3 and BC concentration over the Mediterranean Sea and surrounding area. Model results suggest that ship emissions affect average O_3 concentrations between 6 and 11 % over the Mediterranean Sea and between 5 and 9 % over the coastal and inland areas, while where maritime traffic is particularly high (the Strait of Gibraltar and the Strait of Sicily) the influences in modelled concentration exceed the 30 %. Shipping emissions clearly play an important role in local and regional air quality in Mediterranean coastal areas, however they also influence the local energy budget because O_3 produced as a result of NO_x emissions and BC which is directly emitted both absorb radiative energy and therefore have a local heating effect. Therefore temperature increases which result from global climate change are likely to be exacerbated in the Mediterranean due to the influence of anthropogenic emissions on atmospheric composition.

Estimation of the groundwater supply coming from the melting of the Chimborazo glacier (Ecuador)

B. Mendoza T.[1], F. Chidichimo[2], S. Straface[2]

[1] *Universidad Nacional de Chimborazo, Ecuador*
[2] *University of Calabria, Department of Environmental and Chemical Engineering, Italy*
francesco.chidichimo@unical.it

The basin of the Chambo river is located on the highland in the north-west of the Amazon river, inside the Chimborazo district. It is characterized by areas with both low natural availability of water and high density of population. The increasing of the already large population, and the consequent rise of water demand together with the reduction of rain phenomena, have led, in the last years, to a conflictual relationship between the various communities of the area, because of the uncertainty on the exploitable stock of water. The drinkable water system of the cities located within the basin (Riobamba and Guano), is supplied only by the groundwater coming from the Chambo aquifer. The hydrologic studies performed on the area have only led to the knowledge of the superficial water balance without taking into account the groundwater contribution, causing a lack of information affecting the decisional capacity of the authorities responsible of the care and preservation of the basin. Moreover, a study performed on a small portion of the aquifer by means of radioactive isotopes (^{14}C) (Bigo, 2012), states that the groundwater in the aquifer, dates back to 8000 years ago. This result leads the community to think that the aquifer is fossil, so that the water reserve is limited because of the lack of lateral and vertical recharge.

The aim of this study is to demonstrate that the aquifer is recharged in time, and to estimate the amount of water coming from the melting of the glacier located on the Chimborazo volcano. A three-dimensional mathematical model of the basin has been developed, in which the information coming from the water balance have been adopted. The hydraulic conductivity distribution has been derived from the interpretation of several pumping tests performed on the basin. The estimation of the water amount coming from the volcano has been obtained by means of an iterative inverse procedure based on the capacity of the model to reproduce the hydraulic heads observed in wells, sources and ponds.

The results of this study, together with the ones coming from the ^{14}C analyses, suggest that the reserve of ancestral ice of the Chimborazo glacier are dissolving, highlighting the influence of the climate change in Ecuador and, hence, in the world. This study can be seen as starting point for possible future modeling improvements through the adoption of a fully-coupled approach, which providing a better representation of the relationship between climate forcings, surface water and groundwater, will help to produce even more accurate estimation of the involved volumes of water.

Extended Abstracts

Integrated Climate and Hydrology Modelling - Catchment Scale Coupling of the HIRHAM Regional Climate Model and the MIKE SHE Hydrological Model

Morten A. D. Larsen[#1], Martin Drews[#], Jens C. Refsgaard[*], Karsten H. Jensen[^], Michael B. Butts[+], Jens H. Christensen[x], Ole B. Christensen[x]

[#] Technical University of Denmark, DTU Climate Centre, Frederiksborgvej 399, 4000 Roskilde, Denmark

[1]madla@dtu.dk

[*]Geological Survey of Denmark and Greenland, Øster Voldgade 10, 1350 Kbh K, Denmark

[^] University of Copenhagen , Dep. of Geosciences and Natural Resource Management, Øster Voldgade 10, 1350 Kbh K, Denmark

[+]DHI, Agern Alle 5, 2970 Hørsholm, Denmark

[x]Danish Meteorological Institute, Lyngbyvej 100, 2100 Kbh Ø, Denmark

***Keywords* - Coupled modelling, catchment scale hydrological modelling, regional climate modelling, atmosphere – land surface feedback**

I. Abstract

Applying regional climate models (RCM) at finer scales, down to even a few kilometres, representing the complex atmosphere/land-surface/subsurface hydrology interactions is crucial for understanding climate feedbacks. The ability of many current climate models to fully represent the terrestrial water cycle is however limited and particular true for surface and subsurface processes.

We here present a dynamically coupled version of the MIKE SHE (Graham and Butts 2005) hydrology model nested inside the DMI-HIRHAM RCM (Christensen et al. 2006). A major challenge in the coupling resides in the vastly different philosophies between such model codes as RCM's generally implement primary physical equations while hydrological models typically require substantial calibration. Further challenges include differences in spatial and temporal resolutions and computational platform differences (Windows and Linux based codes) necessitating the use of the OpenMI cross-platform model interface.

The coupled model is evaluated for a catchment in Denmark embedded within the RCM domain. Inside the shared model domains the coupled model enables two-way atmosphere/land-surface interactions via the energy-based land-surface model (SWET) (Overgaard 2005) embedded in MIKE SHE in the current configuration. In this manner the simpler DMI-HIRHAM land-surface scheme is effectively replaced by the superior land-surface component of the combined MIKE SHE/SWET model, which includes a wider range of processes at the land-surface and 3D subsurface flows as well as higher temporal and spatial resolution. The setup has proven stable and has been used for simulations of several years.

II. Method

The task of individually calibrating and preparing each of the two modelling systems is performed in two studies preceding the coupled simulations: (i) In Larsen et al. (2013) the DMI-HIRHAM performance of simulated seasonal precipitation and air temperature is investigated through systematic variations in domain size (1350x1350 km to 5500x5200 km), domain location and model grid resolution (5.5 to 11 km) in a total of eight simulations. The coupled RCM domain is chosen based on the DMI-HIRHAM results from these eight domains (Figure 1). (ii) In Larsen et al. (submitted) the MIKE SHE hydrology model is calibrated against energy flux components (sensible and latent heat), discharge and soil moisture focusing on both water balance closure and atmospheric exchange.

After the successful preparation of each of the two models the coupled simulations between the DMI-HIRHAM RCM and the MIKE SHE hydrological model are performed. To facilitate communication between the differing computation platforms the OpenMI external coupling software is used in the Windows environment (personal workstation) whereas additional code is developed in the Linux environment (Cray XT5). The coupling codes handle the temporal 'wait-execute' timing between the models, define the exchange variables and the related unit conversion factors, handle the spatial mapping and interpolation as well as handling the interpolation of variables with regard to the individual time step of the models in relation to the data exchange frequency.

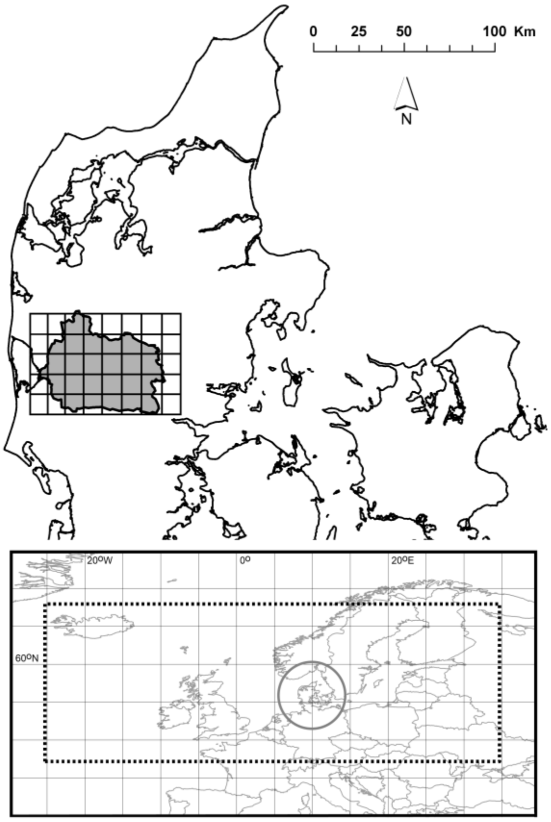


Fig. 1 The DMI-HIRHAM regional climate model domain used in the coupled simulations and the Skjern River catchment location within Denmark. Also shown is the DMI-HIRHAM grid cells of the overlapping area.

In the coupled setup DMI-HIRHAM is used as the climatic forcing for MIKE SHE supplying six climatic variables (Precipitation, air temperature, relative humidity, surface pressure, global radiation and wind speed). In the present MIKE SHE setup the SWET energy-based (Shuttleworth-Wallace scheme) land-surface model is used within MIKE SHE to facilitate the exchange of energy fluxes to DMI-HIRHAM (latent heat and surface temperature – the latter recalculated to sensible heat).

The DMI-HIRHAM domain covers app. 2800 km x 4000 km in 11 km resolution with the coupling area located with a 60 % stretch to the west wherefrom most weather systems originate. The MIKE SHE model setup embedded within the RCM domain covers the groundwater-dominated Skjern river catchment in Denmark (Jutland peninsula) consisting of mainly sandy soils and agricultural land (61 %) and having a water balance of roughly 1050 mm precipitation (gauge undercatch corrected), 500 mm discharge, 475 mm evapotranspiration and 75 mm pumping.

The coupled simulations are performed for two different periods with differing aims:

(1) 26 simulations are performed for a one-year period (1 May 2009 to 30 Apr 2010) to investigate the influence of the

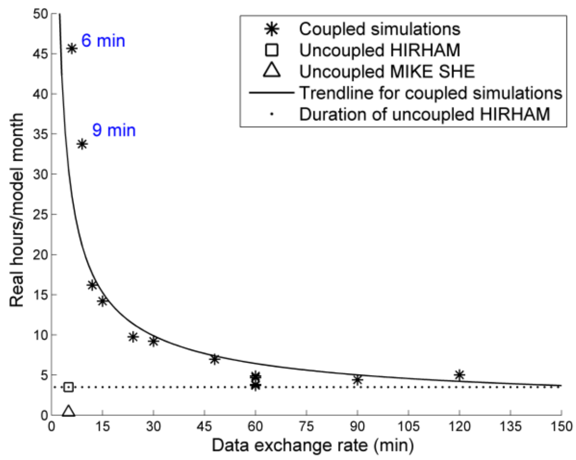


Fig. 2 The computation time for different data transfer intervals between the coupled models, DMI-HIRHAM and MIKE SHE, expressed in units of wall time per month of simulation time. The dashed line is the uncoupled DMI-HIRHAM simulation time.

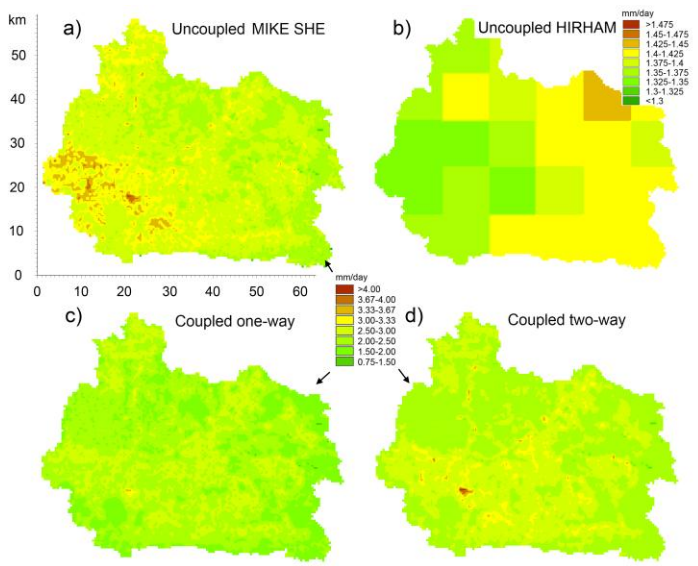


Fig. 3 The simulated spatial distribution of mean daily evapotranspiration for the period June 5-11, 2009, from MIKE SHE alone (a) (observed forcing data), DMI-HIRHAM alone (b), coupled one-way (c) (MIKE SHE simulation with DMI-HIRHAM forcing data and no feedback to DMI-HIRHAM) and fully two-way coupled with dynamic feedback (d).

inter-model data transfer interval on model performance and computation time (varied from 12 to 120 min) as well as the influence DMI-HIRHAM coupled and uncoupled model variability.

(2) 8 simulations (ongoing and therefore subject to increase) are performed in selected periods from 2000-2010 having good observation data, evaluating the coupled model

performance, as opposed to uncoupled, with regard to more severe events of drought, high precipitation and warm/cold periods.

III. Results

The data transfer interval between the two models greatly influenced the computation time which was partly related to the data exchange being file-based as opposed to memory-based due to security constraints at the computation facility. A drastic increase in computation time was seen with more frequent data exchange (Figure 2). An optimal data transfer interval in terms of model output statistics and computation time was therefore seen for data transfer rates of approximately 30 min, which was chosen for the coupled runs performed hereafter.

The resulting spatial patterns of evapotranspiration from MIKE SHE (Figure 3a) (uncoupled – observation driven), DMI-HIRHAM (Figure 3b) (uncoupled), one-way coupled (figure 3c) (DMI-HIRHAM input to MIKE SHE without feedback) and two-way coupled (Figure 3d) for a one week summer period is shown in figure 3. The plots raise several issues: (i) The higher detail in resolution when extracting results from MIKE SHE is obvious whereas the feedback to DMI-HIRHAM is aggregated into the RCM grids. (ii) The regional distribution of evapotranspiration minima and maxima varies between model runs (e.g. between figure 3a and 3b), whereas an inspection of the geographical precipitation patterns in this and preceding weeks (not shown) shows a clear correlation between the geographical distribution of higher precipitation and corresponding evapotranspiration. (iii) MIKE SHE is greatly influenced by the driving variables (observations or RCM – figure 3a and 3c) and the two-way coupled runs with MIKE SHE feedback into DMI-HIRHAM (3d) is higher as compared to one-way coupled (3c) reflecting the general higher evapotranspiration rate from MIKE SHE.

The coupled runs were assessed against the same six climatic variables exchanged from DMI-HIRHAM to MIKE SHE as these were available as gridded high resolution observation data for the periods in question. Four of these show statistical improvements with an increase in the data transfer frequency; precipitation, air temperature, wind speed and relative humidity whereas global radiation and surface pressure remain largely unaffected. Figure 4 shows time series plots of these six variables for a summer period. A high degree of variability is related to the simulated precipitation with general higher precipitation levels in the one-year period (summarized – not shown) for the coupled simulations (1048 mm) compared to uncoupled simulations (926 mm). Also, relative humidity, air temperature and wind speed is clearly more affected by method (coupled/uncoupled) than by variability. For all of these six variables however, the coupled simulations show poorer output statistics as compared the uncoupled results.

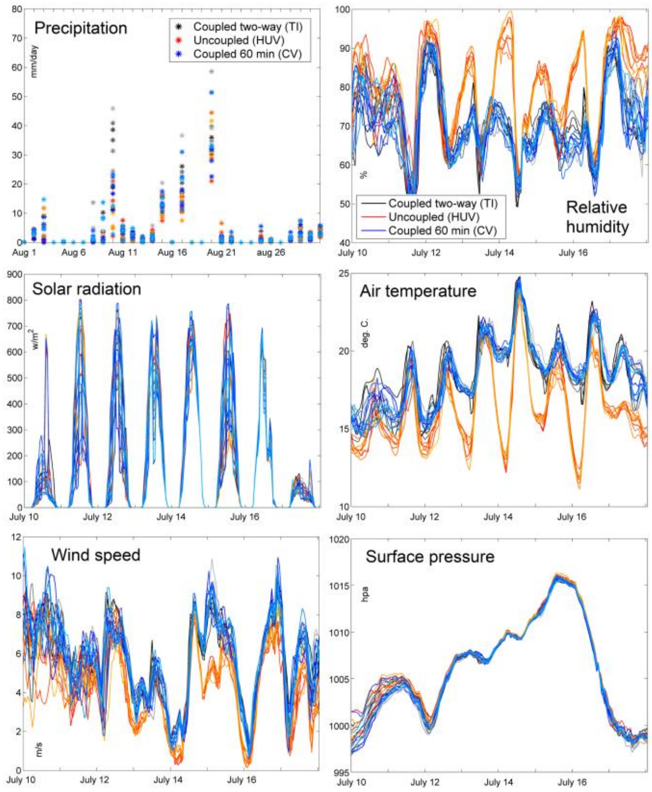


Fig. 4 The six climatic variables used in the assessment of the coupled setup for the 10-18 July period, 2009, (precipitation is 1-31 August). The TI, HUV and CV runs each represent groups of eight simulations varying the data transfer interval of 12-120 minutes (TI), assessing HIRHAM uncoupled variability (HUV) as well as fully coupled variability (CV).

IV. Discussion and Conclusions

We here present the results from two full studies employing a fully dynamic coupling performed on several years with a sub-diurnal data exchange frequency between the DMI-HIRHAM RCM and the MIKE SHE/SWET hydrology-land-surface model including full 3D subsurface flow, river flow and an energy flux based atmospheric exchange.

The poorer performance of the coupled model setup, as compared to the uncoupled setup, is explained by the calibration and refinement of both DMI-HIRHAM and MIKE SHE over a number of years, or even decades, to reproduce observations. These alterations however, are completely ignored by imposing a new model over the shared domain which inevitably results in model deterioration.

Further, the results clearly show the need to account for the RCM induced variability in the assessment methodology: The higher evapotranspiration rates from the downstream river-near areas in figure 3a/d are clearly related to the higher detail in the hydrological processes included in MIKE SHE as opposed to the ‘bucket type’ hydrology in DMI-HIRHAM (Figure 3b) but a strong influence is also induced by temporal and geographical variations in mainly precipitation.

With regards to coupled model performance an important aspect for future studies is to pursue a strategy for calibrating the coupled model setup as a whole to overcome the danger of having the model calibration compensate for biases in the other model. Further experiments would also benefit from utilizing a larger shared domain and simulating other regions. However, in the present study we emphasize the overall feasibility of the coupling tool and suggest that modelling studies of the future climate are likely to benefit from the coupled model setup.

REFERENCES

1. Christensen, O. B., Drews, M., Christensen, J. H., Dethloff, K., Ketelsen, K., Hebestadt, I., and Rinke, A. (2006). The HIRHAM regional climate model version 5, Danish Meteorological Institute, Copenhagen, Denmark, Technical Report 06-17.
2. Graham, D. N. and Butts, M. B.: Flexible, integrated watershed modelling with MIKE SHE (2005). in Singh, V. P. and Frevert, D. K., eds, Watershed Models, CRC Press, Bosa Roca, USA, ISBN: 0849336090, 245–272 .
3. Larsen, M. A. D., Thejll, P., Christensen, J. H., Refsgaard, J. C., and Jensen, K. H. (2013). On the role of domain size and resolution in the simulations with the HIRHAM region climate model, Clim. Dynam., 40, 2903–2918, doi:10.1007/s00382-012-1513-y.
4. Larsen, M. A. D., Refsgaard, J. C., Jensen, K. H., Butts, M. B., Stisen, S., and Mollerup, M (*submitted*). Calibration of a distributed hydrology and land surface model using uncertain energy flux measurements, Water Resour. Res.
5. Overgaard, J (2005): Energy-based land-surface modelling: new opportunities in integrated hydrological modeling, Ph.D. thesis, Institute of Environment and Resources, DTU, Technical University of Denmark, Denmark.

Evaluation of a Fully Coupled Atmospheric-Hydrological Modeling System for the Sissili Watershed in the West African Sudanian Savannah

Joel Arnault[#*1], Luitpold Hingerl[#2], Jan Bliefernicht[#3], Sabine Andresen[#4], Thomas Rummler[#5], Aaron Aduna[+6], Harald Kunstmann[#*7]

[#] *Institute of Geography, Augsburg University, Alter Postweg 118, 86159 Augsburg, Germany*

[*] *Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Germany*

[1]joel.arnault@geo.uni-augsburg.de, [2]luitpold.hingerl@geo.uni-augsburg.de,
[3]jan.bliefernicht@geo.uni-augsburg.de, [4]sabine.andresen@student.uni-augsburg.de,
[5]thomas.rummler@geo.uni-augsburg.de, [7]harald.kunstmann@kit.edu

[+] *WASCAL Competence Center, Ouagadougou, Burkina Faso*

[6]aaronaduna@yahoo.com

***Keywords*— Coupled modeling, West Africa, precipitation, discharge, eddy covariance measurement, energy flux partionin**

I. Abstract

The atmospheric-hydrological system of the Sissili watershed, a sub-catchment of the Black Volta river located between Burkina Faso and Ghana in West Africa, has been simulated with WRF-Hydro, i.e. the Weather Research and Forecasting (WRF) model coupled with the NCAR Distributed Hydrological Modeling System (NDHMS), for the year 2013. Model results are validated with the precipitation product from the Tropical Rainfall Measuring Mission (TRMM), and eddy covariance flux measurements at one tower site. Modelled streamflow will be validated in a future study, when discharge observations at two hydrological stations along the Sissili river will be available. Compared to a WRF stand-alone simulation, it is shown that the WRF-Hydro simulation slightly improves the flux partitioning at the location of the tower site, and that it modifies the pattern of the seasonal averaged of low-level humidity fluxes.

II. Introduction

The aim of this ongoing work is to provide a coupled modeling system able to realistically reproduce both atmospherical and hydrological components of the West African climate, which in the future will be used for land use change and climate change impact studies by the West African Service Center on Climate Change and Adaptive Land Use (WASCAL[1]).

As reported by Xue et al. (2012) in a review study, there has been a growing scientific interest for several decades to understand the causes of climate variability and Sahel droughts in West Africa. It is now admitted that this region is characterized by a strong land-atmosphere coupling, so that potential land use changes are expected to strongly affect the West African climate. However, as claimed by Agustí-Panareda et al. 2010, the full value of additional land surface information may improve the accuracy of a numerical simulation only if the basic atmospheric processes involved in the West African monsoon system are already adequately captured. Indeed, as highlighted by Nicholson (2013) in a review study, the latitudinal displacement of the tropical rainbelt over West Africa is the result of a complex scale interaction process involving sea surface temperature fluctuations of each of the global oceans, the Tropical Easterly Jet, the African Easterly Jet, the low-level African Westerly Jet, the Saharan Heat Low and Mesoscale Convective Systems (MCSs).

Regional climate models generally include one-dimensional land-atmosphere exchange processes, so that feedbacks of the three-dimensional hydrological processes on the West African climate have never been fully addressed so far. Several studies using stand-alone hydrological models have already attempted to close the terrestrial water budget in West Africa (e.g. Wagner et al. 2006 ; d'Orgeval and Polcher, 2008). Gochis et al. (2013) recently released a fully coupled version of the Weather Research and Forecasting (WRF) model (Skamarock and Klemp, 2008) referred to as WRF-Hydro, enhancing the one-dimensional NOAH land surface model (Chen and Dudhia, 2001) with surface routing, underground routing, river channel routing and a ground water module.

In this paper we present two one-year simulations for 2013, one with WRF and the other with WRF-Hydro (see simulated domain in Fig. 1a). The results are focused on the Sissili watershed (Fig. 1b), a sub-catchment of the White Volta river in North Ghana / South Burkina Faso, where streamflow and surface flux measurements are being conducted in the framework of WASCAL (Bliefernicht et al. 2013). Section II provides a description of the WRF and WRF-Hydro numerical simulations, section III details our comparison analysis between model outputs and precipitation data from the Tropical Rainfall Measuring Mission (TRMM, Huffman et al. 2007), flux measurements at the Eddy Covariance (EC) tower site in the nature reserve of the Nazinga park, and streamflow data at two sites along the Sissili river (see Fig. 1b for the location of these stations), section IV finally gives some conclusions and perspective of this on-going work.

a)

b)

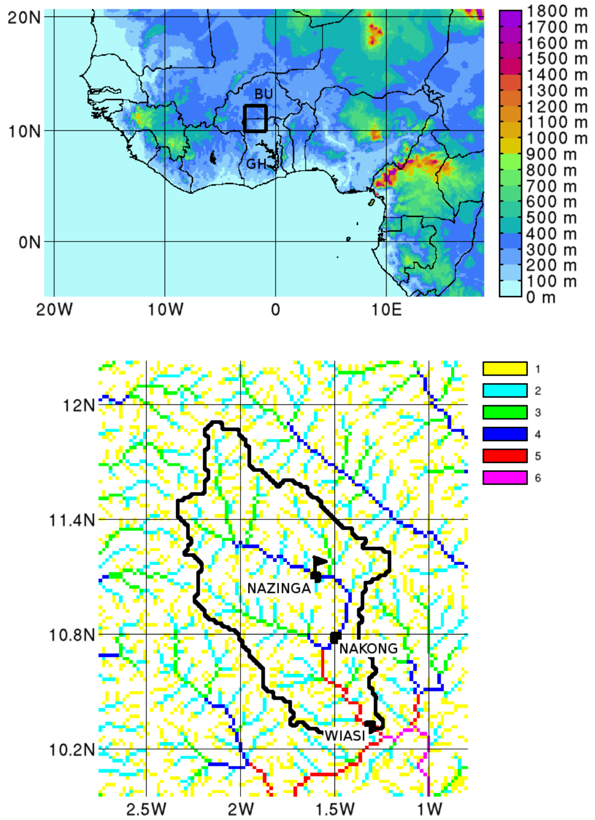


Fig. 1a Terrain elevation (m) of the outer domain used for the WRF and WRF-Hydro simulations. The height scale is given by the coloured bar on the right-side of the panel. The curved black lines delineate the West African coast and geopolitical boundaries. The black rectangle shows the location of the inner domain. Labels indicate locations of West Africa quoted in the text: BU= Burkina Faso, GH=Ghana. 1b. River network of the routing grid coupled with the inner domain of the WRF-Hydro simulation. The Strahler stream order for each of the river channels is indicated by a color, with a legend provided on the right-top corner of the panel. The bold black contour delineates the Sissili watershed. The location of the tower site in the Nazinga park and hydrological stations at Nakong and Wiasi are indicated by dark symbols and labels.

III. Coupled Modeling

A. *Setting of the Experiment*

The WRF (Skamarock and Klemp, 2008) and WRF-Hydro (Gochis et al. 2013) simulations presented here consist of two nested Mercator domains at horizontal resolutions 10 and 2 km (Fig. 1a), using one-way nesting, with 35 vertical levels up to 20 hPa (approximately 25 km). The vertical spacing is stretched from 70 to 1000 m at the lowest and highest level, respectively. The two numerical experiments start on 1st January 2013 and are run for one year. They are coupled with ERA-interim data at 0.75° horizontal resolution (Dee et al., 2011) at the initial time and every 6 h at the boundaries of the outer domain. Convection is explicit in the inner and outer domains and microphysics is parameterized with the five-class liquid and ice hydrometeors scheme of Hong et al. (2004). Radiative processes are represented with the long and short-wave radiation schemes of Mlawer et al. (1997) and Dudhia (1989), respectively. Turbulent transport of heat, moisture, and momentum is parameterized in the whole atmospheric column with the scheme of Hong et al. (2006). Land-atmosphere heat and moisture exchanges are calculated with the 1-dimensional Noah Land Surface Model (LSM) predicting soil temperature and soil moisture in a 2-m-depth four-layer column and taking into account vegetation effects (Chen and Dudhia, 2001). The model equations are integrated in the outer and inner domains at time steps of 50 and 10 s, respectively. Model outputs containing surface and soil variables, as well as the integrated terms of the surface energy budget from the NOAH LSM, are finally saved every hour.

In the WRF-Hydro simulation the inner domain is coupled with a so-called routing grid at 2 km resolution to compute overland flow and river streamflow. Note that this routing grid has the same resolution as that of the inner domain, although a disaggregation and aggregation method already implemented in the code would have allowed using a finer resolution. Subsurface flow and ground water module have not been tuned yet for the case of the Sissili watershed, so that they are not included in the numerical simulation presented here. The routing grid is obtained with the ArcGIS Stand-alone WRF-Hydro Pre-processing Tool, taking as input data the Digital Elevation Data (DEM) from the Hydrological data and maps based on SHuttle Elevation Derivatives at multiple **S**cales (HydroSHEDS) data base. It provides elevation, surface flow direction and the river network illustrated in Fig. 1b, obtained by setting the minimal pixel number defining a stream channel to three in the Pre-Processing Tool. In more details the surface water flow determined by the 1-dimentional NOAH land surface model, i.e. the sum of infiltration excess and ponded water depth, is passed to the overland flow terrain-routing module. This overland flow occurs if the depth of water on a model grid cell exceeds a specified retention depth. It is represented by a fully unsteady, spatially explicit, diffusive wave formulation taking into account adverse slopes' flows (Julien et al. 1995, Ogden 1997), using the default overland flow roughness coefficients from Vieux (2001). The overland flow discharging into a stream channel occurs when the ponded water depth of a stream channel grid cell exceeds a pre-defined retention depth. The water within the stream channel network is then routed on a pixel-by-pixel basis using a diffusive wave formulation to compute stream flow and river head, taking into account the channel parameters of Tab. 1 prescribed as functions of Strahler stream order (see Fig. 1b) (cf. Gochis et al. 2013). The remaining ponded water depth is finally used by the NOAH LSM for updating soil moisture infiltration, thus including feedbacks of surface lateral water fluxes in the inner domain of the WRF-Hydro simulation.

B. *Model Tuning*

The simulated soil moisture in the upper soil layer of the NOAH LSM at the nearest grid point to the Nazinga tower site (location shown in Fig. 1b) has been compared with the measured soil moisture at 3 cm depth during rain events at the beginning of the rainy season, i.e. in low vegetation cover condition. It was found that after the soil moisture increase accompanying the rain event the default value of the parameter fx controlling the direct evaporation, i.e fx = 2 (Ek et al. 2003), resulted in soil moisture falling off too slowly in comparison with the observation (not shown). On the other hand setting fx to one allowed the direct evaporation extracting more soil moisture in the upper soil layer, resulting in more realistic soil moisture's falling off (not shown). Fx was therefore set to one in the above simulations.

TABLE I
CHANNEL PARAMETERS

Strahler Streamorder	Bw (bottom width)	HLINK (Initial river head)	ChSSlp (side slope)	MannN (stream roughness)
1	1.5	0.02	3.0	0.55
2	3.0	0.02	1.0	0.35
3	5.0	0.02	0.5	0.15
4	10	0.03	0.18	0.10
5	20	0.03	0.05	0.07
6	40	0.03	0.05	0.05

In the NOAH LSM the infiltration excess is controlled by the tuning parameter kdt_{ref}, a higher value of kdt_{ref} leading to more infiltration, less overland flow, and lower river streamflows (Chen and Dudhia, 2001). Since the default values, i.e. $kdt_{ref} = 3$, already provides plausible results (see fig. 4), this parameter has not been further tuned. Nevertheless it is hypothesized that the tuning of this parameter is sensitive to the resolution of the routing grid, and more particularly to the density of the river channel net work (e.g. fig. 1b).

The channel parameters of Tab. 1 are the ones provided in the so-called « Noah test case » for WRF-Hydro, available on-line at http://www.ral.ucar.edu/projects/wrf_hydro. These channel parameters certainly need further tuning for the special case of the Sissili watershed, and also the overland flow roughness coefficients and retention depths. The model sensitivity to these parameters will be investigated in a future study.

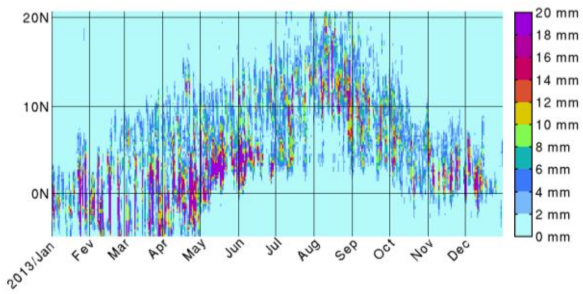
IV. RESULTS

A. *Precipitation*

A preliminary step before applying WRF-Hydro to our Sissili case-study is to make sure WRF stand-alone is able to represent the large-scale features of the West African monsoon (e.g. Augustí-Panareda et al. 2010), and to simulate precipitation fields in the region of the Sissili watershed that are close to the observations. Fig. 2 displays the latitudinal displacement of the rain belt between 8°W and 8°E during the year 2013, derived from TRMM data (2a), and from the outputs of the outer domain of the WRF simulation of section III (2b). It shows that this WRF simulation is able to reproduce the northward displacement of the rainbelt from May to August, with comparable daily precipitation amounts, especially between 10 and 12°N where the Sissili basin is located (cf. fig. 1b). It is however noticeable that the width of the modelled rainbelt during the period June-September is shrunk by about two degrees at its northern boundary compared to TRMM. Also the oceanic rainfall in TRMM is generally much higher than in the WRF simulation (compare Figs. 2a and b for January, February, November and December), certainly due to the fact that oceanic convective cells are much smaller than the continental MCSs, thus requiring a cumulus parameterization to resolve them. It is hypothesized here that the unresolved oceanic convection does not impact much model results on the continent.

The ability of the WRF and WRF-Hydro simulations to simulate realistic distribution of daily rainfall in the Sissili watershed during the rainy season of 2013 is assessed in Fig. 3. This figure shows that the outer domain of the WRF simulation and the inner domains of the WRF and WRF-Hydro simulations catch relatively well the precipitation distribution deduced from TRMM data. It is remarkable that the WRF outer domain provides the closest distribution to TRMM with a root mean square (rms) error of 3%, although TRMM data should not be considered here as the ground truth, and such a result certainly requires further validation with additional datasets (e.g. Wagner et al. 2009). The inner

a)



b)

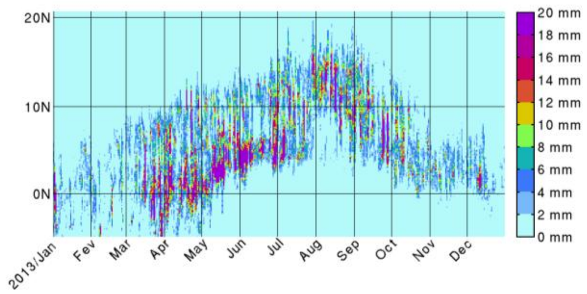


Fig. 2a Time-latitude diagram of daily precipitation zonally averaged between the longitude 8°W and 8°E, derived from the TRMM product. The horizontal axis gives the time in months from 1 January 2013 to 31 December 2013, and the vertical axis gives the latitude in degrees. The precipitation scale is given by the coloured bar on the right hand of the panel. 2b As in 2a, except from the outputs of the outer domain of the WRF simulation.

domain of the WRF simulation gives 10% more dry days (P<0.1 mm/d), while the inner-domain of the WRF-Hydro simulation gives 10% less, with respect to TRMM data. Remarkably, WRF-Hydro also increases the number of rainy days with 0.1 to 20 mm/d (Fig. 3).

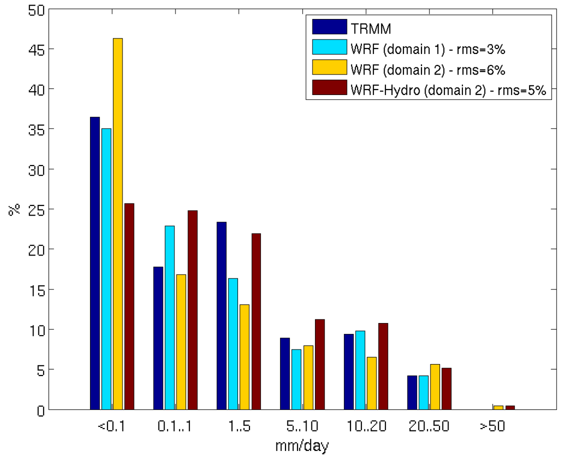


Fig. 3 Histogram of daily areal precipitation amount for the area of the Sissili watershed (see location in Fig. 1b) for the period 1st April 2013 to 30th October 2013, from TRMM, from the outputs of the outer domain of the WRF simulation, and from the outputs of the inner domain of the WRF and WRF-Hydro simulations. The horizontal axis gives spatially-averaged daily precipitation amounts in mm/day, and the vertical axis gives a percentage with respect to the whole time series used for the histogram. The rms error between each of the model-derived histogram and the TRMM-derived one is provided in the top-right corner.

B. *Discharge*

It is planned to validate surface and river routing in the WRF-Hydro simulation with two discharge observations along the Sissili river at the Nakong and Wiasi sites (see location in Fig. 1b). These observational data are not available yet so that a tuning of the hydrological parameters in WRF-Hydro has not been done, so far (cf. section III.B). The modelled daily discharges at Nakong and Wiasi are illustrated in Fig. 4. A comparison with previous years when observed discharges at these two stations are available suggests that these modelled discharges have at least the correct order of magnitude (not shown).

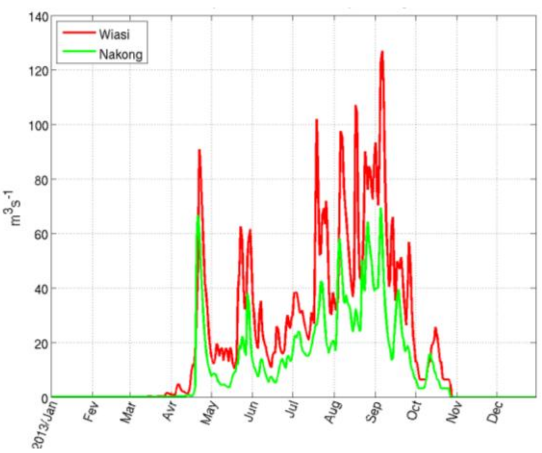


Fig. 4 Daily discharges at Wiasi (red curve) and Nakong (green curve) (see location in Fig. 1b) derived from the outputs of the WRF-Hydro simulation. The horizontal axis gives the time in months from 1 January 2013 to 31 December 2013, and the vertical axis gives discharge rates in m^3s^{-1}.

C. *Flux Partioning*

It is proposed here to compare the surface energy flux partioning ratio, i.e. the ratio between latent heat flux and the sum of latent and sensible heat fluxes, derived from the EC measurements at the Nazinga site (see location in Fig. 1b), and from outputs of the WRF and WRF-Hydro simulations. More particularly this ratio is computed daily, estimated for a one hour laps time between 12 and 13 UTC when solar radiation is maximum, for the period from 1 January 2013 to 1 December 2013. The obtained daily time series from the EC data and from the model outputs are visualized as a scatter plot in Fig. 5. It has to be noticed here that almost 45% of the daily time series deduced from the EC data is missing, including a two-month data gap in April-May. Nevertheless Fig. 5 shows that at the location of the Nazinga site the inner domain of the WRF-Hydro simulation slightly better represents the surface energy flux partitioning, with a rms error of 14% with respect to the EC data, as compared to the inner domain of the WRF simulation, (cf. rms error of 15%), and to the outer domain of the WRF simulation (cf. rms error of 16%).

D. *Large-scale impact of surface water lateral flow*

The differential map of Fig. 6, temporally averaged between 1st April 2013 and 31th October 2013, shows that the WRF-Hydro simulation predicts more soil moisture in some localized area of the Sissili watershed compared the WRF simulation, in association with a modified pattern of the averaged low-level humidity fluxes. Such a result means that taking into account surface water lateral flows in the WRF-Hydro simulation has an impact on the large-scale monsoon flux. This is certainly related to the precipitation increase discussed in section IV.A (cf. Fig. 3) (e.g. Taylor et al. 2011 ; Kunstman and Jung, 2007).

V. CONCLUSION

The atmospheric-hydrological system of the Sissili watershed has been simulated with WRF stand-alone and WRF-Hydro for the year 2013. Both WRF and WRF-Hydro simulations were able to reproduce more or less realistically

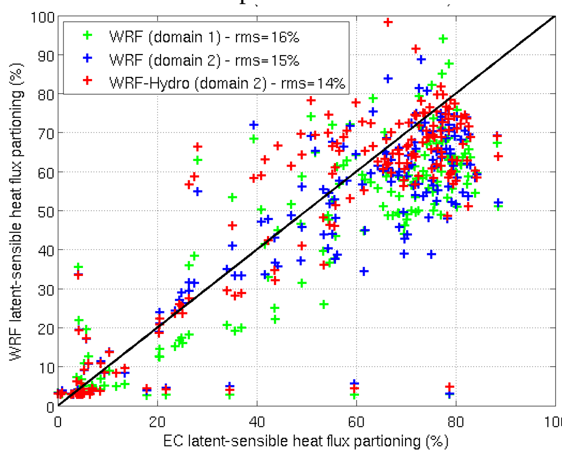


Fig. 5 Scatter plot of daily ratio between latent heat flux and the sum of latent heat and sensible heat fluxes evaluated between 12 and 13 UTC for the period from 1 January 2013 to 1 December 2013, between WRF modelled data at the grid point closest to the Nazinga site (see location in Fig. 1b), and those measured by the Eddy Covariance (EC) tower at the Nazinga site. The horizontal axis indicates this ratio from the EC measurements in percentages, and the vertical axis indicates this ratio from the WRF outputs also in percentages. Results are given in green for the outer domain of the WRF simulation, in blue for the inner domain of the WRF simulation, and in red for

the inner domain of the WRF-Hydro simulation. The rms error between each of the model outputs and EC data is provided in the top-left corner.

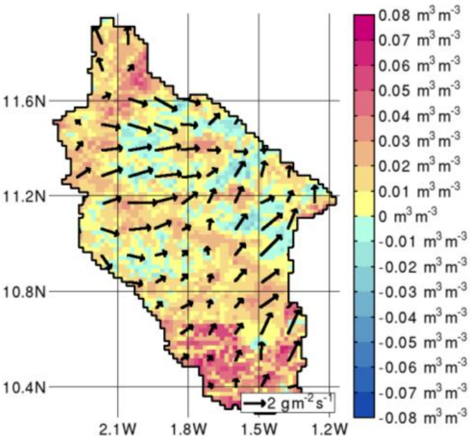


Fig.6 Differential first layer soil moisture (colour shades) and low-level humidity flux (arrows), temporally averaged for a seven-month period between 1 April 2013 and 31 October 2013, computed as a difference between the outputs of the inner domain of the WRF-Hydro and WRF simulations. The soil moisture scale is given by the coloured bar to the right, and the moisture flux scale by the arrow at the bottom-left corner.

observed characteristics of daily rainfall in the Sissili watershed as derived from TRMM data. The WRF-Hydro simulation produced a larger amount of moderate rainy days (from 0.1 to 20 mm/day) than the WRF simulation, certainly in relation with a large-scale feedback of the surface water lateral fluxes taken into account in WRF-Hydro, but not in WRF. Indeed, resolving the fate of surface water in the WRF-Hydro simulation resulted in local increase of soil moisture, evapotranspiration (not shown), and modified pattern of low-level humidity fluxes for the whole rainy season (Fig. 6). Both WRF and WRF-Hydro simulations reproduced more or less realistically the surface energy flux partitioning measured at the Nazinga tower site, WRF-Hydro improving WRF results by 1% (fig. 5).

The hydrological parameters in WRF-Hydro will be tuned in a future study, when daily discharge observations at Nakong and Wiasi for 2013 will be available. In particular routing grids at finer resolution will be tested, and the sensitivity of model results to the minimal pixel number defining a stream channel (cf. WRF-Hydro Pre-Processing Tool) and to the kdt_{ref} infiltration tuning parameter will be evaluated. Subsurface flow and ground water module will also be taken into account in order to include further processes describing the terrestrial water cycle. Finally, multi-year simulations will be carried out for model validation and for in-depth analysis of the simulation outcomes produced by WRF-Hydro.

VI. Credits

The study is part of the core research program of the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) funded by the German Ministry of Education and Research. The WRF and WRF-Hydro simulations presented here were run at the Leibniz-Rechenzentrum (LRZ, http://www.lrz.de/). Test simulations were also run of at the Deutsches Klimatrechnenzentrum (DKRZ, https://www.dkrz.de). We thank Benjamin Fersch, Christof Lorenz, Kevin Sampson, Dave Gochis, Dominikus Heinzeller, Cornelia Klein, Jonathan Siegmund, Sven Wagner, Michael Warscher, Christoph Sörgel, Johannes Werhahn, and Noah Misati Kerandi for their scientific and technical support.

References

1. Agustí-Panareda, A., G. Balsamo, and A. Beljaars. (2010). Impact of improved soil moisture on the ECMWF precipitation forecast in West Africa, Geophys. Res. Lett., 37, L20808, doi:10.1029/2010GL044748.
2. Bliefernicht, J., H. Kunstmann, L. Hingerl, T. Rummler, U. Gessner, S. Andresen, M. Mauder., R. Steinbrecher., R. Frieß, D. Gochis, U. Gessner, E. Quensah, A. Awotuse, F. Neidl, C. Jahn and B. Barry. (2013). Field- and simulation experiments for investigating regional land-atmosphere interactions in West Africa: experimental setup and first results, conference proceedings IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden
3. Chen, F. and J. Dudhia. (2001). Coupling an Advanced Land Surface-Hydrology Model with the Penn State-NCAR MM5 Modeling System. Part I: Model Implementation and Sensitivity. Mon. Wea. Rev., 129, 569-585.
4. Dee, D. P., with 35 co-authors. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quart. J. R. Meteorol. Soc., 137, 553-597.
5. Dudhia, J. (1989). Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two-dimensional model. J. Atmos. Sci., 46, 3077-3107.
6. Ek, M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley. (2003). Implementation of Noah land surface model advancements in the National Centers for Environmental Prediction operational mesoscale Eta model, J. Geophys. Res., 108(D22), 8851, doi:10.1029/2002JD003296.
7. Gochis, D.J., W. Yu, and D. N. Yates. (2013). The WRF-Hydro model technical description and user's guide, version 1.0. NCAR Technical Document. 120 pages.
8. Hong, S.-Y., J. Dudhia, S.-H. Chen. (2004). A Revised Approach to Ice Microphysical Processes for the Bulk Parameterization of Clouds and Precipitation. Mon. Wea. Rev., 132, 103-120.
9. Hong, S.-Y., Noh, Y. and Dudhia, J. (2006). A new vertical diffusion package with an explicit treatment of entrainment processes. Mon. Wea. Rev. 134, 2318–2341.
10. Huffman, G.J., R.F. Adler, D.T. Bolvin, G. Gu, E.J. Nelkin, K.P. Bowman, Y. Hong, E.F. Stocker, and D.B. Wolff. (2007). The TRMM Multi-satellite Precipitation Analysis: Quasi-Global, Multi-Year, Combined-Sensor Precipitation Estimates at Fine Scale. J. Hydrometeor., 8: 38-55.
11. Julien, P. Y., Saghafian, B., and F. L. Ogden. (1995). Raster-Based Hydrologic Modeling of Spatially-Varied

Surface Runoff", Water Resources Bulletin , AWRA, 31(3), p. 523-536.

12. Kunstmann, H., and G. Jung. (2007). Influence of soil moisture and land use change on precipitation in the Volta Basin of West Africa. International Journal of River Basin Management, 5, 9-16.
13. Mlawer, E. J., S. J. Taubman, P.D. Brown, M. J. Iacono, and S. A. Clough. (1997). Radiative transfer for inhomogeneous atmosphere: RRTM, a validated correlated-k model for the long- wave. J. Geophys. Res. 102(D14), 16663–16682.
14. Nicholson, S. E. (2013). The West African Sahel: A Review of Recent Studies on the Rainfall Regime and Its Interannual Variability, ISRN Meteorology, vol. 2013, Article ID 453521, 32 pages. doi:10.1155/2013/453521
15. Ogden, F.L. (1998). CASC2D Reference Manual. Department of Civil and Environmental Engineering, U-37, University of Connecticut, 83 p.
16. d'Orgeval, T, and J. Polcher. (2008). Impacts of precipitation events and land-use changes on West African river discharges during the years 1951–2000, Clim. Dyn., 31, 249–262.
17. Skamarock, W. C. and J. B. Klemp. (2008). A time-split nonhydrostatic atmospheric model for weather research and forecasting applications. J. Comp. Phys. 227, 3465_3485.
18. Taylor A. M., A. Gounou, F. Guichard et al. (2011). Frequency of sahelian storm initiation enhanced over mesoscale soil-moisture patterns, Nature Geoscience, vol. 4, no. 7, pp. 430–433.
19. Vieux, B. E. (2001). Distributed hydrologic modeling using GIS, Kluwer Academic Publishers, Dordrecht, The Netherlands.
20. Wagner, S., H. Kunstmann, A. Bárdossy, C. Conrad, and R. R. Colditz. (2009). Water balance estimation of a poorly gauged catchment in West Africa using dynamically downscaled meteorological fields and remote sensing information. Physics and Chemistry of the Earth 34, 225-235.
21. Wagner, S., H. Kunstmann, and. A. Bárdossy. (2006) Model based distributed water balance monitoring of the White Volta catchment in West Africa through coupled meteorological-hydrological simulations. Adv. Geosci. 9, 39-44.

Using the WRF-Hydro Model for 100 Years Flood Event in Israel

A. Givati[1], E. Fredj[2], T. Rummler[3], D. Gochis[4], W. Yu[4], H. Kunstmann[5]

[1]*Israeli Hydrological Service, Water Authority, Israel*
[2]*The Jerusalem College of Technology, Israel*
[3]*University of Augsburg, Germany*
[4]*National Center for Atmospheric Research, Boulder, Colorado, U.S*
[5]*Karlsruhe Institute of Technology, Germany*

Keywords - Flood forecasting, Extreme flood event, Floods in Simi arid environment

I. Abstract

The WRF-Hydro model was employed for the first time to provide precipitation forecasts on a country-wide scale and examined vs. observations in three flood events during the 2012-2013 and 2013-2014 winters (wet season) in Israel and the surrounding region. This period was characterized by unique climate and hydrologic conditions: severe drought on the one hand, and extreme flood events on the other hand. The WRF model has been coupled with the NCAR distributed Hydrological model system (WRF-Hydro) to simulate stream flows at several locations in the Ayalon basin in central Israel for different types of floods: relatively small magnitude, relatively high magnitude and 1% extreme flood event. The WRF-Hydro forecasts were verified against measurements from rain gauges and hydrometric stations in the basin. The simulation results indicated a good correlation with the actual measurements, even for the rare events. The total storms-simulated precipitations were close to the actual measurements and the peak discharges were at the same level of excess probability as the observed peak flow. However, the timing of the simulated peak discharges and the hydrograph shape showed significant bias in some cases. Using observed precipitation as an input to the hydrological model in exchange for the simulated precipitation leads to a much more accurate simulations which indicates that much of the bias was due to the WRF input.

The hydro-meteorological modeling system that ingests the high-resolution gridded WRF forecasts coupled with the hydrological components was proven to be a useful tool for flood forecasting and warning purposes, and an improvement on the current situation in this region. The modeling tools presented in this study will be used operationally to support the water-drainage and resource-assessment process, and can be applied to studies of seasonal hydro-climate forecasting and to future scenarios of climate change.

II. Introduction

Several studies indicated that floods and drought are the most dangerous hazard in the Mediterranean due to both the number of people affected and to the relatively high frequency by which human activities and goods suffer damages and losses (Llasat-Botija et al., 2007). This is especially true for arid and semi-arid regions such as in the Middle East, where estimation and prediction of the highly variable precipitation .

During the rainy season is critical for predicting stream flows and the recharge of reservoirs.

Lastly, it is widely expected that climate change will increase the occurrence of severe rainfall events in many regions around the world (Milly et. al, 2001; Wagener et. al, 2010; Kundzewicz et. al, 2010; Trenberth, 2011; Zwiers et. al ,2013; Andersen et. al, 2013). In the Mediterranean, the effects could be increasing droughts on one hand (Törnros and Menzel, 2014; Hoerlin et. al, 2012; Dai, 2011) and intense floods on the other hand (Alpert et. al, 2011; Samuels et. al, 2011). Land use changes and increasing urbanization are also factors that may enhance flood intensity and frequency (Bronstert et. al, 2002; Chang et. al, 2008; Githui et. al, Delgado et. al 2010; Kalantari, 2014).

Advanced warning systems can be very beneficial in reducing flood risk and will allow authorities to be better prepared and by that to mitigate damages. The accuracy of flood forecasting is highly determined in the quantitative precipitation forecasts and it spatial distribution (Younis et. al, 2008). Hydrological models can use precipitation input from various sources like rain gauges, radar, remote sensing or simulated precipitation from numerical weather models. The simulations may be improved by coupling atmospheric and hydrological models (Chen et. al, 2001; Jasper et. al 2002; Seuffert et. al, 2002; Yanhong et. al, 2006; Bouilloud et. al 2010; Wang et. al 2012; Marty et. al, 2013; Davolio et. al, 2013).

Operational weather forecast centers provide relatively coarse (~16-27 km grid increment) precipitation forecasts, which are incapable of resolving the necessary details of the complex precipitation structures that are forced by mesoscale orography, land-surface heterogeneities, and land-water contrasts. In the Eastern Mediterranean region, strong sea-air interaction and orographic forcing produce precipitation with dramatic gradients that are generally missed by the coarse-grid operational models. In Israel, the precipitation patterns are particularly complex, and large precipitation contrasts occur over a relatively small geographical distance (2–10km). Large climatological precipitation gradients in Israel are caused by the preferred tracks of extra-tropical cyclones, the complex orography and the coastline shape (Saaroni et al. 2009). In order to overcome this problems Givati et.al (2012) used the Weather Research and Forecasting (WRF) model to provide precipitation forecasts during the 2008-2009 and 2009-2010 winters (wet season) for Israel and the surrounding region where complex terrain dominates. The daily precipitation input used for calculating daily stream flow at the upper Jordan River. They showed that by using high-resolution (4–1.3km) grids, the WRF was capable of forecasting daily precipitation amounts and structures in northern Israel reasonably well, and by that they improved the hydrological simulations.

Despite the progress that has been done in numerical weather predictions and hydrological simulations, real-time stream-flows predictions for a big domain such as a country scale that includes various climatological and hydrological regimes with extreme arid terrains was not present for this region up to now.

During the rainy seasons of 2012-13 and 2013-14 two severe floods events took place in Israel and the surrounding countries (January 2013 and December 2013) which caused tremendous flooding both in urban areas like the Tel Aviv metropolis and in arid areas at the Negev desert in the southern part of the county. Those floods enlarged the awareness for flood protection and forecasting in Israel and the region.

The main purpose of this study is to present a new tool that it aim is to improve the current situation in respect to flood forecasting in this region by using the NCAR fully coupled high-resolution WRF-Hydro model. The model offers opportunities for further Hydro-climate simulations under different climates and future scenarios of land use for the 21th.

III. Methodology

The WRF-Hydro model coupling extension package (WRF setup with dx=3km and NDHMS, NCAR distributed hydrological model, subgrid dx=100m) provides a means to couple hydrological model components to atmospheric models and other Earth System modeling architectures. The model has been developed to facilitate improved representation of terrestrial hydrologic processes related to the spatial redistribution of surface, subsurface and channel waters across the land surface and to facilitate coupling of hydrologic models with atmospheric models.

An initial suite of terrestrial hydrologic routing physics is contained within version 1.0 of WRF-Hydro. The model is a fully distributed, 3-dimensional, variably-saturated surface and subsurface flow model. The implementation of terrain routing and, subsequently, channel and reservoir routing functions into the 1-dimensional Noah land surface model was motivated by the need to account for increased complexity in land surface states and fluxes and to provide physically-consistent land surface flux and stream channel discharge information for hydrometeorological applications. The original implementation of the surface overland flow and subsurface saturated flow modules into the Noah land surface model were described by Gochis and Chen (2003). The entire modeling system was coupled to the Weather Research and Forecasting (WRF) mesoscale meteorological model thereby permitting a physics-based, fully coupled land surface hydrology-regional atmospheric modeling capability for use in hydrometeorological and hydroclimatological research and applications.

The main parameters for calibration in the model are for setting the amount of surface water for a giving volume of precipitation (surface infiltration and the partitioning of total runoff into surface and subsurface runoff) and determine the water movement from the slopes and the channels, and by that the hydrograph shape. The model allows setting a Manning roughness coefficient for each stream order in the domain. Surface roughness values for a specific land use class at a specific basin are also possible. Detailed information regarding the model physics and calibration can be found at Gochis et al 2013.

The WRF-Hydro model domain was set up with 3 domains: 140x140 (27 km) 187x 184 point horizontal-grid outer domains with a 9km grid interval, and a third 120x222 point nested-grid domain at 3km grid spacing, which is nested in domain 2. The WRF model simulations were initialized with 0.5 degree NOAA/NCEP GFS (Global Forecasting System) model data. The domain covers areas in southern Lebanon, Israel, West Jordan and South Egypt. This study is focusing on the Ayalon basin, locate in central Israel. This watershed is a sub-basin of the Yarqon basin and it drainage 800km^2. The River starts to flow from the Judea and Samaria hills at the East and drainage west towards the Mediterranean Sea, crossing the city of Tel Aviv. There is a large variability in elevation along this watershed, from 800-900 meters at the headwaters to sea level. The watershed area is located in a semi-arid climate zone with a mean annual precipitation of about 580 mm/y. This watershed contains the most densely populated region of the country and cross the Tel Aviv Metropolis. Five hydrometric stations are located in the basin: Ayalon – Lod, Natuf, Ayalon–Ben Gurion A.P, Beit Arif and

Ayalon–Ezra. The Ayalon–Ezra is located at the bottom of the basin at the entrance to Tel Aviv. During extreme flood events the water level at the Ayalon River raise more than 5.5 m (17.5 m above sea level) and floods the Ayalon Highway (the busy road in the country), the rail way and even some neighborhoods in south Tel Aviv. Beside it importance and vulnerability at the country scale, another motivation for simulating the flow at the Ayalon basin is the 1% floods event that hit the basin on 08/01/13. During this flood an historical peak discharge record was broken at Ayalon–Lod hydrometric station and the Ayalon Highway and railway were flooded.

2.3 Case studies for the WRF-Hydro simulations at the Ayalon basin. The WRF-Hydro was run and verified against measured hourly stream flow during the major flood event that took place in 04-11/01/2013, Extremely rare flood events with excess probability of 1% for peak discharges at some parts of the basin. The January 2013 storm was unusual in several aspects: precipitation amount (up to 300 mm in some areas in the basin), the intensity of the precipitation (over 30 mm/h in some stations), the storm duration (6 days of non-stop precipitation) and the high values of soil moister and storm rainfall-runoff coefficients (rainfall-runoff ratio of 40% according to the IHS reports).

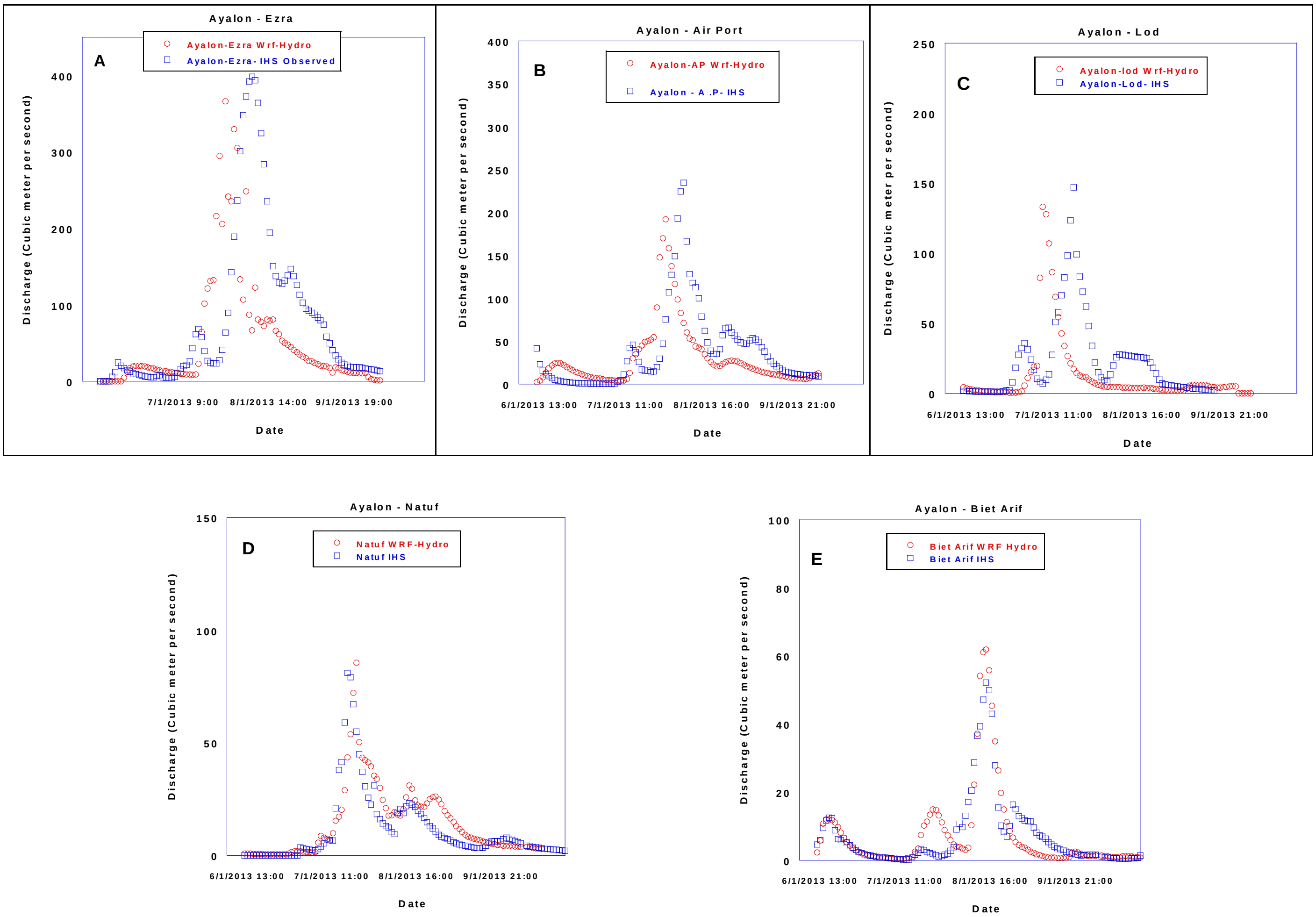


Fig. 2 A-E: WRF-Hydro Simulated discharge (in red) vs. observed discharge (in blue) at 5 hydrometric stations at Ayalon basin: Ayalon-Ezra (A), Ayalon-A.P (B), Ayalon-Natuf (B), Ayalon-Lod (C), Ayalon-Natuf (D), Biet Arif (E)

IV. RESULTS

Figure 1A-E displays the WRF-Hydro simulated vs. observed hydrographs for the five hydrometric stations in the basin at the January 2013. This storm was the strongest and caused to the most severe floods across central Israel. It can be seen that the WRF-Hydro was able to simulate well the general development of the floods either at the bottom of the basin (1A, Ayalon-Ezra station, at the entrance to the city of Tel Aviv), at the middle of the basin (1B, Ayalon-Ben Gurion A.P station) and at the 3 upward tributaries (1C, 1D, 1E). At all five cases the observed peak discharges were higher than the simulated and almost all simulated peak discharges were few hours early then the observed. However, the simulated peak discharges were at the same range of excess probability of the observed. This was the case even for the Lod station were the excess probability of the peak discharge was only 1%.

V. DISCUSSION AND CONCLUSIONS

The results presented this study show the high potential of using the WRF-Hydro model for flood forecasting in semi-arid areas like Israel. The WRF model was able to simulate well the total accumulated precipitation for the 3 different storms and those results in agreements with previous studies at this region (Givati et. al, 2012; Lynn et al, 2014). The peak discharges calculated by the WRF-Hydro were relatively close to the observed and where at the same level of excess probability values as the observed flow, which can be considered as a successful flood forecasting. Such results can be beneficial and helpful to design makes.

The model is still high, but it seems that the value is still worthwhile. A possible way to reduces bias is running the WRF-Hydro using data assimilation for short predictions (Tsai et. al, 2014).

More studies and simulations are needed in order to represent better the hydrological responses to different meteorological and soil moister conditions (for example the extreme arid catchments at southern Israel) and varies soil and land use properties. Using initial conditions based on ensemble of meteorological models (like ECMWF in addition to the GFS and also the GEFS, the GFS ensemble) may improve the WRF precipitation input and so the hydrological simulations. Using probabilities for floods stages/level (change for floods) based on ensemble can also help to overcome the precipitation accuracy issue. Davolio et al, 2013 found that a multi-model ensemble provides a better indication concerning the occurrence, intensity and timing of the two observed discharge peaks in northern Italy, using COSMO-LEPS as a mesoscale meteorological model coupled with a distributed rainfall-runoff model (TOPKAPI). This study represents cases with unique Hydro-meteorological conditions from arid and semi-arid regions such in the Middle East.

REFERENCES

1. Andersen, T. K., and Marshall Shepherd, J., 2013. Floods in a Changing Climate. Geography Compass, 7: 95–115. doi: 10.1111/gec3.12025
2. Alpert, P., T. Ben-Gai, A. Baharad, Y. Benjamini, D. Yekutieli, M. Colacino, L. Diodato, C. Ramis, V. Homar, R. Romero, S. Michaelides and A. Manes, 2002. The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values, Geophys. Res. Lett., 29, 11, 31-1- 31-4, June issue.
3. Bouilloud, L., Chancibault, K., Vincendon, B., Ducrocq, V., Habets, F., Saulnier, G. M., & Noilhan, J., 2010. Coupling the ISBA Land Surface Model and the TOPMODEL Hydrological Model for Mediterranean Flash-Flood Forecasting: Description, Calibration, and Validation. Journal of Hydrometeorology, 11(2).
4. Bronstert, A., Niehoff, D. and Bürger, G. 2002, Effects of climate and land-use change on storm runoff generation: present knowledge and modeling capabilities. Hydrol. Process., 16: 509–529. doi: 10.1002/hyp.326.
5. Chang, H. and Franczyk, J. 2008. Climate Change, Land-Use Change, and Floods: Toward an Integrated Assessment. Geography Compass, 2: 1549–1579. doi: 10.111.1.
6. Chen, F. & Dudhia, J. 2001. Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity. Monthly Weather Review, 129(4), 569-585.
7. Dai A.. Drought under global warming: a review. 2011. WIREs Clim Change , 2: 45-65. doi: 10.1002/wcc.81
8. Davolio, S., Miglietta, M. M., Diomede, T., Marsigli, C., and Montani, A.: 2013. A flood episode in northern Italy: multi-model and single-model mesoscale meteorological ensembles for hydrological predictions, Hydrol. Earth Syst. Sci., 17, 2107-2120, doi:10.5194/hess-17-2107-2013, 2013.
9. Delgado, J.,Llorens, P., Nord, G., Calder, I.R., Gallart, F., 2010. Modelling the hydrological response of a Mediterranean medium-sized headwater basin subject to land cover change: The Cardener River basin (NE Spain). Journal of Hydrology , 383(1-2) 125-134.
10. Gao, B., Yang, D., Gu, X., & Xu, J. 2012. Flood forecast of Three Gorges reservoir based on numerical weather forecast model and distributed hydrologic model. Journal of Hydroelectric Engineering, 1, 005.
11. Givati, A., Lynn B., Liu Y. and A. Rimmer, 2012. Using the WRF Model in an Operational Streamflow Forecast System for the Jordan River, J. Applied Meteorology and Climate, Vol. 51, No. 2., 285-299.
12. **Givati A., D. Rosenfeld, 2013. The Arctic oscillation, Climate change and the effects on precipitation in Israel, Atmospheric Research, 133, 114–124.**
13. Gochis D J, Chen F. Hydrological Enhancements to the Community North Land Surface Model. NCAR/TN-454+STR, NCAR Technical Note[M]. Research

Applications Program, National Center for Atmospheric Research, Boulder, Colorado ,2003.

14. Githui, F., Mutua, F., Bauwens, W., 2010. Estimating the impacts of land-cover change on runoff using the soil and water assessment tool (SWAT): case study of Nzoia catchment, Kenya. Hydrological Sciences Journal , 54(5) 899-908.
15. Gochis, D.J., W. Yu, D.N. Yates, 2013. The WRF-Hydro model technical description and user's guide, version 1.0. NCAR Technical Document. 120 pages. Available online at: http://www.ral.ucar.edu/projects/wrf_hydro/ .
16. Hoerlin, M.,Eischeid, J., Perlwitz, J., Xiaowei, Q., Zhang, T., Pegion, P., 2012. On the Increased Frequency of Mediterranean Drought, Journal of Climate. 25, 2146-2161.
17. Hong, S. Y. and J. O Lim, 2006. The WRF Single-Moment 6-ClassMicrophysics Scheme (WSM6). J. Korean Meteor. Soc., 42, 2, 129−151.
18. Hong, S. Y. and J. O Lim, 2010: Evaluation of the WRF Double-Moment 6-Class Microphysics Scheme for Precipitating Convection, Advances in Meteorology, vol. 2010, Article ID 707253, 10 pages, 2010. doi:10.1155/2010/707253.
19. Llasat-Botija, M., Llasat, M.C., López, L., 2007. Natural hazards and the pressin the western Mediterranean region. Adv. Geosci. 12, 81–85.
20. Lynn, B., Leung R., Khain, A, Givati, A., 2012. Sensitivity of Precipitation Forecasts to Microphysical Parameterization and Grid-Resolution at Convective-Allowing and Cloud-Allowing Scales, Monthly Weather Review, In review.
21. Lin, C. A., L. Wen, M. Beland, and D. Chaumont, 2002. A coupled atmospheric-hydrological modeling study of the 1996 Ha! Ha! River basin flash flood in Quebec, Canada. Geophys. Res. Lett., 29, 1026, doi:10.1029/2001GL013827.
22. Marty, R., Zin, I., & Obled, C. 2013. Sensitivity of hydrological ensemble forecasts to different sources and temporal resolutions of probabilistic quantitative precipitation forecasts: flash flood case studies in the Cévennes-Vivarais region (Southern France). Hydrological Processes, 27(1), 33-44.
23. Milly. P. C. D ., R. T. Wetherald., K. A. Dunne, & T. L. Delworth., 2001. Increasing risk of great floods in a changing climate, Nature, 415, 514-517.
24. Wagener, T., M. Sivapalan, P. A. Troch, B. L. McGlynn, C. J. Harman, H. V. Gupta, P. Kumar, P. S. C. Rao, N. B. Basu, and J. S. Wilson, 2010. The future of hydrology: An evolving science for a changing world, Water Resour. Res., 46, W05301, doi:10.1029/2009WR008906.
25. Tsai, C.C., Yang, S.C., Liou Y-C., 2014. Improving quantitative precipitation nowcasting with a local ensemble transform Kalman filter radar data assimilation system: observing system simulation experiments, Tellus A, 66, 21804.
26. Trenberth, K. E. 2011. Changes in precipitation with climate change. Climate Research, 47(1), 123.
27. Törnros T. and L. Menzel, 2014. Addressing drought conditions under current and future climates in the Jordan River region, Hydrol. Earth Syst. Sci., 18, 305–318.
28. Yanhong, G., Guodong, C., Wenrui, C., Fei, C., Gochis, D., & Wei, Y. 2006. Coupling of Enhanced Land Surface Hydrology with Atmospheric Mesoscale Model and Its Implement in Heihe River Basin . Advances in Earth Science, 21(12) 1283-1282 .
29. Kalantari, Z., Lyon, S. W., Folkeson, L., French, H. K., Stolte, J., Jansson, P. E., & Sassner, M. 2014. Quantifying the hydrological impact of simulated changes in land use on peak discharge in a small catchment. Science of the Total Environment, 466, 741-754.
30. Kundzewicz, Z. W., Hirabayashi, Y., & Kanae, S. 2010. River floods in the changing climate—observations and projections. Water resources management, 24(11), 2633-2646.
31. Jasper, K., Gurtz, J., & Lang, H. 2002. Advanced flood forecasting in Alpine watersheds by coupling meteorological observations and forecasts with a distributed hydrological model. Journal of hydrology, 267(1), 40-52.
32. Jianzhu Li, Ping Feng, Zhaozhen Wei, 2013. Incorporating the data of different watersheds to estimate the effects of land use change on flood peak and volume using multi-linear regression, Mitigation and Adaptation Strategies for Global Change, 18, 8, 1183.
33. Wang, L., Koike, T., Wang, M., Liu, J., Sun, J., Lu, H., & Xu, X. 2012. Use of Integrated Observations to Improve 0–36 h Flood Forecasting: Development and Application of a Coupled Atmosphere-Hydrology System in the Nanpan River Basin, China. Journal of the Meteorological Society of Japan, 90, 131-144.
34. Saaroni, H., N. Halfon, B. Ziv, P. Alpert and H. Kutiel, 2009. Links between the rainfall regime in Israel and location and intensity of Cyprus lows, Int. J. Climatol. DOI: 10.1002/joc.1912.
35. Seuffert, G., P. Gross, C. Simmer, and E. F. Wood, 2002. The influence of hydrologic modelling on the predicted local weather: Two-way coupling of a mesoscale land surface model and a land surface hydrologic model. J. Hydrometeorology., 3, 505–523.
36. Samuels, R., G. Smiatek, S. Krichak, H. Kunstmann and P. Alpert, 2011. Extreme value indicators in highly resolved climate change simulations for the Jordan River area, JGR, 116, 10.1029/2011JD016322.
37. Younis, J., Anquetin, S., and Thielen, J. 2008. The benefit of high-resolution operational weather forecasts for flash flood warning, Hydrol. Earth Syst. Sci., 12, 1039-1051, doi:10.5194/hess-12-1039-2008.
38. Zwiers, F. W., Alexander, L. V., Hegerl, G. C., Knutson, T. R., Kossin, J. P., Naveau, P.,. & Zhang, X. 2013. Climate extremes: Challenges in estimating and understanding recent changes in the frequency and intensity of extreme climate and weather events. In Climate Science for Serving Society (pp. 339-389). Springer Netherlands.

High Resolution Numerical Modeling of an Idealized Daytime Urban Heat Island Circulation

S. Falasca[#1], F. Catalano[*2], M. Moroni[#3]

[#] *DICEA, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy*

[1]serena.falasca@uniroma1.it, [3]monica.moroni@uniroma1.it

[*]*ENEA, Via Anguillarese 301, 00123 Rome, Italy*

[2]franco.catalano@enea.it

***Keywords*— Boundary Layer turbulence, Large Eddy Simulations, Turbulent Kinetic Energy budget, Urban Heat Islan**

I. ABSTRACT

Large Eddy Simulations of an idealized diurnal Urban Heat Island (UHI) have been performed using the Weather and Research Forecasting (WRF) model. The influence of several control parameters on the structure of the Planetary Boundary Layer over the urban areas is investigated through the study of the second order statistics distributions and Turbulent Kinetic Energy budget analysis.

The scaling relationships, as a function of the control parameters, allows to correlate UHI breeze characteristics to bulk parameters.

II. INTRODUCTION

Modifications to the land properties connected to the urbanization produce alterations of the local surface energy balance, originating the Urban Heat Island (UHI) phenomenon. The circulation associated to the UHI circulation influences local weather patterns (Giovannini et al. 2014) and the hydrological cycle (Li et al. 2013) and can contribute to natural hazards interacting with larger scale phenomena.

III. METHODOLOGY

The Weather Research and Forecasting (WRF) model (Skamarock et al. 2008) is used in Large Eddy Simulation mode.

The urban area is centered with respect to the x axis and extends for the whole length along the y axis. The land use properties (soil characteristics and the anthropogenic heat flux release) are differentiated for the urban and rural regions. The UHI is simulated using the following surface energy balance equation:

$$(1-\alpha) R_S \downarrow + R_L^* + Q_f - H_{sg} - H_e = Q_G \qquad (1)$$

Where α is the albedo, R_S is the shortwave radiation term toward the soil, R_L^* is net long wave radiation term, H_{sg} is the sensible heat flux at the ground toward the atmosphere, H_e is the latent heat flux. Q_G is the soil heat flux. The shortwave radiation term in (1) is computed using the WRF Dudhia scheme and R_L^* is parameterized. The same value of the incident radiation is imposed on the entire domain and the different thermal behavior of the urban and rural areas is reproduced. The net radiative forcing has a sinusoidal law and simulations start with a radiation equal to zero and a stably stratified environment.

The grid has a horizontal constant resolution equal to 50 m and a vertical parabolic stretching such that Δz is about 2 m close to the ground and 90 m at the top of the domain. A modified version of the WRF Turbulent Kinetic Energy (TKE) scheme is used in order to consider the effect of the grid's anisotropy in the calculation of the filter width (Catalano and Moeng 2010). The surface model based on the Monin-Obukhov similarity theory, and the 5-layers slab land surface scheme are used. Periodic lateral boundary conditions are imposed on both x and y directions. At the model top, constant pressure, free slip and zero vertical velocity conditions are assumed. The Coriolis effects are neglected and the atmosphere is assumed to be dry.

Twelve cases reproducing a diurnal UHI are considered. Constant imposed parameters in the simulations are: domain and urban area dimensions, initial ambient temperature profile, incident solar radiation. The varying control parameters are: geostrophic wind intensity, albedo, thermal inertia, roughness, anthropogenic heat flux. Case 1 is the reference case and the other simulations represent test cases for the study of the influence of each control parameter; then every simulation presents the same values of parameters as Case 1, except for one of the control parameters.

Results are normalized according to the similarity theory proposed for nighttime low aspect-ratio UHI by Lu et al. (1997a and b).

IV. RESULTS

The bottom thermal forcing for both urban and rural areas is expressed in terms of kinematic surface heat flux. The PBL height is computed using a hybrid method proposed by Catalano and Moeng (2010) for inhomogeneous terrains. The UHI intensity is computed as the difference between the surface temperature over the urban and rural area.

First- and second- order statistics are obtained through an averaging procedure along the y-axis and along five contiguous grid cells along the x-axis.

TABLE II
CONSTANT PARAMETERS FOR SIMULATIONS

N_x, N_y, N_z		400x100x58
UHI width D (m)		2000 (rectangular)
Surface heat forcing ($W\ m^{-2}$)	U	R_S= 450
	R	R_L^* = -50
Brunt-Vaisala frequency N (s^{-1})		0.0128

TABLE III
NUMERICAL SIMULATIONS AND COMPUTED PARAMETERS

	$\overline{w'\theta'}_s$ (Kms^{-1})		$\Delta\theta_m$ (K)	z_i (m)
	R	U		
Case 1	0.105	0.170	2.42	1106
Case 2	0.105	0.175	2.18	1107
Case 3	0.106	0.171	2.55	1107
Case 4	0.109	0.177	2.65	1107
Case 5	0.105	0.179	1.24	1106
Case 6	0.105	0.178	1.63	1106
Case 7	0.011	0.196	7.23	697
Case 8	0.063	0.179	4.15	994
Case 9	0.096	0.173	2.67	1106
Case 10	0.104	0.222	3.89	1165
Case 11	0.106	0.197	3.19	1165
Case 12	0.105	0.211	3.61	1165

Fig. 1 shows the UHI aspect-ratio (z_i/D) versus the Froude number computed according to the Lu theory for the numerical results produced in this study and literature data (Falasca et al. 2012); both the axis in the plot are in logarithmic scale. The plot shows that the numerical results produced in this work collapse on the line of equation $z_i/D=2.86Fr$ together with literature data.

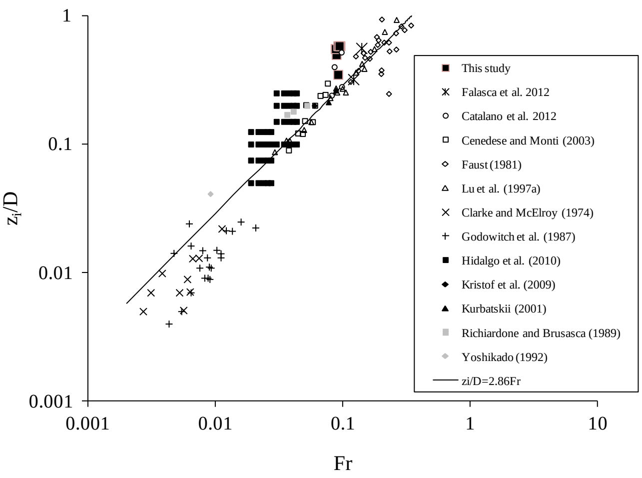


Fig. 3 Ratio of UHI aspect ratio z_i/D versus Froude number for numerical results produced in this study compared with literature data

Fig. 2 shows the cross-sections of the y-averaged heat flux and the PBL depth estimate for Case 1 at t = 6 h. The heat flux is positive except in the entrainment area, near the PBL top, which corresponds to the estimated PBL height, z_i, shown in the same plot.

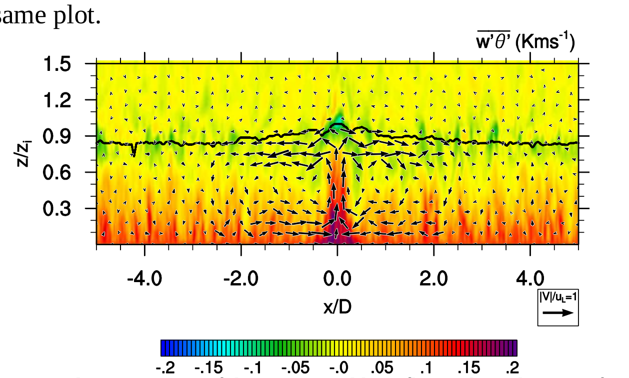


Fig. 4 Vertical cross-section of the y-averaged heat-flux and wind vectors for Case 1 at t = 6 h. The black full line represents the PBL depth estimate over the entire domain

The governing equation for the total (resolved plus subgrid components) turbulent kinetic energy E reads for the present study as follows:

$$\frac{\partial E}{\partial t} = \underbrace{-\bar{u}\frac{\partial E}{\partial x}}_{adv\_h} \underbrace{-\bar{w}\frac{\partial E}{\partial z}}_{adv\_v} \underbrace{-\left(\overline{u'^2}\frac{\partial \bar{u}}{\partial x} + \overline{u'w'}\frac{\partial \bar{w}}{\partial x} + \overline{u'v'}\frac{\partial \bar{v}}{\partial x} + \overline{w'^2}\frac{\partial \bar{w}}{\partial z} + \overline{u'w'}\frac{\partial \bar{u}}{\partial z} + \overline{v'w'}\frac{\partial \bar{v}}{\partial z}\right)}_{S}$$
$$+ \underbrace{\frac{g}{\theta}\overline{w'\theta'}}_{B} \underbrace{-\left(\frac{\partial}{\partial x}\overline{u'E} + \frac{\partial}{\partial z}\overline{w'E}\right)}_{T} - \varepsilon \qquad (1)$$

The analysis of the vertical profile of terms in (1) allows to characterize the PBL turbulence related to the UHI presence. Fig. 3 shows the vertical distribution of the TKE budget terms investigated for Case 1 at the UHI center, where the highest TKE values are located, at t = 6h. In the lower part of the PBL the buoyancy is the primary source of turbulence; the shear is important near the surface, and in the upper part of the layer. The dissipation term is nearly constant with height and balances the buoyancy at the bottom of the domain. The turbulent transport term is the main source of TKE at the PBL top and determines an important redistribution of TKE from the lower half of the PBL to the upper half of the PBL. As regard to the advection terms, the horizontal one is almost equal to zero and the vertical one has values near zero in the lower part of the PBL and becomes significant in the upper part.

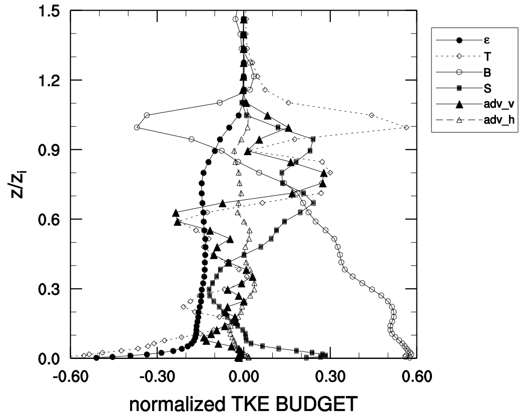


Fig. 5 Normalized vertical profiles of the y-averaged TKE budget for the reference case (Case 1) at t = 6 h at the center of the domain

V. Discussion and conclusions

The structure of the PBL in presence of the UHI is similar to that of a convective BL and the incidence of the geostrophic wind of increasing velocity makes it similar to a shear driven PBL.

This study demonstrates that the TKE spatial distribution is especially influenced by the geostrophic wind, while the albedo and the anthropogenic heat flux have a great impact on the TKE magnitude. The geostrophic wind determines a deep redistribution of the TKE budget. The higher albedo difference between urban and rural area determines lower absolute values of the TKE budget normalized profiles, despite the dependence of the scaling parameter from the surface heat flux. Thermal inertia influences the dissipation profile that presents a bulge up to the PBL top and the vertical advection term in its maximum value.

The verified relation between the Froude number and the UHI aspect ratio connects land use and geometric attributes of the city to PBL structure features.

Reliable hydro-meteorological information included in the framework of a coupled multiscale model (as WRF-hydro) are expected to significantly improve UHI modeling and the development of appropriate mitigation strategies.

References

1. Falasca, S., M. Moroni, Cenedese A. (2012). Laboratory simulations of an urban heat island in a stratified atmospheric boundary layer, Journal of Visualization, 16, 39-45.
2. Catalano, F., Moeng, H.-C. (2010). Large-eddy simulation of the daytime boundary layer in an idealized valley using the Weather Research and Forecasting numerical model. Boundary-Layer Meteorology, 137, 49-75
3. Giovannini, L., Zardi, D., de Franceschi, M., Chen, F. (2014). Numerical simulations of Buondary-layer processes and urban-induced alterations in an Alpine Valley. International Journal of Climatology, 34, 1111-1131
4. Li, D., Bou-Zeid, E., Baeck, M.L., Jessup, S., Smith, J.H. (2013). Modeling land surface processes and heavy rainfall in urban environments: sensitivity to urban surface representations. Journal of applied hydrometeorology, 14, 1098-1118
5. Lu, J., Arya, S.P., Snyder, W.H., Lawson, Jr R.E. (1997a). A laboratory study if the urban heat island in a calm and stably stratified environment. Part I: Temperature field. Journal of Applied Meteorology, 36, 1377-1391
6. Lu, J., Arya, S.P., Snyder, W.H., Lawson, Jr R.E. (1997b): A laboratory study if the urban heat island in a calm and stably stratified environment. Part II: Velocity field. Journal of Applied Meteorology, 36, 1392-1402
7. Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D. O.D., Barker, D.M., Duda, M.G., Huang, X.-Y., Wang, W., Powers, J.G. (2008). A description of the advanced research WRF version 3. NCAR/TN-475, 113 pp