low parameterization and computational efforts) is able to accurately simulate the LAI. Results also highlight the importance of including the plant growth model in the LSM when studying the climate-soil-vegetation interactions and the impact of watershed management practices on the scarce water resources over moderate to long time scales. The inclusion of the vegetation model in the LSM is demonstrated to be essential for assessing the impact of climate change (e.g., decrease of precipitation and increase of air temperature) on the water budget of a water limited region.

H42M-06 1715h

Role of Vegetation in Controlling Water Balance at the Land-Atmosphere Interface in Water Limited Ecosystems

Bridget R Scanlon[1] (512 471 8241; bridget.scanlon@beg.utexas.edu); Dan Levitt[2] (505 424 6955; dlevitt@seabase.com); Kelley E Keese[1] (512 791 5921; kelley.keese@beg.utexas.edu); Robert C Reedy[1] (512 471 7244; bob.reedy@beg.utexas.edu); Jirka Simunek[3] (909 369 4855; jsimunek@ussl.ars.usda.gov); Lloyd T Desotell[4] (702 295 1494; desotellt@nv.doe.gov); Charles F Lohrstrofer[4] (702 295 5688; lhorstcf@nv.doe.gov)

[1]Univ. of Texas at Austin, Jackson School of Geosciences, 10100 Burnet Rd., Bldg. 130, Austin, TX 78758, United States

[2]Science & Engineering Associates, 3205 Richards Land, Suite A, Santa Fe, NM 87505, United States

[3]US Salinity Laboratory, 450 W. Big Springs Rd., Riverside, CA 92507, United States

[4]US Dept. of Energy, Bechtel Nevada, Las Vegas, NV 89193, United States

Understanding the role of vegetation in the water balance at the land-atmosphere interface is critical for assessing the impact of changes in vegetation and climate on the near surface water balance. Monitoring nonvegetated and vegetated weighing lysimeters in the Mojave Desert in Nevada USA over an eight-year period demonstrated strong coupling between large increases in soil-water storage in response to El Nino cycles in 1994/1995 and 1998 winter periods and vegetative response that rapidly removed the infiltrated water through evapotranspiration (ET). Soil water storage in the vegetated lysimeter was about half of that in the nonvegetated lysimeter at the end of the 8 yr monitoring period, which indicates that even in this arid climate, vegetation is extremely important in removing water from the soil through ET. The lack of monitored drainage in the nonvegetated lysimeter is an artifact of the seepage face lower boundary condition, which prohibits drainage unless the soils become almost saturated. Modeling analysis indicated that increased soil water storage in the nonvegetated lysimeter should result in drainage if the seepage face is replaced with unit gradient conditions as in the natural system. Traditional approaches for water balance modeling that use vegetative parameters, such as Leaf Area Index (LAI), as forcing greatly underestimated soil water storage because they did not include the two-way coupling between water storage and vegetation dynamics. Inverse modeling was used to demonstrate the two-way coupling between soil water storage (related to climate) and vegetation dynamics and involved minimizing the sum of squared residuals between measured and simulated soil water storage by varying LAI, which was used as a surrogate of vegetation dynamics. Inverse modeling reproduced the measured water storage much better than forward modeling using prescriptive LAI because feedback between water availability and vegetation dynamics was included in the inverse modeling approach. This monitoring and modeling analysis reveals strong coupling between vegetation dynamics and soil water storage changes related to precipitation and underscores the need to incorporate this dynamic interaction between climate and vegetation in numerical simulations to reproduce the monitored water balance. The role of vegetation in controlling the water balance of these arid systems has important implications for water resources and waste containment. The tight coupling between vegetation and soil water storage indicates that land use change could significantly alter the water cycle and that vegetation changes associated with climate change could affect the impact of climate change on the water cycle.

H42M-07 1730h

Ecotonal Control on Vadose-Zone Fluxes in Arid Regions Over Very Long Time Scales

Fred M Phillips[1] (505-835-5540; phillips@nmt.edu)

Michelle A. Walvoord[2] (303-236-4998; walvoord@usgs.gov)

Renee Sandvig[1] (505-835-5484; rsandvig@nmt.edu)

[1]New Mexico Tech, 801 Leroy Place, Socorro, NM 87801

[2]U.S. Geological Survey - WRD, Denver Federal Center, Box 25046, MS 413, Lakewood, CO 80225-0046

Recent studies indicate that vegetation plays an important role in regulating recharge in semiarid and arid basins over very long time scales. Several lines of evidence from desert floor environments in the southwestern United States suggest that vegetation has established essentially permanent upward hydraulic gradients, effectively precluding diffuse recharge since the transition from woodland to xeric scrub in the early Holocene. However, less xeric vegetation (such as the pygmy piñon and juniper forest) may support significant diffuse recharge. We show comparative water potential and porewater chemistry profiles collected from various vegetation communities in the Chihuahuan Desert of west Texas. The modeled soil water (vapor and liquid) flux regimes illustrate a conversion from substantial downward fluxes under the mixed woodland to upward fluxes under grassland and xeric scrub. Model results also indicated a trend in increasing drying front propagation depth from the grassland to recently-encroached xeric scrub to well-established xeric scrub. Drying fronts are the result of upward soil water fluxes initiated up to 16 thousand years ago in the xeric scrub community. In contrast, the nearby woodland community supports active, and likely episodic, recharge on the order of 5 to 15 mm yr^{-1}. The mechanism by which some vegetation takes up essentially all seasonally available moisture within the root zone, preventing downward soil water fluxes for periods of thousands of years, but adjacent vegetation communities regularly permit downward fluxes, remains to be determined. Nevertheless, these results suggest that understanding the relation between vegetation community and vadose-zone hydrological processes may be the most profitable avenue toward quantifying diffuse groundwater recharge. We hypothesize that vegetation type may be a reasonable proxy for estimating recharge in semiarid and arid basins. Ongoing research is intended to test the hypothesis of ecotonal control on soil water fluxes by means of a vadose-zone drilling project along an aridity index gradient in central New Mexico.

H42M-08 1745h

Vegetation, climate change, and diffuse groundwater recharge in arid and semiarid environments

Eric Small (eric.small@colorado.edu)

CU Boulder, Geological Sciences Box 399 2200 Colorado Ave, Boulder, CO 80309

Several different types of data show that there is currently little or no diffuse groundwater recharge at many arid and semiarid sites worldwide. However, evidence for diffuse recharge has been found at some sites where mean annual precipitation (P) is much less than mean annual potential evapotranspiration (PET), particularly where soils are coarse and hydroclimatic conditions are variable. In addition, there is evidence suggesting that diffuse recharge was widespread during the last glacial period, likely a result of the climate or vegetation (or both) at that time. We investigate how vegetation and climate control the rate of diffuse groundwater recharge using a one-dimensional, liquid-only flow model for desert vadose zones. The flow model is driven by a stochastic parameterization of climate at a point that includes storm size distribution and seasonality of precipitation and potential evapotranspiration, constrained by data from over 700 climate records from the southwestern U.S. The type of vegetation is varied to investigate how constraints on transpiration resulting from physiological and phonological limitations impact recharge. Storm size distribution and seasonality control the frequency of intervals when P exceeds PET and the amount of water that accumulates in the root zone during these intervals, which in turn controls the flux out the bottom of the root zone. Climates with larger and more infrequent storms yield recharge at lower values of P/PET. Seasonality has a larger influence on recharge than storm size distribution, and the effects are similar for both coarse and fine soils. The relative timing of P and PET maxima is critical: recharge occurs at P/PET values that are lower by 0.2 when the rainy season occurs during the winter instead of the summer. The type of vegetation also provides a critical control on recharge. In particular, when plant phenology excludes transpiration during part of the year, recharge occurs at much lower values of P/PET. In contrast, the most negative water potential at which a plant can sustain transpiration has little impact on recharge, at least for the desert species studied. Finally, interactions between climate and vegetation change are critical to explain the long-term variations in diffuse recharge observed in arid and semiarid regions worldwide.

H51A MCC: 3022 Friday 0800h

Catchment Processes in the Tropics I

(joint with B)

Presiding: **R C Sidle,** Kyoto University**; A Ziegler,** National University of Singapore

H51A-01 0800h INVITED

Overland Flow in Tropical Rainforests: Causes and Consequences

Helmut Elsenbeer[1] (helsenb@rz.uni-potsdam.de)

Sarah Godsey[2] (godseyse@email.uc.edu)

[1]Institute of Geoecology University of Potsdam, PO Box 60 15 53, Potsdam 14415, Germany

[2]Dept of Earth and Planetary Science UC Berkeley, 307 McCone Hall, Berkeley, CA 94720-4767

With the expansion of forest hydrology research from mid-latitudinal to tropical areas, a diversity of hydrological process patterns began to emerge that has since been tentatively explained along geographical lines. Our much improved knowledge of runoff generation processes, however, allows us to discard geographical straitjackets and explain the quite diverse hydrological functioning of tropical rainforests world-wide in terms of those soil, meteorological, and geomorphologic factors that control the movement of water on landscapes. An appreciation of these factors, which do not include land cover, is essential for an understanding of the occurrence of overland flow in tropical rainforest, which still seems to be viewed as a contradiction in terms in spite of mounting evidence to the contrary. A perceived link between hydrological processes and land cover and the intuitively appealing, perceived role of forests in the water cycle has resulted in overland flow being viewed as a consequence of human intervention, but not as the natural consequence of a set of environmental factors inherent in many tropical rainforests. This set of environmental factors includes characteristic permeability-depth profiles and rainfall regimes that, in combination, will yield overland flow as a matter of course; in fact, overland flow has emerged as a hydrological process characteristic of vast areas of rain forest-covered tropical soilscapes. These characteristic permeability-depth profiles may, in a simplifying approximation, be reduced to a sequence of two soil layers: a thin (compared to the overall soil depth) surficial layer of high permeability (compared to prevailing rainfall intensities), and a thick subsurface layer of very low permeability. This sequence reflects the decrease of nonstructural, or bioturbation-induced, macroporosity (which is in many places accompanied by a textural change) observed in some widespread tropical soils; it contrasts with rather uniform permeability-depth profiles that reflect nearly depth-independent structural, or mineralogy-controlled, macroporosity observed in other tropical soils. The latter result in a generally vertical movement of soil water, whereas the former tends to generate saturation overland flow. With overland flow established as a characteristic hydrological process of some extensive tropical rainforest ecosystems, we explore its implications for land-use change and nutrient budget studies. Where overland flow is part of undisturbed ecosystem processes, land-use change cannot possibly result in a qualitative change of hydrological processes: it may increase the amount of overland flow, but it cannot cause its occurrence. Although land-use and land cover change of tropical rainforests do affect hydrological processes in many ways, there is no evidence to support generalizations about abrupt shifts in hydrological pathways. Likewise, the effect of land-use change on nutrient losses is likely to be overestimated where the natural' nutrient losses were underestimated by ignoring overland flow-mediated and hence rainfall event-related catchment outputs. Overland flow must be recognized as an intrinsic, even typical, hydrological process of many tropical rainforests, while the casual assumption of its occurrence as the unique consequence of land-use change is not defensible.

H51A-02 0815h

Overland Flow Generation and Soil Hydraulic Properties in Two Catchments in Central Panama

Sarah Godsey[1]

Helmut Elsenbeer[2]

Robert Stallard[3]

[1]University of Cincinnati, Dept. of Civil and Environmental Engineering P.O. Box 210071, Cincinnati, OH 45221-0071, United States

[2]Institute of Geoecology, University of Potsdam, PO Box 60 15 53, Potsdam 14415, Germany

[3]USGS-WRD, 3125 Marine St. (RME127), Boulder, CO 80303-1066, United States

Land management decisions in the Panama Canal watershed directly impact the hydrological functioning of the canal itself. Knowledge of the hydrological conditions in the forested portions of the watershed provides a baseline comparison for future land use changes. We chose to work on two streams on Barro Colorado Island that are representative of large regions of the watershed. These two streams respond differently to the same storm events: Conrad Trail Stream exhibits a fairly subdued and delayed response and Lutz Creek stream is flashier. In order to understand these differences, we investigated the soil saturated hydraulic conductivity (Ks) of the two catchments and studied the frequency of overland flow generation. The Ks measurements in dominant geologies in Lutz Creek as well as in Conrad Trail Stream are great enough at shallow depths (median Ks = 29.7, 65.6 and 38.3 mm/hr) that Hortonian overland flow is rare, but a marked decrease in Ks in Lutz Creek catchment at 30 cm (to 1.4 and 5.8 mm/hr) indicates that a perched water table leading to saturated overland flow is the likely runoff mechanism in Lutz Creek. In Conrad, Ks does not decrease as markedly with soil depth, and a perched water table would form at about 60 cm below the surface (median Ks = 0.7 mm/hr). Therefore, more water is able to infiltrate into the soil in Conrad Trail Stream and saturated overland flow is less common. Overland flow was generated much more frequently in Lutz Creek than in Conrad Trail Stream, with lower thresholds of storm magnitude, duration, antecedent wetness and intensity required to generate overland flow. We also quantified the importance of microtopographic features such as concentrated flow lines and the results have implications for experimental design at other field sites. The Lutz Creek and Conrad Trail stream information will provide a useful baseline for land management decisions.

H51A-03 0830h

Runoff Production in the Upper Rio Chagres Catchment, Panama

Justin M. Niezialek[1] (justinn@engr.uconn.edu)

Fred L. Ogden[1] (860-486-2771; ogden@engr.uconn.edu)

[1]Dept. of Civil and Environmental Engineering, 261 Glenbrook Rd, U-2037 University of Connecticut, Storrs, CT 06269, United States

Runoff production in watersheds in the seasonal tropics is governed by a number of factors. The mountainous 414 sq. km upper Rio Chagres watershed offers a unique opportunity to better understand the runoff production mechanisms in seasonal tropical catchments through data analysis and modeling. The upper Rio Chagres catchment provides the majority of inflows to the Panama Canal, has been monitored for over 60 years as part of canal operations. Discharge data are available at both the catchment outlet (Chico gaging station) and an internal catchment location (Rio Piedras gaging station). There are also seven tipping bucket recording rain gages in and around the catchment. Analysis of runoff data reveals anomalously-high runoff production efficiencies early in the wet season. Furthermore, the existence of two quasi-stable base flow regimes during the wet season imply critical threshold storages. Initial field studies have shown that the soils are water repellent during the dry season. Runoff data from the 80 sq. km Rio Piedras subcatchment reveal ephemeral flows throughout the wet season, indicating significant heterogeneity in runoff production and deep groundwater circulation. Preliminary hydrologic modeling is performed with the Sacramento Soil Moisture Accounting Model (SAC-SMA), calibrated using data from 1988 and verified using data from 1989. Further modeling on the flood of 28-31 December, 2000 is also performed. Modeling using the distributed parameter GSSHA model combined with the Sacramento groundwater module allows simulation of distributed runoff. However, the role of interception by the triple-layer tropical canopy and the magnitude of evapotranspiration are uncertain. New data collection is proposed in the Rio Chagres catchment to help quantify interception and evapotranspiration. This instrumentation will include measurements of rainfall above the canopy, cloud stripping, stemflow, throughfall, soil moisture, groundwater, interflow, evapotranspiration and overland runoff. Intensive field observations during the transition from dry to wet season are proposed to develop predictive understanding of unusually-high runoff production efficiencies.

H51A-04 0845h

Assessing Land Cover Change in Sumber Jaya, Indonesia, by Rainfall-Runoff Time Series Analysis

Tumiar K Manik[1]

Roy C Sidle[2] (81-774-38-4116; sidle@slope.dpri.kyoto-u.ac.jp)

[1]National University of Singapore, Department of Geography, Singapore 117570, Singapore

[2]Kyoto University, Disaster Prevention Research Institute, Gokasho, Kyoto, Uji 611-0011, Japan

Sumber Jaya catchment in South Sumatra, Indonesia, has experienced rapid land use change in the past 20 years. To investigate the impact of land cover change on catchment function for large spatial and temporal scales, a frequency distribution and time series analysis of daily rainfall and water discharge (1974-1998) were used. Rainfall from three gages distributed along the main river conformed to Gamma distributions. Most of the water discharge also followed Gamma distributions, but with different scale and shape parameters; for some years these data better fit a normal distribution. The autocorrelation coefficients showed that rainfall means were non-stationary and exhibited no seasonal pattern (i.e., random). Water discharge was also non-stationary, but exhibited some trends and a strong seasonal pattern. Because no differences were detected for either spatial or temporal patterns of rainfall in the area and the large scale topography was assumed to be similar, the differences in frequency distribution and time series pattern between rainfall and water discharge is inferred as effects of land cover change. Results from both analyses imply that the land functions as a buffer for infiltrated rainfall and discharges more water to the river as subsurface flow rather than surface runoff. This finding was consistent for > 20 yr of annual records and for every 5 yr period. However, sub-catchment and hillslope studies currently underway may indicate differences in hydrologic response that cannot be elucidated by such rainfall-runoff statistical analyses.

H51A-05 0900h

Effects of Forest Roads on Internal Hydrological Process in Tropical Catchments

Roy C Sidle[1] (81-774-38-4116; sidle@slope.dpri.kyoto-u.ac.jp)

Junjiro Negishi[2] (artp1469@nus.edu.sg)

Ruyan Siew[2] (heehahoo@singnet.com.sg)

Shoji Noguchi[3] (noguchi@affrc.go.jp)

Nik Abdul Rahim[4] (rahimnik@frim.gov.my)

[1]Kyoto University, DPRI, Gokasho, Kyoto-fu, Uji-shi 611-0011, Japan

[2]National University of Singapore, Department of Geography, 1 Arts Link, Singapore 117570, Singapore

[3]JIRCAS, FRIM office, Kepong, Kuala Lumpur 52109, Malaysia

[4]Forestry Research Institute of Malaysia, Kepong, Kuala Lumpur 52109, Malaysia

Hydrological response within a headwater forest catchment in Peninsula Malaysia was monitored during a series of storms to assess the influence of unimproved logging roads on hydrological pathways. Four small to moderate sized storms occurred on consecutive days in December 2002, producing a sequence of relatively dry to wet antecedent conditions. Storm duration and maximum 5-min intensity ranged from 1 to 2.4 h and 25 to 102 mm/h, respectively; the last storm was the largest. Discharge was measured at two v-notch weirs at natural drainage outlets along the 50 m-section of the road, at another weir at the truncated outlet of a geomorphic hollow along the road cutslope, and at the 13 ha basin outlet. Peak runoff from the road surface corresponded closely (within minutes) to rainfall peaks; at the basin outlet, lag times between rainfall peaks and peak runoff varied from 40 to 66 min. During the first three storms, no discharge was measured from the hollow and most of the road runoff was Hortonian overland flow with runoff coefficients increasing from 36 to 118% (unit contributing area basis) for the sequential storms. During the third storm some subsurface flow was intercepted at the cutslope. Large water storage in the upper catchment prior to the fourth storm facilitated outflow from the zero-order basin that was almost 6 times greater than the unit area discharge of the 13 ha basin. This discharge from the hollow and subsurface flow intercepted at the road cut extended the falling limbs of these hydrographs about 10 h after the cessation of rainfall; road runoff from earlier storms ceased within minutes of the storm end. Discharge from the 50 m road segment contributed 4.4% of the total catchment runoff during the fourth storm; scaled to the entire road system, this constitutes about 60% of storm runoff. For the three smaller storms with drier antecedent conditions, roads contributed 4 to 10% of total basin stormflow. Clearly roads have a major effect on storm runoff generation and hydrological pathways in tropical catchments, especially during wet antecedent conditions.

H51A-06 0915h

Effects Of Forest Roads On Internal Biogeochemical Pathways In Tropical Catchments

Junjiro N Negishi (artp1496@nus.edu.sg)

Roy C Sidle[2] (sidle@slope.dpri.kyoto-u.ac.jp)

Shoji Noguchi[3] (noguchi@affrc.go.jp)

Nik Abdul Rahim[4] (rahimnik@frim.gov.my)

Alan D Ziegler[1] (thaihawk@hotmail.com)

[1]National University of Singapore, Department of Geography, 1 Arts Link, Kent Ridge, Singapore 117570, Singapore

[2]Kyoto University, Geohazards Division, Gokasho, Uji, Kyoto, Kyoto 611-0011, Japan

[3]Japan International Research Center for Agricultural Sciences, 1-1, Ohwashi, Tsukuba, Ibaraki, Ibaraki 305-8686, Japan

[4]Forest Research Institute Malaysia, Kepong, Kuala Lumpur 52109, Malaysia

Knowledge of the effects of forest roads on biogeochemical processes within headwater catchments is limited in the tropics. Hydrological response along with fluxes and yields of fine sediment ($<$ 250 mm) and dissolved nutrients (e.g., DOC and K+) were measured from a 50-m segment of logging road and the greater catchment (13 ha; harvested in winter 1999-2000) in Peninsular Malaysia during four consecutive storms in December 2002. Due to very low infiltration capacities, Hortonian overland flow was generated almost instantaneously on the road surfaces during the storm events. Maximum specific flux of sediment, DOC and K+ were observed during the fourth storm with the highest intensity, precipitation, and antecedent moisture: 5.15 kg/sec/ha, 473 g/sec/ha, and 465.81 g/sec/ha at the road segment; and 37.81 g/sec/ha, 53.27 mg/sec/ha, and 17.83 mg/sec/ha at the catchment outlet, respectively. The average enrichment ratio, i.e., road yield divided by catchment average yield on an unit area basis, for four storms was always greater than ten-fold (72.3, 16.1, and 12.4 for sediment, DOC, and K+, respectively), indicating the road surface produced disproportionately high amounts of those elements relative to the other parts of the catchment. The relatively high enrichment ratio for sediment relative compared to DOC and K+, suggests that subsurface and riparian sources also contributed to fluxes of dissolved nutrients. Furthermore, the enrichment ratio for DOC and K+ were generally higher during low intensity storms, indicating that a higher proportion of the catchment yield was attributed to roads, probably because the other parts of the catchment were not as hydrologically responsive. Thus, even for relatively small rain events with dry antecedent conditions, forest roads may alter internal biogeochemical pathways by acting as a source of dissolved nutrient and sediment (with adsorbed nutrients) and by redirecting natural hydrological pathways into the stream.

H51A-07 0930h

Using Distributed-Hydrology-Soil-Vegetation Model to Study Road Effects on Stream flow and Soil Moisture

Lan Cuo[1] (+1 808 956-6453; cuo@hawaii.edu)

Thomas W. Giambelluca[1] (+1 808 956-7390; thomas@hawaii.edu)

Alan D. Ziegler[1,2] (thaihawk@hotmail.com)

Michael A. Nullet[1] (+1 808 956-6453; mnullet@hawaii.edu)

[1]Department of Geography, University of Hawaii at Manoa, 2424 Maile Way, Honolulu, HI 96822, United States

[2]Department of Geography, National University of Singapore, 1 Arts Link, Kent Ridge, Singapore 117570SGP, Singapore

The distributed-hydrology-soil-vegetation model (DHSVM) was applied in Pang Khum Experimental Watershed (PKEW), located near 19.05°N, 98.65°E in the mountainous region of northern Thailand, headwaters of the Chao Phraya River system. PKEW has a highly seasonal rainfall regime, with 90% of the annual 1200-1400 mm rainfall occurring during the southwest summer monsoon. The elevation of PKEW ranges from approximately 1100 to 1500 m. Total road area including road banks is about 1.2% of the basin area. About 57% of the road area occurs on slopes steeper than 10%. All roads are unpaved. Land cover in PKEW is affected by swidden agriculture. Six land cover and nine soil classes are identified in the basin. We have been working in the area since 1997 as part of the Thailand Roads Project (TRP). Within the basin, we are monitoring microclimate at two sites, soil moisture at four sites, and rainfall at five sites. Streamflow is measured at the outlet. Based on digital elevation data, DHSVM explicitly accounts for the spatial distribution of the stream and road networks, soil depth, soil and vegetation types. The model run period, including warm up, calibration and validation, is from August 1997 to January 2001. Field measurements provide forcing data, calibration data, and guidance in parameter selection. Model calibration and validation were done by aggregating simulated hourly soil moisture and stream flow into daily values and comparing them with aggregated daily measurements. For the calibration period, RMSEs of soil moisture and streamflow were lower than the observed variability as represented by the standard deviation, median absolute deviation, and (for stream flow) interquartile range. Model performance drops in validation period, but RMSEs remain near or lower than observed variability. We ran DHSVM with and without roads to examine their effects. Significant effects of roads were found despite the very low proportion of the watershed covered by roads and road banks. Streamflow for road and non-road cases was significantly different ($p < 0.0001$) based on the Wilcoxon signed rank test. In general, roads increase peak volume for short, intense storms, but reduced whole-period discharge by about 5.5%. Soil moisture was affected in cells where roads occur. In cells where water exited the road onto the hillslope, soil moisture was higher than it was without the road. In cells with roads, but without water flowing onto the hillslope, soil moisture was higher in some cases and lower in others.

URL: http://webdata.soc.hawaii.edu/climate/Roads1/Roads.html

H51A-08 0945h

Observation And Simulation Of Monsoon Rainfall Over A Tropical Mountainous Region In Southeast Asia

Koji Dairaku[1] (81(29)-850-2102; dairaku.koji@nies.go.jp)

Seita Emori[2] (emori@jamstec.go.jp)

Taikan Oki[3] (oki@chikyu.ac.jp)

[1]National Institute for Environmental Studies, 16-2 Onogawa Tsukuba, Ibaraki 305-8506, Japan

[2]Frontier Research System for Global Change, 3173-25 Showamachi, Kanazawa-ku, Yokohama City, Kanagawa 236-0001, Japan

[3]Research Institute for Humanity and Nature, 335 Takashima-cho, Marutamachi-dori Kawaramachi nishi-iru, Kamigyo-ku, Kyoto 602-0878, Japan

From 1998, as a part of GAME-Tropics (the Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment (GAME)) research activities in Thailand in Southeast Asia, high-temporal-resolution ground-based rainfall observations have been conducted in a mountainous area. It is clear that the quantity of rainfall varies with elevation in this watershed throughout the rainy season. The orographic characteristics of rainfall are attributed to higher duration and frequency rather than to intensity. A two-dimentional, nonhydrostatic compressible dynamic-equations model was used. In this numerical experiment, two mechanisms were observed: 1) Convective clouds over mountains are activated in the evening, and 2) stratus formed by radiative cooling or heating at the tops of clouds and low-level orographically triggered convective clouds cause a seeder-feeder mechanism. The results of the simulation are quite consistent with the fact that a larger quantity of rainfall recorded at a higher altitude can be attributed to a greater duration and higher frequency rather than to a greater intensity of rainfall.

H51B MCC: 3024 Friday 0800h

Interactions Between Fluids and Fractures II *(joint with T, V, NG, MR)*

Presiding: **L C Murdoch,** Clemson University**; L Germanovich,** Georgia Institute of Technology

H51B-01 0800h

Experimental Analysis of the Role of Fluid Transport Properties in Fluid-Induced Fracture Initiation and Propagation

David Boutt[1,2] (dboutt@nmt.edu); Brian J.O.L. McPherson[2] (brian@nmt.edu); Benjamin K Cook[3] (bkcook@sandia.gov); Laurel B Goodwin[2] (lgoodwin@nmt.edu); John R Williams[4] (jrw@mit.edu); Moo Y Lee[1]; Ray Patteson[1]

[1]Geomechanics Department, Sandia National Laboratories, New Mexico , PO Box 5800, Albuquerque, NM 87123-0751, United States

[2]Department of Earth and Environmental Sciences, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, NM 87801, United States

[3]Infrastructure and Information Systems Center, Sandia National Laboratories, New Mexico, PO Box 5800, Albuquerque, NM 87123-0576, United States

[4]Department of Civil and Environmental Engineering, MIT, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, United States

It is well known that pore fluid pressure fundamentally influences a rock's mechanical response to stress. However, most measures of the mechanical behavior of rock (e.g. shear strength, Young's modulus) do not incorporate, either explicitly or implicitly, pore fluid pressure or transport properties of rock. Current empirical and theoretical criteria that define the amount of stress a given body of rock can support before fracturing also lack a direct connection between fluid transport and mechanical properties. Our research goal is to use laboratory experimental results to elucidate correlations between rock transport properties and fracture behavior under idealized loading conditions. In strongly coupled fluid-solid systems the evolution of the solid framework is influenced by the fluid and vice versa. These couplings often result in changes of the bulk material properties (i.e. permeability and failure strength) with respect to the fluid's ability to move through the solid and the solids ability to transmit momentum. Feedbacks between fluid and solid framework ultimately play key roles in understanding the spatial and temporal evolution of the coupled fluid-solid system. Discretely coupled models of fluid and solid mechanics were developed a priori to design an experimental approach for testing the role of fluid transport parameters in rock fracture. The experimental approach consists of first loading a fluid saturated cylindrical rock specimen under hydrostatic conditions and then applying a differential stress such that the maximum stress is perpendicular to the cylinder long axis. At the beginning of the test the minimum stress and the fluid pressure are dropped at the same time such that the resulting difference in the initial fluid pressure and the final fluid pressure is greater than the final minimum stress. These loading conditions should produce a fluid driven tensile fracture that is perpendicular to the cylinder long axis. Initial analyses using numerical simulations with similar boundary conditions suggest that resulting fracture propagation rates and fracture spacing are controlled by the rocks hydraulic diffusivity. Modeled rocks with higher permeability had fractures with larger apertures, more localized deformation, and greater fracture spacing. Intuitively, these results are consistent with permeability controlling the time required for pressure to come to equilibrium with the new boundary conditions. Finally, more general goals of this research include using these core-scale experimental data and discrete simulation results to calibrate larger-scale, more traditional continuum models of geologic deformation.

URL: http://www.nmt.edu/~dboutt/AGUFALL03/

H51B-02 0815h INVITED

Fluid Flow in Rock Fractures

Robert W. Zimmerman (+44-207-594-7412; r.w.zimmerman@ic.ac.uk)

Department of Earth Science and Engineering, Imperial College, London SW7 2AZ, United Kingdom

Understanding the hydraulic properties of rock fractures is an issue of great importance in fields such as petroleum engineering, groundwater hydrology, and underground waste isolation. Traditionally, models of fluid flow through rock fractures have been based on the cubic law, which asserts that the local value of the fracture transmissivity is equal to $h^3/12$, where h is the fracture aperture. The local cubic law is mathematically equivalent to assuming that flow in the fracture is governed by the Reynolds lubrication equation. However, this equation is only applicable if the aperture does not change too abruptly, and flowrates are suitably low. These two limitations have led, over the previous decade or so, to a series of computational and experimental investigations aiming to better understand the applicability of the lubrication approximation. These investigations (Mourzenko et al., J. Phys., 1995; Brown et al., GRL, 1995; Yeo et al., Int. J. Rock Mech., 1998; Nicholl et al., WRR, 1999) have showed that the Reynolds equation may over-predict the transmissivity of a fracture by as much as 100%. Other analyses, both theoretical and computational, have concluded that the linear relationship between pressure drop and flowrate will break down if the Reynolds numbers reach some critical value, variously estimated to be between 1-100 (Oron and Berkowitz, WRR, 1998; Brush and Thomson, WRR, 2003). The implication of these results has been that the full three-dimensional, nonlinear Navier-Stokes equations are needed to accurately simulate fluid flow in a rock fracture. In a recently completed project at Imperial College, a surface profilometer was used to measure fracture profiles every 10 microns over the surface of a replica of a fracture in a red Permian sandstone, to within an accuracy of a few microns. These surface data were used as input to two finite element codes that solve the Navier-Stokes equations and the Reynolds equation, respectively. Numerical simulations of flow through these measured aperture fields were carried out at different values of the mean aperture, corresponding to different values of the relative roughness. Flow experiments were also conducted in molds of two regions of the fracture. At low Reynolds numbers, the Navier-Stokes simulations yielded transmissivities for the two fracture regions that were within 6% and 11% of the measured values, whereas the value predicted by the Reynolds simulations were too high by 21% and 43%. We interpret these results as verifying, for apparently the first time in a real rock fracture, that (a) that the Reynolds equation over-predicts the transmissivities, and (b) the Navier-Stokes equation, with the no-slip boundary condition on the fracture walls, is indeed the correct model for fluid flow in a fracture. The initial deviations from linearity, for Reynolds number around 1, are consistent with the "weak inertia" model developed by Mei and Auriault (J. Fluid Mech., 1991) for porous media, and with the results obtained computationally by Skjetne et al. (J. Fluid Mech., 1999) on a two-dimensional self-affine fracture. In the regime $15<Re<100$, both the computed and measured transmissivities could be fit very well to a Forchheimer-type equation, in which the additional pressure drop varies quadratically with the Reynolds number. The computed and "measured" Forchheimer coefficients differed by about 30%, however. Examination of computed velocity profiles indicates that, in some regions of the fracture, there are strong deviations from a parabolic velocity profile. This should have implications for processes such as solute transport, and dissolution/precipitation of minerals.

H51B-03 0830h

Hydraulic Fracturing in Cohesionless Particulate Materials

Hong Chang[1] (gte004k@prism.gatech.edu)

Leonid N Germanovich[1] (leonid@ce.gatech.edu)

Ruiting Wu[1] (gte755q@prism.gatech.edu)

J Carlos Santamarina[1] (carlos@ce.gatech.edu)

Peter E Dijk[1] (peter.dijk@ce.gatech.edu)

[1]Georgia Institute of Technology, School of Civil and Environmental Engineering, Atlanta, GA 30332-0355, United States

This work examines the mechanisms of hydraulic fracturing in cohesionless particulate materials. The fracturing liquid is injected into dry particulate materials, which are practically cohesionless. The liquid flow is localized in thin self-propagating crack-like conduits (Figure 1). By analogy we call them 'cracks' or 'hydraulic fractures.' When a fracture propagates in a solid, new surfaces are created by breaking material bonds. Consequently, the material is in tension at the fracture tip. Because the particulate material is already 'fractured,' no new surface is created and no fracturing process per se is involved. Moreover, all material parts are in compression since the material cannot bear any tension. Therefore, the conventional fracture mechanics principles cannot be directly applied. Based on the laboratory observations, performed on three dry particulate materials (Georgia Red Clay, silica flour, and fine sand), this study offers a physical concept to explain the observed phenomenon. The goal of this study is to determine the controlling parameters of fracture behavior and to quantify their effects. The presented model is based on fracture propagation due to unloading caused by the opening of the propagating fracture. The sufficiently unloaded particulate material yields in the fracture process zone, creating