

High elevation energy and water balance: The role of surface albedo

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Abstract: Observation and modelling of the coupled energy and water balance is the key to understand hydrospheric and cryospheric processes at high elevation. The paper summarizes the progress to address this aspect in relation with different earth system elements, from glaciers to wetlands. The energy budget of two glaciers, i.e. Xiao Dongkemadi and Parlung No. 4, was studied by means of extended field measurements and a distributed model of the coupled energy and mass balance was developed and evaluated. The need for an accurate characterization of surface albedo was further documented for the entire Qinghai Tibet Plateau by numerical experiments with Weather Research and Forecast (WRF) on the sensitivity of the atmospheric boundary layer to the parameterization of land surface processes. A new approach to the calibration of a coupled distributed watershed model of the energy and water balance was demonstrated by a case - study on the Heihe River Basin in North West China. The assimilation of land surface temperature did lead to retrieval of critical soil and vegetation properties as the soil permeability and the canopy resistance to the exchange of vapour and carbon dioxide. The retrievals of actual Evapo - Transpiration (ET) were generated by the ETMonitor system and evaluated against eddy covariance measurements at sites spread throughout Asia. As regards glacier response to climate variability, the combined findings based on satellite data and model experiments showed that the spatial variability of surface albedo and temperature is significant and controls both glacier mass balance and flow. Experiments with both atmospheric and hydrosphere - cryosphere models documented the need and advantages of using accurate retrievals of land surface albedo to capture land - atmosphere interactions at high elevation.

Key words: ice; snow; albedo; energy water balance

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1 INTRODUCTION

The last decade has seen an increasing interest for cryospheric and hydrologic processes in cold, high elevation regions. This is due to a two - fold relevance:

- (1) The cryosphere in high elevation regions is a very sensitive indicator of climate change;
- (2) Meltwater from glaciers, permafrost and snow is a signifi-

cant fraction, and a critical one at times, of fresh water resources in many parts of the world, particularly in China and in the Countries receiving waters from the Qinghai - Tibet Plateau.

An analysis of recent literature shows that Cryosphere and Hydrology questions should be linked towards better science on the terrestrial water cycle across a range of spatial and temporal scales. This leads to the need of connecting regional and global analyses of water resources.

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Fully integrated use of satellite, ground observations and hydrological distributed models is necessary to support water resources management in S and E Asia and to clarify the roles of the interactions between the land surface and the atmosphere over the Tibetan Plateau in the Asian monsoon system.

Hydrological data products will be generated taking advantage of the synergies of European and Chinese data assets and spaceborne observation systems, taking advantage of the improved accessibility and standardization of Chinese data products;

Develop an energy-budget-based glacier mass balance model driven by satellite observations and linked with a distributed river basin model to describe glacier-melt contribution to river flow;

Use satellite hydrological data products for forcing, calibration, validation and data assimilation in basin scale hydrological models;

Progress to date has been achieved in the following areas:

Observation and modeling of glacier mass balance: (1) Energy budget Xiao Dongkemadi and Parlung No. 4 Glacier; field measurements; distributed model + Influence of topographic shadows on energy and water processes; (2) Albedo parameterization; (3) Validation with field measurements of albedo, glacier melt, sublimation, sensible and latent heat fluxes; (4) Relationship between net radiation snow and ice melt; (5) Relationship between glacier thickness change and surface albedo and temperature; (6) development and validation of a distributed mode of glacier energy and mass balance. See e.g. (Ding et al. (2017), Ren et al. (2019), Zhang et al. (2019), Zhang et al. (2019)

Modeling of land – atmosphere interaction associated with high elevation hydrometeorology: (1) Aerosols retrieval vs. surface albedo; (2) WRF + NOAH-MP to model surface temperature of glaciers; energy + mass balance of snowpack and glacier; (3) Experiments on Parlung nr.4 to evaluate the response to Monsoon in early June to early August; d) WRF experiments to improve the ac-

curacy of WRF precipitation in relation with glacier mass balance, in particular the estimation of the liquid and solid precipitation fractions. See e.g. Liu et al. (2019), Li et al. (2018 a), Chen al. (2019)

Generation of satellite data products on the land surface radiative and convective fluxes: (1) Retrieval of cloud properties and validation of data products on solar radiation product retrieved from image data collected by Himawari – 8; (2) data products on water resources, particularly transpiration, evaporation and sublimation; (3) Analyses on relationship of in-situ river discharge with water level and soil moisture; (4) All – weather LST data products using both AATSR and SLSTR data; (5) generation of a daily ET data set on entire China for the period 2001 – 2015 validated against eddy covariance flux stations in Asia; (6) improvements of an integrated watershed model of energy and water balance, including estimation of model parameters by assimilating image data on LST; (7) Consolidation of the watershed observation system in the Hei He Basin; (8) Analyses on changes in the terrestrial water cycle and development of the DSS on water resources for the Hei He Basin;. See e.g. Li et al. (2018 b), Jia et al. (2018), Gao et al. (2019)

2 METHODS AND DATA

The energy and mass balance of glaciers was analyzed by combining, field experiments, analysis of satellite data and numerical models. Work was specifically focused on the evaluation and improvement of parameterization of the snow and ice surface albedo, particularly of the dependence of glacier albedo on snow age and thickness.

The satellite data used for the studies summarized in this paper are listed in Table 1.

Table 1 List of satellite data used by all Investigators to carry out the studies under project 32439 “Multi – source hydrological data products to monitor High Asian River Basins and regional water security (MUSYCADHARB)” since kick – off in June 2016; number of scenes is indicated for each type of data

ESA Third Party Mission	Nr. of scenes	ESA, Explorers & Sentinels data	Nr. of scenes	Chinese EO data	Nr. of scenes
ESA-CCI soil moisture products	910	Sentinel-1	120	ZY-3 TLA stereo images	14
ESA CCI land cover	1	Sentinel-2	233	FY3-B/C SM products	1920
L5 / TM	29	Sentinel-3	200	GF-1	60
		SMOS	150	GF-2	50
		ESA 1km LAI products	324	GF-3	1
				GF-5	1
Total	940		1027		

Parameterization of snow and ice albedo. Albedo changes are modelled (Fig. 1) following a point-based study on Parlung 4 by Ding et al. (2017); see block "albedo" in Fig.1, where α is the actual albedo value, α_b is the clear-sky surface albedo at nadir (hereafter "basic albedo"), α_c indicates the cloud fraction effect and α_{ps} the solar elevation effect. α_b is dependent on the aging of old snow and on new snowfall. When snowfall or sleet occurs, α_b changes drastically with the snow mass, solid percentage of precipitation, and snow cover fraction according to the Equations in the block "inputs" (Fig. 1), where α_s is the basic albedo of the surface covered by fresh snow; α_{ns} is the basic albedo of the surface not covered by fresh snow, i.e., the albedo before the start of a snowfall or sleet event, which is taken from the previous time step; α_{fs} is the albedo for a fresh and deep snow surface, which depends on the snow grain diameter; K is a dimensionless parameter derived by compar-

ing measured albedo with a physically-based single-layer implementation of the Snow, Ice, and Aerosol Radiation (SNICAR) model (Flanner et al., 2007); f_{sn} is the snow cover fraction of the new snowfall, which is also estimated by comparison with the SNICAR model (see Ding et al. (2017)); M_{sn} is the cumulative mass of solid precipitation per unit area since the beginning of a snow or sleet event (kg m^{-2}); p_r is the total precipitation rate ($\text{kg m}^{-2} \text{s}^{-1}$); and p_s is the solid precipitation ($\text{kg m}^{-2} \text{s}^{-1}$). Following Ding et al. (2017), the albedo is assumed to evolve linearly from the initial basic albedo (α_{ns}) to the estimated new snow albedo (α_s) when the solid fraction in sleet increases from 50% to 100%. If the solid fraction is lower than 50%, the basic albedo remains unchanged (i.e., equal to α_{ns}). When no new snowfall occurs, α_b decays with time due to the aging of the snow (see block "snow aging" in Fig. 1), using α_{ns} from the previous time step, the minimum value of surface albedo (α_{\min})

and scaling parameters, f_s and a_s for the time step, Δt . The albedo of the cloud fraction α_c (block "cloud fraction") and the solar elevation

effect α_β (block "Sun elevation angle") are estimated following Petzold (1977).

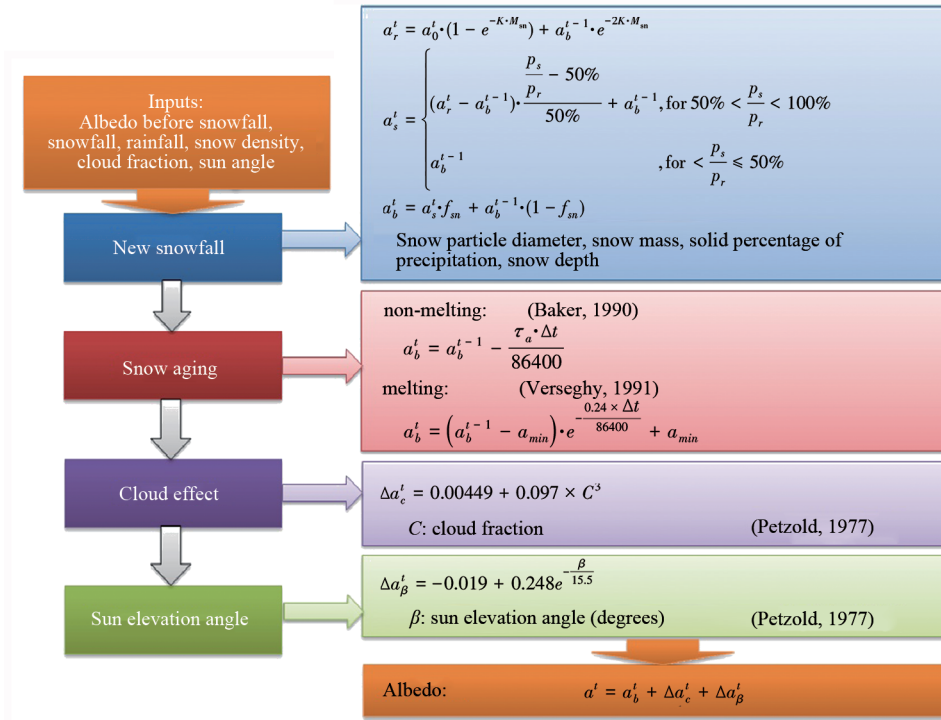


Fig.1 A new albedo scheme considering sleet and shallow snow implemented in the new distributed model of glacier energy and mass balance (adapted from Ding et al., 2017)

The mass balance of the snowpack and glaciers has been linked with hydrological processes in an entire watershed and the entire Plateau using hydrological and atmospheric models:

Heihe Data Assimilation System (HDAS);

Flash - flood Event - based Spatially - distributed rainfall - runoff Transformation - Energy Water Balance (FEST-EWB)

Weather Research and Forecasting (WRF)

The Heihe Data Assimilation System (HDAS) is a watershed scale land/hydrological data assimilation platform that can assimilate multi-source remote sensing observations (Han et al. 2015). The system integrates multiple hydrological/land process models and various data assimilation algorithms. Under the framework of the distributed hydrological and land process models, multi-source remote sensing observations are assimilated, producing very high spatial-temporal resolution estimates of hydrological and ecosystem variable, hence providing datasets for understanding eco-hydrological processes at watershed scale. The main special characteristics of the HDAS include: (1) reasonable watershed modeling, (2) efficient data management, (3) strong ability of remote sensing data processing, and (4) combination of data assimilation of high-performance computing. Based on the framework of HDAS, several recent efforts have been focused on function-extension and application of watershed scale hydrological and ecological modeling and data assimilation. Tian et al., coupled a groundwater flow model into a simple biosphere model and simulated evapotranspiration and energy transfer over the middle reaches of Heihe River Basin. Simultaneously, coupled models over upper reaches of Heihe were developed and applied, such as a distributed ecohydrological model proposed by Yang et al. and a coupled heat and water model by Zhang et al. In addition, a soil moisture assimilation scheme that jointly assimilated the brightness temperature of Advanced Microwave Scanning Radiometer-Earth Observing System and Land Sur-

face Temperature products of Moderate Resolution Imaging Spectroradiometer was proposed (Chen et al., 2017). The data assimilation scheme could correct model bias by simultaneously updating model states and parameters with a dual ensemble Kalman filter. In system development and extension, a physically based hydrological data assimilation system was proposed using the gridded and parallelized Soil and Water Assessment Tool distributed hydrological model (Zhang et al., 2017). The system integrated remotely sensed and ground-based observational data with the Parallel Data Assimilation Framework. The system could accurately characterize watershed hydrological states and fluxes. As to the application of data assimilation to hydrological flux, significant progress has been obtained as well. For instance, Pan et al. assimilated the two satellite precipitation products (The Tropical Rainfall Measuring Mission: TRMM and Fengyun-2D: FY-2D) into the weather research and forecasting model under framework of the 4D-Var data assimilation method in Heihe River Basin. The improved precipitation forecasting has been observed.

The Flash - flood Event - based Spatially - distributed rainfall - runoff Transformation - Energy Water Balance (FEST-EWB) model is a distributed hydrological hydraulic model (Mancini, 1990; Ravazzani et al., 2007; Corbari et al., 2011). It solves pixel-wise the energy-water balance equation respect to LST computing continuously in time and distributed in space soil moisture and evapotranspiration fluxes thanks to a double link with satellite data as input parameters (e. g. LAI) and as variables for model states update (LST). A recent effort has focused on using remotely sensed LST for hydrological models soil parameters (Corbari & Mancini, 2014) calibration at pixel scale instead of traditional dedicated precise site ground measurements. The idea makes the model simulations over large areas more consistent and easier to use respect to the model calibration procedure. In fact, this technique determines

parameter values that are responsible of latent heat fluxes at pixel scale instead than parameter retrieved from local soil analysis.

FEST-EWB algorithms was proved to make accurate predictions of actual evapotranspiration against energy and mass exchange measurements acquired by eddy covariance stations (Corbari et al., 2011) and of continuous discharges in river cross sections compared with observed one for the Po river basin and for Upper Yangtze river basin (Corbari and Mancini 2014; Corbari et al., 2015).

The Weather Research and Forecasting (WRF) Model is a state-of-the-art mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications (Skamarock et al., 2008). It is a fully compressible and non-hydrostatic model that employs a terrain-following mass vertical coordinate and Arakawa C-grid and uses Runge-Kutta second- and third-order integration in time and a second- to sixth-order integration in its advection scheme. The WRF model allows for the application and evaluation of several alternative parametrization schemes addressing both boundary layers and land surface processes and feeds into a wide range of meteorological applications across scales from tens of meters to thousands of kilometers (Chen & Dudhia, 2001; Niu et al., 2011; Pleim & Xiu, 1995; Smirnova et al., 2000; Xue et al., 1991). The WRF model can be accurately applied to the QTP complex terrain, and is able to provide meteorological variables at high resolution to compensate for any uneven distribution and scarcity of in situ meteorological observations (Gao et al., 2015; Li et al., 2009; Ma & Ma, 2016; Maussion et al., 2011; Sato et al., 2008). Various land surface schemes have been implemented in the more recent versions of the WRF model. The use of WRF to model a full snowfall / snowmelt event in the entire QTP has been demonstrated by Liu et al. (2019).

3 RESULTS

3.1 Energy and mass balance of snow and ice: the role of surface albedo

In the period 2016 – 2018 the first main stream of research was focused on the role of surface albedo in the energy and mass balance of the snowpack and glaciers.

Mountain glaciers are one of the major fresh water resources. Glacier mass balance on the Tibetan Plateau (TP) can directly reflect local climate change and plays a crucial role in the terrestrial water cycle and food security of local people. We analyzed the relationships between glacier thickness change and mean surface albedo

and mean surface temperature of Yalung glacier in Southeast of the Tibet Plateau (TP) during 2000 – 2014 (Fig. 3) (Ren, et al.,). The glacier thickness change was calculated by differential SAR interferometry (D-InSAR) method using TanDEM-x images in 2014 and Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) in 2000) (Wu et al., 2018), the mean surface albedo and mean surface temperature were retrieved from with cloud-free images of Landsat Thematic Mapper (TM) in 2000 – 2011. The glacier was divided into accumulation zone and ablation zone by Equilibrium Line Elevation (ELA, the blue dotted line in Fig. 3).

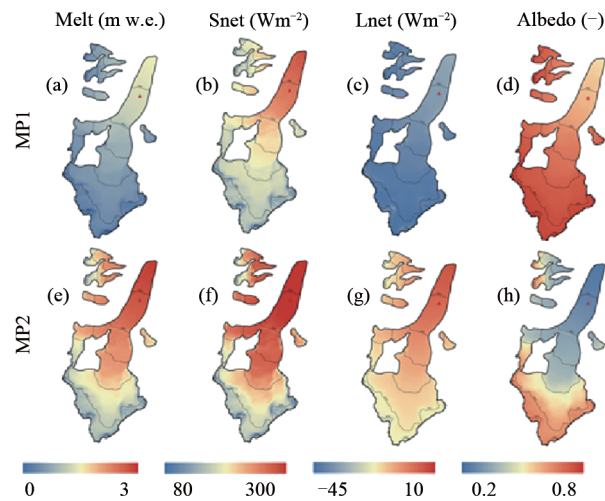


Fig. 2 Spatial variability of glacier surface energy balance due to surface albedo controlling net radiation; Parlung nr.4 glacier; MP: Monsoon Periods May through September (adapted from Shaw et al., 2018)

The results show that the glacier thickness change is clearly related to mean surface albedo and mean surface temperature (Fig. 3). The relationship between glacier thickness change and glacier surface temperature is non-linear, i.e. both the glacier thickness and glacier surface temperature decrease slightly in the accumulation zone and decrease rapidly in the ablation zone. The glacier thickness change has an obvious negative correlation with glacier surface albedo in the glacier ablation zone, but there is no distinct relationship in the accumulation zone. These results imply that the glacier thickness change pattern is strongly related to surface albedo and surface temperature in the Yalung glacier.

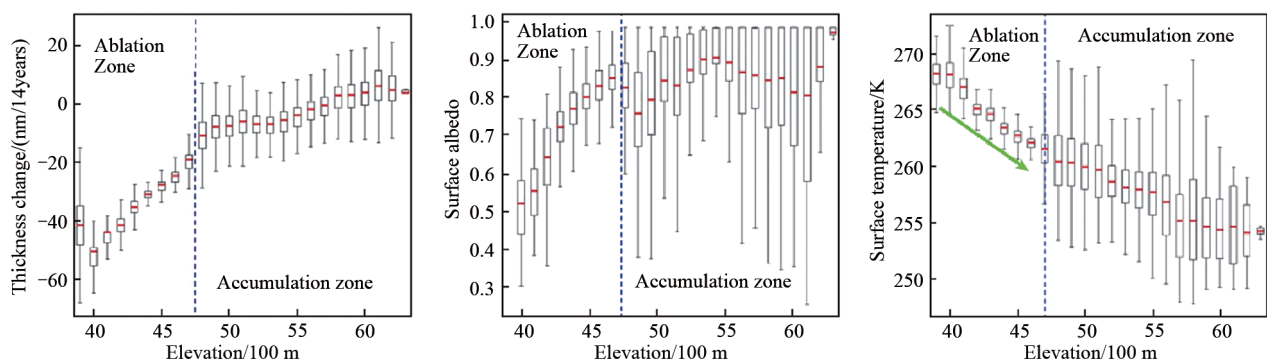


Fig. 3 Glacier thickness change 2000 – 2014 vs. mean surface albedo and temperature; Yalung glacier;

Evolution of daily mean surface albedo of the Parlung nr.4 glacier is displayed in Fig. 4. The surface albedo rapid changes due to snowfall and subsequent evolution of snowpack with large value in fresh snow and decrease in snow melt process. The observed daily mean albedo declines remarkably before 24 June, and exhibits a rather low constant value of about 0.23 at the end of June (Fig. 4). The daily variation of albedo indicates that the seasonal snowpack in the ablation zone did not disappear until 24 June, when ice became exposed on the surface. Rainfall frequently happens in summer and surely increases glacier water content, causing observed albedo decrease. The observed albedo decreased mainly due to snowfall and subsequent snow melt in early June followed by rainfall from mid to late June.

Due to much different treatment with SWU under different land use, the two experiments show distinct capacity of albedo simulation. From time series of daily mean albedo, obvious decrease was measured from maximal 0.74 to minimal 0.23, while constant albedo 0.12 was modeled in EXP1 in early June. Subsequently, albedo estimate from EXP1 increases to maximal 0.54 in 16 June followed by remarkable decrease in disturbance. Large constant albedo value (~0.8) is modeled and stabilizes on snow and ice surface

in EXP2 (Fig. 4). It is clear that EXP2 estimates albedo reasonably in early June when snowfall appeared, and after that overestimates albedo remarkably.

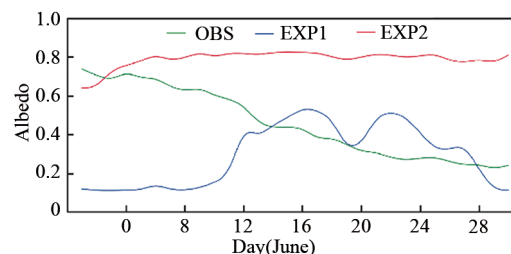


Fig.4 Evolution of surface albedo of the Parlung nr.4 glacier: OBS is in-situ measurements at one location; EXP1 is modeled by WRF - Noah-MP with default MODIS landuse product embedded in WRF; EXP2 modeled by WRF - Noah-MP with snow and ice type in this glacier.

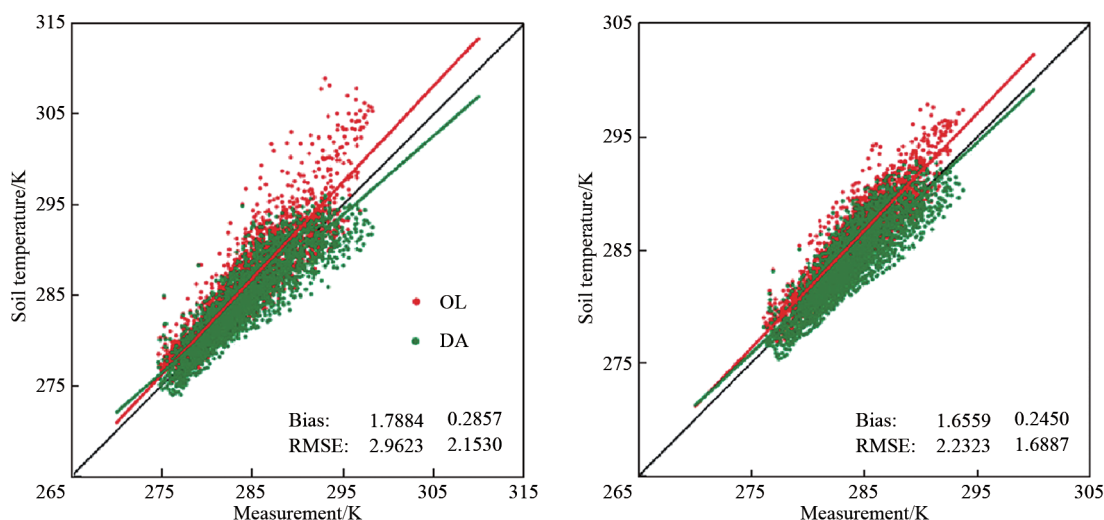


Fig.5 Improved soil moisture estimates by assimilating AMSR-E T_B and MODIS LST

3.2 Observation and modelling of watershed hydrology

In the period 2016 - 2018 the second main stream of research was focused on observation and modeling of cryospheric and hydrospheric processes in a watershed, particularly the Hei He and Red River Basins.

Satellite LST data is then used to calibrate soil parameters of FEST-EWB model in the HeiHe river basin. The calibration pixel wise procedure is based on minimize the differences, between the FEST EWB simulated Land surface temperature, also defined as RET (representative equilibrium temperature) for its physical meaning and the satellite LST data. From sensitivity analysis performed at local scale using eddy tower data (Corbari and Mancini 2014; Corbari et al., 2015), the main surface parameters that have to be tuned are: soil hydraulic conductivity, Brooks-Corey index, soil depth, minimum stomatal resistance. In Fig. 6 the soil hydraulic conductivity K_{sat} is reported before and after its calibration showing a higher heterogeneity.

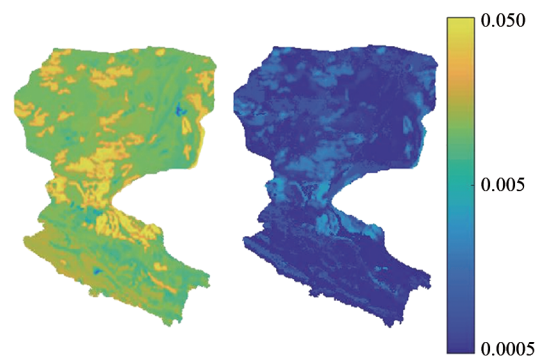


Fig. 6 Energy and water balance modeling by assimilating land surface temperature; estimation of soil hydraulic conductivity K_{sat} : a) initial values; b) after assimilation of MODIS LST image data; c) K_{sat} ($m\ day^{-1}$); Hei He Basin

The DisPATCH algorithm to disaggregate SMOS Soil Moisture (SM) has been implemented in the Red River Basin. DisPATCH provides 1 km resolution SM data from coarse-scale microwave-derived SM. In DisPATCH, the soil evaporation from the 0 – 5 cm soil layer and the vegetation transpiration from the root zone soil layer are partitioned by separating MODIS LST (Land Surface Temperature) into its soil and vegetation components. The partitioning method relies on a contextual interpretation of MODIS LST and MODIS NDVI (Moran et al., 1994). MODIS-derived soil temperature is first used to estimate Soil Evaporative Efficiency (SEE) de-

finied as the ratio of actual to potential soil evaporation, which is known to be relatively constant during the day on clear sky conditions. DisPATCH then distributes high-resolution soil moisture around the low-resolution observed mean value using the instantaneous spatial link between optical-derived SEE and near-surface soil moisture (Merlin et al. 2013).

Fig. 7b shows the monthly average for January 2017 of the 1km SM over the Red River Basin. The SM product shows some missing data due to high Radio Frequency Interference (RFI) events occurring over the study area.

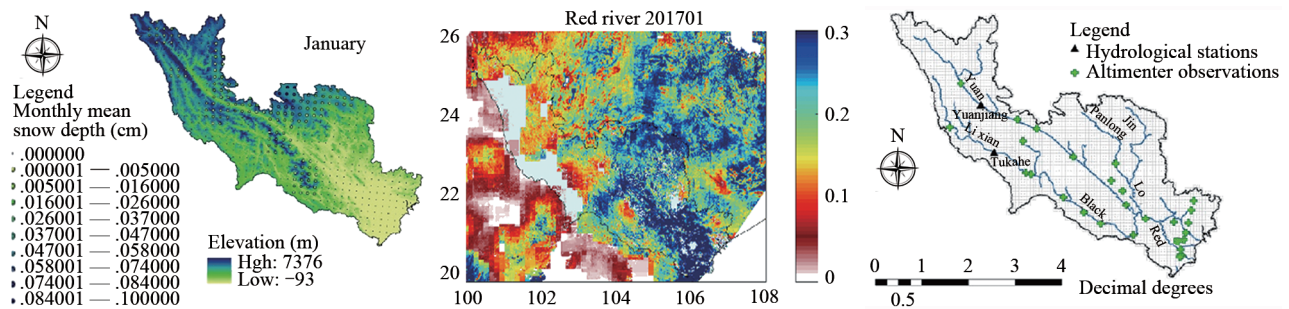


Fig. 7 Hydrological study of Red River: a) monthly mean snow depth (after CMC global analysis); b) soil moisture retrieved and downscaled from SMOS data and c) locations of S3 Altimeter observations

4 CONCLUSIONS

The results presented above document the role and the variability of the snow and ice albedo in determining the energy and mass balance at high elevation in the Qinghai – Tibet Plateau. Moreover, the response of glacier albedo to snowfall and subsequent melting can be parameterized using detailed in – situ observations, but such parameterizations may not easily transferred to hydrological and land – atmospheric models due to the requirement for multiple observations on e.g. snow and ice conditions. The observed response of the glacier mass balance to the surface energy balance and its spatial variability captured by satellite retrievals of surface albedo and temperature clearly indicates a way to understand the spatial and temporal variability in glacier melting. The results of this study link the observed variability in glacier facies with a glacier mass balance. This leads to a general objective for our research in 2nd half of Dragon 4, i.e. to experiment with advanced, coupled land – atmosphere models such as WRF and NOAH-MP to describe the energy and mass balance of the snowpack and of glaciers. A similar effort needs to be done on watershed hydrological models to link hydrosphere processes in the upper and lower reach of river basins on and around the QTP.

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