COST
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SHORT TERM SCIENTIFIC MISSION (STSM) – SCIENTIFIC REPORT

The STSM applicant submits this report for approval to the STSM coordinator

Action number: ES1404
STSM title: Data Assimilation of Satellite Snow Products through Hydrological Modelling
STSM start and end date: 05/08/2018 - 11/08/2018
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PURPOSE OF THE STSM/

Analyzing and forecasting the temporal and spatial variability of snow is important for hydrological purposes as well as for weather prediction and climatic models especially in mountainous regions. Snow observations are necessary for running hydrological and meteorological models for calibration, validation and updating. On the other hand, Data Assimilation (DA) is a very important process in hydrological modelling due to its ability to correct the model estimates of the snow state by using observations.

I am currently a researcher within the Department of Civil Engineering of Anadolu University in Turkey. I have scientific works, experience, publications on hydrological modelling and usage of snow observations. In these studies, different types of hydrological models and snow data sources (in-situ data, satellite data products) are used together with different Numerical Weather Prediction data for runoff simulation and real time runoff forecasting. DA techniques hold considerable potential for improving hydrologic predictions as demonstrated in numerous research studies. In my previous studies, Moving Horizon Estimation method was used for data assimilation approach in conceptual models.

Concerning the importance of snowmelt in the mountainous Eastern Turkey, incorporating different DA techniques with different snow data sources is crucial in the runoff predictions over the region. Given the limited availability of data for mountainous regions, DA becomes even more relevant. This Short Term Scientific Mission (STSM) contributed to my knowledge on hydrological models with an expected better prediction by sequential DA method. The work is carried over the DA applications through previously calibrated hydrological models and comparisons will be done for different DA techniques using satellite snow products.

Rodolfo Alvarado, the host from Deltares, has extensive experience in these topics and the host institution, Deltares, located in Delft (Netherland), is a non-profit institute for applied research in the field of water. In the STSM period, we have worked on previously calibrated conceptual hydrological models as a case study in the Upper Euphrates Basin, Turkey. The STSM has provided an important piece of knowledge in the development of DA methods in Turkey, with potential to replicate it in other basins. Furthermore, it has contributed to adding strength to the research team in Turkey and future international cooperation between the institutes.

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DESCRIPTION OF WORK CARRIED OUT DURING THE STSMS

For this study, we used lumped HBV conceptual rainfall-runoff model to simulate conditions at a basin scale. A subdivision according to elevation zones and land use was adopted to represent the characteristics of each catchment and later combined to compute the response of the model. A detailed description of the HBV model structure is given in **Lindström et al., (1997)**.

Our dedicated implementation of the HBV model is documented in **Schwanenberg and Bernhard (2013)** and refers to the implementations of **Bergström (1995)** and **Lindström et al. (1997)**. The implementation of the HBV model, also refer to as forward model, follows an implementation according to:

$$x_k = \tilde{x}_k + \eta_k = M_k\left(x_{k-1}, \mu_k, \delta_k\right) + \eta_k \tag{1}$$

$$z_k = \tilde{z}_k + \varepsilon_k = H_k \cdot x_k + \varepsilon_k \tag{2}$$

where *x*, *z*, *δ* are the state, output, and external forcing vectors, respectively, ~ represents a simulated variable, *μ* is a noise term introduced both to forcing and model states, *η, ε* are the model and the observation error with covariance *Q* and *R* respectively, *M()* represents the forward model, *H()* is the observation operator and *k* is the time step index.

Before the DA application, a proper calibration and validation of the hydrological model are required. At this point, DA is set upon a previously calibrated hydrological model in between 2002-2012 (Akkol, 2016).

For Ensemble Kalman Filter is done first by adding (bounded) perturbations to the forcing vector:

$$\delta_k^i = \delta_k + \xi_k^i \quad \text{with: } \xi_k^i \approx N\left(0, U_k\right) \tag{3}$$

where Uk is the covariance of δk, we obtain the state variables from the forward model:

$$x_k^{-,i} = M\left(x_{k-1}^{+,i}, \delta_k^i, u_k^i\right) \tag{4}$$

Then the state updating from the implementation of the EnKF is provided by:

$$x_k^{+,i} = x_k^{-,i} + K_k \cdot d_k^i$$

Where dk is the distance between observed and simulated variables defined as:

$$d_k^i = z_k - \varepsilon_k^i - H_k \cdot x_k^{-,i} \tag{5}$$

And K_k is the Kalman Gain for time step k, computed from:

$$K_k = E\left[x_k^-, z_k^-\right] \cdot \left(E\left[z_k^-, z_k^{-,T}\right] + R_k\right)^{-1} \tag{6}$$

Hindcasting period is selected from 2009-2012 water years. A warm-up period is set to 180 days (6 months). This part is required for the robustness of DA as long as it is selected long enough to capture sufficient improvement in the initial states for T0. Forcing variables such as inputs (P and T) are perturbed with defined intervals and member numbers.

In this study, the main aim is to examine the contribution of the assimilation of satellite snow data. Snow Covered Area (SCA) data is produced as a function of Snow Water Equivalent (SWE) data by HBV model. Mainly, two DA setups are generated as shown in Table 1 by using with and without SCA data (named as 01_Karasu_SeqDA and 02_Karasu_SeqDA, respectively). To that end, SCA is added to observation vector and observation operator. Thus, the first model assimilates only discharge (Q) while the second assimilates both Q and SCA at the same time. In both methods, perturbations on inputs (within tail limit at ± 30% for P and ± 3.0°C for T) are taken in a suitable range. An additional test is computed by increasing SCA uncertainty up to 10 % (named as, 03_Karasu_SeqDA). After trial-error procedure using 200 members is considered to be enough to capture the uncertainty.

Table 1. Set up of the sequential DA models

SeqDA Model Name	Observations Uncertainty		Perturbations	
	Q	SCA	P (%)	T (°C)
01_Karasu_SeqDA	1%	~0%	15	±0.5
02_Karasu_ SeqDA	1%	5%	15	±0.5
03_Karasu_ SeqDA	1%	10%	15	±0.5

where Q, SCA, P and T stand for discharge, snow cover area, precipitation, temperature, respectively.

Consequently, Sequential EnKF-DA system is coupled with RTC-Tools and Python and tested using observed hydro-meteorological data and remote sensing SCA data from MODIS. We analyze the performance of the forecast using the Continuous Ranked Probability Skill Score (CRPS) which is computed using the following equations:

$$CRPS_L = \frac{1}{n}\sum_{k=1}^{n}\left[\int_{-\inf}^{\inf}\left(F_t\left(y_{k,L}\right) - \Gamma\left(y_{k,L} \geq \hat{y}_k\right)\right)^2 dy\right] \quad (4)$$

where: yk,L represents the value of the forecast k-L with a lead time L, k is the indicator of the forecast, n is the number of ensembles, F is the cumulative distribution function, and Γ is a function which assumes probability 1 for values higher or equal to the observation and 0 otherwise.

The CRPS metric is equivalent to the mean absolute error when using deterministic forecasts. This metric is computed in this study using the Ensemble Verification System developed by NOAA (Brown et al., 2010).

References:

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DESCRIPTION OF THE MAIN RESULTS OBTAINED

The developed methodology is applied to Upper Euphrates (Karasu) Basin which is located in the eastern part of Turkey and forming the headwaters of the Euphrates River Figure 1. The basin with a drainage area of 10,275 km^2 has an elevation range from 1125 m to 3500 m and a hypsometric mean elevation of 1983 m. The main land cover types are pasture, cultivated and bare land. Snowmelt runoff in the mountainous eastern part of Turkey is of great importance as it constitutes approximately 2/3 in volume of the total yearly runoff during spring and early summer months. Long term studies indicate that around 60-70% of the total annual volume of water comes during the snowmelt season (March-June). Furthermore, Karasu Basin is divided into 10 elevation zones between 1125-3500 m.

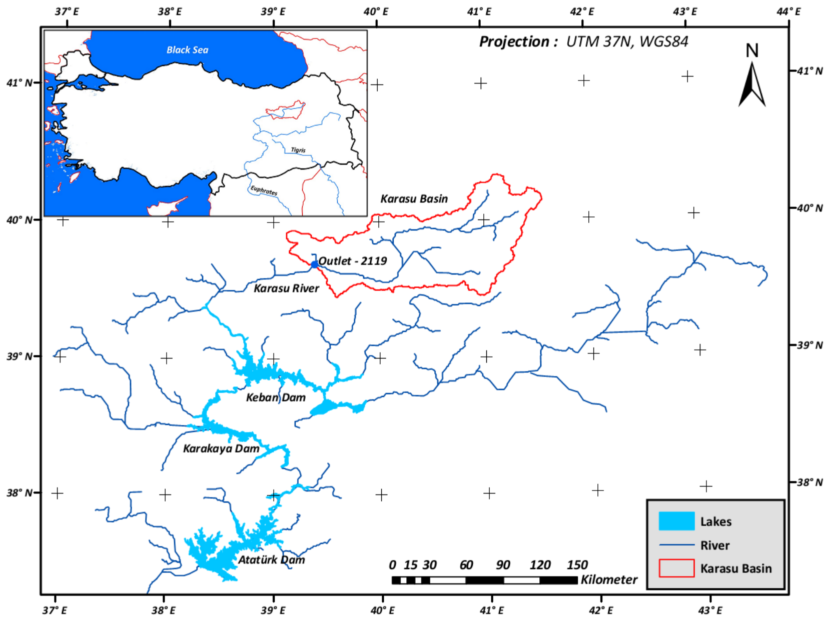
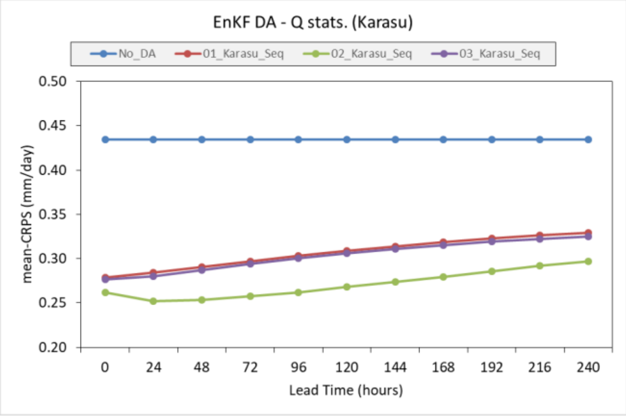


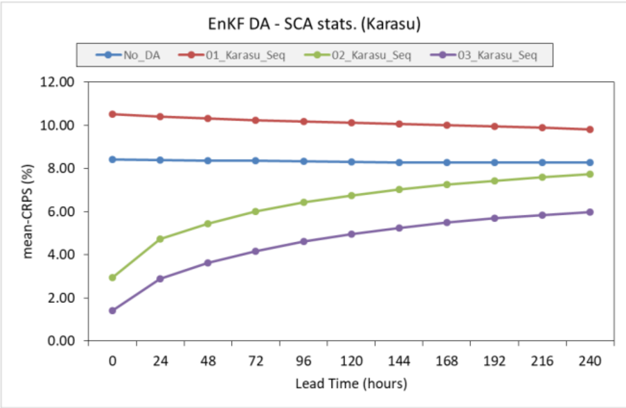
Figure 1. Location of Karasu Basin and Euphrates River

The required input data for HBV model are Precipitation (P), Temperature (T) and Potential Evaporation (PE). In this study, P and T data are provided from zone based areal distributed values whilst PE data are given as same to all zones. Figure 2 presents the preliminary results from hindcasting experiments for different forecast lead time. According to that, there is a promising improvement in the DA application results in terms of discharge statistics for all models in comparison with No DA model result. The performance of SCA is worse than no DA application if SCA is not assimilated at the same time. Since SCA is one of the important element of snow melting process, the accuracy of SCA play important role to have a reliable model. Therefore, it is preferable to assimilate discharge and SCA at the same time. Increasing uncertainty of SCA in experiment 3 (03_Karasu_Seq) yields an improvement in the performance of the SCA forecast with lower CRPS error observed at all lead time.

The developed model is tested with extensive experiments by changing uncertainties of the assimilated observations and perturbation range of the forcing variables. In general sense, initial results highlight the main achievement of the STSM and future works are discussed in the next chapter.



(a)



(b)

Figure 2. Mean continuous ranked probability scores (m-CRPS) by forecast lead time (a) Q [mm/day] statistics (b) SCA [%] statistics

FUTURE COLLABORATIONS (if applicable)

After, a beneficial visit in host institute with application of SeqDA in Karasu, joint work also brought with possible further activities as summarized below:

1. Comparisons will be done for different DA techniques (such as variational methods) using satellite snow products in same catchment. The STSM also contributes to joint and comparative studies together with colleague from Spain. At the end, it is decided to prepare and publish a joint paper by combining all methods and application areas.
2. For the future, there is potential use of actual forecast (deterministic or ensemble) in combination with the current data assimilation for lumped model.
3. Possible involvement of the applicant in HEPEX-DA action is discussed.