

Numerical forecasting of drought impact on wheat yield by combining remote sensing, agrohydrological models and data assimilation

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Abstract

This paper addresses the question whether data assimilation of remotely sensed leaf area index LAI and/or relative evapotranspiration ET/ET_p^{-1} estimates can be used to forecast total wheat production as an indicator of agricultural drought. A series of low to moderate resolution MODIS satellite data of the Borkhar irrigation district, Isfahan (Iran), was for the year 2005 converted into LAI and ET/ET_p^{-1} using a land surface energy algorithm. Using spatial information of soil types, land use, groundwater and irrigation on a raster basis with a grid size of 250 m, i.e. moderate resolution the agrohydrology SWAP model was then implemented on a distributed way. To correct the internal variables of the distributed model whenever remotely sensed data were available, a constant gain Kalman filter data assimilation algorithm was used for each data series.

The differences between the field data and the data determined by simulation or low to moderated RS data implied that these methods separately are not accurate estimators for calculating crop yield. The results of data assimilation at both the regional and field scale showed significant improvement in accuracy of simulation in case of using both the RS based data of LAI and ET/ET_p^{-1} in assimilation process. The results showed also that LAI data have a dominant influence in the assimilation process.

Forecasts for one month in advance using simulation with assimilation at regional scale was promising with respect to the statistical data of the district (bias = $\pm 10\%$). Long term predictions i.e. two month in advance, however resulted in a higher bias between the simulated and statistical data.

Introduction

Crop production is a very reliable indicator for assessing the agricultural drought. Fig. 1 illustrates the variation of wheat production in the Borkhar irrigation district for the period 1991 to 2005. The low amount of production in the period of 1999 to 2001 is due to a devastating drought of which its cumulative effects affected Iran's agriculture and

livestock production seriously (Foltz, 2002). Farmers had reductions of 35-75 percent in wheat and barley product and the government had to import a record seven million tons of wheat, partly because of reduced domestic production due to the drought.

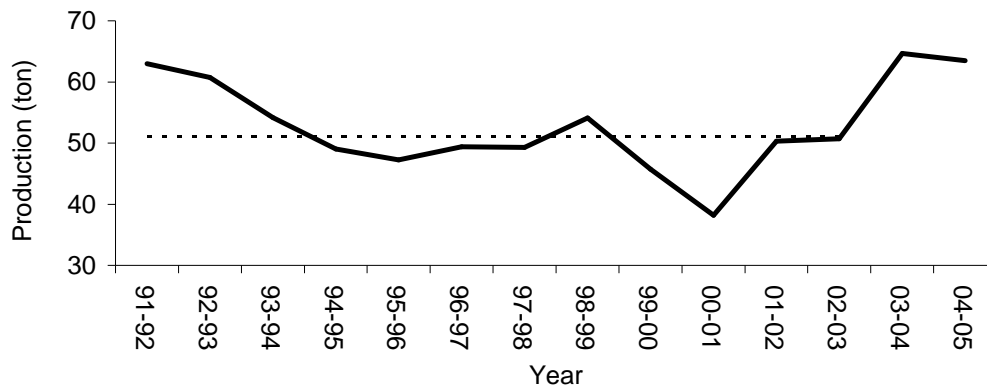


Figure 1 Variation of total wheat production (ton) for the period from 1991 to 2005 in the Borkhar district.

To predict production for the agricultural year 2004-05, distributed simulation with and without assimilation was performed on regional scale. For assimilation three sets of remotely sensed based data (LAI , $T T_p^{-1}$ and $LAI + T T_p^{-1}$) was used in the sequential updating process. To have a prediction of production far in advance, the sequential updating process was stopped one and two months before the end of the wheat growing season. During the sequential updating process known weather data were used, while for the remaining part of growing season different scenarios were considered based on weather data of a dry, wet and normal year.

Application of distributed agrohydrological model SWAP at regional scale

To apply the SWAP (Kroes and Van Dam, 2003) model in a distributed way, the study area was divided into 10655 homogeneous cells with 250 m spatial resolution. Only pixels containing the wheat crop (1589 pixels) were considered. Spatial information parameters like soil types and land use on raster format were derived by remote sensing techniques and were preprocessed in a Geographic Information System (GIS) to derive values for pixels of 250 m. The temporal distributed data of water supply were produced using information from the tubewells and the surface irrigation network in the Borkhar district. For linkage of GIS data with SWAP, a coupling program was written in MATLAB which involves transfer of in- and output data from one system to the other, and running the model for each pixel.

Remotely sensed data of the relative transpiration $T T_p^{-1}$ and LAI

The relative transpiration is an indicator of crop water stress and can be defined as the ratio of actual and potential transpiration, $T T_p^{-1}$. Since separation of the transpiration flux from the remotely sensed ET flux is difficult, hence $T T_p^{-1}$ was set equal to ratio of actual and potential evapotranspiration, $ET ET_p^{-1}$ which is a fair assumption when LAI is bigger than 2 (Feddes et al., 1978).

To derive $ET ET_p^{-1}$, the 1999 version of SEBAL (Bastiaanssen et al., 1998) was applied to 1000 m spatial resolution MODIS data acquired on 15 different dates in the winter growing season of 2005. However due to the coarse spatial resolution of MODIS data (pixels of 100 ha), the outputs represent ET of a mixture of fields. Therefore, $ET ET_p^{-1}$ was defined as ratio of ET from each MODIS pixel and the aggregated value $ET_p(x_i, y_i, t)$ of all components with different crop coefficients within each MODIS pixel. Since wheat was the dominant winter crop, we assumed for simplicity:

$$T T_p^{-1}(x, y, t) \approx ET ET_p^{-1}(x, y, t) = \frac{ET_{MODIS}(x, y, t)}{\sum_{i=1}^m ET_p(x_i, y_i, t) A_{f,i}} \quad (1)$$

where $ET_{MODIS}(x, y, t)$ is the ET derived from each MODIS pixel, $ET_p(x_i, y_i, t)$ the potential evapotranspiration of the i^{th} component within each MODIS pixel, $A_{f,i}$ the area fraction of the i^{th} component within each MODIS pixel, m total number of components within each MODIS pixel, x is the horizontal and y is the vertical location of each MODIS pixel. The $ET_p(x_i, y_i, t)$ data were estimated by applying the Penman–Monteith equation to 250 m spatial resolution MODIS data using the daily weather

Assimilation of remotely sensed data into the distributed SWAP model

The assimilation of RS data into the distributed SWAP model was carried out using the ‘updating’ method. In the updating method, internal variables are continuously updated whenever an observed data is available. In this study, a simple sequential ‘updating’ algorithm was developed to assimilate the RS data into the distributed SWAP model:

$$X_{\text{upd}}(t) = X_{\text{sim}}(t) + K_g [X_{\text{obs}}(t) - X_{\text{sim}}(t)] \quad (2)$$

where X_{upd} and X_{sim} are simulated and updated internal variables i.e. $T T_p^{-1}$ or LAI respectively at time t , X_{obs} is measured data either from remote sensing or field data, and K_g is the optimum gain factor which depends on the relative magnitude of errors in observed and simulated values. To simplify the computation, in this study we did test different values of K_g to investigate which value performs the best with respect to the observations.

Assessment of agricultural drought

Table 1 lists the statistical properties (mean and bias) of simulated Y , Y_{SO} and total amount of production at harvest time of the wheat crop during the agricultural year 2004-05 one and two months in advance. The total amount of production was calculated by aggregation of simulated yield for all wheat pixels within the district. Predictions of crop production through simulation without assimilation two or even one month in advance results in high bias between the statistical data and predicted production (4 to 39 %).

Table 1 Prediction (mean and bias) of total dry matter Y , dry matter of crop yield Y_{SO} and total production using distributed SWAP model with and without assimilation at harvest time of the wheat crop in the Borkhar district during the agricultural year 2004-05. For assimilation, RS based data of leaf area index LAI and relative transpiration $T T_p^{-1}$ was used. The predictions were performed for one and two months in advance. Weather data of a dry, normal and wet year was used for the unknown weather data of the remained part of the year. Bias are based on deviation of predictions from statistical data of Y i.e. 4.5 ton ha⁻¹ and total production of 63297 ton in the Borkhar district in percent.

Method			Y (ton ha-1)		Y _{SO} (ton ha-1)	Production (ton)	
			Mean	Bias %	Mean	value	Bias %
Prediction one month in advance	Without assimilation	Dry	13.8	-	4.7	66145	4
		Normal	14.7	-	5.6	77871	23
		Wet	15.4	-	6.3	88147	39
	With assimilation	Dry	10.2	-	4.1	56835	-10
		Normal	10.9	-	4.7	65558	4
		Wet	10.5	-	4.9	68580	8
Prediction two months in advance	Without assimilation	Dry	13.3	-	5.4	75928	20
		Normal	15.9	-	5.7	79777	26
		Wet	15.4	-	6.2	87386	38
	With assimilation	Dry	13.2	-	5.2	73450	16
		Normal	15.0	-	5.6	77975	23
		Wet	14.9	-	6.1	84842	34

Small bias between the statistical data and short term prediction ($\pm 10\%$) using simulation with assimilation is very promising in prediction of crop production and assessing the impacts of probable drought one month in advance. Longer forecasting i.e. two months in advance, only slightly benefited from data assimilation. The high bias (16 to 38 %) between the statistical data and long term predictions using simulation with or without assimilation is partly due to the fact that the effect of nutrient deficiency, pests,

weeds, and diseases on crop growth and its production have not been implemented in the present 3.0.3 version of SWAP. Extending the assimilation of RS based data into the simulation will incorporate the sudden reduction in Y due to water and nutrient stress, pest or diseases attack.

The predictions of final crop production with or without assimilation is significantly affected by type of weather data i.e. dry or wet year, which is used in one or two last months of growing season in the simulations process.

The predicted production for the agricultural year 2004-05 using distributed simulation with assimilation of RS based LAI and T_p^{-1} is higher than the average value of statistical data in Fig 1. This implies a relatively wet year for the agricultural year 2004-05.

References

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