A PRELIMINARY ASSESSMENT OF THE IMPACT OF SMAP SOIL MOISTURE ON NUMERICAL WEATHER FORECASTS FROM GFS AND NUWRF MODELS

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ABSTRACT

NASA Soil Moisture Active/Passive (SMAP) satellite was launched on January 31st, 2015 and has been providing global soil moisture (SM) data products since April 2015. One of the primary justifications of the mission was to improve numerical weather predictions. With the SMAP SM data becoming available, it is anxiously expected that SMAP SM data could be demonstrated to significantly improve weather forecasts from numerical weather prediction (NWP) models. In this study, the NOAA Global Forecast System (GFS) and NASA Unified Weather Research and Forecast (NUWRF) model coupled with NASA Land Information System are used to carry out the demonstration. A hard-wired Ensemble Kalman filter is implemented within GFS to assimilate surface SM observations. For assimilating SM data into NUWRF model, NASA Land Information System (LIS) is coupled with the NUWRF model. In this paper preliminary results of SMAP soil moisture impact on GFS and NUWRF forecasts are presented after the assimilation algorithms and system designs are introduced. Plans for more comprehensive assessment of the satellite soil moisture data impact on NWP models will be discussed.

Index Terms—SMAP, soil moisture, GFS, NUWRF, NWP

1. INTRODUCTION

Soil moisture is one of the critical land surface state variables that control the exchanges of water, energy and trace gases between land surface and the atmosphere. Initial soil moisture data fields are required to generate weather and seasonal climate forecasts from numerical weather predictions (NWP) models. Chen et al (2001) demonstrated that using more realistic soil moisture to initialize the MM5 model resulted in better 24 hour rainfall forecasts than no soil moisture initialization [1]. Koster et al (2010) showed the importance of accurate soil moisture initialization on sub-seasonal weather forecasts using realistic soil moisture initialization for 12 long-range forecast systems [2]. Currently the initial soil moisture data fields for the Global Forecast System (GFS) of NOAA NCEP and NASA Unified Weather Research and Forecast (NUWRF) model are the soil moisture simulations from the previous time step of the model itself without independently observed soil moisture information. NASA Soil Moisture Active/Passive (SMAP) satellite was launched on January 31st, 2015 and has been providing global soil moisture (SM) data products since April 2015 [3]. One of the primary justifications of the mission was to improve numerical weather predictions. With the SMAP SM data becoming available, it is anxiously expected that SMAP SM data could be demonstrated to significantly improve weather forecasts from numerical weather prediction (NWP) models. In this study, the NOAA Global Forecast System (GFS) and NASA Unified Weather Research and Forecast (NUWRF) model coupled with NASA Land Information System (LIS) are used to carry out the demonstration.

2. SM DATA ASSIMILATION SYSTEMS

The SMAP soil moisture impact assessment is carried out with a global scale model (i.e. NOAA NCEP Global Forecast System – GFS) and a regional model (i.e. NASA Unified Weather Research and Forecast – NUWRF).

The NCEP operational Global Forecast System (GFS) is a spectral model with 64 vertical levels, defined using a hybrid sigma-pressure coordinate. The horizontal resolution uses T574 for week one forecast (0-192 hrs) and T190 for week two forecast (192-384 hrs). This model had substantial upgrades in recent years (http://www.emc.ncep.noaa.gov/GFS). The Noah LSM used in GFS has four soil layers (10, 30, 60, 100 cm thick). A hybrid EnKF - three-dimensional variational (3DVAR) data assimilation system, called GSI, was implemented into the analysis system of GFS called Global Data Assimilation System (GDAS). The atmospheric analysis is generated every 6 hours by the GSI with the GFS previous forecast as the background. This analysis is then used as the initial conditions for GFS subsequent forecasts, and the cycle continues.

GSI has not been implemented to assimilate land surface satellite observations (such as SM) into Noah LSM. For land data assimilation, the ensemble Kalman filter (EnKF) has been widely used [4]. The EnKF works sequentially by
performing in turn a model forecast and a data assimilation update. Following [4], the forecast step for ensemble member \( i \) can be written as

\[
x_{t,i}^* = f(x_{t-1,i}^*, q_{t,i})
\]

(1)

where \( x_{t,i}^* \) and \( x_{t-1,i}^* \) are the forecast (denoted with \(^*\)) and analysis (denoted with \(^-\)) state vectors at times \( t \) and \( t-1 \), respectively. The model error (or perturbation vector) is denoted with \( q_{t,i} \) and its covariance with \( Q_t \). The data assimilation update produces the analyzed state vector \( x_{t,i}^- \) at time \( t \) and can be written as

\[
x_{t,i}^- = x_{t,i}^* + K_t (y_{t,i} - H_t x_{t,i}^-)
\]

(2)

where \( y_{t,i} \) denotes the observation vector (suitably perturbed) and \( H_t \) is the observation operator (which is assumed linear). The Kalman gain matrix \( K_t \) is given by

\[
K_t = P_t H_t^T \left( H_t P_t H_t^T + R_t \right)^{-1}
\]

(3)

where \( P_t \) is the forecast error covariance (diagnosed from the ensemble \( x_{t,i}^* \)), \( R_t \) is the observation error covariance, and superscript \( T \) denotes the matrix transpose. Simply put, the Kalman gain \( K_t \) represents the relative weights given to the model forecast and the observations based on their respective uncertainties and the error correlations between different elements of the state vector.

With \( y_{t,i} \) in Eq. (2) being a single surface layer soil moisture observation and the observation operator \( H_t \) becoming 1, the complexity of matrix operations in Eqs. (2) and (3) can be reduced to scalar operation. Implementation of the EnKF for soil moisture assimilation in GFS can then be realized without the need of matrix conversion procedures, which reduces computational cost for the soil moisture data assimilation within GFS.

A more comprehensive land data assimilation tool for regional weather forecasts is being developed and tested by a NASA research team via coupling the Land Information System (LIS) with the NASA United Weather Research and Forecast (NUWRF) model [5]. For assimilating satellite SM data into NUWRF, the EnKF algorithm implemented in LIS is used for this study.

3. DATA SETS

To test the impact of SMAP observations on GFS forecasts, the soil moisture retrievals from SMAP near real time L1B-TB data for May 2015 are used. These retrievals are obtained with the Single Channel Algorithm (SCA) similar to that used by NASA SMAP project for the NASA official SMAP L2/L3 soil moisture products. The reason for not using the NASA SMAP official L2/L3 SM product is the latency issue. The NASA SMAP SM product latency is 24 hours which is way beyond the 6 hour cutoff time of the NOAA GFS NWP operations. Thanks to NASA SMAP project who is willing to provide their near real time L1B-TB data product with latency mostly shorter than 6 hours.

Using the SCA algorithm and NOAA ancillary data for the algorithm, NOAA NESDIS is capable of retrieving soil moisture for NCEP model within 30 minutes through the Soil Moisture Operational Product System (SMOPS), which could make more than 60% half-orbit SMAP L1B-TB data useful for the NCEP NWP operations. Figure 1 is the composited global soil moisture map retrieved from the NASA SMAP NRT L1B-TB data by SMOPS for August 2015. Refinement of the SMOPS retrieval algorithm parameters and validation of the soil moisture retrievals are currently going on. The retrievals will be evaluated against global in situ soil moisture measurements and other satellite soil moisture data products including NASA official SMAP L2/3 soil moisture data. Results will be presented at IGARSS and the final version of the full paper.

4. METHODOLOGY

For the GFS impact study, the daily SMAP soil moisture retrievals are scaled to the climatology of top layer (0-10cm) soil moisture simulations by matching the cumulative distribution functions of the two data sets. About 4 months SMAP global SM retrievals are used in the scaling procedure, which may not be representative of its climatology and will be improved when more SMAP data
are accumulated. Figure 2 shows the scaled SMAP soil moisture of May 2015 compared with the GFS top layer soil moisture composited for the month. The closeness of the two maps may indicated information loss of SMAP data resulting from the CDF matching scaling approach. The issue is being investigated, but there is no resolution yet [7].

Figure 2. SMAP soil moisture retrieval composite of May 2015 scaled to GFS top layer soil moisture climatology and the GFS top layer soil moisture of the same month.

The scaled soil moisture data products are assimilated into GFS and NUWRF respectively using the EnKF algorithm described in section 2. Forecasts of the 2 meter air temperature (T2m) and humidity (q2m) and 24 hour rainfall accumulation from the NWP models assimilating or without assimilating the satellite soil moisture data sets are compared with their corresponding observations. The impact of assimilating SMAP and CCI soil moisture on the NWP forecasts are then assessed based on their differences between the data assimilation and no DA cases.

5. RESULTS

After daily assimilating SMAP soil moisture retrievals starting from August 1st, 2015, The differences of 144 hour (4 days) forecasts of T2m and q2m are mapped for the CONUS domain for August 16, 2015 as shown in Figure 3. Apparently the SMAP SM data assimilation may make GFS forecasts either warmer (redder) or cooler (greener) for T2m and wetter (redder) or drier (greener) for q2m.

Figure 3. The differences of 144hour (4days) T2m (left) and q2m (right) forecasts from NCEP Global Forecast System with or without SMAP soil moisture data assimilation.

In Figure 4, the 4 day forecasts of GFS T2m and surface skin temperature (Ts) for the DA and no DA cases are plotted together with their observations at Sioux Falls, SD, one representative site of Great Plains. The significant warm biases of the GFS forecasts are shown to be reduced by the SMAP soil moisture data assimilation.

Figure 4. GFS forecasts of T2m (left) and Tskin (right) for the SMAP SM DA and no DA cases plotted with their ground observations at Sioux Falls, SD for days from August 10-17, 2015.

Impacts of soil moisture data assimilation on T2m, q2m and rainfall forecasts are demonstrated with the NUWRF model using the soil moisture data from ESA Climate Change Initiatives. Figure 5 shows the plots of the root-mean-square-errors (RMSEs) of T2m and q2m forecasts from NUWRF with different forecast terms over the whole CONUS domain from April 1st to October 31st, 2012. The SM DA seemed to have reduced the biases of longer term (>18 hrs) q2m forecasts and short term (<=36 hrs) T2m forecasts. The impact of SM DA on longer term T2m is mixed while the impact on shorter term q2m is small.

Figure 5. Root-mean-square-errors (RMSEs) of the forecasts of T2m (top) and q2m (bottom) from NUWRF assimilating or without assimilating CCI SM data over CONUS domain from April 1 - October 31, 2012.
Impact of soil moisture data assimilation on NUWRF rainfall forecasts depends on forecast terms. As shown in Figure 6 the mean-absolute-error (bias) of NUWRF rainfall forecasts becomes larger when the forecast terms increases. The SM DA seemed to reduce the biases of the 2 day forecasts more significantly than those of the 1 day forecasts.

Figure 6. Mean-absolute-error (MAE) of 24 hour accumulated precipitation forecasts of NUWRF model assimilating or without assimilating ESA CCI soil moisture data for the whole CONUS domain from May 10 - May 17, 2012. The bubbles show the forecast hours.

6. SUMMARY AND CONCLUSIONS

In summary, the impacts of SMAP and other satellite soil moisture data products on NOAA GFS and NASA NUWRF NWP model forecasts are preliminarily assessed. It is found that: 1) assimilating SMAP soil moisture retrievals could reduce the warm biases of GFS T2m and Tskin forecasts and the drier biases of GFS humidity forecasts; 2) assimilating ESA CCI soil moisture product could decrease the RMSEs of T2m and q2m forecasts for certain forecast terms; 3) assimilating ESA CCI soil moisture could decrease the biases of NUWRF model longer term rainfall forecasts more significantly than those of the shorter term forecasts.

From these preliminary results, it could be concluded that assimilating satellite soil moisture can indeed improve numerical weather forecasts.

7. ACKNOWLEDGMENT

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9. REFERENCES


