How Satellite Soil Moisture Data Can Help to Monitor the Impacts of Climate Change: SMAP Case Studies

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***Abstract*—Socially and economically costly extreme weather events have become more prevalent in the last decade. Monitoring and early warning systems could help mitigate the impact of such events by allowing people to better prepare themselves to manage their responses to these events. One significant element of an effective warning system is soil moisture because it is a key determinant of the exchange of water and heat energy between the land and atmosphere, the partitioning of precipitation between infiltration and runoff, and therefore has an influence on weather patterns and streamflow. In addition, soil moisture governs plant water availability – the key to crop yield forecasting. For these reasons, a wide range of organizations use soil moisture information to better predict and monitor climate and weather phenomena such as floods and droughts. By improving soil moisture estimates, it may be possible to improve the monitoring and early warning systems upon which these organizations rely, and hence better mitigate the impacts of extreme weather events. Through case studies, this article discusses several uses of soil moisture data products from NASA's Soil Moisture Active Passive (SMAP) mission to help improve soil moisture-related monitoring and early warning systems.**

***Index Terms*—Agriculture, drought monitoring, snowmelt flood prediction, soil moisture active passive (SMAP), soil moisture, weather forecast.**

I. Introduction

THE impacts of climate change have increased and become more prevalent in the last decade. Evidence of climate change impacts include more hurricanes that are destructive [1], increased coastal flooding [2], longer and more damaging wildfire seasons, and more severe droughts in some areas [3]. According to [4], the 3-year drought (2007–2010) was the worst drought in the instrumental record in Syria, causing widespread crop failure and a mass migration of farming families to urban centers and contributing to the conflict in the country. While the devastating civil war that began in Syria in March 2011 is the result of complex interrelated factors, water and climatic conditions have played a direct role in the deterioration of Syria's economic conditions [5]. Similarly, California has recently experienced an exceptional drought (2011–2017) resulting in record-breaking wildfires and causing severe economic losses–including $5.5 billion in agricultural losses from 2014 through 2016 [6], which was followed by other extreme droughts and fire seasons in 2018 and 2019.

Monitoring and early warning systems could help mitigate the impact of such events by allowing people to better prepare themselves to manage their responses to these events. Soil moisture is one of the significant elements of an effective warning system. However, lack of high-quality soil moisture information limits monitoring and early warning system capabilities to effectively reduce impacts of climate change. NASA's Soil Moisture Active Passive (SMAP) Earth-orbiting satellite mission provides global mapping of high-resolution soil moisture and freeze-thaw state every two to three days using an L-band radiometer onboard the observatory; the recent addition of an accurate SMAP 6 pm soil moisture product to complement the baseline 6 am soil moisture product permits soil moisture mapping closer to every 1.5 days. SMAP provides quality soil moisture retrievals with an average error of 0.038 m3 m-3 unbiased-root-mean-square error (ubRMSE) over core validation sites [7], consistent with results from a later SMAP field experiment by [8]. SMAP data products include brightness temperature, surface (5 cm) and root zone (1 m) soil moisture, freeze-thaw state measurement, and an estimate of the exchange of carbon between the atmosphere and the land surface. SMAP's accuracy, global coverage, and frequent revisit are valuable for soil moisture-related monitoring and early warning systems, especially in areas where the ground measurement network is sparse. This article demonstrates how SMAP soil moisture information could help to monitor and possibly mitigate some of the impacts of climate change.

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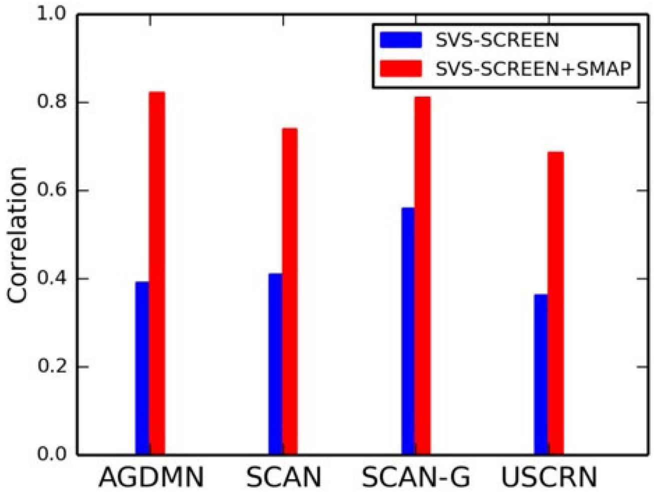
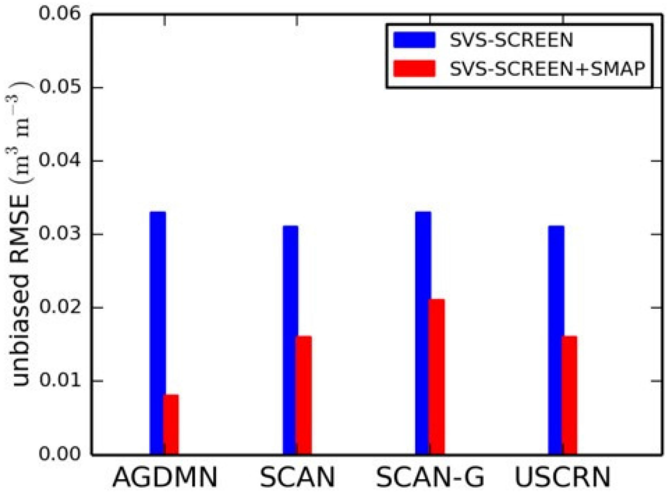


(a)



(b)

Fig. 1. Correlations (a) and Unbiased Root-Mean-Square Errors (b) between in situ soil moisture observations and CaLDAS estimates for the root-zone layer from two different data assimilation experiments: (i) SVS-SCREEN – assimilating only screen-level temperature and dew point temperature and no SMAP brightness temperature (L1B_TB) data; (ii) SVS-SCREEN+SMAP – assimilating screen-level temperatures but also using SMAP L1B_TB data to update soil moisture. The three in situ networks are the Alberta Ground Drought Monitoring Network (AGDMN), the USDA Soil Climate Analysis Network (SCAN), and the US Climate Reference Network (USCRN). SCAN-G refers to the subset of SCAN stations located over predominantly agriculture and croplands.

II. Soil Moisture and Weather Forecasts

SMAP provides global soil moisture, brightness temperature and freeze-thaw state data valuable for weather and climate forecasting. Soil moisture is a key variable in controlling the exchange of water and heat energy between the land surface and the atmosphere through evaporation and plant transpiration [9]. As a result, soil moisture plays an important role in the development of weather patterns and the production of precipitation [10]. Improved characterization of surface soil moisture, vegetation and temperature can lead to greater confidence in weather forecasting systems [11].

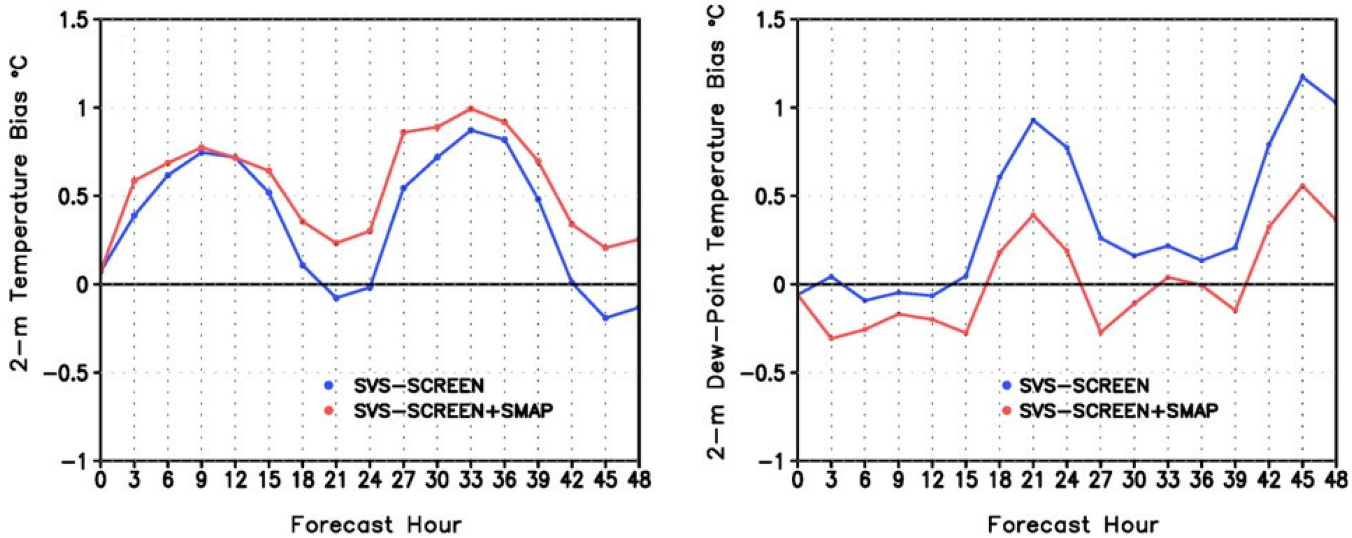
The Science and Technology Branch within Environment and Climate Change Canada (ECCC) investigated the impacts of assimilating SMAP brightness temperatures within the Canadian Land Data Assimilation System (CaLDAS) [12]. The study was performed at a 10-km grid spacing covering North America. CaLDAS is based upon an offline land surface modeling capability and uses the Ensemble Kalman Filter methodology to provide the initial land surface conditions for short-range numerical weather prediction (NWP) [13]. Reference [14] provides a thorough review of land-surface data assimilation activities at different meteorological centers. Reference [12] showed that the assimilation of SMAP brightness temperatures led to substantial improvements in soil moisture estimates, both in terms of temporal correlation and ubRMSE scores, when compared to the assimilation of screen-level temperatures. Fig. 1 shows the impacts of assimilating SMAP over a series of sparse networks over North America for the root-zone layer where improvements with SMAP were significant. These soil moisture improvements with SMAP are consistent with the multiyear results of [15].

Reference [12] showed that the impacts of short-range NWP for the assimilation of SMAP brightness temperatures were mixed. The largest impacts were seen for dew-point temperature biases, as the improved soil moisture estimates resulted in overall drier conditions, which acted to reduce the daytime wet dew-point temperature biases with SMAP, by roughly 0.5°C when integrated over Canada [see Fig. 2(b)]. However, these drier soil moistures with SMAP did lead to daytime temperature biases which were increased by roughly ∼0.25°C when compared to the assimilation of screen-level temperatures [see Fig. 2(a)]. The overall drier soil moisture led to improved precipitation bias scores with SMAP (not shown). For more detailed results on the impact of SMAP brightness temperature assimilation on NWP, reference [12] provide bias and ubRMSE scores as a function of geographic region over North America.

Improved weather prediction is important for the protection of lives and property and continued economic growth increases. More accurate weather forecasts resulting from the inclusion of SMAP data could enable governments, businesses and individuals to make more informed daily and long-term decisions.

III. Soil Moisture and Drought

Soil moisture is considered a key variable in drought analysis and plays an important role in agricultural drought monitoring. However, the observed soil moisture itself may not reveal drought information [16]. Reference [17] suggested that the change in soil moisture between two time periods can provide information on the intensification or improvement of drought conditions. The National Drought Mitigation Center (NDMC) creates monthly, 3-monthly, and 6-monthly soil moisture change maps. These change maps assist the U.S. Drought Monitor (USDM) authors to evaluate and validate the recovery, onset, and severity of the drought status in the contiguous U.S. (CONUS). In [17] work, soil moisture estimated from SMAP was compared



(a) (b)

Fig. 2. Bias scores as a function of forecast range for a series of 48-hour forecasts for the July-August 2015 period over Canada: (a) 2-m air temperature, and (b) 2-m dew-point temperature. All forecasts were initialized at 0000 UTC, corresponding to the late afternoon and early evening time period. Experiment SVS-SCREEN (SVS-SCREEN+SMAP) shown in blue (red).

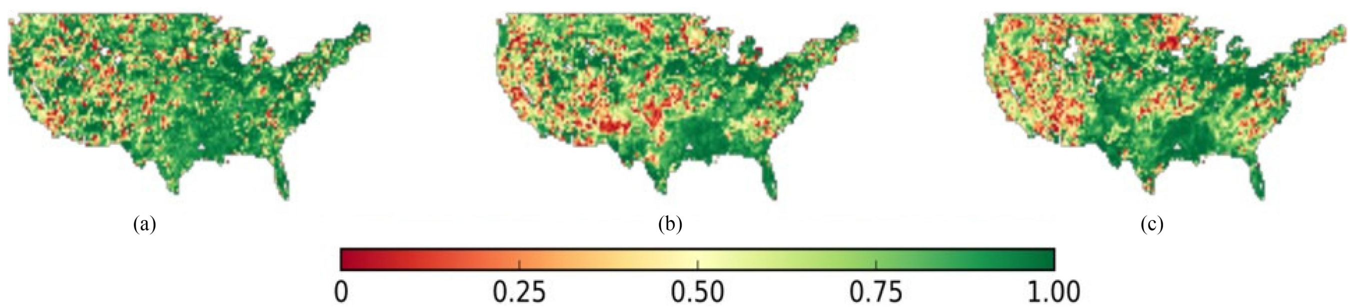


Fig. 3. Correlation maps between the SMAP soil moisture change and USDM change in drought intensity over CONUS domain at: (a) 4 weeks; (b) 13 weeks; and (c) 26 weeks. The Fig. is sourced from Eswar *et al.* (2018).

with the USDM and the Standardized Precipitation Index (SPI) over CONUS at different time intervals, including 4 weeks, 13 weeks, and 26 weeks. Fig. 3 illustrates the correlation map at 4 weeks, 13 weeks and 26 weeks between the change in soil moisture and the change in drought intensity over CONUS. The results from this study indicate that the SMAP soil moisture change is able to capture the changes in drought intensity levels in the USDM, and the change over a four-week interval correlated well with the one- month SPI values (not shown). This suggests that a short-term negative soil moisture change may indicate a lack of precipitation, whereas a persistent long-term negative soil moisture change may indicate severe drought conditions. The results further indicate that the inclusion of soil moisture change will add more value to the existing drought-monitoring products.

Droughts affect the economy, food supply, human health and safety. Improvements in the ability to monitor and forecast agricultural drought will improve famine early warning, especially in the most food-insecure countries in the world. Soil moisture information can also be used to help predict wildfires, determine prescribed burning conditions, and estimate smoldering combustion potential of organic soils. A timely and effective drought monitoring and early warning system is critical, particularly in those regions most prone to droughts, for the preparation of response and mitigation plans.

IV. Soil Moisture and Agriculture

Soil moisture strongly affects plant growth and hence agricultural productivity, especially during conditions of water shortage and drought. Crop production and food security are among the top international concerns due to the impacts of climate change. Global crop monitoring may help to guide agricultural priorities in international disaster risk reduction and adaptation efforts.

The U.S. Department of Agriculture (USDA) Foreign Agricultural Service (FAS) is responsible for providing monthly global crop estimates and projected crop yields to monitor global crop conditions and ensure agricultural economic security. However, the soil moisture estimates traditionally used in

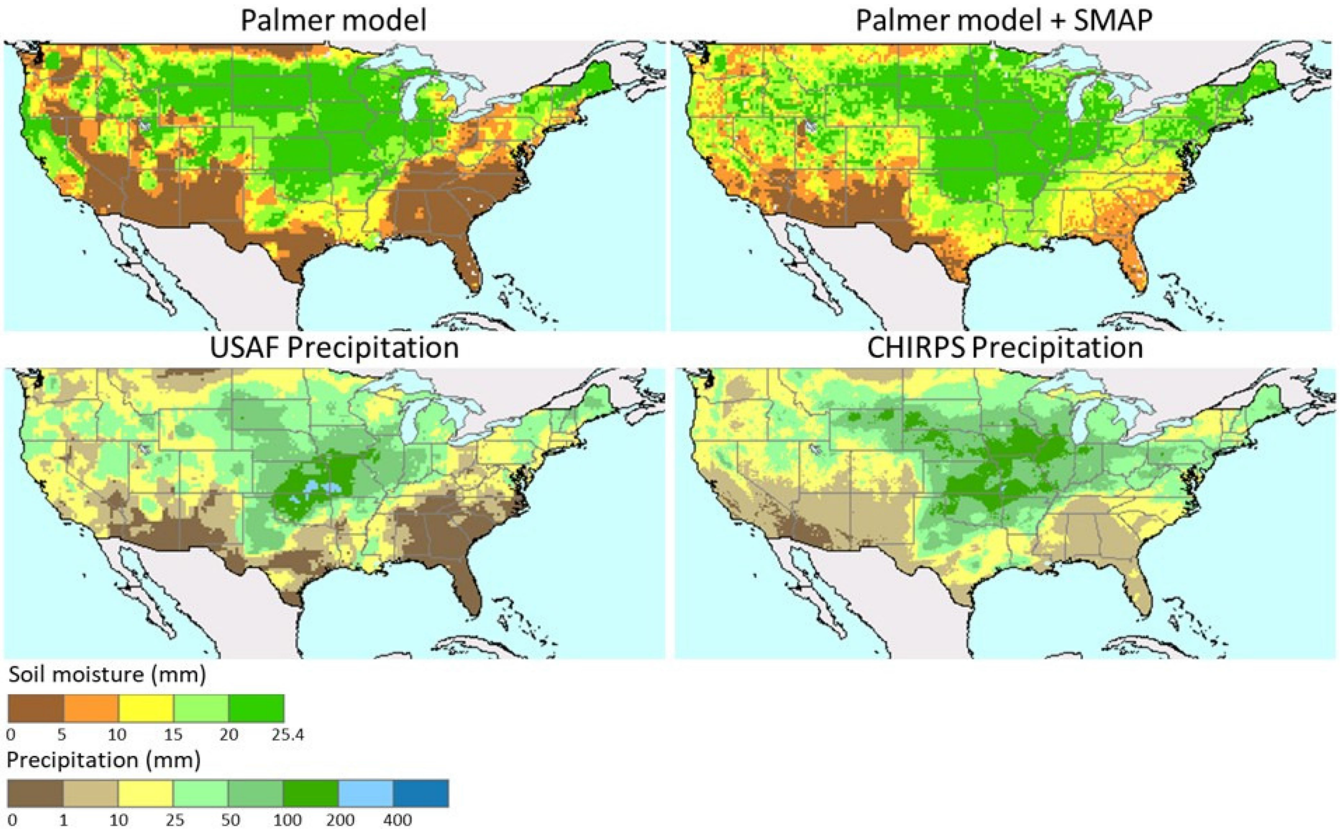


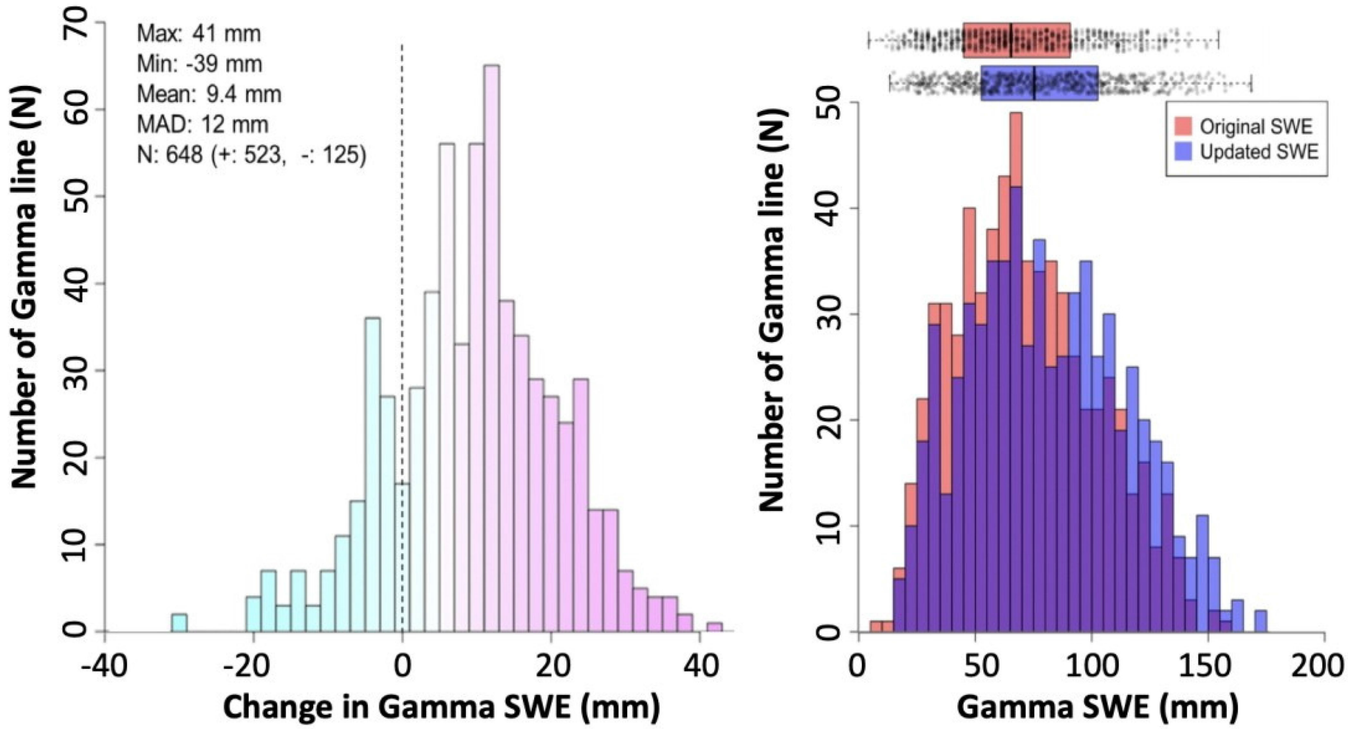
Fig. 4. Maps capture the precipitation variability and the corresponding soil moisture conditions during the week of May 20–26, 2019. The top left Fig. displays the output from the USDA-FAS Palmer model alone and the SMAP enhanced model run is shown in the top right plot. Included also in the Fig. are the U.S. Air Force Precipitation (USAF), which is the default forcing dataset used to run the Palmer model (bottom left plot) and the Climate Hazards group InfraRed Precipitation with Station (CHIRPS) (bottom right plot). SMAP adds additional variability not evident in the original product that is also consistent with the spatial distribution captured by the CHIRPS precipitation product (e.g., Texas, South Carolina, North Carolina, Ohio, etc.).

this type of global modeling suffer from a range of deficiencies including poor quality rainfall input, uncertain parameter values and oversimplified vertical and lateral physics. The USDA FAS now operationally uses SMAP soil moisture to reduce the impact of these deficiencies to improve root-zone soil moisture estimates, which in turn improves global crop yield forecasts. SMAP soil moisture enhances the USDA FAS's ability to predict the availability of root-zone soil water for plant growth and development through improved model-based soil moisture predictions, particularly over poorly instrumented areas of the world that lack good quality precipitation data. An example of the added value of assimilating SMAP soil moisture observations into the USDA FAS Palmer model is shown in Fig. 4. The variability captured in the output from the Palmer model alone (Fig. 4, top left plot) mostly resembles the spatial patterns of the U.S. Air Force agency (USAF) precipitation estimates. SMAP enhances the USDA FAS modeled soil moisture information by adding additional details not evident in the original Palmer output. The spatial variability captured in the SMAP-enhanced model run is more consistent with alternative precipitation data sources such as the Climate Hazards group InfraRed Precipitation with Station (CHIRPS). The methodology used to generate the NASA-USDA FAS soil moisture products has been well described in literature [18]–[20]. Furthermore, extensive quantitative assessment of the data can be found in [21] and [22].

The USDA FAS plays an active role in monitoring and enhancing world food security by informing policymakers of potential food security problems well in advance, working closely with the U.S. Agency for International Development (USAID), and providing direct support to the Famine Early Warning System (FEWS-NET). The U.S. government uses this information to determine food-insecure geographical regions and their potential for affecting national security. The improvements in the reliability and accuracy of FAS's model and decision support system could increase the efficiency and effectiveness of the government's operations on enhancing, preparing and managing the world food and agricultural economic security.

V. Soil Moisture and Snowmelt Flood Prediction

Soil moisture is a key variable in water-related natural hazards including floods and landslides [23]. The surface soil moisture state determines the capacity of the soil to accept additional water infiltration from precipitation, and hence runoff potential. As a consequence, soil moisture strongly affects the amount of precipitation that runs off into nearby streams and rivers, with large runoff potentially causing floods. In cold land regions, the timing



(a) (b)

Fig. 5. Change in gamma snow water equivalent (SWE) measurement after using SMAP soil moisture to update the fall baseline soil moisture estimates for the three winters from 2015 to 2018. The updated SWE was increased by 13% from the original SWE, and now have a better match with the Special Sensor Microwave Imager Sounder (SSMIS) satellite SWE and Soil Climate Analysis Network (SCAN) SWE observations (Cho *et al.* 2019a).

of thawing is coincident with the onset of seasonal snowmelt, soil thaw, and ice breakup on large rivers and lakes. Rapid snowmelt can cause flooding. Soil moisture is a fundamental input which drives flood prediction modeling [24]. Improved soil moisture and freeze/thaw estimates may help improve flood forecasting and flash flood analysis. In turn, this will improve the response of government agencies and emergency managers to a full range of emergencies and disasters.

The Red River of the North (RRN) Basin, bordering eastern North Dakota and western Minnesota, is very vulnerable to frequent snowmelt floods due to its flat terrain and low permeability soil. During the last 40 years, the NOAA airborne gamma soil moisture and snow survey has collected near-surface soil moisture and snow water equivalent (SWE) to help the National Weather Service (NWS)'s regional river forecasting centers over the U.S., especially in North Central U.S. including the RRN region [25], [26]. Due to the reliabilities of the gamma soil moisture and SWE records, they have been successfully used to improve operational spring flood forecasting from 1979 to the current [27], [28]. In the fall from October to November, NOAA measures gamma radiation over snow-free soil to obtain a baseline estimate of soil moisture before winter freeze and snow sets in. The difference in gamma radiations measured between the fall flight and any subsequent identical winter flights over snowpack reflects the amount of snow water equivalent (SWE), which is critical for accurate snowmelt flood prediction [28]. However, since soil moisture often changes after the gamma flights are flown in the fall due to later rainfall and early-winter snowmelt, an update to these values is needed to improve SWE.

Organizations including the University of New Hampshire, NOAA North Central River Forecast Center (NCRFC), North Dakota State University, U.S. Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL), and USDA Hydrology and Remote Sensing Laboratory are using SMAP soil moisture data to improve snowmelt flood prediction in the RRN region [29]. However, since soil moisture often changes after the gamma flights are flown in the fall due to later rainfall and early-winter snowmelt, an update to these values is needed to improve SWE [30]. SMAP soil moisture information has been shown to enhance the capacity of NCRFC to predict snowmelt flooding by capturing antecedent soil moisture conditions prior to freeze up and using this information to update SWE estimates from NOAA's fall gamma flights (see Fig. 5). The updated SWE were increased by 13% from the original SWE, and now have a better match with the Special Sensor Microwave Imager Sounder (SSMIS) satellite SWE and Soil Climate Analysis Network (SCAN) SWE observations [30].

Accurate flood forecasting in cold regions can be difficult due to a suite of conditions that contribute to the region's flooding, including antecedent soil moisture, snow cover area and water equivalent, depth of frost, rate and timing of snow cover melt, spring precipitation, river ice condition, and base hydrologic flows. SMAP soil moisture, particularly prior to winter onset, can provide antecedent spatial soil moisture conditions and lead to improved SWE estimates. In turn, this could improve accuracy of flood forecasts in cold regions.

Accurate prediction of the flood occurrence can reduce the loss of life and damage to property and infrastructure facilities for the citizens living in the region.

VI. Conclusion

As climate change is expected to continue, effective monitoring and early warning systems become increasingly more important as a way to help mitigate the possible adverse impacts of climate change. Applications of SMAP soil moisture information are already helping to better predict and monitor weather and climate phenomena such as floods and droughts, as well as food security and agricultural productivity. Surface soil moisture state information from SMAP helps to determine the capacity of soil to absorb further infiltration due to precipitation and/or snowmelt, thus providing useful guidance on the potential for excess runoff and flooding. Finally, use of SMAP data can improve knowledge of the land surface initial conditions which are critical for accurate weather forecasts for the benefit of society.

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Vanessa M. Escobar is the User Engagement Scientist for NOAA's Geostationary Extended Observations Program (GEO-XO) at NASA Goddard Space Flight Center. She is responsible for engaging and translating user needs into science requirement for GEO-XO as well as bridging user engagement efforts across NOAA and NASA offices. Vanessa specializes in the overall strategy development and analysis that enables the use of Earth observations and mission science into operational and decision-making platforms for the user community. Vanessa comes to NOAA from NASA where she spent the last eight years translating the value of remote sensing data for societal benefits. She lead applications research efforts for missions like SMAP (Soil Moisture Active Passive) and ICESat-2 (Ice Clouds and Elevation Satellite) as well as stakeholder applications research efforts for NASAs CMS (Carbon Monitoring Systems). Prior to joining NOAA Vanessa spent time at NASA Headquarters on detail, leading the development and implementation of NASAs 2016 ESD Directive on Project Applications Program, where user engagement and feedback is identified as a key requirement for future Earth science mission development. Vanessa has spent more than 17 years facilitating communication between scientists, users and stakeholder, translating discussions across scientific and political boundaries related to water resource management, risk, hydrology, remote sensing, public policy, carbon science and decision support frameworks for the Army, commercial companies, Arizona State University, and the University of Maryland. She is an ASU CSPO alumna, having defended her Masters Degree at the ASU Decision Theatre in Tempe. Her role with NOAA will help NOAA NESDIS analyze the needs of users and identify where future geostationary data value can be enhanced and leveraged.