POTENTIAL OF G-CLASS/HYDROTERRA FOR THE ASSESSMENT OF SEVERE HYDROLOGICAL CONDITIONS

Jean-Christophe Calvet, Emily Black, Eleanor Blyth, Stephen Hobbs, Juan Manuel Lopez-Sanchez, Francesco Mattia, Tristan Quaife, Raphael Quast, Gwyn Rees, Wolfgang Wagner

POTENTIAL OF G-CLASS/HYDROTERRA FOR THE ASSESSMENT OF SEVERE HYDROLOGICAL CONDITIONS

Jean-Christophe Calvet[(1)], Emily Black[(2)], Eleanor Blyth[(3)], Stephen Hobbs[(4)], Juan Manuel Lopez-Sanchez[(5)], Francesco Mattia[(6)], Tristan Quaife[(2)], Raphael Quast[(7)], Gwyn Rees[(3)], Wolfgang Wagner[(7)]

[(1)] CNRM, Université de Toulouse, Météo-France, CNRS
42 avenue Gaspard Coriolis, 31057 Toulouse, France
Email:jean-christophe.calvet@meteo.fr

[(2)] University of Reading
Reading, UK
Email: e.c.l.black@reading.ac.uk

[(3)] CEH
Wallingford, UK
Email: hgrees@ceh.ac.uk

[(4)] Cranfield University
Cranfield, Bedford, MK43 0AL, UK
Email: s.e.hobbs@cranfield.ac.uk

[(5)] Universidad de Alicante
03080 Alicante, Spain
Email: juanma.lopez@ua.es

[(6)] CNR-IREA
via Amendola 122/D, 70126, Bari, Italy
Email: francesco.mattia@cnr.it

[(7)] Vienna University of Technology
Department of Geodesy and Geoinformation (GEO)
Wiedner Hauptstrasse 8-10, 1040 Vienna, Austria
Email: raphael.quast@geo.tuwien.ac.at

INTRODUCTION

The call for ideas for the EE10 mission was released in 2017 and three mission candidates were selected for a Phase-0 study out of 21 proposals in July 2018. The three candidate missions selected for the assessment studies are: STEREOID, Daedalus, and G-CLASS. STEREOID (Stereo Thermo-Optically Enhanced Radar for Earth, Ocean, Ice and Land Dynamics) will observe small scale motion and deformation fields of the ocean surface, glaciers and ice sheets, sea ice and solid Earth. Daedalus is a low flying spacecraft for the exploration of the lower thermosphere-ionosphere – a mission to quantify the key electrodynamics processes that determine the structure and composition of the transition region between the atmosphere and space in the upper atmosphere. G-CLASS (Geosynchronous Continental Land-Atmosphere Sensing System) aims to observe the key processes of the daily water cycle to increase the prediction capability of intense rainfall and related flooding and landslides, to improve the understanding of the diurnal water cycle and to enable the near real time prediction of ground motion. G-CLASS is now called Hydroterra. This work is a contribution to the definition of potential scientific needs covered by Hydroterra for improving the monitoring of terrestrial variables and processes related to surface hydrology and to weather forecast.

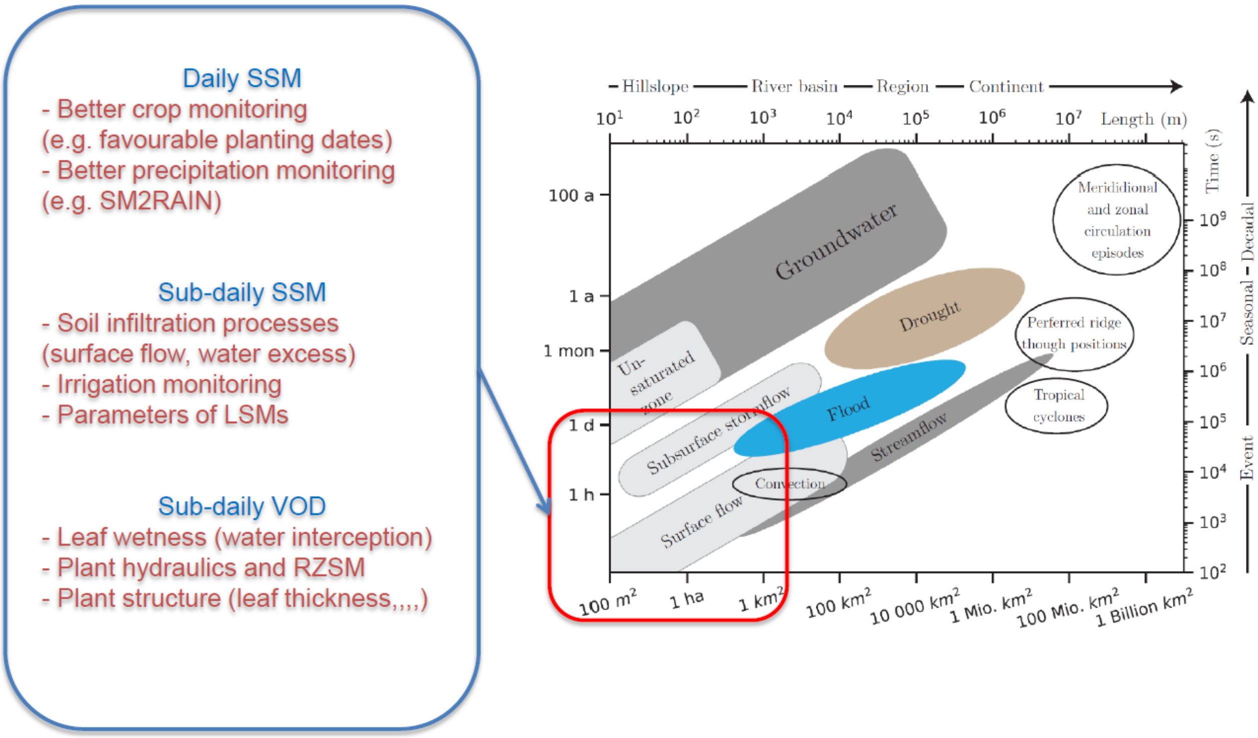

Fig. 1. Potential scientific needs covered by Hydroterra for improving the monitoring of terrestrial variables and processes related to surface hydrology at various scales. SSM, SM2RAIN, LSMs, VOD, and RZSM stand for surface soil moisture, an algorithm to retrieve accumulated precipitation from SSM time series [1], land surface models, vegetation optical depth, and root-zone soil moisture, respectively. Adapted from [2].

SURFACE SOIL MOISTURE

A key variable observable from space is surface soil moisture (SSM): a useful indicator of the hydrological condition and responsiveness of catchments to extreme events. It can be derived using low-frequency passive and active microwave sensors such as SMOS, ASCAT or Sentinel-1. A number of studies showed that systematic SSM retrieval at high resolution and large scale from Sentinel-1 is possible [3-5]. Also the use of SAR coherent change detection (i.e., based on interferometric observations) to identify SSM changes was demonstrated for both C- and L-band [6-10]. In addition, conceptual models relating interferometric SAR observations to SSM changes were developed [11,12] and their use for SSM retrieval was investigated [13]. However, existing microwave sensors provide measurements that are either too coarse or infrequent for capturing many important hydro-meteorological processes taking place at the land-atmosphere interface. As illustrated by Figure 1, convection events, surface flows, irrigation activities, or other important short-term events may be simply missed out. A key message can be derived from Figure 1: processes that are active at a fine spatial scale such as runoff tend to be faster than those occurring at the large scale (e.g. drought). Therefore, there is a high need for sub-daily sub-kilometric microwave observations to depict these dynamic processes in a complete manner. Although the SAR SSM retrieval from radar backscatter (σ_0) is now more advanced than from interferometric observations, the latter could provide additional information, especially with an improved sampling time. In this respect, the hyper temporal imaging capability of Hydroterra will favor the synergy of intensity and interferometric observations in SSM retrievals.

MORE VARIABLES ARE NEEDED

SSM is key but other variables (including vegetation variables) are also useful for monitoring hydrological conditions and managing water resources.

At a global scale, low spatial resolution products can be used to detect the onset of severe conditions but operational responses typically require more detailed descriptions of soil-plant systems that can only be provided by high resolution products. Recent and on-going studies based on Sentinel-1 data show that C-band SAR systems have potential to retrieve SSM and vegetation optical depth (VOD) at sub-kilometric scales. VOD can be considered a proxy for Leaf Area Index (LAI) and also contains information on vegetation water content (VWC). In addition to SSM and VOD, such data can be used to map irrigated areas (Figure 2). Combining VOD with other satellite-derived products such as

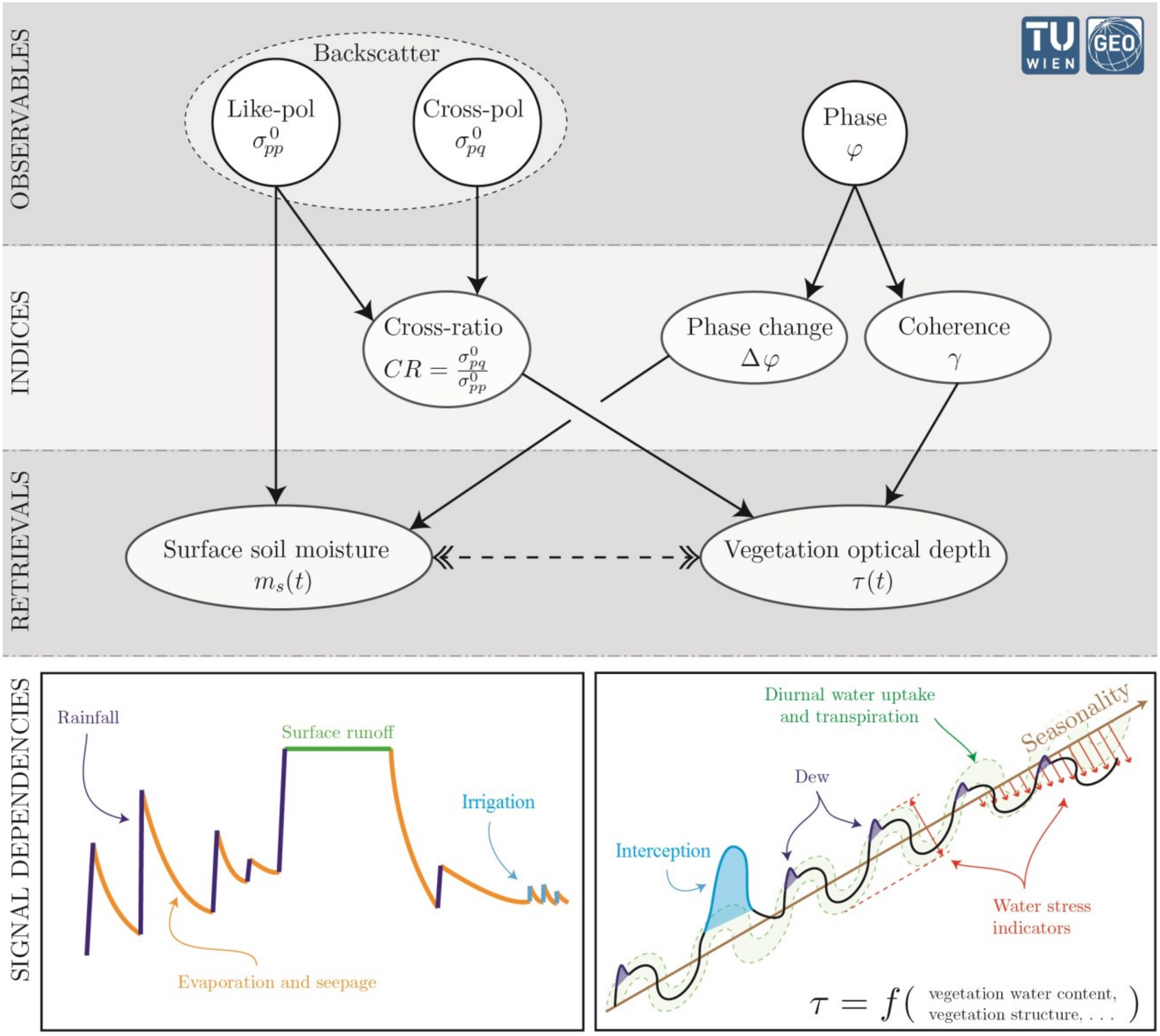

Fig. 2. From Level 1 to Level 2 Hydroterra products

LAI could provide useful information on physiological plant properties such as leaf specific area and plant phenology. This information could be included in land surface models and hence improve simulations of the vegetation phenology and of the terrestrial water cycle.

The main atmospheric variable driving the terrestrial water cycle is precipitation. It was shown that SSM time series can be used to estimate accumulated precipitation values and SM2RAIN, an algorithm to retrieve accumulated precipitation from SSM time series, was developed by [1].

A number of studies have investigated the σ_0 difference between descending and ascending orbits for ERS and ASCAT instruments. For example, it was found that changes in low resolution ASCAT backscatter diurnal cycle is much reduced over the USA during droughts [14]. These studies suggest that the diurnal cycle can give useful information on plant water stress. Steele-Dunne et al. [15] has recently revisited the use of the overpass time in ASCAT data over North American grasslands. The authors used carefully processed σ_0 data covering the whole range of available incidence angles. They found that vegetation density (or water content) as derived from the observations tends to be larger for the evening orbit than for the morning one. This is in contradiction with previous studies. An explanation could be that the morning overpass at 09:30 am is probably too late to capture the pre-dawn VWC maximum. This indicates that a better temporal sampling is needed to capture diurnal changes in VOD.

THE DIURNAL CYCLE

As highlighted above, the diurnal cycle is a new dimension that is inaccessible to existing space-borne microwave sensors. Sub-daily observations of σ_0 and phase as provided by Hydroterra will provide seamless time series that do not leave out any important changes in the scattering mechanisms in soils and vegetation. In other words, Hydroterra will deliver for the first time interferometric radar observations at the right scale to unambiguously interpret the sources of signal variations, i.e. if stemming from (fast) dielectric or (slower) structural changes in the soil or vegetation. This will boost the understanding of the interaction of microwaves with soil and vegetation, allowing one to disentangle the effects of soil and vegetation on the backscattered signals much better than is possible with existing sensors. This is crucial for overcoming shortcomings of current C-band radar-derived SSM products such as low SSM retrievals at springtime over some vegetation types like wheat croplands. This could be related to a misrepresentation of changes of vegetation structure in the retrieval algorithm. For example, leaf thickness and the ratio of LAI to VOD of wheat crops can rapidly change during the plant growth phase. Also, negative correlation with in situ observations and model estimates over arid areas and karstic areas have been observed [16]. This could be due to soil subsurface scattering and to changes in surface soil roughness. Hydroterra will provide the necessary observables to verify these hypotheses. Cross-polarisation would be useful for characterizing vegetation and subsurface scattering.

More research in needed on disentangling VOD and SSM information at the diurnal time scale. Both quantities may present a marked diurnal cycle. The work of [15] on diurnal changes in vegetation density is based on a range of incidence angles. Situated on a geosynchronous orbit, Hydroterra will not have a multiangular capability. Even if cross-polarization is available, disentangling VOD and SSM and retrieving the phase from the Hydroterra observations alone could be challenging. It is likely that synergies with land surface models and other biophysical data streams such as LAI and SSM will have to be implemented. For this purpose, an observation operator able to simulate the Hydroterra Level 1 observations from ancillary LAI, interception, and SSM information should be developed. Interception is an ephemeral process during and after rainfall episodes corresponding to the evaporation of rain water before it can reach the soil surface. The intercepted rainwater is a component of VOD. It can be disentangled from the VWC component of VOD as it changes much more rapidly. Vegetation precipitation interception is one of the most uncertain component of the water evaporation flux over terrestrial surfaces. Interception can reduce infiltration of rainwater into soils by up to 30% for forests [17] and can have a significant impact on the weather systems.

Apart from a plethora of potential operational applications of Hydroterra, addressing the diurnal cycle would trigger significant progress in the knowledge related to soil model parameters (drying rates, infiltration rates) and plant hydraulics (including the biological redistribution (hydraulic lift) of soil moisture), which currently is missing in the process representation of land surface models. Hydraulic redistribution by roots is a poorly known process. Roots may transfer moisture from deep soil layers to surface soil layers [18] or on the contrary contribute to groundwater recharge [19].

Because both Sentinel-1 and Sentinel-2 images can now be combined at high sampling time, different approaches can be proposed to estimate the irrigation water use in addition to irrigation mapping. This can be achieved through the assimilation of SSM products into land surface models able to work at the field scale. These methods can also be implemented using low resolution SSM products such as those derived from ASCAT [20]. The availability of such information at daily and sub-daily time intervals would greatly improve our understanding of agricultural practices involving irrigation.

Finally, the diurnal cycle of backscatter and of VOD could be used to characterize processes related to agricultural droughts and forest and savanna fire risk. Addressing the diurnal cycle would bring new insight on how to characterize drought in terms of processes in land surface models.

DATA ASSIMILATION

Data assimilation refers to the suite of mathematical tools used to combine data and models to produce the best estimate of the true state of the system being observed, taking into account all available information about uncertainties in the data and the model. Data assimilation has been responsible for significant improvements in operational weather forecasting, the production of reanalysis data from centers such as ECMWF. It has a growing role in land surface modelling activities. For example, both LAI and SSM can be assimilated into a land surface model to derive the Root-Zone Soil Moisture (RZSM). The LAI variable is a key driver of evapotranspiration. The capability of LAI observations to analyze RZSM in a data assimilation process depends on the representation by the model of the surface hydrology processes and the effect of soil water deficit on plant transpiration and plant growth. Albergel et al. [21] showed that the use of a multi-layer discretization of the total soil moisture and soil temperature profile enhances the added value of the assimilation of LAI observations. In particular, RZSM can be analyzed in dry conditions using LAI. In dry conditions, the simulated surface soil moisture is decoupled to a large extent from RSZM and the assimilation of the former to analyze the latter is not very effective [22]. Efforts are ongoing to develop the assimilation of satellite data into models able to represent the diurnal cycle of the soil-plant system variables. The goal is to have realistic simulations of diurnal changes in plant water content in land surface models and build observation operators able to represent the relationship between variables of the soil-plant system (e.g. RZSM) and backscatter and phase. Integrating such data into a LSM would give access to many variables simulated by a LSM at the sub-daily time scale such as water fluxes (evapotranspiration, interception, runoff), sensible heat to the ground and to the atmosphere, land surface temperature, and carbon fluxes. Recent attempts to simulate plant hydraulics showed that simulating plant water potential is feasible [23]. However, more research is needed to go towards VWC in distinct plant elements (leaves, branches, etc.). It is expected that more empirical approaches would be explored. In particular, time derivatives of backscatter could be directly related to applications using statistical models.

POTENTIAL SCIENTIFIC AND SOCIETAL IMPACTS

Human-induced climate change tends to increase the frequency of extreme events, such as heat waves, droughts and floods. The Mediterranean region can be considered as a hotspot of climate change as climate models predict a reduction in precipitation along with a marked warming [24]. The same concern has been expressed for the Sahel river basins [25]. Many regions in the Mediterranean are already under stress or even suffer from water scarcity. For example, shortage of drinking water is an issue in Algeria, Tunisia, Libya, in Catalonia, and in the Sicily and Apulia regions of Italy [24].

In this ever-changing world, monitoring severe conditions over land is needed. Land surface variable products derived from Earth observation can be used together with land surface models for this purpose. Accurate characterization and simulation of hydrological and biophysical variables at the land surface is not an easy task, given that terrestrial surfaces generally present large spatial heterogeneities. Also, certain anthropogenic factors such as the application of water to crops through irrigation, can alter land surface conditions rapidly. Observations and simulations of land surface in the lead-up to, and during, extreme events are needed in order to improve preparedness and to mitigate and adapt to their impacts.

The gain in process understanding and improved observation capabilities will open the door to retrieve the (1) soil moisture profile within the upper soil layers and its diurnal cycle, (2) precipitation volumes, (3) irrigation practices, (4) excess of water and overland flow, (5) plant water stress, and (6) interception. Such products would be particularly useful in arid and data-scarce areas such as North Africa and the Sahel region, and in forested areas for interception.

The development of coupled data assimilation will permit the use of Hydroterra data to analyze land and atmosphere conditions at the same time in Earth system models [26].

REFERENCES

[1] L. Brocca, L. Ciabatta, C. Massari, T. Moramarco, S. Hahn, S. Hasenauer, R. Kidd, W. Dorigo, W. Wagner, and V. Levizzani, “Soil as a natural rain gauge: Estimating global rainfall from satellite soil moisture data,” *J. Geophys. Res. Atmos.*, vol. 119, pp. 5128–5141, April 2014.

[2] K.J. Stahl and H. Hisdal, “Hydroclimatology,” in *Hydrological drought*, vol. 48, Processes and estimation methods for streamflow and groundwater, developments in water science. L.M. Tallaksen and H.A.J. van Lanen, Eds. Elsevier Science B.V., the Netherlands, pp. 12–52, 2004.

[3] Q. Gao, M. Zribi, M. Escorihuela, and N. Baghdadi, “Synergetic use of Sentinel-1 and Sentinel-2 data for soil moisture mapping at 100 m resolution,” *Sensors*, vol. 17, 21 pp., August 2017.

[4] B. Bauer-Marschallinger, V. Freeman, S. Cao, C. Paulik, S. Schaufler, T. Stachl, S. Modanesi, C. Massari, L. Ciabatta, L. Brocca, and W. Wagner, “Toward global soil moisture monitoring with Sentinel-1: Harnessing assets and overcoming obstacles,” *IEEE Trans. Geosci. Remote Sens*., vol. 57, pp. 520–539, January 2019.

[5] A. Balenzano, F. Mattia, G. Satalino, and M.W. Davidson, “Dense temporal series of C-and L-band SAR data for soil moisture retrieval over agricultural crops,” *IEEE J. Sel. Topics Appl. Earth Obs. Remote Sens.*, vol. 4, pp. 439–450, 2010.

[6] K. Morrison, J.C. Bennett, M. Nolan, and R. Menon, R., “Laboratory measurement of the DInSAR response to spatiotemporal variations in soil moisture,” *IEEE Trans. Geosci. Remote Sens*., vol. 49, pp. 3815–3823, October 2011.

[7] F. De Zan, M. Zonno, P. López-Dekker, “Phase inconsistencies and multiple scattering in SAR interferometry,” *IEEE Trans. Geosci. Remote Sens.*, vol. 53, pp. 6608–6616, December 2015.

[8] C.P. Scott, R.B. Lohman, and T.E. Jordan, “InSAR constraints on soil moisture evolution after the March 2015 extreme precipitation event in Chile,” *Sci. Rep.*, vol. 7, 9 pp., July 2017.

[9] S. Zwieback, S. Hensley, and I. Hajnsek, “Assessment of soil moisture effects on L-band radar interferometry,” *Remote Sens. Environ*., vol. 164, pp. 77–89, July 2015.

[10] S. Zwieback, S. Hensley, and I. Hajnsek, “Soil moisture estimation using differential radar interferometry: Toward separating soil moisture and displacements,” *IEEE Trans. Geosci. Remote Sens*., vol. 55, pp. 5069–5083, September 2017.

[11] F. De Zan, A. Parizzi, P. Prats-Iraola, and P. Lopez-Dekker, “A SAR interferometric model for soil moisture,” *IEEE Trans. Geosci. Remote Sens.*, vol. 52, pp. 418–425, January 2014.

[12] S. Zwieback, S. Hensley, and I. Hajnsek, “A polarimetric first-order model of soil moisture effects on the DInSAR coherence,” *Remote Sens*., vol. 7, pp. 7571–7596, June 2015.

[13] F. De Zan and G. Gomba, “Vegetation and soil moisture inversion from SAR closure phases: First experiments and results,” *Remote Sens. Environ.*, vol. 217, pp. 562–572, November 2018.

[14] R. Schroeder, K.C. McDonald, M. Azarderakhsh, and R. Zimmermann, “ASCAT MetOp-A diurnal backscatter observations of recent vegetation drought patterns over the contiguous U.S.: An assessment of spatial extent and relationship with precipitation and crop yield,” *Remote Sens. Environ*., vol. 177, pp. 153–159, May 2016.

[15] S.C. Steele-Dunne, S. Hahn, W. Wagner, and M. Vreugdenhil, “Investigating vegetation water dynamics and drought using Metop ASCAT over the North American Grasslands,” *Remote Sens. Environ*., vol. 224, pp. 219–235, April 2019.

[16] W. Wagner, S. Hahn, R. Kidd, T. Melzer, Z. Bartalis, S. Hasenauer, J. Figa-Saldanã, P. de Rosnay, A. Jann, S. Schneider, J. Komma, G. Kubu, K. Brugger, C. Aubrecht, C. Züger, U. Gangkofer, S. Kienberger, L. Brocca, Y.

Wang, G. Blöschl, J. Eitzinger, K. Steinnocher, P. Zeil, and F. Rubel, “The ASCAT soil moisture product: A review of its specifications, validation results, and emerging applications,” *Meteorol. Z.*, vol. 22, pp. 5–33, February 2013.

[17] L. Wang-Erlandsson, R.J. van der Ent, L.J. Gordon, and H.H.G. Savenije, “Contrasting roles of interception and transpiration in the hydrological cycle – Part 1: Temporal characteristics over land,” *Earth Syst. Dynam.*, vol. 5, pp. 441–469, December 2014.

[18] M. Siqueira, G. Katul, and A. Porporato, “Onset of water stress, hysteresis in plant conductance, and hydraulic lift: Scaling soil water dynamics from millimeters to meters,” *Water Resour. Res.*, vol. 44, W01432, 14 pp., January 2008.

[19] S.S.O. Burgess, M.A. Adams, N.C. Turner, D.A. White, and C.K. Ong, “Tree roots: conduits for deep recharge of soil water,” *Oecologia*, vol. 126, pp. 158–165, January 2001.

[20] F. Zaussinger, W. Dorigo, A. Gruber, A. Tarpanelli, P. Filippucci, and L. Brocca, “Estimating irrigation water use over the contiguous United States by combining satellite and reanalysis soil moisture data,” *Hydrol. Earth Syst. Sci.*, vol. 23, pp. 897–923, February 2019.

[21] C. Albergel, S. Munier, D. J. Leroux, H. Dewaele, D. Fairbairn, A. L. Barbu, E. Gelati, W. Dorigo, S. Faroux, C. Meurey, P. Le Moigne, B. Decharme, J.-F. Mahfouf, and J.-C. Calvet, “Sequential assimilation of satellite-derived vegetation and soil moisture products using SURFEX_v8.0: LDAS-Monde assessment over the Euro-Mediterranean area,” *Geosci. Model Dev.*, vol. 10, pp. 3889–3912, October 2017.

[22] M. Parrens, J.-F. Mahfouf, A. Barbu, and J.-C. Calvet, “Assimilation of surface soil moisture into a multilayer soil model: design and evaluation at local scale,” *Hydrol. Earth Syst. Sci.*, vol. 18, pp. 673-689, February 2014.

[23] A. Tuzet, A. Granier, P. Betsch, M. Peiffer, and A. Perrier, “Modelling hydraulic functioning of an adult beech stand under non-limiting soil water and severe drought condition,” *Ecol. Model.*, vol. 348, pp. 56–77, March 2017.

[24] W. Cramer, J. Guiot, M. Fader, J. Garrabou, J.-P. Gattuso, et al., “Climate change and interconnected risks to sustainable development in the Mediterranean,” *Nat. Clim. Change*, vol. 8, pp. 972–980, October 2018.

[25] M.B. Sylla, A. Faye, N.A.B. Klutse, and K. Dimobe, “Projected increased risk of water deficit over major West African river basins under future climates,” *Clim. Change*, vol. 151, pp. 247–258, November 2018.

[26] J.-C. Calvet, P. de Rosnay, and S.G. Penny, “Editorial for the Special Issue “Assimilation of Remote Sensing Data into Earth System Models”,” *Remote Sens.*, vol. 11, 4 pp., September 2019.