Reply to interactive comments on "Earth observation Water Cycle Multi-Mission Observation Strategy (WACMOS)" by Z. Su et al.

We thank the editor and the reviewers for reviewing our manuscript. In the following, we provide a point by point reply to all issues raised by the reviewers. Our replies are given in bold font and/or heighted for easy reading and traceability.

<u>Anonymous Referee #1</u>

The paper by Su et al. on the description of the WACMOS project could be of interest to the hydrology community as it gives an overview of the current space borne systems for observing hydrologically relevant parameters. However, the main problem with this paper is that on the one hand it tries to give an overview of where EO currently stands and where it aims at (but it fails in being a review) whereas on the other hand, it mentions some progress made by the WACMOS team (without going into detail: only some illustrations are given without any scientific proof). Therefore, in its current version, it is of low scientific value. To improve this paper, I would suggest that the main focus indeed goes to the objectives and the results of the WACMOS project, but that the project, its methodologies and its results should be better positioned within the advances of remote sensing community (i.e. alternative approaches should be (briefly) discussed, or papers confirming similar approaches should be referenced). I.e. the paper should aim at being a review paper (on the topics of WACMOS), demonstrating where WACMOS aims at contributing to the current knowledge.

We thank the reviewer for the constructive comments. The manuscript has been modified to focus on the objectives and the results of WACMOS project. Recent advances and related topics to WACMOS are reviewed and commented in each theme.

The abstract has been modified, with the addition "This paper provides an overview of some preliminary findings of the project with the ultimate goal of demonstrating the potential of innovative multi-mission based strategies to improve current observations by maximizing the synergistic use of the different types of information provided by the currently available observation systems. It describes the rationales and objectives of the WACMOS project and introduces its preliminary products."

Several references are added in the introduction part as given below.

"In recent years, EO technology has proved to be a major source of data to retrieve an increasing number of hydro-climatic variables from space, including radiation and cloud properties (Jacobowitz et al. 2003; Zhang et al. 2004; Schulz et al., 2009), precipitation (Kummerow et al., 2001; Huffman et al., 2007; Kidd and Levizzani, 2010), evapotranspiration (Kalma et al., 2008; Jiménez et al., 2011), soil moisture (Aires and Prigent, 2006; De Jeu et al., 2008), water vapour (Randal et al., 1996; Schulz et al., 2009), and many others (see for example, GEO, 2005; ESA, 2006; CEOS, 2009; Su, 2010)."
"WACMOS is focused on four components of the water cycle that are also thematic priorities identified in close collaboration with the GEWEX scientific community: evapotranspiration, soil moisture, clouds and water vapour (Scientific Consultation Workshop, Vienna University of Technology, 14th April 2008, ESA, 2008). The latter three of these components also belong to the Global Climate Observing System (GCOS) Essential Climate Variables (ECVs) for Long-term systematic observation needs of World Climate Research Programme (WCRP) (GCOS, 2006, http://gcos.wmo.int), *while the retrieval of the evapotranspiration requires the use of several atmospheric, oceanic and terrestrial ECVs. Since the WACMOS project is an exploratory project*

rather than a product development project in its current phase, it is important to note that the boundary conditions (a focus on the use of ESA data) and constraints (limited timeframe and budget), hence the outcomes of the project focus on the development of algorithms and their validation and preliminary generation of sample data products. A more consistent generation and validation of all WACMOS products and their exploratory applications in water and climate researches and applications need to be addressed in a follow up phase.

In this paper, an overview and short summaries are given for each WACMOS component; the more detailed technical descriptions can be found elsewhere in this special issue (Timmermans et al., 2010; Dorigo et al. 2010; Wolters et al., 2010)."

Other changes are indicated in the accompanying supplementary materials.

Reply related to evapotranspiration theme

Section 3.1 is completely rewritten, adding reviews of recent and major international initiatives and published studies related to evapotranspiration.

"Evapotranspiration (ET) is the process whereby water is transferred from the surface to the atmosphere (Kalma et al., 2008) as a combination of soil and water evaporation and vegetation transpiration. Where the evaporation is only controlled by the physical processes of diffusion and advection, transpiration is also controlled by biological process, like photosynthesis.
Evapotranspiration is unique in providing the link between energy balances, water budgets and plant growth as it plays a vital role in the energy cycle, the water cycle and the carbon cycle (Bowen, 1926; Penman, 1948; Monteith, 1965; Famiglietti and Wood, 1994). By returning available water at the surface to the atmosphere, terrestrial evapotranspiration regulates the biological environment and its water use efficiency. In addition, evapotranspiration is a key quantity for the estimation of crop yield, irrigation water management, drought assessment, fire susceptibility, convective precipitation patterns as well as catchment water budgets. To be of routine use, all these applications require an evapotranspiration product with the spatial-temporal constraint of 1 km resolution with a 1 day repeat time. However no global product (land and ocean) based on observations currently exists that fulfils these application requirements.
Over the last couple of years several initiatives, such as the LandFLUX Initiative (Jiménez et al., 2011; Mueller et al., 2011), have targeted to evaluate and develop large scale evapotranspiration products. In general these products can be divided into four groups: the field measurement upscaling methods, land surface models, empirical methods and energy balance methods. Land surface models, like the European Centre for Medium-range Weather Forecasts reanalysis (ECMWF ERA-interim) (Simmons et al., 2007) and the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004), use routine measurements of meteorological parameters to simulate the land surface processes. As these models in general do not use surface remote sensing data for forcing, they have a coarse resolution (>1.0°). Recently the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Satellite Application Facility on Land Surface Analysis (LandSAF) has tackled this problem by incorporating METEOSAT Second Generation (MSG) data into the ECMWF TESSEL model (Ghilain et al., 2010). While the resolution has greatly increased the data products are restricted to the MSG disc area. The field upscaling methods use actual measurements from the field to estimate evapotranspiration in initiatives like Fluxnet (Baldocchi et al., 2001). As these measurements in general have a too small footprint for global application upscaling is performed using satellite observations (Jung et al., 2010). The disadvantage of these methods is that the spatial resolution (0.5°) provided is still too coarse for most hydrological applications. It should be noted that data from the CarboEurope and Fluxnet initiatives are used in the validation procedure. As empirical and energy balance models estimate evapotranspiration from remote sensing data their resolution (<1km) is much better than that of the other methods. Empirical methods (Mu et al., 2007; Fisher et al., 2008) rely on the calculation of a potential/reference evapotranspiration and combining this with crop and environmental coefficients. In a recent study (Miralles et al., 2010), these empirical coefficients are replaced through the use of soil-moisture and rainfall observations. Energy balance methods circumvent the use of crop coefficients by characterising the actual processes on the land surface.

Several studies (McCabe and Wood, 2006; Jiménez et al., 2011; Mueller et al., 2011; Vinukollu et al., 2011) are performed to investigate the performance of energy balance algorithms, like the Surface Energy Balance System (SEBS) (Su, 2002), the Two Source Energy Balance (TSEB) and ALEXI (Anderson et al., 2007; Kustas and Anderson, 2009). While global evapotranspiration from two source models are not available yet, recently a global evapotranspiration product using SEBS and MODIS data has been made available (Vinukollu et al., 2011).

The Surface Energy Balance System (SEBS) (Su, 2002) circumvents problems of local calibration, or complexity, because it uses physical parameterization (Su et al., 2001) of the turbulent heat fluxes for different states of the land surface and the atmosphere based on the similarity theory (Obukhov, 1971; Brutsaert, 1999). For this reason we use SEBS in WACMOS as the baseline algorithm. The algorithm uses three sets of input parameters and variables that can either be measured using remote sensing sensors (like albedo, emissivity, land surface temperature and leaf area index (LAI) or obtained using mesoscale atmospheric models (wind speed, air temperature and humidity, and incoming short and long wave radiation). Since evapotranspiration is most sensitive to land surface temperature, data from a thermal remote sensing sensor is required.

The Advanced Along Track Scanning Radiometer (AATSR) and the Medium resolution Imaging Spectrometer (MERIS) sensors onboard the Environmental Satellite (ENVISAT) fit the spatio-temporal requirement of the evapotranspiration product very well; AATSR provides high resolution accurate land and ocean surface temperature measurements and MERIS provides high resolution optical measurements (needed for estimating albedo and LAI). Using data from these orbiting satellites restricts the temporal resolution of the final product, as the revisit time is more than a single day. The incorporation of data from geostationary satellites could solve this problem and additionally capture the diurnal pattern of evaporative fraction. However this has not been performed currently due to the high computation demands. Therefore the final product will still contain gaps due to missing data and cloud cover. The meteorological parameters have been extracted from the ECMWF database. The meteorological parameters in this database are obtained for both surface height and different pressure levels in the atmosphere, which makes this database highly suitable for scaling between low and high spatial resolutions by employing similarity principles (Su, 2002). "

Reply related to soil moisture theme

To position the WACMOS SM product in the context of current research issues and missions focusing on soil moisture from microwave satellites, Section 3.2 was completely revised and significantly extended. The following text was added:

"Recently, GCOS has endorsed soil moisture as one of the Essential Climate Variables (ECV) necessary to characterise the climate of the Earth. It is a variable that has always been required in many disciplinary and cross-cutting scientific and operational applications such as numerical weather prediction, ecology, biogeochemical cycles, flood forecasting, etc. (Jackson et al. 1999). With increasing evidence of climate change, it becomes even more urgent to elucidate the critical role of soil moisture. Since in situ measurements of soil moisture are very sparse (Robock et al., 2000; Dorigo et al., 2011), satellite observations in the microwave domain have been broadly recognised as a valuable alternative for capturing its spatio-temporal behaviour.

Soil moisture products from microwave observations dating back to the late 1970s have now become available for several past and present operational radiometer (passive) and scatterometer (active) systems and will soon be complemented with observations from the recently launched Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al., 2001, 2010; Table 4, Figure 1).

In principle, active and passive microwave sensors show similar sensitivity to variations in soil moisture (Ulaby et al., 1986). Nevertheless, the geometric arrangements of objects (vegetation, soil particles, buildings etc.) on the Earth surface have a stronger influence on the backscatter measurements made by active systems than on the emissivity measurements of radiometers. As a consequence, it appears more complicated to model backscatter than emissivity and retrieval

algorithms designed for active systems are more difficult to parameterise (Bindlish et al., 2009, Piles et al., 2009).

Apart from the observation principle, soil moisture estimates are also influenced by the wavelength of observation. Longer wavelengths tend to penetrate vegetation and the upper soil layer better than shorter wavelengths (Calvet et al., 2011). By choosing long wavelengths the sensitivity to the sub-surface soil moisture content can thus be maximised, nevertheless often at the cost of spatial and temporal resolution. The radiometers shown in Figure 1 operate in wavelengths between ~1.5 (Ku-band) and ~21cm (L-band). Both scatterometer systems measure backscatter in wavelengths around 6 cm (C-band).

The less complex models required for soil moisture estimation from radiometers in combination with the increased sensitivity to soil moisture of longer wavelengths explains why the first two spaceborne missions specifically designed for the purpose of soil moisture mapping, i.e. SMOS and SMAP (Entekhabi et al., 2010), are based on passive L-band measurements. In addition, the SMAP mission will be the first space-based initiative that makes synergistic use of low resolution radiometer measurements and high resolution radar observations to obtain a soil moisture product with improved accuracy and spatial resolution. The benefit of combining various independent observations to improve the robustness of soil moisture retrievals was also recognized by Aires and Prigent (2006) who proposed the theoretical framework of such multiple-sensor products. However, such an approach premises that observations are concurrently available, but this condition is very often not met, especially in the case of historic observation series.
From Figure 1 it becomes clear that there is no single mission providing a spatially and temporally consistent record that is long enough to globally address climate issues. Nevertheless, combining all historic and present passive and active microwave soil moisture products would allow us to obtain a soil moisture record that spans a period of more than 30 years. This in turn would facilitate studying long-term soil moisture behaviour e.g. in relation to climate change (Liu et al. 2009). Despite the large increase in temporal coverage that potentially can be obtained by combining the data sets, the use of multi-mission data involves many scientific challenges as well, since the climatologies of the different products need to be harmonised and the complex effects of the various error sources (sensor calibration, retrieval errors, model parameterisation, etc.) on observed variations need to be understood for each product and sensor.

The scope of the soil moisture theme within WACMOS is to establish a solid scientific basis for the development of a long-term consistent soil moisture time series based on active and passive coarse scale microwave observations. In this study we propose a first concept for a merging scheme based on the European Remote Sensing satellites (ERS-1 and ERS-2) Scatterometer (SCAT), the Meteorological Operational satellite (MetOp) Advanced Scatterometer (ASCAT), the Scanning Multichannel Microwave Radiometer (SMMR; C-band), the Special Sensor Microwave Imager (SSM/I; Ku-band), the **Tropical Rainfall Measuring Mission** *(TRMM; X-band), and the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E; C-band). The scatterometer products are based on the TU Wien algorithm (Wagner et al., 1999, Bartalis et al, 2007), whereas all radiometer-based products were obtained with the VUA-NASA method (Owe et al., 2008). Both methods have been extensively validated in literature (e.g. Wagner et al., 2007; Gruhier et al., 2010). These studies reveal that the VUA-NASA product for AMSR-E generally outperforms the official NASA product distributed through NSIDC."*

To improve the results and validation section, several major editing were made in this section. An example showing the improved performance was included in Figure 8. We also added a reference to recent evidence (Jung et al., 2010 in Nature) that the trend map shown in Figure 10 shows realistic values.

Reply related to Clouds theme

For the clouds theme, major additions to section 3.3 are:

"Within the Global Energy and Water Cycle Experiment (GEWEX) community, considerable focus has been put to the assessment of various cloud property retrieval algorithms (see for example Stubenrauch et al., 2008 and Stubenrauch et al., 1999).

Several algorithms have been developed to produce surface solar radiation datasets based on radiative transfer calculations and satellite observations (e.g. Bishop and Rossow, 1991; Pinker and Lazlo, 1992; Deneke et al., 2008; and Mueller et al., 2009). Pinker and Lazlo (1992) use a radiative transfer model to relate the broadband reflectance at the top of the atmosphere to the boadband transmission at the surface, taking account of radiation reductions due to ozone and water vapor, aerosols and clouds. Their algorithm is used in the GEWEX. The method proposed by Mueller et al. (2009), which is used in the Satellite Application Facility on Climate Monitoring (CM SAF) of EUMETSAT, uses satellite-derived parameters to retrieve surface solar irradiance. Their clear-sky irradiance calculations take care of variations in atmospheric water vapour and aerosol, whereas observations from Geostationary Earth Radiation Budget (GERB) instrument are used for the cloudy sky calculations. Alternatively, Deneke et al. (2008) use cloud optical thickness, particle size and cloud phase retrievals to calculate cloudy sky irradiances, whereas the clear sky calculations are climatologically corrected for variations in water vapour and aerosol.

Over the past decades several methods have been developed to detect precipitating clouds and retrieve rain rates. The methods developed for geostationary satellites often use thermal infrared observations, and relate daily minimum cloud top temperatures (Adler and Negri, 1988) or Cold Cloud Durations (CCD) to rain rates (Todd et al., 1995). These methods give fair retrieval accuracies for convective precipitation, but are not for stratiform precipitation. Precipitation retrievals for both stratiform and convective clouds are feasible with the more physically-based microwave radiometer (MWR) based methods (e.g. Wentz and Spencer, 1998). The main drawback of MWR based methods is that they only apply to liquid precipitation and that MWRs are only operated on polar orbiting satellites. Similarly, methods have been developed to derive precipitation from cloud physical properties retrievals of passive imagers (Rosenfeld and Gutman, 1994; Lensky and Rosenfeld, 2006; and Roebeling and Holleman, 2009). Because several passive imagers are operated onboard geostationary satellites the retrievals of these methods can be made available at high temporal resolution. However, the use of visible and near-infrared radiances limits the application of these methods to daylight periods only. Beside single instrument retrievals, methods have been developed that combine measurement from different sources. The Climate Prediction Centre MORPHing (CMORPH) method provides global precipitation estimates by propagating motion vectors derived from geostationary satellite infrared observations on passive microwave satellite scans (Joyce et al., 2004). While the Global Precipitation Climatology Project (GPCP) merges measurements from three different sources i.e., precipitation estimates from low-orbit satellite microwave data, geosynchronous-orbit satellite infrared data, and surface precipitation gauge observations from the Global Precipitation Climatology Centre (GPCC) (Adler et al., 2003)."

Reply related to Water Vapour theme:

To better position the WACMOS WV product within the advances of remote sensing a paragraph mentioning different datasets and methods was added in Section 3.4. As a consequence the explanation of some abbreviations (e.g. SEVIRI) in the remaining to the paragraph become obsolete and were removed.

Text added:
"In addition, satellite observations are used within assimilation methods to generate model-based reanalysis products like ECMWF's ERA-40 (Uppala et al., 2005) and ERA-INTERIM, the Japanese ReAnalysis (JRA-25, Onogi et al., 2007) and the Modern-Era Retrospective analysis for Research and Applications (MERRA) produced by NASA's Global Modeling and Assimilation Office

(GMAO) (Rienecker et al., 2011). Exemplary sensors are the Special Sensor Microwave/Imager (SSM/I) carried aboard Defense Meteorological Satellite Program (DMSP) satellites, the Meteorological Operational satellite (MetOp) Infrared Atmospheric Sounding Interferometer (IASI), the METEOSAT Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI), the Environmental Satellite (ENVISAT) Medium Resolution Imaging Spectrometer (MERIS) and the MetOp Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS). Global single and combined sensor products are publicly available: The daily and monthly mean total column water vapour over ice free ocean with a spatial resolution of (0.5)² from SSM/I data (Anderson et al., 2010) is available for the time period July 1987 to August 2006 from the Satellite Application Facility on Climate Monitoring (CM SAF) and from the University of Hamburg/Max-Planck-Institute for Meteorology. A similar data set is available from Remote Sensing Systems (Wentz, 1997). Atmospheric water vapour profiles (daily, 5-day and monthly means) gridded on a 1° x 1° latitude-longitude grid for the time period 1985-1999 are part of the TIROS (Television Infrared Observation Satellite) Operational Vertical Sounder (TOVS) Pathfinder Path A dataset (Susskind et al., 1997). Within the GEWEX GlobalWater Vapour Project (GVaP), the NVAP total column water vapour product was derived from a combination of SSM/I, TOVS and radiosonde data covering the time period 1988-2001 (Randal et al., 1996). Total column water vapour and integrated water vapour for five thick layers based on the Advanced TIROS Operational Vertical Sounder (ATOVS) suite of instruments is provided by CM SAF (Schulz et al., 2009). Available are global daily and monthly means at a horizontal resolution of (90 km)² for the time period from 2004 onwards. Up to now, the ATOVS water vapour products are the only ones for which a merging of different instruments in horizontal space is done over a long time period. Lindenbergh et al. (2008) present a Kriging method for combining Global Positioning System (GPS) and MERIS total column water vapour estimates in space and time for a single day in August 2003."

To focus more on the results, the Section 4.4.2 Water Vapour: Results and validation was partly rewritten and some results were added. The main changes made are:

- *It is mentioned that only representative results are shown here. A more through analysis dealing with the WACMOS water vapour products will be published in a separate paper.*
- *The correlation functions originally shown in Figure 16 were replaced by results of the merged layered water vapour from SEVIRI and IASI. Hence, results from both WACMOS water vapour products are shown now to give potential users an idea of what could be available.*
- *Validation results of the SEVIRI+IASI product using radiosondes are presented and discussed now.*
- *In the meanwhile, it was decided to restrict the area of the SEVIRI+MERIS product to the Elbe/Oder basin only. Hence, the results in Figure 17 were updated, i.e. the same results are shown, but the region is smaller now.*

Some minor comments:

1. The scale which is aimed at should also be made clear to the readers: apparently only coarse scale is being studied, and fine scale RS is not included (e.g. SAR).

The scales of all WACMOS products are given in Table 1.

2. line 6 of page 7908: Scatterometer is wrongly spelled.

Corrected.

3. Please add reference to the statement on p. 7916 line 23-25 stating that AMSRE is known to provide the most reliable soil moisture estimates and climatology of all

considered passive systems.

We carefully revised this paragraph. In fact, not the AMSR-E as such provides the most reliable soil moisture estimates (e.g. the official NASA product performs rather poorly over most areas) but the VUA-NASA algorithm based on this sensor. Nevertheless, of all radiometers considered in this study AMSR-E provides the best prerequisites for a reliable soil moisture retrieval, given its operation in C-band and the superior radiometric quality and spatial resolution compared to the other radiometer (SMMR) operating in C-band. A reference to the work of Owe et al., 2008 is provided.

4. Title of 4.3 should read "Cloud products: methodology, results and validation"

Corrected.

5. page 7921, line 20: reflectance is wrongly spelled.

This went wrong in the typesetting and slipped through during proofreading. This will be taken care in new typesetting and proofreading.