Soil Moisture Active Passive (SMAP)

Ancillary Data Report

Vegetation Water Content

Preliminary, v.1
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Preface

The SMAP Ancillary Data Reports provide descriptions of ancillary data sets used with the science algorithm software in generation of the SMAP science data products. The Ancillary Data Reports may undergo additional updates as new ancillary data sets or processing methods become available. The most recent versions of the ancillary data reports will be made available, along with the Algorithm Theoretical Basis Documents (ATBDs), at the SMAP web site http://smap.jpl.nasa.gov/science/dataproducts/ATBD/.

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1 Overview

1.1 Purpose

The purpose of this report is to develop a vegetation water content dataset for use in generating SMAP science data products. The vegetation water content dataset is one of a suite of ancillary datasets used by the SMAP science processing algorithms. The algorithms and ancillary data are described in SMAP algorithm theoretical basis documents (ATBDs) and ancillary data reports. The ATBDs and ancillary data reports are listed in Appendices A and B and are available at the SMAP web site: http://smap.jpl.nasa.gov/science/dataproducts/ATBD/.

1.2 Requirement

Vegetation water content (VWC), expressed in units of kg/m^2, is an important modeling parameter for SMAP active and passive algorithm development. For SMAP radar observations it is used to model the amount of volume scattering experienced by the radar signal due to leaves, branches and trunks in the NMM3D formulation (Xu et al., 2010b). For SMAP radiometer observations it is used to model the amount of attenuation of emission by and through vegetation in the tau-omega model (Njoku and Li, 1999).

Because of its critical role in both the active and passive models and algorithms, VWC is an essential ancillary dataset for SMAP. Accurate estimates of VWC, at high spatial resolution on a global basis, will enable the following activities:

1. Realistic forward simulation of radar and radiometer observations. This is important for objective inter-comparison among retrieval algorithms and their respective error allocation characteristics.

2. Accurate inverse simulation of soil moisture by active and passive algorithms. For certain passive algorithms VWC can be used as an ancillary parameter to correct for the attenuation of emission due to vegetation, leading to the more accurate retrieval of soil moisture.

3. Determination of geographical regions where the SMAP retrieval accuracy (0.04 cm^3/cm^3) can likely be met. According to the SMAP Level 1 Mission Requirements "*the baseline science mission shall provide estimates of soil moisture in the top 5 cm of soil with an error of no greater than 4% volumetric (one sigma) at 10 km spatial resolution and 3-day average intervals over the global land area excluding regions of snow and ice, frozen ground, mountainous topography, open water, urban areas, and vegetation with water content greater than 5 kg/m^2 (averaged over the spatial resolution scale).*"

Despite its prominence in microwave active and passive modeling, VWC is not a routinely measured quantity in most ecosystem-climate interaction studies, where the emphasis may be more on biomass (wet or dry) than on their water content. Even in studies where in situ VWC samples have been acquired the data are typically sparse and cover limited crop types.

For these reasons, researchers have relied on indirect measurements to perform large-scale mapping of VWC (Jackson et al., 1999). Unfortunately, this approach is not without challenges. First, the transfer function that converts the input measurements into VWC is usually empirical. Therefore, the validity of the conversion is limited by the scope of data that were used to develop the transfer function. Second, depending on the nature of the indirect measurements, these may not be an accurate proxy of VWC. An example of this limitation is the Normalized Difference Vegetation Index (NDVI), which is based on data acquired in the visible (red) and near-infrared optical bands. Within a range of VWC, NDVI is known to vary with VWC in a predictable way. However, it saturates (i.e., loses sensitivity to VWC) as the water content reaches a threshold (Jackson et al., 1999).

The approach used here is based on a method described by Hunt et al. (1996). This approach uses an NDVI-based approach to estimate the foliage water content, and uses a combination of past field observations and Leaf Area Index (LAI) modeled by NDVI to account for the stem water content. The result is an estimate of VWC with water content contributions from the foliage and stem components, adjusted for land cover types using the MODIS IGBP classification scheme (Hunt et al., 1996).

2 Dataset Description and Selection

2.1 Approach and Methodology

As described above, VWC estimates, especially at high spatial resolution on a global basis, are in general derived indirectly from other proxy measurements. These estimates usually rely on field observations over limited vegetation types (e.g., wheat, soybean) to extend the calculations globally. Validation of these estimates over other vegetation types is usually scant, absent, or accepted 'as-is.' As a result, there may be large uncertainty associated with these estimates. To date, only one approach has been implemented with microwave remote sensing for routine soil moisture retrieval (Jackson et al., 2010). This method uses a single global VWC-NDVI transfer function for all land cover types (Jackson et al., 1999). As noted, there are issues associated with both land cover and saturation. Applications of this approach to date have focused on higher frequencies (e.g., AMSR-E soil moisture retrieval) that have lower limits of VWC by which the soil moisture algorithm can provide reliable estimates.

Research leading up to SMAP modified the VWC function to account for L-band considerations, which include adding a woody fraction component (Crow et al., 2005). A further review of this approach revealed that this approach led to underestimates of VWC for most vegetation types. As a result, an effort was initiated to re-examine the fundamentals of the VWC-NDVI transfer function and to incorporate more information available within the research community. The following describes the baseline approach used by SMAP to generate a VWC ancillary dataset.

The approach is based upon work described by Hunt et al. (1996). In this approach, VWC is expressed as a sum of canopy water content and stem water content – the first component is estimated using NDVI and the second component is estimated using a combination of past field observations and LAI modeled by NDVI. Preliminary results indicate that the VWC derived using this approach results in a credible global distribution of the parameter and the expected ranges of seasonal variability for many vegetation types[1].

2.2 VWC Formulation

The VWC estimation approach consists of two parts. The first part makes use of NDVI to estimate the foliage water content (Jackson et al., 1999). The second part makes use of annual NDVI extremes, along with a coefficient – the *stem factor* – to estimate the stem water content. Depending on the vegetation type, the stem water content could refer to the water content residing

[1] Dr. Raymond Hunt, USDA, personal communication.

in the herbaceous stems of crops (e.g., corn stalks) or the woody stem of trees. Analytically, the approach takes the following form:

$$\mathrm{VWC} = (1.9134 \times \mathrm{NDVI}^2 - 0.3215 \times \mathrm{NDVI}) + \text{stem factor} \times \frac{\mathrm{NDVI}_{max} - \mathrm{NDVI}_{min}}{1 - \mathrm{NDVI}_{min}} \tag{1}$$

To implement this approach to VWC estimation, four input parameters are required:

1. **NDVI**: The NDVI can be obtained from the Terra/MODIS product suite (MOD), or the Aqua/MODIS product suite (MYD), or the combined Terra/Aqua MODIS product suite (MCD). This input is considered dynamic (i.e., temporally varying) and is responsible for the temporal variability of VWC. The figures in this document were generated using a global 10-day NDVI climatology derived from the Terra/MODIS-based NDVI (Jackson et al., 2011).

2. **NDVI max**: This parameter refers to the annual maximum NDVI at a given location. Like NDVI, it is a strong function of land cover types. For croplands and grasslands, the current NDVI is used in place of NDVI max[2].

3. **NDVI min**: This parameter refers to the annual minimum NDVI at a given location. Note that this parameter applies only to snow-free condition. A global constant value of 0.1 was suggested[2].

4. **Stem factor**: This is an estimate of the *peak* amount of water residing in the stems. In Hunt et al. (1996) NDVI was used to estimate the average values of LAI and tree height for a given biome. Based on these values, the maximum stem water content was derived for many vegetation types. For other vegetation types that were not included, biomass data from the literature was used to estimate the proportion of sapwood area/leaf area[2]: savannas (House and Hall, 2011; Schole and Hall, 1996; Bucini and Hanan, 2007; ankaran et al., 2005; De Castro and Kaufmann, 1998), crops (Yilmaz et al., 2008), broadleaf forests (Brown and Gaston, 1995; Calvo-Alvarado et al., 2008; Saatchi et al., 2007), needleleaf forests (Brown et al., 1999; McDowell et al., 2002; Mencuccini and Grace, 1995; Vertessy et al., 1995; Gower et al., 1997), shrublands (Yilmaz et al., 2008; Ganskopp and Miller, 1986), and boreal forests (Gower et al., 2001). Table 1 tabulates the stem factors associated with different MODIS IGBP land cover types.

2.3 NDVI Climatology Dataset

The NDVI data set used here to compute VWC in Equation (1) is based on a data set (~3 TB in volume) of vegetation indices (NDVI and EVI) derived from the Terra/MODIS MOD13A2 product (MOD13A2, 2011). The vegetation indices represent a 10-day climatology resampled from 16-day composites of the respective indices acquired by Terra/MODIS from 2000 to 2010. The details of the MOD13A2 data product are given in Table 2 below (Jackson et al., 2011).

[2] Dr. Raymond Hunt, USDA, personal communication.

Table 1. Stem factors for different MODIS IGBP land cover types

IGBP	Land Cover	Stem Factor
1	Evergreen needleleaf forest	15.96
2	Evergreen broadleaf forest	19.15
3	Deciduous needleleaf forest	7.98
4	Deciduous broadleaf forest	12.77
5	Mixed forest	12.77
6	Closed shrublands	3.00
7	Open shrublands	1.50
8	Woody savannas	4.00
9	Savannas	3.00
10	Grasslands	1.50
11	Permanent wetlands	4.00
12	Croplands	3.50
13	Urban and built-up	6.49
14	Cropland/natural vegetation mosaic	3.25
15	Snow and ice	0.00
16	Barren or sparsely vegetated	0.00

Table 2. Specifications of Terra/MODIS' MOD13A2 product

Specifications	Description
Developers	NASA MODIS Team
Spatial Resolution	1 km
Temporal Coverage	2000-2010
Temporal Resolution	16 days
Data Sources	MODIS ftp/website
Version	5 (latest)
Raw data format	318 10° × 10° HDF-EOS tiles in sinusoidal projection
Availability	https://lpdaac.usgs.gov/lpdaac/products/modis_products_table/vegetation_indices/16_day_l3_global_1km/mod13a2
Documentation	https://lpdaac.usgs.gov/lpdaac/products/modis_products_table/vegetation_indices/16_day_l3_global_1km/mod13a2
Size	~ 2.8 TB (for 10 years)
Contact	https://lpdaac.usgs.gov/lpdaac/get_data

Production of the 10-day NDVI climatology used the following steps (Jackson et al., 2011):

1. Individual tiles for each 16-day period were downloaded from the MODIS DAAC,
2. Four HDF layers including NDVI, EVI, Quality Flags, and Day of Year were extracted for each tile,
3. Extracted layers were mosaicked together to obtain a global product for each layer in sinusoidal projection,
4. Each layer was re-projected to Geographic Lat/Long at a spatial resolution of 0.01 degree (~1 km),
5. VI values of multi-year data were filtered out by the quality flags described above,
6. Time series of VI was created for each location based on DOY,
7. 10-day averages were computed using quality-controlled observations,

8. Piecewise linear interpolation was conducted over each pixel to fill in missing/bad data points, and
9. Climatological data was saved as binary files in BSQ format along with the flags.

The result of these processing steps is an NDVI climatology with specifications described in Table 3. To generate VWC according to Equation (1) all 36 global NDVI files must first be processed to produce a static global map of VWC max. The resulting VWC max, along with NDVI and stem factor, is then applied to Equation (1) to produce a global estimate of VWC according to different land cover types. For operational product generation the 10-day NDVI climatology time series will be temporally interpolated prior to VWC estimation.

Table 3. Specifications of 10-day NDVI climatology

Specifications	Description
Developers	Tom Jackson, Rajat Bindlish, Tianjie Zhao
Spatial Resolution	0.01 degrees ~ 1 km
Temporal Coverage	NA
Temporal Resolution	10 days
Data Sources	MODIS MOD13A2, MOD44W
Raw data format	16-bit signed integers in little-endian byte order, arranged in row-major order
Scaling factor	0.0001
Size	36 files of size 3,164,062.5 KB per 10-day period
Contact	Tom Jackson, Rajat Bindlish

3 Processing Results

3.1 VWC Maps and Statistics

Using the 10-day NDVI climatology and stem factors described in Table 1, global, high-resolution VWC maps can be generated. Examples of the derived VWC data are shown in Figures 1-4. The VWC maps show the expected spatial distribution patterns and range of seasonal variability (seasonal differences between January and July are apparent). While the VWC over broadleaf forests does not change much, over other vegetation types (e.g., woody savannas, savannas, shrublands, grasslands) the VWC shows noticeable changes.

In terms of rank statistics, the derived VWC results in the percentiles listed in Table 4. The same statistics are also summarized by the boxplot in Figure 5. With reference to Table 4, if we use the median VWC (the 50th percentile column) as the defining VWC estimate for a given land cover type, it is clear that except for classes 1 through 5 (i.e., from evergreen needleleaf forests to mixed forests), all other classes have median VWC less than 5 kg/m2. If we ignore the class 15 (snow and ice) and inland water bodies (rivers, lakes, etc.) further, the remaining classes, which include closed shrublands (1.2%), open shrublands (14.3%), woody savannas (9.3%), savannas (6.1%), grasslands (10.1%), croplands (8.2%), urban built-up (0.5%), permanent wetlands (1.0%), vegetation mosaic (5.4%), and barren/light vegetation (12.6%), constitute to a total of 1.2% + 14.3% + 9.3% + 6.1% + 10.1% + 8.2% + 0.5% + 1.0% + 5.4 %+ 12.6%, or 68.7% of total global land area. The combined coverage (based on MODIS IGBP land cover classification at 1-km grid resolution) is shown in Figure 6.

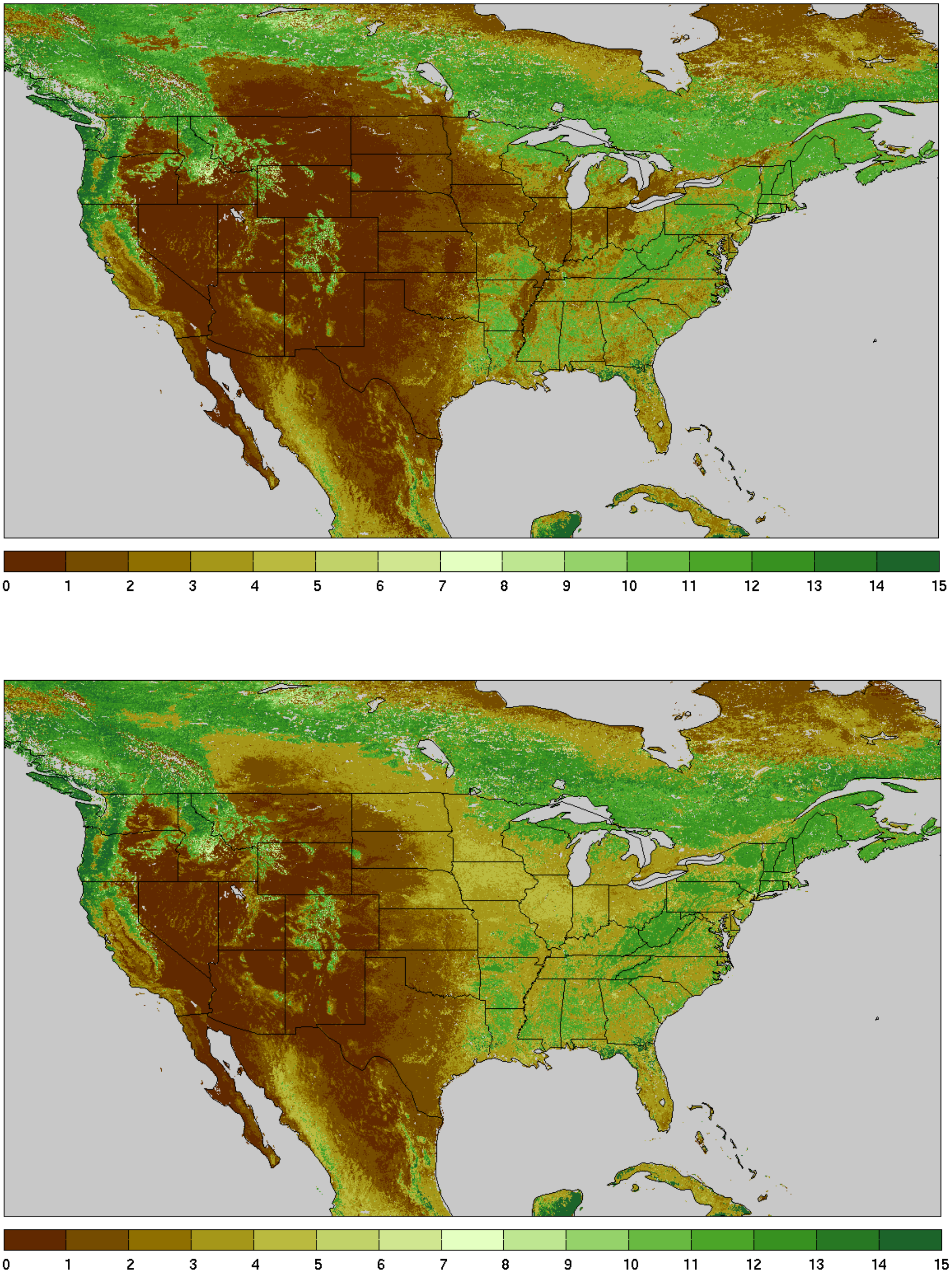

Figure 1. VWC over the U.S. in January (top) and July (bottom).

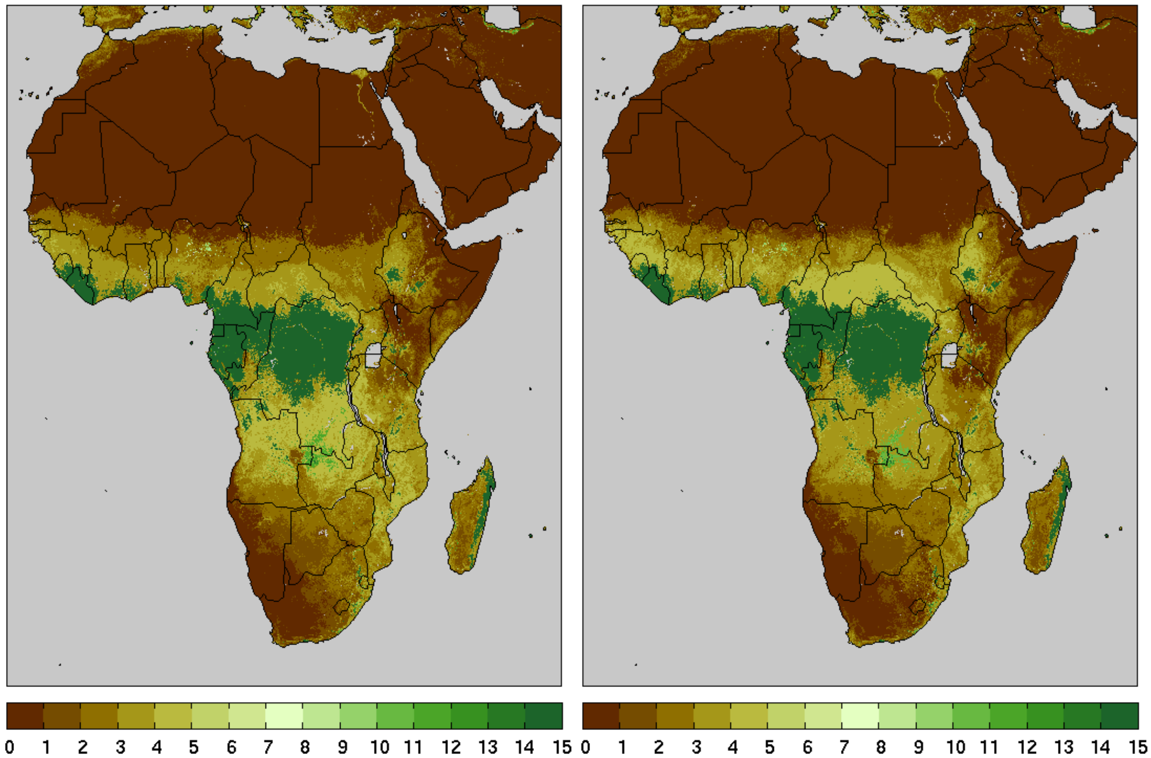

Figure 2. VWC over Africa in January (left) and July (right).

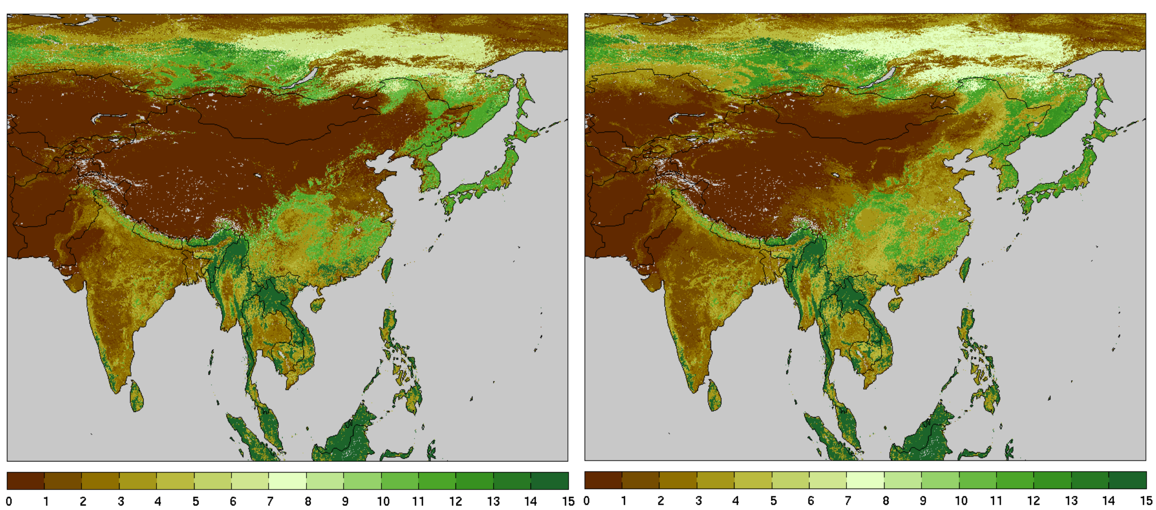

Figure 3. VWC over Asia in January (left) and July (right).

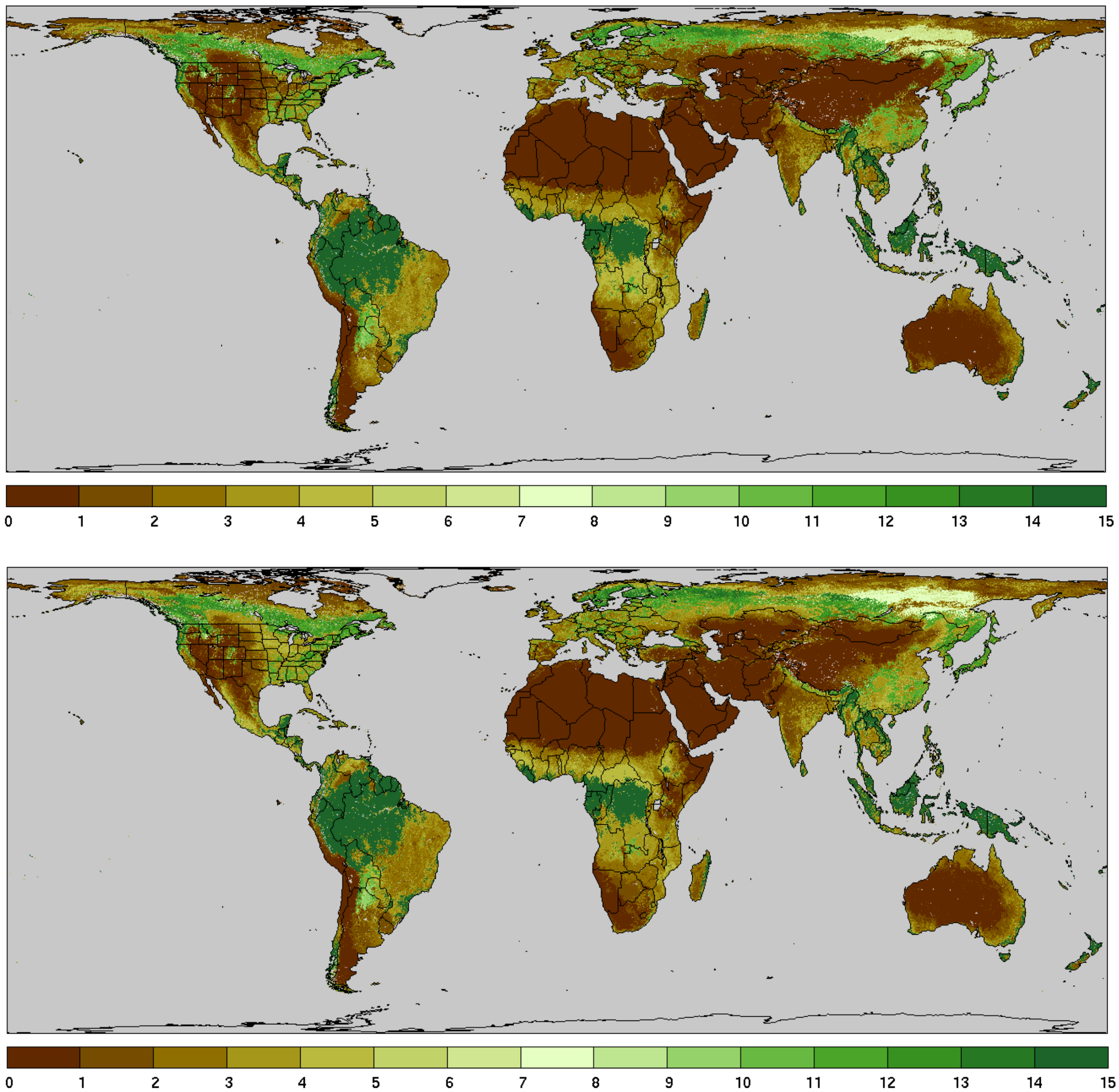

Figure 4. Global VWC in January (top) and July (bottom).

Table 4. Rank statistics of global VWC using full NDVI climatology time series

IGBP	Land Cover	5th	25th	50th	75th	95th
1	Evergreen needleleaf forest	9.79	11.82	12.59	13.19	13.97
2	Evergreen broadleaf forest	15.35	16.79	17.55	17.93	18.21
3	Deciduous needleleaf forest	5.93	6.32	6.55	6.84	7.36
4	Deciduous broadleaf forest	9.54	10.49	11.23	11.72	12.40
5	Mixed forest	10.04	10.74	11.12	11.51	12.11
6	Closed shrublands	0.89	1.28	1.56	1.89	2.45
7	Open shrublands	0.12	0.28	0.54	1.11	1.47
8	Woody savannas	2.42	3.07	3.43	3.78	4.21
9	Savannas	1.46	2.04	2.39	2.74	3.18
10	Grasslands	0.04	0.16	0.33	0.66	1.40
11	Permanent wetlands	2.78	3.03	3.23	3.42	3.80
12	Croplands	0.51	0.98	1.59	2.39	3.32
13	Urban and built-up	2.53	3.41	4.14	4.79	5.31
14	Cropland/natural vegetation mosaic	2.04	2.67	2.97	3.30	3.61
15	Snow and ice	0.00	0.00	0.00	0.02	0.25
16	Barren or sparsely vegetated	0.00	0.00	0.00	0.00	0.00

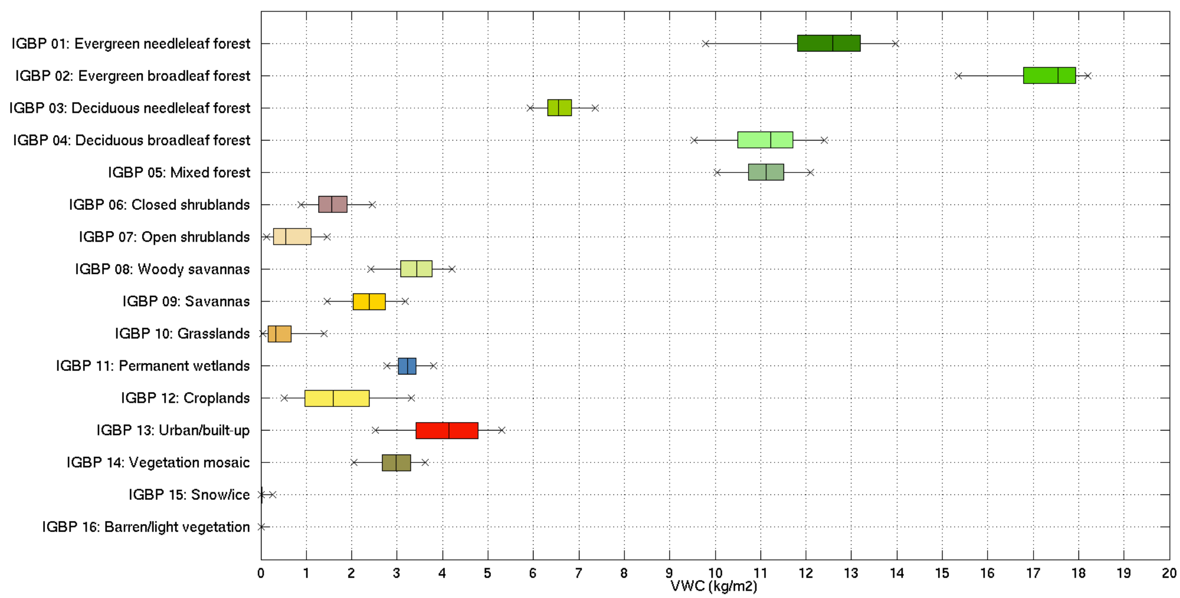

Figure 5. Boxplot of VWC rank statistics at 36-km grid resolution. The statistics represent VWC variability over all MODIS IGBP land cover types (except for water) throughout the year. The left- and right-hand whiskers of each box correspond to the 5th and 95th percentiles of the distribution.

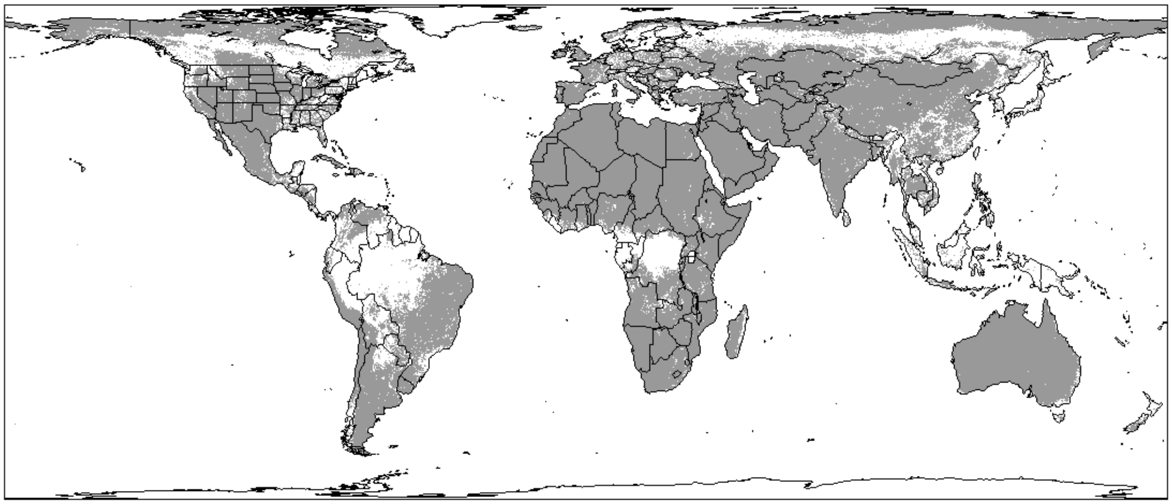

Figure 6. Without dense forests, permanent snow and ice, and inland water bodies, there remains about 68.7% of total global land area that is of interest to SMAP soil moisture retrieval.

3.2 Data Accuracy

Work is underway to validate the VWC derived using this approach. The following datasets are under consideration as validation data for the derived VWC dataset:

1. Olson's Major World Ecosystem Complexes Ranked by Carbon in Live Vegetation: An Updated Database Using the GLC2000 Land Cover Product (Gibbs et al., 2011). This dataset should display reasonable correlation with the derived VWC.

2. MODIS MOD15A2 LAI data product (MODIS_LAI, 2011). Within a land cover type, there should be good correlation between annual maximum of LAI and the derived VWC because the VWC calculations are derived using the ratio of LAI/maximum lifeform LAI.

3. National Biomass and Carbon Dataset for the year 2000 (Kellndorfer et al., 2011). Allometric equations can be used with these biomass data to derive an independent VWC estimate.

4 Conclusion

In this document, a global VWC derivation approach has been developed for use by SMAP based on NDVI input data. The approach models the foliage water content directly from NDVI, while the stem water content is modeled indirectly using annual maximum and minimum NDVI adjusted for different land cover types. Using an NDVI climatology time series to illustrate the approach, a dynamic global database of VWC was generated at ~1 km spatial resolution. This dataset is also useful for SMAP algorithm development since it enables realistic simulation of the microwave emission and backscatter processes. The approach has been shown to produce reasonable estimates of global VWC for the major vegetation classes.

5 Acknowledgment

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Appendix A: SMAP Science Data Products and ATBDs

The SMAP Algorithm Theoretical Basis Documents are available at the SMAP web site http://smap.jpl.nasa.gov/science/dataproducts/ATBD/.

Data Product	Description	ATBD
L1A_Radar	Radar raw data in time order	(Joint with L1C_S0_HiRes)
L1A_Radiometer	Radiometer raw data in time order	(Joint with L1B_TB)
L1B_S0_LoRes	Low resolution radar σ_o in time order	(Joint with L1C_S0_HiRes)
L1C_S0_HiRes	High resolution radar σ_o (half orbit, gridded)	West, R., L1B & L1C radar products, JPL D-53052, JPL, Pasadena, CA.
L1B_TB	Radiometer T_B in time order	Piepmeier, J. et al., L1B radiometer product, GSFC SMAP-006, GSFC, Greenbelt, MD.
L1C_TB	Radiometer T_B (half orbit, gridded)	Chan, S. et al., L1C radiometer product, JPL D-53053, JPL, Pasadena, CA.
L2_SM_A	Soil moisture (radar, half orbit)	Kim, S. et al., L2 & L3 radar soil moisture (active) product, JPL D-66479, JPL, Pasadena, CA.
L2_SM_P	Soil moisture (radiometer, half orbit)	O'Neill, P. et al., L2 & L3 radiometer soil moisture (passive) product, JPL D-66480, JPL, Pasadena, CA.
L2_SM_AP	Soil moisture (radar/radiometer, half orbit)	Entekhabi, D. et al., L2 & L3 radar/radiometer soil moisture (active/passive) products, JPL D-66481, JPL, Pasadena, CA.
L3_FT_A	Freeze/thaw state (radar, daily composite)	McDonald, K. et al., L3 radar freeze/thaw (active) product, JPL D-66482, JPL, Pasadena, CA.
L3_SM_A	Soil moisture (radar, daily composite)	(Joint with L2_SM_A)
L3_SM_P	Soil moisture (radiometer, daily composite)	(Joint with L2_SM_P)
L3_SM_AP	Soil moisture (radar/radiometer, daily composite)	(Joint with L2_SM_AP)
L4_SM	Soil moisture (surface & root zone)	Reichle, R. et al., L4 surface and root-zone soil moisture product, JPL D-66483, JPL, Pasadena, CA.
L4_C	Carbon net ecosystem exchange (NEE)	Kimball, J. et al., L4 carbon product, JPL D-66484, JPL, Pasadena, CA.

Appendix B: SMAP Ancillary Data Reports

The SMAP Ancillary Data Reports are available with the ATBDs at the SMAP web site http://smap.jpl.nasa.gov/science/dataproducts/ATBD/.

Data/Parameter	Ancillary Data Report
Crop Type	Kim, S., Crop Type, JPL D-53054, Pasadena, CA
Digital Elevation Model	Podest, E. et al., Digital Elevation Model, JPL D-53056, Pasadena, CA
Landcover Classification	Kim, S., Landcover Classification, JPL D-53057, Pasadena, CA
Soil Attributes	Das, N. et al., Soil Attributes, JPL D-53058, Pasadena, CA
Static Water Fraction	Chan, S. et al., Static Water Fraction, JPL D-53059, Pasadena, CA
Urban Area	Das, N., Urban Area, JPL D-53060, Pasadena, CA
Vegetation Water Content	Chan, S. et al., Vegetation Water Content, JPL D-53061, Pasadena, CA
Permanent Ice	McDonald, K., Permanent Ice & Snow, JPL D-53062, Pasadena, CA
Precipitation	Dunbar, S., Precipitation, JPL D-53063, Pasadena, CA
Snow	Kim, E. et al., Snow, GSFC SMAP-007, Greenbelt, MD
Surface Temperature	Fisher, J. et al., Surface Temperature, JPL D-53064 Pasadena, CA
Vegetation and Roughness Parameters	Colliander, A., Vegetation & Roughness Parameters, JPL D-53065, Pasadena, CA