TREND ANALYSES OF A GLOBAL SOIL MOISTURE TIME SERIES DERIVED FROM ERS-1/-2 SCATTEROMETER DATA: FLOODS, DROUGHTS AND LONG TERM CHANGES

C. Kuenzer [a, *], Z. Bartalis [b], M. Schmidt [a], D. Zhao[a], W. Wagner [b]

[a] German Remote Sensing Data Center, DFD, of the German Aerospace Center, DLR, Postfach 1116, 82230 Wessling, Germany - claudia.kuenzer@dlr.de (at time of preparation of abstract still at IPF of Vienna University of Technology)
[b] Institute of Photogrammetry and Remote Sensing, IPF, Vienna University of Technology, Gusshausstr. 27-29, A-1040 Austria - zb@ipf.tuwien.ac.at, ww@ipf.tuwien.ac.at
[c] Key Laboratory of Regional Climate-Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, CAS, Beijing 100029, P.R. China - zhaodm@tea.ac.cn

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ABSTRACT:

Soil moisture is a governing parameter in many complex environmental processes from the disciplines of meteorology, hydrology and agriculture. Since rainfall is partitioned into runoff and infiltration, the soil moisture content allows for direct information on further infiltration capability and expected runoff behavior. Spatial and temporal soil moisture variability are thus important factors to be included into predictive agricultural, hydrological and climate models. Furthermore, long term soil moisture pattern analyses can support the derivation of regional trends. In this paper we present the results of analyses of the 15 year long, remote sensing based soil moisture time series of TU Wien. Based on ERS scatterometer derived data soil moisture has been derived at a spatial resolution of 50km, and a temporal resolution of 3-4 days globally since 1992. This time series is currently being extended and reprocessed with 25km Metop Ascat derived data. We have processed the time series with respect to global anomaly derivation, whereas an anomaly in the soil moisture dataset depicts “wetter than normal” or “drier than normal” conditions with respect to the long term mean. Findings indicate that extreme events such as confirmed floods and droughts are clearly represented in the dataset. Anomaly analyses in months prior to known extreme events indicate that the time series holds a strong potential for flood early warning activities. Furthermore, long term trend derivation allows to depict regions, which have become significantly wetter or drier over the course of the last 15 years. Trends investigated for Mongolia and Australia correlate with trends from in-situ station data. We consider the TU Wien time series to have a high potential for further detailed global long term trend analyses.

1. INTRODUCTION

1.1 Remote Sensing of Soil Moisture

Soil moisture is a governing parameter in many complex environmental processes from the disciplines of meteorology, hydrology and agriculture. Since rainfall is partitioned into runoff and infiltration, the soil moisture content allows for direct information on further infiltration capability and expected runoff behavior. Spatial and temporal soil moisture variability are thus important factors to be included into predictive models (Scipal et al. 2005, Wagner et al. 2007a, Koster et al. 1999, Zhao et al. 2006, Pellarin et al. 2006).

In-situ soil moisture measurements are costly and work intensive to perform and are thus only available in limited regions of the world (Scipal 2005, Hollinger and Isard 1994). Major in-situ soil moisture networks exist in China, Russia, the Ukraine, and parts of the US (Scipal 2002, Wagner et al. 2007b, Jackson et al. 1999, Robock et al. 2000). However, long term temporal coverage and sampling intervals vary strongly. Due to these reasons and due to the very sparse spatial representation these stations do not enable to represent country-wide-, continental- or even global soil moisture patterns. Thus, remote sensing has come to play a major role in large scale soil moisture assessment during the past two decades (Engman and Chauhan 1995, Wagner et al. 1999, Wagner et al. 2007a, Jackson 1993). Due to the cloud cover problem approaches based on optical or thermal satellite data are strongly limited for global applications. Therefore, especially microwave remote sensing based on instruments such as the scatterometers onboard ERS-1, ERS-2, or the AMSR radiometer onboard of AQUA as well as the advanced scatterometer, ASCAT, onboard the new satellite METOP, are employed for the derivation of large scale soil moisture products (Wagner et al. 1999, de Ridder 2000, Njoku et al. 2003).

The significance of global soil moisture products has been presented by numerous authors. Many of them applied the ERS-1/2 scatterometer derived soil moisture time series provided by Vienna University of Technology (in following: TU Wien data set); for example to improve rainfall simulation in eastern China Zhao et al. 2006), to establish moisture-runoff relationships for different catchments (Scheffler et al. 2003, Scipal et al. 2005), or for data assimilation purposes. Furthermore, numerous authors successfully validated the ERS derived TU Wien soil

* Corresponding author. Claudia Kuenzer, DFD of DLR, Postfach 1116, 82230 Wessling, Germany, email: claudia.kuenzer@dlr.de, fon: +49 (0)8153-28-3280

moisture time series with regional soil moisture in situ data (e.g. Scipal 2002, Wagner et al. 2003, Zhao et al. 2006).

Compared to synthetic aperture radar (SAR) systems scatterometers offer multiple incidence angles for each overpass, which enables to better account for the effects of vegetation and surface roughness. Furthermore, contrary to SAR, lower resolution scatterometer sensors allow to map the Earth surface within less than three days. Here a coarse spatial resolution of 50 km (ERS Scat) or 25 km (ASCAT) is accepted, since an excellent temporal resolution can be achieved. Soil moisture can be investigated at two different spatial scales. The first is the spatial scale below 100 meters, where spatial and timely soil moisture variability are mainly driven by vegetation, soil type and topography (Scipal et al. 2005, Vachaud et al. 1985). The second scale at several kilometers represents soil moisture variability induced by atmospheric forcing effects, thus mainly being influenced by climatic conditions and large scale precipitation events (Vinnikov et al. 1999, Ceballos et al. 2002). Scatterometer derived soil moisture data at the scale of 25 to 50 km therefore contains information about large scale meteorological events. Furthermore, especially spatio-temporal changes in longer time series of data with expected seasonal soil moisture patterns can indicate the occurrence of slow onset natural hazards such as floods or droughts.

1.2 The TU Wien Dataset: ERS-Scatterometer derived Surface Moisture

The active ERS scatterometer with three sideways looking antennae collects backscatter measurements in the 5.3 GHz domain (C band) with vertical polarization over an incidence angle range from 18° to 57°. Global coverage is achieved every 3-4 days (Scipal et al. 2005). Strictly speaking, the backscattered signal σ^0 is mainly a function of dielectric properties of materials depending on frequency, *f*, polarization, *pp*, and incidence angle θ. The dielectric constant of a material mainly depends on its water content. The function $S(f,\theta)$ describes backscattering according to surface roughness and is also influenced by frequency and incidence angle. This basic principle of dielectric properties and geometric surface structure is used by the majority of electromagnetic backscattering models to derive soil moisture (Knabe 2004).

$$\sigma_0(pp\,f,\theta) = D(f,pp,\theta)\cdot S(f,\theta) \qquad (1)$$

Since one is only interested in the part of the signal, which represents the moisture content other influences need to be corrected for. Heavily vegetated areas like rainforests are masked out from the TU Wien data set. In dense forest areas volume scattering dominates and the backscattered signal from the ground covers a too small portion of the overall backscattered signal. Furthermore, snow covered areas are masked to exclude areas, where no statement about soil moisture is possible. Coastal zones and inland water bodies are also excluded. Incidence angle dependencies and effects of surface roughness, heterogeneous vegetation cover, and land cover are fully accounted for with the change detection approach implemented and presented by Wagner et al. (1999). Thus, after corrections the relationship between backscatter (normalized to an incidence angle of 40°, σ^0 (40)) and soil moisture variability is linear (Scipal 2002). The change detection approach thus only requires a time series of data to be available. From this time series surface soil moisture information equivalent to the degree of saturation in relative units, ranging between 0-100 %, can be retrieved. In this change detection method the current backscattering coefficient is compared to the highest and lowest measurement record (referred to as σ^0_{wet} and σ^0_{dry} respectively) for this spatial location within the available time series. If σ^0_{dry} and σ^0_{wet} represent a completely dry soil surface and a saturated soil surface then m_s is equal to the degree of saturation, equaling the soil moisture content in percent of porosity. m_s can be derived from every backscatter measurement for a point on earth and is thus available every 3-4 days. From the TU Wien Global Soil Moisture Archive surface moisture data sets can be extracted on a weekly, ten-day, or monthly basis for every defined area.

2. METHODS FOR TIME SERIES ANALYSES

2.1 Method: Anomaly Extraction and Analyses

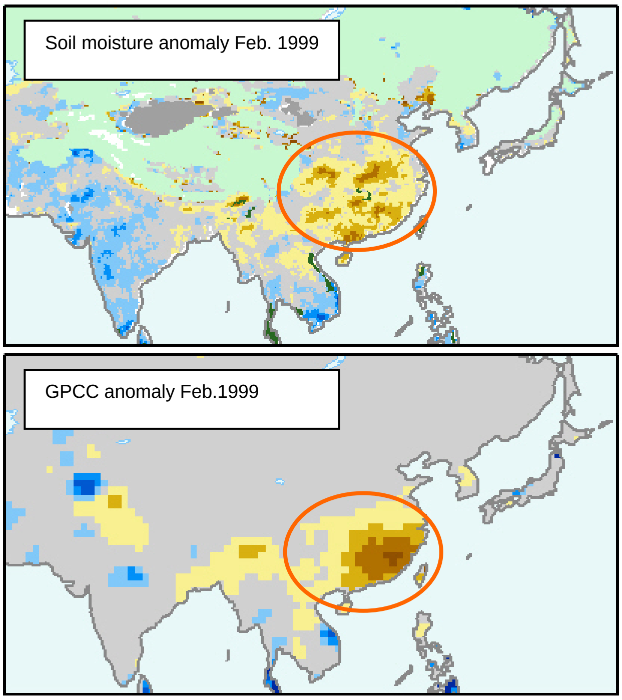

Figure 1. “La Nina” (post El Niño event) related drought in south-eastern China as observed in soil moisture anomaly data (top), and highly correlated also occurring in GPCC data (gridded precipitation data of the German Weather Service)

As a first focus of analyses, we extracted major anomalies from the time series. The term anomaly refers to the deviation of surface soil moisture at a given spatial location with respect to the time series mean of all soil moisture values for this month. The extracted strong anomalies reflect severe drought and flood conditions over the course of over 15 years in many countries worldwide. The following figure 1 shows an example, representing a “La Niña” related drought situation in China in February 1999 after the very strong 1997/1998 El Niño. In the upper part of the figure green areas are masked out areas (snow cover), grey areas indicate soil moisture conditions within the normal range, while blue areas indicate wetter than normal conditions and yellowish to brown areas indicate drier than normal conditions.

2.2 Method: Time Series Long-Term Trend Analyses

The second analysis focused on the extraction of trends from the 15 year time series. For a global context, we depict, which areas have become wetter or drier between 1992 and today. A period of 10-15 years is not enough to conclude on large scale climatic change – however, no other soil moisture time series of this length exists. It is furthermore the first time that the TU Wien time series underwent a trend analyses. Some areas show no change at all, while in several regions worldwide a clear tendency towards drier or wetter soil conditions could be observed. We furthermore investigated critically, which areas of the global dataset are suitable for trend analyses. “Suitable” means that, firstly, landcover conditions should favor unbiased surface moisture extraction, and secondly, enough measurements need to be available. Thus, we firstly masked the data set to work with areas, which have favorable conditions for highly accurate surface moisture extractions (see figure 2)

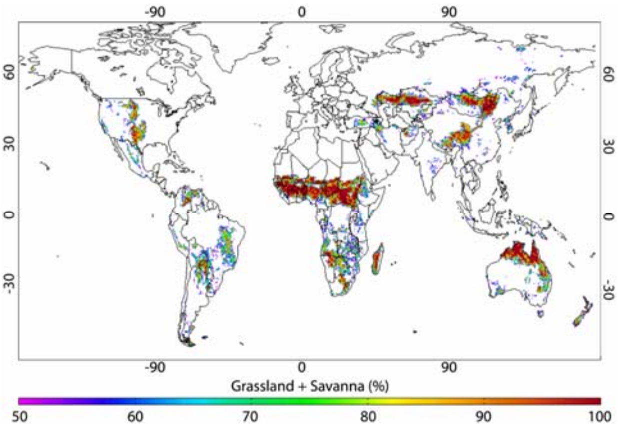

Figure 2. The considered study area. Since soil moisture derivation works best in unforested areas, a mask for the present analyses has been generated from SPOT-based GLC-product derived land-cover information. Only areas with at least 50% grassland or Savannah were considered.

Examples of variation in the number of measurements per month over the course of the time series are presented in figure 3. Due to sensor problems and data downlink capacities not every spot on the earth is evenly covered with measurements.

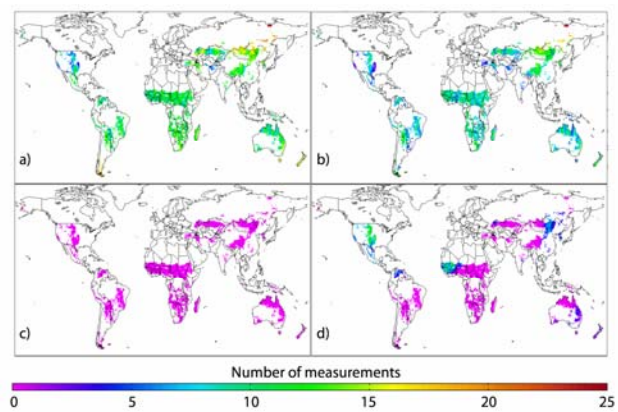

Figure 3. Variation of data availability over time – from around 25 measurements per month to no data acquisition. a) 1994 December; b) 2000 July; c) 2001 February; d) 2007 January. Overall the time-series between 1992 and January 2001 shows optimal global coverage. From 2001 to mid-2003 sensor problems lead to a gap in data acquisition. Since August 2003 data is only available within the visibility range of a limited number of ground receiving stations.

The time series (only for the unmasked areas from figure 2 was then analyzed in the following way:

1) Two arrays were created (for wet anomalies and dry anomalies) with the dimension 15 x 12 (15 years time series, 12 months per year).
2) For these arrays, the number of wet (respectively dry) anomalies as a percentage of the total number of measurements for that month has been calculated. A wet anomaly is defined as a surface soil moisture measurement, which is above the long-term mean for that day of the year plus 10 times the noise level associated to that long-term mean. A dry anomaly is defined as a surface soil moisture measurement , which is below the long-term mean for that day of the year minus 10 times the noise level associated to that long-term mean
3) The yearly means of the percentage values in the arrays were calculated by taking the arithmetical mean of the 12 monthly values, for each year resulting in 2 arrays of 15 years each.
4) Then a linear "a+bx" line was fit to each of the arrays from Step 3. The 2 plots of figure 7 in the results section for time series analyses show the "b" value of this fit, hence its unit is "percentage per year".

3. RESULTS

In the following two subchapters we present 1) results of anomaly analyses in the context of flood and drought monitoring and 2) results for trend analyses of the complete global time series.

3.1 Results of Anomaly Analyses

Among several example cases investigated the representation of major floods and droughts, e.g. the 1999 drought in Southeast China (figure 1) has been confirmed.

Furthermore, the potential of the 15 year time series for flood forecasting has been analyzed. Figure 4 depicts the powerful potential of the TU Wien time series for possible early warning scenarios. A strong flood hit the UK in November 2000. 13 people died, 6000 inhabitants had to be dislocated, and the estimated damage exceeded 3 Bio. USD. 22 rivers and an overall area of 96950 km² were affected. The Dartmouth Flood Observatory assigned Severity Class 3

The upper sequence of images in figure 4 depicts surface soil moisture from January to December for the year 2000. Dark blue areas indicate wettest conditions, light blue areas slightly wet conditions and yellowish to dark brown areas drier to completely dry conditions. The lower sequence depicts anomalies. Grey areas indicate no outstanding / deviating behavior while blue areas indicate “wetter than normal” behavior and yellow-brownish areas “drier than normal” conditions with respect to the 15 year monthly mean. It is obvious that during the months January to March soil moisture values in the year 2000 are high. However, the anomaly sequence indicates that this is rather normal, except for some slightly wetter occurrences in Ireland and Scotland in February. During the summer, soil moisture is low and the anomaly sequence indicates that also this behavior is to be expected. Very differently appear the months September to November. Already in September it can be seen that most of the UK is much wetter than usual. Soils are by far not saturated (still some yellow areas below 50% soil moisture), however, according to expectations this month should be drier. In October soil moisture values are high. The anomaly sequence again indicates “wetter than normal” conditions for the whole country. The same applies for November – the month when soils were so saturated that all buffer capacity had diminished and increased surface runoff lead to severe floods. Comparing the two time intervals (Jan-Mar and Sept-Nov) it can clearly be seen that the anomaly time series could support the prediction of future soil moisture saturation situation and flood danger.

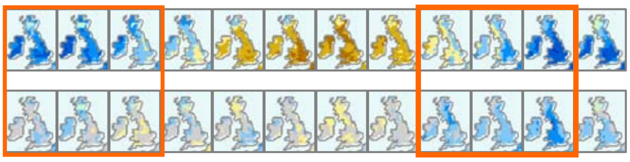

Figure 4: Upper sequence: Soil moisture between 0-100% saturation (dark brown to dark blue), lower sequence: soil moisture anomalies with respect to the long term mean of the specific month (grey: no deviation, yellow: drier than expected, blue: wetter than expected)

3.2 Time series long term trend analyses

During time series processing the whole global soil moisture data set underwent the procedure described under subchapter 2.2.. Thus, the percentage of wet anomalies and the percentage of dry anomalies had to be calculated for each month and all years. Figure 5 depicts the percentage of wet anomalies, which occurred during the month of July for the two years 1996 and 1998. Pink areas indicate regions with no obvious deviations, while blue-green to yellowish-red tones indicate a large number of outstandingly wet measurements. In July 1996 most areas (except some parts of Mongolia and the western Sahel) show now obvious changes. In July of 1998 (a strong El Niño year) the whole Sahel zone, as well as larger parts of Australia, Central Asia, and the Great Plains show anomalous behaviour.

Figure 6 shows the global trend for areas to become wetter (upper) or drier (lower). Based on figure 6 we can observe that there are some regions with very outstanding trends concerning soil moisture deviation from the mean and an increase in wet and dry anomalies.

It is obvious that the northern part of Australia has become slightly wetter over time, as have parts of south-eastern Africa. Furthermore, Mongolia shows some very impressive trends, indicating that especially the eastern part of the country has become significantly drier over time. To investigate if these observations coincide with meteorological ground station measurements we analyzed precipitation-, temperature- and “number of rainy days” information from Australian and Mongolian stations.

While the upper and lower figure 6 are mostly complementary (in areas , where the percentage of wet anomalies increase, the number of dry anomalies usually decreases), there are also some regions, where these complementarities cannot be observed. In these regions an increase of extreme events is likely.

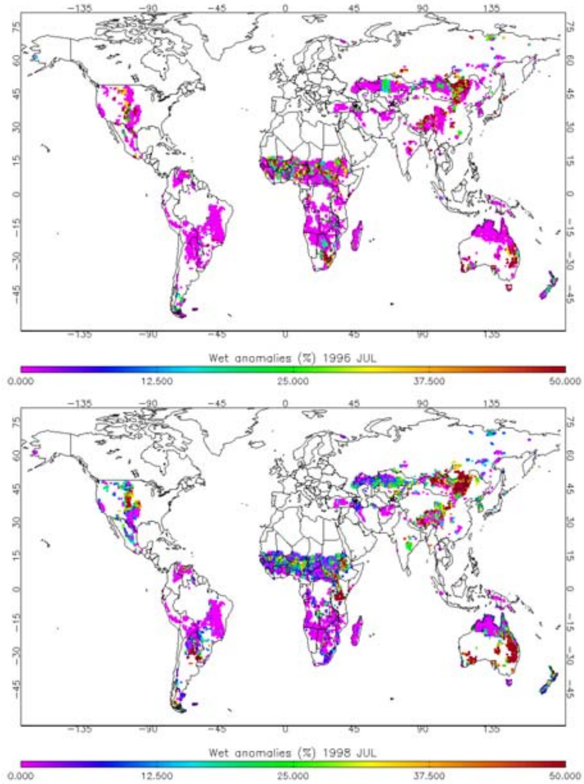

Figure 5: Percentage of wet anomalies for the month July in the years 1996 and 1998.

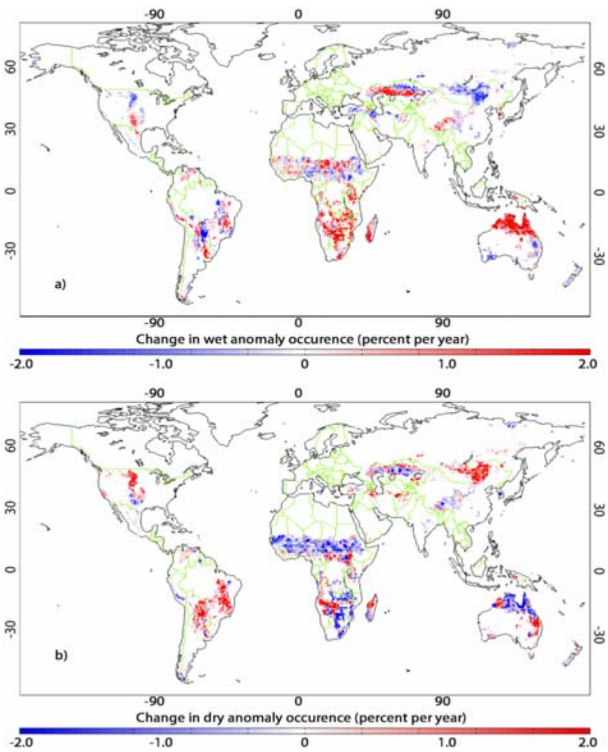

Figure 6: Global trend for areas to become wetter (upper) or drier (lower), respectively areas with an increase in wet or dry anomalies.

Figure 7-a shows surface soil moisture (black), with the yearly mean reproduced for all years (orange), for a location near Sainshand, southeast Mongolia. The difference between the surface moisture and the mean is shown in figure 7-b. Rainfall-, snow and temperature information has been available from ground stations (7-c). Figure 8-d depicts the total precipitation in mm (black line) and the number of rainy days per year (pink line). It can be noted that after the data gab from 2001-2005 (7-a, 7-b) the surface moisture signal is much lower than during the measuring period before. The decrease is not sensor related. This behaviour could be observed from numerous locations in eastern Mongolia (which also all show a decrease in the number of rainy days and precipitation in mm), such as the stations in Bajndelger and Barum-Urt, while other areas in other countries show a completely different behaviour.

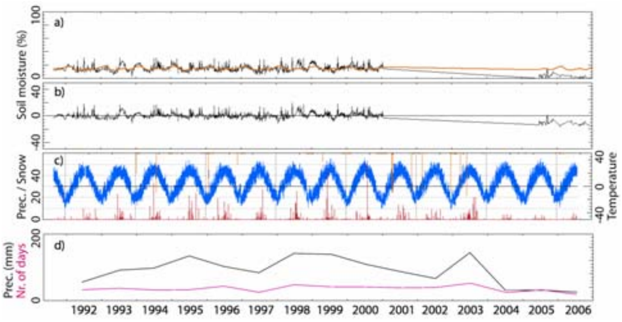

Figure 7: Surface soil moisture development for a station near Sainshand, Inner Mongolia. a) surface moisture (black) and long term mean (orange), b) difference between the two, c) ground station information d) precipitation and number of rainy days.

Figure 8 shows a similar plot for a location in Northeast Australia near Palmerville. According to this figure there is a slight increase in surface moisture especially since 1998 (8-b: curve is starting to slightly move upwards compared to the zero-line) However, this is only a shorter phenomenon, which can not be further observed after 2001 (no data).

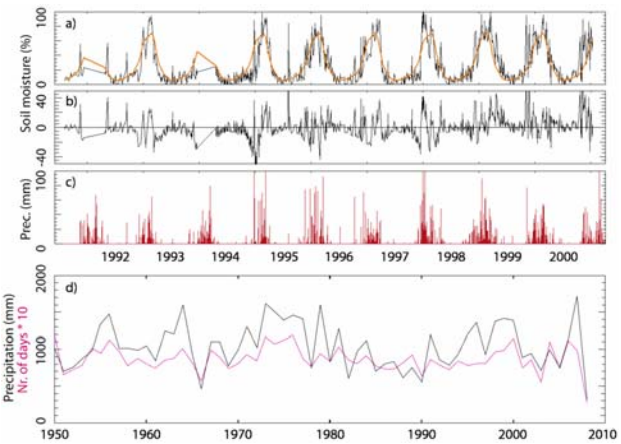

Figure 8: Surface soil moisture development for a station near Palmerville, Australia. a) surface moisture (black) and long term mean (orange), b) difference between the two, c) ground station information d) precipitation and number of rainy days (from Australian quality controlled rainfall data, available daily since the 1890's from the Australian Bureau of Meteorology)

4. CONCLUSION

Usually, the derivation of trends, analyzed under the scope of climate change phenomena or related studies is performed on time series of 20+ years. One could thus argue that the TU Wien soil moisture time series is not yet long enough to derive meaningful trends. However, previous studies, anomaly analyses and the finding of this study indicate that the soil moisture time series processed by TU Wien has a large potential for long term trend analyses. It is the only time series of its kind existing since 1992. Results presented within grassland- and savannah-dominated areas clearly indicate regions, which have become drier or wetter over time. These findings could be verified through available in-situ data for a few selected sites. Currently the ERS-Scatterometer based time series is being extended and reprocessed with first data derived from the METOP Advanced Scatterometer (Ascat). Therefore, the extension and continuity of the time series based on two sensors is guaranteed. Even though spatial coverage is not always global, and temporal gaps do exist, the time series allows for the observation of short term trends, and the detection of the onset of probable long term trends. Furthermore, the time series clearly reflects all global deviating events such as strong droughts, floods, or El Niño events. We propose to investigate the TU Wien dataset further, focussing on medium- to long-term trend analyses and frequency analyses of anomalous events.

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