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Statistical analysis of soil moisture content changes in Central Europe using GLDAS database over three past decades

Research Article

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Abstract: This paper examine soil moisture trends changes in inhomogeneous area of Central European countries - Poland, the Czech Republic and neighbouring territories. The area suffered from the lack of large-scale soil parameters research. Most of them are limited to ground measurements performed for a small part of land. Although there were extensive water conditions studies performed for the whole Europe, such as drought analysis, they were focused on Western European countries, neglecting situation in Central Europe (taking exception to Austria). The NOAH model of Global Land Data Assimilation System database has been used as a data source. It delivers one degree spatial resolution data and variables which describe soil moisture values for four depth levels (0–10 cm, 10–40 cm, 40–100 cm and 100–200 cm). Data covering years 1979–2011 has been averaged in order to analyse summer and winter terms separately. Descriptive statistics and regression analysis have been prepared on the software Statistica, Research reveals that area is losing water content. Due to promising results of water content trend analysis, the authors plan to run a large-scale analysis using other variables from the GLDAS database, especially concerning soil temperature and evapotranspiration.

Keywords: Europe • Global Land Data Assimilation System (GLDAS) • regional studies • soil moisture statistical analysis

1. Introduction

1.1. Overview

Recent studies reveal soil moisture (SM) impact on climate change [1]. This parameter [2] is generally defined as an amount of water stored in an unsaturated soil zone. It plays a crucial role in global water cycle and energy exchange. Proper soil moisture content (SMC) description is one of the most important issues in many fields of environmental protection such as pollution detection, land management systems, food security research, flow of nutrients, wildfire detection, (desert) locust and carbon balance modelling (models such as C- Fix – Carbon fluxes model [3]. Soil moisture can be seen as a soil status condition, a major environmental variable related to land surface climatology, hydrology and ecology. SMC variations entail impact on a vegetation productivity, transfer of land surface energy and a runoff. Relation between water availability (especially green water, i.e., the part of water which infiltrates through soils) and food production is the subject of a long-term analysis.

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Table 1. Description of four models used by GLDAS database.

Model	Number of layers	Layer coverage
Mosaic	3 layers	0-0.02, 0.02-1.5, and 1.5-3.0 m
CLM2 (NOAH the Community Land Model)	10 layers	0-0.018, 0.018-0.045, 0.045-0.091, 0.091-0.166, 0.166-0.289, 0.289-0.493, 0.493-0.829, 0.829-1.383, 1.383-2.296, and 2.296-3.433 m
NOAH	4 layers	0-0.1, 0.1-0.4, 0.4-1.0, 1.0-2.0 m
VIC (Variable Infiltration Capabillity)	3 layers	0-0.1, 0.1-1.6, and 1.6-1.9 m

Complex simulations reveal future issues associated with both population growth and water amount decrease [4]. Soil moisture [5] plays a substantial role in transforming energy into latent and sensible heat fluxes. Both of them have a strong impact on boundary layer conditions. Consequently they are important factors in Numerical Weather Prediction and running climate models. From Kyoto protocol followers' perspective, it is important to notice that SMC affect the global change effects [1]. As a result [6], this parameters' variation should be considered during adopters' meeting. Farmers need dry soil (potential drought) conditions data to use them as an early warning system and optimize crop harvesting. It is important for missions in famine stricken areas as well. On the other hand, SMC might be used as a flood probability detector (soil waters become completely saturated). It helps to define a runoff, especially in a deforested cover. SMC might serve as a fire risk indicator.

SMC is strongly correlated with a drought definition. However, the latest study reveals that further analysis concerning this relation is still needed [7]. Regarding simulation run using WaterGAP model, more extreme conditions are expected to occur in Europe. In the north, it is expected that there will be many more floods, while in the south - drought will be more frequent [8]. Moreover, there have been major drought events noted during the past 30 years, namely in 1976, 1989 and 1991, but it is not clear if drought conditions became more severe [9].

Information about this parameter can be obtained from the GLDAS database [10]. It combines results of modelling from both land and satellite observations by means of one of four land surface models (Table 1).

Although the GLDAS database is considered as robust and having adequate theoretical foundations, it has not been widely used in soil moisture changes study for Central Europe so far. An example of such an effort was an article dedicated to renewability of water storage in the Łasica catchment. Łasica is a river which flows through Kampinos National Park - one of National Parks located in the central Poland, in Mazovian Lowland, in the north-west outskirts of Warsaw. By means of selected hydrological variables (rainfall, snowfall, evapotranspiration, soil moisture and soil surface temperature) acquired from the GLDAS database, yearly indexes of soil water renewability (1980 to 2007 time period) have been calculated. All of them show decreasing tendency, although they are insignificant in terms of statistics [11].

Another study was the SMOS data analysis conducted by Bohdan Dobrzański Institute of Agrophysics, Polish Academy of Sciences. The SMOS (Soil Moisture and Ocean Sailinity) mission is European Space Agency mission, which objective is to provide soil moisture and ocean salinity values by means of brightness temperature [12]. Results of PAS research have been partially published at EGU conference [13]. It was shown that the territory of Poland is losing soil moisture content. A short period of time has been analyzed since 2009, when the mission was launched.

1.2. Simulation purpose

As stated in the Overview, soil moisture is one of the most important factors in energy and water fluxes balance. It is both input and output to many hydrological and atmospheric models. Its fluctuation is important for a wide range of people, most notably farmers, woodsmen and meteorologists. Regardless of being such an important factor for analysing a long-term trend, there was a lack of extensive analysis for Central Europe. Most of it described only a local phenomena and avoided using data contained in the GLDAS database.

The purpose of this analysis was to check if it is possible to determine a statistically significant trend of soil parameters changes for a large, inhomogeneous area. Moreover, it was appropriate to describe a direction of

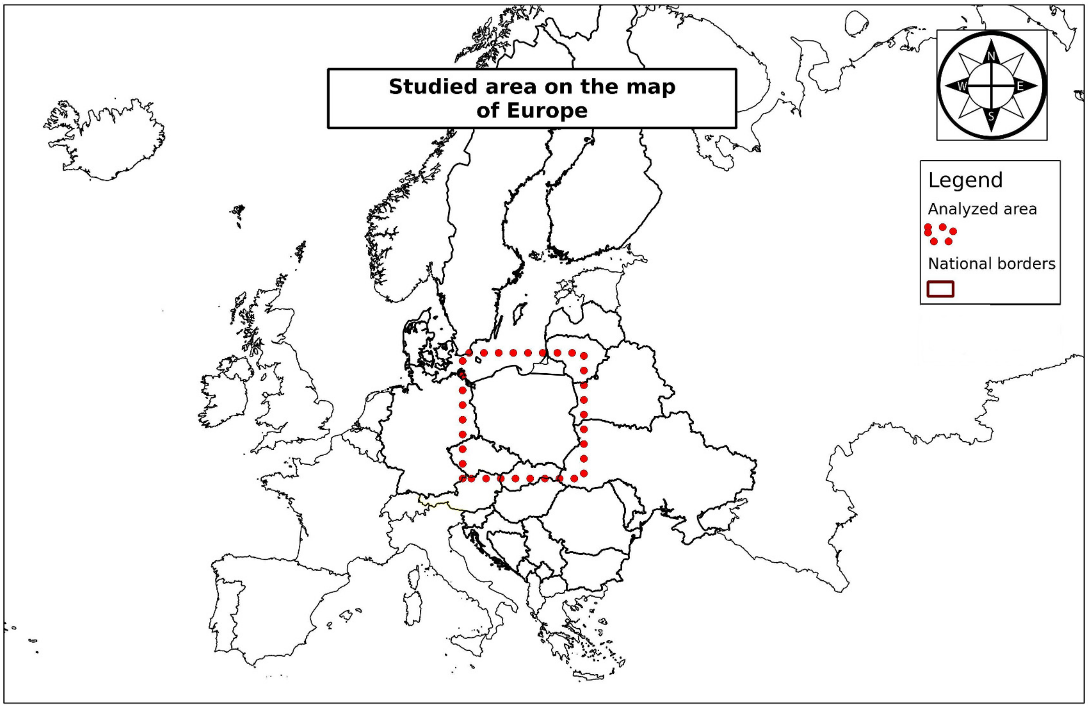


Figure 1. Analyzed area presented on the map of Europe.

mentioned changes for all depths together and separately at the same time.

2. Materials and methods

2.1. Study areas and data collection

The studied area was located in the central part of Europe (Figure 1, Table 2).

The area composed of territories of such countries as Poland (69% of the studied area) or the Czech Republic (18% of the analyzed area) and their nearest neighbours. All values for pixels located on the Baltic Sea have been excluded from further analysis.

2.2. Data source

Goddard Earth Sciences Data and Information Services Center (GES DISC) GrADS stores 12 GLDAS products, i.e., two for CLM, two for Mosaics, six for NOAH and two for VIC models - with different spatial and temporal resolutions. In order to obtain reliable trends (in terms of significance measured by p-value), it was expected to maximise the number of analyzed time periods.

All variables have been obtained from "GLDAS_NOAH10SUBP_3H" product which delivers data with 1.0 degree spatial resolution and 3-Hourly temporal resolution. The following variables have been examined:

- soilm1 - soil moisture at the depth of 0–10 cm
- soilm2 - soil moisture at the depth of 10–40 cm
- soilm3 - soil moisture at the depth of 40–100 cm
- soilm4 - soil moisture at the depth of 100–200 cm

All variables have been expressed in kg of water per square meter.

3. Methodology

3.1. Remote analysis

In order to communicate with GrADS server, DODs protocol has been used [14]. It provides a stable way of conducting a remote analysis. A user is able

Table 2. Analyzed area corners (in WGS 84 system.

Corner name	Coordinates
Upper Left	13.50, 55.50
Lower Left	13.50, 48.50
Upper Right	24.50, 55.50
Lower Right	24.500, 48.50

Table 3. Descriptive statistics for winter terms (N=30; 1979 and 1980 excluded).

	Minimum	Maximum	Average	Standard deviation	Coefficient of variation	Lower quartile	Upper quartile	Interquartile range
soilm1	26.05	36.95	31.71	2.14	0.07	30.79	33.28	2.49
soilm2	73.38	111.59	90.41	8.17	0.09	83.93	94.85	10.92
soilm3	116.63	183.19	158.48	19.03	0.12	147.04	172.22	25.17
soilm4	180.78	283.72	239.41	28.16	0.12	215.24	257.59	42.35
SUM	414.06	598.20	520.01	47.15	0.09	483.70	550.16	66.46

to send requests which contain mathematical operands and execute functions on raw data. It is simple to average, aggregate and count correlation coefficients. All computations are conducted on server. The user is able to download a small amount of results data instead of large data sets.

Results are delivered as a text (ASCII string) which makes further processing easy. According to hydrological (water) year definition [15], data has been analyzed for two halves of a year separately, later referred to as winter and summer terms. Winter term starts on the first day of November and ends on the last day of April. Summer term starts on the first of May and lasts until the end of October.

Python [16] script has been written to request averaged data and save the result in ASCII GRID format [17].

3.2. Data preprocessing

MODIS Water Mask [18], produced at University of Maryland has been adopted by GLDAS as a standard land/sea mask. Global map has been divided into 0.01 degree pixels. In case of GLDAS pixels which contain more than 50% water pixels, they are marked as water (zero value) and all the others as land (value is equal to one). Consequently, all pixels located on water areas should be excluded from further analysis and marked as "No Data" value.

Regardless of this precaution, retrieved data contains some values for pixels located on the Baltic Sea. However, the raw data stored on the server are free of unexpected values. Such strange behaviour occurs when an averaged area is outside GRID points only.

Raster layer which describes Baltic Sea area has been obtained from Helcom WMS server [19] to prepare list of 'uncertain' pixels. All of them have been removed from retrieved data set.

There was no further preprocessing steps - all values have been transformed to coordinate-value, plain text format as well as ASCII Grid and further analyzed.

4. Results and discussion

In case of both terms - summer (Figure 2) and winter (Figure 3) - a pixel for the last analyzed half of the year has lower values in comparison with the first analyzed term. Values for remaining time periods reveal that we will be unable to observe constant decreasing or increasing trend of soil moisture values.

While averaged data values for most pixels decrease, values for some of them slightly increase (1999-2000). Based on literature and our previous experience, the number of analyzed time periods and averaging technique used have crucial impac on improving legal certainty to formulate hypotheses for large and not homogeneou area. Received results are statistically significant and allow us to state that soil moisture tends to decrease (Figure 4(a)–(d)).

Described relation seems to be a layer depth independent - even values for the most outer layer (in terms of available soil moisture products) clearly prove that the content of

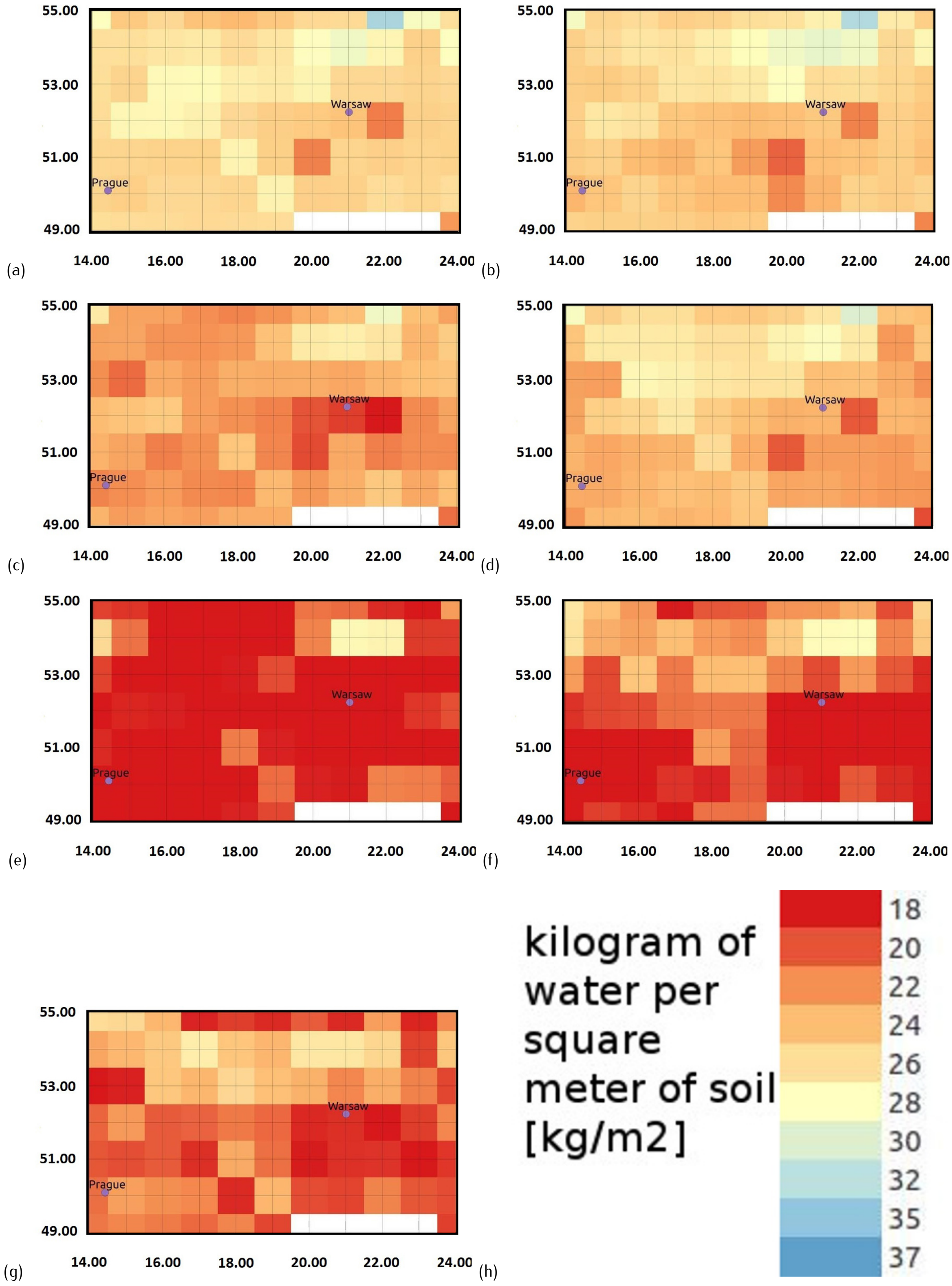


Figure 2. Maps of first layer (0-10 cm) soil moisture values for summer terms expressed in kilogram per square meter. From the left: May - October values for following years: 1980, 1985, 1990, 1995, 2000, 2005, 2011, scale applied to maps.

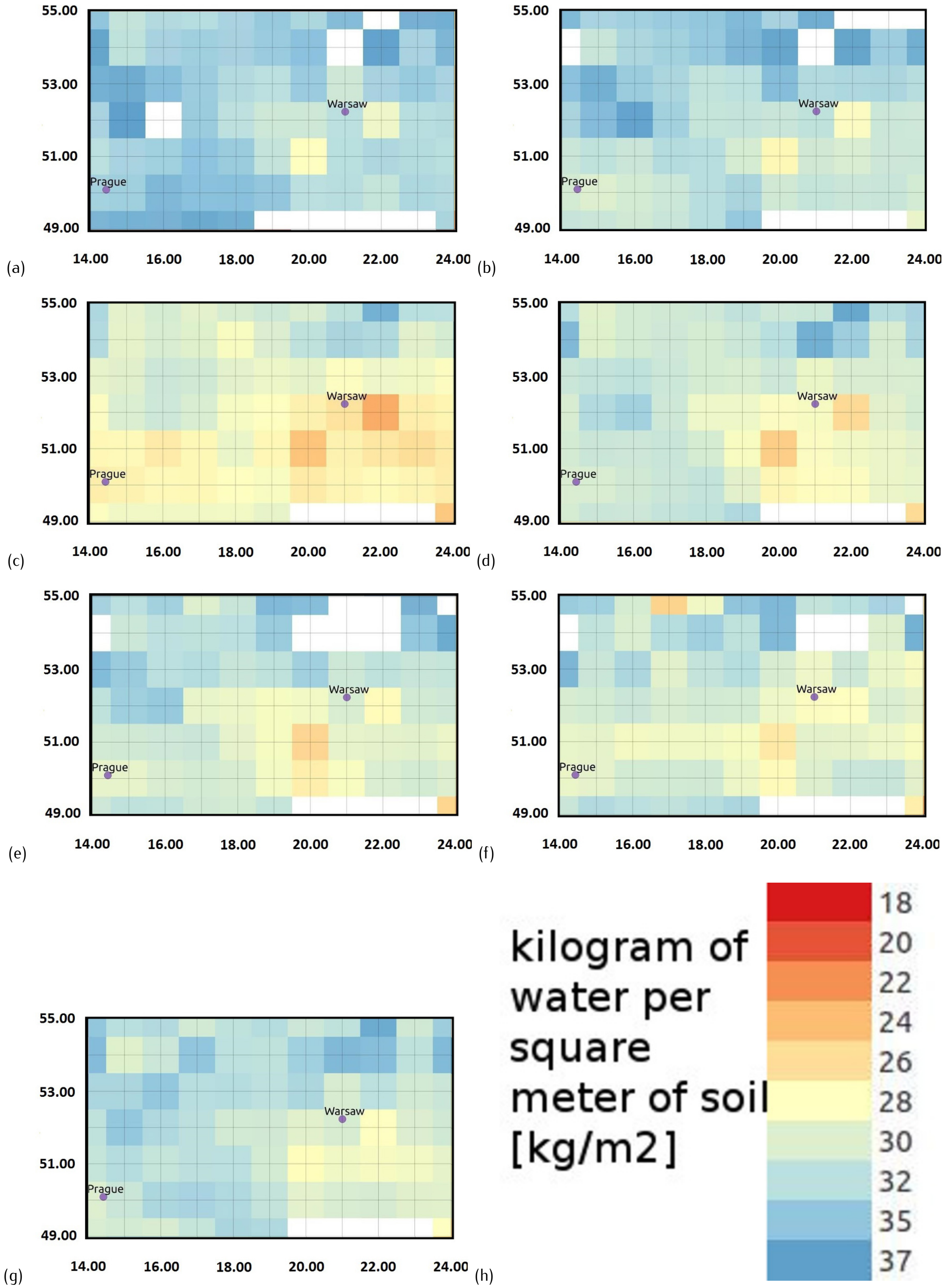


Figure 3. Maps of first layer (0-10 cm) soil moisture values for winter terms in kilogram per square meter. From the left: November - April values for following years: 1979-1980, 1984-1985, 1989-1990, 1994-1995, 1999-2000, 2004-2005, 2009-2010, scale applied to maps.

Table 4. Descriptive statistics for summer terms (N=32).

	Minimum	Maximum	Average	Standard deviation	Coefficient of variation	Lower quartile	Upper quartile	Interquartile range
soilm1	17.77	26.87	22.70	2.44	0.11	20.45	24.51	4.05
soilm2	47.15	80.49	65.95	8.92	0.14	57.39	72.89	15.50
soilm3	78.14	160.48	122.43	23.70	0.19	99.09	141.32	42.23
soilm4	186.49	268.28	227.63	21.04	0.09	208.51	244.13	35.61
SUM	329.80	536.12	438.71	55.54	0.13	383.91	482.19	98.28

Table 5. Descriptive statistics for summer terms (N=32).

	P – value		Coefficient of determination (R^2)		Standarized coefficient (β)	
	summer	winter	summer	winter	summer	winter
0 – 10 cm	0.0001	0.0193	0.3736	0.0952	-0.63	-0.35
10 – 40 cm	0.0001	0.0039	0.3972	0.1815	-0.65	-0.46
40 – 100 cm	0.0000	0.0001	0.4277	0.3775	-0.67	-0.63
100 – 200 cm	0.0000	0.8035	0.4232	-0.0291	-0.66	0.064

soil water is decreasing. It is also independent of the analyzed term. It is important to note that determining soil moisture changes is much easier for summer terms than for winter ones.

As presented in tables by standard deviation (Table 3 and Table 4), in case of summer periods, soil moisture changes fluctuations are less frequent than in winter season. Since exactly the same color palette has been used for both summer and winter, it is easy to observe generally higher water content in winter than in summer. It seems that it does not change with time. Those factors prove that analyzing both terms separately is an appropriate approach.

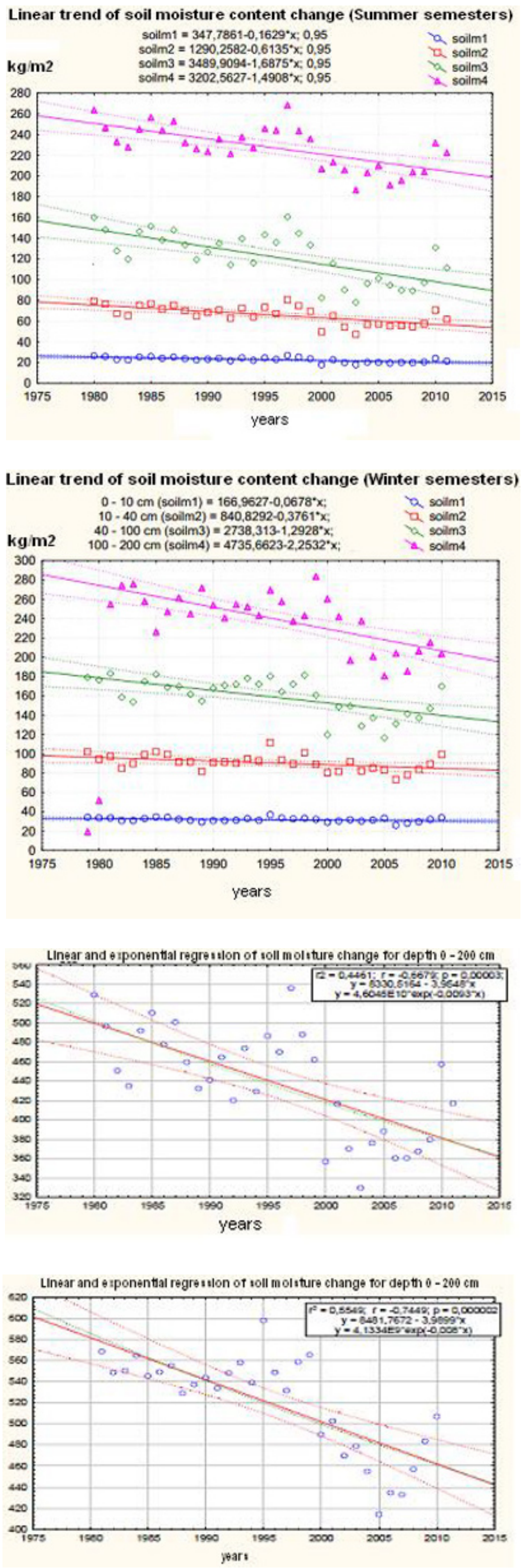
Regardless of differences, both terms values indicate that soil moisture is decreasing. Furthermore, the lowest values were observed in year 2000.

Fitting a linear model (Figure 4) to the obtained data leads to the conclusion that soil moisture content is decreasing. It is true for all four analyzed data layers and most reliable for the first depth level (0–10 cm). Values for all four layers (0–200 cm) have been averaged and the linear model has been fitted as well. Regression line graph (Figure 4(c),(d))as well as comparison of two maps taken from the starting and the final date of the analysis (Figure 5(a),(b)), prove decreasing trends for both, i.e. winter and summer terms. Similarly, as it was shown in Figure 2 and Figure 3, the area which loses most soil moisture is Mazowsze region (particularly - Warsaw agglomeration). A part of northern Poland preserved the most of soil moisture content. However, a decreasing trend is noticeable for this part of the analyzed area as well.

5. Conclusion

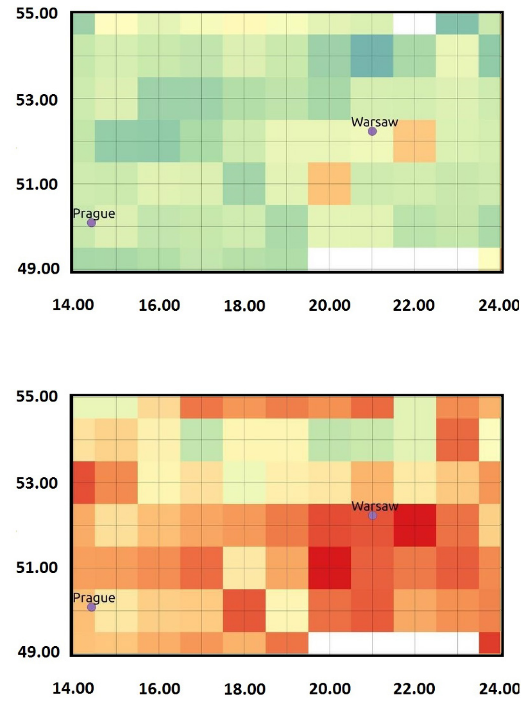
In this paper the soil moisture content for area of central European countries have been analyzed for four depth levels: 0–10 cm, 10–40 cm, 40–100 cm, 100–200 cm and an averaged value for 0–200 cm. Data has been averaged remotely on the GrADS-DODS server. Values for summer and winter terms have been analyzed separately. Maps of soil moisture values have been presented. Linear regression functions have been fitted to the data, using the software Statistica. It was proven that during 1979–2011 time period, soil water content was decreasing. This conclusion was most clearly seen for the first depth level of soils (0–10 cm) for summer terms. However, for each of analyzed soil depth levels, as well as for averaged 0–200 cm values, the direction of changes remained exactly the same.

The process of obtaining information about the soil moisture using ground measurements is relatively expensive and difficult to manage. On the other hand, satellite image processing (performed for example on the Polish territory as a part of SWEX programme) requires the elimination of the impact of a number of confounding factors. The GLDAS database is a product which links these two types of information. The GLDAS



(a) (b) (c) (d)

Figure 4. Non-aggregated (a,b) and aggregated (c,d) regression lines for 4 soil moisture layers; on the left summer (a,c) and on the right winter (b,d).



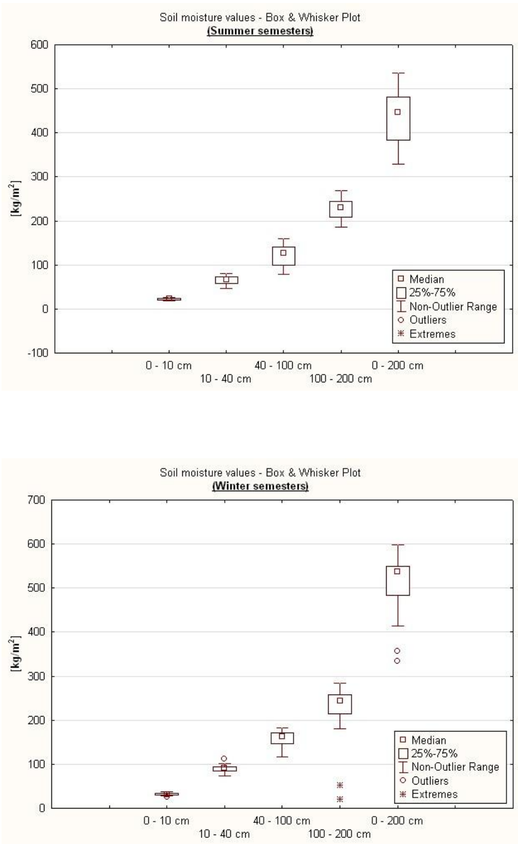
(a) (b)

Figure 5. Comparison of data values for May - October 1980 (a) and May - October 2011 (b).

database stores information that is valuable for a number of institutions within the European Union, particularly to Water Framework Directive and the INSPIRE Directive. Although it does not provide a high spatial resolution, the information stored within it is ideal for the analysis of long-term changes. Even for larger and more heterogeneous area of Central Europe it is possible to receive large values of correlation coefficients and low p-values. Due to satisfactory results, it is reasonable to investigate changes for a larger area than described in the "Study area" paragraph.

The GLDAS database makes it possible to analyze soil and atmosphere parameters which are related to soil moisture. One of them is an evapotranspiration, which changes are still under extensive research [20]. It will be reasonable to study trends for this parameter as well.

ESA, NASA and JAXA manage numerous satellites. Part of their missions were directly designed to provide soil moisture data, for example SMOS (which is one of the inputs to GLDAS models). However, related information is obtained from other sensors. It is worth to notice two similar missions - NASA's GRACE (Gravity Recovery and Climate Experiment - measure temporal variations of the Earth's gravity field) and ESA's GOCE (Gravity



(a)

(b)

Figure 6. Boxplot graphs for summer (g) and winter terms.

Field and Steady State Ocean Circulation Explorer - obtaining high resolution, stationary gravity field). GOCE, showed an extraordinary correlation with SMOS signal on the Antarctic Plateau, caused by ice melting, January, 2014 [21]. GRACE is widely used for modelling soil moisture changes [22] and some results might seems contradictory to our conclusions. Although, they provides interesting input for large-scale analysis, they are not tailored for regional studies, presented in this paper. Scale problem is significant obstacle to simply compare our results with GRACE, but obviously worth for further research.

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