APPLICATION OF SATELLITE IMAGERY AND GIS TOOLS FOR LAND SURFACE TEMPERATURE ESTIMATION AND VERIFICATION

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Land surface temperature (LST) plays an important role in many land-surface processes on regional as well on global scales. It is also a good indicator of energy flux phenomena and is used as a parameter in various Earth observation related studies. However, LST estimation based on processing and utilisation of satellite derived data constitutes several problems in terms of time limitations, accessibility, atmospheric influence etc. The aim of the study was to verify and compare the algorithms especially in the context of minimalisation of errors in LST estimation by satellite observation using various means of GIS data processing and integration. Also, the indirect verification of the LST estimation methods, based on the utilisation of statistics and dependencies of LST, NDVI and air temperature values has been presented and discussed. The presented work has the form of a case study, and due to limited amount of verification data used in the current stage of the investigation, the results should be treated as preliminary. The developed GIS solution for integrating spatial data from many sources needed in the course of this study is also presented.

INTRODUCTION

The acquisition, processing, integration, visualization and utilisation of various kinds of airborne or satellite derived data constitute several important problems, in the context of time limitations with respect to accessibility of sensors, the atmosphere influence (clouds presence, need for atmospheric corrections of measured radiance), insufficient spatial resolution, imperfection of models for the desired parameters derivation, etc. [1] In this paper, the operationally applicable methods to retrieve some important weather parameters from satellite Earth observation and proposed methods of their verification are described. The details of the methods used in data processing, the implementation, as well as the overall diagram of the proposed GIS (Geographic Information System) are presented below.

It is known that in the terms of satellite Earth observation, remote sensing based methods for land surface temperature (LST) or sea surface temperature (SST) estimation are easier accessible and characterised by better accuracies, resolution etc. than the methods for air temperature estimation. Attempts to derive LST from satellite observations have been ongoing for several decades. They are mainly focused on polar orbiting systems such as Advanced Very High Resolution Radiometer (AVHRR), because of global coverage, quite high spatial resolution, and relatively short revisiting time. However, the accurate LST retrievals require the precise determination of atmospheric corrections, as well as land surface emissivity [2]. The split-window algorithm (split window technique, SWT), which is widely used due its simplicity, addresses both of the above effects.

Satellite images used for air temperature and humidity estimation have been acquired by the 1.5 metre HRPT/MetOp-A Satellite ground station operated by Gdańsk University of Technology (GUT). The station is capable of obtaining data from AVHRR sensor which is available in NOAA-N and MetOp-A satellites. These satellites were used as the data source in the mentioned investigation.

Along with development of algorithms for satellite data processing and other tools for data assimilation, storing, management, dissemination etc., the overall architecture of the relevant GIS has been designed.

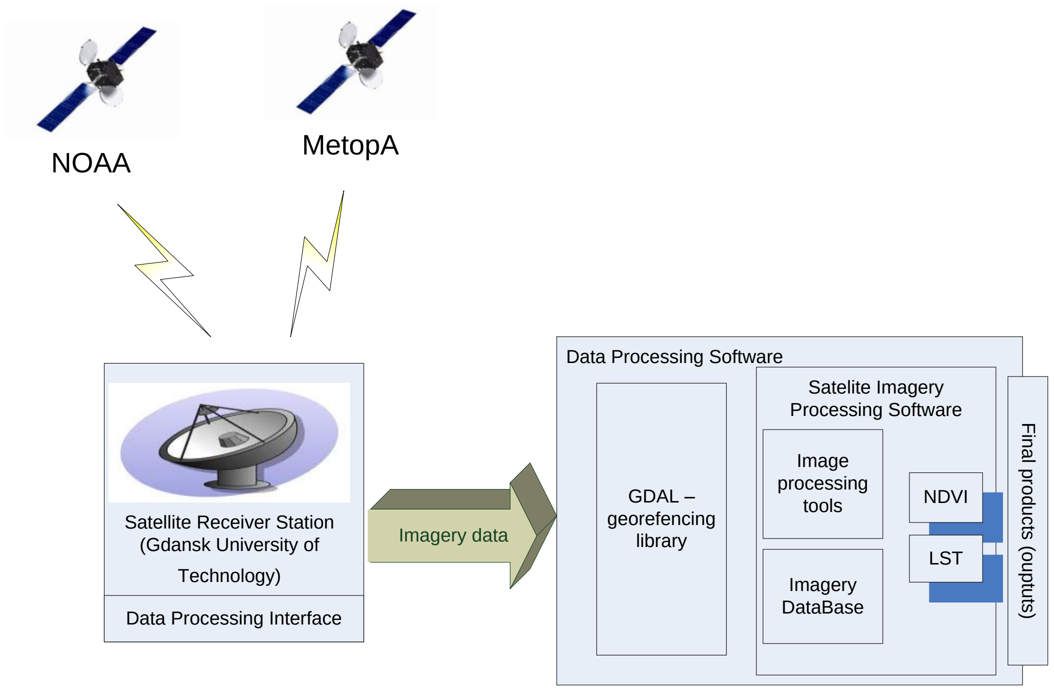

Fig.1. The architecture of proposed GIS tool for satellite data processing.

Satellite imagery data are received by the 1.5 metre HRPT/MetOp-A ground station from NOAA-N and MetOp-A satellites. The data processing software provided by the vendor of the station is responsible for acquisition process control (including selection of satellites as

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data sources, definition of an investigated area borders etc.) and basic processing (e.g. basic radiometric corrections). The acquired data are transferred in real time via TCP/IP connection and assimilated by the main module of the system. It consists of several software packages developed in Java and C++. The geometric corrections and transformations of satellite images are performed by the Geospatial Data Abstraction Library (GDAL) georeferencing package, and then the data are stored in the Imagery DataBase. The Image Processing Tools include the algorithms implemented for the desired quantities estimation from satellite data, i.e. temperature and NDVI (Normalized Difference Vegetation Index).

1. BASICS OF LAND SURFACE ESTIMATION

As it was mentioned, we decided to utilise the method for LST measurement for air temperature estimation. The widely used SWT (split-window technique) algorithm was utilised for this purpose. It relays on calculation of brightness temperatures from several satellite channels on the basis of the Planck Law [1], which connects the temperature T_s of a radiating surface with the radiation B of the wave length λ by the exponential formula:

$$B(\lambda, T_s) = \frac{c_1 \lambda^{-5}}{\exp\left(\frac{c_2}{\lambda T_s}\right) - 1}$$

where c_1 = 1.19104·10^8 W μm^4 m^{-2} sr^{-1} and c_2 = 1.43877·104 μm K are the first radiation constant (for spectral radiance) and second radiation constant respectively. $B(\lambda, T_s)$ is given in W m^{-2} sr^{-1} μm^{-1} if the wavelength is given in μm.

In SWT algorithm, the first-order Taylor series expansion of the Planck's is used, what allows for linear approximation of the relation between radiance and temperature. Then, the results from particular channels (here, 4th and 5th AVHRR channels) are combined, with taking into account also the atmospheric corrections as well as the LSE for particular channels. The simplified form of the base SWT equation for land surface temperature T estimation may be written as follows:

$$T = T_4 + A + B(T_4 - T_5),$$

where

T_4, T_5 - brightness temperature values in °C for 4th and 5th AVHRR channel respectively,

A, B - coefficients that depend on atmospheric transmittances.

The temperature calculations were performed for each pixel of a scene, under the condition that the calculated normalised differential vegetation index (NDVI, see text below) was not less than 0.2. Otherwise, land surface was assumed to be covered by clouds (or belonging to sea area) for a given location, and calculations of temperature and humidity were not performed. Subsequently, the raster maps of the estimated temperatures were constructed for investigated areas on the basis of calculations.

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2. IMPLEMENTATION OF LST INCLUDING WATER VAPOUR

There are several improvements or modification for SWT algorithm proposed by many authors. In conducted research, the further improvement of the LST algorithm has been obtained by applying the approach proposed by Y. Julien et al. [5]. It is based on the so-called Radiative Terasfer Model (RTM) described by Sobrino et al. [3]. It describes the land surface emissivity and atmospheric transmittance (mainly, it's the most significant component connected with the water vapour content – WVC) relation with AVHRR channels radiations, in more advanced and complicated form than models on which previously used approached were based. The authors proposed several exact formulae for emissivity, WVC, and finally, for LST calculation from AVHRR channel 4 and 5 (and channel 1 and 2 as well because of their utilisation for NDVI (Normalized Difference Vegetation Index) calculation which is also used. The influence of SZA (satellite zenith angle) is also taken into account.

In this algorithm, the average emissivity for 4th and 5th AVHRR channel ε_{avr} and the difference of these channels emissivities $\Delta\varepsilon$ are calculated on the basis of NDVI. Namely, for 0.2 < NDVI < 0.5 (the pixels for which the NDVI values are less than 0.2 are being masked in our approach and no calculations of LST are performed for them) the ε_{avr} and $\Delta\varepsilon$ are calculated using the following formulae:

$$\varepsilon_{avr} = 0.971 - 0.018\,P, \qquad \Delta\varepsilon = 0.006\,(1 - P),$$

where $P = \dfrac{(NDVI - 0.2)^2}{0.09}$.

For NDVI > 0.5 they are fixed as:

$$\varepsilon_{avr} = 0.985, \qquad \Delta\varepsilon = 0.$$

Next, the total atmospheric vapour W (in g cm^{-2}) is calculated as:

$$W = 0.26 - 14.253 \cos\varphi \ln R_{54} - 11.649 (\cos\varphi \ln R_{54})^2,$$

where φ is SZA (satellite zenith angle) and R_{54} is the variance-covariance ratio calculated for a neighbourhood of N pixels of channel 4 and 5 images:

$$R_{54} = \frac{\sum_{k=1}^{N} (T_{4k} - T_{4o})(T_{5k} - T_{5o})}{\sum_{k=1}^{N} (T_{4k} - T_{4o})^2},$$

where T_{4k} and T_{5k} are the radiometric temperatures (in K) for the k-th pixel of the neighborhood in channels 4 and 5 images, respectively, and T_{4o} and T_{5o} are the average values for the neighborhood in channels 4 and 5 images, respectively.

Finally, the LST is estimated as:

$$LST = T_4 + 1.4(T_4 - T_5) + 0.32(T_4 - T_5)^2 - 0.83 + (57 - 5W)(1 - \varepsilon_{avr}) - (161 - 30W)\Delta\varepsilon.$$

The preliminary results show that this method of LST estimation (according to the indirect verification procedure described in following sections) is capable of producing the results with the accuracy of 3 °C or better. In literature, the reports of achieving the error level of 1.3 K by using this algorithm may be found. Example raster maps presenting the results of calculations were shown in Fig. 2.

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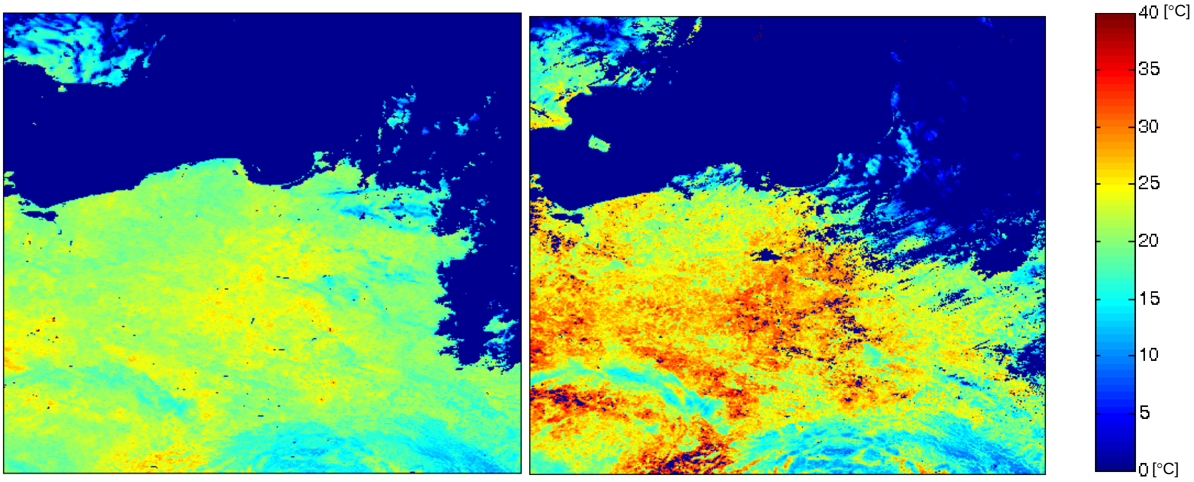

Fig.2. Example results of AVHRR LST estimation for two selected scenes: 19-08-2012 7:16 UTC (left) and 19-08-2012 11:16 UTC (right).

3. DATA AND METHODS USED FOR VERIFICATION OF LST ESTIMATION ALGORITHMS

The reliable approach to verification of LST estimation from satellite imagery accounts for having the reference data measured with higher level of accuracy. These data might be acquired by in-situ measurements of the land surface radiative temperature. Such measurements may be conducted, but in the most cases the collected datasets are insufficient to allow for the comparison of them with the results obtained from the AVHRR scenes and to verify the proposed algorithms. Another solution could be the use of LST estimation data obtained from MODIS sensor as reference datasets. But due to selective availability of MODIS imagery with respect to time localisations of analysed AVHRR scenes, this method also could not be efficiently applied at the present stage of the research. Therefore, the indirect verification method has been proposed, besides of the possible use of the methods mentioned above. The indirect method utilises the dependencies connecting the LST, air temperature and NDVI values and their statistics for the investigated area. It relies on calculation the near-surface air temperature from estimated LST and NDVI values and then the comparison with air temperature data from another source (e.g. meteorological in-situ measurements, numerical weather modelling and prediction system etc.).

To implement the latter approach, first of all the GIS system for integration and comparison of data from several sources has been created to allow for the verification procedure. The system allowed for indirect comparing of the obtained LST estimation results from AVHRR sensor with:

- SYNOP reports on near-surface air temperature,
- distributions of air temperature obtained by numerical weather prediction (NWP) system.

Next, the choice of an air temperature reference data source was made, i.e. the decision whether the discrete data from meteorological stations or the quasi-continuous data from NWP should be used as primary reference data set. As it was shown in literature (e.g. [5]), and is also visible in general in processed data, the verification of satellite LST estimation results with air temperature *in-situ* measurements for limited set of point localisations in the investigated area is rather not reliable due to the heterogeneity of terrain and large spatial variability of measured and estimated quantities.

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The better method for verification of the temperature estimation from satellite imagery is the one relying on the reference data which are, similarly as the satellite scene, in a form of the spatial field of the quantity defined continuously over the investigated area. Such data are provided by NWP system and the authors decided to use them as the reference data in verification of LST estimation procedure. The applied approach assumes that it is better to have much more reference data characterised by lower accuracy than to have much less reference data of higher accuracy. The overall concept of GIS data processing and integration is presented in Fig. 3.

It must be pointed out that the NWP air temperature data used in this investigation have been obtained by reprocessing of the output of WRF EMS (Weather Research and Forecast Environmental Modeling System) prediction model [6][7] with adjustment to true meteorological conditions. It results in high conformability of the NWP and in situ measured temperature data, with the mean difference of 1 °C what was shown in Table 1. This table compares the NWP data with *in-situ* data from SYNOP reports on air temperature for several time points during the day of 11th August 2012 for selected localisations in Poland.

Tab.1. Comparison of sample WRF EMS data with *in-situ* data from SYNOP reports on air temperature for selected localisations in Poland.

Station ID	**Name / Localisation**	**Lat [deg]**	**Lon [deg]**	**In-situ temperature [°C]**	**NWP air temperature [°C]**	**Difference (mean) [°C]**	**Date / Time**
12125	LEBORK	54,33	17,45	17,8	18,5	0,7	2012-8-11 12:00 UTC
12125	LEBORK	54,33	17,45	17,8	19,5	1,7	2012-8-11 15:00 UTC
12125	LEBORK	54,33	17,45	12,2	9,5	2,7	2012-8-11 21:00 UTC
12210	RESKO	53,46	15,25	19,5	19,1	0,4	2012-8-11 12:00 UTC
12210	RESKO	53,46	15,25	19,3	20,4	1,1	2012-8-11 15:00 UTC
12210	RESKO	53,46	15,25	10,6	10,6	0,0	2012-8-11 21:00 UTC
12215	SZCZECINEK	53,43	16,41	19,5	18,7	0,8	2012-8-11 12:00 UTC
12215	SZCZECINEK	53,43	16,41	18,8	18,3	0,5	2012-8-11 15:00 UTC
12215	SZCZECINEK	53,43	16,41	10,6	10,8	0,2	2012-8-11 21:00 UTC
12270	MŁAWA	53,06	20,21	19,9	19,2	0,7	2012-8-11 12:00 UTC
12270	MŁAWA	53,06	20,21	19,4	18,9	0,5	2012-8-11 15:00 UTC
12270	MŁAWA	53,06	20,21	10,3	9,9	0,4	2012-8-11 21:00 UTC
12595	ZAMOSC	50,42	23,15	16,9	21,4	4,5	2012-8-11 12:00 UTC
12595	ZAMOSC	50,42	23,15	17,1	17,3	0,2	2012-8-11 15:00 UTC
12595	ZAMOSC	50,42	23,15	10,4	10,2	0,2	2012-8-11 21:00 UTC
12530	OPOLE	50,4	17,58	16,8	16,7	0,1	2012-8-11 12:00 UTC
12530	OPOLE	50,4	17,58	17,6	16,9	0,7	2012-8-11 15:00 UTC
12530	OPOLE	50,4	17,58	14	10,6	3,4	2012-8-11 21:00 UTC
12695	PRZEMYŚL	49,48	22,46	18	19,2	1,2	2012-8-11 12:00 UTC
12695	PRZEMYŚL	49,48	22,46	16,9	16,9	0,0	2012-8-11 15:00 UTC
12695	PRZEMYŚL	49,48	22,46	13,1	10,7	2,4	2012-8-11 21:00 UTC
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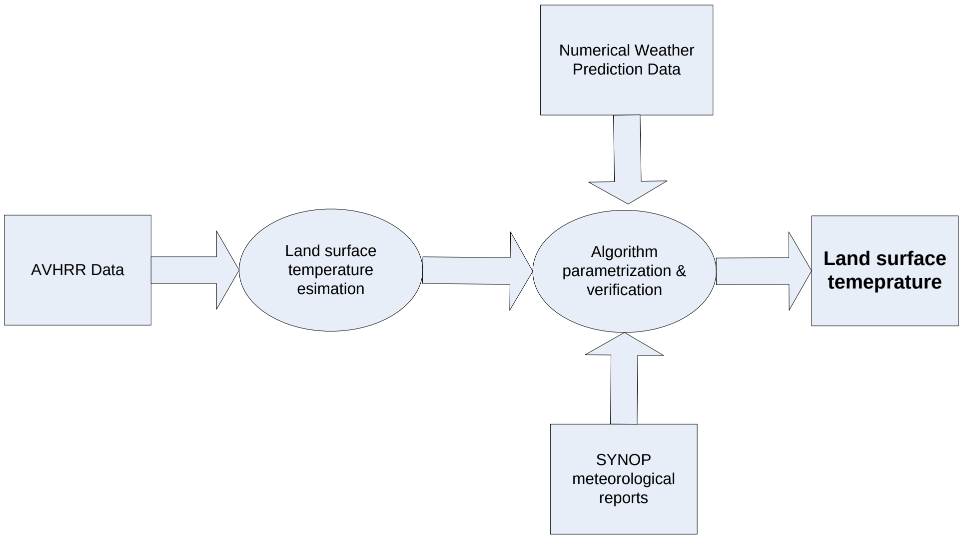

Fig.3. Data sources used in LST estimation and its verification by indirect method.

4. INDIRECT VERIFICATION METHOD FOR AVHRR LST ESTIMATION

Finally, the procedure for indirect verification of AVHRR LST estimation has been developed and tested. As it was mentioned in section 3, it relies on the dependencies connecting the LST, air temperature and NDVI values and their statistics for the investigated area, allowing for calculation of near-surface air temperature from estimated LST and NDVI values and then comparing it with air temperature data from another source, here, from the NWP system.

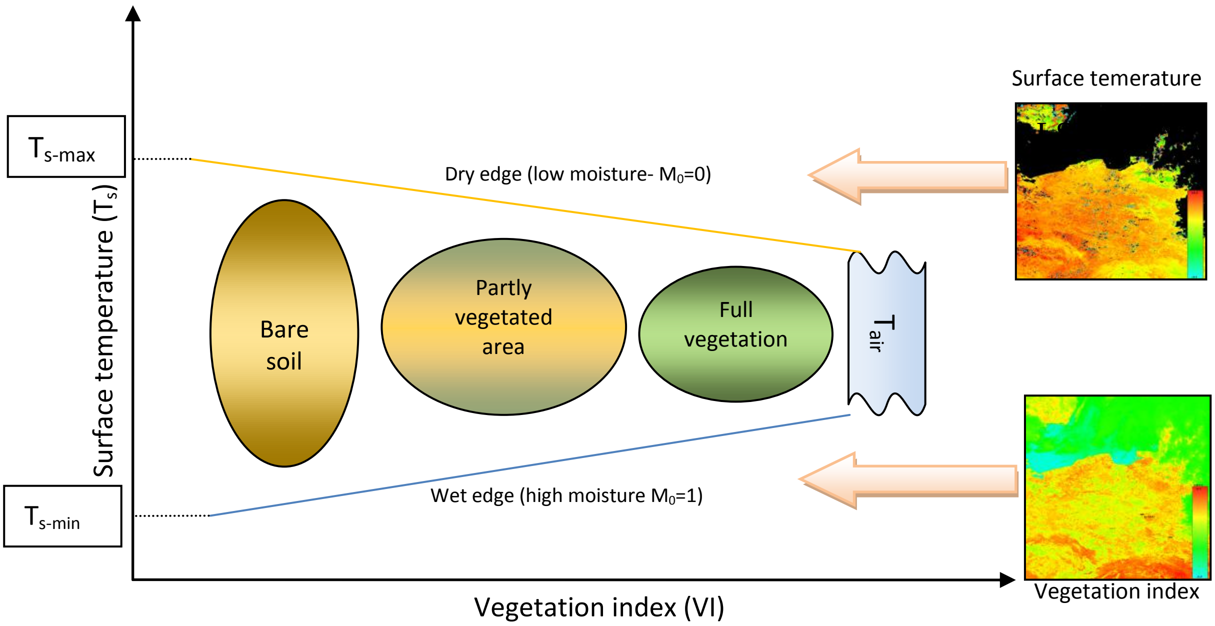

Fig.4. Summary of the key descriptors and physical interpretations of the T_s/VI feature space. LST is denoted as T_s. M_0 denotes the surface soil moisture.

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Air temperature can be estimated with utilisation of statistical features of NDVI and LST distribution for larger dataset, e.g., for the whole scene or some its part, and using relations between NDVI and temperature values, which may be observed on the 2^D plot in the NDVI-LST feature space. The schematic view presenting the typical attributes of the NDVI-LST feature space for a scene covering both wet and dry vegetated areas, is presented in Fig. 4 taken from [7].

Typically, the region within which the NDVI and LST values are distributed, is limited from the bottom side by so-called “wet edge” line which may be expressed by the equation:

$$LST_{min} = a' + b' \cdot NDVI$$

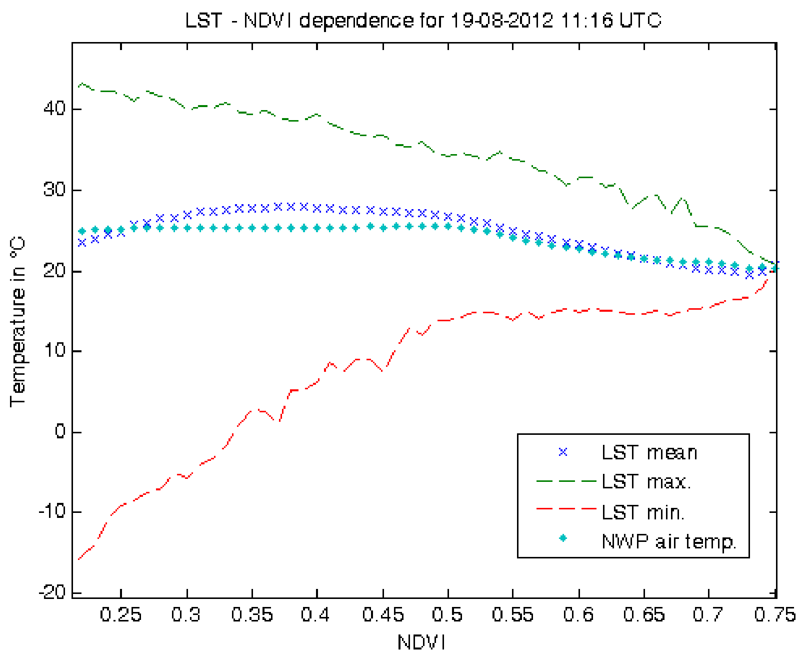
and is limited from the top side by so-called “dry edge” line which may be expressed by the equation:

$$LST_{max} = a + b \cdot NDVI \ ,$$

where *a*, *b*, *a'* and *b'* are coefficients in directional equations of a straight line.

For large NDVI, the "dry egde" and "wet edge" lines converge to one value (or approach to each other decreasing the difference between LST_{min} and LST_{max}) which may be treated as an estimation of T_{air} (at least for areas of large NDVI).

The authors proposed and tested the approach to T_{air} estimation (which may then be compared with reference data) using the features of (NDVI, LST) values distribution. To illustrate the idea, the large part of AVHRR scene has been taken and LST minimum, maximum and mean values for subsets of pixels characterised by similar (belonging to small range) NDVI value have been calculated. The results for two scenes not differing much in time are presented in Fig. 5. The mean value of T_{air} provided by the WeatherSense system has been also plotted as a function of NDVI. The estimation of LST has been performed using the algorithm described in section 2.



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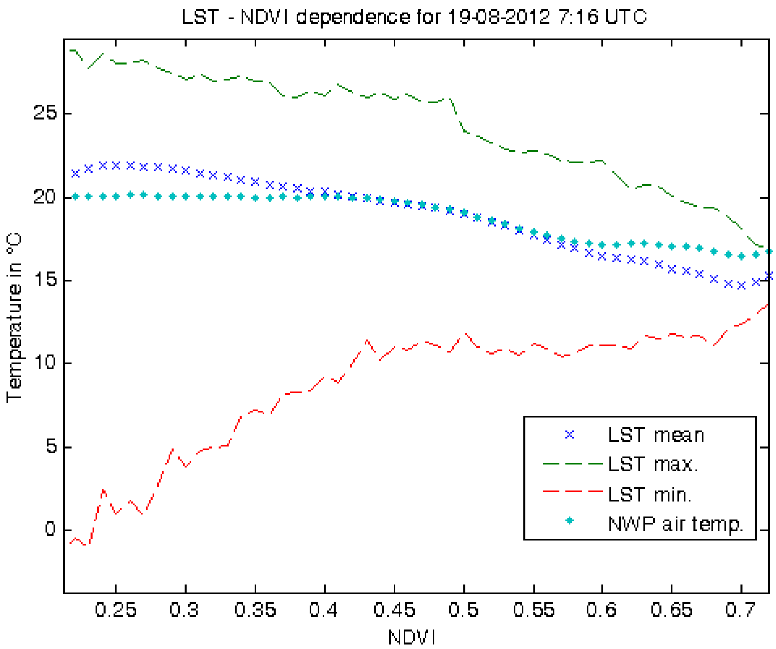

Fig.5. Plots of LST minimum, maximum and mean values for subsets of pixels characterised by similar (i.e. belonging to small range) NDVI value, as a function of NDVI, for large part of a scene. Poland, 19th August 2012, two time moments during the morning.

The expected convergence of minimum and maximum LST values (corresponding to the most wet and the most dry areas respectively) with increase of NDVI is visible in both cases. The LST convergence value is in general in agreement with the NWP mean value. What is more, the comparison of mean LST with mean T_{air} values from NWP reveals very high consistence of data from these two sources. As it is visible, for most of data the difference between mean LST and mean T_{air} value is on the level between 1 and 3 °C. It allows to treat mean LST as an estimator of mean T_{air} for local area of NDVI not varying too much. This indirectly proves the good performance of the investigated AVHRR LST estimation algorithm. The appearance of smaller mean LST values than T_{air} values for NDVI close to 0.2 on the lower picture may be explained by the effect of thin cirrus cloud contamination described in section 5. The discrepancy between mean LST and T_{air} for high NDVI (about 0.7) may be explained by relatively small number of pixels of this NDVI value in the scene.

5. CONCLUSIONS

The estimation of LST by satellite measurements using several algorithms was described along with the proposed indirect verification approach based on the utilisation of statistics and dependencies of LST, NDVI and near-surface air temperature values. The distributions of air temperature obtained by the WRF numerical weather prediction system were used as reference data what allowed for the significant increase of the reference dataset size in comparison with using only *in-situ* measurements data. The obtained verification results are promising and they preliminarily prove the appropriateness of the applied LST estimation algorithms. The authors realise that the applied verification procedure has strong limitations, as it relates only the mean LST and T_{air} values, not the current at-pixel values. Therefore the other approach, e.g. one of mentioned at the beginning of section 2, is needed for more reliable verification of LST estimation from satellite imagery. Also, it is difficult to

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estimate the actual accuracy of the proposed AVHRR LST estimation algorithms. The authors predict than it may be on the level of 5 °C for the algorithm described in section 1 and on the level of 3 °C for the algorithm described in section 2.

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