ESTIMATION OF ATMOSPHERIC STATIC STABILITY WITH THE USE OF SATELLITE REMOTE SENSING

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ABSTRACT

The potential use of MODIS/AQUA data products in assessing atmospheric instability is examined. These images can provide temperature and humidity profiles for twenty isobaric levels. In this study 8 radiosonde stations from Southeastern Europe are utilized. For the examination of atmospheric instability three instability indices, commonly used in Meteorology, are computed based on radiosonde data and satellite derived atmospheric profile products. The indices examined in this study are: Boyden Index, K Index and Lifted Index. Firstly, the indices are computed from the midday radiosonde data for the months April and May of 2003. Then the same indices are estimated based on the required thermodynamic parameters as provided by the MODIS/AQUA archives. All selected images are georeferenced. From the above analysis it seems that the three satellite derived instability indices are well correlated with those derived with radiosonde data. This can allow the spatial interpolation of the indices in areas where previously no available data existed. It seems that this kind of remotely sensed data can make a very good simulation to the assessment of instability, contributing significantly to forecasting.

ΕΚΤΙΜΗΣΗ ΤΗΣ ΑΤΜΟΣΦΑΙΡΙΚΗΣ ΣΤΑΤΙΚΗΣ ΕΥΣΤΑΘΕΙΑΣ ΜΕ ΧΡΗΣΗ ΔΟΡΥΦΟΡΙΚΗΣ ΤΗΛΕΠΙΣΚΟΠΗΣ

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ΠΕΡΙΛΗΨΗ

Στην παρούσα εργασία εξετάζεται το δυναμικό των δορυφορικών δεδομένων MODIS/AQUA στον προσδιορισμό της ατμοσφαιρικής στατικής ευστάθειας. Από τα δεδομένα MODIS, προκύπτουν οι κατακόρυφες κατανομές θερμοκρασίας και υγρασίας και μέσα αυτών υπολογίζονται τρεις ευρέως χρησιμοποιούμενοι δείκτες αστάθειας, οι Boyden, K και Lifted, για την περιοχή της ΝΑ Ευρώπης με ακρίβεια 5x5km. Οι ίδιοι δείκτες υπολογίζονται για συγκεκριμένα σημεία, με βάση δεδομένα ραδιοβολίσεων από 8 Μετεωρολογικούς σταθμούς στην περιοχή μελέτης, για τους μήνες Απρίλιο και Μάιο 2003. Τα αποτελέσματα της ανάλυσης των δορυφορικών δεδομένων για τα σημεία που αντιστοιχούν στις συντεταγμένες των σταθμών συγκρίνονται με τα αποτελέσματα του υπολογισμού των δεικτών από τις ραδιοβολίσεις. Παρατηρείται πολύ ικανοποιητική συσχέτιση. Το γεγονός αυτό, δίνει τη δυνατότητα προσδιορισμού των δεικτών αστάθειας σε κάθε σημείο της περιοχής μελέτης με πολύ καλή χωρική ακρίβεια, συμβάλλοντας στη βελτίωση της ακρίβειας πρόγνωσης των καταιγιών.
1. INTRODUCTION

Atmospheric instability is a major determinant in warm period weather. An unstable atmosphere tends to fire up showers and thunderstorms while a stable atmosphere usually brings sunny skies. Thunderstorms are formed within three distinct stages: the developing-stage, the mature-stage and the dissipation stage. Generally, for forecasting tools, it is useful to estimate when the first stage is going to come about.

The estimation of atmospheric instability is usually based on instability indices (Showalter, 1953; Galway, 1956; George, 1960; Rackliff, 1962; Boyden, 1963; Jefferson, 1963a, b; Litynska et al., 1976; Stone, 1984; Michalopoulou and Jacovides, 1987; Peppler, 1988; Peppler and Lamb, 1989; Reuter and Aktary, 1993). Instability indices have been developed and used to aid both research and operational forecasting of severe weather and thunderstorms by quantifying the thermodynamic instability with the aid of radiosonde data. A thorough comparison of instability indices for the Greek peninsula has been carried out in the near past (Dalezios and Papamanolis, 1991). All these studies suffer from data deficiency and reliability that comes from the sparse existing radiosonde network. In general, it should be noticed that all the instability indices describe the potential of convection but the referred threshold values are not definite, but may vary with geographical location, season and synoptic situation (Michalopoulou and Jacovides, 1987; Dalezios and Papamanolis, 1991; Haklander and Van Delden, 2003). Three Instability indices are used in this study: The Boyden Index (Boyden, 1963), the K-index (George, 1960) and the Lifted Index (Galway, 1956).

The knowledge of the vertical distribution of temperature and water vapour requires radiosonde measurements; as a result few measurements are available at the global scale (Elliot and Gaffen, 1991). Therefore, radiosonde-derived instability indices are limited by the coarse spacing of the point-source data, too large to pinpoint local regions of probable convection. Earth Observation (EO) data is capable of supporting atmospheric instability studies, because, satellites can provide spatial–temporal distributions of various atmospheric parameters. A great deal of progress has been made in EO over the last years. This has been driven largely by the realisation that the observation of global climate processes requires the type of spatial and temporal coverage only afforded by remote sensing. Atmospheric temperature and humidity profile data at high spatial resolution from MODIS (Moderate resolution Imaging Spectrometer) onboard EOS-AM1 (Terra) and EOS-PM1 (Aqua) platforms provide a wealth of new information on atmospheric structure in clear skies. Therefore, the MODIS instrument offers an opportunity to characterize gradients of atmospheric stability at high resolution and greater coverage.

The objective of this study was to examine the potential of satellite remote sensing in assessing atmospheric instability at regional and local levels in order to improve severe weather forecasting. Atmospheric instability was assessed by calculating the spatial distribution of three instability indices throughout the Southeast Europe. MODIS (Aqua) data were used to estimate atmospheric temperature, humidity and geopotential height profiles. Following, a grid with 5x5km cells covering the study area was used to calculate the value of each instability index in each grid cell. Finally, radiosonde derived instability indices, at eight meteorological stations within the study area, were used for validation.

1.1. About MODIS

MODIS is a key instrument aiming at providing comprehensive monitoring of land, ocean and atmosphere at moderate resolution, with high temporal coverage and capabilities to provide global estimates of land cover characteristics, surface temperature, albedo, vegetation indices, snow cover, ocean color, chlorophyll fluorescence etc. MODIS views the entire Earth’s surface every 1 to 2 days, acquiring data in 36 spectral channels, with instantaneous fields-of-view (IFOVs) of 250m (visible channels 1–2), 500m (near infrared channels 3–7) and 1km (infrared channels 8–36). The high radiometric accuracy measurements can be used by the scientific community to detect subtle signatures of climate change, study regional and global phenomena.

While MODIS is not a sounding instrument, it does have many of the spectral bands found on the High resolution Infrared Radiation Sounder (HIRS) currently in service on the polar orbiting NOAA TIROS Operational Vertical Sounder (TOVS). Thus, it is possible to
generate profiles of temperature and moisture as well as total column estimates of precipitable water vapor, ozone, and atmospheric stability from the MODIS infrared radiance measurements. The atmospheric profile product (MOD07_L2) developed by MODIS Science Team, NASA, consists of several parameters: total-ozone burden, atmospheric stability, temperature and moisture profiles, and atmospheric water vapor. All of these parameters are produced day and night for Level 2 at 5x5km pixel resolution when at least 9 FOVs are cloud free. Table 1 (Menzel et al., 2002) shows the MODIS spectral bands that are used in MYD07_L2 product for temperature and moisture profiles. Atmospheric-stability estimates can be derived from the MODIS temperature and moisture retrievals contained in MYD07_L2 product (NASA, 2003). Layer temperature and moisture values are used to estimate the temperature lapse rate of the lower troposphere and the low-level moisture concentration.

Table 1. MODIS spectral bands that are used in MYD07_L2 product for temperature and moisture profiles

<table>
<thead>
<tr>
<th>Primary Atmospheric Application</th>
<th>Band</th>
<th>Bandwidth µm (at 50% response)</th>
<th>Typical T(K)</th>
<th>Radiance at Typical T(K) (Wm⁻²sr⁻¹µm⁻¹)</th>
<th>NE(δT(K)) Specification</th>
<th>NE(δT(K)) Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature profile</td>
<td>24</td>
<td>4.433-4.498</td>
<td>250</td>
<td>0.17</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>4.482-4.549</td>
<td>275</td>
<td>0.59</td>
<td>0.25</td>
<td>0.10</td>
</tr>
<tr>
<td>Moisture profile</td>
<td>27</td>
<td>6.535-6.895</td>
<td>240</td>
<td>1.16</td>
<td>0.25</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>7.175-7.475</td>
<td>250</td>
<td>2.18</td>
<td>0.25</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>8.400-8.700</td>
<td>300</td>
<td>9.58</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Temperature profile</td>
<td>33</td>
<td>13.185-13.485</td>
<td>260</td>
<td>4.52</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>13.485-13.785</td>
<td>250</td>
<td>3.76</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>13.785-14.085</td>
<td>240</td>
<td>3.11</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>14.085-14.385</td>
<td>220</td>
<td>2.08</td>
<td>0.35</td>
<td>0.35</td>
</tr>
</tbody>
</table>

* NE(δT) = Noise-equivalent temperature difference

2. DATA AND METHODOLOGY

The data used MODIS/AQUA images, acquired on April and May 2003 over the broader area of Southeast Europe and daily radiosonde measurements of the same period, from eight meteorological stations within the study area. The location of each station is presented in Figure 1. All radiosonde data have been provided from the archives of University of Wyoming, USA (2003). MODIS images have been preprocessed in NASA-Goddard Space Flight Center (GSFC) producing the Level-2 MODIS Atmospheric Profile Product MYD07_L2. It consists of 30 gridded parameters related to atmospheric stability, atmospheric temperature and moisture profiles, total atmospheric water vapour, and total ozone. Atmospheric temperature, moisture and geopotential height profiles are produced at 20 atmospheric pressure levels (hPa): 5, 10, 20, 30, 50, 70, 100, 150, 200, 250, 300, 400, 500, 620, 700, 780, 850, 920, 950, and 1000. MYD07_L2 product contains data that has a spatial resolution of 5x5km (at nadir). MYD07_L2 output grid is 270 5-km pixels in width and 406 5-km pixels in length. Cloud Mask derived from the 1km MYD35_L2 MODIS product, is remapped to 5km resolution, by using only the center 1Km pixel in the 5x5 pixel retrieval array. Finally, infrared Meteosat images were used for the same period for validation.

Figure 1. Map of the study area, showing the location of each radiosonde station.
As it has already been mentioned, three instability indices are examined in this study: The K Index (KI), the Boyden Index and the Lifted Index.

The K Index (KI) represents the thunderstorm potential as a function of vertical temperature lapse rate at 850hPa temperature and 500hPa temperature, low level moisture content at 850hPa dewpoint, and the depth of the moist layer at 700hPa dewpoint (George, 1960). The index is given by the formula:

\[
KI = (T_{850hPa} - T_{500hPa}) + T_{d850hPa} - (T_{700hPa} - T_{d700hPa})
\]  

(1)

KI increases with decreasing static stability between 850 and 500 hPa, increasing moisture at 850hPa, and increasing relative humidity at 700hPa. The KI can be used as an indicator of convection but not as a discriminator of severe versus non-severe convection. Values of KI>20 generally represents a convective environment capable of producing scattered thunderstorm activity, while KI>30 represents an atmospheric potential for numerous thunderstorms to occur (Haklander and Van Delden, 2003). Table 2 presents an indication of the possibility of thunderstorms forming (Sturtevant, 1994):

<table>
<thead>
<tr>
<th>KI</th>
<th>Thunderstorm Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 15</td>
<td>0%</td>
</tr>
<tr>
<td>16 to 19</td>
<td>20% unlikely</td>
</tr>
<tr>
<td>20 to 25</td>
<td>35% isolated thunderstorm</td>
</tr>
<tr>
<td>26 to 29</td>
<td>50% widely scattered thunderstorms</td>
</tr>
<tr>
<td>30 to 35</td>
<td>85% numerous thunderstorms</td>
</tr>
<tr>
<td>&gt;36</td>
<td>100% chance for thunderstorms</td>
</tr>
</tbody>
</table>

The Boyden Index (BI) is given by the formula (Boyden, 1963):

\[
BI = Z_{700hPa} - T_{500hPa} - 200
\]

(2)

where Z is the difference between the geopotential height between 700hPa and 1000hPa, in other words the 1000 – 700hPa thickness and T is the atmospheric temperature at 700hPa. As it seems, unlike most instability indices, the BI does not take moisture into account. It merely describes the vertical temperature profile between 1000 and 700hPa and was originally designed to assess thunderstorm risk at frontal passages over the UK. Generally, a threshold value of 94 is indicative of thunderstorm activity in the troposphere (Boyden, 1963).

The Lifted Index (LI) is defined as the difference between the observed temperature at 500hPa and the temperature of a parcel (T_{parcel}) after it has been lifted pseudo-adiabatically from its original level to 500hPa. It is given by the formula (Galway, 1956):

\[
LI = T_{500hPa} - T_{parcel}
\]

(3)

Therefore, it focuses on the latent instability of an air sample. The Lifted Index can be calculated for any sample of air at pressure P > 500hPa if the ambient temperature at 500hPa is known. It should be noted that the Lifted Index depends on the properties of the particular air parcel that was used. Originally, Galway (1956) developed the Lifted Index for the prediction of latent instability during afternoon hours by using the forecast maximum temperature. Lifted Index is not a measured quantity but is only a parameter derived theoretically. Following other studies on this subject Lifted Index is used as an observed static index instead of a forecast index (Peppler and Lamb, 1989; Huntrieser et al., 1997). Generally there is no specific threshold value that correlates LI to thunderstorm severity. However, a negative lifted index indicates an unstable atmosphere, so the larger the negative number, the more unstable the atmosphere is.
 Firstly, the three instability indices were computed from the midday radiosonde data for April and May 2003. Results for each of the eight meteorological stations (Figure 1) will be later compared with MODIS derived instability indices. For this reason, a grid with 5x5km cells, covering the study area was used. All indices were computed from radiosonde data at each cell corresponded to each meteorological station. Following, MYD07_L2 data for May 2003 were analyzed. These data were handled as multiple-layer satellite images. The original MYD07_L2 files were processed using ERDAS Imagine commercial software. Each MYD07_L2 image was geometrically corrected using Ground Control Points and it was registered to the 5x5km cell grid. The nearest neighbor resampling method was used.

Since MYD07_L2 images were registered to the used grid, temperature, humidity and geopotential height profiles were computed for each grid cell using ERDAS Imagine GIS capabilities. Following, K, Boyden and Lifted Indices were computed for each cell using the Equations (1), (2) and (3), respectively. The spatial distribution of each instability index over the area of concern was defined by its values in each grid cell. Therefore, the detection of localized areas with specific (high or low, compared with a given threshold) values of each instability index was straightforward. Thus, by using the predefined threshold values for each index, atmospheric instability was estimated in local level within the study area. Moreover, the MODIS derived indices at the grid cells corresponded to the locations of the eight meteorological stations (Figure 1) were compared with the respective radiosonde derived indices.

Given that the spatial resolution of MYD07_L2 product is 5x5km, the potential for thunderstorm activity, which is directly related to the atmospheric instability, can be calculated in each grid cell. It is therefore obvious the important role of MODIS in thunderstorm studies, since it has the potential to increase the spatial accuracy of forecasting. MODIS contributes also in atmospheric monitoring, since it can provides accurate spatial distributions of atmospheric parameters, like temperature and humidity. The latter is easily understood from the present study, because there are about 40000 grid cells within the study area, therefore 40000 MODIS derived temperature, humidity and geopotential height profiles, whereas there are only 8 radiosonde derived profiles.

The usability of MODIS in detecting instability in areas where previously no available data existed is presented in this study by analyzing a case study of May 16, 2003, when convective activity observed over northern Greece. In this case, convective clouds detected in Meteosat images are qualitatively compared to the spatial distribution of the MODIS derived instability indices.

3. RESULTS AND DISCUSSION

It is clear that if we were to estimate the potential for thunderstorm activity from the three different instability types only we should first consider low-level latent instability—especially near the surface—then potential instability and finally conditional instability. Nonetheless, we stress that these three instability types are certainly not independent. It seems that because of the manifold of the Balkan Peninsula, air masses have many and different geographical sources. This fact jointly with the great elevation differences lead to a very complex response of the instability indices. An ideal index should, presumably, delineate space-time domains inside which the forecast events occur and outside of which the forecast events do not occur. Generally, an index is a necessary ingredient but is not by itself sufficient. The fact is that an index can focus attention on places and times where the forecast events are likely to occur.

Scatter diagrams of radiosonde and MODIS derived indices BI, KI and LI and the corresponding correlation coefficients are given in Figure 2 for the locations of the eight meteorological stations and for the period April-May 2003. The number of pairs varies from 100 to 170 depending on the availability of the data. LI presents the best performance with a correlation coefficient 0.49 which is reflected in the relatively narrow pattern of the scatter diagram. The correlations of BI and KI are lower and comparable (0.37) but statistically significant at 99% level. KI, however, performs better at higher values (> 20) which generally represent a convective environment.
Figures 3 show comparison between the radiosonde and satellite derived indices for three stations where both data types were simultaneously available. Attention was given in each case because in some cases there was data loss. Izmir station was selected for depicting the K-Index (figure 3a), Athens station for Lifted index (figure 3b) and Heraklion station for Boyden Index (figure 3c). As it seems from Figure 3 there is a considerable consistency between radiosonde and MODIS based values.

Figure 2. Scatter diagrams of observed and satellite retrieved Boyden Index, K Index and Lifted Index for April and May 2003.

Figure 3. Comparison of temporal evolution between radiosonde and MODIS derived (a) K Index (Izmir), (b) Lifted Index (Athens) and (c) Boyden Index (Heraklion) for May 2003.

3.1. The case of 16 May 2003

The synoptic situation on 16 May, at 00:00 UTC is presented in Figure 4. The surface analysis shows that there is no system affecting Greece. The combination of a low-pressure system located over Turkey with an anticyclone covering central Europe generates moderate northerly winds over north Greece. A weak cold advection is evident over Greece at the 850hPa surface whilst the 500hPa analysis indicates a zonal flow over the eastern Mediterranean Sea. The heating in continental Greece during the day with combination to the weak middle and upper level cold air advection caused thermodynamic instability and therefore favourable conditions for isolated convective activity.

For this example it is desirable to estimate the instability at continental Greece. Figure 5 shows the spatial distribution of the three indices over the study area for May 16, 2003, as it has
been derived from MODIS measurements. Indices values in each 5x5km grid cell have been computed and therefore atmospheric instability in each cell was estimated. Atmospheric instability is higher in cells presented in dark grey shades. White cells correspond to unavailable data due to the presence of clouds. The K index generally is an instability index useful in predicting non-frontal thunderstorm situations since it takes into account temperature and moisture conditions at three different isobaric layers. On the other hand Lifted Index depends on the properties of the particular air parcel that was used (Haklander and Van Delden, 2003). Even though the Boyden Index does not allow by definition for any moisture (does not consider moisture at all), it serves surprisingly well as a dichotomous thunderstorm predictor (Haklander and Van Delden, 2003). Thereby, there is an imperative need for additional indices for assessing the instability (with the synergy of them). A comparison of Figures 5a, 5b and 5c yields that Boyden index overestimates atmospheric instability, but there are many locations (i.e. Northern Greece, Thessaly, Viotia, Attica and Northern Peloponnesus,) where all indices indicate strong atmospheric instability. There is no conventional way to estimate upper air temperature and moisture for these areas, except the interpolation between adjacent stations. The only alternative way to estimate atmospheric instability for these areas is the MODIS/AQUA data.

Figure 4. Synoptic analysis for 16 May 2003 (0000UTC) (a) Mean sea-level pressure map (b) 850hPa height analysis map and (c) 500hPa height analysis map.

Figure 5. Spatial distribution of (a) Boyden Index, (b) K Index and (c) Lifted Index at 1120UTC, 16 May 2003. (d) Composed Meteosat satellite image expressing the frequency (%) of the detected convective clouds over Greece for the period of 1100-2200UTC, 16 May 2003.
Convective activity can be monitored with a high temporal and spatial resolution using infrared satellite data from geostationary satellites. Cloud top temperatures less than 230K have been considered as indicators of convective activity by many researchers (Mamoudou and Gruber, 2000). Figure 5d is a composed Meteosat satellite image presenting the frequency (%) of occurrence of clouds, defined as individual bodies delimited by the isotherm of 230K in the infrared channel, for the period 1100-2200UTC, May 16, 2003, when convective clouds were observed over Greece. Comparison with the instability indices maps (Figure 5a,b,c) shows that the instability detected by MODIS over Greece resulted in convective clouds developed over Halkidiki, Thessalonica, central northern Greece, northern Thessaly, parts of Viotia and northern Peloponnesus. There areas, however, where no convective clouds have been observed, as the major part of Thessaly and Minor Asia coastline. This discrepancy does not question the validity of the satellite method for instability estimation since instability indices may be considered only as indicators of an environment which is favorable in triggering convection.

4. CONCLUSIONS

In this case study, three instability indices (Boyden, K and Lifted) were calculated at a grid cell 5x5km derived from MODIS/AQUA data. Temperature, humidity and geopotential height profiles were derived from MODIS measurements at twenty isobaric levels. Moreover, radiosonde derived instability indices were calculated at cells corresponded to eight meteorological stations within the study area. MODIS derived instability indices were compared with radiosonde derived indices and a very good agreement was found. This allows the spatial interpolation of the indices in areas where previously no available data existed. It seems that this kind of remotely sensed data can make a very good simulation to the assessment of instability, contributing significantly to forecasting, because local scale events can be detected and monitored using MODIS data, whereas it is very difficult to detect such events using radiosonde data, especially if they do not occur within the neighbourhood of any radiosonde station. In general, MODIS has two major advantages in atmospheric instability assessment: it is more accurate than radiosondes since a radiosonde may be drifted on its vertical movement due to the variable wind profile and it can be a useful tool for estimating instability at every region with 5x5km pixel resolution where radiosonde data is not available.

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