TOWARDS MONITORING OF REGIONAL ATMOSPHERIC INSTABILITY THROUGH MODIS/AQUA IMAGES

N. Chrysoulakis¹, M. Spiliotopoulos², C. Domenikiotis³ and N. Dalezios³

¹ Foundation for Research and Technology–Hellas, Institute of Applied and Computational Mathematics, Heraklion, Crete, Greece, e-mail: zedd2@iacm.forth.gr, Tel: +302810393762.
² Department of Management of Environment and Natural Resources, University of Thessaly, Fitokou Str, Volos, Greece, e-mail: spilioto@uth.gr, Tel: +302421093256.
³ Department of Agriculture Animal Production and Aquatic Environment, University of Thessaly, Fitokou Str, Volos, Greece, email: cdomen@uth.gr, dalezios@uth.gr, Tel: +302421093261,+302421093252.

ABSTRACT

The potential of MODIS (Moderate Resolution Imaging Spectroradiometer) data products in assessing atmospheric instability is examined. MODIS provides temperature and humidity profiles for twenty isobaric levels. In this study eight radiosonde stations from Southeastern Europe are used. 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 May 2003. Then, the same indices are estimated based on the required thermodynamic parameters as provided by the MODIS archives. From the above analysis it seems that the three satellite derived instability indices are well correlated with those derived from radiosondes. 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 local level weather forecasting.

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 first stage is the cumulus-stage. Certain atmospheric conditions, such as moisture in the unstable air as well as a considerable lifting force, create atmospheric instability. This unstable air is always warm and moist. Surface heating, which acts as the primary lifting force, heats the air near the ground. The air, in turn, becomes buoyant and begins to raise, otherwise known as an updraft. These updrafts, warm, moist swells of rising air, eventually begin to cool, and, as it happens, the air begins to condense into a
cumulus cloud. As the warm air within the cloud continues to rise, it eventually cools and condenses. Finally, condensation releases heat into the cloud, warming the air. This, in turn, causes it to rise adiabatically. This process works to form a towering cumulus cloud. The second stage in thunderstorm development is the mature-stage, where the condensed solid and liquid water, within the upper-levels of the cloud, begins to fall, causing a downdraft. The last stage of the thunderstorm, the dissipation-stage, occurs when finally the strength of the updrafts diminish while the downdrafts remain. Generally, for forecasting tools, it is useful to estimate when the first stage is going to come about. Therefore, there is a need to estimate where and when atmospheric instability occurs.

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 vapor 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. The current sophisticated, versatile and multi-purpose payloads exemplified by the NASA EOS program (Kaufman et al., 1998). The EOS program is designed to monitor the interchanges of energy, moisture and carbon, land use, and ocean and atmospheric circulation for at least eighteen years. The EOS era began with the launch of the EOS-AM1 (Terra) and EOS-PM1 (Aqua) platforms. MODIS (Moderate resolution Imaging Spectrometer) is a key instrument onboard both platforms 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 such as albedo (Justice et al., 1998). As it has been already mentioned, atmospheric instability measurements are predictors of convective-cloud formation and precipitation. Atmospheric temperature and humidity profile data at high spatial resolution from MODIS 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.

2 ABOUT MODIS

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 (channels 1–2), 500m (channels 3–7) and 1 km (channels 8–36). The performance of the MODIS instrument may be affected by any potential small change in the optical status of the instrument caused in the rapid launch process and in the long period of post-launch instrument outgases in the orbit (Sobrino et al., 2003). The instrument is able to estimate surface temperature with a spatial resolution of 1 km. Furthermore, it is equipped with channels to measure the ocean colour from 415 to 653 nm (1km resolution), determine chlorophyll fluorescence at the water surface and measure the chlorophyll-A amount. Besides that, it is capable of obtaining information on vegetation and land properties, land cover type, vegetation indices and snow cover and reflectance (500 m resolution). MODIS can obtain cloud cover with 500 m resolution at day and 1000 m at night, furthermore it determines cloud and aerosol properties, biomass burning, global distribution of atmospheric stability and total rain water. Visible, shortwave infrared, and near infrared measurements are only made during the daytime, while radiances for the thermal infrared region (bands 20-25, 27-36) are measured continuously. 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 MODIS Science Team, NASA, has developed 44 products (MOD01-MOD44). The MODIS Atmospheric Profile product (MOD07) consists of several parameters: they are 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 5 x 5 km pixel resolution when at least 9 FOVs are cloud free. There are two MODIS Atmosphere Profile data product files: MOD07_L2, containing data collected from the Terra platform; and MYD07_L2 (used in this study), containing data collected from the Aqua platform. Table 1 (Menzel et al., 2002) shows the MODIS spectral bands that are used in MYD07_L2 product.

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. The objective of this study was to examine the potential of satellite remote sensing in assessing atmospheric instability. Monitoring the atmospheric instability at regional and local levels level can improve severe weather forecasting. Atmospheric instability was assessed by calculating the spatial distribution of three instability indices throughout the Southeastern Europe.
MODIS/AQUA data were used to estimate atmospheric temperature, humidity and geopotential height profiles. Following, a grid with 5 x 5 Km 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.

Table 1. MODIS spectral bands that are used in MYD07 L2 product.

<table>
<thead>
<tr>
<th>Primary Atmospheric Application</th>
<th>Band</th>
<th>Bandwidth μm (at 50% response)</th>
<th>$T_{typical}$ (K)</th>
<th>Radiance at $T_{typical}$ (Wm$^{-2}$sr$^{-1}$μm$^{-1}$)</th>
<th>NEΔT(K) Specification</th>
<th>NEΔT(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>Ozone</td>
<td>30</td>
<td>9.580-9.880</td>
<td>250</td>
<td>3.69</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>31</td>
<td>10.780-11.280</td>
<td>300</td>
<td>9.55</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>Temperature profile</td>
<td>32</td>
<td>11.770-12.270</td>
<td>300</td>
<td>8.94</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>13.185-13.485</td>
<td>260</td>
<td>4.52</td>
<td>0.25</td>
<td>0.20</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>

3 DATA AND METHODOLOGY

The data used MODIS/AQUA images, acquired on May 2003 over the broader area of Southeastern 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 vapor, 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, 1000. MYD07_L2 product contains data that has a spatial resolution of 5 x 5 Km (at nadir). Each MYD07_L2 image file covers a five-minute time interval, which means the MYD07_L2 output grid is 270 5-km pixels in width and 406 5-km pixels in length for nine consecutive granules. Every tenth granule has an output grid size of 270 by 408 pixels. MYD07_L2 image files are stored in Hierarchical Data Format (HDF-EOS). Cloud Mask derived from the 1 Km MYD35_L2 MODIS product, is remapped to 5 Km resolution, by using only the center 1 Km pixel in the 5x5 pixel retrieval array.
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:

$$KI = (T_{850\text{hPa}} - T_{500\text{hPa}}) + T_{d\text{850hPa}} - (T_{700\text{hPa}} - T_{d\text{700hPa}})$$

(1)

KI increases with decreasing static stability between 850 and 500 hPa, increasing moisture at 850 hPa, and increasing relative humidity at 700 hPa. 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):
where, \( Z \) is the difference between the geopotential height between 700 hPa and 1000 hPa, in other words the 1000 – 700 hPa thickness and \( T \) is the atmospheric temperature at 700 hPa. Thickness in synoptic meteorology is the vertical depth, measured in geometric or geopotential units, of a layer in the atmosphere bounded by surfaces of two different values of the same physical quantity, usually constant-pressure surfaces. 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 700 hPa 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 500 hPa and the temperature of a parcel (\( T_{\text{parcel}} \)) after it has been lifted pseudo-adiabatically from its original level to 500 hPa. It is given by the formula (Galway, 1956):

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

Therefore, it focuses on the latent instability of an air sample. The Lifted Index can be calculated for any sample of air at pressure \( P > 500 \) hPa if the ambient temperature at 500 hPa 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 (e.g. 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 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 5 x 5 Km 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 HDF files were processed using ERDAS Imagine commercial software. Each MYD07_L2 HDF image was geometrically corrected using Ground Control Points and it was registered to the 5 x 5 Km cell grid. The nearest neighbor resampling method was used. Afterwards, temperature records were separated from humidity and geopotential height records and each atmospheric parameter was stored in a separate multiple-layer image. Thus, each “temperature” image was stored as a 20-layer file which was consisted of temperature retrievals for the study area, with spatial resolution of 5 Km, for the following atmospheric pressure levels (hPa): 5, 10, 20, 30, 50, 70, 100, 150, 200, 250, 300, 400, 500, 620, 700, 780, 850, 920, 950, 1000. In other words, these types of images were representations of three dimensional spatial distributions of temperature over the study area.
area. Humidity and geopotential height measurements were accordingly handled by creating the respective three dimensional representations.

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. A very good accordance was observed, reflecting the high potential of MODIS instrument in estimating the spatial distribution of atmospheric instability.

Given that the spatial resolution of MYD07_L2 product is 5 x 5 Km, 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 local scale events is presented in this study by analyzing a case study of May 16, 2003, when a thunderstorm (with 11mm of rain) was reported in Kastoria Airport (40.27N, 21.17 E) located in Northwestern Greece (Fig.1). In this case, none of the meteorological stations within the study area gave an instability alarm. Although, the MODIS derived instability indices at the grid cell corresponded to Kastoria Airport indicated a strong instability potential just before the thunderstorm occurrence.

4 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.
Figure 2 shows the spatial distribution of Boyden Index over the study area for May 12, 2003, as it has been derived from MODIS measurements. Boyden values in each 5 x 5 Km grid cell, have been computed and therefore atmospheric instability in each cell was estimated. Atmospheric instability is higher in cells presented in orange or brown. The spatial distributions of K and Lifted indices are presented in Figures 3 and 4, respectively. 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). Thereby, there is an imperative need for additional indices for assessing the instability (with the synergy of them). A comparison of Figures 2, 3 and 4 yields that Boyden index overestimates atmospheric instability, but there are many locations (i.e. Central Peloponese, Greece) where all indices indicate strong atmospheric instability. In fact even though the Boyden Index does not account 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).

Figures 5-7 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 5), Athens station for Lifted index (figure 6) and Heraklion index for Boyden Index (figure 7). As it seems from figures 5, 6 and 7 there is a considerable consistency between radiosonde and MODIS based values.
Figure 3. Spatial distribution of K Index over the study area.

Figure 4. Spatial distribution of Lifted Index over the study area.

Figure 5. Comparison between radiosonde and MODIS derived K Index (Izmir).
4.1 The case of 16 May 2003

On 16 May 2003, at 12:00 UTC, no particular instability activities were recorded at Greek radiosonde stations. For example at Thessaloniki the BI was 97.7 (> 94), LI was -1.58 (< 0), and KI was 35.8 (> 20) where the thresholds referred to critical values for characterizing stability/instability. At the same day and time at Brindisi the value 94 is extracted for BI (threshold=94), LI was 6.27 (> 0), and KI was 20.5 (> 20). For this example it is desirable to estimate the instability at Northwestern Greece. There is no conventional way to estimate upper air temperature and moisture for this region, except the interpolation between adjacent stations. Kastoria airport is located near in the middle of the distance between Thessaloniki and Brindisi. It could be assumed that if there were no indicative instability recorded at these stations, the same would be true for Kastoria. However, Kastoria Airport has recorded at this day 11mm of rain (with a thunderstorm). This indicates that the only alternative way to estimate atmospheric instability for Kastoria region is the MODIS/AQUA data. The region of Kastoria Airport from MODIS/AQUA gives BI= 95.44 (> 94), LI = 0 (threshold 0) and KI= 21.70 (> 20). The combination of the three indices’ values shows that this day can be
considered as unstable. (The considerable fact is that MODIS/AQUA data can yield to a true estimation which maybe was impossible to achieve with conventional methodologies.)

5 CONCLUSIONS

In this case study, three instability indices (Boyden, K and Lifted) were calculated at a grid cell 5x5 km 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 5x5 km pixel resolution where radiosonde data is not available.

Acknowledgements. The authors thank ….. , University of Wyoming, USA for the provided atmospheric soundings data through the website and University of Albany, USA for the ground observation data.

REFERENCES


