Applications of Meteosat data for the characterization of atmospheric instability

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Abstract. The European geostationary Meteosat Second Generation satellite (MSG) offers a variety of channels to use for various purposes, including nowcasting of convection. A number of applications have also been developed to make use of these new capabilities for nowcasting, especially for the detection and prediction of severe weather. The MSG infrared channel selection makes it possible to assess the air stability in pre-convective, i.e. still cloud free conditions. Instability indices typically combine measures of the thermal and the moisture properties and often only use a small quantity of vertical profile parameters. MSG based temperature and moisture retrievals are used for the derivation of stability indices, which are a part of the MSG meteorological products derived centrally at EUMETSAT and disseminated via EUMETCast. Such indices are of empirical nature, are often only applicable to certain geographic regions and their thresholds are dependent on seasonal variation, but they can assess the likelihood of convection within the next few hours, thus providing a warning lead of about 6 to 9 hours. Examples are shown to demonstrate the generally good warning potential of the derived instability field, together with a more quantitative verification analysis provided by the South African Weather Service. The paper will at the end provide a brief outlook on other potential benefits of MSG in nowcasting the different stages of convection, which is a very active area of current research.

Keywords: convection, nowcasting. MSG, GII, Convection Working Group

1. Introduction

Since 2002, EUMETSAT operates the advanced generation of geostationary imager, the SEVIRI (Spinning Enhanced Visible and Infared Imager) instrument onboard the Meteosat Second Generation (MSG) satellites. Two of these satellites have so far been launched and are operated under their operational names Meteosat-8 and Meteosat-9. The SEVIRI instrument is specially designed to provide nowcasting information by scanning the Earth's disk every 15 minutes in 11 spectral channels; an additional high spatial resolution broadband visible channel is also available. The MSG system is described in detail by Schmetz et al. (2002). The channel selection is based on the well-known AVHRR imagers of polar orbiters, together with additional channels to allow for the detection of specific surface, cloud, and atmospheric features, like identification of fog, dust storms, fires, air masses, and cloud microphysical parameters. Table 1 gives a summary of the MSG channels.

Table 1. MSG SEVIRI spectral channels.

Channel	Centre wavelength (μm)	Range (μm)	Sampling distance at subsatellite point (km)
VIS0.6	0.635	0.56 – 0.71	3
VIS0.8	0.81	0.74 – 0.88	3
NIR1.6	1.60	1.50 – 1.78	3
IR3.9	3.92	3.48 – 4.36	3
WV6.2	6.25	5.35 – 7.15	3
WV7.3	7.35	6.85 – 7.85	3
IR8.7	8.70	8.30 – 9.10	3
IR9.7	9.66	9.38 – 9.94	3
IR10.8	10.80	9.80 – 11.80	3
IR12.0	12.00	11.00 – 13.00	3
IR13.4	13.40	12.40 – 14.40	3
HRV	(broadband)	0.5 – 0.9	1

Since the launch of MSG, a number of applications have been developed to make use of these new capabilities for nowcasting, especially for the detection and prediction of severe weather. As a correct and timely prediction of convective processes – especially their severe stages –is an important area for nowcasting, many MSG-based observations of clouds and their temporal evolution have been used in both qualitative and quantitative aspects to identify the most severe parts of a convective cloud system, as e.g. described by Setvák and Rabin (2005) and Rosenfeld and Lensky (2006). In addition, the MSG infrared channel selection, makes it also possible to assess the air stability in pre-convective, i.e. still cloud free, conditions. Air instability indices as single-valued numbers have a long history of evaluating the convective potential of the atmosphere. A comprehensive summary can be found in Peppler (1988). They are usually used such that some convective potential can be inferred if the respective index exceeds a certain threshold. Traditionally derived from radiosonde profiles, such indices typically combine measures of the thermal and the moisture properties and often only use a small quantity of vertical profile parameters. Due to the limited spectral resolution, MSG based temperature and moisture retrievals will only have coarse vertical resolution, which is, however, fully sufficient for the derivation of instability indices, as they typically utilize a lower quantity of observations within a vertical profile. Details can be found in Peppler (1988) and Fuhrhop et al. (2000).

It should be noted that such indices are of highly empirical nature and are often only applicable to certain geographic regions. Also, the above mentioned threshold criteria may change between regions and seasons. Such indices can only assess the likelihood of convection within the next few hours, and should still be seen in combination with other triggering lifting mechanisms.

A satellite derived map of instability parameters has the advantage of a very good spatial and temporal resolution – e.g. 3 km pixel size and 15 min repeat cycle for MSG - which is a significant improvement over the sparse locations of radiosonde stations with at best two daily soundings.

2. Methodology

Atmospheric instability parameters are routinely extracted from the MSG imagery within the Meteorological Products Extraction Facility (MPEF) at EUMETSAT and are disseminated via EUMETCast. Since these parameters are provided on a global scale (i.e. the entire MSG field of view), the product has been termed Global Instability Index (GII). From the algorithm side, the GII parameters can be produced on any spatial scale ranging from a single MSG pixel and as averages over n x n pixels. The current operational setup is such that the product is derived as 3 x 3 (formerly 15 x 15) pixel averages, i.e. over an area of approximately 10 x 10 km^2 (formerly 50 x 50 km^2).

The MPEF GII includes two instability indices, the Lifted Index and the K-index, as well as the total precipitable water content TPW as a further airmass analysis parameter. The instability indices are defined as (Equation 1):

$$\begin{aligned} \text{K-index} &= [T(850ha)-T(500hPa)] - [T(700hPa)-TD(700hPa)] + TD(850hPa) \\ \text{Lifted Index} &= T(500hPa) - T(\text{near surface, lifted to } 500hPa) \\ \text{TPW} &= \text{Vertically integrated water vapour concentration} \end{aligned} \quad (1)$$

where T is the air temperature and TD the dew point temperature at the indicated levels.

The atmospheric layer is potentially unstable for a negative Lifted Index, and a K-index of more than 20°C is a good indicator of unstable conditions.

The GII retrieval is a “physical” method, i.e. it tries to infer an actual temperature and humidity profile from the satellite observed radiances in a given set of channels. The air mass parameters are then derived from this profile. The physical retrieval is often referred to as an optimal estimation or 1DVar type of retrieval. An inversion algorithm is applied to find an atmospheric profile which best reproduces the observations, as outlined by Rodgers (1976), Hayden (1988) or Ma et al. (1999). In general, this is a multi-solution problem – a wide range of temperature and moisture profiles and of surface conditions may exist that produce identical satellite measurements in such limited number of spectral channels. A suitable "background" or "first guess" profile is used as a constraint to the solution. As this retrieval problem has an iterative solution, the first guess is fed to the iteration scheme as an initial proposal for a solution. The original first guess is then modified in a controlled manner until its radiative properties (the simulated radiances at the top of the atmosphere for the MSG channels) fit the satellite observations. A typical first guess field is a short-term forecast. Major limitations of this method are the high computational effort and the fact that the retrieved profiles tend to retain features of the first guess, especially coupled with the low-spectral resolution.

In its application to the SEVIRI instrument onboard MSG, the physical retrieval uses six channels: the three longwave window channels IR8.7, IR10.8, and IR12.0, the two water vapour channels WV6.2 and WV7.3, and the CO_2 channel IR13.4. The background profile is taken from the ECMWF (European Centre of Medium range Weather Forecast) global model forecasts, which are provided on a 1° latitude/longitude grid.

A full description of the GII retrieval technique is provided by König and de Coning (2009).

Figure 1 shows a visualization of the operational product, which is derived for every 15 minute MSG repeat cycle, for the full disk up to a satellite viewing angle of 70°. It should be noted that a GII value is assigned to a processing box if 50% or more of the box is cloud free, where the cloud information is taken from the MSG Cloud Mask product, described by Lutz (2007).

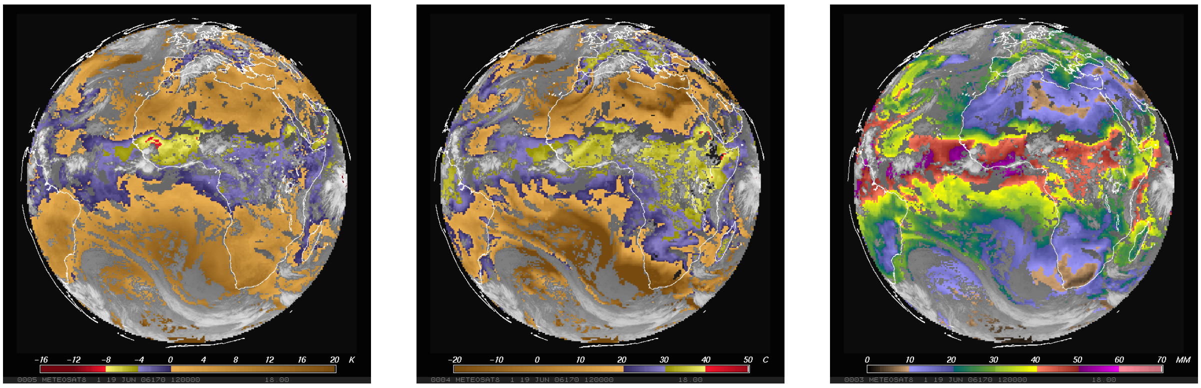

Figure 1. Example of the Lifted Index (left), the K-index (centre) and the total precipitable water (right) as provided by the operational GII product for the entire MSG disk (19 June 2006, 1200 UTC). Detected clouds, where a GII retrieval is not possible, are overlaid in various grey scales to roughly indicate the cloud top temperature.

3. Results and Discussion

A typical GII "use case" is shown in Figure 2: This is taken from the operational display at the South African Weather Service (SAWS) of the disseminated GII product. Each box in this visualization represents a colour coded view of the at that time 15 x 15 MSG pixel GII product, in this case the K-index, together with the precise K-index value written in the box. Again, cloudy areas are shaded according to the corresponding IR10.8 image to give some visual impression of the cloud situation. Usually K-index values exceeding 20° C are indicative of strong convective potential, and K > 40° C indicate a highly likely chance of convective storm occurrence (see e.g. Peppler (1988)). In this case, K-index values of around 40° C were reached just east of the Pretoria/Johannesburg region (in red), where a few hours later a convective storm occurred (Figure 3).

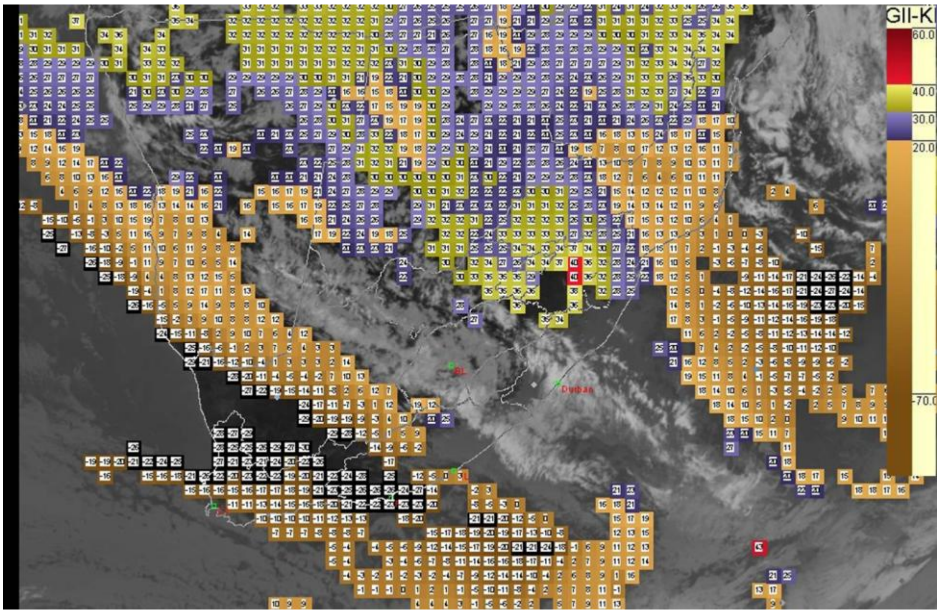

Figure 2. K-Index (values of increasing instability are shown in blue to yellow to red) over South Africa, for 26 October 2006, 0800 UTC. This product shows the operational GII product which was locally received and processed in South Africa. (Picture courtesy of South African Weather Service).

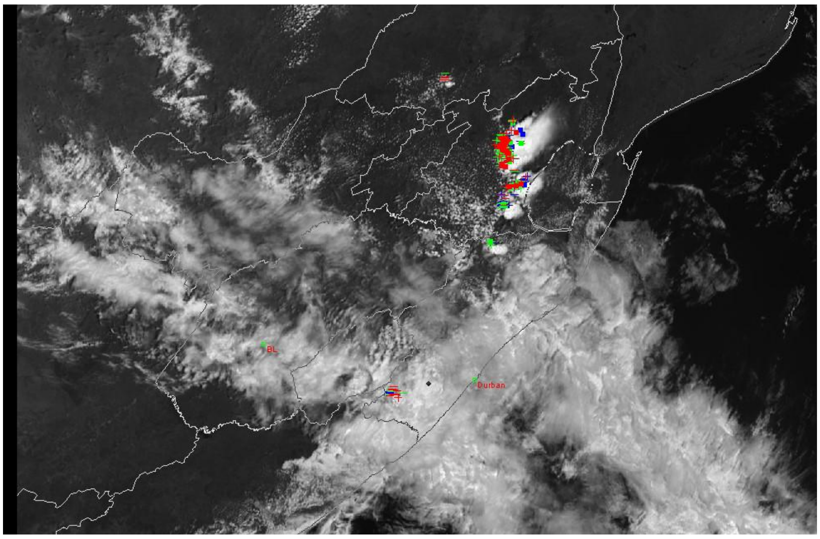

Figure 3. Image of the MSG HRV channel for 26 October 2006, 1030 UTC: A strong storm has developed over the area of the previously high (near 40 °C) K values. Lightning reports are overlaid. The lightning strokes on the display are either "-" or "+" signs, indicating the polarity of the stroke. Colours red, green blue indicate when the lightning strokes occurred (red: within last 5 min, blue: 5-10 min ago, green: 10-15 min ago). (Picture courtesy of South African Weather Service).

SAWS also conducted an objective long-term verification of the GII nowcast potential by comparing the GII product to occurrence of lightning in the following hours. In 2005, SAWS commissioned a National Lightning Detection Network using nineteen Vaisala lightning detection sensors which provide real-time information on lightning activity associated with convective activity (Gill, 2006). Although instability indices like the K-index or the Lifted Index are not specifically designed to provide a measure of the likelihood of lightning, this comparison is nevertheless useful from a user's perspective: Forecasters are interested to know whether areas of strong instability, as derived from the satellite, indeed experience strong convective processes within the next hours, which are at least strong enough to produce cloud-to-ground lightning. Collocation of the lightning and the GII data were done within a 0.5° x 0.5° latitude/longitude box. The GII results were seen as a correct forecast of severe convection if

- More than 5 lightning strokes occurred in the box between 1100 and 1800 UTC

and

- The K-index exceeded 35° C between 0400 and 0800 UTC (for the K-index verification)
- The Lifted Index was less than –5 K between 0400 and 0800 UTC (for the Lifted Index verification).

Results for a specific convective season are listed in Table 2.

Table 2. GII verification results for the convective season 2006/2007 over South Africa.

GII Index	Probability of Detection POD	False Alarm Rate FAR	Accuracy (Equation 2)
K-index	0.77	0.33	0.70
Lifted Index	0.84	0.36	0.68

"Accuracy" is here defined as

$$Accuracy = \frac{CorrectHits + CorrectNonHits}{Total} \quad (2)$$

where *CorrectHits* is the number of correctly forecasted storm occurrences according to the above index and lightning criteria, and *CorrectNonHits* is the number of correctly forecasted no-storm conditions, i.e. where none of the above criteria were met.

In summary, we see fairly high values for POD, together with low False Alarm Rates over South Africa, bearing in mind that this verification was only done against the occurrence of lightning, i.e. storms that did not product lightning are even excluded.

4. Conclusions and Outlook

The current EUMETSAT GII product is aimed at helping forecasters to turn their attention to a certain region, which they can then monitor more closely with other means like satellite imagery and radar data over the next several hours. The MSG GII data have proven to provide lead times between 6 and 9 hours. Within a fully developed convective nowcasting system, the GII can provide a first level of warning, usually covering a larger area. When time progresses, other satellite derived parameters like cloud coverage, cloud top cooling and growth rates, together with the development of microphysical parameters, will then help to further indicate the exact location of the most severe parts of the clouds, as e.g. described by Mecikalksi and Bedka (2006) or Rosenfeld and Lensky (2006). These satellite derived convective products are shown to still have some lead time over radar observations, i.e. are even useful when good radar coverage is available, but will be especially beneficial for areas without any radar information. The recently established EUMETSAT Convection Working Group (http://convection.satreponline.org) focuses on satellite based research and forecasting applications, encompassing the pre-convective conditions as e.g. described by the GII product together with all stages of cloud evolution. Active areas of research, which will hopefully transfer to operational applications, are the convective initiation phase, its relation to cloud microphysical parameters, and the mature convective cloud phase, especially the signature of overshooting tops. Examples are shown in Figure 4, Figure 5 and Figure 6.

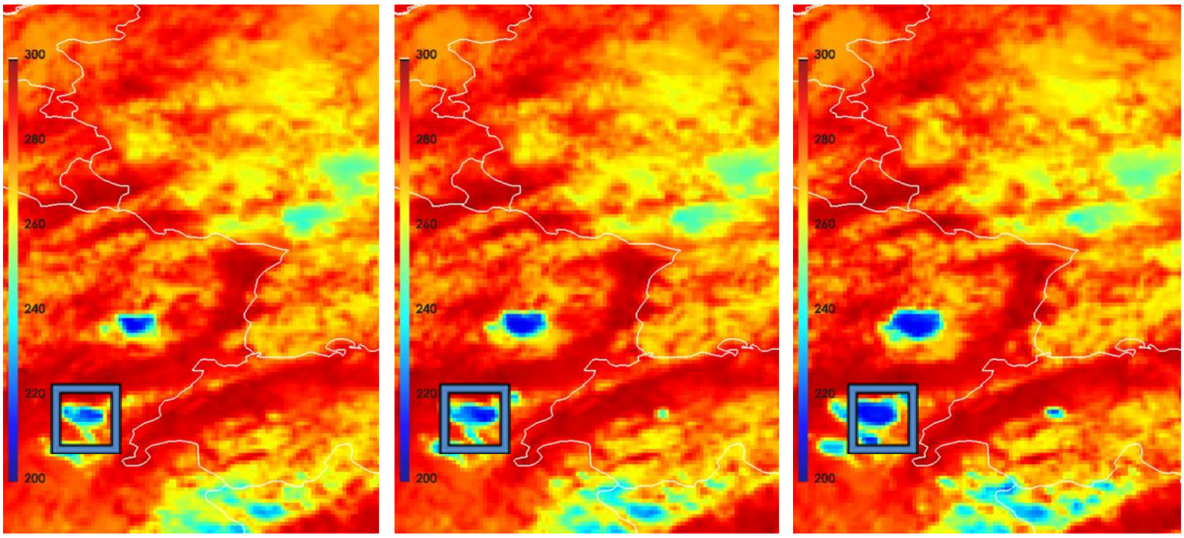

Figure 4. Concept of a the Convective Intiation product: automatic detection of rapidly growing Cu cloud (box), as shown in this sequence of 15 min IR10.8 MSG imagery over Northeastern France (05 June 2007, 1145, 1200, 1215 UTC from left to right).

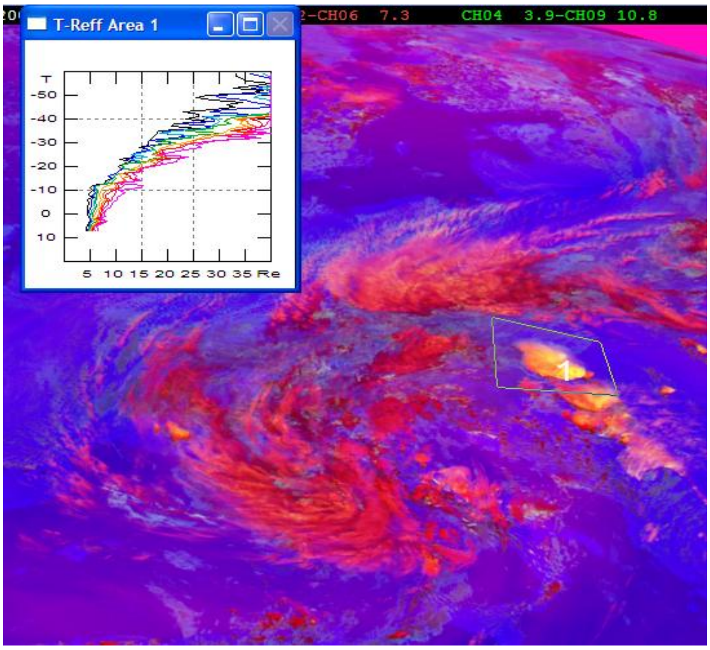

Figure 5: Convection RGB colour composite shows areas of strong updrafts in bright yellow over Hungary. The quantitative analysis of cloud top microphysics in the indicated area shows a severe storm signature. This cloud later produced a tornado. (20 May 2008, 1300 UTC). The method is described in detail in Lensky and Rosenfeld (2008).

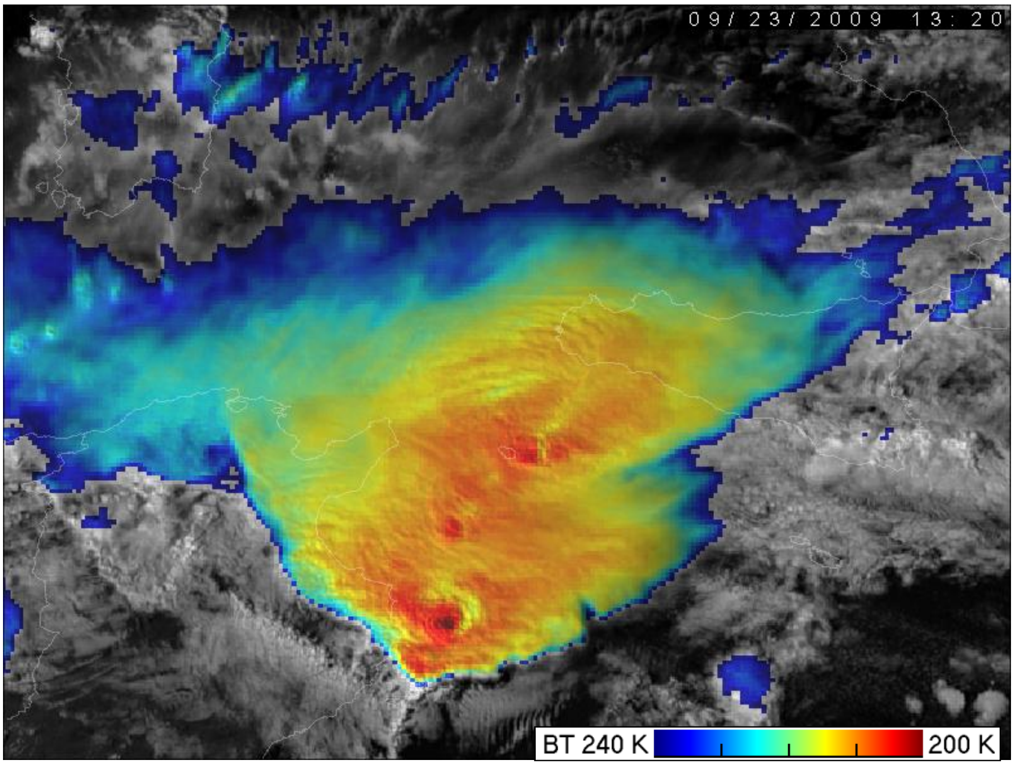

Figure 6. Overshooting tops can be well visualized through a combination of the 1 km HRV channel (providing small scale texture information) and the IR10.8 channel (providing cloud top temperatures). A specific IR10.8 colour enhancement highlights the coldest tops in red. Overshooting tops coincide with severe weather on the ground (hail, wind gusts). An automatic detection scheme is proposed by Bedka et al. (2010).

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