WATER VAPOUR IMAGERY ANALYSIS IN 7.3µ/6.2µ
FOR DIAGNOSING THERMO-DYNAMIC CONTEXT OF
INTENSE CONVECTION

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ABSTRACT

The paper presents results, which may add to the understanding of mid- to upper-level dynamics responsible for development of intense convection as seen by satellite images in water vapour channels. In addition to the well-known upper-level dynamic structures visible in the 6.2 µm imagery, typical moisture features associated with low- to mid-level thermodynamic conditions can be distinguished in 7.3 µm images. For example in 73% of the most severe convective cases over southern part of Europe in 2004 and 2005, a mid-level jet (MLJ) is present at about 600 hPa in a south-westerly flow and appears as a specific boundary on the 7.3 µm image grey shades. In these cases, the distinct MLJ boundary in 7.3 µm image grey shades is also a signature for presence of a low-level baroclinic zone–related to the MLJ origin–that plays a critical role in destabilisation of the atmosphere for intense convection.

The use of 7.3 µm and 6.2 µm images in diagnosis of convection over Europe and the Mediterranean area is stressed. This approach is based on imagery analysis for identifying dynamic features responsible for initiation and maintenance of intense convection. The WV images are used to distinguish types of coupling between low-/mid-level conditions and upper-level dynamics associated with intense convective developments.

1. INTRODUCTION

In Europe, strong convective systems are amongst the most dangerous atmospheric phenomena, generating catastrophic flash floods or strong gusts. As discussed in Doswell (1987), the problem of forecasting convection involves more than large-scale processes, but there does seem to be clear observational evidence for an association between large-scale systems and moist deep convection. Intense and durable convection requires low-level warm and moist air supply (moist and warm air is the necessary “fuel” of convective systems), and generally lifting of the air by upper-level divergence to get instability. Usually, the thermodynamic environment favourable for intense convection is created via large-scale processes before the mesoscale low-level thermodynamic factors act to initiate convection.

The numerical weather prediction has been improved these last years, even regarding convective systems. Nowadays very often the models, such as the Limited Area Fine Mesh, do well in predicting the intensity of the convective storms, but they are not perfect and their abilities still have to be validated in operational forecasting environment. The job of the forecaster is to recognize those situations when the numerical guidance should not be followed. To do this, the main tool of the forecaster is the satellite imagery. Meteorological satellites set out around the Earth allow a complete surveillance of the atmosphere. Satellite imagery gives a global and consistent view of the organization of atmospheric features on large areas. A great amount of data is now available thanks to the new channels of the new generation of the European Geostationary Satellite System which consists of the
Meteosat Second Generation –MSG– and the images updating rate has increased with a cycle of repetition of 15 minutes. Such tools help the human forecaster in the early recognition of high-impact weather phenomena. Water vapour channels provide with valuable information about the moisture and dynamical properties of the troposphere. Sequences of WV images of the geostationary satellites may be used in detecting favourable environment and understanding how the significant factors for the development of intense convection interact.

Different authors have stressed on specific meso- and large-scale features related to the environment of severe convection that are seen on water vapour (WV) imagery in 6.3/6.7 µm channels (e.g. Ellrod, 1990; Thiao et al., 1993; Georgiev, 2003; Krennert and Zwatz-Meise, 2003). Images in 6.2 µm (equally 6.3 µm and 6.7 µm) channel are efficiently used for upper level diagnosis (Weldon and Holmes, 1991; Santurette and Georgiev, 2005). Although radiances in 7.3 µm WV channel measured by geostationary satellites contain information for low- to mid-level moisture distribution, there is still a lack of reports for using these data in synoptic scale analyses.

Chapter 2 and 3 focus on the use of 6.2 µm and 7.3 µm WV imagery analysis of jet streams and related elements of atmospheric dynamics that are responsible for initiation and maintenance of intense convection over the Mediterranean area. Chapter 2 shows the use of 7.3 µm channel imagery to identify specific low-level thermodynamical conditions favourable for strong convection.

### 2. UPPER-LEVEL FORCING OF INTENSE CONVECTION

At mid-latitudes, severe convection often develops under the influence of upper-level forcing for ascending motions. Using potential vorticity (PV) concepts, upper-level forcing can be seen thanks to low areas of 1.5 PVU surface (the so-called “dynamic tropopause”) moving down to mid- or low levels. Such a low tropopause area (moving in a baroclinic environment) is referred to as a “tropopause dynamic anomaly”. One of the most effective ways for using 6.2 µm (equally 6.3 µm and 6.7 µm) WV imagery for operational weather forecasting is to observe the structure and behaviour of dynamical features as jet streams (Weldon and Holmes, 1991) and tropopause dynamic anomalies seen in potential vorticity fields (Santurette and Georgiev, 2005).

Fig. 1 shows a 6-hour sequence of images in 6.2 µm in the case of severe convection on 5 August 2005 that produced a catastrophic flash-floods over Bulgaria. The active upper-level dynamics shows marked signatures on the water vapour imagery for PV anomaly advection into a cut off circulation over the Mediterranean seen by the image sequence. In particular, there are two features linked to the tropopause perturbations:

- Jet streaks and areas of strong geopotential gradient of the tropopause height; these are generally characterized by strong dark/bright gradients on water vapour imagery, with the dry air (dark area) on the polar side, as seen in Fig.1a, blue arrow.
- Tropopause dynamic anomalies are quasi-conservative structures well seen as minima (or troughs) of the 1.5 PVU surface height. They are well seen as moving dark zones on the WV imagery, that is seen in Fig. 1a (blue arrow) at the polar side of the jet (red wind arrows), Figs 1b, 1c 1e and 1f.

The diffluent pattern of the 1.5 PVU surface height at the exit region of the upper-level jet represents upper-level divergence and therefore ascent ahead of the PV anomaly. This moistens the upper troposphere and produces lightening of the WV image at the yellow arrow in Fig. 1c (moist wedge feature at the yellow arrow).

As seen in Fig. 1d, vertical motion is clearly associated with the intrusion of PV anomaly in the troposphere: notice the dipole ascent/descent (orange/blue in Figure 1d, respectively) just below the 1.5 PVU line (thick brown), as well as the deformation of the iso-θ surfaces (green contours). This imposes significant ascending motion ahead of the PV anomaly (and therefore favourable area for convection), and subsiding motion behind the anomaly.
Fig. 1. Upper-level PV anomaly. Meteosat-8 WV images in 6.2 µm overlaid by geopotential heights (brown) and wind vectors (red, only ≥ 70 kt) at the dynamical tropopause (1.5 PVU surface): Six hour sequence from 18 UTC on 4 August to 18 UTC on 5 August 2005 at (a), (b), (c), (e) and (f). (d) Vertical cross sections from ARPEGE analysis for 12 UTC of PV (brown) and vertical velocity (10-2 Pa/s, descending blue, ascending orange) and potential temperature (green) along the axis depicted in (e).

3. DYNAMIC MOISTURE SUPPLY INTO CONVECTION ENVIRONMENT

3.1 Moisture movements

A dynamic moisture supply into the convection environments can be easily seen by WV imagery as movements or surges of well shaped large scale bands of mid- to upper-level moisture. These features have been defined as WV plumes of light shades in 6.7 µm channel images (see Thiao et al., 1993) that usually are associated with the upper-level moist surges of subtropical/tropical origin over Mexico and United States. Such patterns are referred here to as WV movements in order to generalise the concept for both upper- and mid-level.

Fig. 2 illustrates the importance of 7.3 µm channel for detection large-scale horizontal transport of moist air at low- to mid-level. Fig. 2a shows the 7.3 µm image overlaid by the wind at 500 hPa equal or greater than 60 kt. A mid-level jet stream is visible as a specific moisture boundary in the WV image. The cross section of wind speed normal to the cross section (black contours) in Fig. 2b shows that advection of mid-level moist air is associated with a mid-level jet at the red arrow that is located just at the poleward side of the moist area (pink contours). The jet boundary at the WV image in Fig. 2a is formed between dry and moist mid-level air seen as dark and light image grey shade respectively. The zone of the maximum wind speed is located at the moist side of the jet stream boundary.
The 6.2 µm image in Fig. 2c for the same situation shows no significant moisture boundaries associated with the mid-level jet. Therefore, the 7.3 µm WV channel of MSG is a tool for observing moisture flow features (often associated with jet stream) at the middle troposphere. The studies show that the 7.3 µm channel is a useful tool to supplement the 6.2 µm channel: the generation and maintenance of conditions favourable for intense convection are present where the images of the two WV channels, seen simultaneously, show combination of specific WV movements between upper-level and low-level circulations.

3.2 Mid-level jet stream seen in 7.3 µ channel images

Blocking regime patterns of the atmospheric circulation over the south-west of Europe associated with increasing of south or south-westerly wind in its eastern flank over the Mediterranean Sea are favourable for intense convection. In 11 of the 15 most severe convective cases in the two years study period (2 in 2004 and 9 in 2005), a mid-level jet (MLJ) at about 700/600 hPa is present in the southwesterly-southerly flow as an important feature acting for the development of intense convection over the Mediterranean regions.

Fig. 3 shows images in the VW 7.3 µm and WV 6.2 µm channels overlaid by the wind vectors at 600 hPa isobaric surface in blue and 300 hPa in red as well as a vertical cross section of wet-bulb potential temperature, θw (red, °C) and wind speed (black, kt) normal to the axis shown in the images.

Fig. 3. Mid-level jet stream on 17 August 2005 at 0000 UTC. Meteosat–8 images in (a) 6.2 µm and (b) 7.3 µm channels overlaid by wind vectors at 300 hPa (red, only > 50 kt) and 600 hPa (blue, only > 35 kt). (c) Vertical cross-section of wet-bulb potential temperature (red, °C thick) and wind speed normal to the cross section plane (black, kt) along the axis shown in (b).
The two MSG WV channels are sensitive to water vapour content at different altitudes and may serve as tools for observing moisture and dynamic regimes in different layers of the troposphere. Concerning the problems of relating jet stream conditions to the patterns and features of satellite imagery the WV channels exhibit the following information content:

- The 6.2 imagery gives a clear view of the upper-level dynamics and may be used for upper air jet analysis. The moisture boundaries produced by upper-level dynamics are seen in the 6.2 µm radiance (e.g. at the position of the black arrow in Fig. 3a). These boundaries between dark and light image grey shades are transition zones between different upper-level wind regimes, depicted in Fig. 3c.
- The 7.3 µm channel radiation is able to detect moisture at lower level and the images in 7.3 µm channel can be interpreted for studying low- to mid-level humidity flow. In many cases a mid-level jet streams may be seen as a specific moisture boundary in 7.3 µm channel imagery, while it is not present or may be indistinct in the images of other channels of the MSG satellites.

A typical example of such a MLJ is illustrated in Fig. 3b. The MLJ is distinctly seen only in the 7.3 µm image along the moisture boundary indicated by the yellow arrow. The grey shade appearance of the images concerning the mid and low level moisture feature in the two channels is quite different. The MLJ in Fig. 3b is associated with the most distinct dry wedge in the 7.3 µm image that is not visible in the 6.2 µm image. Therefore, moist air is present in a layer located anywhere between 500 and 300 hPa that highly absorbs the 6.2 µm radiation and makes the mid-level differences of humidity invisible on the image in Fig. 3a.

The cross section in Fig. 3c is performed across the upper-level southwesterly jet streak and helps to understand the existence of MLJ. The appearance of this feature in 7.3 µm WV imagery is always associated with the existence of a low-level baroclinic zone: strong horizontal gradient of wet-bulb potential temperature (θw) as well as surface θ-w-anomaly beneath the MLJ, as seen in Fig. 3b. Let us consider the thermal wind relation

\[
\frac{g}{\theta_o} \frac{\partial \theta}{\partial x} = f \frac{\partial V_g}{\partial z} \tag{1}
\]

where \( \theta \) is potential temperature with reference value \( \theta_o \), \( g \) is the acceleration of gravity, \( f \) is the Coriolis parameter, \( V_g \) is the y-component of the geostrophic wind. Equation (1) tells that a strong horizontal θ-gradient creates a strong vertical geostrophic wind gradient. Therefore, the origin of the MLJ is likely due to the strengthening of a baroclinic zone (increasing θ-gradient at low- to mid-level) that is associated with a surface θ-anomaly, and the MLJ boundary seen in the 7.3 µm WV images is first the mark of this low level temperature context.

### 3.3 Dynamic wind-shift structure seen by 7.3µ and 6.2µ channel images

Imagery from the two MSG WV channels (6.2 µm and 7.3 µm) are complementary may be used jointly to indicate the differences in the circulations between upper-level, on one hand, and, on the other hand, low- to mid-level.

As regards to the problem of early diagnosis of upper-level forcing of convection, it is reasonable to use a concept defined as “dynamic (environmental) wind shift”. The dynamic wind shift can be a concept that describes the thermo-dynamic context of two flows of different origin intertwining in a deep layer from mid- to upper troposphere and seen in the imagery comparison of the two WV channels.

The two moisture boundaries at upper and mid-level are seen by the two WV images. They originate from two different flow branches (Figs 4a and 4b): The moisture boundary in the 6.2 µm channel is associated with an upper-level jet stream (the red wind vectors) coming from the Atlantic, while the moisture boundary in the 7.3 µm channel marks a mid-level jet (the blue wind vectors) associated with increasing of a south-westerly warm-moist flow. Such a situation of dynamic wind shift allowing
coupling of upper-level dynamic and cold air advection from the north with enhancement of warm air advection from the south in low-level is particularly favourable for strong convective development.

The exit region of a dynamic wind shift zone is the inflection zone of changing from a rightward to a leftward wind shear pattern of the two flows from mid- to upper-level, as seen in Fig. 4c. It is the zone of changing the direction of the two flows relative to each other:
- Upstream, turning the wind vector to the right and increasing wind speed with height is observed from mid- to upper level (at the white arrows).
- Downstream, turning the wind vector to the left and increasing wind speed with height is observed from mid- to upper level (at the black arrows).

Therefore the dynamic wind shift concept is important since it may allow better understanding the mechanism for convection initiation in the downstream area, that is: Strengthening upper level cold advection associated with leftward wind shear from mid- to upper level in the forward diffuulent side of a tropopause dynamic anomaly (at the black arrows in Fig. 4c) above pronounced low-level warm advection. Hence, the dynamic wind shift concept may help diagnosing mid- to upper tropospheric forcing of intense convection. The presence of a dynamic wind shift feature in the WV images may be considered as a precursor of organised convective activity in the downstream area. The required tools for diagnosis are coherent satellite imagery in two appropriate wavelengths (6.2 µm and 7.3 µm) to detect moisture dynamic features at two levels in the upper and middle troposphere.

Different configurations of the two jets and wind direction from mid- to upper-levels may be identify or anticipate following the positions and curvature of the corresponding moisture boundaries in the imagery. Two types of intense convective development have been observed depending on the curvature of the upper-level jet boundary as well as on the associated position of the mid- and upper-level jets. These are described in points 1) and 2) bellow.

1) **Sharp dynamic wind shift conditions.** These conditions meet in meridional circulation typically in cases of blocking regime. At first, the upper-level polar jet and corresponding moisture boundary in the 6.2 µm image starts to curve eastward after a meridional extension, while a southwesterly flow increases more in the south that generates warm advection and the appearance of a mi-level jet and associated moisture boundary in the 7.3 µm image. The upper-level jet sharply curves cyclonically moving eastward and progressively the two jets from different origin tend to come in phase; so on the WV images the two jets become connected downstream the inflection zone. In this upper-level evolution the upper-level forcing (potential vorticity) is significant. First two areas of convective activity develop separately, in association with the upper-level forcing and with the mid-level wind maximum features in relation to the associated warm advection (as with the case in Fig. 5).
- The northern convective system develops well correlated with the upper-level PV advection.
- The southern convective system develops related to upper-level cold advection above the low-level \( \theta_w \) anomaly, associated with mid-level jet. Latter one strong convective event can develop with the phasing between upper-level forcing and warm advection.

Fig. 5. WV images showing loose dynamic wind shift conditions on 9 September 2005 in (a) 6.2 \( \mu m \) at 0000 UTC, (b) 7.3 \( \mu m \) at 0000 UTC and (c) 7.3 \( \mu m \) at 0900 UTC.

2) Smooth dynamic wind shift conditions. These are cases of zonal upper level jet-stream where upper-level forcing (potential vorticity) is not a significant factor in intense convection initiation. The wind shift is weak and middle and upper-level jets tend to be closely connected, with associated WV boundaries quasi parallel. Two convective developments can initiate separately, and then they are merging and produce a more or less vigorous intense convective system, depending on the intensity of the warm advection. Fig. 6 shows a case of smooth dynamic wind shift conditions seen in the 6.2 \( \mu m \) and 7.3 \( \mu m \) images. First convective cells develop in association with the two moisture boundaries at the positions of the blue and red arrows in Figs 6a and 6b. Six hours later, the resulting intense convective system is closely related to the middle jet.

Fig. 6. WV images showing tight dynamic wind shift conditions on 4 October 2005 in (a) 6.2 \( \mu m \) at 0000 UTC, (b) 7.3 \( \mu m \) at 0000 UTC and (c) 7.3 \( \mu m \) at 0900 UTC.

4. CONCLUSION

The results of this study show that 6.2 and 7.3 \( \mu m \) WV imagery can indicate the impact of mid- to upper-level thermo-dynamic factors for development and maintenance of intense convection as follows:
- Tropopause dynamic anomalies responsible for upper-level forcing of vertical motion, and associated with upper-level cold air
- Large-scale moisture movements into the convection environment at middle and upper troposphere.
Jet-stream features at two tropospheric layers related to upper- and low-level baroclinic zones. Changes in structure and behaviour of the dynamic features seen in the WV imagery may be extrapolated to predict time changes in related thermo-dynamic and moisture conditions.

A relevant interpretation of images in 6.2 and 7.3 µm WV channels may increase the abilities of the forecasters to diagnose convection environment and thus to improve nowcasting of strong convective events.

5. REFERENCES


