Nowcasting severe convection in the Alpine region: the COALITION approach

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The purpose of the operationally oriented system named the Context and Scale Oriented Thunderstorm Satellite Predictors Development (COALITION) is automatically to detect severe thunderstorms early in their development and consequently help weather forecasters to increase lead times when issuing severe weather warnings. This new object-oriented system integrates data provided by different sources. Data from the *Meteosat* Second Generation Rapid Scan Service, weather radar and numerical weather prediction, as well as climatology, are utilized by the system. One of its primary purposes is to use all the best operationally available information about convective processes and to integrate it into a heuristic model. Furthermore the orographic forcing, which is often neglected in heuristic nowcasting models, is taken into account and included in the system as an additional convective triggering mechanism. This is particularly important for areas characterized by complex orography like the Alpine region. The COALITION algorithm merges evolving thunderstorm properties with selected predictors. The forecast evolution of the storm is the result of the interaction between convective signatures and surrounding storm environment. Eight different 'object-environment' interactions are analyzed in eight modules, providing ensemble nowcasts of thunderstorm attributes (satellite- and radar-based) for the following 60 min. All ensemble nowcasts are then combined through a weighting and thresholding scheme and the results are summarized into a single graphical map in order to facilitate user interpretation. The COALITION nowcast system has an update frequency of 5 min. The output highlights the cells having a high probability of severe thunderstorm development within the next 30 min. Verification statistics confirm that COALITION is able to nowcast the intensity of developing convective cells with sufficient skill up to a lead time of about 20 min.

Key Words: convection initiation; orographic triggering; nowcasting; Meteosat Second Generation.

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1. Introduction

This article describes the Context and Scale Oriented Thunderstorm Satellite Predictors Development (COALITION) system, an application providing cell-based 0–60 min nowcasts of thunderstorm severity. The application can be classified as belonging to a group of 'expert systems' and has been tested at MeteoSwiss since May 2012. Since May 2013, COALITION has been used operationally.

The basic physical mechanisms governing severe thunderstorms are relatively well understood (e.g. Rosenfeld and Woodley, 2000; Doswell, 2001). Usually, convection forecasts rely mainly on the analysis of temperature and humidity profiles of the troposphere or on derived indices, considering synoptic forcing as well. Low-level and mid-level moisture, thermodynamic instability and kinematic parameters like 3–6 km wind shear are key convective predictors for the Alpine region (Huntrieser *et al.*, 1996). Nevertheless, thunderstorms are governed by processes that range from the synoptic to the microphysical scale and are considered one of the most challenging and difficult weather phenomena to predict, especially in the context of operational weather forecasting. Moreover, they pose serious hazards to society and the economy. For example, it is estimated that on average between 50% and 80% of all weather-related damage in Switzerland is caused by strong thunderstorms (Hilker *et al.*, 2010). Hail, flash floods and severe wind gusts are the main causes.

Forecast verification is necessary for improving thunderstorm forecasting, yet observational networks resolve convective phenomena poorly at spatial and temporal scales down to 10–100 m and 1 min. Since the MeteoSwiss operational weather

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prediction model (COSMO2-CH: http://cosmo-model.org/) operates with lower resolution, deep convection is treated explicitly only on a 2.2 km horizontal scale and shallow convection is parametrized. Numerical weather predication (NWP) models face major limitations in resolving the dominant nonlinear processes and the characteristically strong gradients associated with thunderstorms adequately (e.g. Weisman, 1997; Bryan *et al.*, 2003; Kain *et al.*, 2008). Nowcasting and very short-range forecasting techniques still remain the most skilful forecasting tools for strong convection at adequate temporal and spatial resolution. Remote sensing observations and imagery can reveal specific features at various scales and stages of the thunderstorm life cycle to help improve nowcasting skill. Typically, the thunderstorm life cycle can be subdivided into five main steps (Mecikalski *et al.*, 2012).

(1) The pre-convective stage ('clear air'), where dry convective processes take place caused by solar heating of the boundary layer, low-level advection of warm air and/or low-level convergence.
(2) The convective initiation stage, where shallow moist convective processes take place and cloud formation begins (e.g. cumulus humilis and mediocris). Typically, in this phase, only warm cloud processes take place.
(3) The deep convection stage, where deep moist convection takes place, clouds develop to higher altitudes (e.g. towering cumulus) and cloud glaciation processes initiate.
(4) The mature stage, when the thunderstorm reaches its maximum intensity. Updraughts feed the storm with warm moist air and the downdraught begins to form due to the fallout of precipitation and subsequent evaporative cooling of low-level air, known as the cold pool.
(5) The dissipating stage, when the storm's cold pool stabilizes its environment and updraught formation consequently ceases as precipitation gradually tapers off.

For over half a century, a number of applications for diagnosing, monitoring and nowcasting convective storms have been developed. In the 1950s, the first attempts to track precipitation echoes and to extrapolate their future position were developed by analyzing consecutive radar images (Ligda, 1953). Fujita (1968) later developed a cloud-motion extrapolation technique using satellite imagery. Since the 1990s, many applications focusing mainly on the analysis of real-time radar products have been developed (e.g. Dixon and Wiener, 1993; Steinacker *et al.*, 2000; Mecklenburg *et al.*, 2000; Lang, 2001; Handwerker, 2002; Hering *et al.*, 2004; Kober and Tafferner, 2009). The main advantage of radar-based systems is that the most active part of the thunderstorm can be identified and analyzed using reflectivity information and the spatial and temporal resolution is generally superior to that of satellite imagery. Radar-based nowcasting techniques that detect, classify and extrapolate the position of convective cells (based on Lagrangian persistence) for the next 5–30 min usually perform well and satisfy the needs of operational forecasters. Nevertheless, radar-based techniques are unable to identify convection in its early stages (shallow convection and initial stages of deep convective processes) due to the lack of radar echo and are often not able to detect thunderstorm initiation and forecast thunderstorm motion before the storm approaches its mature stage.

Other supplemental data, such as satellite imagery, can help to improve thunderstorm detection during its earliest stages. In the past decade, many satellite-based applications or multisensor approaches have been developed to improve nowcasting at various stages of the thunderstorm's life cycle. Studies of the pre-convective environment (e.g. Martinez *et al.*, 2007; Koenig and De Coning, 2009; Goodman *et al.*, 2012), the convective initiation phase (e.g. Mecikalski and Bedka, 2006; Mecikalski *et al.*, 2008, 2010, 2013) and the mature stage (e.g. Setvák *et al.*, 2003; Rosenfeld and Woodley, 2000; Schulz *et al.*, 2009; Bedka *et al.*, 2010) have been presented. Some applications, in particular multisensor ones, have the ability to cover more than a single phase (e.g. Pierce *et al.*, 2000; Mueller *et al.*, 2003; Puca *et al.*, 2005; Zinner *et al.*, 2008; Autonés, 2012). These 'expert systems' have greatly improved our ability to detect the location of convective cells and to estimate their magnitudes at different stages.

Despite these recent improvements in nowcasting, thunderstorms are heavily affected by nonlinear and chaotic processes. For this reason, the convection intensity nowcasts remain notoriously challenging. Nowadays a satisfying modelling of the convective processes is still prohibitive. One of the reasons is that the predictability of these processes is partially limited intrinsically, because of their chaotic nature. Particularly in regions with complex orography like the Alps, heuristic nowcasting models, which are implicitly based on conservation assumptions like Lagrangian persistence, often fail (Mandapaka *et al.*, 2011). Mountain chains play a crucial role by driving the conditions at the boundary layer and convective features can be triggered, strengthened or weakened by orographic forcing (Barthlott *et al.*, 2005; Kottmeier *et al.*, 2008; Davolio *et al.*, 2009). Furthermore, the foothills of the Alpine chain represent one of the regions in Europe where thunderstorm initiation is most likely to happen (Collier and Lilley, 1994; Huntrieser *et al.*, 1996). Thus, nowcasting systems for regions with complex orography should account for orographic influence as well as a multiple-sensor technique.

COALITION is focused on the Alpine region in central Europe. Typically, the thunderstorms in this area are affected by strong orographic forcing coupled with moderate synoptic-scale forcing. According to a climatology study performed in the framework of the Convective and Orographically-induced Precipitation Study field experiment (COPS: Wulfmeyer *et al.*, 2008; Craig *et al.*, 2012) and other studies presented by further authors (e.g. Huntrieser *et al.*, 1996), thunderstorms over the Alpine chain can be classified into four different types.

(1) Airmass convection: characterized by isolated, stationary convection, generally in the case of uniform pressure conditions and missing upper-level forcing. Local instability, combined with low-level convergence or another triggering mechanism produced by solar radiation and thermal circulation, results in short-lived deep convective cells.
(2) Forced non-frontal convection: when synoptic-scale, upper-level disturbances cause widespread fast-moving convection. Surface fronts are missing, but often low-level flow convergence and orographic forcing are important for storm initiation.
(3) Forced prefrontal convection: found ahead of approaching cold fronts, where the low-level flow often converges along terrain-locked quasi-stationary prefrontal bands. Prefrontal convection is often characterized by strong, regenerating deep convective cells and echo training in specific areas within the pre-Alpine region. In these cases, rapidly moving convective cells tend to initiate over the western pre-Alpine and Jura areas. In some cases, if the environment is favourable, the convection may become organized into supercellular thunderstorms and/or mesoscale convective systems (MCS).
(4) Forced frontal convection: results from deep convective processes along surface cold fronts, dominated and driven by synoptic-scale forcing. In these cases the convective precipitation is often embedded within stratiform and orographic precipitation.

1.1. *Objectives*

The goal of COALITION is to provide early identification of potentially severe thunderstorms in terms of intensity and location by rapidly combining and modelling the available predictors. Through a similar 'ingredient-based' approach (Doswell *et al.*, 1996) and a new methodology derived from the physics of general dynamic systems, COALITION integrates and models the best operationally available information about convective cells and their surrounding environment. The aim is to provide convection intensity nowcasts for 60 min. The output updates frequently, every 5 min, and the cells having a high probability of becoming severe in the next 15–30 min are highlighted.

This nowcasting product is intended to support weather forecasters in the decision-making process for issuing severe thunderstorm warnings. The user community is very interested in new methods aimed at improving the accuracy and increasing the lead time of severe storm warnings. One of the basic goals is to understand the end users' needs and to provide them with reliable, easy-to-use, high-quality information in real time.

1.2. *Outline*

This article is organized into the following sections. The acquisition of remote sensing data and environmental information, which are processed and ingested into the algorithm, and their spatial and temporal resolution characteristics are described in section 2. The configuration of the COALITION model is described in detail in section 3, illustrating the eight different modules modelling thunderstorm intensity parameters with convective environmental information. In section 4, the selection of the case studies and a show case are presented. Then, in section 5, after the description of the forecast verification methodology and the presentation of the skill scores used to evaluate the system, the verification statistics of the COALITION model are described and evaluated. Finally, we conclude and summarize the results of our study in section 6.

2. Datasets

The algorithm ingests data obtained from five different sources: geostationary meteorological satellites, weather radars, numerical weather prediction models, climatology and digital terrain information (Figure 1).

The ingested products can be subdivided into three groups (see Table 1):

(1) *Primary products*. Represent the algorithm's basic data. If one or more of these products is not available, the algorithm cannot operate.
(2) *Secondary products*. Increase the quality and reliability of the results. If one of more of these products are not available, the algorithm can still operate but in general the output is of a lower quality.
(3) *Auxiliary products*. These data improve the quality of the graphical output by visualizing the information on the standard grid of the Swiss radar composite. If one or more of these products is not available, the algorithm can still be run and the output information is visualized on a standard polar-stereographic infrared (IR 10.8 μm) image over central Europe.

The spatial domain of COALITION is depicted in Figure 2. It includes the central and western Alpine area between 43.6–49.3°N and 2.9–12.2°E.

2.1. *Meteosat Second Generation (MSG)*

The main instrument of the payload of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) geostationary satellite *Meteosat* (Schmetz *et al.*, 2002) is a passive radiometer referred to as the Spinning Enhanced Visible and Infrared Imager (SEVIRI). This instrument has 12 spectral bands at wavelengths between 0.4 and 13.4 μm with a horizontal resolution of 3 km at the satellite subpoint (SSP). The high-resolution visible band (HRV) has a horizontal resolution of 1 km at SSP. The temporal resolution is 5 min for all 12 channels, thanks to a scanning strategy called Rapid Scan Mode (RSS).

Several visible and infrared channels are used to compute advanced products, which are then ingested into the COALITION algorithm. The first product presented in this article is SATellite Convection AnalySis and Tracking (SATCAST) or Convective Initiation (CI). CI was originally developed for the US Geostationary Operational Environmental Satellite (GOES: Mecikalski and Bedka, 2006) and it was then adapted to *Meteosat* Second Generation (MSG: Mecikalski *et al.*, 2010). In order to

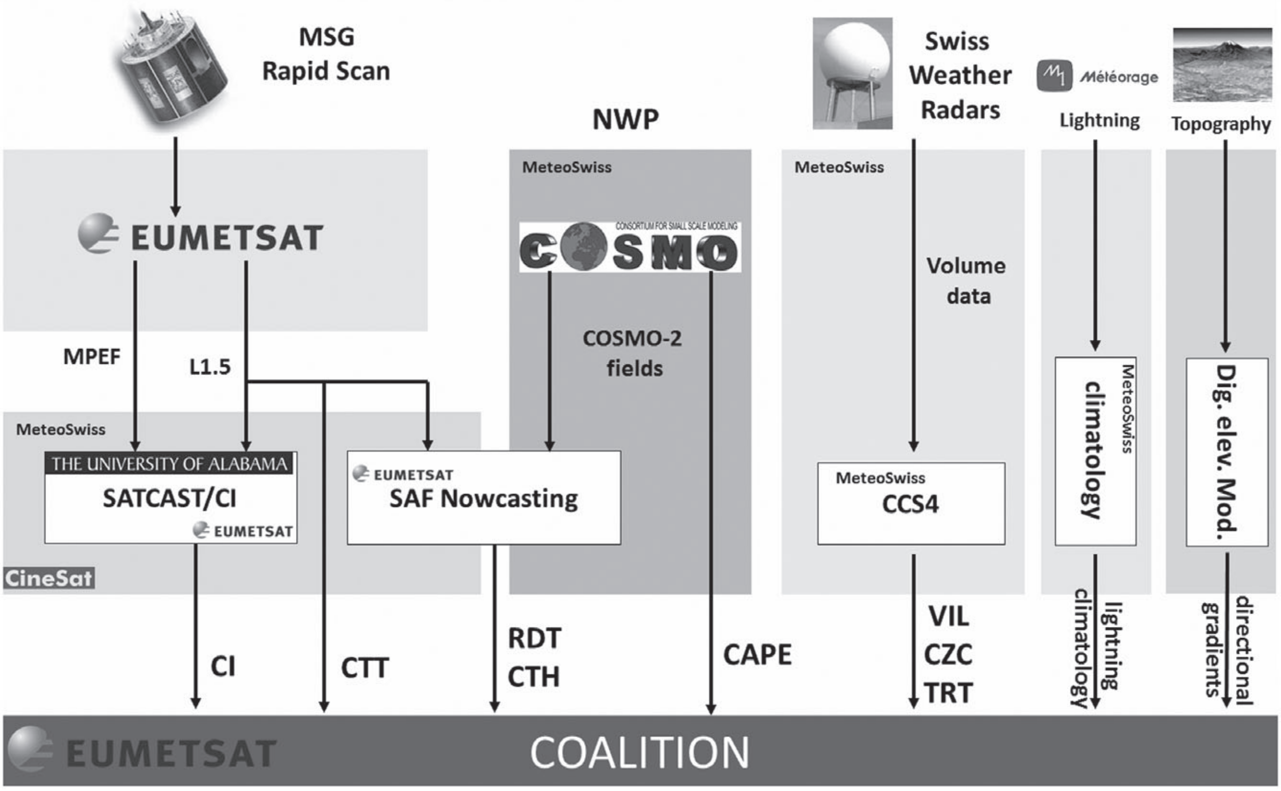

Figure 1. COALITION input data for the current version of the algorithm. For acronym descriptions and product classifications, refer to Table 1.

Table 1. COALITION real-time ingested data subdivided into three groups.

Input data	Name	Acronym	Source	Resolution	Frequency
Primary	Cloud-Top Temperature	CTT	Satellite (MSG–RSS)	3 km	5 min
	Cloud-Top Temperature and Height	CTTH	Satellite (MSG–Nowcasting SAF)	3 km	5 min
	Rapid Developing Thunderstorms	RDT	Satellite (MSG–Nowcasting SAF)	3 km	5 min
	Vertically integrated Liquid content	VIL	Radar (Swiss Radar Network)	1 km	2.5 min
Secondary	Convective Initiation	CI	Satellite (MSG–RSS)	3 km	5 min
	Convective Available Potential Energy	CAPE	NWP (COSMO-2 Switzerland)	2.2 km	180 min
	Lightning Climatology	LC	Lightning (Meteorage)	1 km	1 year
	Directional Slope Gradients	DGRAD	Digital Elevation Model	0.5 km	Static
Auxiliary	Thunderstorm Radar Tracking	TRT	Radar (Swiss Radar Network)	1 km	5 min
	Max Echo	CZC	Radar (Swiss Radar Network)	1 km	2.5 min

For each product an abbreviation, the operational dissemination frequency and nominal resolution are presented.

Figure 2. COALITION domain over central Europe. The algorithm is run over an area of 640 × 710 km^2.

identify the location of CI, three physical cloud characteristics are investigated. Cloud-top cooling, cloud glaciation and cloud depth are estimated using brightness temperatures from five infrared channels (8.7, 9.7, 10.8, 12.0 and 13.4 μm) and a cloud mask product (e.g. from the EUMETSAT Meteorological Product Extraction Facility (MPEF)). With CI, COALITION assimilates two further advanced satellite products:

- the Cloud-Top Temperature and Height (CTTH) and
- the Rapid Developing Thunderstorm (RDT) product (Autonés, 2012),

which were developed in the framework of the EUMETSAT Nowcasting Satellite Application Facilities (NWC–SAF) Consortium and generated locally with the Nowcasting SAF software installed at MeteoSwiss. These are two automatically generated meteorological products, where MSG data are combined with data from numerical models (in our case the freezing level extracted from the MeteoSwiss regional model COSMO-2). These products provide information about temperatures and heights of cloud tops as well as an object-oriented identification of rapid developing convective cells, respectively. In order to help RDT detect convective clouds at a very early stage, some default parameters (e.g. the threshold for minimum thunderstorm cloud area and maximum cloud-top temperature) in the Nowcasting SAF software have been modified and regional tuning has been carried out. The temperature of the cloud top is one of the basic parameters in COALITION, since, as demonstrated in many studies (e.g. Zinner *et al.*, 2008; Kober and Tafferner, 2009; Mecikalski *et al.*, 2010, 2012; Roberts and Rutledge, 2003), its rate of change in time provides an estimation of the storm updraught intensity.

2.2. *Swiss weather radar network*

The algorithm also ingests the grid-based Vertically Integrated Liquid (VIL) product provided by three ground-based C-band polarimetric Doppler radars located in the Swiss Alps. This product is obtained from radars performing volume-scanning and represents the three-dimensional characteristics of precipitation systems, with particular emphasis on the convective ones, in a two-dimensional display (Greene *et al.*, 1972; Johnson *et al.*, 1998). VIL is represented by radar columnar reflectivity, which is then converted into liquid water equivalent. It is a useful indicator of short-term rainfall and intensity of convection used in nowcasting methods (Boudevillain and Hervé, 2003). The horizontal spatial resolution of the VIL map is 1 km × 1 km and the temporal resolution is 2.5 min.

In order to improve the quality of the graphical output of COALITION, the Max Echo radar reflectivity product (Joss *et al.*, 1998) and the output of the Thunderstorm Radar Tracking (TRT) algorithm (Hering *et al.*, 2004; Rotach *et al.*, 2009) are also taken into account. Max Echo is a grid-based product, which is retrieved using the maximum detected radar reflectivity in a vertical column. TRT detects the position of convective cells: it classifies them according to selected radar parameters (Hering *et al.*, 2004) and extrapolates their position for the next 60 min based on Lagrangian persistence rules. TRT is very important for COALITION, since it provides the storm's future location and it is used as an independent data source for the verification of convection intensity nowcasts (see section 5). At present, the decision process at MeteoSwiss for issuing severe thunderstorm warnings relies mainly on TRT, which determines the intensity of the cells according to thresholds of radar-based parameters e.g. VIL, Echo Top 45 (dBz) and Max Echo. Once a thunderstorm is identified as 'severe' or 'moderate' for at least two consecutive 5 min steps, a warning is issued. Hereafter, the *warning lead time* will be defined as the difference between the moment when a severe thunderstorm warning is issued and the moment of the first detection of the thunderstorm provided by COALITION.

2.3. *Regional NWP model COSMO2-CH*

The algorithm incorporates the most unstable Convective Available Potential Energy (CAPE) indicated by COSMO2-CH forecasts. COSMO2-CH is a non-hydrostatic, regional, high-resolution model (2.2 km) operated by MeteoSwiss. CAPE represents an integral value of the available convective potential in the troposphere and therefore it is a robust indicator, used for determining the potential of convective intensity (Emanuel, 1994).

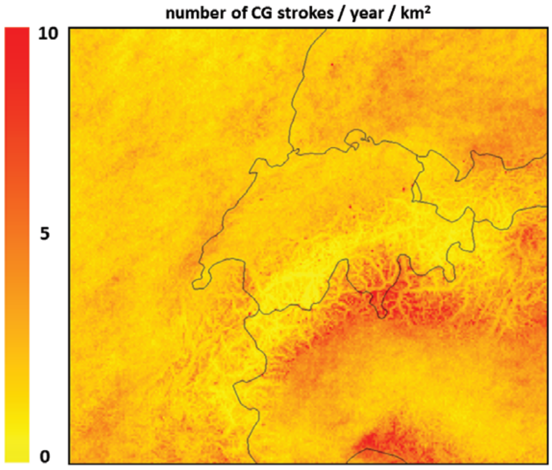

Figure 3. Average number of CG strokes per square kilometre in the Alpine area calculated with a data period of 10 years (2000–2010). [Correction added on 26 June 2014 after original online publication: the scale for Figure 3 has been amended to 'number of CG strokes per year per km^2'.]

2.4. *Lightning climatology*

Lightning data provided by the Meteorage–European Corporation for Lightning Detection (EUCLID) network are included in COALITION. Positive and negative Cloud to Ground strokes (CG) over the Alpine area over a period of 10 years (2000–2010) are used to build a climatological database. This product, referred to in this article as Lightning Climatology (LC), provides a yearly average number of CG strokes per square kilometre. As illustrated in Figure 3, this climatological stroke frequency correlates strongly with the orography. This correlation has been already documented by several studies, where lightning data were used for verification (e.g. De Coning *et al.*, 2011).

2.5. *Directional slope gradients*

The ability of mountain chains to trigger, invigorate and decay convective processes is well acknowledged (Huntrieser *et al.*, 1996; Kottmeier *et al.*, 2008). Nowcasting systems, designed for regions with complex orography, should take into account terrain features. The contribution of the topography to precipitation patterns can be described by an extensive set of topographical descriptors computed from a digital elevation model (e.g. Foresti and Pozdnoukhov, 2011). The relationship between the mesoscale flow, which largely determines the direction and speed of convective cell propagation, and one of these topographic descriptors, namely the slope gradient, is very important. In the Alps, upward velocities caused by upslope flows often act as a trigger for CI and intensification (Pielke and Segal, 1986; Barthlott *et al.*, 2005). Area, direction and velocity of convective cells have been used together with data provided by a digital elevation model (horizontal resolution of 1 km) in order to estimate directional slope gradients (hereafter DGRAD). According to a Lagrangian extrapolation of the position of the cells for the following 30 min, an average terrain slope of the area intersected by cells is considered. The relation between topographic descriptors and precipitation depends on the spatial scale. A sensitivity study (not carried out in this version of the algorithm) should help to increase the skill of such topographic predictors. Figure 4 provides two examples of DGRAD: the left panel presents a case where a uniform westerly flow is assumed, whereas the right panel assumes a uniform southerly flow.

3. Methodology

3.1. *Theoretical description of the algorithm: Hamiltonian formulation of the model*

COALITION assimilates data provided by different sources and integrates them according to a conceptual model. Two physical attributes, namely the CTT and the VIL, are selected for assessing the thunderstorm severity. These two parameters are independent and have been used in many studies as well as in nowcasting models for assessing and forecasting the storm intensity and evolution (e.g. Dixon and Wiener, 1993; Hering *et al.*, 2004; Puca *et al.*, 2005; Kober and Tafferner, 2009; Zinner *et al.*, 2008; Mecikalski *et al.*, 2010; Autonés, 2012). Rapid cooling of cloud tops and increasing vertical columnar liquid content are clear indicators of storm intensification processes. In the algorithm, cell-based CTT and VIL are forecast independently. The first is used to assess possible CI and intensification processes of cells at a very preliminary stage when no rain data, and consequently no radar observations, are available. VIL content is later used to forecast further intensification and re-intensification of already developed storms. The other data products, representing the convective predictors, describe the surrounding environment of the thunderstorm cells. The algorithm models the evolution of CTT and VIL with convective predictors as interacting elements. Nowcasts of thunderstorm attributes are derived from the analysis and the modelling of present and past observed conditions. The core of the algorithm works as an engine, which links thunderstorm attributes with some selected surrounding environmental conditions. The selection of these conditions is based on the real-time availability of the respective products and on their relation to thunderstorm attributes. The relationship

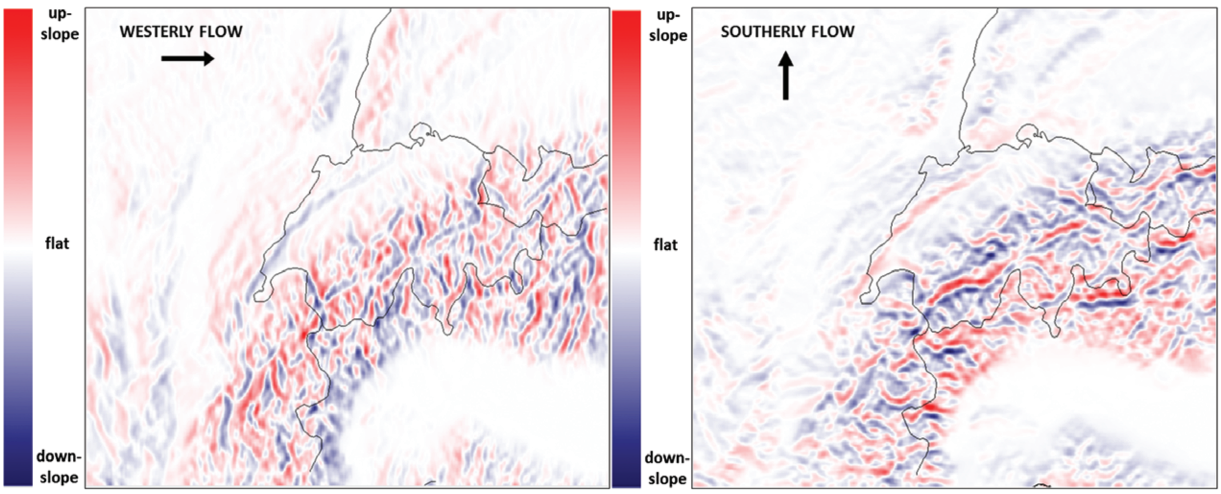

Figure 4. Directional terrain slope gradients in the Alpine area. Red colours indicate upslope, blue colours downslope. Two examples are shown: on the left a westerly flow is assumed and corresponding terrain slopes in the west–east direction are depicted. On the right, a southerly flow is assumed and therefore terrain slopes in the south–north direction are highlighted.

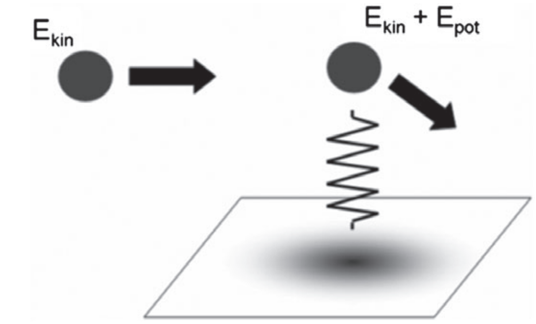

Figure 5. Simplified illustration of the COALITION conceptual model. The object-based approach uses the energy conservation principle from physical mechanics. The total energy is given by the sum of the kinetic (E_{kin}) and the potential (E_{pot}) energy. The forecast of object attributes is the result of the solution of Hamilton's equation (Eq. (2)).

that is applied usually relies on conceptual rules used by weather forecasters. The COALITION methodology borrows its approach from the physics of general dynamical systems, where the orbital evolution of a particle moving within a potential field is commonly described by Hamilton's equations. The interaction between thunderstorm attributes and the surrounding environment is modelled as a particle–field interacting system, as depicted schematically in Figure 5.

A Hamiltonian model formulation has already been used to model thunderstorm processes. Mak (2001) considered a non-supercell tornado as a non-hydrostatic columnar disturbance in a layer of constant density fluid over a flat surface and used the basic form of Hamilton's principle of least action (Miles and Salmon, 1985) to derive the equations governing fluid systems (Salmon, 1998). The COALITION model is formulated in a similar way, using Hamiltonian formalism as analogy. In general, the Hamiltonian function for a time-independent system is given by

$$H(\mathbf{q}, \mathbf{p}) = H(q_1 \dots q_n, p_1 \dots p_n) = E_{\text{tot}}, \qquad (1)$$

where $q_1, \dots, q_n$ is the set of generalized coordinates representing the location of each element in space (e.g. $q_1 = x$; $q_2 = y$; $q_3 = z$) and other element attributes (e.g. $q_4 = CTT, \dots, q_n = VIL$). $p_1, \dots, p_n$ is the set of the corresponding generalized momenta. Hamilton's equations are given as:

$$\dot{\mathbf{q}} = \frac{\partial H}{\partial \mathbf{p}}, \qquad \dot{\mathbf{p}} = -\frac{\partial H}{\partial \mathbf{q}}. \qquad (2)$$

The COALITION algorithm scheme is based on the premise that the energy of the system is conserved. For each interacting system formed by the couplet 'thunderstorm attribute' and 'surrounding environment', the pseudo-total energy is assumed to remain approximately constant over short time-scales. Hereafter, the word 'pseudo' will be used to distinguish energies estimated by the COALITION model from true physical energies (e.g. related to movements or to thermodynamics as analogy). If the inertial state (kinetic energy) is assumed to be conserved, common inertial rules of closed systems can be applied. This happens mostly in cases of mature convective processes, for which nowcasting algorithms based on Lagrangian persistence are suitable. For all other cases, where such conservation is violated (in particular at the initiation and early development stage), the system may no longer be considered to be closed. Energy losses and gains are then explained as import or export of energy from the surrounding environment through dynamical interactions (e.g. see example in Figure 6). Assuming a system without dissipation, the total energy is given by the sum of a kinetic and a potential component:

$$E_{\text{kin}} + E_{\text{pot}} = H(\mathbf{q}, \mathbf{p}) = \text{constant}, \qquad (3)$$

where $\mathbf{q}$ represents the generalized coordinates (CTT, VIL) and $\mathbf{p}$ represents the corresponding momentum ($p_{\text{CTT}}, p_{\text{VIL}}$).

As described in section 3.2, predictors for convective cell attributes are selected from among those accessible in real-time available products and according to conceptual rules. Predictors are used in the model as external potential fields (e.g. CAPE). Potential components of the system are built up using a predictor's characteristics (e.g. value distribution, magnitude, gradients), whereas the computation of the pseudo-kinetic component is based on the rate of change of attributes describing the convective cells (e.g. VIL).

A one-dimensional, time-dependent generalization of a harmonic oscillator (Eq. (4)) involving pairs of predictors and predictands is assumed for each COALITION module (eight in total). A single attribute of the convective cell determines the rate of change in the inertial part (pseudo-kinetic energy), as well as the quadratic term appearing in the interaction part of the equation (potential field).

$$H(q, p, t) = \frac{p^2}{2m} - A\, f(t)\, q^2, \qquad (4)$$

where A is a positive constant, m is the mass of the object's inertia and $f(t)$ is the correlation function between the object's attribute evolution and the external field. The choice of the potential energy in Hamilton's equation is based on an effort to simulate the system in a zero-order approximation. Potentials of far more intriguing complexity may describe the system better, but it is non-trivial to track them down in a systematic way; moreover a simpler model may be more appropriate for operational purposes. Conceptually speaking, the actual number of degrees of freedom in action as well as the way their interaction/coupling takes place determines the level of nonlinearity and, as a consequence, the unpredictability of the system. In some sense, the actual nonlinearity characterizing the system might reflect to a certain extent how fast the nowcast produced by our model disassociates from the actual observation.

In the COALITION model it is heuristically assumed that the total energy remains constant and equal to zero over time:

$$H(q, p, t) = 0. \qquad (5)$$

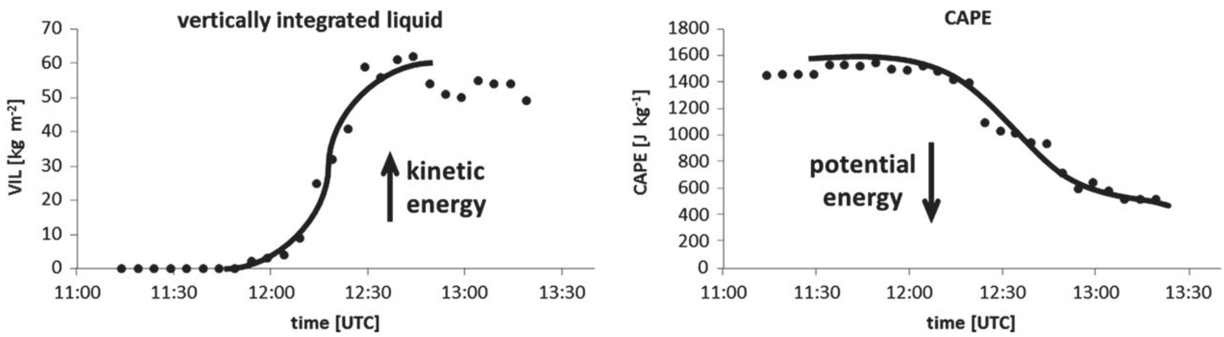

Figure 6. Energy losses or gains in the kinetic component are explained as an exchange of energy with the surrounding environment. In this example, the thunderstorm attribute VIL has been used to estimate the pseudo-kinetic energy, whereas the pseudo-potential energy is estimated from the NWP–CAPE product, which is used as the surrounding environment. Dots represent observations of VIL and the surrounding CAPE of a particular thunderstorm cell, whereas solid lines are an idealized (hand-drawn) representation of the evolution of the kinetic and potential energy.

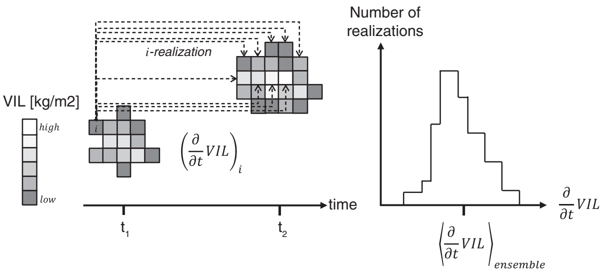

Figure 7. Assuming statistical stationarity (no change in PDFs), the kinetic energy is calculated according to the (discrete) rate of change of the convective cell attribute (in this example the VIL). An energy value is estimated for each possible realization i within the same cell for two consecutive time steps (i.e. taking into account all combinations of VIL values between the cell at time t_1 and t_2). In the right panel, the corresponding distribution is presented.

This assumption is based on the intuitive expectation that losses and gains of the pseudo-kinetic energy relate to and are balanced by an exchange of energy with the surrounding environment. One of the tasks in developing the model was to convert heuristic relations between cell evolution and its surrounding environment into forecast rules. A model for energy conservation has been assumed and verified by means of a number of different functions representing the pseudo-potential energy. The function providing the best estimation scores was finally selected as the most appropriate to be implemented in the model. Under the aforementioned energy-conservation assumption, Eq. (4) can be solved analytically providing the following two solutions:

$$q(t) - q(t_0) = \mathrm{e}^{\pm \int_{t_0}^{t} \sqrt{2(A/m)f(t)}\,\mathrm{d}t} \quad \text{with } q(t),\ q(t_0) > 0. \quad (6)$$

In the model, convective cells are not represented by single values of CTT and VIL, but rather they are described by a set of k attributes corresponding to a set of k pixels within the confined cell. The distribution of the attribute over all pixels provides information about the variability of the attribute within the cell. Figure 7 shows a developing cell at times t_1 and t_2 (with $\Delta t =$ 5 min). VIL is selected as the attribute of this cell. For each object element (pixel), a pseudo-kinetic value for all possible realizations i (with $\Sigma i = k$) is calculated, according to the rate of change of the considered attribute.

Equation (6) can therefore be generalized as

$$q^k(t) - q^k(t_0) = \mathrm{e}^{\pm \int_{t_0}^{t} \sqrt{2(A/m)f(t)}\,\mathrm{d}t} \text{ with } q^k(t),\ q^k(t_0) > 0. \quad (7)$$

The COALITION model nowcasts the evolution of two attributes of convective cells, namely CTT and VIL. These nowcasts are particularly important for cells that are detected in their early stages and likely to develop further. In the current version, to satisfy the primary user needs, only the cell development is taken into account; decaying processes are not considered yet. As a consequence, only the positive solution (Eq. (6)), which represents the forward propagation of our model and allows us to forecast increases in thunderstorm intensity, is taken into account:

$$q^k(t) = q^k(t_0) + \mathrm{e}^{\int_{t_0}^{t} \sqrt{2(A/m)f(t)}\,\mathrm{d}t}, \quad (8)$$

where

$$f(t) = {f_0}^k + B(t - t_0)^{3/2} - {f_0}^{3/2}, \quad (9)$$

$${f_0}^k = \frac{1}{2}\left[\frac{\dot{q}^k(t_0)}{q^k(t_0)}\right]^2, \quad (10)$$

$$B = \frac{\mathrm{d}f}{\mathrm{d}t} + \frac{\mathrm{d}f_{\mathrm{err}}}{\mathrm{d}t} = \frac{\mathrm{d}f}{\mathrm{d}t} + \frac{\partial f_{\mathrm{err}}}{\partial \sigma}\left(\frac{\partial \sigma}{\partial t}\right), \quad (11)$$

and where σ represents the predictor. Potential fields steer the evolution of the object attributes, following the energy conservation assumption. Characteristics of the external environment ($\partial\sigma$) are included in the model (Eq. (11)) and are used to explain the differences between extrapolated (Eq. (9)) and observed (Eq. (10)) pseudo-kinetic energy. We use the correlation between the averaged value of these differences ($\langle f_{\mathrm{err}} \rangle$) and the averaged value of the selected surrounding environment ($\langle \sigma \rangle$). This correlation takes into account regressive information and is used to estimate a set of pseudo-kinetic energies for the following time step, consequently providing an ensemble forecast of the evolution of the considered cell attribute.

In order to validate the underlying assumptions and the COALITION methodology, in the first version of the algorithm a simple function, i.e. a one-dimensional, time-dependent generalization of a harmonic oscillator (Eq. (4)), was used. Later, by applying more complex functions and by using more refined relations between cell attributes and the surrounding environment, the skill of the method and consequently the results will improve.

3.2. *Algorithm structure and modules*

The structure of the algorithm can be summarized in the following steps.

(1) As a primary input, COALITION ingests the Nowcasting SAF/RDT product tuned to detect small convective clouds as well as larger ones (see section 2). For this purpose, the threshold for maximum cloud-top temperature is increased from 5 to 10 °C and the threshold for the minimum cloud area decreased from 60 to 25 km^{-2}. Based on this external information, COALITION selects and confines convective cells on MSG 10.8 μm infrared images.

(2) Once a convective cell is detected, the parallax correction is computed using cloud-top height information provided by Nowcasting SAF. This step is very important in order to reduce the differences in the geolocation of the cells, considering the large number and variety of products ingested by the algorithm (e.g. radar, NWP).

(3) In a third step, the cell is additionally identified and analyzed using the radar-derived VIL. Cell-based CTT and VIL attributes are then modelled using several environmental parameters (predictor fields). In the current version of the algorithm, eight different 'attribute–environment' couples, derived by semi-empirical rules based on forecasters' experience and conceptual models, are implemented (Figure 8 and Table 2). Three of them provide an ensemble nowcast of the CTT attribute, while the remaining five provide an ensemble nowcast of the VIL. Nowcasts are generated for the next 60 min with a time resolution of 5 min. Finally, all 90% quantiles from the ensembles are then used to produce and provide the end user with a single output.

As a fully automatic 'expert system', COALITION verifies the input product availability and quality. If the needed data for one or more modules are missing, COALITION automatically uses available information from the immediate past or it ignores the module concerned, depending on the type of the data and its typical variability in time. For example, if the environmental information CAPE is not available, the previous value is taken (it could be the value of 5, 10 or 15 min earlier), since this product does not change considerably over a short time and a small region. However, if VIL is missing, the modules requiring this input data are automatically excluded from the model, given that VIL is a highly variable parameter over time and space.

3.3. *Combination of module forecasts*

VIL and CTT nowcasts provided by eight modules with a 5 min update cycle are integrated through a weighting and thresholding scheme similar to a fuzzy logic approach. This

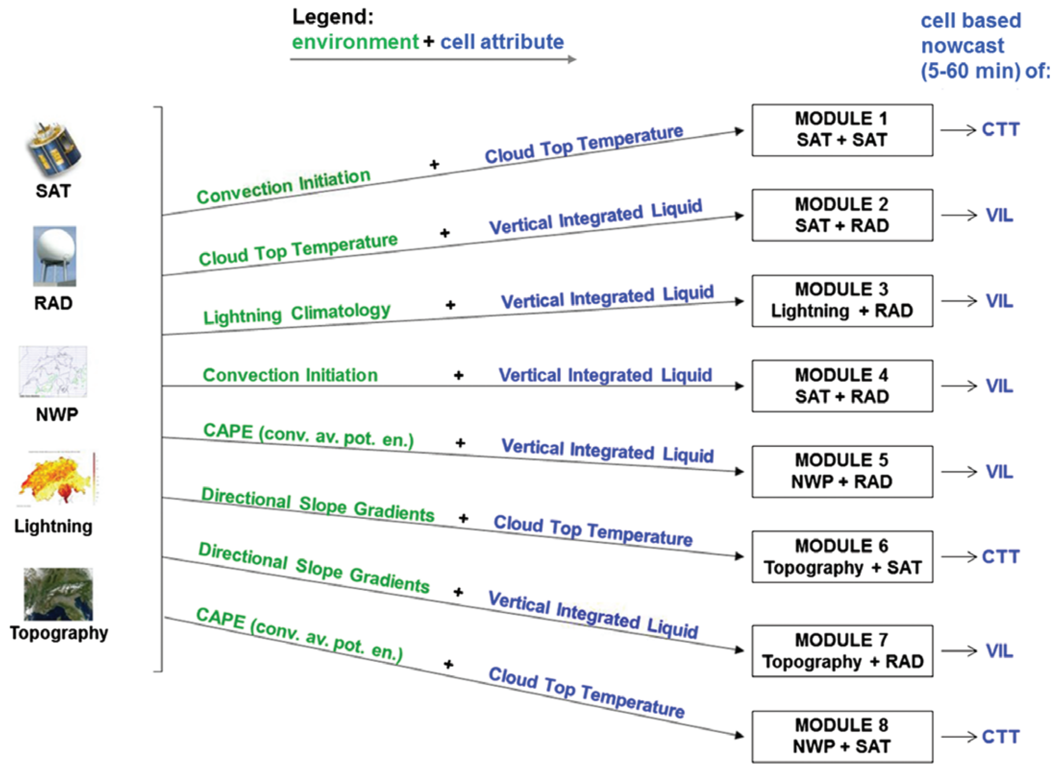

Figure 8. The eight modules implemented in the current version of COALITION. Products used as external environment are in green, cell attributes to be forecast are in blue.

Table 2. Description of the eight modules and the related semi-empirical rules that motivated the selection of predictand–predictor pairs.

Module	Data combination	Semi-empirical rule
1	Evolution of the CTT based on the environment defined in terms of the Convective Initiation product	Stronger convective initiation signal of a cell → stronger updraught is available for its cloud-top cooling (towering of the cloud)
2	Evolution of the VIL based on the environment defined in terms of CTT	Faster cooling of the cloud top of a convective cell → more potential energy is available for increasing its VIL
3	Evolution of the VIL based on the environment defined in terms of a lightning climatology	Higher climatological density of cloud to ground lightning over a specific area → more potential energy is available for increasing the VIL of a convective cell developing in this area
4	Evolution of the VIL based on the environment defined in terms of the Convective Initiation product	Stronger convective initiation signal of a cell → more potential energy is available for increasing its VIL
5	Evolution of the VIL based on the environment defined in terms of the Convective Available Potential Energy (CAPE)	Higher instability values → more potential energy is available for increasing the VIL of a convective cell developing in this area
6	Evolution of the CTT based on the environment defined in terms of orographic information (slope gradients)	A convective cell is moving toward a mountain (orographic forcing) → stronger updraught is available for its cloud-top cooling (towering of the cloud)
7	Evolution of the VIL based on the environment defined in terms of orographic information (slope gradients)	A convective cell is moving toward a mountain (orographic forcing) → more potential energy is available for increasing its VIL
8	Evolution of the CTT based on the environment defined in terms of the Convective Available Potential Energy (CAPE)	Higher instability values → stronger updraught is available for its cloud-top cooling (towering of the cloud)

is an efficient methodology for nowcasting the likelihood of severe storms through the application of a conceptual model (Roberts *et al.*, 2006). According to subjective experience of local weather forecasters, the conceptual model is built on the fact that predictors have a different importance according to the current stage of the convective cell. Different weights are assigned to the modules for each possible stage (first guess based on forecaster experience). By analyzing cell-based characteristics like CTT and VIL as well as their first derivatives, the system automatically computes an estimation of the current cell's stage. A simple sensitivity study based on 40 randomly selected cases has been performed for optimizing the weighting scheme. Figure 9 shows the module weights currently used in the COALITION algorithm. Large datasets, required for example by neural network systems, were not necessary. If needed, the weights can be modified in an easy way for regional tuning purposes. Furthermore, the system can be extended as soon as additional predictands or improved modules become available.

4. Results

4.1. *Selection of cases*

The COALITION application has been run in real time at MeteoSwiss since May 2012. During the convective season (May–September 2012), the algorithm has been subjectively

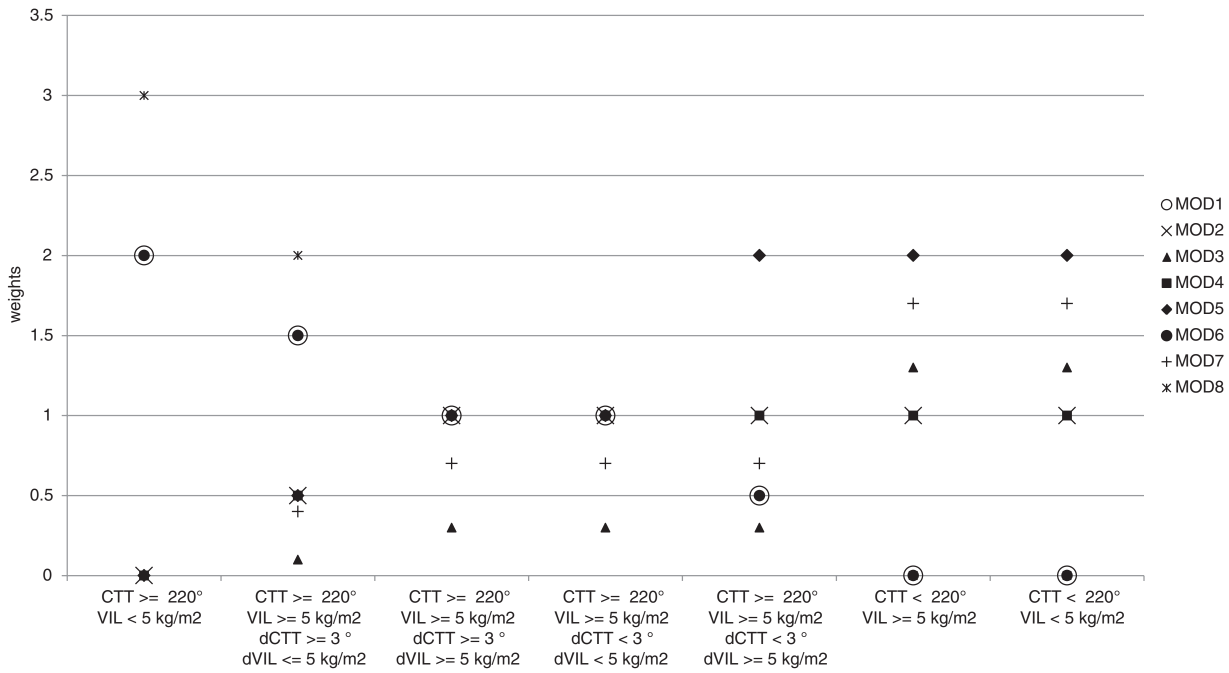

Figure 9. Module weights for different stages of convective processes. Absolute values of CTT and VIL are used to assess warm/cold cloud tops and light/heavy precipitation; first derivatives approximated by finite differences are used to identify important rates of change in time, for example strong cooling of the cloud tops or strong rain/hail intensification.

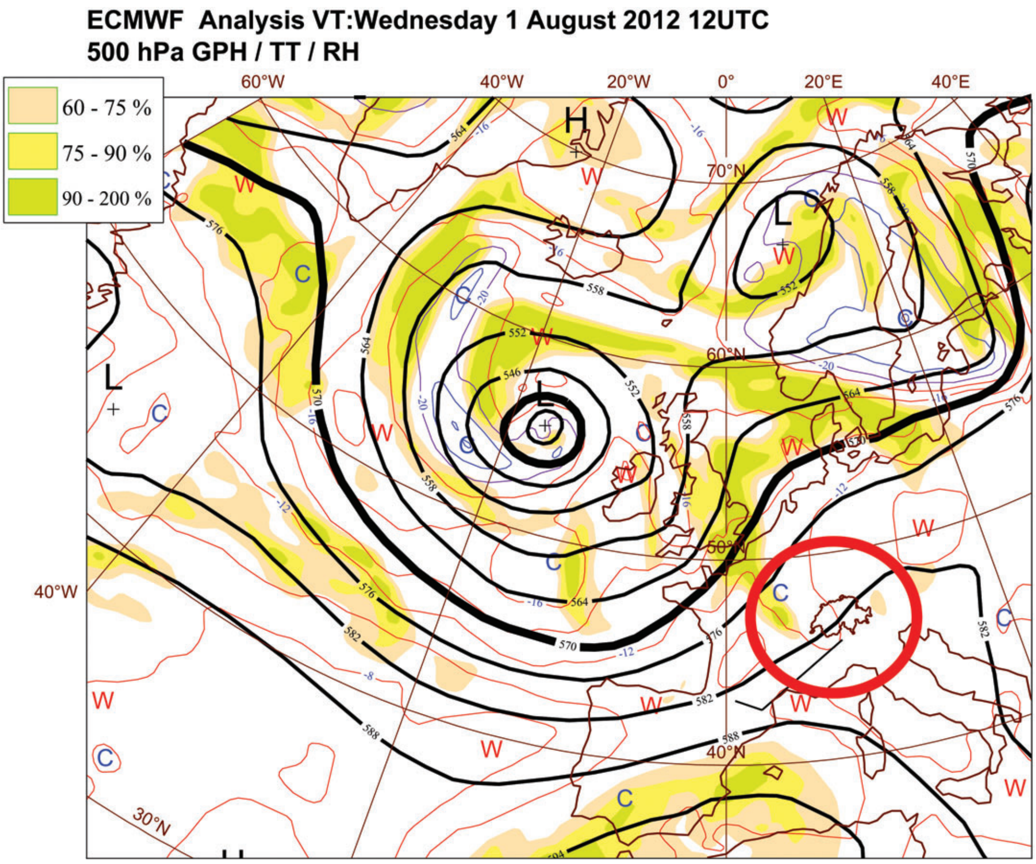

Figure 10. The distribution of geopotential height (black bold lines), temperature (red lines) and relative humidity at 500 hPa (ECMWF) on 1 August 2012 at 1200 UTC shows the trough located over the Atlantic and a short-wave, thermal signature (red circle) determining increased instability over central and western Europe.

verified by weather forecasters and independently and objectively using the output of the TRT system. Since the main purpose of the algorithm consists of automatically analyzing and modelling convective cell parameters using surrounding environmental characteristics, the verification was performed independently of the weather situation and life duration of the cells. 80 convective cases were considered. Based on the severity classification provided by TRT (Hering *et al.*, 2008), 40 weak and 40 moderate to severe thunderstorms were randomly selected from the archive.

4.2. *Example of a real-time application: 1 August 2012*

This section provides an example of a COALITION nowcast for 1 August 2012. The synoptic situation was dominated by a long-wave quasi-stationary trough over the Atlantic Ocean and

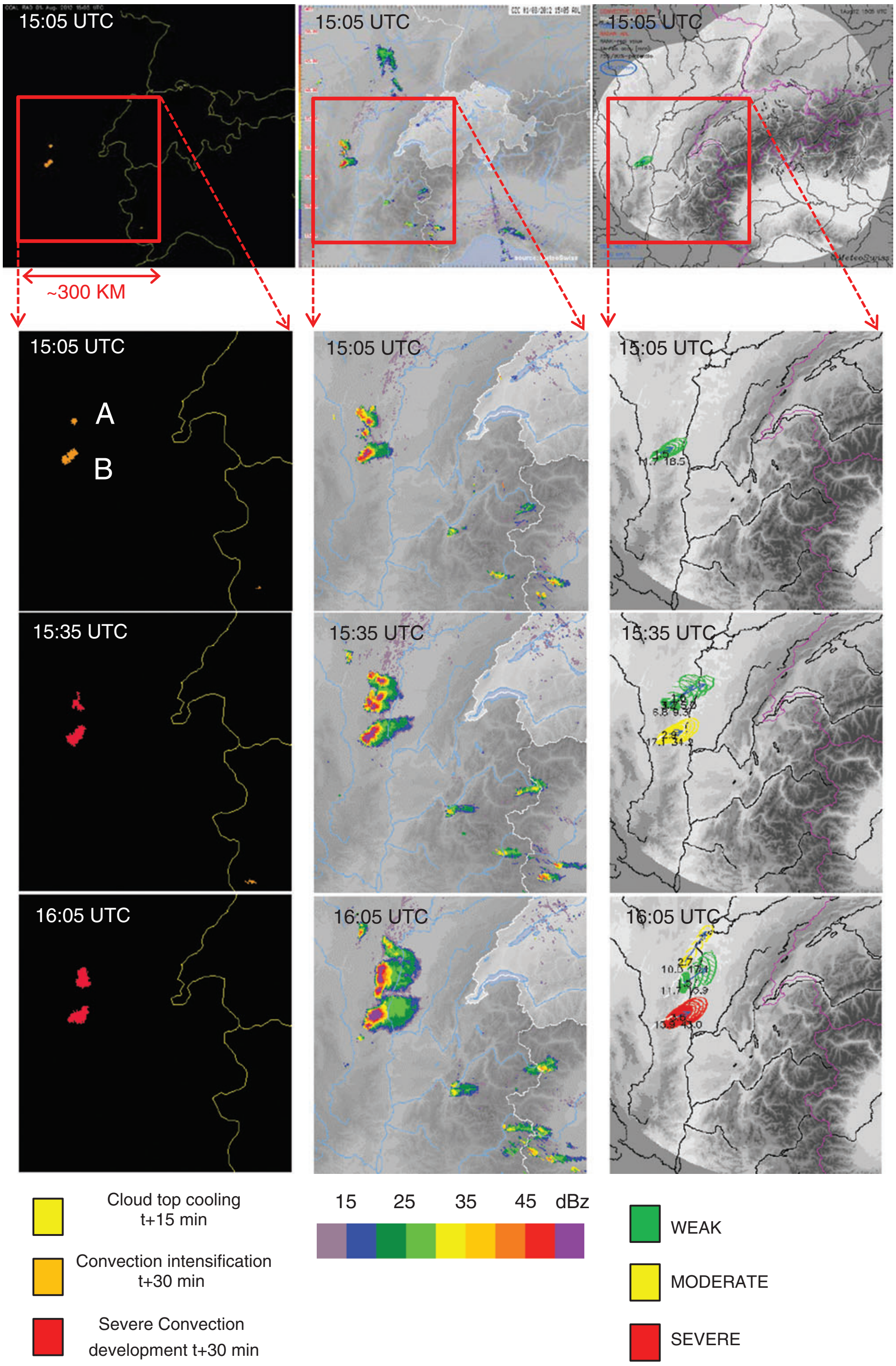

Figure 11. COALITION severe thunderstorm nowcasts and radar estimation references for the western Alpine region on 1 August 2012. Only some selected frames with a 15 min time step (between 1505 and 1605 UTC) are shown. The left column shows the COALITION nowcast, the central column shows the maximum radar reflectivity and the right column shows the thunderstorm classification provided by TRT.

western Europe (Figure 10). A short-wave thermal trough moving around the depression from west to east crossed central Europe and affected the Alpine region.

Over central Europe, moderate south-westerly flow brought very warm, moist unstable air. Initially in the Alpine region there were dry conditions because of weak Foehn winds from the south. During the afternoon, moisture and instability increased and at the same time an upper-level disturbance crossed central Europe from west to east. This moderate synoptic-scale forcing triggered the development of strong thunderstorms over the French pre-Alpine region. Then, later in the evening and overnight, the entire northern Alpine region was affected by convective activity.

The left column in Figure 11 shows COALITION nowcasts. The yellow colour indicates locations where only cloud-top cooling processes were forecast for the next 15 min. Orange and red colours are indicators of VIL intensification for the next 30 min: convective cells are highlighted with these colours when the nowcasts indicate that (i) CTT will decrease by at least 5 K within the next 15 min (yellow), (ii) VIL will increase by 15–25 kg m^{-2} (orange) and (iii) VIL is expected to increase by more than 25 kg m^{-2} in the next 30 min (red).

Radar products, which are used as reference for verification, show that at 1505 UTC two convective cells (highlighted with a red square in Figure 11) have already initiated. At that time, COALITION predicted an important decrease of the CTT for the northernmost cell *A* and an increase of the VIL values for the second one *B*. The first cell was not yet classified by TRT, whereas the second was classified as ‘weak’ (right column). At

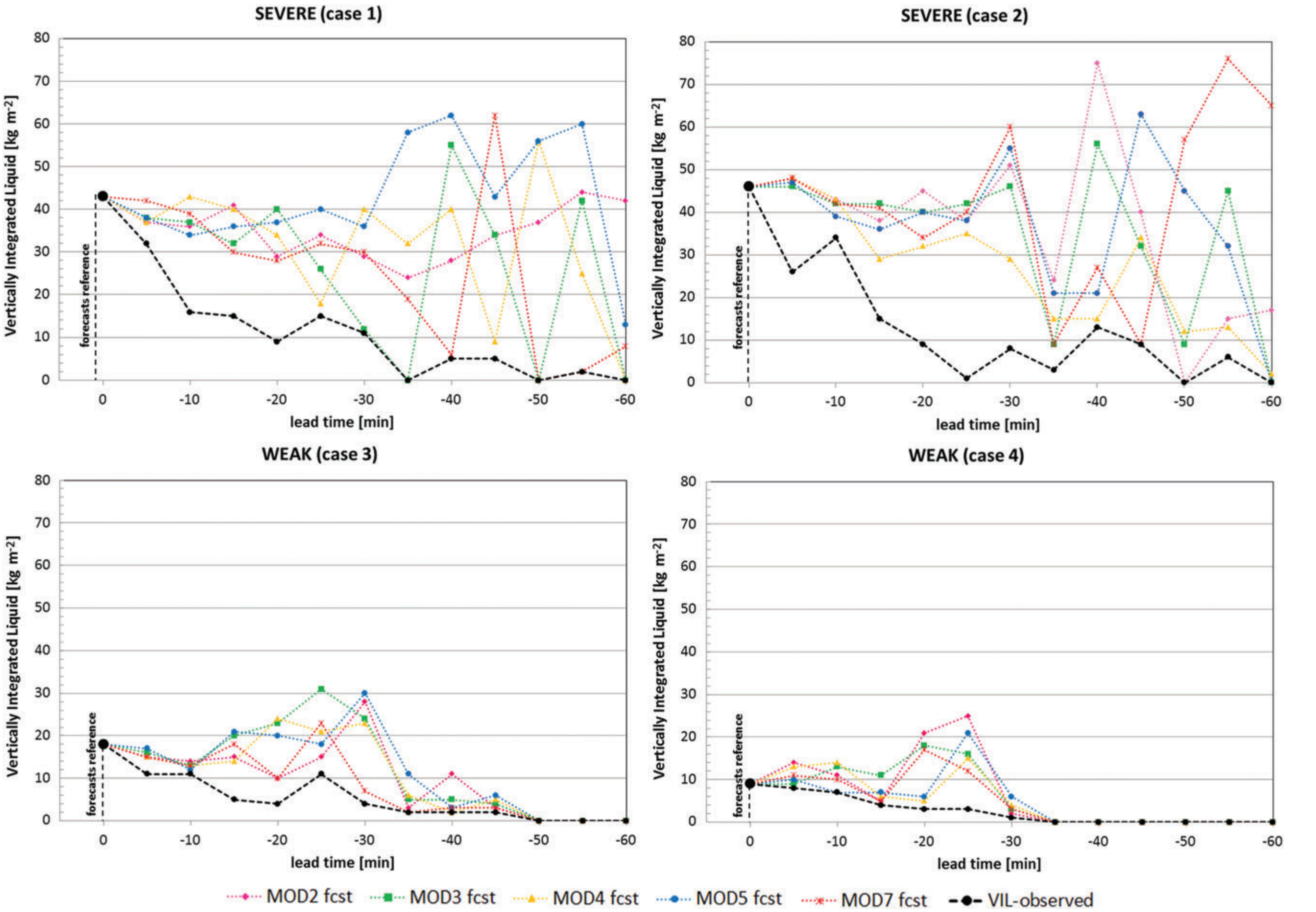

Figure 12. Nowcasted VIL over lead time for four different thunderstorm cells (two severe and two weak ones). In the plots, nowcasts provided by five modules for the selected reference (represented by the vertical black line at lead time = 0) are presented. VIL observations at different lead times are also shown (bold dashed line).

1535 UTC, the radar products showed that cell *B* indeed increased its intensity (max values greater than 50 dBz) and it was already classified as 'moderate' by TRT. At that time, the COALITION nowcast indicated that a probable further intensification up to 'severe' convection was expected within the following 30 min. The rapid cooling forecast at 1505 UTC for cell *A* was confirmed. In fact, the cell slightly increased its intensity and was classified as 'weak' by TRT. If compared with cell *B*, however, the analysis of the surrounding environment (especially the CI product, CAPE and orographic triggering) showed that during this period there were less favourable conditions supporting severe convective development. By 1535 UTC, COALITION indicated a probable intensification of this cell within the next 30 min as conditions for development became more favourable. For every 5 min thereafter, between 1535 and 1605 UTC, the nowcast system continuously indicated that the two cells would increase in intensity (not shown in Figure 11). At 1605 UTC, cell *B* was classified as 'severe' by TRT and cell A after a splitting process, was classified as 'moderate'. For this particular case study, COALITION forecasts verified correctly. A more general verification of the system, where a large number of cases were analyzed, is presented in section 5.

5. Performance statistics

5.1. *Verification of quantitative module forecasts*

In this section, quantitative nowcasts provided by the eight COALITION modules are validated against observations. The panels in Figures 12 and 13 present four randomly selected convective cells. According to the classification provided by TRT, two of them (cases 1 and 2, depicted in the upper panels of Figures 12 and 13) developed into severe thunderstorms. The remaining two (cases 3 and 4, depicted in the bottom panels of Figures 12 and 13) developed into weak thunderstorms.

The plots show a comparison of COALITION's VIL and CTT nowcasts provided by different modules for lead times between 5 and 60 min. Figure 12 shows the VIL forecasts provided by modules 2, 3, 4, 5 and 7, whereas Figure 13 shows the CTT forecasts provided by modules 1, 6 and 8 (see section 3 for a detailed description of the modules).

VIL and CTT observation references are highlighted on the plots with a vertical line. For the severe ones, the forecast reference is represented by the VIL value observed when the thunderstorm cell was first recognized as severe by TRT. For the weak ones, the forecast reference is given by the time when the maximum observed VIL value is observed, considering the whole life cycle of the cell.

As expected, for both weak and severe cases the differences within the nowcast ensemble become larger as the lead time increases. Deviations among the modules are a consequence of the different influence of the external environments on the forecast thunderstorm attribute: some environments may support the development of severe convection, whereas at the same time other environments inhibit it.

As suggested by Wilks (1995), Mean Absolute Error (MAE) and nowcast bias errors are calculated for lead times of up to 30 min (Table 3). Considering the results of the analysis of 40 severe cells, nowcasts generally show good skill up to 20 min before reaching the mature stage [MAE < 8.1 (kg m^{-2}), bias > -3.4 (kg m^{-2})]. Explosive cells constitute an exception, since for this kind of storm the warning lead time is reduced to 5–10 min. The main difficulty is the handling of extremely large and rapid increases of the VIL: in some explosive thunderstorms it jumps by about 30–50 kg m^{-2} within less than 10 min. Although the environment shows favourable conditions for severe convection, it is very difficult to model and nowcast this extremely rapid change of cell attributes. Considering VIL nowcasts for weak thunderstorms, the prediction skill remains good for longer lead times, in general up to 30 min [MAE < 7.1 (kg m^{-2}), bias > -3.8 (m^{-2})]. In these

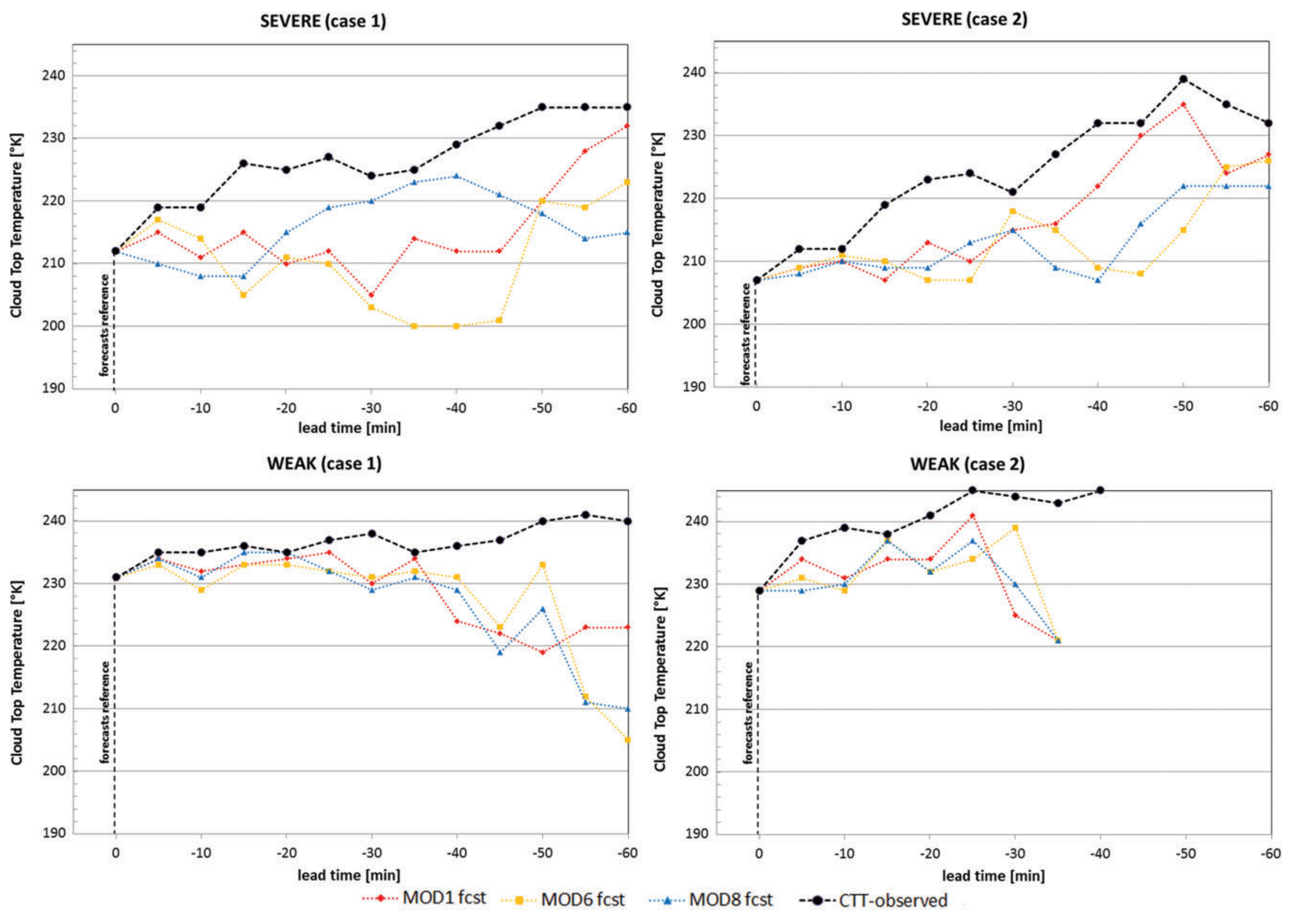

Figure 13. Nowcasted CTT over lead time for four different thunderstorm cells (same as in Figure 12). In the plots, nowcasts provided by three modules for the selected reference (highlighted with the vertical black line) are presented. CTT observations at different lead times are also shown (bold dashed line).

Table 3. Mean absolute error and bias for different lead times and for both VIL and CTT nowcasts.

Lead time (min)	VIL forecast (kg m^{-2})				CTT forecast (K)			
	Weak		Severe		Weak		Severe	
	MAE	BIAS	MAE	BIAS	MAE	BIAS	MAE	BIAS
5	1.1	−0.4	2.1	−1.4	2.9	−0.5	3.1	−0.5
10	2.3	−0.6	4.3	−2.2	3.0	−0.7	3.8	−0.9
15	2.9	−2.4	5.6	−2.6	3.3	−0.9	4.3	−1.7
20	4.1	−2.9	8.1	−3.4	3.6	−1.3	4.6	−2.1
25	5.9	−3.3	9.5	−3.8	4.2	−2.3	5.1	−2.5
30	7.1	−3.8	11.0	−4.4	4.8	−2.4	8.0	−3.4

40 weak and 40 severe thunderstorms have been considered.

cases, most of the surrounding environments agree in showing less favourable conditions for the development of severe cells; consequently, the variability among the modules is smaller.

Figure 13 shows the comparison of CTT nowcasts for the same thunderstorms as shown in Figure 12. The forecast reference has been defined using similar criteria to those described above. For severe thunderstorms, the reference corresponds to the CTT value observed at the moment when the thunderstorm cell is first recognized as severe by TRT. For weak ones, the forecast reference is given by the CTT value observed at the time when the maximum VIL value (considering the whole life cycle of the cell) was observed. Generally, for both weak and severe convective cases, the CTT nowcasts provided by the three modules show good skill for lead times up to 30 min [MAE < 8 (K) and bias > -3.4 (K) for severe thunderstorms and MAE < 4.8 (K) and bias > -2.4 (K) for weak ones]. For a better understanding of the skill, the variability of the thunderstorm CTT and VIL will be analyzed. As demonstrated by the analysis of the life cycle of a large number of convective cells, the distribution of CTT values remains more constant compared with the distribution of VIL values. This property, together with the fact that the CTT attribute is less variable in time compared with the VIL, results in an improved forecast performance of the corresponding modules. However, the good skill of the CTT nowcasts for longer lead times is mitigated by higher false alarm ratios (hereafter FARs); in fact, the VIL attribute is more robust and reliable for discriminating between severe thunderstorm cells and weak ones.

5.2. *Verification of COALITION nowcast*

In this section, the likelihood for a severe thunderstorm provided by COALITION, which is generated using the combination of all module forecasts (as described in section 3.3) and provided to the weather forecasters, is verified against TRT. The goal is to assess the probability of detections and the FARs. 80 cases from the 2012 convective season have been considered. At MeteoSwiss, forecasters use TRT and COALITION synergistically for issuing severe thunderstorm warnings. Based on objective radar parameters, the operational and validated TRT system provides information about the current cell intensity and an extrapolation of its future position. COALITION identifies the cells having a high probability of becoming severe during the next 30 min. For this reason, TRT is considered an independent ground truth in the evaluation of the COALITION algorithm. In particular, the evaluation process should provide answers to the following questions:

(1) what is the skill of COALITION in nowcasting severe thunderstorms; and
(2) do we improve lead time for issuing severe thunderstorm warnings using COALITION forecasts?

Thunderstorm forecasts were evaluated using typical skill scores applied in meteorology to verify weather predictions (e.g. Huntrieser *et al.*, 1996). Strong thunderstorms have been used to assess the probability of detection (POD), whereas weak thunderstorms were used for assessing FARs. Furthermore, the critical success index (CSI) was calculated for different lead times. POD describes the ability of the forecasting system to predict severe thunderstorms: if the occurrence is always forecast (perfect score), the POD is equal to 1. FAR indicates the proportion of thunderstorm forecasts that did not develop into severe cases. A perfect score is represented by a FAR equal to 0, indicating that forecasts were always followed by the occurrence. CSI describes the ability of the forecasting system to have at the same time a high POD and a low FAR. A perfect CSI score equals 1, while 0 indicates that there are no correct forecasts. The three skill scores were assessed according to a 2×2 contingency table for forecasts and observations (Wilks, 1995).

Algorithm performances are described in Table 4. COALITION severe thunderstorm nowcasts were compared with the thunderstorm intensity classification provided by TRT. Again, as described in section 5.1, the lead time represents the time lag between the first identification of the upcoming severe development provided by COALITION and the first detection of a severe thunderstorm by TRT. As presented in Table 4 skill scores decrease with increasing lead time. In the first 20 min, the POD decreases from 100% to 60%, whereas the FAR increases from 0% to 44.2% and the CSI decreases from 100% to 40.7%. For lead times longer than 20 min, however, skill scores decrease very rapidly: the algorithm tends to overestimate the intensity evolution of convective cells, but in some cases it missed the severe ones. In general, considering that COALITION provides fully automated identification and nowcasting of strong thunderstorms, the verification results are promising. Algorithms providing nowcasts with a POD greater than 60% and a FAR below 40% with an averaged lead time of about 15–20 min are considered reliable and potentially useful for operational forecasting purposes (e.g. Kober and Tafferner, 2009). For this reason, it can be concluded that COALITION nowcasts add value to operational thunderstorm nowcasts: in favourable conditions,

Table 4. Performance of COALITION for predicting development of severe thunderstorms.

Lead time	POD	FAR	CSI
5	**0.925**	**0.26**	**0.698**
10	**0.8**	**0.385**	**0.533**
15	**0.725**	**0.42**	**0.475**
20	**0.6**	**0.442**	**0.407**
25	0.375	0.487	0.277
30	0.225	0.64	0.161
35	0.125	0.689	0.098
40	0.05	0.8	0.042
45	0.025	0.8	0.023
50	0.025	0.834	0.022
55	0	0.843	0
60	0	0.85	0

Comparison of three skill scores (POD, FAR and CSI) for lead times between 5 and 60 min. Bold values indicate lead times for which the COALITION forecast can be considered useful. For this summary statistics, 80 case studies have been considered.

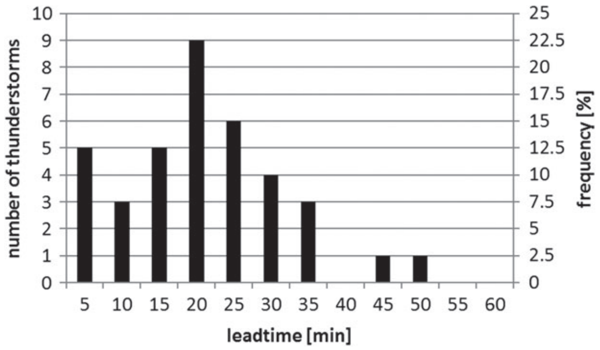

Figure 14. Frequency distribution of the lead times in identifying severe thunderstorms by COALITION. This histogram considers 40 cells that effectively developed into a severe thunderstorm.

severe weather alerts could be issued up to 20 min earlier than without the use of COALITION.

The distribution of 40 severe thunderstorms versus the lead time is presented in Figure 14. The figure shows that about half of all thunderstorms were identified 15–25 min before they were classified as severe by TRT. Only two cases were detected with lead time greater than 35 min, but on the other hand only three cases were not detected at all. Considering all cases, a typical lead time of about 20 min is obtained. Reviewing the different cases, it can be noted that missed forecasts or a detection with very small lead times (5–10 min) are often related to extremely explosive cells or convection embedded in cold fronts.

5.3. *Discussion*

The first real-time test phase of COALITION during the 2012 convective season and the detailed analysis of a large number of thunderstorm cells demonstrated that the nowcasts are generally useful for operational forecasting, providing support for convective intensity nowcasts. The continuity in time (consistency) of COALITION nowcasts is also an important factor to consider. Cells for which COALITION provides a consistent nowcast for two or more consecutive time steps have in fact a higher probability of increasing their intensity and reaching the severe stage. This probability is much lower when the nowcasts are less coherent in time. Usually, in the first case, all the surrounding environmental conditions (more than 80%) are consistent and agree with each other, showing favourable conditions for intensification. In the second case, the different environmental predictors provide less consistent information, resulting in a lower consistency between the different modules. Some of them indicate favourable conditions for the development and intensification of convective cells, whereas others indicate less favourable conditions, yielding a lower prediction skill.

The system showed some difficulties in handling convective development in some specific weather conditions. Typically, the case of strong synoptic-scale forcing in proximity to cold fronts and embedded convective cells is not well forecast, or their prediction has very short lead times (5 min). The reason has to do with the quality of some of the primary input products, in particular RDT. The identification of convective cells through a thresholding scheme and tracking based on the overlap-mechanism applied in the RDT algorithm are less suitable, especially in this case of dense cloudiness in a frontal band and in the absence of significant cloud-top temperature gradients. COALITION can deal fairly well with merging and splitting cells; however, some misdetections originated from embedded convection with a large number of convective cells. For this reason, COALITION performed best in cases with airmass convection, forced non-frontal and prefrontal convection, since the cells rarely become organized into larger mesoscale structures.

As mentioned in section 2, using RDT for early identification of convective processes requires modification and tuning. It was observed that, without these modifications, when the cells were first detected by RDT the first rain signals had already been detected by C-band ground radars. On the other hand, this tuning resulted in a strong increase in the number of false alarms. The ability of COALITION to integrate this information with other data sources allows it to reduce the number of false alarms considerably. Extremely rapidly developing cells, however, are usually detected by COALITION with a shorter lead time than in the average. This is simply due to the very high rate of growth characterizing these explosive storms.

6. Summary and conclusions

In this article, a newly developed object-oriented, heuristic approach to nowcasting severe convective storms over complex terrain has been presented. Severe convective cells are effectively identified in their early stages using a new, operational, convective intensity nowcasting system. The best available information in real time collected from satellites, ground-based weather radars, NWP, climatological data and digital terrain data is assimilated into the model. Cloud characteristics like cloud-top cooling rate, cloud depth and cloud glaciation and instability indices, precipitation intensities, climatological lightning information and terrain slopes are used as predictors. All this information is integrated using a conceptual model and a Hamilton's equation based formulation. The goal is to assess environmental conditions favouring growing storms and to model the evolution of selected storm intensity parameters, namely the vertically integrated liquid content (VIL) and the cloud-top temperature (CTT). The system was specially designed and tuned for the Alpine region and several techniques are applied in order to tackle the challenge of forecasting convective processes in complex terrain areas. In its current version, the algorithm relies on eight modules that integrate thunderstorm attributes with parameters of the surrounding convective environment. The system is able to handle the lack of one or more input datasets automatically and it provides the user, in real time, with information about the quality of the nowcast.

Using TRT as an independent reference, a preliminary cross-verification has been carried out on randomly selected cases for lead times ranging from 5–60 min. The quantitative analysis of thunderstorm attribute nowcasts and the related skill scores show promising results. COALITION nowcasts can be considered a reliable tool for operational forecasting. Skill scores demonstrate that the algorithm can help with early detection of convective cells, which are likely to increase in intensity and become severe, rather than simply highlight large areas prone to convection. For this reason, the concept and methodology are suitable for short-term nowcasts; this adds value for operational forecasts of severe thunderstorms and aids in the severe weather warning decision-making process.

The underlying idea of COALITION is to explain energy losses and gains within cells in the context of energy exchanges with the surrounding environment, according to an assumed total energy conservation rule. This interaction is described as a dynamical process. The fact that module results become much less reliable after 30–40 min (values diverge considerably) indicates that this methodology cannot be used for nowcasting purposes with lead times greater than 30 min. The rapid decrease in forecast skill has to be related to the nonlinearity and the chaotic nature of convective processes. According to Lorenz (1966), the predictability of an atmospheric phenomenon depends strongly on its lifetime. In particular, the lifetime of thunderstorm cells that are not organized in large-scale structures is very short and therefore the predictability decreases rapidly during the first 30 min (Wilson *et al.*, 1998; Wieringa and Holleman, 2006).

The system has been developed and tuned in particular for developing convective cells in their early stages. COALITION is an easily configurable system and it allows multiple extensions. Its modularity allows users to implement and test new input products in an intuitive manner. One possible way to improve the system's useful warning lead time would be through the implementation of other newly developed algorithms. In the same manner as done with RDT, other products providing information about the locations of convective cells in their early stages (e.g. Puca *et al.*, 2005; Zinner *et al.*, 2008; Mecikalski *et al.*, 2010) or clear-air pre-convective features (e.g. Petersen *et al.*, 2010) should be tested.

COALITION has been validated on 80 cases during the summer of 2012. Independent of the weather pattern, 40 weak and 40 severe thunderstorms were selected. The skill scores presented in this article demonstrate that COALITION nowcasts can help the forecaster to anticipate the issuing of severe thunderstorm warnings by about 20 min. The results of this article demonstrate that multisensor approaches can provide added value to convective intensity forecasting. The implementation of the system over new regions requires the availability of primary data sources. Furthermore, a regional tuning of the system is needed. Thanks to the modularity of the algorithm, the user can decide which modules of the COALITION algorithm to use. The skill scores presented in this article refer to a system tuned for the Alpine region and with all available data sources.

Efforts are ongoing to incorporate additional data types (particularly other environmental data) in order to improve the algorithm's skill to forecast cell regeneration and decaying processes better. Real-time lightning information (number of cloud-to-cloud and cloud-to-ground strokes) and low-level moisture convergence, a crucial condition for long-lasting thunderstorms as well as for re-intensification processes (Doswell *et al.*, 1996), are good candidates for future extensions of the algorithm. Furthermore, the employment of monthly and hourly lightning climatology instead of using a single global climatology should be considered. This predictor will help to introduce seasonal and diurnal tuning in the algorithm and therefore improve the skill of the forecast. In general, the addition of meaningful predictors should help to increase the overall skill of the system and increase its forecast lead time.

Concerning decaying processes, there are two possibilities to expand the algorithm. The first includes the formulation of the basic Hamiltonian equation in a statistical form, where the uncertainties are included in the algorithm. The second includes the possibility of modifying the basic equation by including a dissipation term (presented in section 3). During the development stage of a cell, this term is considered to be very small compared with the other terms and is therefore neglected. This assumption is confirmed by the fact that the total energy of the object–environment system remains constant over time. However, during the mature stage of a cell, the dissipation term becomes more and more important since the total energy no longer seems to be conserved.

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References

Autonés F. 2012. 'Algorithm theoretical basis document for 'rapid development thunder storms'', Nowcasting Satellite Application Facility (NWC-SAF) Report Issue 2 Rev. 3, Meteo France: Toulouse, France. http://www.nwcsaf.org/indexScientificDocumentation.html (accessed 9 October 2013).

Barthlott C, Corsmeier C, Meißner C, Braun F, Kottmeier C. 2005. The influence of mesoscale circulation systems on triggering convective cells over complex terrain. *Atmos. Res.* **81**: 150–175.

Bedka K, Brunner J, Dworak R, Feltz W, Otkin J, Greenwald T. 2010. Objective satellite-based detection of overshooting tops using infrared window channel brightness temperature gradients. *J. Appl. Meteorol.* **49**: 181–202.

Boudevillain B, Hervé A. 2003. Assessment of vertically integrated liquid (VIL) water content radar measurement. *J. Atmos. Oceanic Technol.* **20**: 807–819.

Bryan GH, Wyngaard JC, Fritsch JM. 2003. Resolution requirements for the simulation of deep moist convection. *Mon. Weather Rev.* **131**: 2394–2416.

Collier CG, Lilley RBE. 1994. Forecasting thunderstorm initiation in north-west Europe using thermodynamic indices, satellite and radar data. *Meteorol. Appl.* **1**: 74–84.

Craig GC, Keil C, Leuenberger D. 2012. Constraints on the impact of radar rainfall data assimilation on forecasts of cumulus convection. *Q. J. R. Meteorol. Soc.* **138**: 340–352.

Davolio S, Buzzi A, Malguzzi P. 2009. Orographic triggering of long lived convection in three dimensions. *Meteorol. Atmos. Phys.* **103**: 35–44.

De Coning E, Koenig M, Olivier J. 2011. The combined instability index: A new very-short range convection forecasting technique for southern Africa. *Meteorol. Appl.* **18**: 421–439.

Dixon M, Wiener G. 1993. TITAN: Thunderstorm identification, tracking, analysis, and nowcasting –a radar-based methodology. *J. Atmos. Oceanic Technol.* **10**: 785–797.

Doswell CA III. 2001. Severe convective storms –An overview. *Severe Convective Storms*, Meteorological Monographs 28: 1–26. American Meteorological Society: Boston, MA.

Doswell CA III, Brooks HE, Maddox RA. 1996. Flash flood forecasting: An ingredients-based methodology. *Weather and Forecasting* **11**: 560–581.

Emanuel KA. 1994. *Atmospheric Convection*. Oxford University Press: New York, NY.

Foresti L, Pozdnoukhov A. 2011. Exploration of Alpine orographic precipitation patterns with radar image processing and clustering techniques. *Meteorol. Appl.* **19**: 407–419.

Fujita T. 1968. Present status of cloud velocity computations from ATS-1 and ATS-3. *COSPAR Space Res.* **9**: 557–570.

Goodman SJ, Gurka J, DeMaria M, Schmit TJ, Mostek A, Jedlovec G, Siewert C, Feltz W, Gerth J, Brummer R, Miller S, Reed B, Reynolds RR. 2012. The GOES-R proving ground. Accelerating user readiness for the next-generation geostationary environmental satellite system. *Am. Meteorol. Soc.* **7**: 1029–1040.

Greene D, Robert R, Clark A. 1972. Vertically integrated liquid water –a new analysis tool. *Mon. Weather Rev.* **100**: 548–552.

Handwerker J. 2002. Cell tracking with TRACE3D –a new algorithm. *Atmos. Res.* **61**: 15–34.

Hering AM, Morel C, Galli G, Sénési S, Ambrosetti P, Boscacci M. 2004. Nowcasting thunderstorms in the Alpine region using a radar based adaptive thresholding scheme. In *Proceedings of 3rd European Conference Radar in Meteorology and Hydrology (ERAD)*, 6–10 September 2004, Visby, Sweden. 1–6. Copernicus: Goettingen, Germany.

Hering AM, Germann U, Boscacci M, Sénési S. 2008. Operational nowcasting of thunderstorms in the Alps during MAP D-PHASE. In *Proceedings of 5th European Conference on Radar in Meteorology and Hydrology (ERAD)*, 30 June–4 July 2008, Helsinki, Finland. 1–5. Copernicus: Goettingen, Germany.

Hilker N, Badoux A, Hegg C. 2010. Unwetterschaeden in der Schweiz im Jahre 2009. *Wasser Energ. Luft* **102**: 1–6 (in German).

Huntrieser H, Schiesser HH, Schmidt W, Waldvogel A. 1996. Comparison of traditional and newly developed thunderstorm indices for Switzerland. *Weather and Forecasting* **12**: 108–125.

Johnson JT, Mackeen PL, Witt A, Mitchell ED, Stumpf GJ, Eilts MD, Thomas KW. 1998. The storm cell identification and tracking algorithm: An enhanced WSR-88D algorithm. *Weather and Forecasting* **13**: 263–275.

Joss J, Schaedler B, Galli G, Cavalli R, Boscacci M, Held E, Della Bruna G, Kappenberger G, Nespor V, Spiess R. 1998. *Operational Use of Radar for Precipitation Measurements in Switzerland*. vdf Hochschulverlag AG ETH Zuerich: Zuerich, Switzerland.

Kain JS, Weiss SJ, Bright DR, Baldwin ME, Levit JJ, Carbin GW, Schwartz CS, Weisman ML, Droegemeier KK, Weber DB, Thomas KW. 2008. Some practical considerations regarding horizontal resolution in the first generation of operational convection-allowing NWP. *Weather and Forecasting* **23**: 931–952.

Kober K, Tafferner A. 2009. Tracking and nowcasting of convective cells using remote sensing data from radar and satellite. *Meteorol. Z.* **1**: 75–84.

Koenig M, De Coning E. 2009. The MSG global instability indices product and its use as a nowcasting tool. *Weather and Forecasting* **24**: 272–285.

Kottmeier C, Kalthoff N, Bathlott C, Corsmeier U, Van Baelen J, Behrendt A, Behrendt R, Blyth R, Coulter R, Crewell S, Di Girolamo P, Dorninger M, Flamant C, Foken T, Hagen M, Hauck C, Hoeller H, Konow H, Kunz M, Mahlke H, Mobbs S, Richard E, Steinacker R, Weckwerth T, Wieser A, Wulfmeyer V. 2008. Mechanisms initiating deep convection over complex terrain during COPS. *Meteorol. Z.* **6**: 931–948.

Lang P. 2001. Cell tracking and warning indicators derived from operational radar products. In *Proceedings of 30th International Conference on Radar Meteorology*, 19–24 July 2001, Munich, Germany: 245–247. American Meteorological Society: Boston, MA.

Ligda MG. 1953. '*The horizontal motion of small precipitation areas as observed by radar*', Technical Report 21. Massachusetts Institute of Technology, Department of Meteorology: Cambridge, MA.

Lorenz EN. 1966. Atmospheric Predictability, *Advances in Numerical Weather Prediction*. Travellers Research Center, Inc.: Hartford, CT.

Mak M. 2001. Nonhydrostatic barotropic instability: Applicability to nonsupercell tornadogenesis. *J. Atmos. Sci.* **58**: 1965–1977.

Mandapaka P, Germann U, Panziera L, Hering A. 2011. Can Lagrangian extrapolation of radar fields be used for precipitation nowcasting over complex Alpine orography? *Weather and Forecasting* **27**: 28–49.

Martinez MA, Velazquez M, Manso M, Mas I. 2007. Application of LPW and SAFNWC/MSG satellite products in pre-convective environments. *Atmos. Res.* **83**: 366–379.

Mecikalski JR, Bedka KM. 2006. Forecasting convective initiation by monitoring the evolution of moving cumulus in daytime GOES imagery. *Mon. Weather Rev.* **134**: 49–78.

Mecikalski JR, Bedka KM, Paech SJ, Litten LA. 2008. A statistical evaluation of GOES cloud-top properties for nowcasting convective initiation. *Mon. Weather Rev.* **136**: 4899–4914.

Mecikalski JR, Mackenzie WM, Koenig M, Muller S. 2010. Use of *Meteosat* Second Generation infrared data in 0–1 hour convective initiation nowcasting. Part 1. Infrared fields. *J. Appl. Meteorol.* **49**: 521–534.

Mecikalski JR, Bedka KM, Koenig M. 2012. '*Best practice document*'. EUMETSAT, ESSL Convection Working Group. http://essl.org/cwg/?p=178 (accessed 9 October 2013).

Mecikalski JR, Li X, Carey LD, McCaul EW, Coleman TA. 2013. Regional comparison of GOES cloud-top properties and radar characteristics in advance of first-flash lightning initiation. *Mon. Weather Rev.* **141**: 55–74.

Mecklenburg S, Joss J, Schmid W. 2000. Improving the nowcasting of precipitation in an Alpine region with an enhanced radar echo tracking algorithm. *J. Hydrol.* **239**: 46–68.

Miles J, Salmon R. 1985. Weakly dispersive nonlinear gravity waves. *J. Fluid Mech.* **157**: 519–531.

Mueller C, Saxen T, Roberts R, Wilson J, Betancourt T, Dettling S, Oien N, Yee J. 2003. NCAR auto-nowcast system. *Weather and Forecasting* **18**: 545–561.

Petersen RA, Aune R, Rink T. 2010. Objective short-range forecasts of the preconvective environment using SEVIRI data. *Proceedings the 2010 EUMETSAT Meteorological Satellite Conference*, 20–24 September 2010, Cordoba, Spain. 1–7. EUMETSAT: Darmstadt, Germany.

Pielke RA, Segal M. 1986. *Mesoscale Meteorology and Forecasting*, American Meteorological Society: Boston, MA.

Pierce CE, Hardaker PJ, Collier CG, Haggett CM. 2000. GANDOLF: A system for generating automated nowcasts of convective precipitation. *Meteorol. Appl.* **7**: 341–360.

Puca S, Biron D, De Leonimbus L, Melfi D, Rosci P, Zauli F. 2005. A neural network algorithm for the nowcasting of severe convective systems. In *Proceeding of CIMSA 2005-IEEE International Conference on Computing Intelligence for Measurement System Applications*, 20–22 July 2005, Giardini Naxos, Greece. 81–84. IEEE: Piscataway, NJ.

Roberts RD, Burgess D, Meister M. 2006. Developing tools for nowcasting storm severity. *Weather and Forecasting* **21**: 540–558, doi: http://dx.doi.org/10.1175/WAF930.1.

Roberts RD, Rutledge S. 2003. Nowcasting storm initiation and growth using GOES-8 and WSR-88D data. *Weather and Forecasting* **18**: 562–584.

Rosenfeld D, Woodley WL. 2000. Deep convective clouds with sustained supercooled liquid water down to $-37.5\,^{\circ}$C. *Nature* **405**: 440–442.

Rosenfeld D, Woodley WL, Lerner A, Kelman G, Lindsey DT. 2008. Satellite detection of severe convective storms by their retrieved vertical profiles of cloud particle effective radius and thermodynamic phase. *J. Geophys. Res.* **113**: D04208, doi: 10.1029/2007JD008600.

Rotach MW, Ambrosetti P, Ament F, Appenzeller C, Arpagaus M, Bauer HS, Behrendt A, Bouttier F, Buzzi A, Corazza M, Davolio S, Denhard M, Dorninger M, Fontannaz L, Frick J, Fundel F, Germann U, Gorgas T, Hegg C, Hering A, Keil C, Liniger MA, Marsigli C, McTaggart-Cowan R, Montaini A, Mylne K, Ranzi R, Richard E, Rossa A, Santos-Munoz D, Schaer C, Seity Y, Staudinger M, Stoll M, Volkert H, Walser A, Wang Y, Werhahn J, Wulfmeier W, Zappa M. 2009. MAP D-PHASE: Real-time demonstration of weather forecast quality in the Alpine region. *Bull. Am. Meteorol. Soc.* **90**: 1321–1336.

Salmon R. 1998. *Lecture on Geophysical Fluid Dynamics*. Oxford University Press: Oxford, UK.

Schmetz J, Pili P, Tjemkes S, Just D, Kerkmann J, Rota S, Ratier A. 2002. An introduction to Meteosat Second Generation (MSG). *Bull. Am. Meteorol. Soc.* **83**: 977–992.

Schultz CJ, Carey LD, Petersen WA. 2009. Preliminary development and evaluation of lightning jump algorithms for the real-time detection of severe weather. *J. Appl. Meteorol.* **48**: 2543–2563.

Setvák M, Rabin RM, Doswell CA, Levizzani V. 2003. Satellite observations of convective storm top features in the 1.6 and 3.7/3.9 m spectral bands. *Atmos. Res.* **67–68C**(:): 589–605.

Steinacker R, Dorninger M, Wolfelmaier F, Krennert T. 2000. Automatic tracking of convective cells and cell complexes from lightning and radar data. *Meteorol. Atmos. Phys.* **72**: 101–109.

Wieringa J, Holleman I. 2006. If cannons cannot fight hail, what else? *Meteorol. Z.* **15**: 659–669.

Weisman ML, Skamarock WC, Klemp JB. 1997. The resolution dependence of explicitly modeled convective systems. *Mon. Weather Rev.* **125**: 527–548.

Wilks DS. 1995. *Statistical Methods in the Atmospheric Sciences: An Introduction*. Academic Press: Amsterdam.

Wilson JW, Crook NA, Mueller CK, Sun J, Dixon M. 1998. Nowcasting thunderstorms: A status report. *Bull. Am. Meteorol. Soc.* **79**: 2079–2099.

Wulfmeyer V, Behrendt A, Bauer H-S, Kottmeier C, Corsmeier U, Blyth A, Craig GC, Schumann U, Hagen M, Crewell S, Di Girolamo P, Flamant C, Miller M, Montani A, Mobbs SD, Richard E, Rotach MW, Arpagaus M, Russchenberg H, Schlussel P, Koenig M, Gaertner V, Steinacker R, Dorninger M, Turner DD, Weckwerth T, Hense A, Simmer C. 2008. The Convective and Orographically induced Precipitation Study: A research and development project of the World Weather Research Program for improving quantitative precipitation forecasting in low-mountain regions. *Bull. Am. Meteorol. Soc.* **89**: 1477–1486.

Zinner T, Mannstein H, Tafferner A. 2008. Cb-TRAM: Tracking and monitoring severe convection from onset over rapid development to mature phase using multi-channel Meteosat-8 SEVIRI data. *Meteorol. Atmos. Phys.* **101**: 191–210.

