Summary

Deep convective clouds are fascinating but dangerous phenomena of mid-latitude continental summer weather, with a large impact on society due to their associated hazards. Thunderstorm forecasts and warnings are complicated by the stochastic nature of convection, and the small-scale structures involved in the destabilization and convective initiation process. In our proposed work, we target the early detection of convective initiation over Central Europe, and the optimal exploitation of geostationary satellite observations together with complementary information from precipitation radar, the LINET lightning detection network, and atmospheric models. Our central objective is to increase the lead time for thunderstorm warnings, and to enhance our process understanding of convective initiation, the early convective life cycle, and the subsequent development of severe storms. An established scheme for nowcasting convective initiation will be extended into a probabilistic framework, and further optimized through the use of a large, hand-curated training dataset, enabling a detailed analysis of the algorithm's uncertainties and shortcomings. The currently used set of interest fields will be refined and complemented by additional fields including satellite-based cloud products, complementary observations and atmospheric model output, aiming for a significant improvement in overall accuracy. Based on multi-sensor observations and severe weather reports, interrelationships between growth properties and the subsequently observed storm severity will be investigated. The application of our proposed methods to forecasts from the integrated forecast system will allow us to evaluate the realistic representation of the early convective life cycle by the model, and is a first step towards using the CI detection algorithm for model verification. Preparatory activities will also ensure an optimal use of data from the upcoming METEOSAT Third Generation satellites.

1 Goals

Our proposed work focuses on the detection and characterisation of developing deep convection in Central Europe, and is guided by **two main objectives:**

(i) to establish a probabilistic and adaptive Meteosat-based scheme for a reliable detection of developing deep convection, for nowcasting severe thunderstorms and for improving the lead time of severe weather warnings operationally at DWD

(ii) to enhance our understanding of the initiation and life cycle of severe convective storms, and to evaluate their representation in atmospheric models

At DWD, the SATCAST algorithm developed by J. Mecikalski has recently been implemented to identify potentially dangerous convective development prior to the onset of precipitation. In our proposed work, we target an increased accuracy of this algorithm, and in particular a reduction of false alarm rate to improve its suitability for application in an operational forecast environment. The inclusion of probabilistic information will enable a better situation-awareness for forecasters.

This methodology will also be applied to enhance our understanding of the processes governing the initiation and early growth phase of severe convective storms, and evaluate their representation in atmospheric models. Satellite data will be complemented with observations from precipitation radars and the lightning network to study the growth phase and life cycle of deep convective clouds, and investigate their microphysical and dynamical properties along their tracks. The understanding of similarities and differences of individual storms is essential for improving thunderstorm nowcasting and our warning capabilities, and thus will increase the benefit of current and upcoming observational networks for society.

2 Current state of understanding and preliminary work

Geostationary satellites offer unique time-resolved observations of developing convection, and can thereby help to enhance our understanding and improve forecasting capabilities. Current nowcasting systems show good forecast skills once the convective systems are well-developed and detectable in radar imagery. Cumulus clouds in their early growth stage, however, can already be observed by satellites 15–60 min in advance of precipitation formation (Mecikalski et al., 2013). This has led to the development of satellite-based detection schemes of *convective initiation* (CI) based on time sequences of images from the American GOES satellites (e.g. Mecikalski and Bedka, 2006; Walker et al., 2012). Following Mecikalski et al. (2013), the main limitations in current CI detection algorithms are related to: (1) sensor resolution in the IR channels being mostly above the cumulus cloud scale (3–4 km in IR), i.e. **small-scale spatial variability;** (2) the ability to accurately and consistently **identify cumulus clouds** in satellite imagery; and (3) difficulties in tracking and monitoring the properties of growing cumulus clouds across successive images, i.e. **temporal variability**. First successful applications of the satellite-based CI detection to Central Europe have already been performed in e.g. Mecikalski et al. (2010a, 2010b, 2011), Siewert et al. (2010) and Matthee and Mecikalski (2013). Supported by EUMETSAT, an implementation of the CI algorithms was developed by Zofia Kocsis (Kocsis and König, 2012), and is currently being evaluated and further refined for operational use at DWD. The observed high false alarm rates of CI detection does however pose a significant hurdle to its adoption for operational forecasting, and indicates that further research related to CI and convective life cycle is needed. Currently, the proposal authors are incorporating the convective cloud mask of Berendes et al., (2008) in the CI algorithm, and establishing a validation environment based on radar data for quantifying the benefits of such improvements.

The initiation and growth of several severe thunderstorms in Central Europe was investigated in previous studies by the authors of this proposal (Senf et al., 2015; Wapler et al., 2015; Horvath et al., 2012). Several satellite-based storm properties including cloud-top temperature, cloud-top cooling rate and cloud effective radius, but also lightning and precipitation related characteristics were investigated along storm tracks. Senf et al. (2015) discussed the maximum cloud-top cooling rate as a typical growth feature, with a subsequent growth phase lasting around half an hour. Temporal changes in the anvil size were related to the maximum cooling rate. Furthermore, a detailed characterization of two severe thunderstorm cells which caused exceptionally large damages in the Alpine region was performed in Wapler et al. (2015). We showed that cloud-top cooling reaches maximum values around 60 min to 80 min before the maximum in radar cell size. Additionally, lightning jumps and cold U-shaped features in the cloud-top morphology were connected to further storm intensification. To improve our understanding of the mature phase of severe weather systems, a Lagrangian analysis of precipitation cells over Germany was conducted combining geostationary satellite retrievals with radar and lightning observations (Horvath et al., 2012). The radar and lightning signatures of tracked precipitation cells have been composited together with cloud macro- and microphysical satellite products. By analysing a large number of storm life cycles, it was found that lightning intensity is inherently different in phases with increasing vs. decreasing effective ice crystal size. Towards improving the characterization of growing cumuli, a downscaling approach for Meteosat narrow-band spectral radiances based on the high-resolution visible channel has been developed to improve their spatial resolution (Deneke and Roebling, 2010; Bley and Deneke, 2013) and has been applied for cumulus detection (Carabajal-Henken et al., 2011). As an deliverable of the HD(CP)^2 project, a downscaled cloud dataset will be made available, and wiull support the CI-related activities within this project. During our former OASE project within HErZ phase I, a framework for combining multi-sensor data in a composite was developed, and expertise in the synergetic combination of different remote sensing data was gained (Weissmann et al., 2014).

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2.1 Project-related publications of the investigators

Peer-reviewed:

Bley, S. and **Deneke, H.**, (2013): A threshold-based cloud mask for the high-resolution visible channel of Meteosat Second Generation SEVIRI. *Atmos. Meas. Tech.*, **6**, p.2713-23.

Carabajal-Henken, C. C., Schmeits, M. J., **Deneke, H.** and Roebeling, R. A., (2011): Using MSG-SEVIRI Cloud Physical Properties and Weather Radar Observations for the Detection of Cb/TCu Clouds. *J. Appl. Meteor. Climatol.*, 50, p.1587-1600.

Deneke, H. and Roebeling, R., (2010): Downscaling of METEOSAT SEVIRI 0.6 and 0.8 um channel radiances utilizing the high-resolution visible channel. *Atmos. Chem. Phys.*, **10**, p.9761-72.

Senf, F., Dietzsch, F., Hünerbein A. and **Deneke, H.,** (2015): Characterization of initiation and growth of selected severe convective storms over Central Europe with MSG-SEVIRI. *J. Appl. Meteor. Climatol.*, 54 (1), p.207 – 224.

Wapler, K., Harnisch, F., Pardowitz, T., and **Senf, F.**, (2015): Characterisation and predictability of a strong and a weak forcing severe convective event - a multi-data approach. *Meteorol. Z.,* 24(4), p.393-410.

Weissmann, M., Göber, M., Hohenegger, C., Janjic, T., Keller, J., Ohlwein, C., Seifert, A., Trömel, S., Ulbrich, T., Wapler, K., Bollmeyer, C., and **Deneke, H.**, (2014): The Hans-Ertel Centre for Weather Research – Research objectives and highlights from its first three years. *Meteorol. Z.,* 23(3), p.193-208.

Other:

Horvath, A., Wapler, K., **Senf, F., Deneke, H.**, Diederich M., Simon J., Trömel S. (2012): Lagrangian analysis of precipitation cells using satellite, radar, and lightning observations. *Proceedings of the 2012 EUMETSAT Meteorological Satellite Conference*, Sopot, Poland.

3 Research plan

3.1 Research plan for Ph.D. project 2016-2018

The work for the PhD phase of INCITES is structured into four packages, starting with direct enhancements to the current CI detection scheme implemented at DWD (WPs 1 and 2), and extending our research to more experimental topics, which target an improved understanding of the underlying atmospheric processes as well as model verification (WPs 3 and 4).

WP1 Training data set, Probabilistic CI, and Optimization for MSG (Months 1-12): The CI algorithm currently implemented at DWD is based on the original version of the SATCAST algorithm developed for the American GOES satellites (Mecikalski and Bedka, 2006; Walker et al., 2012). It uses a threshold-based approach applied to cloudy radiances including their temporal changes to identify fast-growing and potentially dangerous clouds, and results in a binary decision whether convective initiation will take place or not. Some adaptations have been made to this scheme to be applicable to the European METEOSAT satellites (Siewert et al., 2010). Here, we propose a systematic re-training of all thresholds to optimally exploit the instrumental capabilities of the SEVIRI instrument including the availability of 5 minute rapid scan data. For this purpose, an extensive, hand-curated test data set comprising at least several hundred true CI events over Germany and central Europe from multiple years will be established, using a radar-based threshold of 35dBZ (Roberts and Rutledge, 2003) to identify true CI events. The binary decision tree of the SATCAST algorithm will be reformulated in a probabilistic framework to output the probability of CI instead of a binary decision. For this, logistic regression (see Mecikalski et al., 2015) and alternative state-of-the-art statistical methods such as support vector machines will be considered. In support of this work, tools will be developed to help build the training data set using RADOLAN radar data, and to automatically calculate validation statistics for the CI-algorithm based on a k-fold cross-validation procedure for a large number of cases. This will extend current work carried out within the context of a DWD tender granted to the proposal authors. As final item of WP1, the overall accuracy of the scheme shall be quantified for both daytime and nighttime, the latter missing the availability of the solar channel informatino. Limitations of the detections will be assessed on a case-by-case basis, with the aim of identifying specific aspects requiring further improvements.

WP2 Additional Interest Fields, Tracking Accuracy and Information Content (Months 9-18): Within this WP, the validation framework established in WP1 will be used for an analysis of the information content of existing and new interest fields, and to assess the influence of critical aspects of the algorithm on its overall accuracy. Specifically, the information content of satellite-derived cloud properties including their time trends, like cloud optical depth and effective radius, will be investigated. Here, we plan to exploit a new downscaled set of cloud properties based on the high-resolution visible channel with a 3-fold higher resolution than standard products (developed within the project HD(CP)2, and preliminary work described in Deneke and Roebeling, 2010). This dataset allows to better resolve small-scale structures in cumulus cloud fields. Also, textural information and environmental fields obtained from model forecasts will be considered. The benefits of using the convective cloud mask of Berendes et al. (2008) will be quantified, both as an interest field in the classifier and to limit computations to specific regions. The accuracy of the cloud field tracking as core part of the CI algorithm will be studied in depth. Error estimates will be established on the basis of cross-correlation matrices, where steeper maxima indicate a higher accuracy of tracking than broader ones. The original SATCAST algorithm uses 15 and 30 min time trends to estimate the cooling rates of ascending cloud tops. With the 5 minute rapid scan service of Meteosat, the cloud growth can be much better resolved (Merk and Zinner, 2013), and the benefit of the increased time resolution will be assessed. Furthermore, it will be investigated if the detailed history of past cloud development can provide further clues useful for CI detection. Recursive Feature Elimination or a similar technique will be applied to evaluate the contribution of individual interest fields to the overall accuracy of the CI detection, and to remove redundant information. This allows us to reduce the complexity of the algorithm, which is important due to stringent timing and run-time requirements for the provision of near-realtime forecasts.

WP3 Pre-Convective Environment, CI, and Early Convective Life Cycle (Months 18-24): While the previous WPs have concentrated on the use of satellite data, and have treated CI mainly as a classification problem, this work package seeks a deeper understanding of the physical processes governing the early development and life cycle of convective systems. First, the pre-convective environment under different weather regimes will be considered as important factor that influences both cumulus growth and the quality of satellite-based CI detections. For this, model-based interest fields will be included in the CI detection (see Mecikalski et al., 2015 for details). It will be assessed if a minimal, situation-dependent set of CI parameters can be constructed that introduces information about the environment into an adaptive CI detection framework. In addition, differences in the early convective life cycle and the development into different storm types depending on environmental parameters will be investigated. Here, efforts will be focused on establishing the link between environmental conditions and early growth properties, the subsequent severity of storms, and the probability of detection by the CI algorithm. Secondly, the classical CI definition of an event that produces radar reflectivity above 35 dBZ will be revisited. Using a consistent (likely object-based) treatment of satellite, radar and lightning observations, it will be studied if the binary threshold for the radar reflectivity can be generalized to a categorical multi-sensor based definition of a CI event, which is better suited for the identification of severe and potentially dangerous convection.

WP 4a Integrated Forecast System (Months 24 -36): In the final WP of the PhD phase, the representation of convective initiation and growth properties of convective development in state-of-the-art operational convection-permitting numerical forecasts will be assessed, with a special emphasis on satellite-based cloud observations and properties. Using a radiative transfer code (us of the RTTOV model is planned), synthetic infrared brightness temperatures will be calculated and the applicable analyses of WP3 will be redone based on forecast fields instead of observations. The statistical properties of convective growth in the model will be quantitatively compared to the observations, and possible model shortcomings will be identified. The overall aim is not only to provide guidance on the numerical model performance, but also an on the-fly quality scoring for further use in the integrated forecast system. Furthermore, highly-resolved LES-type model simulations of developing deep convection in realistic situations (obtained through a cooperation with the HD(CP)2 project) will be used to simulate synthetic satellite observations and to study the limitations of the CI detection algorithm due to the current spatial and temporal resolution of observations. With this work, we will also attempt to quantify the benefit of the improved time-space resolution characteristics of upcoming satellite sensors (specifically Meteosat Third Generation) for the quality of convection nowcasting.

3.2 Research plan for full-time scientist (2019)

A preliminary plan for the final year and PostDoc phase of INCITES is given next, which is split into 3 work packages, with the third work package continuing from the previous phase. Only a brief sketch is given here, as details will be decided upon during the project based on the experience gained during the PhD phase of the project, feedback from DWD experts, and the priorities of DWD and TROPOS.

WP5 Operationalization of CI scheme: this WP will target specific shortcomings of the CI detection algorithm which have been identified during the course of the project, and which have shown to be problematic for an adoption of the scheme in operational use. A key element of this work will be to obtain feedback from forecasters on the utility and problematic aspects of the CI detection in an operational forecast environment. Participation in the Testbed organized by the European Severe Stroms Lab is planned for 2019 to ensure this feedback. Efforts for a near-real time generation of CI forecasts and a suitable visualization of results are required to enable an efficient participation in the Testbed.

WP6 Adaptation to MTG: previous WPs have focused mainly on observations from the METEOSAT Second Generation series of satellites. METEOSAT Third Generation due for first launch in 2019 will offer greatly improved observational capabilities for the detection of CI, in particular through increased temporal and spatial resolution, as well as new spectral channels. However, the statistical classifier used in the CI detection scheme will have to be re-trained and adapted to the new data to fully benefit from these capabilities. In collaboration with the Satellite Meteorology Department of DWD, a strategy for a smooth transition from MSG to MTG will be developed, and specific aspects such as the effects of improved spatial and temporal resolution will be investigated. It has to be stressed, however, that additional resources beyond the project phase of INCITES are likely required to fully exploit the additional value of MTG data.

WP4b Integrated Forecast System and Forecast Verification: this WP will continue the work begun within WP4a to extend the CI detection scheme towards an object-based tool for model verification (see description of WP4a for details). A concrete goal is the extension of the work of WP4a through the consideration of model-based simulations of the solar reflectance observations. The feasibility of this goal does depend on the availability of a fast satellite simulator capable of simulating solar satellite channels (there is currently ongoing work to include this functionality into RT-TOV).

3.3 DWD support requested by applicant

A close collaboration with DWD is central to the success of our project. Specifically, our work on improving the detection of CI will be closely coordinated with the Department for Satellite Meteorology at DWD, to ensure that results and improvements are directly applicable to the operational nowcasting system of DWD. Also, interaction with and feedback from forecasters on the benefits and limitations of an improved CI detection scheme would be highly desirable. Access to additional relevant observations including radar- and lightning data is important for our research, in particular for WP3. Also, WP4 requires access to model forecasts from DWD’s integrated forecast system, including simulated satellite observations based on the SynSat scheme if possible at 5 minute or higher time resolution. Coordination of case studies and discussion of our results with DWD experts would be highly welcome and beneficial to our work.

3.4 Realisation plan

A central goal of the project is an improved early detection of developing severe convection based on geostationary satellite and other supplementary observations. This research will facilitate an improved nowcasting of severe convection, and thereby directly support DWD in one of its core tasks, the provision of weather warnings to protect life and property of German citizens. Hence, a quick operationalization of promising results during and after the project is sought and of high priority for both TROPOS and DWD. Our research also targets an improved understanding of the formation and development of severe convection, and thereby contributes to the verification and improvement of atmospheric models.

4 Literature

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5 Utilisation in DWD and applicant institution

5.1 Perspectives for contribution of research to future improvements of operational systems used in DWD and in the German research community

While we plan to utilize additional observations beside satellite data in the present study – specifically the German radar and lightning detection networks, the synergistic combination of multi-sensor data remains a topic with significant future potential for improving nowcasting systems and for gaining additional insights into the atmospheric processes relevant for severe convection, a topic of great interest for understanding weather and climate and thus of high relevance to society.

Improved observational capabilities – especially the upgrade of the DWD radar network to polarimetry and the upcoming METEOSAT Third Generation (MTG) series of satellite - will also offer exciting new opportunities for future research. The launch of the first satellite is currently planned in 2019, and offers great improvements for CI, including a regional rapid scan service for Europe with 2.5 minute repeat cycle, a spatial resolution down to 500m, and additional spectral channels enabling a better detection of thin cirrus clouds. A lightning imager and an infrared sounder will offer new information about convective activity and atmospheric profiles, and could provide valuable new interest fields for CI detection. While some aspects related to the adaptation of the CI detection algorithm for MTG will be investigated within this proposal, further research efforts are needed to exploit the full potential of MTG. The tools established within our projects – for creating a training dataset, for training the classifiers, and for evaluating the accuracy of the CI algorithm – can however serve as solid basis for this work.

Additionally, it seems promising to continue our efforts towards application of the CI detection algorithm as an object-based tool for model verification. This approach allows a consistent observation-based evaluation of the correct timing and location of the initiation of convective events in model forecasts, and to verify the realistic representation of their life cycle. The feasibility for this approach does however depend on the availability of a satellite simulator capable of simulating METEOSAT channels (SynSAT is currently only able to simulate infrared channels). Assimilation of dynamic information gained by the object-based analysis methods applied to the CI detection into models is a further worthwhile avenue for future research.

5.2 Perspectives for contribution of research to strategic and research aims of applicant institution

TROPOS is an internationally renowned institute in the field of aerosol and cloud physics. Its mission is to improve our understanding of the physical and chemical properties of aerosols and clouds, including their relevant processes and interactions. The central goals of INCITES – to better understand the processes involved in the formation and development of severe convection, and to apply this understanding for improved weather warnings – align very well with the mission of TROPOS. In fact, several key aspects of deep convection, including the role of freezing and its modulation by aerosols, represent key research topics at TROPOS. Recently, TROPOS and DWD have submitted a proposal to DFG to investigate the role of aerosols on deep convection, and to evaluate the convective invigoration hypothesis. If funded, both efforts would benefit from strong synergies between them. The Leibniz society also encourages its institutes to actively transfer its knowledge and technology to operational applications for the benefit of society. Hence, a long-term partnership between TROPOS and DWD with the goal of an optimal use of current and upcoming meteorological satellites for better understanding and nowcasting severe convection would be highly welcome.

6 Support of early career scientists and equal opportunities

The PhD student working on the proposed project will join the Satellite Remote Sensing workgroup, which was established in 2010 and is part of the Department of Remote Sensing at TROPOS.The workgroup is strongly committed to the education of young scientists, through contributions to teaching at the University of Leipzig, supervision of undergraduate theses, and training and qualification of doctoral candidates. In fact, two persons currently employed at DWD, Dr. Timo Hanschmann and F. Dietzsch, have written their PhD and Master's Thesis, respectively, within the workgroup. The student shall submit his/her PhD thesis to the Faculty of Physics and Geosciences of the University of Leipzig, with Prof. Andreas Macke (TROPOS), or Prof. Johannes Quaas, (Uni Leipzig) serving as thesis supervisor.

Starting in 2012, TROPOS and the Meteorological Institute of Uni Leipzig have established a joint structured doctoral training program within the framework of the Leipzig Graduate School on Clouds, Aerosols and Radiation (LGS-CAR, see http://www.lgs-car.tropos.de/) to ensure a high quality and attractive doctoral education in Leipzig. All new PhD candidates at both institutions are strongly encouraged to join this program, which will be continued beyond the period of the graduate school from internal funding. It is structured into two parts, the "Research Training" and the "External Training Program". The former consists of research work for the doctoral thesis, 6-monthly meetings with a supervisor team composed of the direct supervisor and two further experienced researchers, and an open doctoral student seminar, where students present and discuss their progress and future plans for their PhD work. The "External Training Program" consists of a number of obligatory elements, including Advanced Training Modules on specific topics, a yearly intersection workshop for the discussion of intersection points between the different research topics, soft skill courses and ring lectures. Optional and strongly encouraged elements include the participation of PhD candidates in summer/winter schools and conferences, and an external research stay at a partner institution. The PhD candidate working on INCITES will strongly benefit from the extra qualification elements offered by this program.

TROPOS is committed to gender equality. In 2010, it has established an equal opportunities plan to implement the Equal Opportunities Agreement, the Framework Recommendation on Equal Opportunities for Women and Men at the institutes of the Leibniz Association, and the DFG Research-oriented Equal Opportunities Standards. This plan is evaluated and updated every two years. Based on the plan, the Institute has implemented a large number of measures to increase the proportion of women in senior scientific positions, to promote young female researchers, and to create a family-friendly working environment. These measures are shaped and implemented in a close and fruitful collaboration between management, the Equal Opportunities Officer and staff.