OPERATIONAL NOWCASTING BASED ON SATELLITE CLOUD MOTION WINDS

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ABSTRACT

Most works and studies on satellite-derived cloud motion winds focus on their extraction and quality control, and on their impact on numerical weather prediction models. But cloud motion winds also provide important real-time information on current cloud movement, thus being a valuable input to short-range weather prediction. This paper addresses this important practical aspect and discusses the use of cloud motion winds for operational nowcasting. It describes how the CineSat software package computes real-time cloud motion fields and converts them into several nowcast products, like predicted satellite images, predicted cloud trajectories, cloud development maps, and smoothly interpolated weather animation movies. CineSat has been validated at two European meteorological institutes for more than a year and is also used successfully in the demanding field of air traffic control. The predicted satellite images turned out to be valid and plausible for up to 3 hours ahead in the infra-red channel, and more than 4 hours ahead in the water vapour channel. All CineSat forecasts are available in real-time, i.e. about 3-5 minutes after reception of the latest satellite image. The paper shortly describes the basic concept and methods, the built-in applications and - most important - it gives an overview on the rich palette of practical applications of cloud motion winds at several meteorological institutes.

1. INTRODUCTION

Atmospheric motion vectors derived from satellite imagery contain valuable information about on-going movement of clouds and cloud systems. However, up to now they have hardly been used in daily routine weather forecasting. This is due to the fact that just providing quality controlled cloud motion winds does not properly convey the nowcast information to the forecaster.

At the 3rd Winds Workshop in 1996, we presented a workstation software for the extraction and quality control of cloud motion winds. The response of the forecasters to that system was almost zero. In the following we involved the forecasters of several meteorological institutes into the future development of the system and have now successfully taken the step towards an automatic production of nowcasting products based on cloud motion analysis.

CineSat Nowcast is a software package that *analyses and forecasts cloud movement in real-time.* Provided with a sequence of weather satellite images, it computes the following real-time products:

- Quality controlled cloud motion *winds* and *cloud motion fields*
- *Forecasted satellite images* for the next 2 - 4 hours (all spectral channels)
- Smooth and accurate *weather animation movies* based on cloud movement analysis
- Automatic *cloud development maps* derived by image change detection
- *Trajectories* that predict the future movement of clouds and thunderstorms.

Real-time in this context means that all forecast products are computed and updated every half-hour, and are available several minutes after reception of the latest satellite image. These built-in applications are also the basis of interesting user-specific nowcast studies and products.

2. METHODS

CineSat's forecasts are based on motion fields that describe the movement of clouds from one image to the next one. They are derived from successive half-hourly or hourly images of a geostationary meteorological satellite.

Motion fields are derived from conventional cloud motion winds being processed in a subsequent refinement step to obtain a consistent vector field that best possibly describes the actual atmospheric flow. The major processing steps involved in CineSat's cloud motion analysis are

- Pattern tracking
- Automatic quality control of motion vectors, and
- Replacement of bad vectors by vectors that best possibly fulfill the selected quality criteria.

2.1 PATTERN TRACKING

Image pattern tracking is the very first and basic algorithm to get a first estimate of the single vectors of a cloud motion field. The user can configure various parameters like vector grid, pattern size, maximum allowed displacement, the similarity measure (Euclidian distance or correlation), the search strategy (full, grid, or optimized search), and the considered pixel range. These parameters allow to interface different image scales, calibrations and projections. Based on these parameters CineSat searches in a local neighbourhood of the last image to find the position of the most similar piece of cloud. This intermediate product are raw cloud (or atmospheric) motion vectors.

The major achievement in this area is a pattern tracking method that is about 20 times faster than the commonly used correlation techniques. This makes it possible to achieve processing times for thousands of wind vectors within only several minutes - even on small workstations or PCs.

2.2 MOTION VECTOR QUALITY CONTROL

Pattern tracking provides perfect results in case of non-overlapping, non-developing objects that follow a rigid motion. But in case of natural scenes, additional methods have to be applied to take into account the floating nature of cloud structures. In particular, when new clouds appear and others disappear, a simple pattern tracker does not find a correct motion vector. The standard approach is to apply a quality control to the motion vectors and mark them with a quality indicator.

Using only vectors above an appropriate quality threshold usually results in vector fields with 40% to 60% invalid locations. A routine forecaster does not benefit from information that is marked as having bad quality to such an extent - in particular if the cloud images show a clear cloud motion and the bad vectors are mostly due to the simple pattern tracking algorithm. For the extraction of the nowcast products discussed in this paper a consistent field of vectors is required.

The following tests are applied to each single vector:

- Local consistency checks
- Timely consistency checks (available with CineSat V2.4)
- Consistency of cloud pattern content (correlation value)
- Significance of cloud texture (pattern structured or homogeneous, cloud borders, edges)
- Significance of the located position (correlation peak)

Very similar to the quality control procedure at EUMETSAT all test values, e.g. the local vector difference, are derived only from neighbouring vectors with similar temperatures, and are then mapped to a quality value by a test specific *arctan* -shaped quality function. Each single test gives a quality indicator between 0 and 100%. The individual tests are combined by a weighted sum to a final quality indicator.

The quality test weights are determined according to the intended further use of the vectors. For CMWs the tests are trimmed to identify those vectors that most probably represent a real wind. For nowcasting, a consistent multi-height description of cloud motion is required, thus preferring vectors at cloud borders (which would be bad wind vectors due to height assignment issues).

This difference is important, since cloud motion is related to but not strictly determined by winds - consider e.g. a strong wind blowing over a mountain chain, but the clouds standing still at the mountain ridge for a long time. Meteorologists report that CineSat perfectly handles such a situation whereas a wind based forecast would fail completely.

For nowcasting you need to accurately estimate the position of clouds and cloud systems in the near future - and exactly this information is provided by CineSat's cloud motion forecasts.

2.3 QUALITY IMPROVEMENT

This is the most important step when bridging from raw cloud motion winds to nowcasting products - *bad vectors are to be replaced by better ones*.

Depending on user parameters, the system replaces all vectors below a given quality threshold by better ones. The term *better* refers simply to the value of the quality indicator. This means that a bad vector is iteratively replaced by a vector that increases its quality.

Since also the local correlation value contributes to the quality value, this procedure may e.g. select the second or third correlation maximum instead of the first (wrong) one.

The result of this procedure is a complete and consistent vector field - allowing for multi-level motion, and being quite different from simply smoothing out a raw cloud motion wind field.

3. BUILT-IN APPLICATIONS

Based on these motion fields, CineSat derives several interesting meteorological products, i.e.

- image animation
- predicted images
- cloud development maps, and
- trajectories

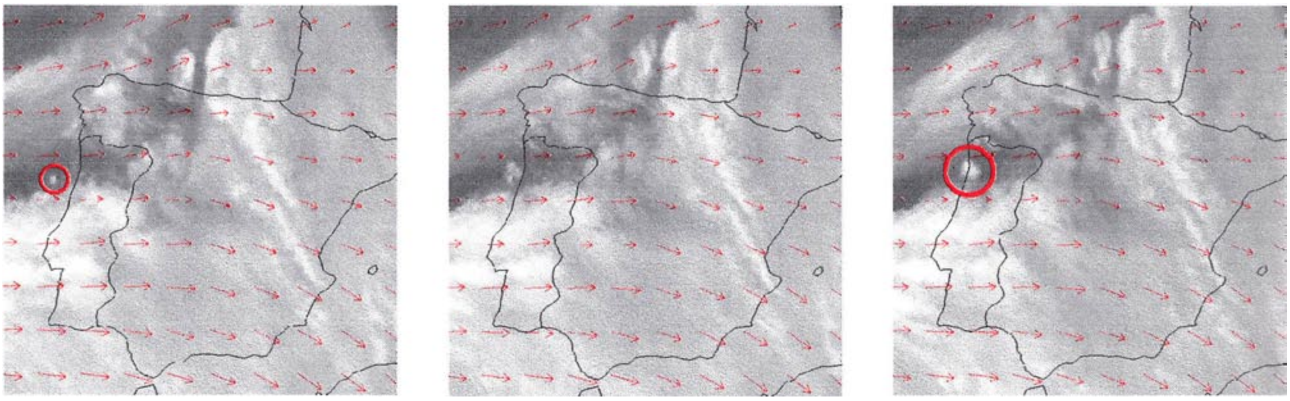
3.1 MOVIES

Having two satellite images - at half-hourly or hourly distance - and the motion field in between them, it is an easy exercise to interpolate the movement of the single pixels down to e.g. 1 minute steps. Thus, CineSat makes the single clouds realistically *moving and developing* along their correct path from one real image to the next.

Conventional animation techniques build image loops by simply fading the half-hourly satellite images. This results in a flickering animation in all regions where clouds move. CineSat overcomes this problem by computing the intermediate images based on the cloud movement information. You get sharp and smooth films with realistically moving and developing clouds. Broadcasting companies confirmed that the products obtained with this technology are significantly better and far more attractive than those obtained by standard techniques.

Another practical application of this technique is the interpolation of missing intermediate satellite images:

Fig. 1 satellite image interpolation:



a) real 12:00 UTC IR image   b) interpolated 12:30 UTC image   c) real 13:00 UTC IR image

3.2 IMAGE PREDICTION

One of the most unique features of CineSat is the prediction of satellite images several hours into the future (see figure 2). Predicted cloud images are an intuitive way to efficiently convey nowcasting information to a forecaster. Looking at an animation loop over the most recent satellite images and extending this animation some hours into the future gives the forecaster an instant and intuitive understanding of the expected flow of clouds and upper tropospheric air masses.

CineSat Nowcast does this extrapolation of the most recent cloud movements in very much the same way a human interpreter would go - but based on a more in-depth analysis of the cloud motion field.

The processing steps are as following:

1) Trend analysis of the last few hours of cloud motion
2) Prediction of future cloud motion
3) Application of predicted cloud motion fields to image data

Although quite good results are obtained when basing the prediction on the last motion field only, CineSat now allows to use the history of the last hours of motion fields - usually the last 2 hours. Motion information older than 2 hours does not contribute significantly to prediction accuracy.

The process of moving image pixels according to a predicted motion field exploits resampling algorithms that have been specifically tailored to the meteorological image content. Studies at meteorological sites have shown that CineSat's forecasted images are convincing and meteorologically plausible for up to:

Meteosat Image Channel	Operational Prediction
Visible channel	1.5 - 2 hours
Infra-red channel	2.5 - 3 hours
Water vapour channel	2.5 - 4 hours

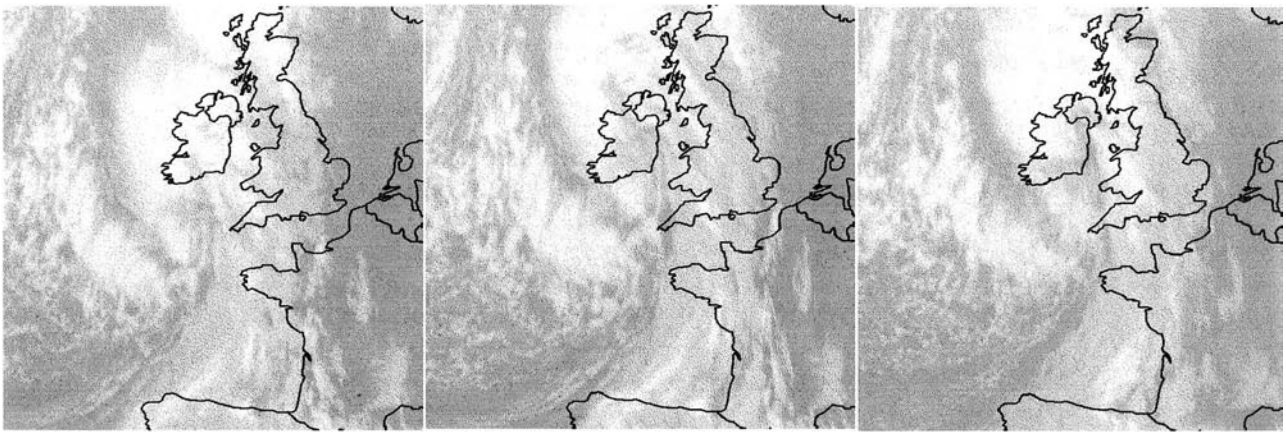


Fig. 2a) real 15:30 UTC IR image Fig. 2b) predicted 18:00 UTC image Fig. 2c) real 18:00 UTC image

3.3 CLOUD DEVELOPMENT MAPS

CineSat's image change detection tool separates cloud movement from cloud development. Cloud development includes the emergence, enlargement, shrinking, deformation, temperature change and disappearing of clouds.

Meteorologically relevant changes in cloud images are a combination of cloud motion and cloud development. Cloud development maps can therefore be computed by

1) Extracting the motion field between successive images
2) Compensate both images for the cloud motion
3) Analysing the remaining image differences of the motion-compensated images

Having available a cloud development map, the forecaster can immediately focus his attention on areas of interesting on-going developments without the need to scan the entire image. The forecaster thus gets e.g. immediate pointers to upcoming convective cells. An example is given in figure 3 below.

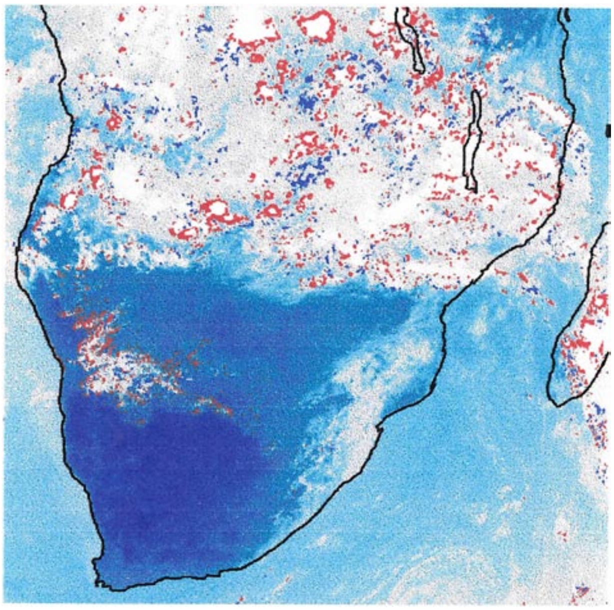
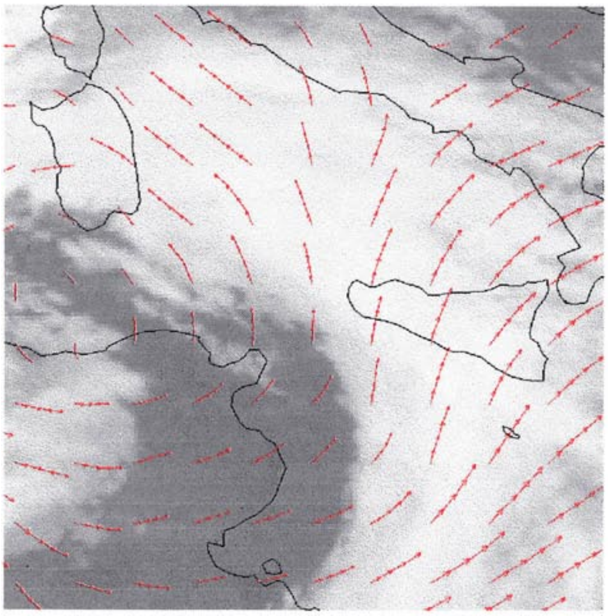


Fig. 3 Cloud development map of exploding thunderclouds over Africa.

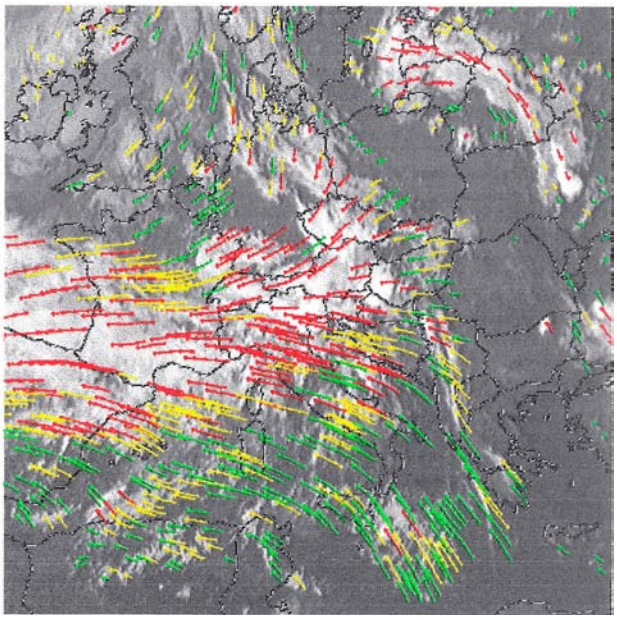
The overlay shows:

- new developing clouds in red
- and disappearing clouds in blue.

Fig. 4 predicted trajectories



4a) 2-hourly predicted trajectories on a regular grid



4b) Trajectories of convective cloud cells predicted for the next 4 hours

red - high, cold cells
yellow - medium level cells
green - warm, low cells

3.4 PREDICTED TRAJECTORIES

CineSat's trajectories describe the expected future path of clouds for the next few hours. In addition to the predicted images, trajectories are an important means for visualizing cloud motion. Their benefit is that the movement can be shown in a static single picture. They are especially useful for communicating nowcasting results in printed form (see figure 4 on previous page).

In principle, CineSat takes the start points set by the user and moves these points according to the predicted motion fields several hours into the future. Predicted trajectories can be computed at user defmed scales and positions, but can also be applied to synoptic measurements (e.g. rainfall), to lightning positions, weather radar cloud positions, and image features (e.g. to the centres of convective cloud cells as shown in figure 4b).

4. PERFORMANCE

Time is a crucial factor in operational nowcasting - and real-time methods are mandatory.

CineSat runs an advanced image dynamics analyser module that computes the movement of clouds from a pair of successive images more than 20 times faster than standard image processing techniques. This is achieved by new algorithms and mathematically optimized procedures.

Fast algorithms enable accurate real-time forecasts on today's standard workstations within a few minutes after image reception. In typical configurations, CineSat computes e.g. the cloud motion and the half-hourly forecasted Meteosat IR images for the next three hours, plus trajectories for hundreds of cloud related observations, and a smoothly interpolated animation movie within 5 minutes after image reception.

5. METEOROLOGICAL APPLICATIONS

In the following, some practical applications of real-time cloud movement information are discussed:

Image prediction (0 - 4 hours), cloud development maps

> These built-in nowcast products seem currently to be the most important for operational routine forecasting (e.g. in air traffic control). They have already been discussed in previous chapters.

Cloud border prediction

> The central meteorological office in Austria (ZAMG) extracts the contour lines in the current IR image at three temperature thresholds and computes the 2-hourly predicted contour lines by use of the cloud motion field. This nowcast product is displayed as overlay on the current IR image. It is being issued operationally for more than 3 years.

Trajectories of weather radar rain cells

> The German weather service (DWD) runs a CB detection software that performs a joint multi-spectral classification of the weather radar image and the Meteosat IR and VIS image pixels. The identified CB positions are passed on to CineSat as trajectory start points. The trajectory predictions are computed by use of the IR motion fields.

Trajectories of synoptic observations

> ZAMG applies the trajectory prediction to cloud-related synoptic observations like rain measurements. Overlaying this product on the current IR image gives an instant overview where to and at which speed the observed rain patterns are moving.

Interpolation of cloud related NWP parameter fields

At DWD, selected one-hourly NWP parameter fields are being converted to artificial images which are fed to CineSat to interpolate them down to 5 minute intervals. The smooth sequence of NWP fields forms then the basis of special weather animation techniques.

Production of high-quality TV animation movies

Since about 2 years the German weather service (DWD) serves its media clients with CineSat's smooth Meteosat weather animation movies. The interpolation uses cloud motion information.

Automatic classification of conceptual models

For Meteosat 2nd generation ZAMG develops a Nowcasting Satellite Application Facility - the classification of conceptual models. This is in principle, a multi-spectral and multi-source classification of structures in satellite imagery and NWP model data. Nowcasting products come into this process at several stages, e.g. by using cloud development maps as additional artificial image channel, by deriving image structure features from the motion field (vorticity, divergence), by optionally interpolating half-hourly WV images during daytime, and by interpolating the classifications between the 6-hourly NWP data.

Independent verification of NWP model fields

Users report that they come to appreciate CineSat's image based predictions as an assessment of a situation that is independent from numerical weather prediction models. Knowing once where an NWP model does not exactly match a situation, its parameters can nevertheless often being used by taking into account their observed geographical displacement.

6. CONCLUSION

Although of increasing importance, nowcasting currently suffers from lack of practical applications that convert real-time measurements, like meteorological imagery, to useful nowcasting products. CineSat is one of the rare operational forecast application of cloud motion analysis. Its forecasts are valid for about 3 hours into the future, which covers e.g. most continental flights. Thus, it is not a competition but a completion of numerical weather prediction, since this forecast period is currently not well addressed by existing operational numerical weather prediction models.

The use of cloud motion data has been successfully demonstrated by more than two years of operation at several sites. This cloud movement information is not only used as plain cloud motion wind data, but in a rich variety of practical nowcasting applications.

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