P2C.10 DETECTION OF DUST STORMS WITH A C-BAND DOPPLER RADAR

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1. INTRODUCTION

Weather Radars are able to detect dust storms, if the number concentration and size of dust particles is large enough.

Typical sizes of dust storm particles are in the range of microns to about one tenth of a millimeter: According to figures in Niu et al. (1999), more than 90 percent of dust storm particles have sizes between 0.5 and 3.0 microns. In contrast to such extremely small particles, Goldhirsch (1982) reports that about 45 percent of dust storm particles have sizes of more than 10 microns. Fedorov and Stepanenko (1978) found that particles of 30 to 60 micron size are displaced by several hundred kilometers during dust storms.

The backscattering constant $|K^2|$ of dust particles is different from that of water droplets. The real part of the complex refractive index ε of water is about 81. For dust storm particles, Goldhirsch (1982) lists several observations. On average, $\varepsilon \approx 5.0 - 0.5j$ was found. As a result, $|K^2|$ of dust storm particles is about 0.3, which is a factor of three less than $|K^2|$ of water droplets.

From these observations it can be summarised that dust storm particles are very small compared to precipitation. As a result of this and due to the reduced backscattering constant of dust particles compared to water, reflectivity values measured with a C-Band Weather Radar will be very low in dust storms, if detectable at all.

2. ALGORITHM DESCRIPTION

The typical characteristics of dust storms can be used to identify such phenomena by means of radar measurements. Already mentioned was the small dust particle size, which indicates that the reflectivity level of a dust storm must be quite weak. Dust particles are lifted by wind, so the wind speed (and as a consequence, the turbulence, which can be measured more directly by radar than the absolute wind speed) must be relatively high. Fedorov and Stepanenko (1978) report of wind speeds between 15 and 25 m/s in dust storms; Semenov (1999) observed wind speeds between 6 and 20 m/s (in a height of 20 m AGL) during dust storm events.

Since the dust particles are risen from the ground, the corresponding reflectivity echoes must extend from the ground (i.e., lowest elevation angle of a multiple-slice scan) up to a height of not more than a few kilometers. Furthermore, the larger the particles are, the less high they will be lifted. Due to the power-of-6 law of the Rayleigh-approximation, the echoes will be strongest close to the ground. Thus a dust storm should exhibit a negative vertical reflectivity gradient.

In general, high-reflectivity echoes cannot result from dust storms but must be clutter or precipitation echo. However, some Dust storms may also be triggered by active fronts with precipitation. In such a case, the dust storm area may contain small sub-areas with high echoes from the precipitation. Not to discard such areas, the upper reflectivity threshold must tolerate a (quite small) percentage of the area to exceed that threshold.

As a consequence of these considerations, the dust storm detection (DSD) algorithm performs the following steps:

2.1 Calculation of mean wind speed

The mean wind speed is calculated in a height interval typically for dust storms (upper and lower level to be specified by the user), using a VVP regression (Waldteufel and Corbin, 1979). The standard deviation is also calculated.

If the derived wind speed can be regarded as reliable (i.e. if the standard deviation is low enough), it must exceed the a minimum wind speed threshold (default 10 m/s), otherwise the wind speed is regarded as too low to create dust storms and the algorithm stops. If the wind speed cannot be trusted (i.e. if the VVP standard deviation is too high), this threshold is not applied, and the algorithm continues anyway.

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2.2 2D-Segmentation of reflectivity data

The reflectivity data of each elevation slice are smoothened to two-dimensional *segments*. Therefor, a minimum reflectivity limit is applied (default –5 dBZ).

To separate precipitation echoes (with rather high dBZ values) from dust storm echoes, the total volume percentage of "too high" reflectivity data is calculated for each segment (for which another high-reflectivity threshold with +20 dBZ as default value is applied). If the volume percentage of “too high“ reflectivity data exceeds a certain threshold (default 10 percent), the 2D segment is discarded.

Volume of a 2D-segment means that the vertical extent of the radar beam is considered, i.e. locations are weighted linearly with the distance from the radar.

2.3 3D-Segmentation of reflectivity data

All remaining 2D-segments of all elevation slices are merged into three-dimensional segments. Merging appears if 2D-segments of subsequent elevation slices have horizontal overlap. 2D segments which do not have any overlap with other segments are rejected. For all resulting 3D-segments, a couple of quantities are calculated, e.g. top and base height and mean spectrum width (as a measure of turbulence).

If no 3D-segment can be found, the algorithm stops at this point.

2.4 Further thresholding of 3D-segments

Each identified 3D-segments must meet the following conditions:

- The vertical extent must be OK, i.e. the top height must be between a user-selectable upper and lower level (default values are 4.0 and 0.5 km, respectively) and the segment must extend down to the lowest elevation slice.
- The mean spectrum width (in m/s) must exceed a user-selectable threshold (default value 2.0 m/s).
- The reflectivity should decrease with height, so the vertical reflectivity gradient must not be larger than another threshold (default -1.0 dB/km).
- To avoid small-scale false alarm phenomena, the 3D-Segment must have a minimum volume (default 500 km³, i.e. an area of approx. 200-300 km²).

Any 3D-segment missing one or more of these checks is discarded from further processing. If no segments at all pass the checks, the algorithms stops here.

The areas of remaining 3D-segments are considered as dust storms. They can be displayed as overlay to a reflectivity image. Properties of the dust storm(s) are given in tabular form.

3. RESULTS

At the Kuwait International Airport, a C-Band Doppler Radar is operated. Several data sets of dust storm occurrences in March and April 2003 are available. The dust storm detection (DSD) algorithm was applied on data sets from various cases within in this period (with and without dust storm occurrence), covering a total period of 42 hours.

Figure 1 shows an example image of the DSD algorithm output: Weak clear air echoes (reflectivity less than –6 dBZ) can be seen in the 1.0 deg PPI display up to 30 km around the radar. The image shows several precipitation echoes (including second-trip echoes) in the eastern and north-eastern sector at distances beyond 30 km. From west, a dust storm is approaching the radar site. It exhibits stratified echoes between –6 and +11 dBZ at distances between roughly 10 and 50 km. The DSD algorithm performed well in this case: The dust storm was identified by the three-dimensional properties of the radar

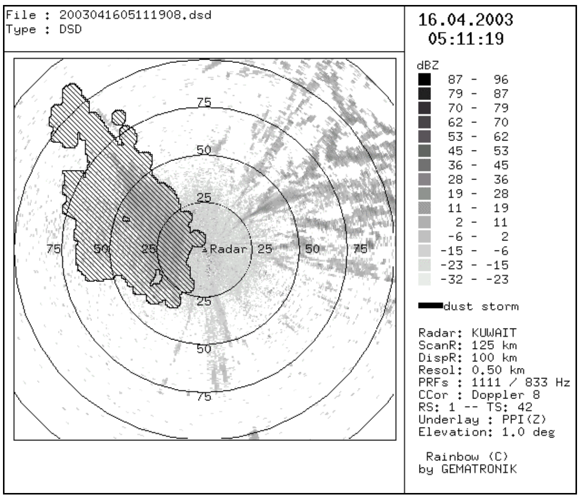

Figure 1: A dust storm west of the radar site was auto-detected by the algorithm (hatched area). Echoes from other sources were correctly not considered as part of the dust storm.

data and its coverage is indicated by the hatched area.

In other situations, however, dust storms were not detected correctly, or echoes from other sources were falsely identified as dust storms. The settings of the algorithm thresholds and parameters described in section 2 have significant influence on the DSD algorithm performance. To demonstrate this, the probability of detection (POD), the false alarm ratio (FAR), and the critical success index (CSI) were calculated for the total period under investigation, using different values for the selectable thresholds.

First of all it turned out that the wind speed and turbulence during the observed dust storm occurrences was too weak to apply the default thresholds of 10 m/s for mean wind speed and 2 m/s for mean spectrum width. With these default values, almost every dust storm data set was rejected, resulting in a POD of only 0.015. Reduction of the minimum wind speed threshold to 5 m/s resulted in less rejection of data, but only in a little increase of the POD to 0.02. After the minimum spectrum width threshold was reduced to 1 m/s, POD raised to 0.26, and FAR was 0.33. Further reduction of the spectrum width threshold increased POD, but resulted in a higher FAR as well. Thus the other thresholds were varied using a minimum velocity threshold of 5 m/s and a minimum spectrum width threshold of 1 m/s. Table 1 lists these and the other reference thresholds.

Table 1: Reference thresholds for the DSD algorithm

Threshold	Abbr.	Ref. value
Minimum velocity[a]	MinV	5 m/s
Minimum spectrum width[b]	MinW	1 m/s
Maximum high-reflectivity[c]	MaxZ	20 dBZ
Maximum percentage of “too high” reflectivity data[c]	MaxPerc	10 %
Maximum top height[b]	MaxH	4 km
Max. reflectivity gradient[b]	MaxGrZ	–1 dB/km
Minimum 3D-seg. volume[b]	MinVol	500 km³

[a] Cf. section 2.1 [b] Cf. section 2.4 [c] Cf. section 2.2

Table 2 gives POD, FAR, and CSI for different settings of the algorithm threshold. A single threshold only was modified each time (with the value given in Table 2), the other thresholds were set to the reference values of Table 1. Each single threshold was first set a little higher and a second time a little lower than the reference value.

Table 2: POD, FAR, and CSI for different settings of the thresholds. *CSI-Ref* denotes the change of the CSI compared to the reference case. For the meaning of the threshold abbreviation (column *T.Abbr.*) refer to Table 1.

T.Abbr.	Value	POD	FAR	CSI	CSI-Ref
Reference case		0.26	0.33	0.23	
MaxZ	[a] 10 dBZ	0.12	0.58	0.11	–0.13
MaxZ	30 dBZ	0.24	0.44	0.20	–0.03
MaxPerc	5 %	0.24	0.46	0.20	–0.03
MaxPerc	20 %	0.25	0.39	0.21	–0.02
MaxH	3 km	0.10	0.41	0.09	–0.14
MaxH	5 km	0.26	0.49	0.21	–0.02
MaxGrZ	-3 dB/km	0.13	0.46	0.12	–0.12
MaxGrZ	+2 dB/km	0.32	0.48	0.25	+0.01
MinVol	200 km³	0.26	0.33	0.23	0.00
MinVol	2000 km³	0.18	0.35	0.16	–0.07

[a] In this case, the minimum reflectivity was reduced from –5 to –10 dBZ (cf. section 2.2).

Usually, if a threshold is weakened (i.e. if a maximum threshold is increased, and a minimum threshold reduced), one would expect an increased POD but also an increased FAR. Strengthening of a threshold, on the other hand, normally rejects more data and thus reduces both POD and FAR. For the thresholds which are applied “directly” according to section 2.4, i.e. *MaxH*, *MaxGrZ*, and *MinVol* in Table 2, this is the case for POD only (which sometimes remains constant), but FAR is increased in almost all cases. For the thresholds being applied more “indirectly” according to section 2.2, i.e. *MaxZ* and *MaxPerc*, the results were worse in all cases, since POD was always reduced and FAR always increased in comparison to the reference case.

As a summary it can be stated that the reference values in general were the best choice. This can be obtained from the last column of Table 2, where the critical success index was compared to that of the reference case (*CSI-Ref*). Only in one case with a modified threshold, the CSI was a little higher (and thus the algorithm performance slightly better) than in the reference case.

4. SUMMARY AND OUTLOOK

Dust storms can be detected with a C-Band Doppler Radar up to several ten kilometers distance, if the amount and sizes of particles are large enough. In such cases, visibility is reduced significantly (to below about one kilometer).

The algorithm presented in this paper detects dust storms from three-dimensional properties of the reflectivity, Doppler velocity and spectrum width data. For that purpose, several thresholds are applied. The thresholds are user selectable to optimise the algorithm performance for site-dependent characteristics of typical dust storms.

A detailed analysis of several radar data sets from conditions with and without dust storms at Kuwait International Airport showed that the default threshold parameters are in general a good choice. Only the minimum wind speed and turbulence thresholds had to be reduced, as the default settings rejected too many cases. The critical success index (CSI), which in general is a measure of performance of an algorithm, was in almost every other case less than in the reference case, either if a threshold was reduced or if the same threshold was increased.

Even though several thresholds are applied to discriminate dust storm echoes from other echoes, the false alarm ratio (FAR) is not negligible, and the probability of detection (POD) remains low. The main reason for this problem is that several echoes resulting from clear air or other targets can have very similar properties than dust storm echoes.

The detection of dust storms can probably be made more reliable (i.e. with higher POD and CSI, and with lower FAR), if polarimetric measurements as Z_{DR}, L_{DR}, K_{DP} and ρ_{HV} are taken into account. Polarimetric quantities are in general much more dependent on the particle type than reflectivity. Hydrometeor classification schemes based on polarimetric measurements already exist (e.g. Bringi and Chandrasekar, 2001). Such schemes may be extended to classify additionally other particle types than hydrometeors.

5. REFERENCES

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