ITERATIVE AMPLITUDE ADAPTED FOURIER TRANSFORM SURROGATE CLOUD FIELDS

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1. INTRODUCTION

It is not possible to measure a 3D field of cloud properties. The best measurements available are 2 dimensional, e.g. a horizontal field or a vertical cross cut. Therefore, cloud fields for research into cloud structure are often either simulated by physical cloud models or they are surrogate cloud fields. Surrogate cloud fields are fields that share certain (typically statistical) properties with real cloud field.

Most methods to make such surrogate fields assume an ideal fractal structure and each method has its own typical shape of the PDF. For example, surrogate cloud fields made with the standard Fourier method typically have linear power spectrum with a -5/3 slope and a Gaussian PDF. The Bounded Cascade algorithm makes fractal fields with a discontinuous structure (Cahalan, 1994) and a 'log-normal-like' PDF.

This paper introduces a new method to generate surrogate cloud field that allows presetting both the power spectrum as well as the shape of the cloud water distribution. This method can use measured cloud water distributions; there is no need to fit this to some theoretical distribution. The algorithm uses the full power spectrum; it does not have to be approximated by a linear power law. Thus this method allows for surrogate cloud fields that have a very close agreement with a specific cloud measurement. The algorithm is based on the Iterative Amplitude Adapted Fourier Transform (IAAFT) method to generate surrogate time series by Schreiber and Schmitz (2000) and has been extended to fields.

The original time series or field on which the statistics are based is called the template. We will only consider water clouds in this paper, which are described in terms of their Liquid Water Content (LWC) or, the Liquid Water Path (LWP).

2. THE IAAFT ALGORITHM

From a measured time series a sorted list is made of all values, to be used in the amplitude conversions. Furthermore, the power spectrum of the measurement is calculated. For theoretical studies, the power spectrum and the values of the amplitude distribution can be predefined. The algorithm starts with a random shuffle of the data points. Then, in each iteration, the Fourier spectrum is adjusted first and secondly the amplitudes. To get the desired power spectrum, the Fourier transform of the iterated time series is calculated and its squared coefficients are replaced by those of the original time series. The phases are kept unaltered. After this step the amplitudes of the iterated time series will no longer be the same. Therefore in the second step the amplitudes are adjusted by sorting their values and replacing the values of the surrogate by the values of the template having the same ranking. Calculation times, for the examples in this paper, range from seconds to several hours, depending on the matrix size.

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3. SURROGATE FIELDS FROM MEASUREMENTS

3.1. 1D LWP surrogate

As a first example, we took a 1 Hz LWP time series measured with the microwave radiometer MICCY. From this LWP time series template (Fig. 1a) we made a 1D surrogate (Fig. 1b) for comparison which shows a very similar structure. However, in the template there are only spikes (which are associated with the fall streaks) in the high LWP part. The surrogates have spikes everywhere, and in a larger number. Figure 1c shows that the power spectra of the template and the surrogate are (almost) identical.

3.2. 2D LWP surrogate field

We can make a 2D LWP field from a 1D LWP time series by assuming horizontal isotropy and rotating and rescaling the 1D Fourier coefficients around the origin in the 2D wavenumber-space, see Fig. 2a. Assume we have an isotropic 2D field with a linear power spectrum with slope $-\gamma$ and we extract a 1D time series from this field. The linear power spectrum of this time series will have a slope ($-\beta$) given by: $\gamma = \beta + 1$ (Austin et al., 1994). In other words, a measured time series where the power is proportional to the wavenumber (k) to the power $-\beta$, i.e. $k^{-\beta}$, was taken from a field with a 2D power spectrum that is proportional to $k^{-\gamma}=k^{-\beta-1}=k^{-\beta}/k$. This relation was derived for a linear power law, and should be a good approximation for isotropic clouds.

This rotation and scaling method seems to work well. In Fig. 1c we find that the average 1D power spectrum, calculated from the rows and columns of the

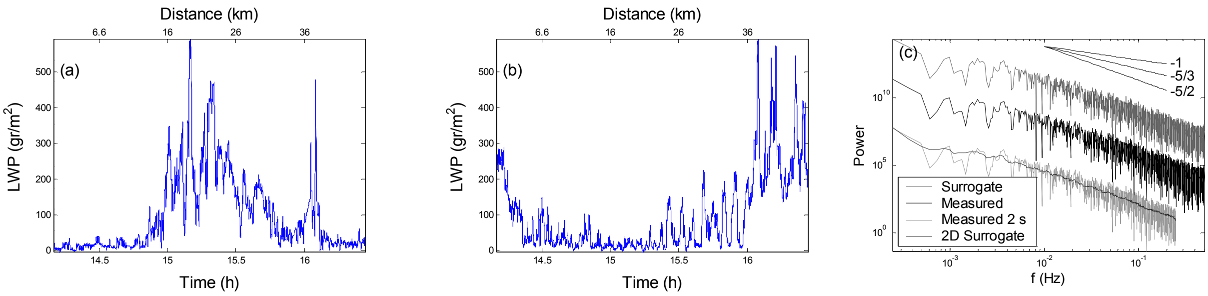

Figure 1. a) Microwave radiometer LWP time series (template) which was measured at Cabauw, The Netherlands, during the BALTEX Bridge Campaign (BBC) on the 5th of September 2001. b) Iterative Fourier (IAAFT) surrogate of the same measurement. c) Power spectrum of the 1D template (black, noisy) and the 1D surrogate (offset 30 dB, upwards, grey). Furthermore, the power spectrum of a 0.5 Hz version of the 1D template (offset -30 dB, downwards, grey) and on top of this, in black, the scaled average 1D power spectrum calculated from the 2D surrogate shown in Fig.2, which was generated based on the 0.5 Hz template.

2D surrogate field, is almost the same as the power spectrum of the 1D template. Only the typical Fourier noise is missing. Evans and Wiscombe (2004) use an optimizing method to find a 2D horizontally isotropic power spectrum that has the same 1D power spectrum as the template. This may provide a more accurate power spectrum as fewer assumptions have to be made.

One of the resulting surrogate time series of the IAAFT algorithm can be seen in Figure 2b.

The strongly correlated cloud time series are not stationary, i.e. the fields are inhomogeneous. Thus a local sample from a non-stationary data set will on average have a smaller width of the amplitude distribution. Imagine, a line measurement going through the maximum of a 2D field. Due to the strong correlations, also a large part of the other values will be higher than average. Thus the width of the PDF of this 1D measurement will be lower than that of the 2D field.

As an illustration, consider the standard deviation of the LWP cloud field (Fig. 2b). The standard deviation of the entire 2D field is 109 g m^{-2}, but the average standard deviation of the 1D vectors of this field is only 90 g m^{-2}. Thus if we would have made a zenith pointed measurement of this correlated field we would found a 17 % smaller width of the LWP distribution.

3.3. LWC profiles

In this section we will make 3D LWC fields from 2D LWC profiles, i.e. a vertical 2D space height field (see Figure 3). These LWC profiles were derived using an optimal estimation technique (Löhnert et al., 2003) which combines microwave radiometer brightness temperatures, with other measurements and with a priori information from a microphysical cloud model.

This vertical LWC field is clearly anisotropic and we would like the surrogate to have exactly the same LWC amplitude distribution at every height level. Thus not one sorted vector with all LWC values is used, but rather this operation is carried out for every height level, i.e. we utilize a 2D sorted LWC field.

The mean LWC profile was subtracted from the template before a 2D Fourier transform was utilized to calculate the 2D power spectrum. The structure is thus

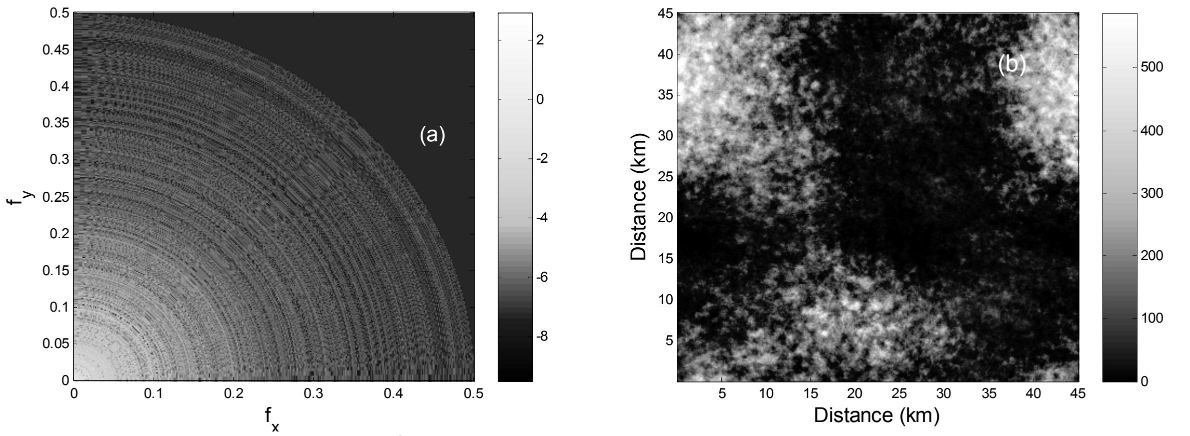

Figure 2. a) The 1D power spectrum from Fig. 1d is rotated and scaled to create a 2D isotropic power spectrum. The values for the upper right corner are set to zero. b) 2D surrogate calculated using the 1D LWP time series of Fig. 1 as a template for the statistics. The temporal scale was converted into this spatial scale using a wind speed of 5.5 m/s, taken from a close by radiosonde. The high peaks are due to the fall streaks in the virga.

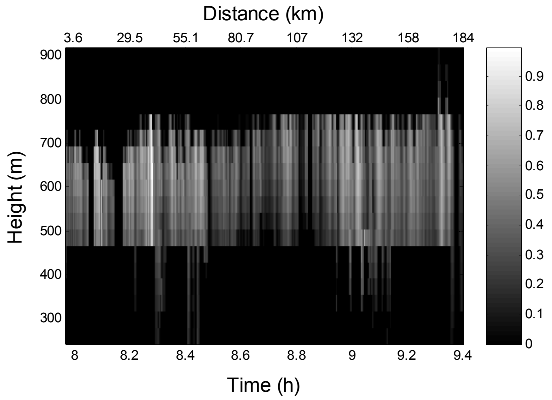

Figure 3. Retrieval of liquid water content profiles of a cloud field made during the BBC campaign on the 23rd September 2001.

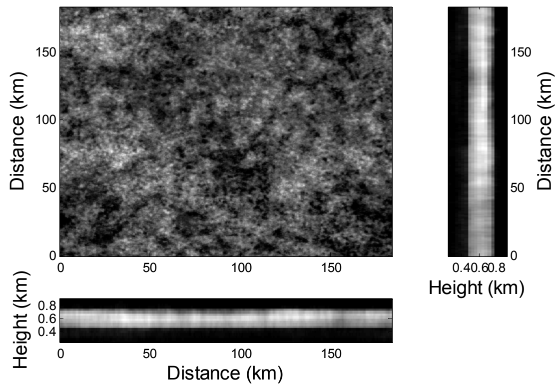

Figure 4. 3D surrogate LWC cloud field made from the 2D template shown in Fig. 3. The 2D fields should be interpreted as the integrated values of the 3D field as seen from the top (large picture), the side (right picture) or the front (bottom).

defined globally, whereas the amplitudes are defined per height level. The 2D Fourier coefficients are rotated cylindrically around the vertical wavenumber axis and scaled to make a 3D horizontally isotropic field. Figure 4 shows a 3D surrogate field made from the 2D template from Fig 3.

<u>3.4. 3D LES stratocumulus field</u>

The limitation of the IAAFT statistics become apparent when stratocumulus and altocumulus are considered that often display beautiful cell structures, similar to Bénard convection. Figure 5a shows a stratocumulus calculated with a Large Eddy Simulation model (Schroeter and Raasch, 2002), with these Bénard cells. The 3D IAAFT surrogate calculated from this cloud does not show cell structures. Nevertheless, the radiative properties of IAAFT stratocumulus are good.

4. VALIDATION

The most prominent application of 3D surrogate cloud fields is the study of 3D radiative transfer. In order to verify the suitability of our surrogates for this purpose, we used 3D LES cloud fields as templates for 3D LWC surrogates. The difference in the radiative properties between such cloud pairs shows the quality of surrogates with the conserved statistical properties. In other words, we want to know how good a cloud field is described with only an amplitude distribution and a power spectrum, with respect to its radiances and irradiances. As input templates, we used two sets of LES clouds: 33 stratocumulus LWC fields and 52 cumulus LWC fields.

Duynkerke et al. have modeled maritime stratocumulus clouds (P.G. Duynkerke et al., 2004) These LES clouds have a resolution of 50 m horizontally (52 grid boxes) and 10 m vertically (122 grid boxes). Drop sizes were calculated for each cloud box by assuming a monospectral distribution (i.e. one drop size) with 300 drops per cm^3. The average reflectance was 0.66.

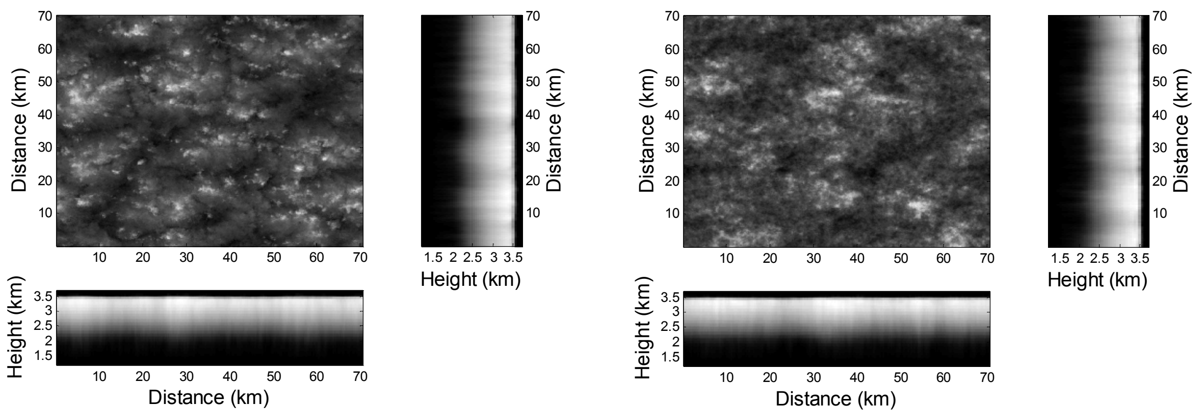

Figure 5. The left picture is a 3D LWC field from a stratocumulus that was calculated by an LES model. The right picture is its surrogate

The cumulus case represents the diurnal cycle of cumulus over land (Brown et al. 2002). The clouds have a resolution of 100 m in the horizontal and 40 m in the vertical. The number of grid boxes is 66x66 horizontally with 112 height levels. Drop sizes were calculated from these clouds by assuming a monospectral distribution with 1000 drops per cm^3, resulting in an average reflectance of 0.08.

All calculations are made assuming the wavelength of the incoming monochromatic solar radiation to be 550 nm and a solar zenith angle of 60°. The radiances were calculated with the Monte Carlo model MC-UNIK (Macke et al., 1999). These radiances were calculated in all four wind directions and at four zenith angles: 0, 30, 45, and 60 degrees. This results in total 16 calculations for each cloud field. The upward and downward flux densities were calculated with Leipzig Monte Carlo Model (LMCM; Gimeno and Trautmann, 2003). The results of the calculation can be found in Table 1. The radiative properties of the surrogates are very similar to LES clouds. Especially, the radiative budget is matched very well: within 0.5 % of the incoming radiation.

Concluding, the radiative properties of the surrogate fields are close to those of the original fields. Best results are achieved for the stratocumulus fields and the flux densities. The deviation of the radiances of surrogate cumulus fields are probably mainly due to insufficient convergence, not the insufficiency of the statistical description.

5. OUTLOOK

The cloud properties that we impose do not have to be purely statistical. In future we want to try if it is possible to include spatial constraints, e.g. a cloud mask. With scanning LWP measurements one can improve the estimate of the LWP distribution and generate anisotropic surrogate LWP fields

The code of all methods is available on our website: http://www.meteo.uni-bonn.de/victor/themes/surrogates/

Acknowledgements. This research was carried out in the framework of the 4D clouds project, which is sponsored by the German ministry of research, BMBF, in the AFO2000 program on atmospheric research.

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Cloud type	Parameter	Mean value[1]	Number of fields	Relative bias (%)	RMS error (%)	Slope linear regression	Offset linear regression
Stratocumulus	Transmittance	0.34	33x2	0.031	0.040	1.0001	-0.0001
	Reflectance	0.66	33x2	-0.016	0.020	1.0001	0.0000
	Radiance(0°)	51	4x33x2	-0.13	0.76	0.9980	0.0000
	Radiance(30°)	55	4x33x2	0.056	0.71	1.0039	-0.0002
	Radiance(45°)	60	4x33x2	0.0094	0.75	1.0012	-0.0001
	Radiance(60°)	72	4x33x2	0.076	0.87	1.0038	-0.0002
Cumulus	Transmittance	0.92	49x2	0.44	0.35	1.0489	-0.0491
	Reflectance	0.080	49x2	-5.1	4.0	1.0489	0.0001
	Radiance(0°)	4.0	4x52x2	3.2	3.8	1.0359	0.0000
	Radiance(30°)	4.8	4x52x2	4.7	5.2	1.0493	0.0000
	Radiance(45°)	5.9	4x52x2	7.1	7.8	1.0803	-0.0001
	Radiance(60°)	8.8	4x52x2	11	12	1.1287	-0.0002

[1] The unit of the radiances is W m^{-2} sr^{-1}, using a solar intensity of 1000 W m^{-2}.

Table 1. Comparison of the radiative properties of LES template clouds and their surrogates.