Time dependent correlations in marine stratocumulus cloud base height records

N. Kitova,¹ K. Ivanova,² M. Ausloos,³ T.P. Ackerman,⁴ and M.A. Mikhalev¹
¹Institute of Electronics, Bulgarian Academy of Sciences, 72 Tsarigradsko chaussee, Sofia 1784, Bulgaria
²Department of Meteorology, Pennsylvania State University, University Park, PA 16802, USA
³SUPRAS, B5, University of Liège, B-4000 Liège, Belgium
⁴Pacific Northwest National Laboratory, Richland, WA 99352, USA

Abstract

The scaling ranges of time correlations in the cloud base height records of marine boundary layer stratocumulus are studied applying the Detrended Fluctuation Analysis statistical method. We have found that time dependent variations in the evolution of the $\alpha$ exponent reflect the diurnal dynamics of cloud base height fluctuations in the marine boundary layer. In general, a more stable structure of the boundary layer corresponds to a lower value of the $\alpha$ - indicator, i.e. larger anti-persistence, thus a set of fluctuations tending to induce a greater stability of the stratocumulus. In contrast, during periods of higher instability in the marine boundary, less anti-persistent (more persistent like) behavior of the system drags it out of equilibrium, corresponding to larger $\alpha$ values. From an analysis of the frequency spectrum, the stratocumulus base height evolution is found to be a non-stationary process with stationary increments. The occurrence of these statistics in cloud base height fluctuations suggests the usefulness of similar studies for the radiation transfer dynamics modeling.

Keywords: stratus cloud base height, fluctuations, correlations, power spectrum, detrended fluctuation analysis, multifractals
I. INTRODUCTION

Cloud base height (CBH) profiles are difficult object to describe and analyze. The base of a cloud is determined by the local condensation level up to which unsaturated air parcels rise. CBH has a complex structure, that varies with the coordinates of the observation point and time. Such a complexity is due to a variety of processes that take place in the marine boundary layer (MBL) formed over the sea surface. Some of these processes are, e.g., turbulent motions, entrainment, radiative transfer and changes in the cloud microphysical structure. Thus the CBH looks like an erratic quantity in time and space. Therefore, advanced methods of computational statistical analysis are required in order to extract meaningful physical information from data series with such a high level of complexity that traditional analysis techniques fail to provide. The detrended fluctuation analysis (DFA) method is designed to search for long-range correlations in non-stationary, highly fluctuating signals. The method has been successfully applied in the investigation of turbulence, DNA sequences, ionic transport trough cell membrane, foreign currency exchange rates, meteorological phenomena and stratus clouds dynamics. Using this technique we hereby sort out correlations and anti-correlations in stratocumulus cloud base height fluctuation data records. Our findings of the time evolution of the local $\alpha$-exponent (which is the Hurst exponent), i.e. describing a scaling law over a certain time range, are related to the physical processes in the cloud. These results reflect the ability of the method to indicate the type of physics that underlies the CBH profile phenomenon.

II. MARINE BOUNDARY LAYER - STRUCTURE AND PROCESSES

A variety of physical processes takes place in the atmospheric boundary layer. At time scales of less than one day, significant fluxes of heat, water vapor and momentum are exchanged due to entrainment, radiative transfer, and/or turbulence. The turbulent character of the motion in the atmospheric boundary layer (ABL) is one of its most important features. The turbulence can be caused by a variety of processes, like thermal convections, or mechanically generated by wind shear, or following interactions influenced by the rotation of the Earth. This complexity of physical processes and interactions between them create a variety of atmospheric formations. In particular, in a cloudy ABL the radiative fluxes produce local sources of heating or cooling within the mixed-layer and therefore can greatly influence its turbulent structure and dynamics. Moreover the variations in the turbulent structure and dynamics of the clouds cause subsequent changes in the cloud boundaries, especially in the cloud base.

The atmospheric boundary layer is characterized by an inner (surface) layer at heights above the aerodynamic roughness length and below one tenth of the depth of the ABL, while the outer (Eckman) layer is at higher distances within the ABL. The outer region of an unstably stratified ABL is often referred to as the mixed layer because of the dominating convective motions that take place there, generated by strong surface heating from the Sun or by cloud-topped radiative cooling processes. In contrast, a stably stratified ABL occurs mostly at night in response to the surface cooling due to long-wave length radiation emitted into the space.
The top of the boundary layer in convective conditions is often well defined by the existence of a stable layer (capping or subsidence inversion), beneath which clouds form, the so-called cloud-topped boundary layer (CTBL). In presence of clouds (shallow cumulus, stratocumulus (Sc) or stratus (St)) the structure of the ABL is modified because of the radiative fluxes. Phase changes become more important. During cloudy conditions one can distinguish mainly: (i) the case in which the cloud and the subcloud layers are fully coupled; (ii) two or more cloud layers beneath the inversion, with the lower layer well-mixed with an upper elevated layer, decoupled from the surface mixed layer or (iii) a radiatively driven elevated mixed cloud layer, decoupled from the surface.

An interesting case is that of the marine boundary layer characterized by high concentration of moisture. It is wet, mobile and has a well expressed lower boundary. The competition between the processes of radiative cooling, entrainment of warm and dry air from above the cloud and turbulent buoyancy fluxes determine the state of equilibrium of the cloud-topped marine boundary layer. The Atmospheric Stratocumulus Transition Experiment (ASTEX) was designed to clarify the transition from stratocumulus to trade cumulus clouds in the MBL in the region of the Azores Islands. Several papers have been dedicated to the relevance of the main processes causing this transition. In Ref. Betts et al. found a relationship between the thermodynamic structure of the marine boundary layer and the diurnal variation of the cloudiness.

III. DFA METHOD AND SPECTRAL ANALYSIS

A method that relaxes the requirement of stationarity of the investigated signal is the detrended fluctuation analysis (DFA) method. The DFA method is a tool used for sorting out long range correlations in a non-stationary self-affine time series with stationary increments. The method has been used previously in the meteorological field. It provides a simple quantitative parameter - the scaling exponent $\alpha$, which is a signature of the correlation properties of the signal. The Detrended Fluctuation Analysis technique consists in dividing a random variable sequence $y(n)$ of length $N$ into $N/t$ (non-overlapping) boxes, each containing $t$ points ($N/t = 4, 5, ...$). Then, the trend (assumed to be linear in this investigation, but it can be generalized without any difficulty) $z(n) = an + b$ in each box is computed using a linear least-square fit to the data points in that box. The detrended fluctuation function $F^2(t)$ is then calculated following:

$$F^2(t) = \frac{1}{t} \sum_{n=kt+1}^{(k+1)t} [y(n) - z(n)]^2 \quad \text{for} \quad k = 0, 1, 2, \ldots, \left(\frac{N}{t} - 1\right).$$

Averaging $F^2(t)$ over the $N/t$ intervals gives the mean-square fluctuations

$$< F^2(t) >^{1/2} \sim t^{\alpha}.$$  

If the $y(n)$ data are random uncorrelated variables or short range correlated variables, the behavior is expected to be a power law with an exponent $\alpha=1/2$ if the fluctuations are not correlated. An exponent $\alpha \neq 1/2$ in a certain range of $t$ values implies the existence of long-range correlations in that time interval as, for example, in fractional Brownian motion.
A small value of $\alpha$ indicates antipersistence of correlations, i.e. a positive fluctuation is more likely to be followed by a negative one than a positive one. An $\alpha$ value between 0.5 and 1 indicates persistence of correlations, i.e. a positive fluctuation is more likely to be followed by a positive one than a negative one. The $\alpha$-exponent value that holds true for a certain time interval called scaling range, is a characteristic of the correlations in the fluctuations of a signal $y(t)$ defined between the beginning $t_0$ and end of the observations $t_M$, i.e. $[t_0, t_M]$. The value can vary in time if the process is not stationary and/or the scaling range is finite (see Sect.6). The $\alpha$ exponent is related to the usual fractal dimension $D$.

The concept of the invariance of the fractal shapes at different scales (self-similarity) can be transposed in the statistical analysis of a time series. One searches for a given scale range where the statistical properties of the signal are invariant. By definition the time series is self-affine if its spectrum has a power law dependence.

$$S(f) \sim (1/f)^\beta.$$  \hspace{1cm} (3)

It has been shown by Heneghan and McDarby that the relationship $\beta = 1 + 2\alpha$ holds true for stochastic processes, i.e. for fractional Brownian walks. Depending on the value of the spectral exponent $\beta$, one has the following cases: if $\beta < 1$, the process is stationary; if $\beta > 1$, the process is non-stationary; if $1 < \beta < 3$ the process is non-stationary with stationary increments. In the case of white noise $\beta = 0$ while $\beta = 2$ for a Brownian walk signal.

\section*{IV. DATA}

Cloud base height data has been obtained during the Atlantic Stratocumulus Transition Experiment (ASTEX) in June 1992, at the Azores Islands using a laser ceilometer. The wavelength of the vertically transmitted into the atmosphere laser beam is 0.904 mm. The ceilometer works with a 15 m spatial resolution and reaches the maximum measurable height of 4 km. The time resolution of CBH records is 30 seconds. The cloud base height values were selected from the profiles of the backscattered signal intensity, using manufacturer’s algorithm based on a voltage threshold for the maximum value of the backscattered radiation at a height giving the local condensation level up to which unsaturated air parcels rise. We use data records measured on June 15, 1992 (Fig. 1(a)) and June 18, 1992 (Fig. 2(a)) to determine (i) the scaling properties of CBH fluctuations; (ii) to classify the type of time correlations, (iii) to investigate the diurnal changes in the CBH evolution, and (iv) to identify the type of the time dependent long-range correlation evolution.

According to on June 15, 1992 an anticyclone was centered north of Santa Maria - one of the Azores Islands, where the measurements were taking place, producing a strong subsidence inversion beneath which were observed marine boundary layer clouds. The nocturnal MBL was found to be well-mixed, generally coupled to the surface, with a solid layer of stratocumulus, while the daytime MBL was observed to be decoupled from the surface, because of the coexistence of a stratocumulus cloud layer and a cumulus marine subcloud layer. After the sunrise the MBL became intermittently decoupled and CBH varied dramatically as a cumulus formed at the top of the marine subcloud layer. In this decoupled MBL, the cumulus convection, that arises from the latent instability generated in the marine...
subcloud layer, acts toward a recoupling of the formally decoupled cloud layers that persist beneath the trade inversion. Five sequences of strong decoupling were observed that day (Fig. 1(a)).

For June 18, 1992 we do not have any information about the meteorological situation, but in analogy with data in Fig. 1(a), the CBH profile on Fig. 2(a) leads one to distinguish periods of increased variability of CBH, followed by short CBH fluctuations.

V. SCALING PROPERTIES OF THE CBH DATA

The CBH evolution, reported in Figs. 1(a) and 2(a) through $S(f)$, can be regarded as a non-stationary process with stationary increments, since their spectral exponents are $\beta = 1.28 \pm 0.1$, for June 15, 1992 (Fig. 3) and $\beta = 1.49 \pm 0.08$, for June 18, 1992 (Fig. 4). The data error bars are calculated from the r.m.s deviations in the fit according to standard techniques and have their 95% confidence interval conventional meaning.

The type of correlations of the CBH fluctuations can be probed using the Detrended Fluctuation Analysis (DFA) method. Applying the DFA method, we find that long-range time correlations in CBH fluctuations exist and are of an anti-persistent type with $\alpha = 0.24 \pm 0.002$ for June 18, 1992 and $\alpha = 0.21 \pm 0.005$ for June 15, 1992 (Fig. 5). They hold for a time interval approximately equal to 140 min in the first case and 40 min for the second. In this scaling range, the relationship $\beta = 1 + 2\alpha$ is reasonably satisfied. The flat like regions of both curves (Fig. 5) correspond to low values of the Hurst exponent $\alpha$ ($\alpha = 0.06 \pm 0.003$ for June 15, and $\alpha = 0.10 \pm 0.003$ for June 18) and indicate the presence of $1/f$-like noise.

For completeness, we show in Fig. 6, the distribution function of the CBH fluctuations for the 30 sec time lag interval. Notice the similarity between both cloud cases and the marked departure from the Gaussian behavior, as numerically exemplified in the $S(f)$ and DFA correlation methods in fact. A similar double triangular pyramid shape has been observed in other meteorological cases.

VI. TIME CORRELATION ANALYSIS

It is of interest to test if the correlations remain the same for shorter intervals accommodated into $[t_0, t_M]$ or if they change with time, as should be anticipated for nonstationary time series data. In order to probe the existence of so called locally correlated and decorrelated sequences, one can construct an “observation box” with a certain width, $\omega$, of size $7h$, place the box at the beginning of the data, calculate $\alpha$ for the data in that box, move the box by $\Delta \omega = 30$ min (or 60 points) toward the right along the signal sequence, calculate $\alpha$ in that box, a.s.o. up to the $N$-th point of the available data. A time dependent $\alpha$ exponent may be expected, and is given at the end of each box, thus for $t$ ranging from $\Delta \omega$ to $N$.

Thus we obtain an ”instantaneous measure” for the degree of long-range correlations. Results for this instantaneous $\alpha$-exponents are shown in Figs. 1(b) and 2(b) for the cloud base height data on June 15, 1992 and June 18, 1992. Note that each $\alpha$ value represents the behavior resulting from all points in the box, which continuously overlap. This approach
seems suitable to cloud base height data because it can be expected to reveal changes in the correlations dynamics of the clouds at various times for a given time lag $\Delta \omega$.

The $\alpha$ evolution is within the limits of a quite anti-persistent behavior with a transition from weak to strong, at various instant, in other words, anti-persistence is found in the underlying dynamics. Five regions in the CBH evolution, corresponding to the description given in section 2, can be distinguished for the CBH data measured on June 15. The first region lasts from 0 to 6 h, the second from 6 to 13 h, the third holds from 13:00 to 16:00 h, the fourth - from 16:00 to 20:00 h and the fifth one from 20:00 to 24:00 h. The transition occurring from 08:00 to 10:30 in the evolution of the $\alpha$ exponent indicates the increasing role of a process that generates the second structure in the CBH that appears between 10-13 h in Fig. 1(b). This process is characterized by a mean value of the local $\alpha = 0.24 \pm 0.01$ and is understood as a process of destabilization, in the decoupled MBL. Between 14-18 h the downward trend of the $\alpha$ exponent indicates the increasing dominance of a process that generates the third part of CBH evolution that exists between 17-19 h in Fig. 1(b). The mean value of the local $\alpha$ exponent is $\alpha =0.20 \pm 0.02$. From 19 h to 20:30 h a very slow upward trend leads to the process of the fourth region between 21:30 h - 24 h in Fig. 1(b), with a mean local $\alpha =0.26 \pm 0.02$.

For June 18 we distinguish three main regions in the CBH evolution: 0-10 h, 10-19 h and 19-24 h. The trends in the $\alpha$ exponent evolution are as follows: 0-10 h - process, generating the first CBH structure, with mean local $\alpha =0.17 \pm 0.02$. This corresponds to the dynamics of the MBL before its decoupling. For the period 10-16 h a large upward transition leads to a weak anti-persistent correlation in CBH fluctuations with a mean value of the local $\alpha =0.35 \pm 0.02$. Hence the dominant process is destabilizing the MBL structure. For the time 16-20 h the dynamics of the process changes again, characterized by a mean local $\alpha =0.26 \pm 0.01$ and a return to more stable MBL structure.

Thus the evolution of the Hurst exponent $\alpha$ in the cases that we have investigated, consists in the successive transitions from lower to higher values and vice versa. This corresponds to transitions from strong to weak anti-persistent correlations and reflects the changes in the underlying dynamics of the MBL.

Notice that the DFA function being a measure of the root mean square deviation from the linear best fit (a ”local trend”) is therefore a measure of a height-height correlation function. The so-called height is nothing else than a mass threshold. Therefore this DFA function informs on a corresponding physical property, i.e. the local compressibility (or bulk modulus) of the cloud fluid.

VII. CONCLUSIONS

We have presented an analysis of a marine stratocumulus cloud base height data series using the DFA method and the spectral density method in order to investigate the scaling range of time correlations in the CBH fluctuations searching for scaling laws and persistence effects. In all cases anti-persistent correlations hold with a well established day-night evolution measured by the instantaneous $\alpha$ index , - itself characterizing the dominant physical process. The transition, revealed by the trend in the $\alpha$ evolution, between processes inducing different levels of anti-persistent correlations of the fluctuations could be used as a
trace parameter of the CBH dynamics. The accuracy of these statistics in CBH fluctuations suggests the usefulness of similar studies for the radiation transfer dynamics.

The DFA method allows one to obtain the scaling ranges and crossovers of the correlations between the fluctuations of a signal. The $\alpha$ exponent is in fact directly related to that for the auto correlation function.\textsuperscript{[6]} Incidentally, if the relationship $\gamma = 2(1 - \alpha)$ is supposed to hold for describing the power law dependence of the autocorrelation function, a value $\gamma = 1.56$ is expected. This means that the CBH fluctuations can be empirically represented by a fractional Brownian motion process.\textsuperscript{[6]} The oscillations between different stability regimes could thus be mapped onto a Kramer problem\textsuperscript{[38]} itself mimicking the basic Langevin equation for the signal increments.

Nevertheless this knowledge of the second moment of a signal is not usually enough in order to have a full understanding of the physical process nor of its underlying physical mechanisms governing the CBH. It would be of interest to couple these results to some analysis of the local (vertical and horizontal) velocity fluctuations, and of the temperature fluctuations in order to obtain additional information, whence the viscosity and thermal conductivity, for a better understanding of cloud physics and weather predictability.

VIII. ACKNOWLEDGMENTS

This research was partially supported by Battelle grant number 327421-A-N4.
REFERENCES

1. J.S. Turner, *Buoyancy effects in Fluids* (Cambridge University Press, Cambridge, 1973)
2. D.K. Lilly, *Quart. J. Roy. Met. Soc.* 94, 292 (1968)
3. R.N. Mantegna, H.E. Stanley, *Nature* 376, 46 (1995)
4. S. Ghashghaie, W. Breymann, J. Peinke, P. Talkner, Y. Dodge, *Nature* 381, 767 (1996)
5. H.E. Stanley, S.V. Buldyrev, A.L. Goldberger, S. Havlin, C.-K. Peng, M. Simons, *Physica A* 200, 4 (1993)
6. S. Mercik, K. Weron, *Phys. Rev E* 63, 051910 (2001)
7. Z. Siwy, S. Mercik, K. Weron, M. Ausloos, *Physica A* 297, 79 (2001)
8. N. Vandewalle, M. Ausloos, *Physica A* 246, 454 (1997)
9. N. Vandewalle, M. Ausloos, *Int. J. Comput. Anticipat. Systems* 1, 342 (1998)
10. K. Ivanova, M. Ausloos, *Physica A* 274, 349 (1999)
11. M. Ausloos, K. Ivanova, *Phys. Rev E* 63, 047201 (2001)
12. E. Koscielny-Bunde, A. Bunde, S. Havlin, H. E. Roman, Y. Goldreich, H.-J. Schellnhuber, *Phys. Rev. Lett.*, 81, 729 (1998)
13. P. Talkner, R.O. Weber, *Phys. Rev. E* 62, 150 (2000)
14. K. Ivanova, M. Ausloos, E.E. Clothiaux, T.P. Ackerman, *Europhys. Lett.,* 52, 40 (2000)
15. N. Gospodinova, K. Ivanova, *InProc. LTL Plovdiv’99- Laser Thechnology and Lasers*, p.111, Plovdiv, Bulgaria (1999)
16. C.-K. Peng, S.V. Buldyrev, S. Havlin, M. Simmons, H.E. Stanley, A.L. Goldberger, *Phys. Rev. E* 49, 1685 (1994)
17. H. E. Hurst, *Trans. Amer. Soc. Civ. Engin*. 116, 770 (1951)
18. J. R. Garratt, *The Atmospheric Boundary Layer* (Cambridge University Press, Cambridge, 1992)
19. D. G. Andrews, *An Introduction to Atmospheric Physics* (Cambridge University Press, Cambridge, 2000)
20. U. Frisch, *Turbulence: The legacy of A.N. Kolmogorov* (Cambridge University Press, Cambridge, 1995)
21. H.A. Panofsky, J.A. Dutton, *Atmospheric Turbulence* (John Wiley & Son Inc. New York 1983)
22. A. G. Driedonks, P.G. Duynkerke, *Bound. Layer Meteor.* 46, 257 (1989)
23. R.A. Anthens, H.A. Panofsky, J.J. Cahir, A. Rango, *The Atmosphere* (Bell & Howell Company, Columbus, OH, 1975)
24. J.A. Brudsaert, *Evaporation into the Atmosphere* (Reidel, Dordrecht, 1982) p.299
25. World Meteorological Organization, Report of the JSC/Cas Workshop on Modeling of Cloud Topped Boundary Layer, WMO World Climate Program, Report WCP-106, World Meteorological Organization, Geneva, 29 (1985)
26. P.G. Duynkerke, H.Q. Zhang, P.J. Jonker, *J. Atmos. Sci.* 62, N16, 2763 (1995)
27. C.S. Bretherton, R. Pincus, *J. Atmos. Sci.* 62, N16, 2707 (1995)
28. C.S. Bretherton, P. Austin, S.T. Siems,*J. Atmos. Sci.* 62, N16, 2724 (1995)
29. A.K. Betts, C.S. Bretherton, E. Klinker, *J. Atmos. Sci.* 52, 2752 (1995)
30. P.S. Addison, *Fractals and Chaos* (Institute of Physics, Bristol, 1997)
31. B.D. Malamud, D.L. Turcotte, *J. Stat. Plann. Infer.* 80, 173 (1999)
32. C. Heneghan, G. McDarby, *Phys. Rev E* 62, 6103 (2000)
33. A. Davis, A. Marshak, W. Wiscombe, R. Cahalan, *J. Geophys. Res.* 99 8055 (1994)
M.A. Miller, Surface-Based Remote Sensing of Marine Boundary-Layer Mesoscale Cloud Structure During ASTEX, Ph.D. Thesis, The Pennsylvania State University, University Park, PA (1994)

A.C. Bajpai, I.M. Calus, J.A. Fairley, Statistical Methods for Engineers and Scientists (Wiley, Chichester, 1978)

K. Ivanova, E. Clothiaux, H.N. Shirer, N. Kitova, M.A., Mikhailov, T.P., Ackerman, M., Ausloos, unpublished, submitted to Physica A

P.M. Chaikin, T. C. Lubensky, Principles of Condensed Matter Physics, Cambridge Univ. Press, Cambridge, 1995)

L.E. Reichl, A Modern Course in Statistical Physics (Univ. Texas Press, Austin, 1980).
FIGURES

FIG. 1. (a) CBH fluctuations for June 15, 1992; (b) The $\alpha$ evolution, clarifying the transitions between strong and weak anti-persistent behavior of CBH fluctuations.

FIG. 2. (a) CBH fluctuations for June 18, 1992; (b) The $\alpha$ evolution, clarifying the transitions between strong and weak anti-persistent behavior of CBH fluctuations.
FIG. 3. The power spectrum of the cloud base height data (data in Fig. 1(a)). A spectral exponent $\beta = 1.28 \pm 0.1$ characterizes the correlations of fluctuations.

FIG. 4. The power spectrum of the cloud base height data (data in Fig. 2(a)). A spectral exponent $\beta = 1.49 \pm 0.08$ characterizes the correlations of fluctuations.
FIG. 5. The DFA function $< F(t) >^{1/2}$ for the CBH data measured on June 15, 1992 (data in Fig. 1(a)). Scaling properties change from $\alpha_1 = 0.21 \pm 0.005$ to $\alpha_2 = 0.06 \pm 0.003$ for time lags longer than 40 min. CBH data measured on June 18, 1992 (data in Fig. 2(a)) scale with $\alpha_1 = 0.24 \pm 0.002$ for time lags smaller than 140 min and $\alpha_2 = 0.10 \pm 0.003$ after that.

FIG. 6. Partial distribution function (PDF) of the CBH signal increments (discretization step = 30 s) for both June 15 (black dots) and June 18, 1992 (black squares) stratuscumulus clouds observed on Azores Islands. The x-axis is normalized in units of the standard deviation of the corresponding PDF for a time lag 960 s, - supposedly long enough such that each PDF then corresponds to a Gaussian distribution. The standard deviation for June 15 is 198.9 m and the one for June 18 is 323.4 m. The June 15 data has been displaced vertically by one decade.