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Variability of scaling time series in the sea ice drift dynamics in the Arctic Ocean

A. Chmel[1], **V. N. Smirnov**[2], **and I. B. Sheikin**[2]

[1]Ioffe Physico-Technical Inst., Russian Academy of Sciences, 194021 St. Petersburg, Russia
[2]Arctic and Antarctic Research Inst., 38 Bering str., 199397 St. Petersburg, Russia

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Correspondence to: A. Chmel (chmel@mail.ioffe.ru)

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Abstract

A motion of an individual ice field in the Arctic Ocean was monitored at the Russian research station North Pole 35 established on the ice pack in 2008. The ice field velocity (V) was found to be correlated with wind velocity (v) in main features, such as the positions of maxima and minima of V and v. However, the fine structure of the V-variation cannot be explained by the wind forcing only. There were periods of time when the field drift was highly affected by either the tidal activity or the interactions of ice sheets between each other. These data were put in comparison with the "waiting times" statistics that is with the distributions of lengths of time intervals between subsequent important local accelerations of the ice field. These distributions were measured in several time windows differing in the average wind velocity and/or the mechanical state of the ice pack. The distribution functions $N(>\tau)$ (N is the number of successive events of accelerations separated by the time interval that exceeds τ) constructed in different time windows demonstrated fractal or multifractal nature in the consolidated ice pack but were truly random when the ice field drifted in the highly fragmented sea ice. The latter result evidences the existence of a relationship between the long-range mechanical interactions in the pack and long-term memory (time scaling behavior) of the sea ice motion.

1 Introduction

Recent studies of the sea ice drift and mechanical behavior of the ice pack, including its deformations and fragmentations, revealed that the Arctic sea ice cover (ASIC) exhibits well-pronounced scaling properties typical for the dynamics of the non-equilibrium, permanently critical systems (Marsan et al., 2004; Korsnes et al., 2004; Smirnov et al., 2006; Chmel et al., 2007; Rampal et al., 2008). The spatial, energy and temporal distributions of the mechanical events in the ASIC follow the power law with varying exponents thus indicating the existence of a latent relationship between the scaling features and underlying physical processes.

The temporal invariance of the geophysical processes is highly debated in seismology (Bak et al., 2002; Davidsen and Goltz, 2004; Varotsos et al., 2006; Telesca and Lovallo, 2008), because the recurrence time between earthquakes is the key parameter of the problem of catastrophe forecasting. The studying of the correlated in time events that take place in the polar cap (where the areas of interacting components are close to that in tectonic formations) allows one to establish some common trends in the behavior of large-scale systems and to obtain new knowledge on the role of the time correlation in geophysics.

There were reported previously (Chmel et al., 2005, 2007) some time characteristics of the sea ice drift in the Arctic Ocean as revealed from the field observations that were carried out at the research station "North Pole 32" (NP 32) established on the ice pack in 2003–2004. The sequences of events of accelerations of an individual ice field were found to be self-similar (or, in terms of the critical dynamics, fractal) during quasi-stationary periods of drift and fully disordered (truly random) when the great pack fragmentation occurred in the region of the NP 32 activity. The field investigation of the sea ice drift dynamics was continued at the stations NP 33 and NP 35 where the data on the sea ice mobility were collected during 2005 and 2008, respectively. In this communication, we present the original data recorded at these stations and the analysis of the ice field motion in different periods of time. A particular attention was paid for the response of the drift dynamics to varying outer conditions, such as the wind forcing, tidal activity, and sea ice sheets interactions. The cases of monofractal, multifractal and random time series are considered in the context of relative significance of physical processes that govern the sea ice drift.

2 Experimental technique and data processing

The permanent motion of the ice-pack consists of an infinite sequence of events of displacements caused, mainly, by the wind forcing (Martin and Drucer, 1991) and, to

OSD
6, 1595–1610, 2009

lesser extent, by the ocean currents and tidals, which transform, at least partially, to the direct force interactions between the sea ice cover components. The interactions of all kinds cause the local accelerations of individual ice fields, that is, the sea ice sheets limited by leads and cracks. In this work, the local accelerations were derived from the data on the ice field displacements measured using GPS transducers that were established and actuated simultaneously on the same ice field at the distance of about 180 m. The data from two transducers were collected using a field PC in sampling intervals of a minute. The observation accuracy when using the GPS transducers was characterized by the twice distance root mean square (2DRMS) value. The 2DRMS refers to a horizontal distance from the true position, on which 95% of measured points fall. The spatial anisotropy of the measurement errors and the symmetric shape of the cloud of measured point are usually supposed in such estimate. However, the latter assumption fails to be quite valid when carrying out the observations on the drifting ice at high latitudes; therefore, an elliptic approximation was applied for the analysis of spatial scattering of the measured points. One of the GPS transducers was conventionally referred as “master”, while the other one was referred as “slave”.

Figure 1 shows a cloud of scattering and the 2DRMS ellipse for positions of the slave transducer measured in the orthogonal coordinates centered at the position of the master transducer. The ellipse is constructed using the compatible function of the two-dimensional probability distribution with taking into account a correlation of the orthogonal measurements. Two semiaxes of 6.2 m and 4.0 m characterize the 2DRMS along the main directions.

In order to obtain estimates for the non-correlated measurement errors of the drift velocity, as well as to assess their dependence of a sampling interval, the regression analysis of the data from two GPS transducers was performed. The distances between sequent measurement points in the sampling interval were used as the input data of the regression, and the standard error of the regression was taken as an estimate for the drift velocity measurement error. Table 1 presents the obtained estimates for the standard error of regression, the non-correlated errors of the drift velocity measurements

OSD

6, 1595–1610, 2009

Variability of scaling time series in sea ice drift dynamics in Arctic Ocean

A. Chmel et al.

and the errors of the calculation rounding-off in different measurement intervals. The estimates show a significant decrease of the non-correlated noises with the decrease of the measurement interval, and this trend does not depend, in fact, on the drift velocity (Fig. 2). One can suppose that this behavior is caused by the increase of the stability of the navigational satellites configuration with reducing the measurement interval. In addition, the data in Table 1 indicate that the rounding-off errors dominate in short measurement intervals.

Provided that the current geographical coordinates are known, the ice field velocity (V) and the absolute values of accelerations (A) can be calculated as

$$A \equiv |A| = |\Delta V|/\Delta t \qquad (1)$$

Here ΔV is the variation of the drift rate measured in regular intervals Δt=1 min. Only the values V that exceed the standard error of velocity (Table 1) 5 times or more were taken into account in the subsequent data analysis. The percentage of such velocities (and, correspondingly, the percentage of reliable accelerations $A > A_{\text{cut-off}}$) was about 50% of all measured values V. The time intervals between the events of acceleration whose amplitude exceeded $A_{\text{cut-off}}$ were regarded as waiting times for the nearest event of acceleration. A collection of all waiting times was used to obtain the distribution function $N(>\tau)$ (N is the number of successive events of accelerations separated by the time interval that exceeds τ).

3 Results

Figure 3a shows the ice field velocity measured in the period of time from 16 February 2008 to 15 March 2008. This time interval was selected for analysis because it covers a few periods with quite different character of the ice motion.

A comparison of the V-variation with the data on the wind velocity (v) in the same period of observations demonstrate a relationship between V and v in main features, such as the positions of maxima and minima (Fig. 3b). However, the fine structure of the V-variation cannot be explained by the wind forcing only. One can distinguish, at least, two periods of time when the field drift was affected by the action of another source of forcing.

First, on 21–23 February 2008, the ice field exhibited quite excited motion, whose actual variability was much stronger than the variability of the wind velocity in the same period of time. The wind-independent "jumps" seem to be due to the local interactions between ice sheets, such as stick-slips and shearing. Second, on 11–16 March 2008, a cyclic V-variation with a period equal to 12 h took place. This periodicity is undoubtedly related with the tidal effect superimposed on the wind forcing. The motion of this kind one could expect for the sea ice cover fragments, which are weakly connected with neighboring components. Hence, we suggested that an event of substantial sea ice fragmentation occurred in the period of time preceded 10 March 2008. This supposition was confirmed by studying the satellite images of the region of interest. The image of 10 March reveals the highly fragmented sea ice pattern of disconnected pieces instead of the relatively consolidated pack seen in the image of 29 February (Fig. 4). Thus, one can divide the whole period of observations into a few conventionally separated time windows characterized by particular drift conditions, that is window (A) from 16 to 20 February ("stationary" wind-driven drift); (B) 21 to 23 February (highly excited movement); (C) 24 February to 6 March (wind-driven drift); (D) 7 to 10 March (a cycle of the sea ice cover fragmentation); (E) 11 to 15 March (tidal-driven drift). In order to estimate the response of the ice field motion on the varying conditions of drift, the sequences of ice field accelerations were calculated for each time window.

To construct the distribution function $N(>\tau)$ graphically, the number of waiting times exceeding an arbitrary given τ was plotted against τ in doubly logarithmic coordinates.

The obtained waiting time distributions for selected time windows are depicted in Fig. 5. The distributions are unambiguously different. In windows A–D the $N_{\text{versus}\,\tau}$ dependence exhibits a power law

$$N(>\tau) \propto \tau^{\delta} \tag{2}$$

The dependences in windows A, B and D demonstrate the mono-exponent behavior, while there is a dual exponent dependence in window C. The function $N(>\tau)$ does not follow the power law in window E.

4 Discussion

The power law decay of time correlations between physical events over wide time scale are typical for fractal the behavior inherent in permanently critical systems, that is in the systems where correlations are much larger than the length scale of direct interacting.

The absolute value of the power exponent characterizes the relative contribution of “short” and “long” waiting times to the whole $N(>\tau)$ distribution. Really, one can see that the largest absolute value of $\delta=-3.4$ was obtained for window B (Fig. 3a) that is during the highly excited motion characterized by predominantly short recurrence times. Two different exponents equal to 1.0 and 1.3 characterize the ice field motion in window B. This means that the waiting time distribution is multifractal, that is the ice field is involved into two critical processes of different time scale levels. Since the temporal characteristics of the permanently critical systems are interrelated with their spatial properties (Maslov et al., 1994; Rampal et al., 2008), one can suggest that the time multifractality is caused by the fact that the detected accelerations were corresponded with the simultaneous motion of the sea ice formations belonging to different hierarchy levels, say, local and regional ones in terms of the Overland's classification (Overland et al., 1995).

The waiting time distribution measured in window E does not exhibit a log-linear dependence. In the light of the data presented in this work, we conclude that the loss of the temporal correlation occurred after the beginning of the fragmentation as a result of the multiple breakage of structural links in the fracturing sea ice sheets. In the current study, the prevailing tidal forcing in the period of time 11 to 15 March (window E) signalizes the low interactions of the ice field with neighboring sea ice structures. The lack of long-range interactions excludes the possibility of long-term time correlations since the structural memory of preceding events in a multi-component system is, in fact, a cooperative response of the system as a whole on the behavior of its individual components. In our case, an ice field itself does not store the information about its prehistory, while its environment does. The highly variable contact interactions (stick-slips, impact, etc.) play the role of dynamical structural links in the mobile collection of sea ice pieces.

The effect of the mechanical connectedness of the non-equilibrium statistical system on its scaling properties was considered of a number of model simulations (Christensen and Olami, 1992; Olami et al.,1992; Abaimov et al., 2007). A scenario close to our situation was analyzed by Abaimov et al. (2007) using a slider-block model for slip events. The authors obtained that the scale-invariant statistics of the recurrence times depends on the system's stiffness: the lower the stiffness (and, hence, the energy conservation), the smaller size of elements that interact following the power law waiting time statistics. In a highly stiff system the power law waiting time statistics covers the events of all spatial scale levels. The qualitative conclusion of this simulation – the lower conservative properties of the system, the lesser pronounced its time scale invariant behavior – is consistent with the loss of the time scaling during the as-free drift of the ice field observed in our study.

5 Conclusions

The length distributions of time intervals between subsequent important (as defined) local accelerations of an ice field drifting in the consolidated pack demonstrate the power law behavior. The values of the power law exponent are sensitive to the intensity of the wind forcing because the contribution of "short" and "long" time intervals to the waiting time distribution depends on the variability of the ice field velocity. However, in the highly fragmented sea ice, the waiting-time statistics becomes non-scaling because the memory on the space-time trajectory of the low-connected, low-interacting system cannot be efficiently maintained.

OSD

6, 1595–1610, 2009

References

Abaimov, S. G., Turcotte, D. L., Sherbakov, R., and Rundle, J. B.: Recurrence and interoccurence behavior of self-organized complex phenomena, Nonlinear Proc. Geoph., 14, 455–464, 2007.

Bak, P., Christensen, K., Danon, L., and Scalon, T.: Unified scaling law for Earthquakes, Phys. Rev. Lett., 88, 178501(1–4), 2002.

Chmel, A., Smirnov, V. N., and Astakhov, A. P.: The Arctic sea ice cover: fractal space-time domain, Physica A, 357, 556–564, 2005.

Chmel, A., Smirnov, V. N., and Panov, L. V.: Scaling aspects of the sea ice-drift dynamics and pack fracture, Ocean Sci., 3, 291–298, 2007, http://www.ocean-sci.net/3/291/2007/.

Christensen, K. and Olami, Z.: Scaling, phase transitions, and nonuniversality in a self-organized critical cellular-automation model, Phys. Rev. A, 46, 1829–1838, 1992.

Davidsen, J. and Goltz, C.: Are seismic waiting time distributions universal?, Geophys. Res. Lett., 31, L21612–L21616, 2004.

Korsnes, R., Souza, S. R., Donangelo, R., Hansen, A., Paczuski, M., and Sneppen, K.: Scaling in fracture and refreezing of sea ice, Physica A, 331, 291–296, 2004.

Marsan, D., Stern, H., Lindsay, R., and Weiss, J.: Scale dependence and localization of the deformation of Arctic Sea ice, Phys. Rev. Lett., 93, 178501(1–4), 2004.

Martin, S. and Drucer, R.: Observation of short-period ice floe accelerations during leg II of the Polarbjorn drift, J. Geophys. Res., 96, 10567–10580, 1991.

Maslov, S., Paczuski, M., and Bak, P.: Avalanches and 1/f noise in evolution and growth models, Phys. Rev. Lett., 73, 2162–2165, 1994.

Olami, Z., Feder, H. J. S., and Christensen, K.: Self-organized criticality in a continuous, non-conservative cellular automaton modeling earthquakes, Phys. Rev. Lett., 68, 1244–1247, 1992.

Overland, J. E., Walter, B. A. Curtin, T. B., and Turet, P.: Hierarchy and sea ice mechanics: a case study from the Beaufort Sea, J. Geophys. Res., 100, 4559–4571, 1995.

Rampal, P., Weiss, J., Marsan, D., Lindsay, R., and Stern, H.: Scaling properties of sea ice deformation from buoy dispersion analysis, J. Geophys. Res., 113, C03002(1-12), 2008.

Sheikin I. B. and Smirnov, V. N.: Accuracy estimation of the GPS measurements at the Russian drifting stations North Pole-33 and North Pole-35, Proc. 19th IAHR International Symposium

OSD

6, 1595–1610, 2009

Variability of scaling time series in sea ice drift dynamics in Arctic Ocean

A. Chmel et al.

on Ice, Vancouver, Canada, July, 2008.
Smirnov, V. N., Chmel, A. E., Panov, L. V., and Tulaikova T. V.: Ice of the Arctic: the processes of self-organized dynamics and mechanics, Stockholm Intern. Fairs, Abstract 6360–24, 2006.
Telesca, L. and Lovallo, M.: Investigating non-uniform scaling behaviour in temporal fluctuations of seismicity, Nat. Hazards Earth Syst. Sci., 8, 973–976, 2008, http://www.nat-hazards-earth-syst-sci.net/8/973/2008/.
Vorotsos, P. A., Sarlis, N. V., Skordas, E. S., Tanaka, H. K., and Lazaridou, M. S.:Attempt to distinguish long-range temporal correlations from the statistics of the increments by natural time analysis, Phys. Rev. Lett., 74, 021123(1–12), 2006.

OSD

6, 1595–1610, 2009

Table 1. Sampling interval influence on the empirical error estimates*.

Sampling interval, min	1	2	5	10
Standard error of regression, m	0.8	1.14	1.62	1.91
Standard error of velocity, m/sec	0.013	0.009	0.005	0.003
Rounding error m/sec	0.031	0.015	0.006	0.003

* For more detailed accuracy analysis of this experiment see (Sheikin and Smirnov, 2008).

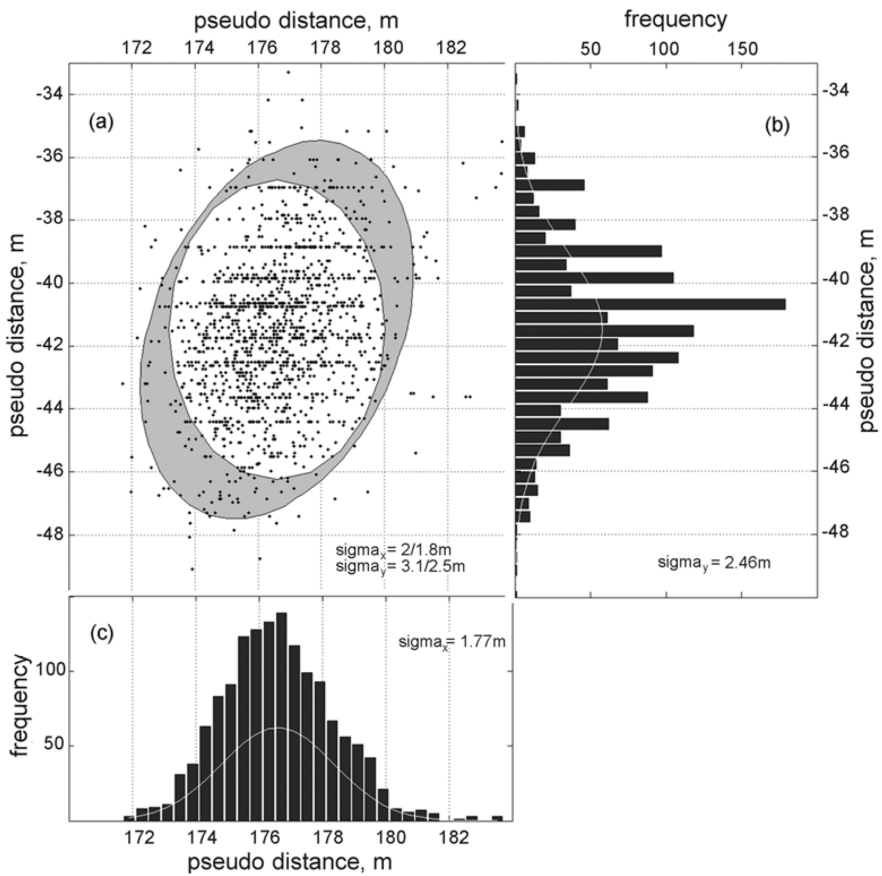

Fig. 1. 24-h scattergram of the slave transducer data presented in the local orthogonal coordinates. The ellipse **(a)** shows the 2DRMS (95% concentration) for the compatible function; **(b, c)**: the frequency histograms of the partial pseudo distance distributions with normal approximations and partial standard deviations.

OSD
6, 1595–1610, 2009

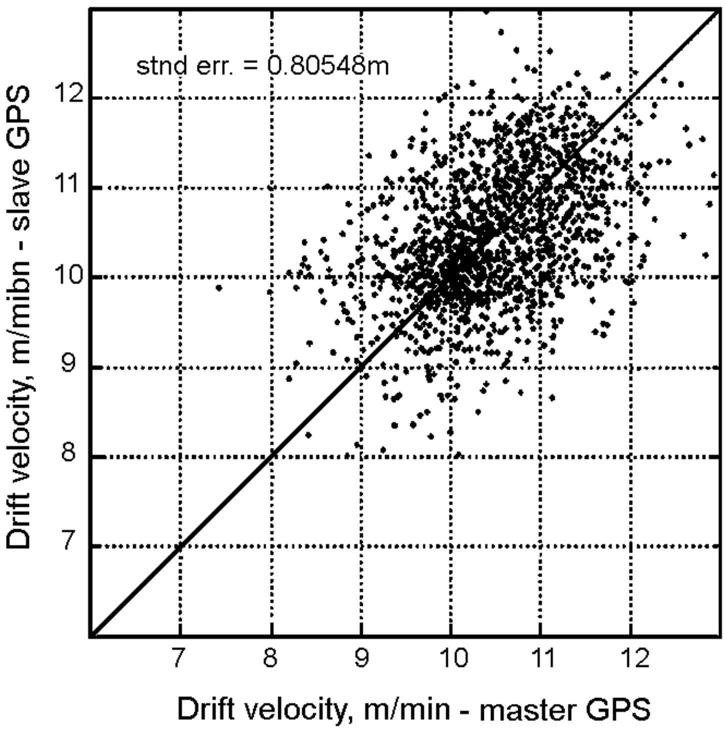

Fig. 2. Standard error estimates of the drift velocity.

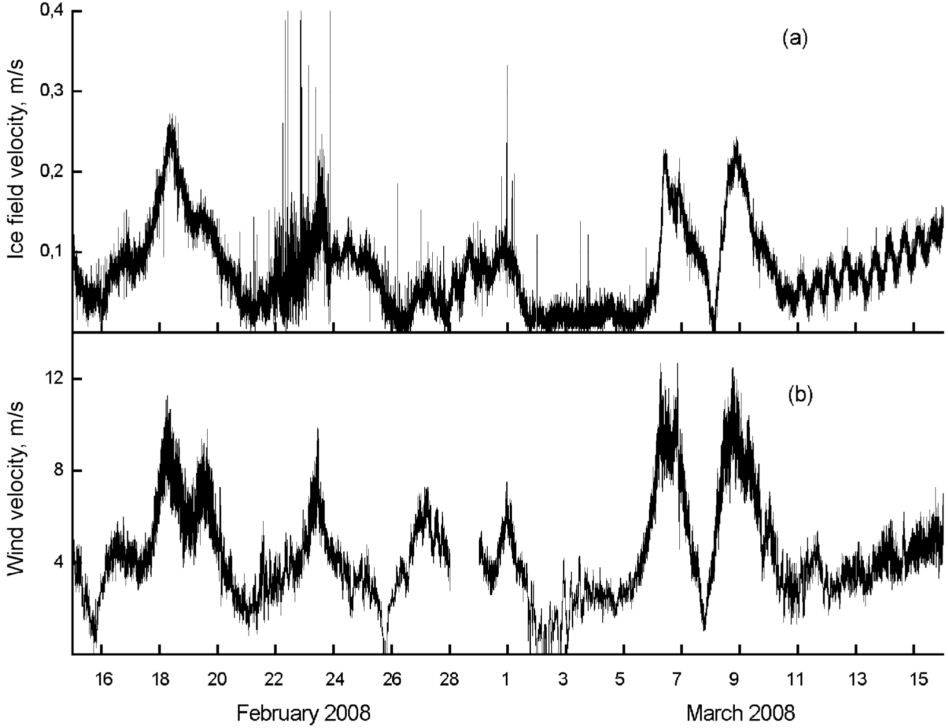

Fig. 3. Wind velocity **(a)** and ice field velocity **(b)** in the period of time from 16 February to 15 March 2008.

OSD
6, 1595–1610, 2009

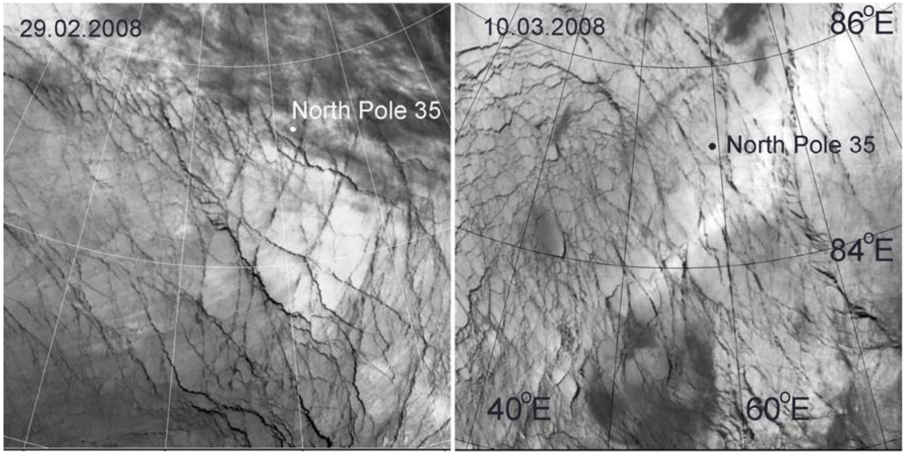

Fig. 4. Fragments of the AVHRR images of the region of NP 35 drift obtained on 29 February **(a)** and 10 March 2008 **(b)**.

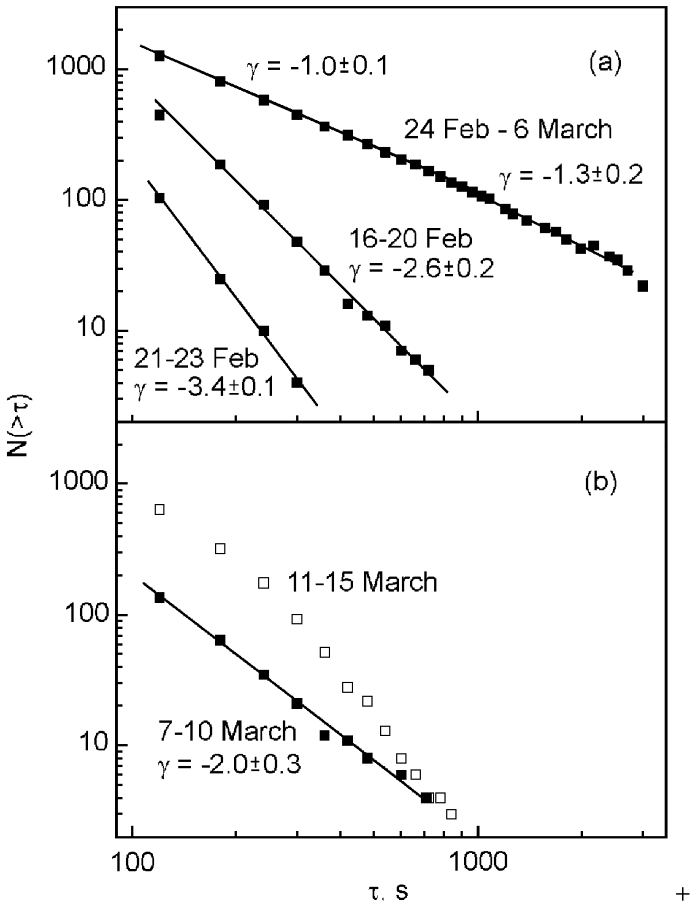

Fig. 5. The waiting time distributions $N(>\tau)$ in different time windows in February **(a)** and in March 2008 **(b)**.