MANIFESTATIONS OF THE INDIAN OCEAN TSUNAMI OF 2004 IN SATELLITE NADIR-VIEWING RADAR BACKSCATTER VARIATIONS

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ABSTRACT The paper reports on the first experimental evidence for space-observed manifestation of the open ocean tsunami in the microwave radar backscatter (in C- and Ku-bands). Significant variations of the radar cross section synchronous with the sea level anomaly were found in the geophysical data record of the altimetry satellite Jason-1 for the track which crossed the head wave of the catastrophic tsunami of 26 December 2004. The simultaneous analysis of the available complementary data provided by the satellite three-channel radiometer enabled us to exclude meteorological factors as possible causes of the observed signal modulation. A possible physical mechanism of modulation of short wind waves due to transformation of the thin boundary layer in the air by a tsunami wave is discussed. The results open new possibilities of monitoring tsunamis from space..

KEY WORDS: ManuscriptsAltimetery, Radar backscatter, Tsunami, Wind waves

1.INTRODUCTION

The catastrophic tsunami of 26 December 2004 emphasized the need in a functioning global system of tsunami early warning. A space-borne system of tsunami monitoring would have been an ideal solution because of global coverage and instant access to the information. At present, the only known way of tsunami satellite remote sensing is via space-borne altimetry[1,2] , which, unfortunately, is of limited practical value due to the high level of the ambient noise. It could be reduced, for example, by a coherent processing such as pattern recognition. In this context, it would have been preferable to employ side-looking instruments providing large-scale panorama of the sea surface, for example, synthetic aperture radars. The key open question was, whether a tsunami can produce a signature at a radar image, that is, cause modulation of the short waves ("sea roughness") sufficient for instrumental registration. Here we report on the first experimental evidence for space-observed manifestation of the open ocean tsunami in the microwave radar backscatter (in C- and Ku-bands; wave-lengths 6cm and 2 cm

There are some of reports on manifestations of the tsunami of 26 December in optical and infrared satellite imagery[3,4,5] in the coastal zone, where the tsunami was strong enough and a noticeable effect of modulation the of "sea roughness" could be expected. Note that according to some earlier eyewitness observations[6,7,8], the so-called "tsunami shadow" occurs in the vicinity of the shore as a dark band along the tsunami front, presumably caused by modulation of wind waves. However, for the open ocean conditions, visibility of a tsunami was in question. The unique case of the huge tsunami of 26 December 2004 enables one to elucidate the situation.

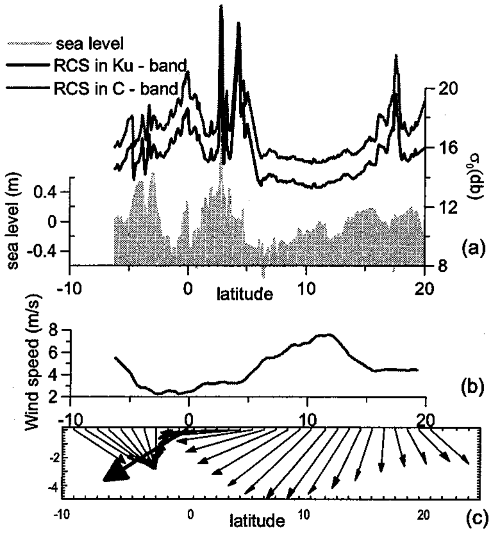

Figure 1. Latitude dependencies of parameters from the geophysical data record of the Jason-1 altimetry satellite 26 December 2004 (cycle 109, track 129) a) sea level anomaly and C- band and Ku-band radar cross section (RCS), b) the altimeter wind speed at 10 m height , c) the directions of wind speed (black arrows) according to the ECMWF model and the tsunami wave propagation (blue arrow) near the equator according to numerical simulations [10,11].

2. ANALYSIS OF THE GDR OF JASON-1.

Unfortunately, neither radar, nor infrared or optical images of the tsunami on December 26, 2004 were acquired in the open ocean. At the same time, the satellite Jason-1 track crossed the head tsunami wave at 5^0 *S* 82^0 E at 2h 53min UTC, that is, 1 h 55 min after the earthquake (track 129 of cycle 109). The radar altimeter duly reliably registered the sea level displacements associated with the head tsunami wave and even its shape[9,10,11], which was corroborated by numerical simulations[10,11]. Having these data we checked, whether there are variations of received power of radio waves synchronous with the tsunami and associated with variations of the sea roughness. *The* radar cross section (RCS), which is included in the geophysical data record (GDR) of Jason-1 for the radar altimeter operating in C and Ku bands (electromagnetic wave lengths 6cm and 2 cm, respectively). The data collected by Physical Oceanography Distributed Active Archive Center (PODAAC) are available online. Time series of the Sea Level Anomaly and C- and Ku-band RCS are presented in Fig.1a. The sea level variations due to the tsunami are clearly seen north of the latitude -5^0, the surface displacements exceed 0.6m and the spatial scale of the wave is a few hundreds of km. RCS varies significantly (a few decibel) simultaneously with the sea level. Note that according to the wind velocity vector data obtained from the meteorological model of the European Center for Medium Range Weather Forecasting (ECMWF) and shown in (fig.1b,c) (also see GDR) the tsunami front near the equator passed an area of weak wind and our further analysis will be focused on this case.

RCS variations associated with modulation of short wind waves by tsunami waves can be masked by variations due to some other physical mechanisms, in particularly, due to some other meteorological factors.

To relate unambiguously the RCS variations in fig.1 with the tsunami, below we carefully analyze the GDR data in the latitude range -5 - +5 (fig.2a) and rule out some background meteorological factors.

Measurements of the atmospheric conditions independent from the radar altimeter data aboard Jason-1are provided by the 3-channel radiometer operating at frequencies 18.7 GHz, 23.8 GHz, 34 GHz. These measurements are used for retrieving water vapor content in the atmosphere (fig.2b). The corresponding brightness temperatures also reflect the variations of the sea surface roughness, however, under the conditions of the weak wind, which occur in the domain ±5°, the wind velocity cannot be reliably determined on the base of radiometry. We supposed that the water vapor content is independent on the sea level elevation in the tsunami wave and can be taken as a measure of background meteorological variations. We retrieved the empirical dependence of RCS on the water vapor content C_V from the GDR data taken within the range ±5°, which reflects the local weather conditions, the best fit for it is:

$$\sigma_{0Ku}(C_V)=-3.18\ C_V+32.5 \qquad (1)$$

To rule out the meteorological factor we considered the value

$$\Delta\sigma_{0Ku}=\sigma_{0Ku}-\Sigma_{0Ku}\ (C_V)$$

The along track section of $\Delta\sigma_{0Ku}$ is presented in fig.2c. The cloud of points $\Delta\sigma_{0Ku}$ via the sea level anomaly (fig.3) demonstrates significant correlation among these two values. The correlation coefficient is about 0.5 in the range $-5^o\div2.5^o$, where there is no significant fluctuations of the electron content in the ionosphere (see fig.2c), and it is about 0.65 in the range $-5^o\div0^o$, where the sea level anomaly is reliably interpreted as the tsunami wave [10,11].

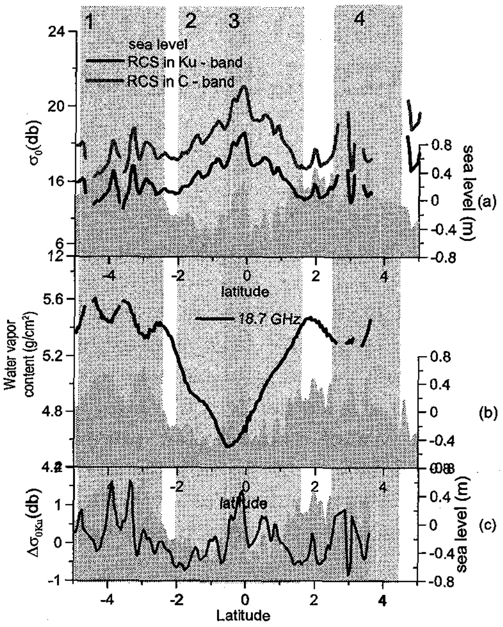

Figure.2. The enlarged segment of the record.

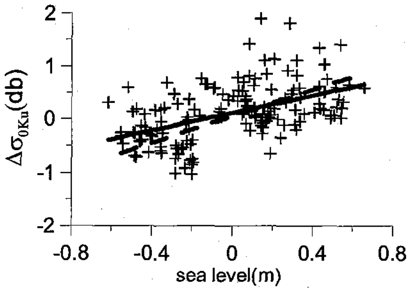

Fig.3 Dependence of $\Delta\sigma_{0Ku}$ on the sea level elevation (points). The solid line is the best fit for points between –5° and 2.5^0 (correlation coefficient is 0.49), the dashed line is the best fit for points between –5° and 0^0 (correlation coefficient is 0.65).

3. POSSIBLE MECHANISM OF MODULATION OF SURFACE WAVES IN THE PRESENCE OF THE TSUNAMI WAVE.

Mechanisms of modulation of short wind waves responsible for the scattering properties of the sea surface in the presence of inhomogeneous unsteady flow caused by tsunami are unknown. Those previously developed to describe similar modulation in the context of internal waves, as result of straining of surface waves due to inhomogeneous currents prove to be practically negligible, taking into account, that in the open ocean typical tsunami waves have elevations not exceeding one meter, orbital velocities of just a few centimeters per second, and wavelengths of several hundred kilometers. The following possible physical mechanism seems to be the most likely candidate to explain the effect of a tsunami on short surface waves. The orbital velocities of the tsunami wave cause modulation of wind velocity over the sea surface. This results in the modulation of the surface wave growth rate that in turn causes variations of the intensity of short surface waves. This mechanism was earlier discussed in detail in the context of radar probing of long surface waves and swell [13,14] and is used below to estimate the RCS variations due to tsunami (see, also[6]). It should be mentioned, that natural variations in wind field are much stronger than the tsunami induced velocity. Fortunately, the spatial scale of such variations is about 1 km, and it is averaged due to the spatial resolution of the altimeter at 1 Hz measurements; taking into account the ground track speed for Jason1, 5.8 km/s gives resolution about 6 km. which is about 5 km for 1-second averaging.

We estimated hydrodynamic contrast caused by the tsunami wave in the field of surface wind waves, basing on the model [13,14]. It is worth mentioning, that nonlinear wave-wind interaction, i.e. modulation of the roughness parameter, should be taken into account (see [10]). To describe disturbances induced in the air by the tsunami wave, we employ the model of the atmospheric boundary layer over the waved water surface[15], which include the Reynolds equations closed on the base of the gradient approximation of turbulent stresses, where the eddy viscosity coefficient ν_t is a definite function.

The system of equations for the disturbance induced in the air by the tsunami wave can be reduced to the diffusion equation for the horizontal velocity:

$$\frac{\partial U}{\partial t}=\frac{\partial}{\partial \eta}\nu_t\frac{\partial U}{\partial \eta}-\frac{\partial}{\partial \eta}\tau_{wave} \qquad (2a)$$

$$U\big|_{\eta=0}=U_w\left(t-x/c\right) \qquad (2b)$$

$$U\big|_{\eta\to\infty}=\frac{u_{*0}}{\kappa}\ln\frac{\eta}{z_0} \qquad (2c)$$

Here τ_{wave} – is the wind wave stress, $U_w\left(t-x/c\right)$ is the orbital velocity of the tsunami wave, $c=\sqrt{gH}$ is the tsunami wave velocity, u_{*0} is the wind friction velocity; z_0 is the roughness parameter. The coordinate line $\eta=0$ coincides with the water surface bended by the tsunami wave. Since wind flow over the water surface is hydrodynamically smooth for the case of weak winds , we used the expression for ν_t obtained on the base of experiments with the turbulent boundary layer over a smooth plane:

We estimated the hydrodynamic and RCS contrasts in the field of orbital velocities U_w corresponding to measurements of sea surface elevation in the tsunami wave of 26 December 2004 provided by Jason-1. The long wave theory gives:

$$U_w=c\eta_0/H, \qquad (3)$$

where H=4000 *m* is the depth of the ocean, c=200 *m/s* is the tsunami wave velocity, η_0 is the displacement of the sea level taken from GDR.

The problem (2) was solved by the method of the Fourier decomposition in time variable:

$$U_w=\int_{-\infty}^{\infty}U_{w0}e^{-i(\omega(t-x/c))}d\omega$$

For each single harmonic the scale of the unsteady boundary layer in the airflow, $\delta_{ts}=\kappa u_*/\omega$. If δ_{ts} significantly exceeds the scale of the viscous sub-layer $\delta_{wave}=(20\div 30)\nu_a/u_*$, then near the water surface the wind velocity profile is logarithmic:

$$U(\eta)=\frac{u_*}{\kappa}\ln\frac{\eta}{z_*}+U_{w0}e^{-i\omega(t-x/c)}+\Delta u\ ,$$

and the roughness parameter, $z_*=0.11\nu_a/u_*\exp\left(-\kappa\Delta u/u_*\right)$ and the friction velocity u_* are modulated with the tsunami wave period.

Here $\Delta u=\int_0^{\infty}\tau_{wave}/\nu_t d\eta_1<0$ is the negative non-linear addition to the wind velocity caused by the momentum flux from wind to waves. If the wind friction disturbance, u_{*1} , caused by the tsunami wave, is small ($\left|u_{*1}\right|<<u_{*0}$), then solution to (2) gives

$$u_{1*}=\frac{\kappa U_{w0}}{\ln\left(\dfrac{3.178\omega\nu_a 0.11}{\kappa u_{*0}^2}\right)-1-\dfrac{\partial\Delta u}{\partial u_*}\Big|_{u_*=u_{*0}}+\dfrac{\pi i}{2}}\ .$$

Near the threshold of wind wave excitation, Δu can be calculated within the asymptotical model developed in [15].

For a narrow spectra realized near the stability threshold $|s|^2$ is proportional to the slope spectrum at $k=k_c$ [12]. Then the hydrodynamic spectral contrast *C(k$_c$)* of variations of the surface wave intensity for $k=k_c$ can be estimated as $C\left(k_c\right)=\Delta|s|^2/|s|_0^2=u_{*1}/\left(u_{*0}-u_{*c}\right)$, where $\Delta|s|^2$ is the variation of the slope caused by variations of the wind friction velocity. Expressions for u_{*1} and Δu give

$$C\left(k_c\right)=\frac{\kappa U_{w0}}{u_{*0}-u_{*c}}\frac{1}{\ln\left(\dfrac{3.178\omega\nu_a 0.11}{\kappa u_{*0}^2}\right)-1+Q\dfrac{2u_{*0}-u_{*c}}{u_{*c}}+\dfrac{\pi i}{2}}, \qquad (4)$$

where Q =5.38.

For the orbital velocity in the tsunami wave 2.25 cm/s and frequency 0.007 s^{-1}, corresponding to the local elevation of the water surface in the band 3 fig.2. the modulus C is approximately 0.2, and phase is close to π. It means, that under fair wind conditions elevation of the water surface in the tsunami wave is accompanied by reducing of the wind ripples and increasing RCS, that is in agreement with fig.2a (band 3).

The hydrodynamic contract of the ripples in the velocity field (2) can be calculated by the Fourier transformation of (4):

$$C_{hydro} = \int_{-\infty}^{\infty} C\left(k_c\right) e^{-i(\omega(t-x/c))} d\omega$$

Let us now relate the variations in the spectrum of short wind waves due to tsunami with variations of RCS. According to the composite model of scattering the nadir RCS can be written as

$$\sigma_0 = \frac{R_{eff}}{2 s_u s_c} \qquad (5)$$

where $R_{eff} = |R(0)|^2 \exp(-4k_r^2 \langle h_s^2 \rangle)$, $R(0)$ is the Fresnel reflection coefficient at normal incidence, k_r radar wavenumber, $\langle h_s^2 \rangle$ is the mean squared height of short wind waves (smaller than approximately 3 times the radar wavelength), s_u, s_c the RMS long wave slopes in along and crosswind directions, respectively (see, e.g.[16], and cited literature).For Ku band it easily follows from (5), that $\Delta\sigma_{0Ku} = -C_{hydro}$.

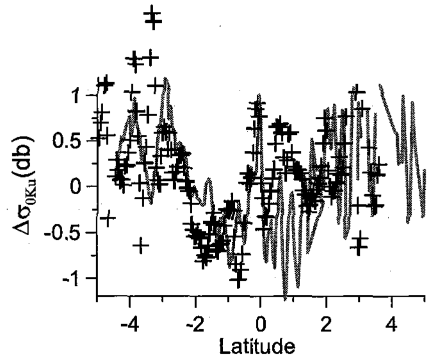

Figure 4. Comparison of the measured C-band RCS and the theoretical estimation. Here crosses are the C-band RCS taken from the GDR of Jason-1, where large-scale background variations in the domain between -5^0 and 5^0 are subtracted. Line is the theoretical estimations.

Comparison of these theoretical estimations with the dataset of GDR is presented in fig.4. The large-scale background variations of $\Delta\sigma_{0Ku}$ in the domain between $+5^\circ$ and -5° are subtracted. For this purpose we calculated the background variations of σ_{0Ku} using the empirical dependence $\sigma_{0Ku}(T_{238})$ given by expression (1).

Some discrepancy between the observations and theory can be attributed to poor accuracy in estimations of wind speed and direction (errors exceed 1 m/s and 20 deg, respectively[14].

Thus, there is both an unambiguous experimental evidence of observation from space of tsunami in the open ocean through variations of radar cross-section in phase with the water elevation and a plausible mechanism explaining the effect. To decide on the perspectives of this finding for tsunami monitoring and, possibly, tsunami warning systems the following points should be taken into consideration. On one hand, the effect was observed under favorable conditions of weak wind and large tsunami wave amplitude, when high hydrodynamic contrasts of short surface waves are expected. On the other hand, it was an observation "by chance", performed by an instrument, which was not designed for measurements of the sea roughness, without even rudimentary signal processing. It is expected, that the use of special algorithms of coherent signal processing (for example, image recognition) and optimal filtering could strongly enhance contrasts of tsunami images in the open ocean even at much less favourable conditions.

Acknowledgements

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References

1. E.A.Okal, Piatanesi, A., Heinrich, P.Tsunami detection by satellite altimetry. *J. Geophys. Research* ,**104**,.599-615 (1999).
2. Zaychenko M., Kulikov E., Levin B. and Medvedev P. Examples of offshore tsunami registration according to satellite altimeter data (1993-2001). M.:Yanus-K, 30, (2004).
3. http://www-misr.jpl.nasa.gov/gallery/galhistory/2005_jan_12.html
4. http://crisp.nus.edu.sg/tsunami/tsunami.html
5. Zaitsev, A. *et al.* Numerical simulation of propagation of the catastrophic tsunami in the Indian Ocean (December 26, 2004) *Doklady Earth Sciences*, Vol, No 3, (2005), pp..
6. Godin, O.A. Air-sea interaction and feasibility of tsunami detection in the open ocean. . *J. Geophys. Research,* **109**, C05002 (2004).
7. Walker, D.A. Observation of tsunami "shadows": A new technique for assessing tsunami wave heights?, *Sci.Tsunami Harards*, **14**(1), 3-11 (1996).
8. Dudley, W.V., M. Lee Tsunami!, Univ.of Hawaii Press, Honolulu. (1996)
9. Gower, J. Jason 1 Detects the 26 December 2004 Tsunami. *Eos*, **86**(4), 37-38 (2005)
10. Schapirroo, R; Smith, W; Titov, V; Arcas, D. Observing the Indian Ocean tsunami with satellite altimetry. *Geophysical Research Abstracts*, 7, 09407, SRef-ID: 1607-7962/gra/EGU05-A-09407 (2005)
11. Lay, T. *et al* The Great Sumatra-Andaman Earthquake of 26 December 2004 *Science* **308**, 1127-113320 (2005)
12. F.G. Bass and I.M. Fuks, *Wave Scattering from Statistically Rough Surface*, International Series in Natural Philosophy, v.93, C. B. Vesecky and J. F. Vesecky (eds.), Pergamon Press, Oxford (1979).
13. V.N.Kudryavtsev, C. Mastenbrock, V.K.Makin Modulation of wind ripples by long surface waves via the air flow: A feedback mechanism. *Boundary Layer Meteorology*, **83**, 99-116 (1997).
14. Yu.I.Troitskaya. Modulation of the growth rate of short surface capillary-gravity wind waves by a long wave. *Journal of Fluid Mechanics*, **273**, 169-187 (1994).
15. Reutov V.P., Troitskaya Yu.I. On nonlinear effects due to water wave interaction with turbulent wind. *Izv., Atmospheric and Oceanic Physics*, **31**(6), 825-834 (1995).
16. C.Anderson, J.Trevor, CD. Gommenginger, and M.Srocosz, A comparison of the sea-state sensitivity in empirical and theoretical models of altimeter ocean backscatter, *Can.J.Remote Sensing,* Vol.28, No.3, pp.475-483, 2002