On discriminating swell and wind-driven seas in Voluntary Observing Ship data

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[1] The global visual wave observations are reanalyzed within the theoretical concept of self-similar wind-driven seas. The core of the analysis is one-parametric dependencies of wave height on wave period. Theoretically, wind-driven seas are governed by power-like laws with exponents close to Toba’s one 3/2 while the corresponding swell exponent (−1/2) has an opposite signature. This simple criterion was used and appeared to be adequate to the problem of swell and wind-driven waves discrimination. This theoretically based discrimination does not follow exactly the Voluntary Observing Ship (VOS) data. This important issue is considered both in the context of methodology of obtaining VOS data and within the physics of wind waves. The results are detailed for global estimates and for analysis of particular areas of the Pacific Ocean. Prospects of further studies are discussed. In particular, satellite data are seen to be promising for tracking ocean swell and for studies of physical mechanisms of its evolution.


1. Introduction
[2] The understanding physics of wind-driven waves and wind-wave coupling is extremely important both for fundamental science and numerous practical applications. This is why experimental efforts are targeted at getting reliable information on wind waves in a wide range of spatiotemporal scales: from campaign measurements in areas of special interest to global monitoring wind seas using sophisticated satellite methods. Being collected in global databases (like ICOADS and others) these experimental data form a basis of climate studies, wave forecasting and maritime safety.

[3] At the same time, there is a lack of experimental data which are suitable for relating observations and measurements to wave theory. Precise wave measurements in special field experiments are very few, extremely expensive and their correspondence to theoretical concepts and models is, in many cases, quite questionable. On the other hand, the most abundant sources (e.g., satellite data) quite often provide incomplete, inaccurate or irregular (in space and time) wave information.

[4] An example of such a rich data source is Voluntary Observing Ship (VOS) data that cover all the World Ocean since 1870. Last 50 years of the data collection are characterized by more high and homogeneous density of observations and the errors in the well-sampled regions are estimated as less than 10\% of monthly mean values [Gulev and Grigorieva, 2003]. Thus, the VOS collection can be regarded as a self-consistent source of wave data of limited (not high) accuracy. The relatively low accuracy of these data is balanced by their abundance and, to an extent, by the well-elaborated methods of the data quality control.

[5] In addition to the longest continuity these data contain an important supplement, separate estimates of wind wave and swell parameters. These estimates are made visually and, evidently, suffer from subjectivity. But they represent, in a sense, two dynamical extremes of sea state. A conceptual difference of these extremes is in their tie with a wind: wind waves are generally considered as affected heavily by wind while the swell is seen as a wind-independent phenomenon that evolves mainly due to its inherent dynamics [Komen et al., 1995]. This conceptual difference causes trouble for conventional analysis of wave data: wind speed is considered as a useful physical scale for wind-driven waves but is not relevant to the swell case.

[6] In this paper we are trying to fit VOS data [Gulev and Grigorieva, 2003] to a theoretical concept of self-similar wind driven seas presented as split balance model [Badulin et al., 2005, 2007]. The core of the concept is an assumption of dominating inherently nonlinear wave dynamics as compared to wind input and wave dissipation. This does not mean a disregard of wind-wave coupling but just putting each physical mechanism in its proper place when describing evolution of spectra of wind-driven waves. As a result,
wave dynamics due to the dominating four-wave resonant interactions causes extremely fast relaxation of wave spectra to an inherent state while total external forcing (wind generation plus dissipation) affects parameters of this inherent state at relatively slow spatiotemporal scales. This model (when the theory key assumptions are true and it is valid) leads to conceptual gains.

[7] First, within the model the strong nonlinearity provides a strong tendency of wave spectra to universal shapes. It is in line with conventional idea of quasi-universality of wind wave spectra that found their implementation in the widely used parameterizations of wave spectra like one by Pierson and Moskowitz [1964] or JONSWAP spectrum [Hasselmann et al., 1973] when wave spectra evolution can be described reasonably well in terms of small number of parameters, first of all, mean wave height $H_m$ (or significant $H_s$) and mean period $T_m$ (or significant one $T_p$ or spectral peak one $T_p$).

[8] Secondly, wave input and dissipation contribute at relatively slower scales as integral quantities and transforms the quasi-universal wave spectra “as a whole.” This integral effect of external forcing (input and dissipation) makes the wave evolution to be robust: particular mechanisms of wave generation or dissipation and their distributions in wave scales become unimportant, in a sense. Their net integral values only affect the wave growth. The recent attempts to treat experimental [Badulin et al., 2007] and numerical results [Gagnaire-Renou et al., 2011] in terms of the integral quantities and key spectral parameters $H_m$ ($H_s$), $T_m$ ($T_p$) showed “the right to live” of the concept of self-similar wind-driven seas.

[9] This paper analysis, at the first glance, is based on very particular result of the above theory: for standard setups of duration- and fetch-limited growth (spatially homogeneous and stationary problems, correspondingly) it predicts power law dependence

$$ H = B \tilde{T}^R $$

for nondimensional wave heights $\tilde{H}$ and periods $\tilde{T}$ which scaling will be specified later. The relationship (1) is widely used in wind-wave studies. For exponent $R = 3/2$ it gives the well-known law of Toba [1972] with scaling of friction velocity $u^*$ and significant heights and periods $H_s$, $T_p$. The preexponent $B$ within the theory becomes a universal constant $B = 0.062$ under assumption that “the work done by wind stress to wind waves, or the time rate of the average wave energy” is constant [Toba, 1972, p. 112].

[10] Similar one-parametric dependence for $R = 5/3$ has been obtained by Hasselmann et al. [1976] as a particular solution of the wave balance equation with a net wave input corresponding to constant rate of wave momentum. This special case has been detailed by Resio and Perrie [1989] and justified later by thorough analysis of equilibria ranges of wave spectra [Resio et al., 2004].

[11] Zakharov and Zaslavsky [1983] were the first who associated the case $R = 4/3$ with the weakly turbulent theory of wind waves: they related it with spectral flux cascading rather than with a particular model of wind-wave coupling and parametrization of the coupling in terms of wind speed. Their solution provides a constant time rate of wave action growth.

[12] From our “weakly turbulent viewpoint” the family of one-parametric dependencies (1) with arbitrary $R$ varying in a wide range describes different regimes of wind-wave coupling. The particular values of $R$ (4/3, 3/2 or 5/3) can be considered as reference cases when this coupling keeps rates of one of the basic physical quantities, momentum, energy or action, to be constant.

[13] In our analysis of the VOS data we use exponent $R$ in (1) as an indicator of wind wave dynamics. There is a critical point of such analysis, the coefficient $B$ that varies in a wide range and depends on a number of parameters of wind-sea interaction: wind speed, stratification of air flow, gustiness, etc. High dispersion of $B$ does not allow for reliable discriminating particular cases of wave growth basing on (1). Fortunately, the solution of the kinetic equation for swell gives the power law dependence (1) as well [see Zaslavskii, 2000; Badulin et al., 2005]. In this case $R = −1/2$ has an opposite signature as compared to the case of growing wind sea. We use this simple fact as a yardstick of our analysis of VOS data for discriminating swell and growing seas.

[14] We start with a brief overview of the physical background of our approach to the data analysis in section 2. The VOS data and features of their processing are given in section 3. Relatively low quality of these data requires special procedures of data selection and discriminating wave dynamics (wind sea and swell). Results of the data analysis are presented in section 4. The paper is finalized by conclusions and discussion in section 5.

2. Split Balance Model and Reference Cases of Sea Wave Growth

[15] The today research and wind-wave prediction models start with the basic equation for statistical description of random field of weakly nonlinear water waves, the kinetic equation, widely known as the Hasselmann [1962, 1963a, 1963b] equation

$$ \frac{\partial N_k}{\partial t} + \nabla_k \omega_k \nabla_r N_k = S_{nl} + S_{m} + S_{diss}. $$

Subscripts $k$, $r$ for $\nabla$ are used for gradients in wave vector $k$ and coordinate $r$ correspondingly. For $N_k(r, t)$, wave action spectral density and linear wave frequency $\omega_k = \sqrt{g|k|^2 \tan \theta |k| d}$ (d is water depth) the subscript $k$ means dependence on wave vector. Further we discuss the deep water case only, i.e., the power law dependence $\omega_k = \sqrt{g|k|}$.

[16] Strictly speaking, Klauss Hasselmann derived the conservative kinetic equation for potential water waves with the only term $S_{nl}$ that describes four-wave resonant interactions. This term given by explicit cumbersome formulas is extremely inconvenient for simulation (time-consuming, requires special accuracy control, etc.). Its accurate and effective calculation in research and operational models remains a burning problem so far [e.g., Cavaleri et al., 2007, Figure 7]. At the same time, homogeneity properties of $S_{nl}$ in the deep water limit allows to advance in theoretical studies of the conservative Hasselmann equation. Exact solutions of the equation [Zakharov and Filonenko, 1966; Zakharov and Zaslavsky, 1982] that correspond to constant spectral fluxes of wave energy and action (the so-called direct and inverse
Table 1. Reference Cases of Self-Similar Evolution of Sea Waves

<table>
<thead>
<tr>
<th>Case</th>
<th>Regime of Wave Production</th>
<th>R</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( \frac{d(M)}{dt} = \text{const} )</td>
<td>5/3</td>
<td>Hasselmann et al. [1976]</td>
</tr>
<tr>
<td>B</td>
<td>( \frac{d(E)}{dt} = \text{const} )</td>
<td>3/2</td>
<td>Toba [1972]</td>
</tr>
<tr>
<td>C</td>
<td>( \frac{d(N)}{dt} = \text{const} )</td>
<td>4/3</td>
<td>Zakharov and Zaslavsky [1983]</td>
</tr>
<tr>
<td>D</td>
<td>( \frac{d(N)}{dt} = 0 )</td>
<td>-1/2</td>
<td>Zaslavskii [2000]</td>
</tr>
</tbody>
</table>

cascades) laid the foundation of the today theory of weak turbulence of wind waves.

[17] These basic results can be generalized for cases when \( S_{in} \) and \( S_{diss} \) in (2) are not plain zeroes. The key assumption of the split balance model [Badulin et al., 2005, 2007] is dominating of wave-wave interactions over the effects of wave generation and dissipation. A naive treatment of the assumption as inequalities

\[ S_{in} \gg S_{nl}; \quad S_{nl} \gg S_{diss} \]

does not reflect the physical roots and consequences of the model. As it has been noted by Young and van Vledder [1993] the significance of the wave-wave interaction term is in its ability to provide very fast relaxation of a wave spectrum to an inherent quasi-universal shape. This effect has been detailed in an extensive numerical study [Badulin et al., 2005] and in recent analysis of the nonlinear transfer term \( S_{nl} \) as a relaxation term [Zakharov and Badulin, 2011]. The \( S_{nl} \) can be presented as a sum of two terms, nonlinear forcing \( F_k \) and nonlinear damping \( \Gamma_k N_k \) which absolute magnitudes are much greater than one of \( S_{nl} \) itself. Thus, terms \( S_{nl}^+ S_{diss}^- \) should be compared with \( F_k, \Gamma_k N_k \) but not with \( S_{nl} \). Evidently, this assumption of dominating wave-wave interaction is valid for certain range of physical conditions only. These conditions are likely satisfied quite often for wind sea as the cited works showed [e.g., Badulin et al., 2005, 2007; Gagnaire-Renou et al., 2011]. Somewhat indirect but important support of the assumption can be found in the well-known fact of quasi-universal wind-wave shaping. This fact is widely used in parameterizing wave spectra and features of wind-wave growth [e.g., Pierson and Moskowitz, 1964; Hasselmann et al., 1973; Babanin and Soloviev, 1998b].

[18] Accepting this assumption one can propose an asymptotic model of wind-wave growth described by the following system of two equations:

\[ \frac{dN_k}{dt} = S_{nl}, \]  
\[ \frac{d(N_k)}{dt} = (S_{nl} + S_{diss}). \]  

The conservative kinetic equation (3) represents the lowest-order approximation of the asymptotic theory while the second equation (4) can be considered as a closure condition of the theory for formally small terms \( S_{nl} \) and \( S_{diss} \). The model (3) and (4) is physically transparent: (3) gives a family of solutions that are determined by nonlinear transfer only and does not depend explicitly on wave input or dissipation while (4) controls an integral balance of the wave spectra.

[19] The good prospects of the model (3) and (4) become apparent when analyzing its self-similar solutions for particular cases of duration- and fetch-limited wave spectra evolution [Badulin et al., 2005]. These solutions correspond to power law dependencies of wave energy (action, momentum) and a characteristic wave scale (wave frequency, wave number) on duration (time) or fetch, i.e.,

\[ E = E_0 t^{\theta_E}, \quad \omega = \omega_0 t^{-\phi_\omega}; \]  
\[ E = E_0 x^{\theta_E}, \quad \omega = \omega_0 x^{-\phi_\omega}. \]  

Equations (5) and (6) can be related to widely used forms of experimental laws of wave growth [e.g., Babanin and Soloviev, 1998b]. Total wave action and wave momentum, evidently, can be expressed as power law dependencies in a similar way.

[20] Cases of linear in time growth of wave energy (5), action and momentum are of special interest because they correspond to constant rates of production of these quantities. They provide a physical ground for speculating about mechanisms of wave growth. For instance, wave momentum can be associated naturally with turbulent wind stress and, hence, the corresponding case takes its self-consistent physical treatment: waves acquire a permanent fraction of the turbulent wind stress at permanent wind conditions.

[21] It is useful to pass from expressions (5) and (6) to time- and fetch-independent one-parametric dependencies of wave height on wave period for wind-driven waves

\[ H \sim T^{\Phi}. \]  

In such form exponents \( R \) appear to be the same for duration- and fetch-limited dependencies (5) and (6) in the special cases of constant production of wave energy, action or momentum. These special exponents and the corresponding references are given in Table 1.

[22] This list of Table 1 can be extended by the swell case. The corresponding self-similar solution is one of the conservative kinetic equation (3) with an additional condition of conservation of wave action

\[ \int \int N(k, \omega) dkd\omega = \int \int N(\omega, t) dt = \text{const}. \]  

The total energy of the solution \( E = \int E(k, t) dk \) decays slowly with time

\[ E_{tot} \sim t^{-1/11}; \]  
\[ E_{tot} \sim x^{-1/12}; \]

that is very difficult to observe in experimental studies.

[23] The key property of the swell solution, nonconservation of total energy in absence of wind input and dissipation is well known [Zakharov, 2010; V. E. Zakharov, Direct cascade and inverse cascades in the wind-driven sea, unpublished paper, 2005, available at http://math.arizona.edu/~zakharov/1Articles/Cascades.pdf] but quite often is not taken into
account when treating swell observations or its simulations. The observed swell decay is usually considered as a result of quasi-linear dissipation due to various dissipation mechanisms while the inherent nonlinear wave dynamics is not discussed as one responsible for this decay. These quasi-linear models predict rather strong attenuation of sea swell [see Kudryavtsev and Makin, 2004] that is in contradiction with available observations [e.g., Arduhin et al., 2009; Soloviev and Kudryavtsev, 2010].

The essentially nonlocal effect of nonconservation of energy is quite difficult to capture within simulations in a finite domain of wave scales and within the Discrete Interaction Approximation [Hasselmann et al., 1985] widely used for calculation $S_{NL}$. Dissipation terms are usually introduced to make such calculations stable. Nowadays, exact calculation of the wave–wave interaction term $S_{NL}$ allows for reproducing theoretical features of swell in their full [Badulin et al., 2005; Benoit and Gagnaire-Renou, 2007] without an additional dissipation.

Two features of the swell solutions (8) and (9) should be stressed. First, this is a power law decay in contrast to exponential one as usually discussed for quasi-linear dissipation mechanisms. Second, exponents of the swell decay are quite low ($1/11$ and $1/12$) and are difficult for observing this phenomenon in the sea. The one-parametric height-to-period relationship for the swell looks like a good luck in the context of the problem of quantifying the swell evolution. One gets the law

$$H \sim T^{-1/2} \quad (10)$$

with “observable” exponent $-1/2$.

Figure 1 gives a graphical summary of four reference cases of Table 1 where these cases are shown as different $R$, tangents of one-parametric dependencies height-to-period in logarithmic axes. Reference cases of growing wind sea are shown as the young sea growth at permanent wave momentum production (exponent $R = 5/3$ by Hasselmann 1976], growing Toba’s sea ($R = 3/2$) and old premature sea by Zakharov and Zaslavsky [1983] with $R = 4/3$. The stage ranges in terms of wave age

$$a = \frac{C_{ph}}{U_{\text{wind}}} \quad (11)$$

estimated for spectral peak phase speed $C_p$ (deep water case)

$$C_p = \frac{gT_p}{2\pi} \quad (12)$$

have been estimated recently in numerical study [see Gagnaire-Renou et al., 2011, Figure 10]. Wind speed in definition (11) is usually taken for neutrally stable atmosphere at a reference height of observations (as a rule, at $h = 10$ m) in the dominant wave direction

$$U_{\text{wind}} = U_{10} \cos\Theta \quad (13)$$

($\Theta$ is angle between wind and dominant wave directions). Note, that definitions (11)–(13) are conventional rather than physically based.

3. Voluntary Observing Ship Data as a Source of Wave Data

Besides model hindcasts, satellite and buoy measurements Voluntary Observing Ship (VOS) data represent now an important source of global wave information. We used the latest update of the global archive of visual wind wave data based on the ICOADS (International Comprehensive Ocean-Atmosphere Data Set) [Woodruff et al., 2011] collection of marine meteorological observations. Visual wave observations were extensively used for the description of climatological characteristics of wind waves [Gulev and Grigorieva, 2003], for the assessment of the long-term tendencies in wave parameters [Gulev et al., 2004] and for the study of extreme waves [Gulev and Grigorieva, 2006; Grigorieva et al., 2011].
and Gulev, 2008, 2011]. However, they have not been yet employed for regular testing any wave theories. We used these data to check consistency of the theoretical criterium of discriminating wind-driven and swell seas in terms of exponents $R$ in (1) with visual results of observers. Visual data are not as accurate as other sources of wave information, but their strong points are (1) great number of observations (that is crucial for statistical evaluation) and (2) separate estimates of wind sea and swell.

3.1. General Quality Check

[31] First visual wave observations in ICOADS date back to 1870. Coding systems have been changed several times, but the most meaningful change was in 1950s, when officers started to report sea and swell parameters separately but not the significant wave height (SWH) only. Additionally, the upper code limit for the highest waves was extended from 16 to 25 m.

[32] The data since 1970 have been taken for our study in order to provide a representative statistical analysis of the global wave parameters within the proposed theoretical paradigm. In the last 40 years the number of observations became stable and exceeded 100,000 per month. The distribution of reports of different quality is shown in Figure 2. All the records have been reduced to a uniform format and passed thorough quality check. Totally, more than 35 billion records underlie the experimental basis of the study even after the very strict quality control.

[33] Preliminary data control and data preprocessing are regarded as important preconditions of substantial analysis of visual wave observations. Note the most important points of the procedure: (1) Only reports containing all the basic wave parameters, sea and swell heights, directions, periods and wind observations have been taken for further analysis, i.e., almost 80% of total number of records have been withdrawn from use. (2) Screening for observational artifacts, such as reports of unrealistic dates or nonzero wave heights with zero periods eliminated about 3% of total number of records. (3) Wave steepness control (values well above the theoretical limit of wave breaking $2\pi H_s/(gT_s^2) > 1/7$ [e.g., Longuet-Higgins, 1988, 1996]) has eliminated up to 10% of all reports for some months. (4) Wave age control $a < 1.6$ (see for details section 3.3) was applied to remove unrealistically long waves from reports of wind-driven waves. The number of the records can reach 15% of data left after checkpoints (1)–(3). All the above checkpoints can be considered as quite general and self-evident. They do not involve wave physics explicitly and after all leave no more than 10% of total data collection for further analysis.

3.2. Discriminating Swell and Wind-Driven Seas in Visual Estimates

[34] The next step of preprocessing follows a way of discriminating swell and wind sea based on a “traditional” vision of sea wave dynamics. It does not eliminate any significant portion of selected data and could be missed in the paper as an optional comment. Nevertheless, we give some details of the procedure in order to emphasize key points of our approach once more.

[35] The discriminating wind and swell sea is an important and quite delicate problem that comes from actual needs of sea state forecasting. The most advanced methods operate with wave spectra [e.g., Tracy et al., 2007]. They are aimed at delineation of wind sea and swell for their separate use in numerical models of sea state. Such approach implies conceptually different physics of the sea wave constituents: wind waves are considered as locally generated and closely

Figure 2. Number of VOS reports for the period 1950–2007 and quality of the data (in legend).
linked to wind conditions while the swell is associated with wave generation at distant sites and its directional and scale characteristics are not linked definitely with local wind.

[36] Similar ideas allow for reducing uncertainty in discriminating swell and wind seas in visual estimates. The problem appears when the well-developed wind sea is reported as swell and when low swell is treated as wind waves. Gulev and Hasse [1999] computed joint probability distributions of wave height and wind speed for both wind sea and swell and overplotted these distributions by the JONSWAP curves, representing wave height as a function of wind speed and duration [Carter, 1982]. Dependencies of wave height on wind speed at durations 6 and 18 h for JONSWAP parameterizations of wave growth have been used as low and upper bounds of wind sea state. Gulev and Hasse [1999, Figure 4] showed that the main portion of [1982]. In fact, = const in (1). Within = T = 5/3 in (1). As we Carter will be slightly underestimated reasonings. [1998a] that leads to high > 1). H preexponent T in our (say, [1972] (case B in Table 1) and case of premature sea = const in (1) at scaling T* > 1.2. Our and period on wind speed. In fact, there is no apostasy = 1 m and = < 1) and arrest of the growth or even Zakharov and Zaslavsky and period (1) is estimated as [39] VOS data provides an abundant source of all wave characteristics with an important supplement, separate estimates of swell and wind sea. Global climatology based on these data demonstrates quite consistent spatial distributions of wave heights and periods and partitioning of sea waves into wind waves and swell (see Global Wave Atlas on http://www.sail.ms.ku.atlas/index.html). Deeper analysis of the data, generally, follows a conventional vision of sea wave physics where wind-sea coupling predetermines wave dynamics completely. The corresponding wind speed-based criteria of JONSWAP growth curves (section 3.2) and wave age (section 3.3) allow to delineate wind sea and swell and, to an extent, to strengthen our confidence to visual observations. At the same time, these approaches impoverish heavily the physics itself of sea waves, leaving no room for inherent wave dynamics, different scenarios of wave growth and wave-swell interactions. Wind speed data themselves appear to be an additional source of uncertainties and errors. Therefore, the wind speed scaling must be avoided both by “conceptual” and this purely “technical” reasonings.

[40] Within our split balance approach the data should be scaled by spectral flux (total net input). At the first glance, such scaling is advantageous theoretically only as far as the spectral flux is not easy to specify basing on available data (in contrast to inaccurate but easy-to-measure wind speed).

[41] The gain of the spectral flux scaling becomes apparent when considering the swell. In this case the spectral flux is provided by leakage of wave energy at constant total wave action. For the one-parametric dependence (10) it immediately dictates a link of observed swell height and period with a distant swell state (“initial” height H0 and period T0)

\[ HT^{1/2} = H_0 T_0^{1/2}. \]  

An important question how to specify the initial state H0, T0 requires a special thorough study. For the problem discussed we propose a simplified solution basing on our preliminary study of statistical features of the quantity H0T0^{1/2}. Estimates for the whole World Ocean and for some particular regions where strong swell is generated (Roaring Forties) showed that H0T0^{1/2} has a sharp distribution and decays rapidly both with H0 and T0. It allows to fix the scales H0 and T0 in our study and, hence, to fix preexponent B = const in (1). Within such scaling the exponents R will be slightly underestimated (exponents will be shifted to higher negative values). In other words, keeping B = const in (1) at scaling H and T on arbitrary but fixed values H*, T* (say, H* = 1 m and T* = 1 s) makes the gap between domains of swell reference case D and growing wind waves (cases A, B, C) in Figure 1 to be wider.

[42] As far as we follow the fixed scaling H* = const1, T* = const2 for estimation exponent R for swell, continue to use the same approach for wind waves. Similar statistical argumentation can be proposed basing on distributions of wind speed (see below). First, as a rule, these distributions appear to be relatively narrow, i.e., strongly localized near a certain value of wind speed. Secondly, at fixed scales H*, T* preexponent B in (1) is estimated as growing function of wind speed (e.g., the Toba law H* = 0.062(gux)^{1/2}T^{3/2}). The latter means overestimating of the exponent R in (1), again, the fixed scaling makes a gap between reference cases of swell and wind sea to be wider (see Figure 1).

[43] In our argumentation of the fixed H*, T* and B we deviated, in a sense, from our spectral flux line when refer to dependence of B on wind speed. In fact, there is no apostasy
The “red line” of further data processing and analysis can be presented as “homogenization” of data subsets in order to minimize the effect of uncertainty of the pre-exponent $B$ in (1). Abundance of the VOS data gives a good chance when following this “red line”. We consider two ways of the “homogenization” in this study. First, we make estimates for particular regions of the World Ocean where sea state conditions are “more or less homogeneous”. Secondly, we specify subranges of wave periods for wind sea and swell in order to minimize poorly known conditions of wind wave and swell generation. Note, that the VOS data itself are inherently “more or less homogeneous”: generally, marine officers prefer regular routes and avoid severe sea.

4.1. Swell and Wind Sea Discriminating: A General Look

As the very first step of our analysis look at one-parametric dependencies for swell and wind sea derived from the whole data collection (after preprocessing procedures described in sections 3.1–3.3). Average values of wave heights are given for each value of wave period for wind and swell components separately in Figure 3.

Coarse sampling is a well-known problem of the VOS data: 1 s for periods and 0.5 m for wave heights. Thus, average or interpolated values should be used for tracking one-parametric dependencies $H(T)$ and correct estimates of their power law fits. In this study we operated with subsets of wave heights at fixed wave periods. A weighted mean values of $H$ at the given periods $T$ were calculated for the whole World Ocean or coordinate boxes $20^\circ \times 20^\circ$ and monthly or all data of the full duration of observations 1970–2007 years. Typically, more than 1000 values of $H$ were averaged for each period $T$ in coordinate boxes $20^\circ \times 20^\circ$ and more than 50,000 for the whole World Ocean. The resulting dispersions are ranged from 1% for the most abundant subsets up to 10% for some coordinate boxes and periods. Generally, dispersions are high for rarely observed big periods and heights. Subsets shorter than 10 values were eliminated from further consideration. Different weight function were tried to get the $H(T)$ dependencies. An important but not surprising outcome of the attempts is that choice of a weight function does not affect significantly the resulting dependencies. Such robustness is, evidently, dealing with great number of observations and thorough data preprocessing. A simple average values of $H$ have been used for further analysis that eased verification and treatment of the results.

The resulting dependencies and their power law fits show nothing but clear difference of wind sea and swell components: slope of $H(T)$ curve for wind sea (Figure 3, top) is much steeper than one for swell. At the same time, exponent $R = 0.96$ for wind waves is significantly lower than ones of reference cases A, B, C of Table 1. Similarly, $R = 0.54$ of swell observations is definitely higher than the case D reference value $R = -1/2$. The presented general look is not a failure of our theoretical approach. It reflects nothing but a wide range of conditions of wave generation or, in other words, high dispersion of preexponents $B$ in (1).

Figure 4 presents histograms of exponents $R$ calculated separately for different months and coordinate boxes $20^\circ \times 20^\circ$ (totally 1481 dependencies containing data subsets valid for our analysis). The distributions are rather

Figure 3. Dependencies $H(T)$ and their power law fits (1) for the whole World Ocean, 1970–2007 for (top) wind waves and (bottom) swell. Lines marked as $A$, $B$, $C$, $D$ show reference power laws of Table 1. The exponents of the experimental fits $R = 0.96$ for wind sea and $R = 0.54$ for swell are found to be quite far from the reference cases. Totally, 36,356,695 reports have been used for wind waves and 31,041,169 for swell observations.
set off the effect of the flaw of the VOS collection. This is one of a number of reasons why we avoid the use of wind speed scaling in this study.

4.2. Swell and Wind Sea: Wave-Scale Selection

[51] Generalized wave growth curves $H(T)$ in Figure 3 show clearly an important feature: they are markedly steeper for short waves. The curve slope is milder for long wind waves and manifests a sort of saturation for long swell. The pronounced break for swell curve at wave period $T = 10$ sec corresponds to phase speed $C_{ph} \approx 16$ m/s. The latter is consistent with global wind speed distributions in Figure 5 where more than 90% of records give wind speeds below 16 m/s. In other words, generally, waves with periods $T > 10$ s are traveling faster than wind and, hence, are affecting by wind slightly. It can explain a sort of saturation for $T = 10$–20 s. For longer swell one can see a sudden change and rather high dispersion. Partially it can be explained by low number of observations of swell with periods $T = 20$–30 and extreme wavelengths exceeding 600 m.

[52] The features of the generalized curves $H(T)$ in Figure 3 give an idea to focus on special ranges of swell and wind waves. We took the range $T = 5$–10 s for such “true” wind-driven waves and 10–20 s for “true” swell basing on Figure 5 hints. The growth curves for the corresponding data subsets of wind waves and the whole World Ocean in Figure 6 (top)

Figure 4. Histograms of exponents $R$ of power law fits of $H(T)$ dependencies calculated monthly for $20^\circ \times 20^\circ$ boxes of the World Ocean (1481 dependencies of total 8 latitudes $\times$ 18 longitudes $\times$ 12 months = 1782 subsets): (top) wind sea and (bottom) swell.

broad both for wind sea (Figure 4, top) and swell (Figure 4, bottom) and overlapped by about 1/3. At the same time, the corresponding peaks are well separated: $R_{\text{max}} = 1$ for wind waves and $R_{\text{max}} = 0.6$ for swell. Both patterns resemble those of wind speed in Figure 5. For the histograms of wind speeds we used the same reports as for constructing $H(T)$ dependencies. Annual observations (Figure 5, top) and subsets for particular months (Figure 5, bottom, January observations shown) give rather broad distributions that explains why the effect of wind speed variability on exponent R can be so strong. Thus, global estimates of the power law fits and exponent R can be treated tentatively only as ones reflecting the most pronounced effects and tendencies. Such pronounced effect, difference of $R$ for swell and wind-driven sea is clearly seen when comparing power law fits for swell and wind waves in Figure 3.

[50] Figure 5 shows a critical problem of wind speed data of the VOS collection. For the abundant data set containing millions records one can see pronounced peaks in the distribution at bins 13, 16, 18 m/s that looks quite strange for the huge data set. In our opinion, an explanation of the strange fact can be quite trivial: low accuracy and inaccurate conversion of the measurements when observations in knots are recasted in m/s. Speed 13 m/s gives 25 knots with high accuracy. Similar strange peaks correspond to 16 m/s $\approx$ 30 knots and 18 m/s $\approx$ 35 knots. It is extremely difficult to

Figure 5. Histograms of wind speed observations in the World Ocean (top) during 1970–2007 (36,356,695 observations) and (bottom) for January, 1970–2007 (3,124,678 observations).
illustrate this trivial idea perfectly well: the dependence shows very good coincidence with the theoretical scheme recapitulated in Table 1. Exponent $R = 1.37$ is very close to the case of premature sea by Zakharov and Zaslavsky [1983] (Table 1). Thus, in wind wave records one can see manifestations of asymptotic laws of Table 1.

Figures 6 and 7.

- **Figure 6.** Dependencies $H(T)$ and their power law fits (1) for the whole World Ocean, 1970–2007 for (top) wind wave periods 5–10 s and (bottom) swell range 10–20 s. Lines marked as $B$, $D$ show reference power laws of Toba and swell of Table 1. The fits $R = 1.37$ for wind sea and $R = 0.06$ for swell are found to be quite close to the reference cases. Totally, 15,172,871 reports have been used for wind waves and 6,158,859 for swell observations.
- **Figure 7.** Histograms of exponents $R$ of power law fits of $H(T)$ dependencies calculated monthly for $20^\circ \times 20^\circ$ boxes of the World Ocean (1481 dependencies of total 1782 = 8 × 18 × 12 coordinate boxes) for special ranges of wave periods: (bottom) wind sea with $T = 5–10$ s and (top) swell with periods $T = 10–20$ s.

the statistical description of wind waves is dealing with nonconservation of energy within the kinetic equation (2) where wave input and dissipation are plain zeroes. This loss is supported by inherent wave evolution, an irreversible cascading to infinitely short scales where the energy dissipates (Zakharov, unpublished paper, 2005) but not by external forcing. The dissipation of “true conservative” quantity, wave action, implies $R < -1/2$. Thus, the cases with $R > -1/2$ should be qualified as swell pumping but not as swell decay. We stress once again this point to fix the conceptual difference of our scheme with conventional vision of swell dissipation [e.g., Ardhuin et al., 2009].

[53] Less than one quarter only of the derived dependencies fall into range $R < -1/2$, that is, show true swell decay both for the conventional criterium of energy decay $R < 0$ and for our more restrictive criterium of wave action leakage $R < -1/2$ (a long tail $R < -1$ is not shown in Figure 7, top). In fact, all the speculations around exponents $R$ cannot led to decisive conclusions at the present state of our knowledge. Independence or weak coupling of swell with local wind appears to be a bad luck in this case. Swell evolution depends on physical parameters at distant sites (initial conditions) or/and on the swell “history,” a number of processes that affect the propagating swell (dissipation, swell-current, swell-wave interactions, etc.). Spatial tracking of the swell
using satellite data could be an adequate tool for correct assessment of exponents \( R \) in power law fits (1). Nevertheless, even for rather rough estimates in Figure 7 we see a ground for an important observation. Within our approach at least three quarters of the available dependencies \( H(T) \) show swell pumping \( (R > -1/2) \). The wind effect as a possible mechanism of the pumping looks attractive as an explanation. In fact, we would like to draw attention to an important alternative to the wind-sea coupling, interaction of swell and wind-driven sea. As experimental data [Kahma and Petterson, 1994; Young, 2006] and theoretical models [Badulin et al., 2008] show such interaction can be anomalously strong: the swell can play a role of an effective absorber of locally generated wind waves.

4.3. Swell and Wind Sea Discriminating: Regional Variations

The selection in wave periods is found to be the most effective way of homogenization of initial data collection for the problem of discriminating swell and wind waves. It appears to be very robust: different subsets of the full data collection show consistent picture of coexisting swell and wind sea and their possible coupling. Other ways of selection in direction, wave age, wind speeds do not provide such robustness. In this section we apply our approach to analysis of regional features of sea waves. The regional features provide a specific type of selection. A number of physical parameters can be affected by this selection simultaneously: including wind features, proximity to swell sources, etc.

Table 2. Coordinate Boxes of a Meridional Cross Section

<table>
<thead>
<tr>
<th>Box</th>
<th>Latitude</th>
<th>Longitude</th>
<th>( R_{ww} )</th>
<th>( R_{sw} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>211</td>
<td>140°W–160°W</td>
<td>40°N–60°N</td>
<td>1.02</td>
<td>–0.34</td>
</tr>
<tr>
<td>411</td>
<td>140°W–160°W</td>
<td>0°N–20°N</td>
<td>1.02</td>
<td>–0.20</td>
</tr>
<tr>
<td>511</td>
<td>140°W–160°W</td>
<td>0°S–20°S</td>
<td>1.15</td>
<td>–0.28</td>
</tr>
<tr>
<td>614</td>
<td>80°W–100°W</td>
<td>20°S–40°S</td>
<td>1.13</td>
<td>–0.67</td>
</tr>
</tbody>
</table>

\( ^a \)Exponents of power fits for wind sea \( R_{ww} \) and swell \( R_{sw} \) are estimated for ranges of periods 5–10 and 10–20 s, respectively.

[
56] Results for four coordinate boxes 20° × 20° are presented in this study. The wave characteristics we introduced in this paper being averaged in areas of about 1000 square nautical miles or even more give a consistent physical picture of sea wave dynamics on the meridional cross section in the Pacific Ocean from 60°N to 40°S. Coordinates of the boxes are given in Table 2. Again we construct dependencies \( H(T) \) for data subsets in all coordinate boxes. \( H(T) \) dependencies in Figures 8 and 9 cover shorter range of wave periods as compared to their counterparts in global estimates of Figure 4. At the same time, they allow for estimating exponents \( R \) both for the whole period range and for subranges we introduced for wind waves \( (T = 5–10 \text{ s}) \) and swell \( (T = 10–20 \text{ s}) \). Estimates of \( R \) in Figures 8 and 9 are close to the mean values over the World Ocean (cf. Figure 4). The estimates for the subranges are given in \( R_{ww} \) and \( R_{sw} \) columns of Table 2. Estimates for wind waves \( (R_{ww} \text{ column}) \) are quite homogeneous and look reasonable for monotonic dependencies in Figure 8. On the contrary, high dispersions

Figure 8. Growth curves \( H(T) \) of wind waves for coordinate boxes of Table 2 for January, 1970–2007. Lines marked as \( B, D \) show reference power laws of Toba and swell of Table 1. Exponent of power law fit \( R \) is given for the whole range of observed wave periods \( T \).
of experimental points of swell dependencies $H(T)$ in Figure 9 make the estimates (the swell exponent $R_{sw}$ in Table 2) quite questionable.

Wind speed distributions for all the boxes looks surprisingly close to each other. For three last boxes differences in bins do not exceed, generally, a couple of percents. Similarly, exponents $R$ for wind waves are remarkably close to each other (see Table 2, $R_{ww}$ column). At the same time, all these distributions differ dramatically from the mean over ocean pattern (cf. Figures 5 and 10) and show visible difference in $H(T)$ dependencies where wave amplitudes vary significantly, say, two times for boxes 211 and 511. Thus, we see once again inadequacy of wind speed as a key physical scale in the problem of wave growth.

The dramatic difference of mean over ocean and regional wind speed distributions is twofold. First, mean values are essentially different. Secondly, the distribution shapes are also different: in coordinate boxes low winds are absent almost completely and the patterns themselves are better localized. Accordingly, the effect of wind dispersion in the regional distributions is essentially lower than in global estimates. This note is very important in view of our consideration in section 4: in the regional subsets physical parameters that affect wave growth (wind speed) can be more homogeneous. Thus, the estimates of wave growth exponents $R$ are more reliable and can be used as characteristics of wave dynamics. Very close values of $R$ for wind waves in Table 2 are in agreement with this conclusion.

One more remark can be made on wind speed distributions in Figure 10. Again, quite similarly to the whole ocean distributions (cf. Figure 5) the pronounced peaks are clearly seen at “round bins” 11 m/s ≈ 20 knots, 13 m/s ≈ 25 knots, 16 m/s ≈ 30 knots, etc.

5. Conclusions and Discussion

We apply the theoretical scheme of discriminating wind waves and swell to the VOS data. Within the approach the exponents of power law fits of dependencies $H(T)$ can be considered as indicators of wave growth. Two, in a sense, extremes of sea state, growing wind waves and swell, correspond to opposite signatures of the exponents. This simple fact is suggested for discriminating wind seas and swell.

With the exponent $R$ as indicator of sea wave dynamics we make a conceptual step: we study a link of wave heights $H$ and periods $T$ rather than features of the independent data sets. The separate analysis basing on VOS [Gulev et al., 2004] or satellite data [e.g., Zieger, 2010] gives valuable information on ranges of wave parameters and their geographical variability but propose quite primitive vision of wave dynamics. Recent attempts to combine satellite altimeter observations of wave heights and mathematical modeling of wave dynamics [Laugel et al., 2012] propose reconstructions of full spatiotemporal structure of wind wavefield. This study is based on extensive simulations and requires thorough theoretical analysis. The interpretation of
its results in the context of burning problems of sea wave physics shows a good prospect for further study.

[63] The proposed theoretical scheme relates $H(T)$ dependencies with different cases of wind-wave coupling. This scheme cannot be realized in its full due to features of the VOS data: relatively low data accuracy, coarse data sampling, etc., but is shown to be useful for delineating two extremes, wind waves and swell. A wide gap between values of $R$ for wind waves and ones of swell allows to realize this delineation basing on wave heights and periods data only, without wind speed data also available in the VOS collection.

[64] We avoided to use wind speed data by a number of reasons. Our theoretical scheme implies but does not dictate the wind speed to be a key physical scale. Say, in swell case, such scaling is, evidently, misleading. Additionally, quality of wind data collected by ship observers is rather low, the data flaws are seen clearly in statistical distributions of wind speeds (see Figures 5 and 10).

[65] We accepted an assumption that uncertainty of knowledge of wind wave input (wind speed) and parameters of swell generation (see scaling condition 10) does not affect critically our estimates of exponent $R$ in (1). Fortunately, the proposed approach gave interesting results and showed its promising prospects.

[66] Even for global estimates of exponents $R$ swell and wind wave data showed definite difference in mean values and in distribution patterns (see Figures 4 and 7). First of all, this result can be considered as a justification of good quality of discriminating swell and wind-driven sea by observers. Secondly, it shows robustness of the proposed criterium for delineating wind waves and swell: a gap between values $R$ for wind waves and swell is sufficiently wide.

[67] Selection in wave periods ($T = 5$–$10$ s for wind waves and $10$–$20$ s for swell) makes exponent $R$ to be more definite indicator of wave growth. This selection works quite well for interpretation of wind-wave growth in the spirit of the presented simple theory. In contrast, swell dynamics in terms of $R$ looks more complex. We explain this fact by complexity of swell dynamics itself when its coupling, first of all, with locally generated wind waves can be extremely important.

[68] Example of section 4.3 showed that $R$ is quite good as indicator of growing wind waves. At the same time, it fails to explain strong regional variability of wind wave and swell magnitudes. Surprisingly (at the very first glance), but wind speed is failed to explain these variations as well: all the wind speed distributions are quite close to each other.

[69] The presented results show good prospects of further study, in particular, in constructing a sort of climatology in terms of exponent $R$. Irregular data sampling of VOS data is usually seen as a bad luck when constructing global distributions. In fact, this point of concern can be used in a positive sense. VOS data are associated mostly with regular ship routes, mariners avoid bad weather conditions, etc. All these factors, in fact, homogenize conditions of wave generation and propagation. The latter makes the physical situation closer to the physical model considered in this paper.

Figure 10. Wind speed histograms for coordinate boxes in Table 2 for January, 1970–2007. Box ID and number of observations are shown in legends.
[70] Our main hopes are satellite data that allow for tracking spatial wave evolution. For relatively long swell this task is feasible with today technologies and methods of remote measurements.

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