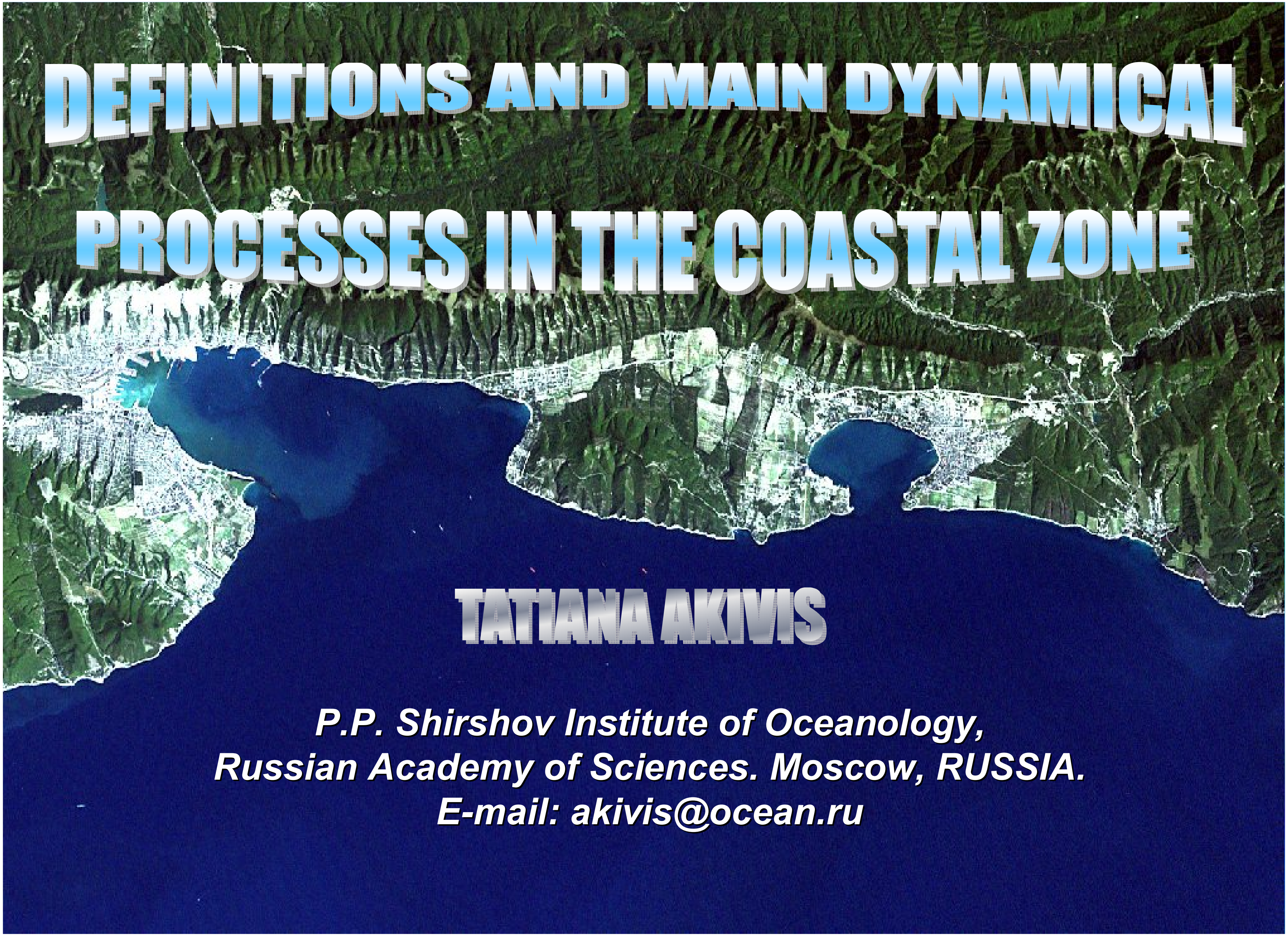

DEFINITIONS AND MAIN DYNAMICAL PROCESSES IN THE COASTAL ZONE

TATIANA AKIVIS

P.P. Shirshov Institute of Oceanology,
Russian Academy of Sciences. Moscow, RUSSIA.
E-mail: akivis@ocean.ru

Introduction

The nearshore zone, though occupying only a small part of seas and oceans, plays an important role in human existence. Situated adjacent to the shore, it has been actively developed by people living in the narrow coastal zone.

What is the coastal zone?

The definitions of the coastal zone are different depending on the purpose of research.

Geological point of view:

The coastal zone cannot be separated from the rest of the shelf.
The seaward boundary of the coastal zone is defined at the shelf edge.
The landward boundary is considered at the highest late Quaternary sea level .

This approach is reasonable for the problems of paleogeography, sediment formation and others (Aibulatov).

Dynamical definition of the coastal zone

The coastal zone is a zone where hydrodynamic processes (waves and currents) actively affect the seabed.

These limits are dynamically mobile depending on the hydrodynamic processes.

For example, very high and long swell waves or mesoscale eddies can affect the seabed and cause bed sediment motion up to the shelf edge.

The shoreward boundary of the coastal zone can be drawn at the line of maximal storm splash.

A long-term goal of the coastal zone research

is to understand and to model the transformation of surface gravity waves propagating across the continental shelf to the beach, the corresponding wave-driven circulation in the surf zone, and the resulting sediment transport and beachface morphology.

The research include both

-field investigation and
-modeling of the nearshore processes.

The field investigation enable understanding the physical picture and spatio-temporal parameters of the processes which is needed for development of both diagnostic and prognostic models.

Understanding of nearshore processes is increasingly important from practical point of view.

Beaches are:

- *a primary recreational area,*
- *essential to economical activity,*
- *important to national defense.*

The majority of the world's coastlines are eroding.

The erosion problems are accelerated because of

- *increased threat of global warming and the resulting*
- *rise in sea level;*
- *anthropogenic impact.*

Figure 1. Abrasion coast of The Azov Sea

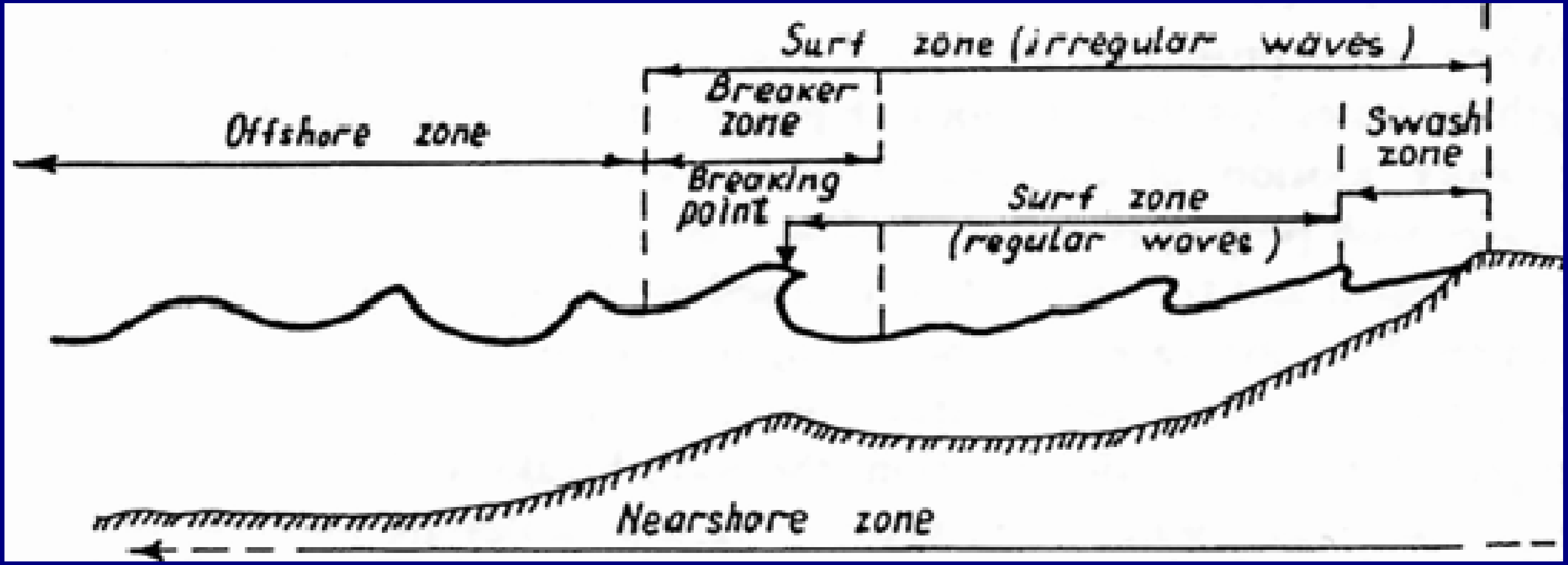

Figure 2. Schematic division of a coastal zone into characteristic sites.

Nearshore zone - The zone extending seawards from landward limit of storm overwash to the limit of initiation of sediment movement.
Offshore zone - The zone from the breaker zone to the sea.
Breaking zone - The zone of breaking of irregular waves.
Surf zone - The zone from seaward limit of breaker zone to the landward limit of swash zone.
Breaking point - The starting point of wave breaking.
Swash zone - The zone from the wave uprush limit to the area of collision backrushing water with incoming waves.

1. Space-time scales of nearshore processes

All dynamical processes in the coastal zone can be roughly separated into three large categories:

- small-,
- intermediate-,
- large-scale

processes based on the space-time scales of near-shore fluid motions.

The bands of the spatial and time scales of the nearshore processes are the following:

Small-scale processes –
0.1 mm –10 m; 0.1 s -1 day;
Intermediate- scale processes –
1 m –10 km, 1 sec- 1 year;
Large-scale processes –
1 – 100 km, months-decades.

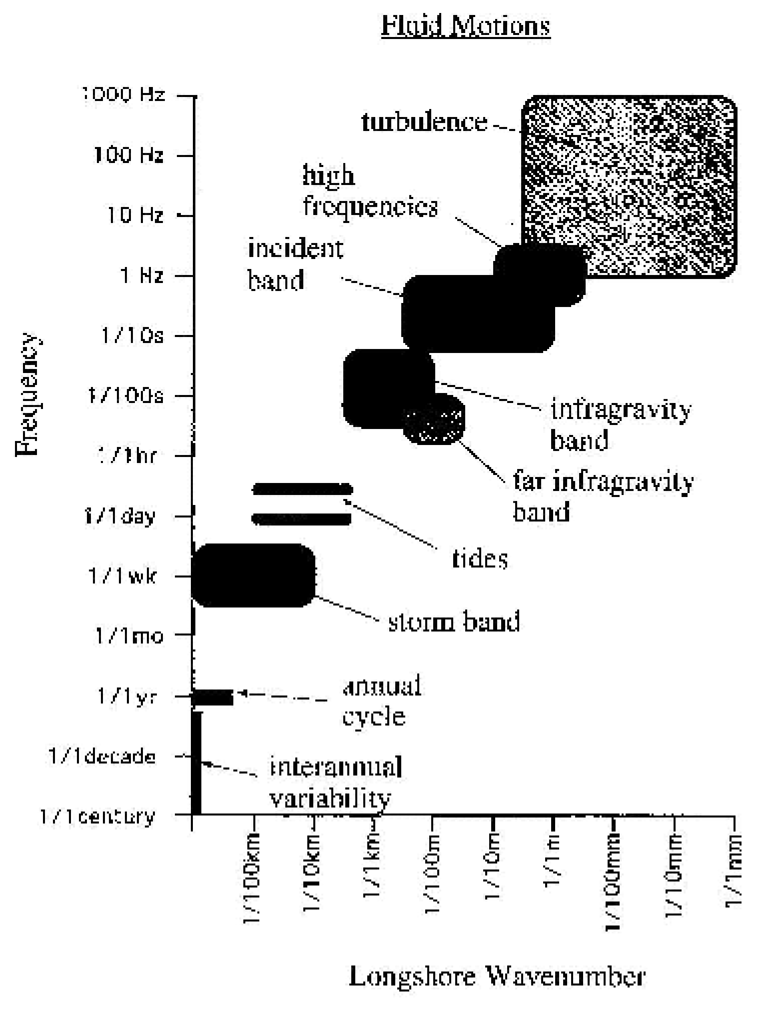

Figure 3 Space-time scales of the nearshore processes

Coupling of the small-, intermediate-, and large-scale processes

Modern field experiments and modeling have shown that nearshore hydrodynamics and bathymetric change involve coupled processes at many spatial and temporal scales.

The properties of waves incident from deep water and the beach profile (large-scale processes) determine the overall characteristics (e.g., surf zone width) of nearshore waves and flows (intermediate-scale processes).

Small-scale processes control the turbulent dissipation of breaking waves, bottom boundary layer and bedforms that determine the local sediment flux.

Cross- and alongshore variations in waves, currents, and bottom slope cause spatial gradients in sediment fluxes resulting in large-scale, planform evolution (e.g., erosion or accretion).

As the surf zone bathymetry evolves, so do nearshore waves and currents that depend strongly on this bathymetry.

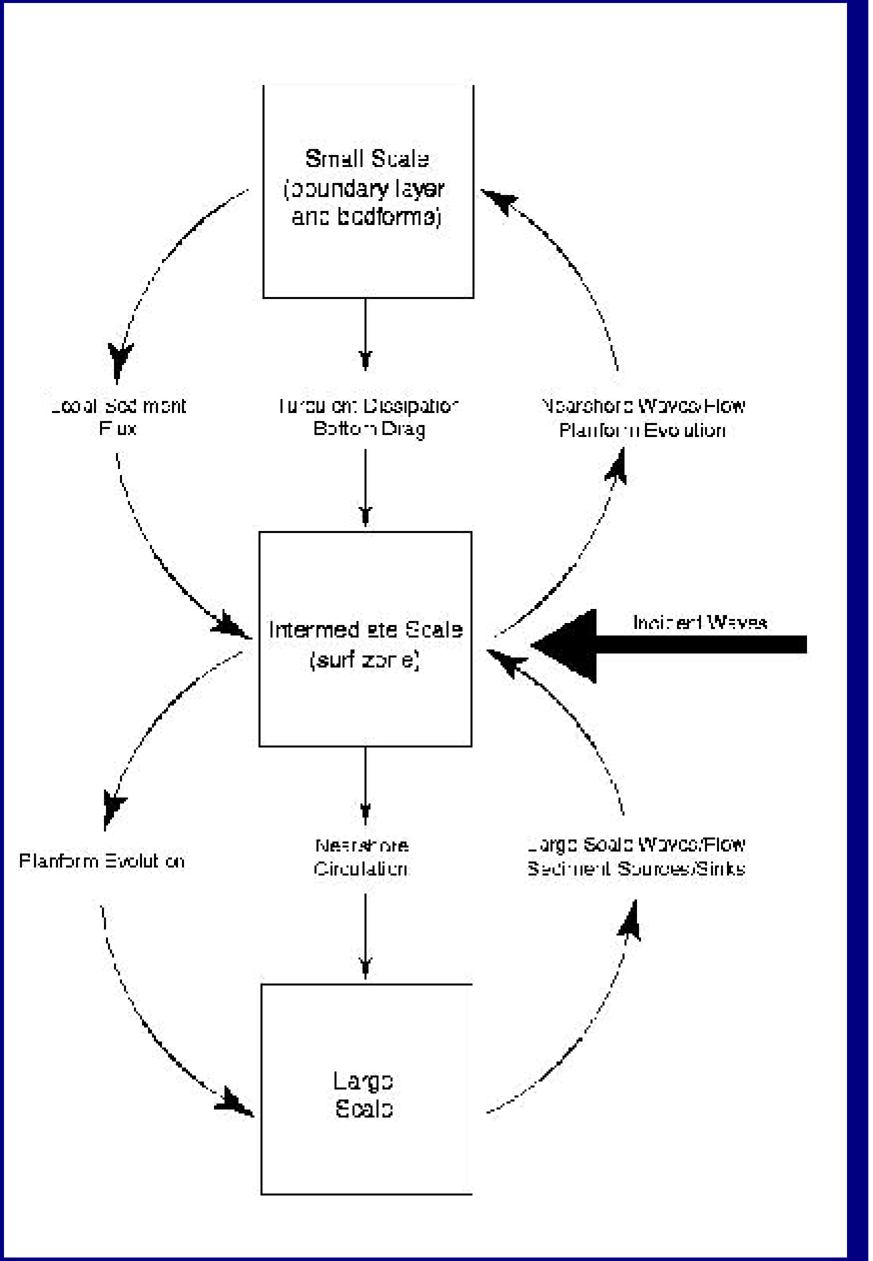

Figure 4.

1.1.Small-scale processes (0.1 mm –10 m; 0.1 s -1 day)

1.1.1. Bed state (2D and 3D bedforms)

When near-bottom velocities of water flow slightly exceed their values for mass transport of bottom sediment, periodic forms of microrelief are built. Depending on intensity of near-bottom flow, sediment composition, and nature of surface, various types of bed forms can be built. The bed forms, in their turn, have an influence on near-bottom hydrodynamics, so the feedback system is formed.

The high-resolution measurements using acoustic altimeters and side scan sonars in storm conditions now quantify the 3-D character of bedforms at high temporal and spatial resolution.

From 10 to 40 cm high lunate and straight-crested megaripples are often seen on the seaward flanks of bars, in the nearshore trough, and in rip channels, but their origin and spatial variability are not understood well.

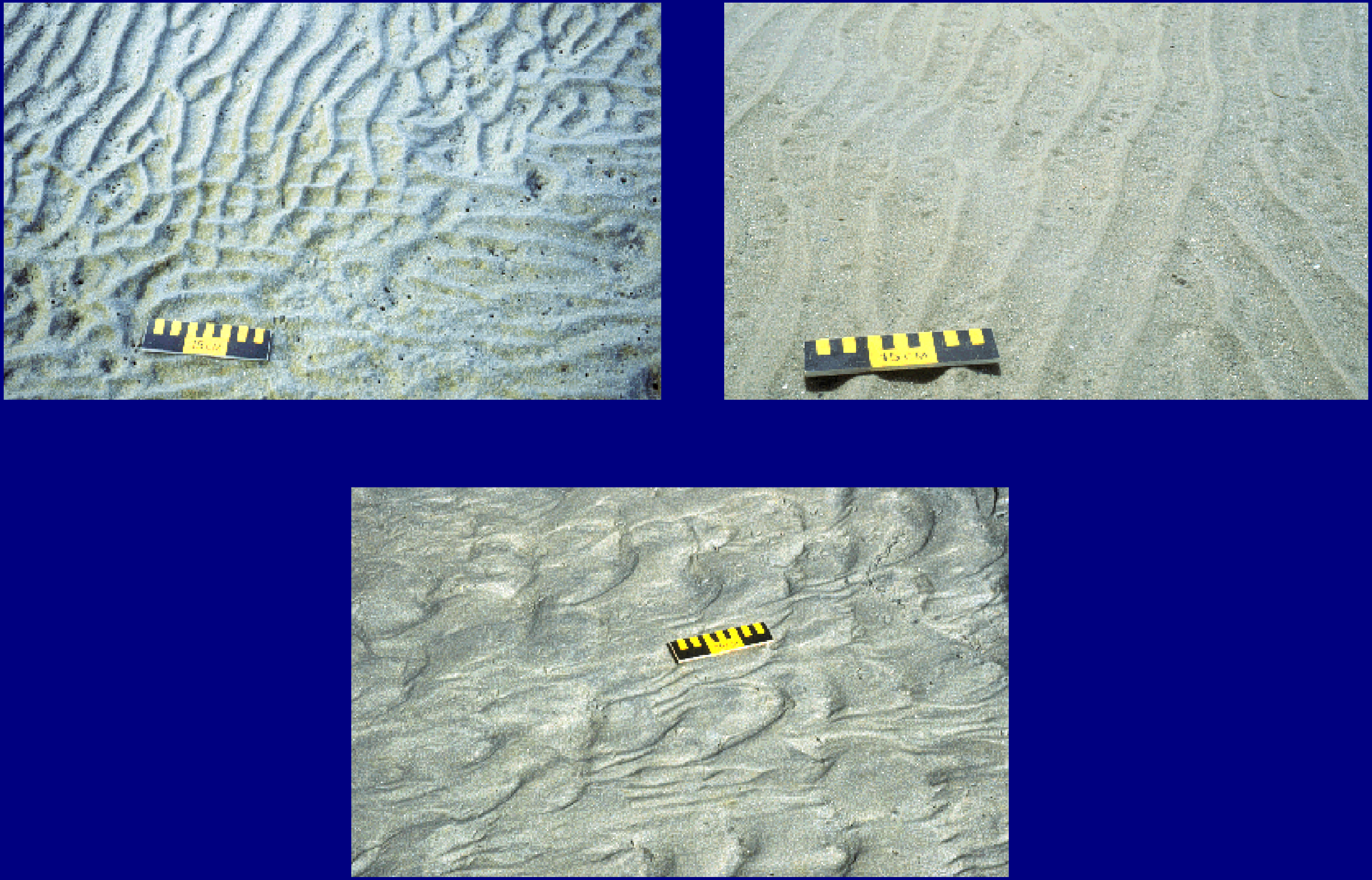

Figure 5. Different types of the bed-forms

1.1.2. Wave Bottom Boundary Layer of wave flow

When surface waves enter shallow water, oscillatory water movements create a boundary layer through friction against bottom. This layer will be called “wave bottom boundary layer" (WBBL). Study of publications on shelf sediment transport shows that lately attention paid to WBBL has increased greatly.

- First, WBBL is the exact site of initiation of sediment transport, bottom erosion, microforms formation, which determine the essential boundary conditions for wave-induced sediment transport modeling.
- Second, two last decades have witnessed intensive development of turbulent current calculation methods. Having reduced the cost of calculations, computerization has also given a real opportunity for numerical modeling of WBBL .
- And, third, development of the new generation of measuring devices, data collection and processing systems enabled carrying out a number of boundary layer precise measurements under laboratory conditions, against which the suggested models were tested.

Nevertheless, in-situ measurements in the WBBL are still inadequate as the available measuring devices do not permit measurements in a few-centimeter thick layer above sea bottom.

WBBL determination and regimes of motion

Consider a flow of incompressible fluid above a flat rough bottom. Assume the flow to be periodic and parallel to the bottom. In this case, water velocity at a distance from the bottom can be written as:

$$U_\infty(t) = U_m \sin \omega t$$

where U_∞ is a mean velocity at instant *t* at some distance from the bottom, U_m is its amplitude and ω is angular frequency.

Due to the bottom friction, a velocity profile is formed. Its typical form for $\omega t = \pi / 2$ is shown in Fig.6.

Different definitions of the WBBL thickness

δ_W is a minimal distance from the bottom to a point where $U = U_m$. In other phases of ωt, WBBL thickness will be less than δ_W

δ_m is a minimal distance from the bottom to a point where $\partial U / \partial z = 0$.

δ_T is the distance where the difference between the velocity and U_m is equal 1%. Another definition suggests WBBL thickness δ_E as a minimal distance from the bottom to the point where the turbulent energy loses 1% of its maximal bottom value.

The length scale that enables comparison between the definitions is chosen as $\delta_S = U_{*m} / \omega$ where U_{*m} is a friction velocity amplitude

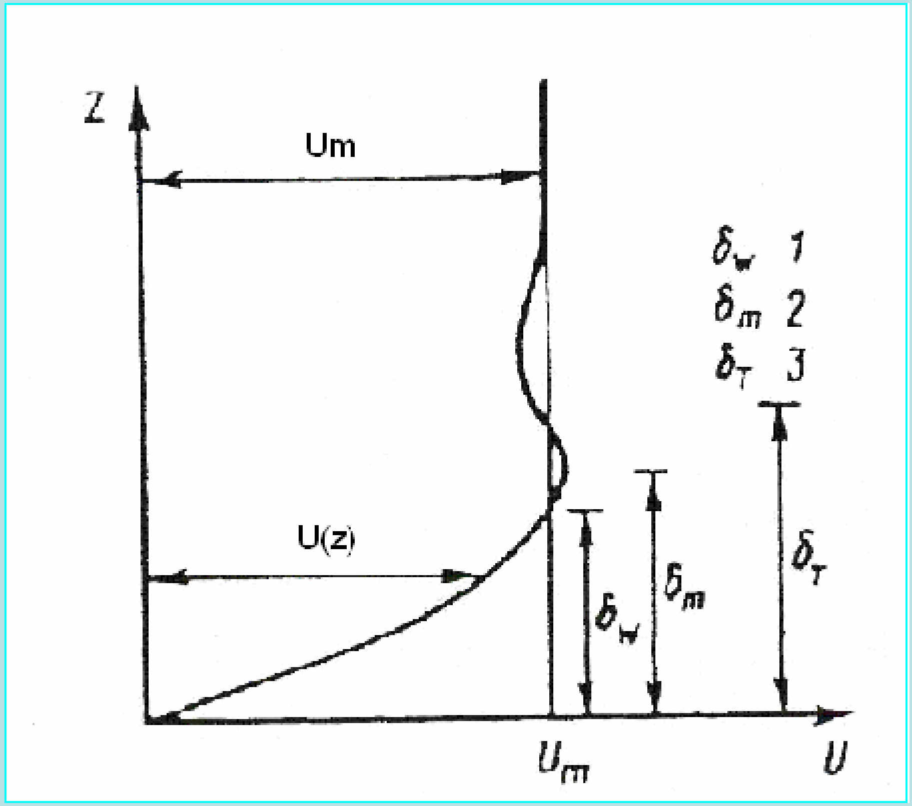

Figure 6. Principal elements of wave bottom boundary layer.

Near-bottom flow is characterized by Reynolds amplitude number:

$$\mathrm{Re} = U_m a_m / \nu$$

or by Reynolds number in terms of bottom roughness

$$\mathrm{Re}_* = U_m K_s / \nu$$

Here $a_m = U_m / \omega$ is amplitude of near bottom water flow; K_s is a linear size of bottom roughness elements, ν is water kinematical viscosity. Water flow in the boundary layer can be laminar, turbulent or transitional between them. In laminar flow, motion in WBBL is determined by viscosity forces.

For the smooth bottom surface, the laminar flow takes place at $\mathrm{Re} < 10^4$, while the turbulent flow exists at $\mathrm{Re} > 3 \cdot 10^5$. When $10^4 << \mathrm{Re} << 3 \cdot 10^5$, the flow is considered to be transitional from laminar to turbulent regimes. In this case the flow character is controlled by both viscosity forces and turbulent Reynolds stresses.

For the rough bottom WBBL motion regime is controlled by relative bottom roughness a_m / K_s in addition to Reynolds number Re.

Hydrodynamic regimes in WBBL

When $Re_* < 5$ the motion regime is called hydrodynamically smooth. This condition is satisfied for weak near bottom currents and for relatively smooth surfaces. For marine environments with ν =1,2*10^{-6} m^2/s and U_{*m} = 0.01 m/s, this pattern will hold at K_s = 0,006 m, i.e., if flat even bottom is composed by medium-grained sand or by finer particles. In this case viscous sublayer directly adjoins the bottom.

For $Re_* > 70$, the motion pattern is defined as hydrodynamically rough. In this pattern bottom roughness elements exceed viscous sublayer thickness, so oscillatory flow and its properties do not depend on Reynolds number, but on a_m / K_s .

For flat sandy bottom composed by uniform grains, $K_s=d$ (particles' diameter).

For flat bottom composed of heterogeneous material, experiments give $K_s=2d_{90}$.

For "not quite smooth bottom" (Nielsen), $K_s= 2{,}5d$, where d is mean diameter of bottom sediment particles.

In real marine conditions the bottom is not smooth, it is usually covered by micro- and macro-forms of different scales. In this case an equivalent roughness K_s is controlled by bed form types and parameters.

Some estimates for the equivalent roughness K_s for 2D wave ripples:

$K_s = 4h_r$, h_r is ripple height (Johnson);

$K_s = 25h_r^2 / \lambda_r$, λ_r is ripple length (de Swart) ;

$K_s = 27.7h_r^2 / \lambda_r$ (Grant, Madsen)

For practical purposes, the following estimates for lower limits of turbulent hydrodynamically rough regime have been suggested (Johnson):

Re = 10^4 for 1 < a_m / K_s < 10,

Re = 10^3 (a_m / K_s) for 10 < a_m / K_s < 10^3

WBBL thickness

The thickness of laminar boundary layer can be found analytically:

$$\delta_\nu = \pi \sqrt{\nu / 2\omega}$$

The thickness of turbulent boundary layer is estimated as 2-4% of a_m in the range 10 < a_m / K_s <$5 \cdot 10^2$

WBBL is only a few cm thick over a flat bed and changes rapidly. Owing to the difficulty of resolving the space-time structure in the field, tests of WBBL models have relied upon laboratory measurements.
In the field conditions, new methods including a traversing laser-Doppler velocimeter, hotfilm anemometers, and acoustic Doppler techniques have been used to profile the WBBL.

Bottom boundary layers associated with mean flow are typically *O*(1 m) thick and can be measured with standard velocity sensors. The vertical structure of mean on-offshore currents (undertow) observed in the field has been modelled using a cross-shore variable eddy viscosity.
The logarithmic profile was found to describe well the vertical profiles of strong (> 1 m/s) longshore currents.

Models for vertical structure of wave-current bottom boundary layer have been under development for some time. However, there is no reliable theory for turbulent flow over the rough and erodable bed typical for nearshore environment. Most models are 1D and depend on either an analytical (e.g., eddy viscosity) or a numerical (e.g., k-epsilon) turbulent closure scheme. Better agreement was found between time-varying eddy viscosity models and k-epsilon models with nonlinearity in the mean stress. Existing 3D models, using direct numerical simulation techniques, are producing realistic pictures of instability development and the onset of turbulence in the WBBL, but are limited to low Reynolds numbers owing to computational constraints.

1.1.3. Turbulence

Turbulence is generated at the surface under breaking waves and in the bottom boundary layer due to hydrodynamic instability.

The details of breaker-induced turbulence and energy dissipation have been studied in laboratory, and both obliquely descending vortices and horizontal vortices have been observed (Fig. 7) , depending of the wave breaking type:

a – spilling;
b – mixed type;
c – plunging.

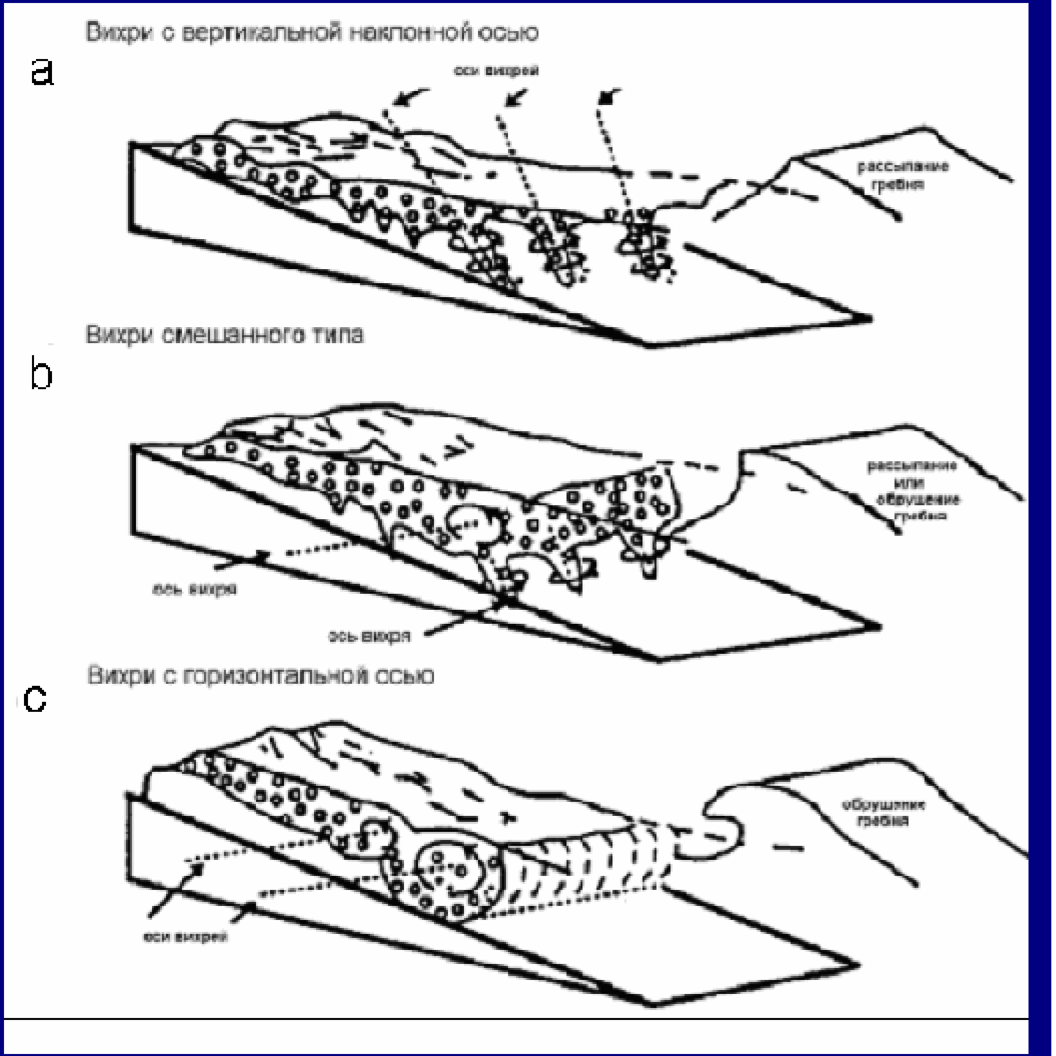

Figure 7. The main types of vortices in the wave breaking zone

The main mechanism of turbulence generation in WBBL is a hydrodynamical instability, when small perturbations of water flow lead to explosive character of turbulence generation. Field observations showed that the magnitude of the turbulent kinetic energy is largest under the wave crests and decreases over the decelerating flow phase until reversal to offshore flow (Fig. 8).

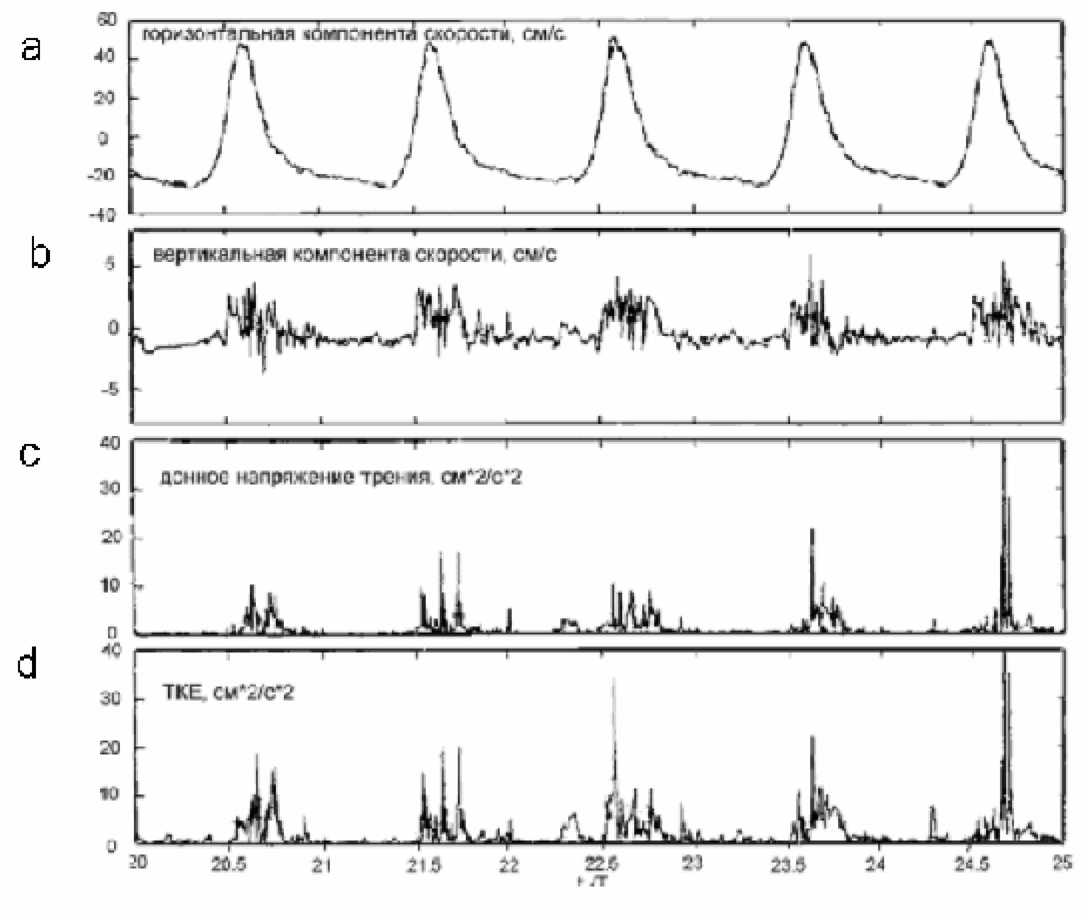

Figure 8. An example of time series of horizontal (a) and vertical (b) components of water velocity, magnitudes of bottom friction stress (c), and turbulent energy (d) in the WBBL at 0.3 cm level above the bottom. T is wave period,
t – current time.

1.1.3. Sediment suspension.

Sand ripples are ubiquitous features that form on sandy beds in response to the oscillatory motion induced by surface waves. Under rippled-bed conditions the sand transport process is quite distinct from its flat-bed equivalent since it relates to the shedding of a large vortex every wave half-cycle.

Fig. 9. shows laboratory photographs illustrating generation and motion of vortices near the 2D ripples crests at different phases of the wave cycle.

This laboratory experiment demonstrated that the concentration is maximum at flow reversal (i.e. 90^0 and 270^0 phase) as a result of the vortex being shed from the ripple crest.

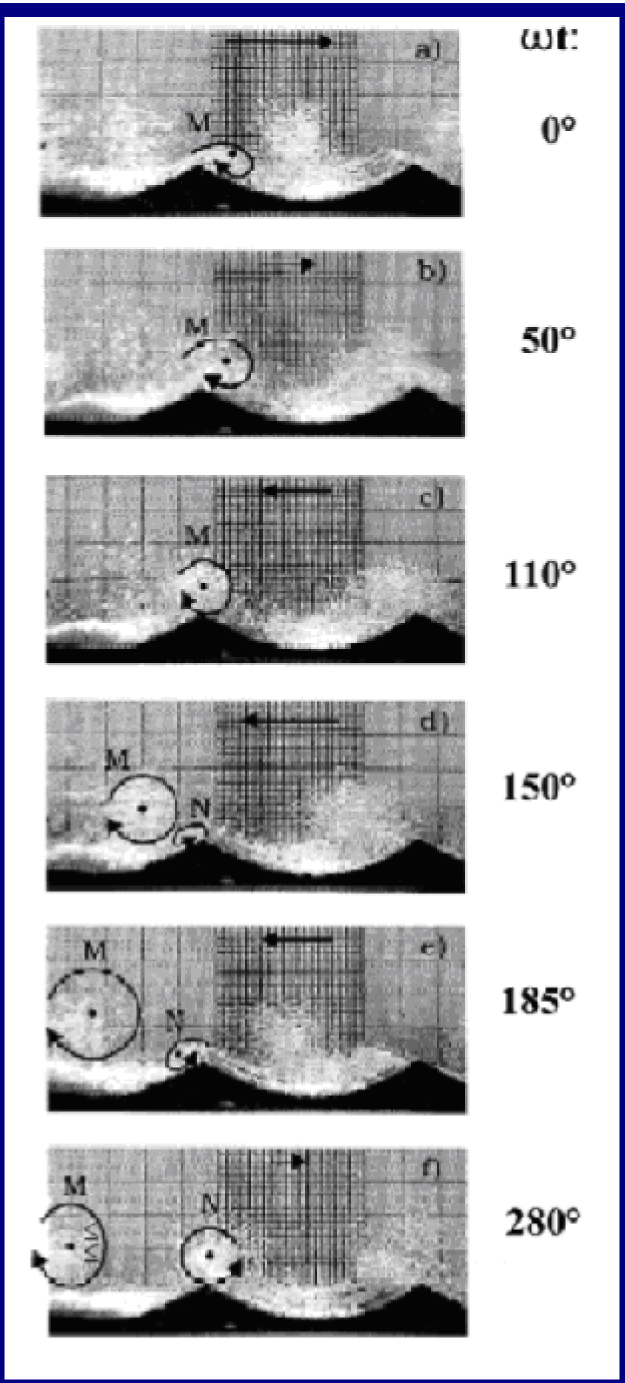

Figure 9.

In the field condition the waves are always irregular and the time scales of sediment suspension can differ from the laboratory case. The measurements showed that suspension events coincide well with groups of waves.

Fig. 10 shows an example of time variability of suspended sediment concentration *C* and cross-shore velocity component *U* illustrating fluctuations of the concentration
a) by some groups of high waves and
b) by individual waves within wide group of high waves.
Dashed horizontal lines show rms value of cross-shore velocity component.

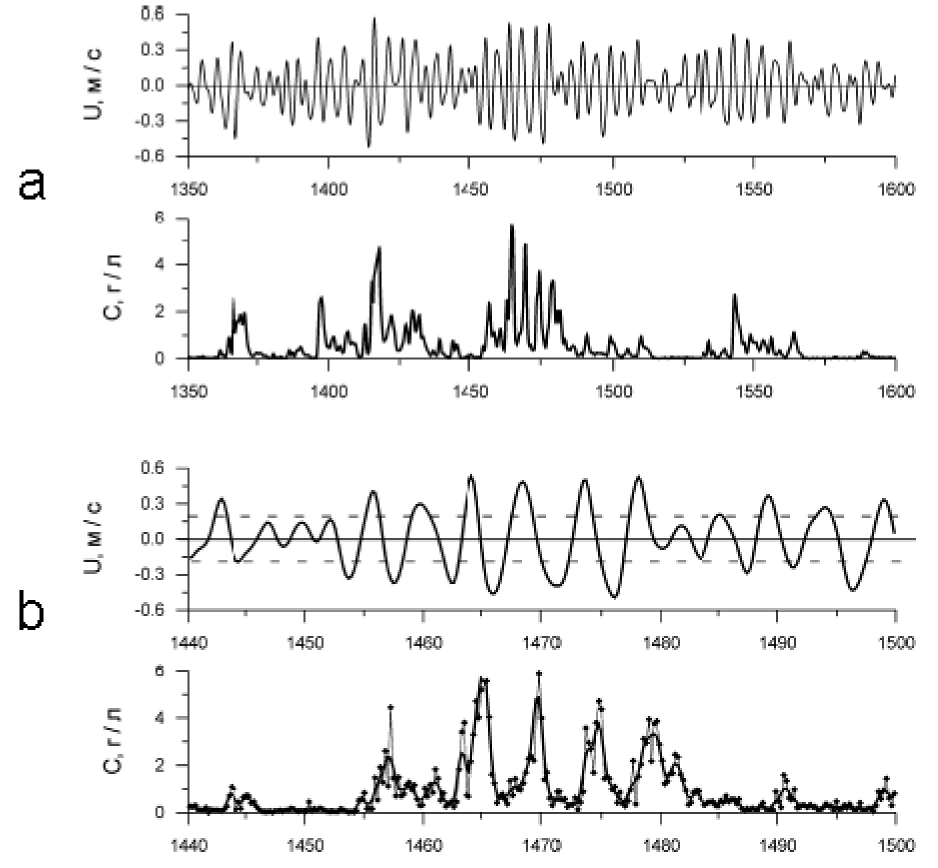

Figure 10

1.2. Intermediate- scale processes [1m –10 km, 1 sec- 1 year]

1.2.1. Surface waves

Wind waves and swell (period 5-20 s). During the last decades, there has been considerable progress toward modeling quantitatively the shoaling wave transformation. Models based on the Boussinesq equations and field observations predict accurately the shoaling of non-breaking near-normally incident swell observed in shallow water on natural beaches.

Infragravity waves are the waves generated due to non-linear interaction between short gravitational waves. Their frequency band depends on the frequency of wind waves spectrum maximum and, for strong storm condition, is of order 0.005 – 0.05 Hz. The nonlinear forcing is strong during storms, and infragravity waves can dominate inner surf zone velocity and sea-surface fluctuations, with heights exceeding 1 m.

Infragravity waves is divided into two main categories:

- waves advancing cross-shore (transversal waves) and
- edge waves with longshore phase variations.

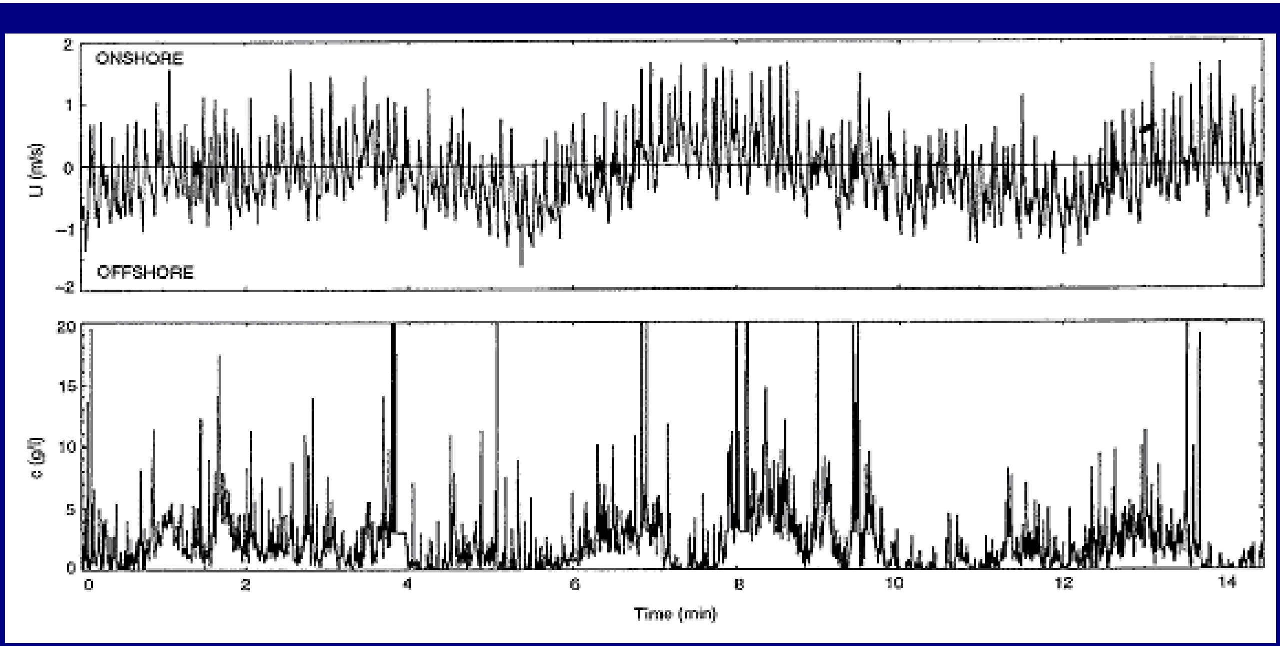

Figure 11. Time series of cross-shore velocity and sediment concentration

The dominant oscillation in velocity field has a period of 5-6 minutes with superimposed oscillations of high frequency. Major re-suspension events are associated with the on-shore phase of the infragravity oscillations.

Infragravity waves are not strongly dissipated by wave breaking in the surf zone. Observations from a range of coastal settings suggest that infragravity energy levels on the continental shelf depend not only on conditions in nearby surf zones, but also on the general geographic surroundings. For example, more infragravity energy is trapped on a steep narrow shelf than on a gently sloping wide shelf.

A swash zone **is the region where the beach face is intermittently covered and uncovered by wave runup.**

Figure 12

Boussinesq models recently have been extended to include swash motions, and model predictions agree well with theories for 1-D runup and with measurements of 2-D runup on an impermeable laboratory beach. But accurate prediction of runup on coarse-grained beaches may require a model that includes filtering effects. Additionally, prediction of fluid velocities in the runup may require inclusion of a turbulent bottom boundary layer.

1.2.1. Nearshore circulation

Sea and swell waves incident on a beach can drive strong (~1.5 m/s) quasi-steady currents in the surf zone. Fig. 13 from the book by Igor Leont'yev illustrates a difference between two types of circulation; it shows schemes of currents within the element of water column in the nearshore zone for homogeneous (a) and heterogenous (b) bed relief. In the last case flows directed to the coast are drawn towards more shallow sites, and flow-out (often in the form of discontinuous flows) is concentrated over the bed lowering to which gradiental longshore currents are directed.

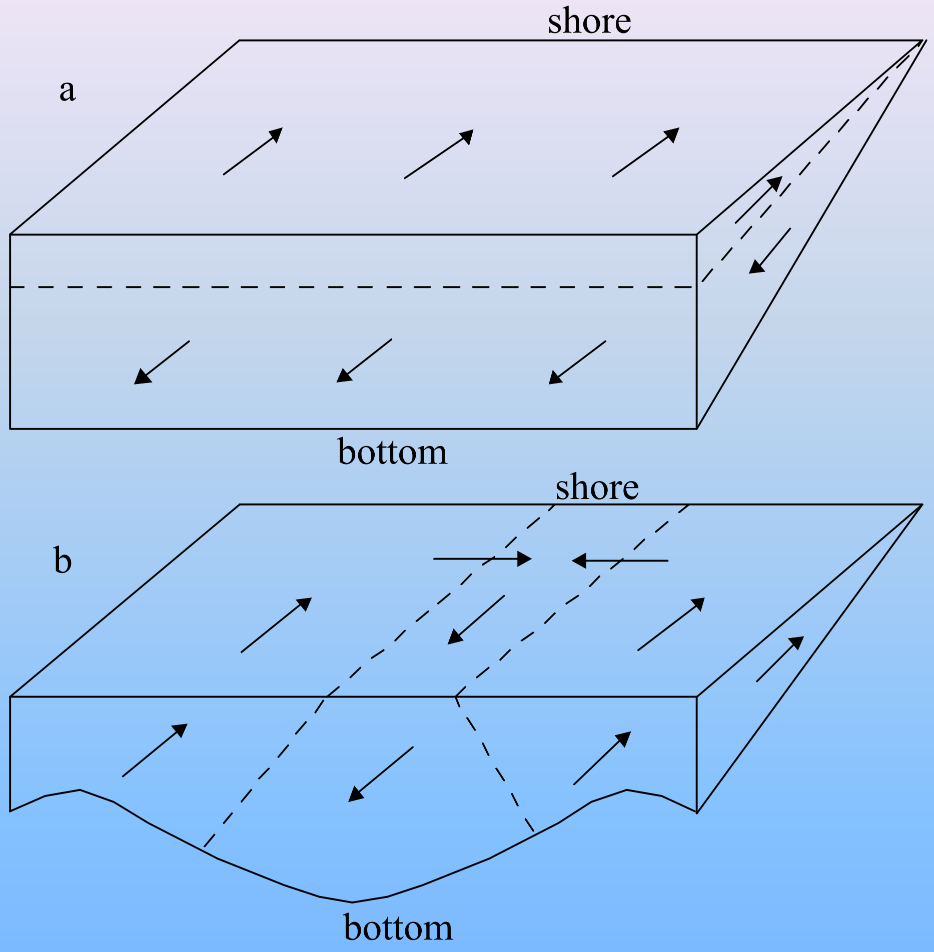

Figure 13. Water circulation in the coastal zone for homogeneous (a) and heterogeneous (b) bottom topography.

From a plane view the circulation looks like so-called circulation cells. Their structure depends on bottom topography, contour of the coast line and wave height and direction. In marine condition under severe storm a rate of longshore current is about 1 m/sec. The velocity of rip currents is higher and can reach 2 m/s even under moderate waves.

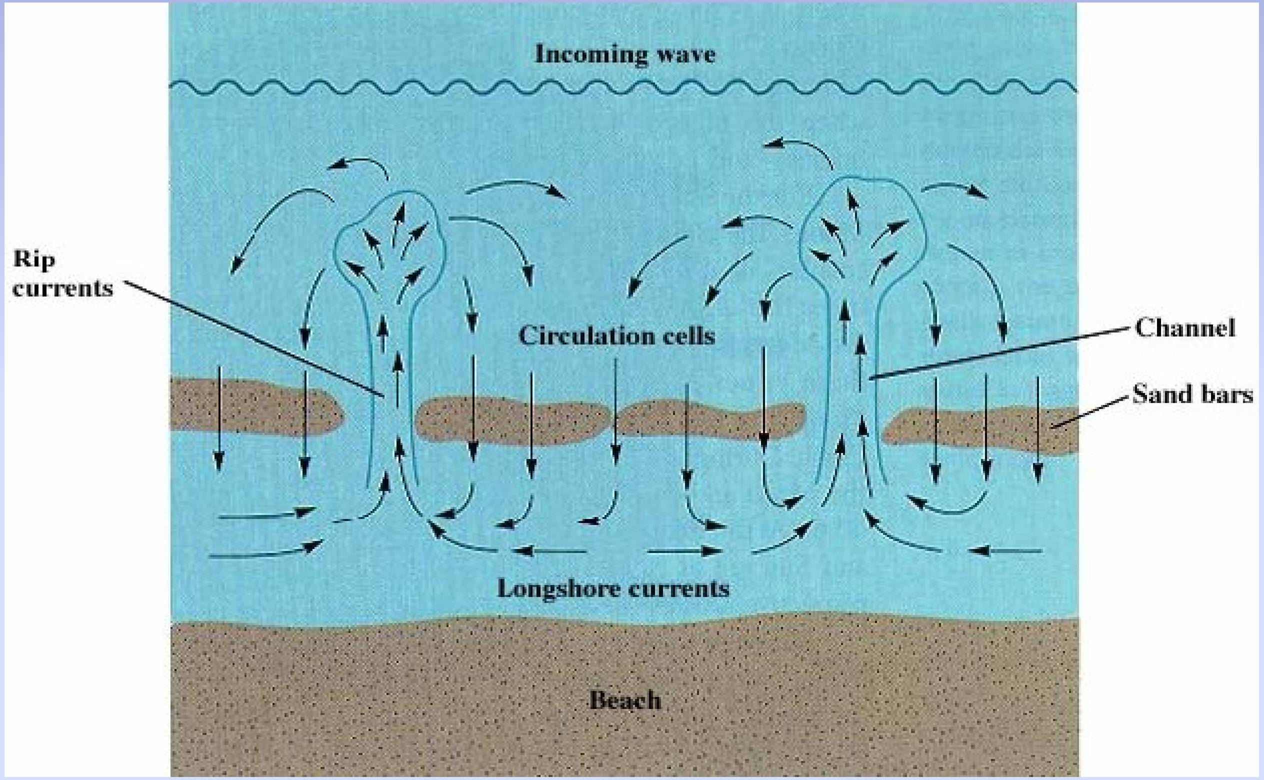

Figure 14. A scheme of nearshore circulation for the case of bottom topography with alongshore bars.

1.2.2. Sediment transport

A prediction of suspended sediment concentration profile in various phases of bottom evolution is one of the key aspects of sediment transport problem.

Sediment transport models for combined wave-current flow are usually formulated either in terms of flow energy or bottom shear stress. In these models, sediment transport is separated into suspended load and bedload. Suspended load is understood much better owing to the difficulty of obtaining non-intrusive measurements of the particles motion in the bedload layer. An important question is what kind of sediment transport modes dominates in different nearshore environments.

Models of sediment suspension are built on a base of fluid boundary layer models by adding a sediment conservation equation and boundary conditions for the sediment flux. Important questions relate to the mechanisms and parameterization of both sediment entrainment from the bed, and upward mixing of sediment into the water column.

Fig. 15. shows the results of two-dimensional model of sediment transport over ripples by A.Davies et al.

This model demonstrated the importance of the vortex shedding process in mixing momentum in the water column.
A particle tracking model developed and driven by the hydrodynamical one was able to show that over ripples the mixing of sediment is even stronger than the mixing of momentum.

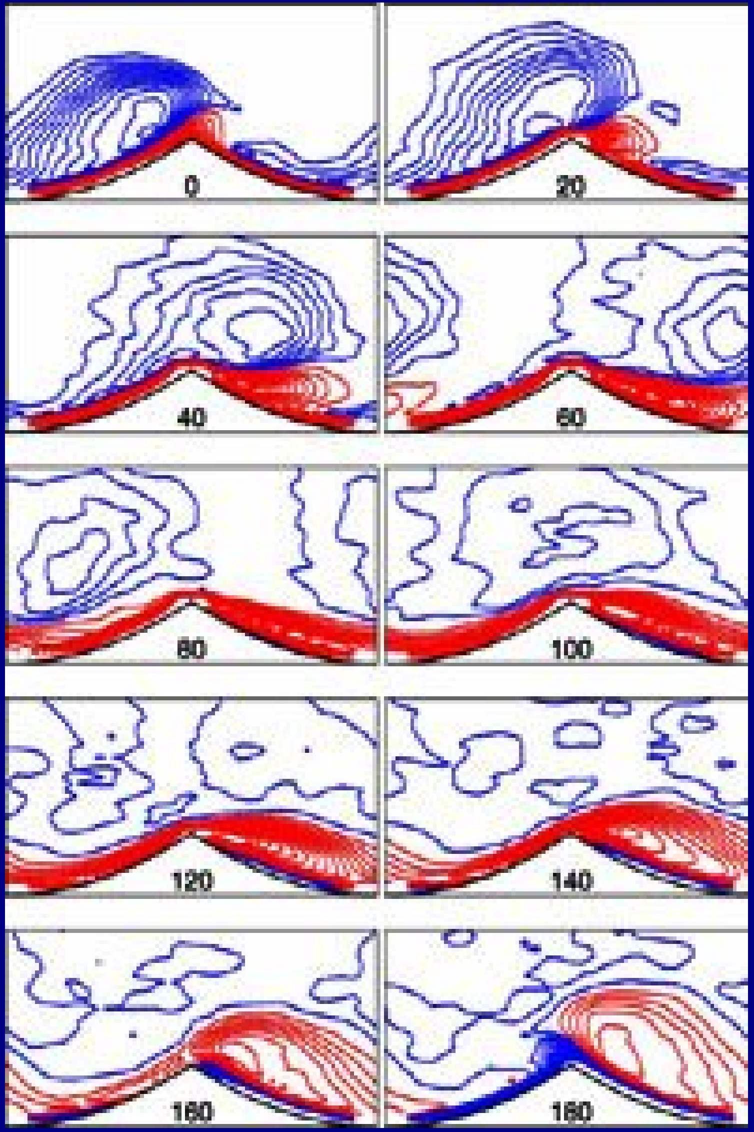

Figure 15.

Fig. 16 shows the comparison between model and measured time series of suspended sediment concentration over rippled bed under irregular waves (Pykhov et al). The correspondence seem to be quite sufficient.

In the model, the concentration change is controlled by the local balance between particles settling and diffusive and convective sediment fluxes upward from the bottom.

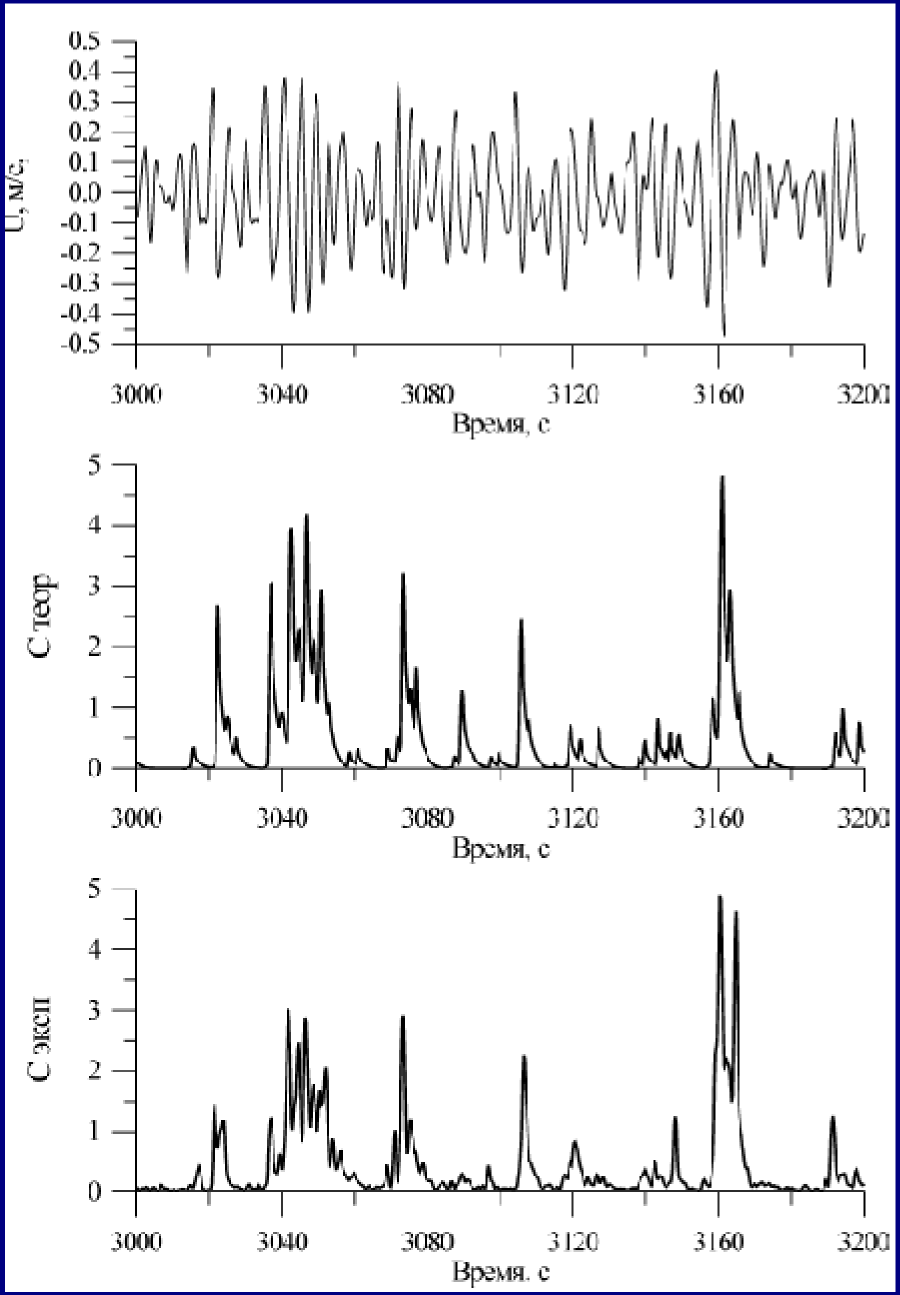

Figure 16

Intensification of near bottom water motion leads to erosion of the bed forms so the bottom becomes flat.

Fig. 17 demonstrates the comparison between modelled (dotted line) and measured (solid line) suspended sediment concentration over the flat bed (Pykhov et al).

The model is based on the semi-empirical theory of bottom boundary layer, so-called k-l model.

Again, both convective and diffusive suspension mechanisms are included in the model.

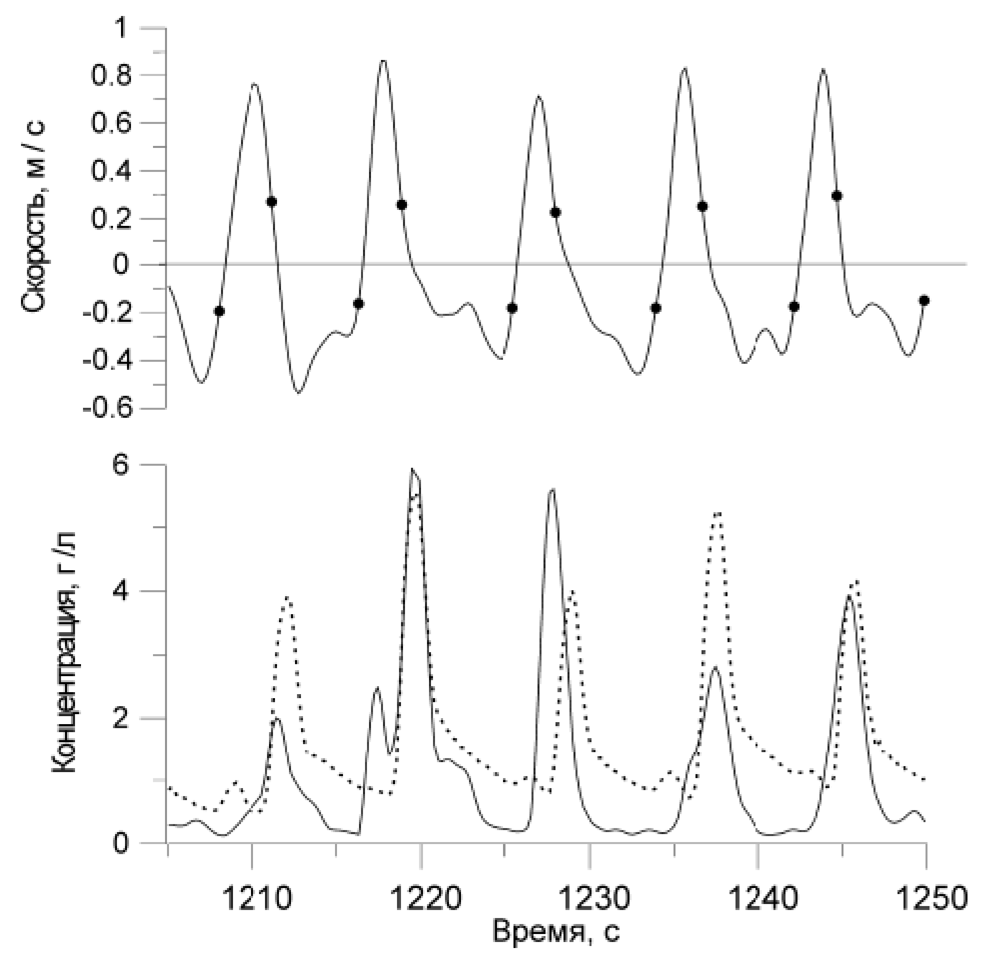

Figure 17

1.2.3. Surf Zone Bathymetry

During the last decades the coupling between waves, circulation, and changes in nearshore bathymetry has been observed and modeled. On many beaches, changes in the position and height of sand bars are the primary source of cross-shore bathymetric variability, and these bars may be either linear, alongshore periodic, or alongshore irregular.

Hypotheses for sand bar formation include both a break-point and infragravity waves mechanisms; each one might be important.

During storms, wave-breaking induced undertow dominates energetics-based modeled sediment transport. Undertow is strongest near the bar crest where wave breaking intensifies.

Models predict resulting seaward bar migration, as observed. As the sand bar moves offshore, the location of intense wave breaking and maximum undertow also migrates seaward. Thus, the coupling and feedback between waves, currents, and bathymetry results in continuous offshore sand bar migration during storms.

Existing models still cannot predict the slower, onshore migration of the sand bars observed in the surf zone during periods of low waves.

1.3. Large-scale processes [1 – 100 km, months-decades]

The general topic of dynamics of the nearshore system at long-time (months to decades) and length (kilometers and longer) scales is known as Large Scale Coastal Behavior (LSCB), which lies between the shorter scales of traditional nearshore processes (represented here in terms of intermediate and short scale processes) and the much longer scales of Coastal Marine Geology.

1.3.1. Large Scale Coastal Behavior (LSCB) - dynamics of the nearshore system at long time and length scales.

At intermediate and small scales, understanding the nearshore implies understanding the dynamics of both its fluid and sediment components. At the longer time scales of LSCB, emergent variables based on a hierarchy of time scales may dominate nearshore processes, i.e. small-scale processes become slaves to large-scale bathymetry at longer time scales.

The most common measure of beach state used by coastal zone managers and coastal engineers is a location of the shoreline (a measure which is obtained easily from survey or remote sensing). To develop a predictive understanding of variability of the shoreline then requires an understanding of how the shoreline is related to, and represents, overall profile variability.

1.3.2. Sources of LSCB Energy (influence of climate, sea level, regional sediment fluxes, and anthropogenic effects on the nearshore)

Forcing of large scale nearshore variability can arise from several possible sources, including external factors (wave climate, currents and winds), nonlinear interactions within these external factors, and internal (to the system) factors.

Directly forced response results from forcing energy at the same frequency. For example, a beach may erode slowly owing to a slow increase in the wave climate energy. Thus, the signature of the forcing in space and time provides a template for the nearshore response.

Nonlinear interactions may transfer energy of the forcing spectrum from high frequencies to LSCB. For example, increased suspended loads under winter storm waves might tend to be carried preferentially offshore by bottom return flows from upwelling-favorable winter winds. The corresponding summer conditions might drive only a weak onshore transport, thus produce a net sediment loss (erosion).

Spontaneous generation of LSCB variance (often called free behavior) is caused by instabilities and feedback within the nearshore system. The presence of fluid motion does not introduce any scales, but acts as a catalyst to the process. In the nearshore, a number of possible feedback mechanisms exist. Sand bars may be generated by, and may induce the onset of wave breaking. Similarly, rip channels through a sand bar may be generated by, and may induce alongshore gradients in wave height.

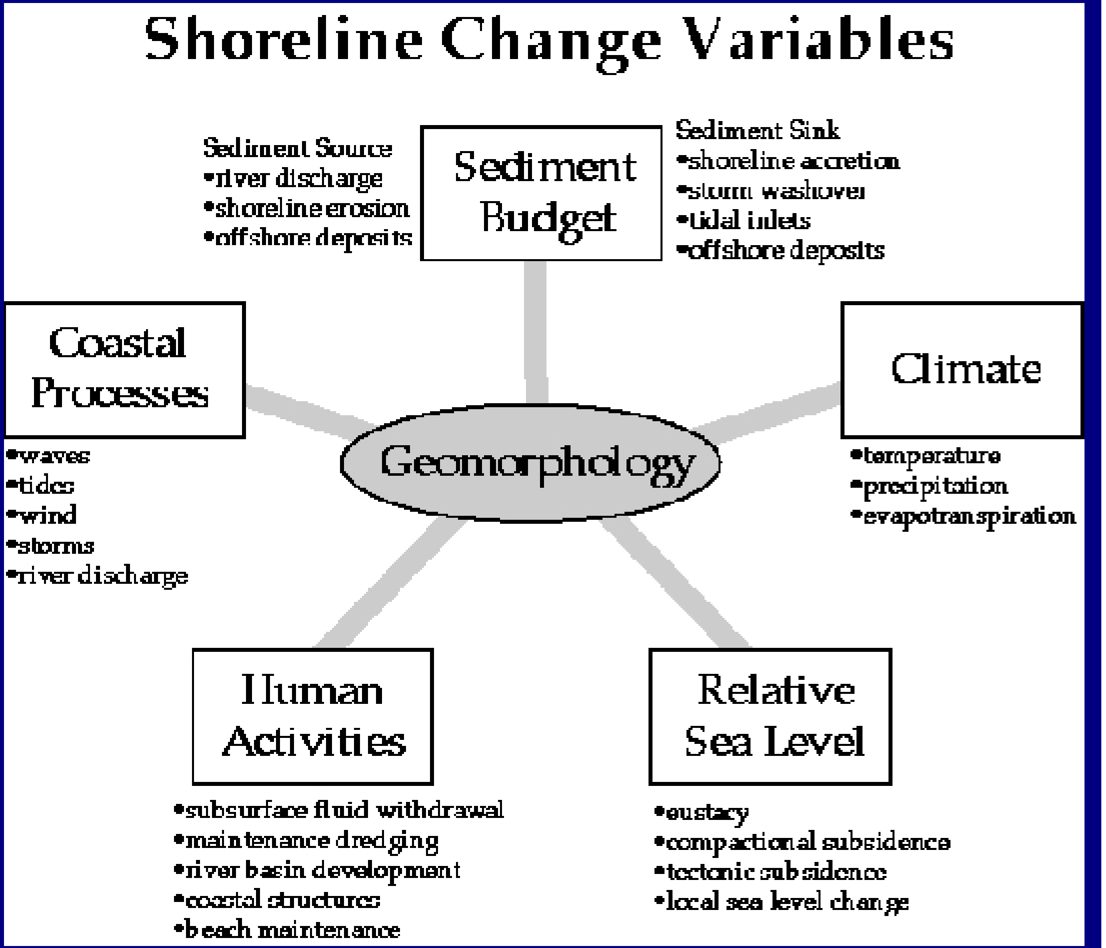

Figure 18. Processes that influence LSCB

When consideration of nearshore behavior is extended to larger scale, many new processes or influences must be considered (Fig. 18). At larger scales the response of the nearshore is also a function of climate, sea level, regional sediment fluxes, and anthropogenic effects.

2. Priority scientific isssues in nearshore processes

1. Fluid and sediment processes in the swash zone

should be studied con-currently within the observations and modeling. A long-term goal is to develop and validate models of wave runup velocities that could provide spatially dense predictions of swash zone flows to drive sediment transport models and to estimate morphological change.

Such models need to account for the effects of bore turbulence, the bottom boundary layer, infiltration into and out of the permeable beach, and longshore currents to predict velocities in the swash zone. Field observations of runup velocities, infiltration, and sediment transport will be necessary to test the models and to determine the importance of these processes on natural beaches.

2. Breaking waves, bottom boundary layers, and associated turbulence

are important to wave energy dissipation and sediment transport, but are not understood well. The breaking of waves in the nearshore zone results in changes of the wave-induced momentum that drive nearshore currents. Breaking wave processes are only qualitatively understood and models are crude. Turbulent wave boundary layers are just starting to be measured in the field using instrumentation with improved spatial and temporal resolution. Observations of these small-scale processes are needed to improve parameterizations used in large-scale models.

Research issues include:

- horizontal and vertical structure of turbulence and vorticity under breaking waves,
- dissipation of the wave energy owing to bubble entrainment during breaking,
- horizontal and vertical distribution of mass flux of breaking waves,
- effects of wind on breaking,
- effects of reflection, infragravity waves, and currents on wave breaking,
- intensity of wave breaking as a function of wave and bathymetric conditions.

3. Wave and breaking-wave induced currents

drive nearshore sediment transport, so understanding these flows is a prerequisite to predicting morphological change. Observed currents contain substantial fluctuations at infragravity periods (approximately 1 minute) that appear to result from a combination of gravity (e.g. edge) waves and vorticity (e.g. shear) waves, but the generation mechanisms and overall significance of these low frequency motions are largely unknown.

To predict nearshore flows for given incident wave fields, and arbitrary nearshore bathymetry, the following issues must be addressed with both observations and models:

- effect of breaking on the frequency-directional distribution and shapes of incident waves,
- role of mixing mechanisms (e.g. shear waves, wave generated turbulence) in nearshore circulation,
- feedback between the time varying circulation (including edge and shear waves) and incident waves,
- effect of complex bathymetry (including bedforms) on nearshore waves and circulation,
- transition from tidally and wind-driven shelf flows to wave-driven surf zone flows,
- three-dimensional structure of mean currents.

4. Nearshore sediment transport

is a nonlinear function of the fluid velocity, and thus highly sensitive to asymmetries in the fluid motion. The results of recent observational research are beginning to provide diagnostic examples of the linkages between asymmetry in the sediment response and asymmetry in the flow.

Research issues:

- predicting bedload and suspended sediment transport under combined wave and current forcing,
- turbulent wave/current boundary layers over 3-D small-scale morphology,
- effects of moving sediment on boundary layer,
- contribution to sediment transport by bedform migration,
- effects of grain size distribution on sediment transport.

5. Morphology

is an important end product that the models will predict.

However, because sediment transport is not understood well, prediction of morphological change is inadequate for most purposes of interest. For example at smaller scales, ripples and megaripples are observed to be ubiquitous, but have not been incorporated into models even though their effect on the flow field (as roughness elements) and sediment transport may be significant. Complex patterns in long-term, large-scale morphology have also been observed. However, models for morphology change have predictive skill only for short-term changes, whereas long-term, large-scale predictions are not yet possible.

Thank you!