The emergence and evolution of the concept "coherent turbulence"

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Abstract. The brief review of the emergence and evolution history of "coherent structure" and "coherent turbulence" concepts in the theory of turbulence is made. The review is based on the data of the world scientific literature and includes some results of the authors' own long-term research on coherent turbulence.

1. Introduction
It is well known that experimental data of turbulence parameters measurements in the different geographical regions and meteorological conditions indicate the existence of large-scale deterministic formations in the turbulent atmosphere – energy-carrying vortices, named "coherent structures" in the world scientific literature. At present, the concepts of "coherent structure" and "coherent turbulence" (a domain with predominance of one coherent structure) are actively used by specialists in the theory of turbulence. Previously, the coherent structures were called "macrostructural turbulence elements" – turbulent formations containing the bulk of turbulence energy. The other terms are also used in the literature: coherent formations, quasi-deterministic coherent structures, correlated (organized) structures, ordered spatio-temporal formations, ordered spatial (eddy) structures, large-scale ordered macrostructures, (self-)organized structures, stable eddy formations, turbulent bodies, coherent (flow) structures, coherent vortex structures, large eddy structures, large coherent eddies, gigantic internal structures, organized structures, etc.

2. Coherent structures and its mixes
The special role of macrostructural elements of turbulence in the energy spectrum of turbulent motions is noted by A.S. Monin (1962 [1]) in the spectrum consisting of four intervals: 1) the region of small wave numbers corresponding to the macrocomponent or averaged fields of wind speed and temperature; 2) interval of macrostructural elements of turbulence, containing almost all the energy of turbulence; 3) inertial interval; 4) dissipation interval. Similarly, the spectrum is represented by P.A. Vorontsov (1966 [2]) for vortices in the atmosphere: 1) the largest vortices in the range of the lowest frequencies, 2) large vortices carrying the main turbulent energy, 3) vortices of the inertial interval, 4) a viscous interval with a small size of vortices. The fact that the main part of the energy of turbulent pulsations is concentrated in large-scale inhomogeneities is indicated by V.I. Tatarsky (1959 [3]). Later, intervals 1 and 2 are combined into single one – the energetical interval or interval of energy [4].
Turbulent vortex structures have been known for a long time. In 1883 O. Reynolds [5] observing a flow in the water tube where the laminar motion turns into vortical, found under the electric spark light in the mass of colours the "distinct curls showing eddies". In 1919 N.E. Zhukovsky [6] pointed to the formation of individual elliptical vortices with centers moving horizontally, in the vortical stream of the river channel at a certain speed. L. Prandtl (1933 [4, 7]) recorded the large eddy structures in flows in channels and pipes. According to H. Dryden [8], in 1938 T. von Karman [9] discussing the measurements of turbulence velocity fluctuations in the channel, expressed the opinion about the existence of a kind of statistical similarity (statistical relationship) between fluctuations at different points in the region; in the subsequent discussion L. Prandtl [7] and W. Tollmien suggested that turbulent fluctuations may consist of two components, one of which is a derivative of the harmonic function, and the other – satisfying the equation of the type of thermal conductivity, i.e., it are non-diffusion and diffusion components. Therefore, one can say with a high degree of confidence that the idea underlying the concept of "coherent structure", that turbulent fluctuations can be represented as a composition of coherent component and random incoherent component, formulated in 1938 in the discussion of the founders of the modern theory of coherent turbulence Prandtl–Karman–Tollmien.

The significant contribution to the coherent structures study was made by A. Townsend (1947–51 [10, 1956]). A.S. Monin (1958 [11]) describes the role of "macrostructural elements" – turbulent formations containing the bulk of the turbulence energy. G.N. Shur (1964 [12]) in aircraft studies of turbulence in the atmosphere have found a deviation of the slope of spectral curves in the inertial interval from Kolmogorov's law −5/3 in the direction of large values, in 1976 [14] have recorded the slope of turbulence spectra with a value of -2.67 = -8/3 (≈ -3), which corresponds to coherent turbulence. Many authors distinguish the special place in the turbulence spectrum for coherent structures (within the energetical interval): A.S. Monin (1962 [1]), P.A. Vorontsov (1966 [2]); N.K. Vinnichenko, N.Z. Pinus, S.M. Shmeter, G.N. Shur (1976 [14]); V.I. Tatarsky (1959 [3]).

The construction of the coherent structures theory at the present stage, according to [4], began from the work of G. Brown and A. Roshko (1974 [15]) on coherent structures. In 1974, The Colloquium on coherent structures in turbulence was held in Southampton. In Russian publications the term "coherent structure" is mentioned in the report (1977 [16]) of E.V. Vlasov, A.S. Ginevsky, R.K. Karavosov on detection of the coherent structure in turbulent jets. At the same time, taking into account the remark of A.S. Monin [4] that "coherent structures" were originally called "macrostructural elements", the date of the first Russian publication on coherent structures, apparently, should be attributed to 1958.

Despite the abundance of publications, it is difficult to indicate the initial date for the term “coherent structure” using, since such a stable word collocation occurs outside the context of turbulence studies in literary sources since at least 1801 [17] and in scientific journals in physics since 1852 [18]. Nevertheless, it can be said with a great degree of certainty that the very idea underlying the concept of “coherent structure”, that turbulent fluctuations can be represented as a composition of a coherent component and random incoherent, was formulated in 1938 in a discussion of Prandtl–Karman–Tollmien — the founders of the coherent turbulence theory [8].

There are many definitions of coherent structures in the literature. For example, H. Liepmann (1952 [19]) speaks of a secondary large-scale structure (superstructure) of turbulent flow. P. Bradshaw (1967 [20]) indicates that large vortices in a turbulent shear flow form a coherent and identifiable group. R. Kaplan and J. Laufer (1968 [21]) noting the increasing amount of confirmations that fully developed turbulent shear flows exhibit a more coherent than usually expected velocity structure, determined the coherent structure as associated with the motion of the interface between the turbulent and non-turbulent fluid. H. Liepmann (1972 [22]) also says that coherent structures are long-lived solitary waves in nonlinear wave theory. Yu.I. Khlopkov, V.A. Zharov, S.L. Gorelov (2002 [23]) defines a coherent structure as a coupled large-scale turbulent liquid mass with vorticity correlated in phase over the entire region of space occupied by the structure. A.S. Monin and A.M. Yaglom are defined [4] the coherent structures as the preferred long-lived nonlinear superpositions of large-scale turbulence components. It seems the simplest definition of a coherent structure (see, for example, [4]). In the first definitions [10], the decomposition of the instantaneous velocity field into coherent large-
scale and random incoherent turbulent components was used: double decomposition. Later, more complex decompositions began to be used (for example, triple decompositions, R.F. Blackwelder (1972 [24]). In accordance with these definitions, turbulence consists of non-random coherent (large-scale) and purely random (small-scale) movements. At the same time, random small-scale movements do not depend on large-scale ones. Random motions are superimposed on coherent ones and usually extend far beyond the boundaries of a coherent structure.

The coherent structures are actively studied at present. The following are under investigation: a near-wall small-scale turbulence, a turbulent convection in the surface layer of the atmosphere in the presence of a wind shear, “cloudy streets” in the atmosphere, "Langmuir circulation" in seas and lakes. The periodic large eddies in engine jets, etc. are also studied. It is shown that in turbulent flows the large-scale ordered vortices are the main energy carriers, they significantly affect the formation of all flow characteristics. It has been established that large-scale turbulent motions are deterministic, i.e. not random. In the studies the various methods of the turbulence visualization are used (usually, a current coloring). However, the resolution of the visualization methods used is small. Therefore, it is possible to accurately register, as a rule, only large-scale components of turbulent flows.

At the same time, as can be seen from our results [25], the energy-carrying vortex (associated with the coherent structure in accordance with its earlier definitions) coherently decays. The process of coherent decay of the major energy-carrying vortex into smaller ones does not terminate in the domain of large-scale (low-frequency) vortices. It continues uninterruptedly into the small-scale (high-frequency) region, up to the size of small vortices that can still exist in air (0.6–1.2 mm [4]). The frequencies of small-scale vortices are multiples of the frequency of the major vortex. The phases of oscillations in these vortices are rigidly connected, and the vortices themselves are coherent (in phase). Therefore, the coherent decay process cannot be limited to the domain of large-scale vortices (as is done on the basis of the old definitions of a coherent structure). In this case, small-scale vortices are dependent on large-scale (from the frequency of the major vortex).

In our works [25] the concept of "coherent structure" was expanded: the hydrodynamic coherent structure is a compact formation that includes a long-lived spatial vortex structure (cell) resulting from the prolonged action of thermodynamic gradients, and the products of its discrete coherent cascade decay. In the extended understanding, the coherent structure is a soliton solution of the hydrodynamic equations (topological three-dimensional soliton, solitary wave). This is either a one-soliton solution or a single soliton in a multi-soliton solution. The coherent structure contains both large-scale and small-scale turbulence. The turbulence resulting from the decay of the major vortex is coherent (in-phase) and deterministic. The frequency of the coherently decaying major vortex is the main feature of the coherent structure. The dimensions of the coherent structure are fuzzy. The currents, which are external to the major vortex, can carry the products of its decay over long distances, forming the long turbulent trail. The lifetime of a coherent structure is determined by the time of action of thermodynamic gradients. Our results also show that the known processes of transition of laminar flows into turbulent ones (Rayleigh-Bernard convection, fluid flow around obstacles, etc.) can be considered as the coherent structures (or sums of such structures).

The coherent structures are important elements for understanding the processes of turbulence formation (occurrence) and further evolution of the turbulence structure. Therefore, in [26, 27], the properties of single coherent structures and the mixtures (sums) of various coherent structures that we previously established are briefly enlisted.

3. Concept of coherent turbulence

The appearance of the term “coherent turbulence” was a natural continuation of a new wave of interest to the coherent structures in the 1960–70s. The use of the new term was noted in the works of A. Michalke and H. Fuchs in 1975 [28], devoted to the processes of the noise occurrence in jets from "large-scale coherent turbulence", as well as in a report by R. Adrian on the detection of "coherent turbulence" in 1975 [29] at the IV-th Symposium on Turbulence in Liquids. The V-th Symposium on Turbulence 1977 was dedicated, among other things, to “... stability and transition in boundary layers,
wall pressure fluctuations related to coherent turbulence, and large-scale turbulent structures in turbulence" [30]. A. Hussain in 1981 [31] notes that "the coherent and background turbulence are uncorrelated", at that, in fact, the background turbulence is created and organized by the coherent structures.

In Russian studies the term “coherent turbulence” ("kogerentnaya turbulentnost" – in Russian) is encountered in 1991 [32]: in relation to the formation of coherent turbulence it has been hypothesized, that although the stability loss of a large-scale flow is the primary source of both stochastic and coherent turbulence, the significant contribution to the formation of the latter is probably made by the self-organization of small-scale turbulence in the process of nonlinear interaction of its elements. L.G. Loytsyansky (1998 [33]) drew attention to the application of nonlinear mechanics methods and the theory of dynamical systems to the description of turbulent processes, to the development of “coherent” turbulence, mentioning in this connection A. Roshko, G.N. Abramovich, A.S. Ginevsky, A.S. Vlasov. In a special monograph by Yu.I. Khlopkov, V.A. Zharov, S.L. Gorelov (2002 [23]) made the interesting and far-reaching conclusion, that coherent structures both create and spatially order the incoherent turbulence, that is, a coherent and an incoherent turbulence are not completely disconnected. L.G. Loytsyansky (2003 [34]), mentioning the relatively new section of the theory of turbulence, devoted to the so-called coherent turbulence, notes that the interaction of large vortices obeys the laws of “coherent turbulence”, which differ from the laws of transfer, as evidenced by the zero coefficient of turbulent viscosity in the experiments. A.V. Kolesnichenko, M.Ya. Marov (2015 [35]), when analyzing the model of coherent turbulence, are adhere mainly to the Landau–Hopf scenario. It should be especially noted the works of M.A. Goldshlik and V.N. Stern (1981 [36] on 1980 report, and 1982 [37]), where the ideas of a new scientific direction – the theory of “structural turbulence” were formulated; at that the essence of the phenomenon lies in the feasibility in the flow field of almost the same deterministic spatiotemporal formation at random intervals in time and space. Given that the presented ideas and concepts in general correspond to the direction of coherent turbulence, the date when the idea of the term has appeared should be attributed to 1980.

The concept of “coherent turbulence” was further developed and detailed in our works [25–43], where the domain of “coherent turbulence” is defined as follows [25]: let there be several coherent structures in some spatial domain. If the size of the major energy-carrying vortex of one of these structures is much larger than the size of the major vortices of all other structures existing in the domain, then this domain is called the domain with the determining influence of one coherent structure or the coherent turbulence domain.

The coherent turbulence (usually 8/3-power-law decrease in the inertial interval, Figure 1) differs from the Kolmogorov (5/3-power-law decrease, Figure 2), first of all, by the faster decrease of the frequency spectrum of the temperature fluctuations in the inertial interval and a smaller contribution of high frequency components (small-scale eddies).

![Figure 1. The frequency spectrum of temperature fluctuations. Coherent turbulence, Sayan solar observatory. Near the surface, 29.09.2013](image1.png)

![Figure 2. The frequency spectrum of temperature fluctuations. Kolmogorov turbulence, Sayan solar observatory. Near the surface, 14.08.2014](image2.png)
As it turned out [25], Kolmogorov turbulence is a mixture of different (and similar in size) coherent structures with incommensurable frequencies of the major energy-carrying vortices.

The real atmospheric turbulence can be considered as mix of various coherent structures with incommensurable frequencies of the major energy-carrying vortices [25]. If in one coherent structure the family of decay vortices (products of cascade disintegration) is coherent (in phase), then at mixing of different coherent structures with incommensurable frequencies of the major vortices the elements of one family will be non-phase (incoherent) elements of another family. Therefore, the turbulence that occurs when the different coherent structures are mixed (with incommensurable frequencies of the major vortices) is naturally to call incoherent. However, if we consider the domain with one coherent structure, the family of decay eddies in which (products of cascade disintegration) is coherent, then such a turbulence is natural to call coherent.

It is possible to express the concepts "coherent turbulence" and "Kolmogorov turbulence" also in language of the spectra of the turbulent motion parameters. The concepts thus formulated are consistent with the previous definitions and specify (concretize) thereof.

So, for example, in [25] it is established that experimental spectra of really observed atmospheric turbulence are the sum of the spectra of individual coherent structures of different sizes (with various outer scales). At identical intensity of turbulence the curve corresponding to an inertial interval of a one-dimensional spectrum of turbulence is the upper envelope of all the spectra of different coherent structures having various outer scales of turbulence.

If the difference between scales is small, then the sum of the spectra of different coherent structures in the inertial interval practically does not differ from Kolmogorov 5/3-degree dependence. Such a turbulence corresponds to the type of turbulent motion by A.N. Kolmogorov [13]. As can be seen, the Kolmogorov's turbulence represents the mix of the various (and close sizes) coherent structures with incommensurable frequencies of the major energy-carrying vortices. According to the above-stated definitions, the Kolmogorov turbulence is incoherent turbulence.

If the difference between the scales is large, then the sum of the spectra has a deep "dip" in which the one large coherent structure "manifests" with 8/3-degree spectrum decrease. The turbulence in this case corresponds to turbulence in one coherent structure; it has the name "coherent turbulence". The coherent turbulence is one family of decayed coherent (in phase) eddies – the products of cascade disintegration of one major energy-bearing eddy.

In general, if in the considered domain the coherent structures have similar dimensions and are "well mixed", then turbulence isotropy described by the Kolmogorov spectrum is observed (Kolmogorov's turbulence [13]). If one of the coherent structures is significantly larger than the others (or the structures are significantly removed from each other), then there is anisotropy of turbulence described by the spectrum of coherent turbulence.

In comparison with Kolmogorov's turbulence, the coherent turbulence is significantly reduce the phase and weak amplitude fluctuations of optical radiation propagating in the atmosphere [25]. Therefore, the information on the occurrence conditions of the atmospheric coherent turbulence is necessary to predict the propagation of optical waves and radio waves (Figure 1).

4. Summary
In conclusion we briefly discuss the issues of local turbulence structure [25]. The local structure of turbulence is understood as the hydrodynamic regularities of turbulent motions within some volume. In other words, the local structure of turbulence is the "internal arrangement" of turbulence in the volume. The local structure of turbulence as it becomes clear is strongly related to the concepts of "coherent structure" and "coherent turbulence". And these concepts are directly related to the physical mechanisms of the turbulence formation. Thus, for example, from the analysis of the properties of coherent structures and its mixtures it is established [25] that the coherent structure (in the extended definition), despite its complex internal structure, can be considered as the basic structural element of which the turbulence consists. This conclusion clarifies the local internal structure of turbulence.
The more detailed review of the origin and evolution of the concepts of "coherent structure" and "coherent turbulence" is given in [25] according to the world scientific literature.

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