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PhD in Environmental Fluid Mechanics

Fluid Dynamics Constrains Affecting the Atmospheric Vortices

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Mesocyclones and Tornadoes are intense atmosphere vortexes and are important in human's activities because they are often associated with the most large and dangerous wind speeds. Moreover mesocyclones are often associated with heavy precipitation and horizontal wind speeds larger than $U \approx 25 \quad ms^{-1}$ while tornadoes have horizontal velocities larger than $30 \quad ms^{-1}$ up to $120 \quad ms^{-1}$ (see, [8] and [9]). The (thermo)dynamics of these phenomena is still not completely understood and, nowadays, it still represents a major scientific challenge because mesocyclones and tornadoes high vorticity concentration often springs out from initial conditions characterized by low vorticity. Moreover, from the forecasting point of view, the predictability of these phenomena is still quite poor even if some phenomenological diagrams have been developed (e.g., CAPE-SHEAR diagrams) but their effective forecasting realiability in different climatic areas is still a matter of debate,(among the wide literature [6] and [5]). In this work, a theoretical and analytical investigation on mesocyclones and tornadoes is presented; the aim is to provide a better understanding of mesocyclone and tornado genesis (i.e., vorticity intensification), keeping in account the variability of atmospheric mesoscale and micro-scale fields. Even if complex three-dimensional numerical models are naturally more realistic in their representation of mesocyclones and tornadoes, the dynamical explanations of how vortices intensify within them is still based on relatively simple conceptual models that fit numerical results and diagnostic computations [7]. Furthermore, in this work, we try to provide a theoretical validation of the most commonly used forecasting parameters and schemes.

The two initial chapters of this thesis are devoted to the topic introduction and review (Chapter 1 and Chapter 2) while from Chapter 3 to Chapter 6 a theoretical interpretation of the most adopted phenomenological forecasting parameters used for tornadic supercell forecasting is presented, starting from the general equation of motion. Indeed, there are a lot of phenomenological schemes usually adopted in tornado forecasting, [15], but each of them misses a theoretical model able to explain their frame of validity and complex behaviour. In order to provide a theoretical model, this work starts (Chapter 3) from the general equations of motion (Navier-Stokes equation) and from the work of Lilly [10] to construct a suitable representation by which it might be possible to *a)* describe the intense dynamics of such phenomena; *b)* reduce the set of variables to a minimum sub-set useful for frecasting purposes. In particular, a remarkable point is represented by the construction of a buoyancy equation that takes into account the ice, vapor and liquid phase of water (Section 3.5). Furthermore, a decomposition of velocity and buoyancy fields in a mean and perturbated state is performed: the mean reference state is associated to a basic state of our troposphere, while the perturbative state refers to an initial rotating velocity profile that evolves in time. The newly developed equations are reported in Section 3.6.

During this phase, attention is focused on the formation of tornadic supercells (i.e. tornadoes that are originated by a pre-existing supercell); then, with the use of an appropriate scalar potential, the initial perturbative velocity is able to represent the initial supercell rotating velocity (Section 4.2). Furthermore, a vertical average over all the tropospheric depth is introduced to obtain in the equations the usual forecasting parameters (Section 4.4 and 4.5). The final result is a non-linear adimensional equations system (Section 4.9) in which the vertical average of perturbative velocity and buoyancy are the new unknown fields. Furthermore, this set of equations contains three quantities that can be assumed as CAPE (Φ) and the two component of mean shear (α and β).

Two point of caution are necessary in the use of this set of equations. First of all, to obtain a close set of equations for the new vertical integrated variables, it is necessary to impose vertical uncorrelation in the fields, i.e. the average of the product of two quantities is the product of their mean values. Furthermore, the forecasting parameters (predictors) are the result of the vertical integration of the Lagrangian quantities (e.g., CAPE is the vertical integrated parcel buoyancy). The connection between the vertical average of Eulerian and Lagrangian quantities is not straightforward (Section 3.6); this introduces a certain degree of approximation when a comparison with real data is performed (Section 6.5). The net effect of the two above mentioned approximations is that the proposed theoretical model should be used only in a restricted appropriate way. It is not devoted to explain the complex evolution of tornado but only its initial stage of life, i.e. the conditions in which an intense small scale rotating phenomena begins to form from a rotating tornadic supercell system in a fixed pre-storm environment characterizated by specific values of mean shear and CAPE.

Through the above developments, the problem of tornado-genesis is then mapped into a problem of non linear stability of a rotating supercell system in a fixed pre-storm environment. In Chapter 5 this stability analysis is developed. Tornadoes are intense and small scale events compared to mesocylones: their velocity profiles (and then their vorticity) are associated to high wave-number component in the Fourier space (Section 5.1). Another key ingredient is the presence of small scale perturbations in our system (Section 5.2): the importance of small scale variability of atmospheric fields seems to be confirmed by recent works discussed in [13], [14] and in recent events like that of 8th August 2008 in Grado (Italy) where a pre-existing mesocyclone crossed a strong horizontal temperature gradient between sea and the hinterland (Stel and Giaiotti, article in preparation). Resonant interaction theory (for more details see [4]) permits to describe the non-linear resonance mechanism in which small large-scale component of vorticity field (associated to mesocyclones) and small small-scale perturbations are able to generate high wavenumber vertical vorticity components (Section 5.4). Tornadoes are small scale intense peaks of vertical vorticity, then it is possible to consider that the instability of high wave-number components of vertical vorticity is related to a tornado formation (Section 5.5). The instability of high wave-number component of vorticity fields is connected to the stability of the solutions of a Poincare Map (Section 6.3). In section (Section 6.4) it is then shown that the formation of an intense peak of vertical vorticity is possible only when the environmental parameters are linked by the following relationship

$$4\frac{HD}{\sigma^2}\frac{CAPE}{U^2} = r = 1, 3, 8, 15, 25\ldots = n^2 - 1 \quad \text{with} \quad n > 0, \quad n \in \aleph \quad (1)$$

in which σ is the horizontal scale lenght of the supercell, D is the vertical scale lenght of the system, and U^2 is the squared modulus of the mean velocity of pre-storm environment. H is the typical vertical height of troposphere connected to vertical density gradient. We have chosen to fix it as $H = 8550m$ following [3]: this values fits very well the usual condition of standard USA tropospheric condition (see page 56 of [3]).

Equation (1) is a new remarkable results. Indeed, the set of equations (1) gives a theoretical explanation of the usual scheme Shear-CAPE or VGP (see, among others, [15], page 1156) usually used for tornado forecasting. Furthermore, the difficulty of the identification of thresholds in Shear-CAPE diagrams for tornado events can be understood with the correction of Shear-CAPE diagrams by the supercell parameters contained in (1). Finally, the bulk-Richardson number (the ratio between CAPE and squared modulus of mean wind) appears in the set of equations (1). The bulk-Richardson number is an important parameter also for the study of storms evolution (see among others [16]) since it has been shown that this quantity determines the evolution of a single storm in multi-cell storm or supercell. This PhD thesis suggests that bulk-Richardson number could be able to discern the evolution of supercell to its tornadic phase. Finally, in this work, the developed theoretical model has been tested with the aid of a tornado database. Even if the comparison between the parameters present in the theorethical model and radiosounding derived parameters is sometimes difficult (Section 6.5) and should be matter of further work and discussion, there is a strong signal on the validity of the theorethical model results shown in (1).

While in the first part of this work the formation of intense and circumscribed vertical vorticity ("vorticity spot") is originated by the interaction of a supercell system with an external perturbation. In the second part of this work another mechanism for the formation of the vertical "vorticity spot" is investigated. Indeed, starting from the vertical vorticity equation, (section 7.1), through the wavelet analysis technique (for more details see [1]) it is shown how formation of vertical vorticity and velocity anomalies are able to create intense vertical vortexs. This happens when these spots are located in the same real space position and they have a similar shape, i.e. when the product of their wavelet transform grwos in time ("resonant wavelet assumption"). These anomalies could be connected to the non-linear dynamics of supercells (and not only to an external forcing) and, because of the impossibility to analytically describe the full non-linear behaviour of a supercell, the use of an high resolution numerical model is required for the simulation of these phenomena. In this work the WRF (weather research and forecasting) model is used and the ideal supercell case is simulated using the pre-storm conditions of two real supercell tornadoes (section 7.2). A suited choice of the parameterizations of WRF model has permitted to reach an horizontal resolution of $100m$ even if the preliminary results (Chapter 8) show that the numerical model is not able to realistically dissipate small scale fields. In particular, the formation of high spatial variability in the velocity field during the early splitting stage of supercell is responsible of the instability that propagates in all the simulation domain. This instability affects the validity of the results (in particular for vorticity fields, which is a derived quantity) and the instability propagation is faster when the horizontal resolution decreases (section 8.4). The problem of small scale dissipation, then, does not permit the check of the "resonant wavelet assumption"; a better understanding of WRF parameterizations (and in particular of Smargorinsky closure scheme) for high resolution simulation is required.

In the third part of this work the physical reasons for the importance of rotation in updraft is investigated. Previous works (see among others [11] and [12]) show how such phenomena are associated to high value of helicity and this could be an explanation of their longevity. In fact, other works (see [2]) observe how helicity inhibits the energy transfer from large to small scale, increasing the longevity of high helicity structures.

Starting from these two facts in this work we tried to test the idea that the perturbation of a steady fluid dynamics system will evolve in such a way to preserve its energy and the mean energy from the turbulent kinetic energy dissipation. To achieve this result, the perturbation transforms itself in order to maximize the time variation of helicity fields. Indeed, the perturbation extracts energy from the mean state and the new state will be that with the configuration that better "safeguard" the perturbation mean energy. This configuration delaies in time the transfer of energy from the ordered large scale to disordered small scale. This assumption is very general and it seems to be confirmed in the case of supercell evolution.

The important result is then that, under this point of view of atmosphere evolution, supercell shape is the best configuration to conserve energy from turbulent dissipation. This is a possible explanation of why rotating updrafts are so common in atmosphere. Furthermore, the maximization of helicity, is able to give some hints on the meso-anticyclones and anticyclonic tornadoes formation because they should be connected to negative helicity formation (Section 9.2). Further exploration of this topics is neded to confirm the preliminary results.

As a final point another attempt to apply a general principle of fluid mechanics on small scale intense vertical atmospheric vortexes is made. In particular, if the maximization of the time variation of helicity volume integral holds, then this fact might be applied at every scale of the fluid. In other words, fluid systems evolve in such a way to maximize the time variation of helicity at all scales in its internal structure. If this is true, we will have the possibility to obtain a law that drives the transfer of helicity from one scale to another (Section 9.3). This law should be able to explain why specific environments are favourable for the formation of intense and local vortexes like tornadoes.

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