A probabilistic prediction scheme for wake vortex evolution in a convective boundary layer

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Abstract

A simple probabilistic prediction scheme for wake vortex behaviour in a convective boundary layer is proposed. Large eddy simulations (LES) of wake vortices (WVs) in an evolving convective boundary layer serve as a test bed to investigate the performance of an engineering WV model which is forced by virtual measurement systems placed in the LES domain. The basic principles of the WV model are taken from literature. We consider a meteorological tower and a profiler from which the input data for the WV model are computed. The stochastic nature of turbulence requires both time and space averaging of wind and temperature data which in consequence leads to statistical WV forecasts. It is shown that both virtual measurement systems yield conservative predictions of WV trajectories. The predicted circulation is within the range analyzed from LES data. Operational aspects of our simple approaches are discussed.

1 Introduction

Wake turbulence is one of the main reasons for capacity problems in air- transport industry. The lift force exerted on aircraft wings produces two counter rotating vortices with long life-times in their wake. Especially during an aircrafts critical landing phase these can endanger any aircraft following close behind. The follower aircraft must therefore maintain a prescribed safety distance from a landing aircraft ahead. The separation regulations are weather independent even though atmospheric conditions may often favour a rapid decay of WVs such that the separation matrix for aircraft of different weight classes is probably often overly conservative (Gerz et al., 2001, Hallock et al, 1998).

In order to increase airport capacities wake vortex prediction systems were designed to reduce separation standards (Gurke and Lafferton, 1997, Hinton et al., 1999). Real-time wake vortex (WV) models are supposed to predict the appropriate aircraft spacings for approaching/landing aircraft along the glide path depending on weather. There is no potential WV hazard if the WV is transported out of a predefined safety corridor by its self-induced descent and/or by advection through cross wind, or if the circulation of the WV has reached a harmless level.

The knowledge of the atmospheric background conditions along the glide path is decisive for the successful prediction of the decay and transport of a WV. However, limited meteorological measurements are available operationally at an airport. Even if a wind profiler is available the measurements may not be representative for the whole glide path due to for example orographic features.

An inherent problem arises from the fact, that meteorological variables are typically time and/or space averaged such that the time scale relevant for a wake vortex ($\tau \approx 2$ min) is not directly available. This averaging of measured data is often required in order to reduce the statistical error of the measured quantity. The required averaging interval depends on the statistical moment of interest (i.e the mean, variance or turbulent flux; see e.g. Lenschow et al. 1994). These aspects apply particularly to a CBL where it is difficult to measure and impossible to predict updraft regions in real time, which might transport only parts of a WV. The nature of turbulence can only be described by statistical means. Therefore, a statistical approach from which forecasts of wake vortex residence probability and circulation can be obtained is required.

The current investigation is based on large eddy simulation (LES) of wake vortex evolution in a convective boundary layer (Holzäpfel et al., 2000). The LES data serve as a test bed to assess the quality of a engineering WV prediction model with respect to the availability of meteorological parameters assuming an operational environment with different meteorological sensors. For the WV predictions, we use a simple WV transport and decay model based on Greene (1986) and Corjon and Poinsot (1996). The main advantage of LES data is the high spatial and temporal resolution of transport and decay of WVs, and the realistic representation of the atmospheric state against which the WV model can be systematically validated. Furthermore, the characteristics of a CBL are well understood and LES have been applied successfully to this type of boundary layer in the past (e.g. Schmidt and Schumann, 1989). In this study we consider an evolving CBL.

A CBL has been previously considered as a potentially dangerous situation in terms of WV risk. It was assumed that the strong coherent updrafts may cause the stall or even rising of WVs. However, the detailed study of Holzäpfel et al. (2000) shows that the CBL turbulence rapidly erodes the WVs which leads to rapid decay of the WVs to presumably harmless levels within about 60-70 seconds, which roughly corresponds to a separation of 2.5 - 3 nmi for approaching aircraft. The statistical WV predictions will be evaluated based on the latter findings.

The results presented in this study are of special interest since little work has been carried out to quantify the uncertainties of simple model approaches against realistic and controlled meteorological conditions. This does not devaluate model validations against field observations which are still necessary (e.g. Robins and Delisi, 1999). However, comparisons between model predictions and observations are often not conclusive because of inherent uncertainties of WV and meteorological measurements.

In the following we first consider the properties of a convective boundary layer (section 2) and briefly describe the engineering WV model (section 3). Different approaches to sample the meteorological data base are introduced in section 4. The processed meteorological data which are the output of these approaches force the WV model. Results of these WV model runs and sensitivity tests are presented in sections 5,6 and 7. Implications are addressed in section 8. Operational aspects are discussed in section 9.

2 The convective boundary layer

A convective boundary layer is associated with strong surface heating and near zero wind speed. Buoyancy is the main production term of turbulent kinetic energy and, therefore, is largest near the surface. The relevant scaling parameters are the boundary layer depth z_i and the free convection velocity scale w_* (e.g. Stull, 1988).

The LES of the wake vortex evolution in a CBL[1] that is briefly introduced here is described in detail in Holzäpfel et al. (2000). To achieve an appropriate resolution of both the characteristic scales of the CBL and the wake vortices a domain size of $L_x = L_y = L_z = 512m$ with a grid volume of $\Delta x \cdot \Delta y \cdot \Delta z = 8 \cdot 2 \cdot 2m^3$ was chosen. The flight direction is denoted by x, the span by y and the height by z. Periodic boundary conditions are employed in the horizontal directions. At the top of the domain free-slip conditions and at the bottom no-slip conditions were prescribed. The surface heat flux is set to 250 W/m^2. Because of the rather small domain size, only an evolving CBL can be realized. Nevertheless, the main characteristic flow features of a CBL are resolved. In nature, the scale of the largest eddies in a stationary CBL is on the order of 1 km.

Three wake vortex pairs were superimposed on the turbulent flowfield at three selected locations of the domain (`Figure 1`). The left part of vortex pair (12) was placed on the shoulder of an updraft (y =209m, z = 404m) and the right part is situated in a quite homogeneous low-turbulence downdraft area to determine maximum lifespans. The second vortex pair (34) was superimposed on a region that covers a strong updraft, a moderate downburst and a rather calm area (y = 386m, z = 222m) to examine the effects of axially varying conditions. The third vortex pair (56), placed on low altitude (z = 64m, y =132m) allows to investigate ground effects. The three vortex pairs are sufficiently separated from each other such that mutual influences can be neglected.

The wake vortices were initialized as the superposition of two Lamb-Oseen vortices

$$v_t(r) = \frac{\Gamma_0}{2\pi r}\left(1 - \exp\frac{-1.26r^2}{r_c^2}\right) \qquad (1)$$

representing the B-747 aircraft with a root-circulation of Γ_0 =565m^2/s, a vortex spacing of b_0 =47m and a unrealistically large core radius of r_c = 8 m. It is shown by sensitivity studies and a literature review that the choice of the core radius does not influence the behaviour of a WV in a CBL significantly (Holzäpfel et al., 2000). Crow linking is not the relevant mechanism in the LES because of the high level of turbulence Sarpkaya, 1998)..

From the CBL velocity field, prior the superposition of WVs, we compute horizontally averaged profiles of the turbulent kinetic energy (TKE), $e = 0.5 \cdot (u'^2 + v'^2 + w'^2)$, and the standard deviation, σ , of the velocity components u, v, w (`Figure 2`). The primed variables denote deviations from the mean.

Although the convective cells of the CBL are still growing, the vertical profiles of standard deviation and TKE agree well with observations of a stationary CBL (Stull, 1988) which are: (a) the quasi constant vertical profile of the horizontal velocity variances in the mixed layer; (b) a peak of the vertical velocity variance at 0.3-0.4 z_i ; (c) a peak of e near 0.3-0.4 z_i in the mixed layer. Close to the surface we find a second peak of e due to buoyancy production.

3 The wake vortex transport and decay model

The wake vortex model used in this study is based on Greene's model (1986) whereas the formulation of ground effect and the kinematics of the interacting vortices are adopted from the model VORTEX by Corjon and Poinsot (1996). The wake vortices are modeled as point vortices that are advected by the local wind throughout the simulation run. Wind differences sensed by the individual vortices cause variable spacing b , vortex tilting and individual decay rates. Herewith, the turbulent wind data from the LES induces dispersion of the vortices. In the model runs Tower and Profiler (see next section) both vortices are advected by the same wind which excludes vortex tilting. The WV model is briefly introduced in the following:

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[1] The animated simulation can be found at http://www.pa.op.dlr.de/wirbelschleppe/conv.html.

Initial conditions are given by the initial root circulation Γ_0 and the vortex separation b_0. Furthermore, the location of the vortex pair at time t=0 s must be prescribed. Circulation decay of the individual vortices $i = 1,2$ is parameterized according to

$$\frac{d\Gamma_i}{dt} = \frac{d\Gamma_i}{dt}\Big|_{viscous} + \frac{d\Gamma_i}{dt}\Big|_{turbulence} \tag{2}$$

where $\Gamma_1 = -\Gamma_0$ and $\Gamma_2 = \Gamma_0$. Vortex 1 corresponds to the right vortex seen in flight direction. The viscous diffusion of Γ_i is

$$\frac{d\Gamma_i}{dt}\Big|_{viscous} = -1.045 w_{s,i}^2 C_D \tag{3}$$

with a viscous drag coefficient $C_D = 0.2$ and a propagation speed $w_{s,i}$. Although the formulation of a viscous decay in terms of a viscous drag on the wake oval is not rigorous and is, in fact, controversial (Sarpkaya 2000) it may well represent decay rates which are observed in quiescent atmosphere. For example, it may simulate the effects of aircraft induced turbulence which is entrained into the wake vortices (Holzäpfel et al., 2001).

The decrease of Γ_i due to turbulence is parameterized as

$$\frac{d\Gamma_i}{dt}\Big|_{turbulence} = -0.41 q \frac{\Gamma_i}{b} \tag{4}$$

with a turbulent velocity scale $q \equiv (2e)^{1/2}$. Overbars denote time or space averaging. The original coefficient of 0.82 has been set to 0.41 based on recent investigations (Robins and Delisi, 1999). Note that the variable vortex spacing in equations (4) affects the decay rates.

The trajectories of the vortex pairs are calculated following the formulations given in Corjon and Poinsot (1996). In the following advection of WVs in axial direction is neglected.

4 WV runs and sampling approaches

Four different approaches, termed Tower, Profiler, BestMet, BestMet stats, to sample the meteorological input data to the WV model are applied. In the subsequent sections, WV predictions based on these four approaches are compared against the WV evolution from LES. For all approaches the inital WV positions are prescribed as in the LES WV positions

Tower:

The approach Tower assumes that an meteorological tower equipped with anemometers at $z = 16$ m is available. From the LES data we compute the standard deviation σ_u and σ_v in a horizontal plane at $z = 16$ m. The standard deviation σ_w is approximated as $\sigma_w \approx (\sigma_u^2 + \sigma_v^2)^{1/2}$. This approximately assumes that the absolute value of the predominantly horizontal velocity fluctuations near the surface has about the magnitude of the vertical velocity fluctuation in the mixed layer where the fact is employed that boundary layer scale coherent structures dominate the dynamics of the CBL (`Figure 3`). In the WV model, the standard deviations σ_u and σ_v are treated as velocity components which advect the wake vortex in vertical and lateral direction without mean wind. Furthermore, the horizontally averaged value of $q = 1.57$ m/s is computed from the LES field at $z = 16$ m. This value is considered as an upper limit for what we expect in this CBL because the TKE is produced near the surface by buoyancy effects (see also `Figure 2`).

Profiler:

The approach Profiler assumes that a wind profiler is available which measures profiles of turbulent fluctuations. The vertical profiles of the standard deviations σ_u, σ_v, and σ_w and the TKE profile from LES determined by horizontal averaging are input to the WV model (see `Figure 2`).

BestMet:

The velocities u, v and w at the location of the WV, and a domain averaged q or alternatively q in a domain around the actual location of the WV are used as input.

BestMet stats:

q, u, v and w at the location of the WV are used as input. For this approach we choose the same initial height level as used in the LES and start the WV model at all possible positions on this initial z-plane. This approach explicitly considers the spatial variability of the meteorological variables.

Both approaches Tower and Profiler consider the effect of time/space averaging by applying standard deviations. During a WV model run the meteorological profiles are kept constant. To take into account the fluctuating nature of the advection velocities four subsequent WV model runs with all combinations of positive and negative sign of the standard deviation are performed ($\pm\sigma_w$ and $\pm\sigma_u$). These four runs define a corridor in which the WV are expected to be located. Near the surface a simple log law is assumed in order to ensure the no-slip condition.

The subsequent analysis will focus on the predicted vertical dispersion and circulation of WVs as function of time. The WVs in ground effect will not be discussed further.

5 Perfect meteorological input data

The approach BestMet can be viewed as the case where meteorological data is directly available at the location and during the whole lifetime of the WV, which is typically not the case in an operational environment. No spatial or temporal averaging is involved for the velocity components advecting the vortex. q is computed in a sub-domain containing the WV (see next section for more details). The comparison of the LES results with the WV model prediction allows the evaluation of the parameterization of the WV decay and transport model. We assume that the WVs experience the same meteorological fields as the WVs in the LES.

A first qualitative impression on the predicted spatial variability of the WV location can be obtained from `Figure 4` where the LES and WV model results of the BestMet approach are compared. Each symbol represents the position of the WV in a plane perpendicular to flight direction. A comparison of the two plots indicates that the WV model predicts larger spreading.

This is substantiated in `Figure 5` where the average vertical positions predicted by the WV model (represented by the median) agree very well with the LES position for both vortex pair 12 and 34. The maximum predicted vertical dispersion and in particular the rebound of WVs is overestimated. There is a slight underestimation of WV descent for WV 12 (which can be considered as a conservative feature) and a good agreement for WV pair 34.

Most likely, the dispersion of the WVs is overestimated because the WV model treats WVs as independent point vortices without taking into account that WVs are coherent structures which in part may resist the dispersion by variable advection velocities.

The corresponding prediction of circulation is shown in `Figure 5`. In the LES, the circulation Γ_{5-15m} has been determined over a radii interval 5 to 15 m. Such a definition is especially appropriate when numerical predictions are to be compared to field measurements due to several reasons: intermediate radii are reliably accessible by all data sources and the averaging of Γ over a radius interval reduces the scatter in turbulent vortices and enables estimations of disintegrating vortices; Γ_{5-15m} correlates well to effects of potential wake encounters (Hinton and Tatnall, 1997). This average circulation value is proportional to the rolling moment a following aircraft experiences in case of an encounter. In the engineering WV model the definition of circulation is not explicitly given (see Holzäpfel, 2001 for more details)

Here, WV pair 12 is on average in good agreement with the LES results for the first 60 sec. In the LES, a rapid decay phase due to mutual instabilities starts at approximately 60 s which is not captured by the WV-model. This in turn causes an underestimation of circulation decay, which is even more pronounced for WV pair 34. The underestimation of circulation decay may be considered as a conservative feature. The increasing range of Γ with time in the LES implies that the fraction of sections where the original vortex is coherent decreases, while these coherent parts still have considerable circulation.

In general, from LES we find two phases of circulation decay. The first phase has a diffusion type decrease of circulation which is followed by a rapid decay phase. This rapid decay phase is typically found at ≈40-60 s for the CBL case and is governed by 3-D instability mechanisms. The WV model prediction follows the diffusion phase very well. However, the rapid decay phase is not reproduced by the WV model since it has a diffusion type decay parameterization which does not account for the decay of vortices due to 3-D instabilities. In consequence, we find that the circulation is always overestimated once the 3-D phase has started. This overestimation is conservative from an operational point of view which on the other hand may lead to a loss of a possible capacity gain. Similar features of circulation decay are found for WVs in turbulent, stably stratified and sheared atmospheres (Holzäpfel et al. 2000, Proctor and Switzter, 2000, Holzäpfel et al. 2001a,b).

Note, that these results show the conservative WV prediction of the WV model as a consequence of the parameterization of the wake vortex transport and decay since uncertainties in meteorological data are essentially eliminated.

6 Sensitivity to TKE variability

This section investigates the impact of spatial TKE variability on the prediction of vertical WV dispersion and circulation decay. We perform runs with the WV model by taking an average constant value of q =1.00 m/s and compare these results to runs where q is computed in an rectangular area with size $(b(t)+12)\times(b(t)+12)m^2$ around the current WV position so that the local state of turbulence is directly considered. For the initial conditions we follow the BestMet approaches. In both cases the WV is advected by the local velocity components determined from the LES data.

The histogram of local q values used in the WV model during the BestMet run for vortex pair 12 shows the variability of q in `Figure 6`. The mean for this data is $\overline{q}=1.03$ m/s, the median is $q_{med}=1.04$ m/s and the standard deviation is $\sigma=0.39$ m/s.

From `Figure 7` we find that the impact of TKE variability on the vertical dispersion of the WVs is negligible for both vortex pairs. Naturally, the differences are larger when looking at the circulation decay. The variability found in the runs with constant q is due to the parameterization of turbulent decay which is dependent on the variable vortex spacing b. Nevertheless the differences between these two approaches appear small considering the median of Γ. The differences between the minimum and maximum Γ curves are larger due to the different Γ decay rates for variable q. These results suggest that a single average q can be used in a WV model run without a substantial loss in prediction quality.

The vertical WV dispersion range for the BestMet stat approach is slightly larger as for the BestMet approaches discussed in this section (not shown).

7 VORTEX runs with mean meteorological quantities

In this section we investigate the predictive capabilities of the approaches Tower and Profiler. Similar to the previous section we will consider the temporal evolution of z and Γ.

Both the predicted vertical dispersion of the two simple approaches cover the vertical WV range analysed from LES in a conservative manner (**Figure 8**). The Profiler approach is closer to the LES results due to the vertical information on the meteorological quantities. The vertical difference between the Profiler approach and LES at t=60 s is about b_0 for both WV pairs. This time corresponds roughly to a separation of 2.5 nmi (minimum radar separation) between generating and following aircraft assuming a true airspeed of 70-75 m/s. The WV model predicts parts of the WV at or above the originating level. If this poses a danger to Abbildung 1a following aircraft depends on the circulation and on the flight path of the follower. We can consider a safety corridor with dimensions of +/-60 m in lateral direction, +/- 40 m in vertical direction (120x80 m^2). These dimensions are chosen according to the expected accuracy of approaching aircraft to follow the glide path (Frauenkron et al., 2001). Parts of both WV pairs are found in the safety corridor at t=60 s based on the Profiler approach whereas in LES, only sections of WV pair 34 are still in the safety corridor. At the same time WV pair 34 has decayed substantially which can be seen from the joint frequency distribution of z and Γ at t=60 s in **Figure 9**. There, we find only a small fraction of the WV stay above the originating level with a strength of about 0.25 Γ_0 or even lower.

The prediction of Γ as a function of time is shown in `Figure 8`. The diffusion type decay regime is well captured by the two approaches. The decay is significantly underestimated for both WV pairs once the rapid decay phase starts. Latter is initiated quite early for WV pair 34. Note, that the vortex spacing is constant during a WV model run for the Tower and Profiler approach which explains why the Γ curves in general are close together.

8 Discussion

The Tower and Profiler approaches provide a statistical prediction of the WV residence corridor. A direct comparison with the LES result may be problematic since it represents just one realization of WV evolution starting from a particular position, whereas the Tower and Profiler results are thought to represent the expected residence corridor for WVs starting anywhere in a plane of constant height. However, the WVs were intentionally placed at characteristic positions in the CBL such that the critical situations associated with e.g. an updraft region could be investigated. They are expected to include the limits of WV behavior ranges in the CBL.

The use of σ_w to advect the WV implicitly assumes a Gaussian distribution of w'. However, it is well known that the distribution of w' in a CBL is skewed (e.g. Stull, 1988). The consideration of just the standard deviation neglects the tail of the implied Gaussian distribution and more over does not account for the skewed distribution. The results shown in this section demonstrate that this simplification still leads to conservative WV prediction of vertical dispersion. As discussed in section 5, this can be attributed to the conservative parameterization of WV transport and decay in VORTEX which compensates for the simplified consideration of the meteorological parameters.

Since we have considered an evolving CBL the question remains to what extend the results can be generalized. The profiles of TKE, σ_u, σ_v and σ_w are in principle in agreement with observations of a fully developed stationary CBL. However, depending on the boundary conditions different length scales of the main transporting eddies and variable turbulence levels are expected. The surface heating applied in this study is moderate. The turbulence levels are expected to be larger with increasing surface heating which would support a more rapid decay of WVs. We believe that the main features of WV transport decay will not change if we would consider a stationary CBL.

In the above analysis we implicitly assume horizontal surface homogeneity. Only with this assumption it is possible to predict WV corridors along the glide path using a point measurement at an airport for example. If there is surface heterogeneity below the glide path (due to e.g. varying surface features or orography) its impact on the evolution of CBL has to be investigated. However, this is beyond the scope of this work and is subject of ongoing research.

9 Operational aspects

The approach Tower relies on the assumption that there is a CBL. Operationally, this CBL situation needs to be diagnosed from measured data in the vicinity of an airport. A tower that is equipped with sonic anemometers can measure temperature fluctuations and all three velocity components at a high sampling frequency. Then, the usual approach is to compute the stability parameter z/L with L the Obukhov length (see e.g. Stull 1988).

As a rule-of-thumb the flow is approximately in free convection if the buoyancy production of turbulent kinetic energy is at least three times larger than the shear generation which means that $z/L < -3$ (Stull, 1994). This stability parameter can be easily computed from sonic anemometer measurements. Furthermore we have to estimate the boundary layer depth z_i to define the layer over which the assumptions of the Tower approach can be applied. If a profiler is available z_i can be determined directly. Otherwise, simple boundary layer models (see e.g. Stull 1988) may be used to estimate z_i.

Once the free convection situation is diagnosed the Tower approach may be applied. Of course the ATC needs to know that the convective situation prevails for the next 20-30 minutes. For this it is necessary to develop a forecast tool which may rely for example on a simple boundary layer model or a statistical approach (e.g. persistence concept). For the approach Profiler we suggest to follow the same outline.

10 Conclusion

We have investigated the predictive capabilities of a parametric wake vortex transport and decay model in an evolving convective boundary layer using LES data. Profiles of the turbulent kinetic energy and variances computed from the LES data agree with profiles of a stationary CBL. The LES data is used to validate the WV model and to investigate WV model predictions relying on limited meteorological data availability at an airport. One approach considers hypothetical tower measurements on the one hand, and a profiler (e.g. Sodar) on the other hand in the LES domain. From these approaches we compute standard deviations of the velocity components and the turbulent kinetic energy which are used as WV model input. Both approaches produce conservative predictions of vertical WV dispersion. This result is based on the comparison with prediction of WVs at characteristic locations within a convective boundary layer. As expected, the Profiler method is closer to the LES reality as compared to the Tower method. The prediction of circulation decay follows closely the LES results until the rapid decay phase starts. At later stages circulation decay is underestimated which is conservative from an operational point of view. In a sensitivity study we demonstrate that there is a weak dependence of vertical WV dispersion predictions on TKE variability. We conclude that average TKE values are sufficient for WV predictions.

Operationally, a CBL situation can easily be diagnosed from surface flux measurements. Further work is necessary to study the impact of surface heterogeneity along the glide path and to develop a short term prediction scheme to predict boundary layer properties for the next 30 minutes.

In this study we have focused on the convective boundary which previously has been considered as potential hazardous due to rising WVs. Other meteorological situations which may cause critical WV behavior, such as shear layers (Hofbauer and Gerz, 2000), also need to be considered in a WV prediction scheme. The approach presented here is considered as a necessary step towards a WV prediction system which covers the whole glide path.

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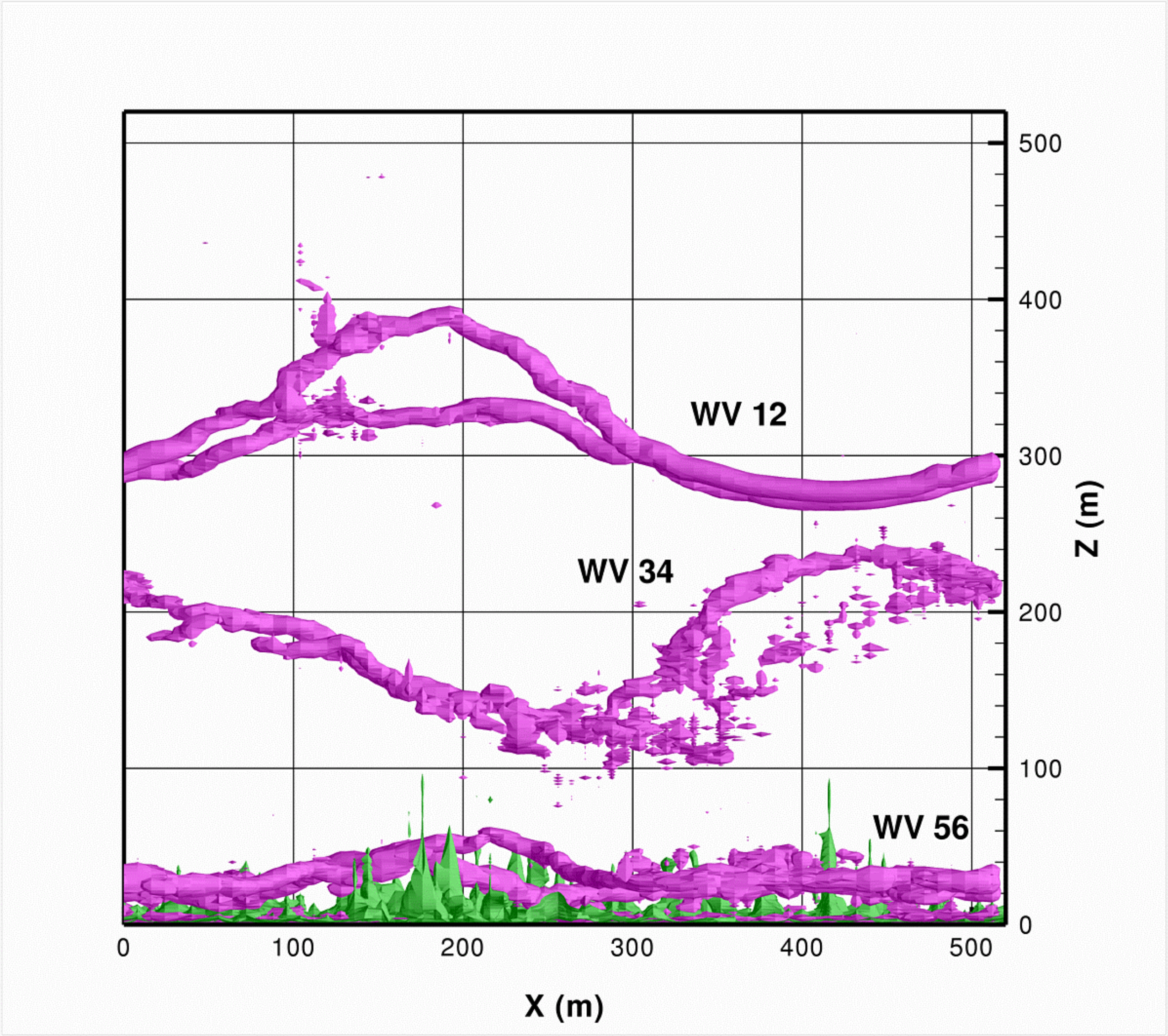

Figure 1: Side view of three WVs at t=40 sec. Shown are λ-isosurfaces ($1/s^2$) which are a measure of coherent vorticity structures (Jeong and Hussain, 1995). In addition a temperature isosurface is shown near the surface illustrating the heating from below.

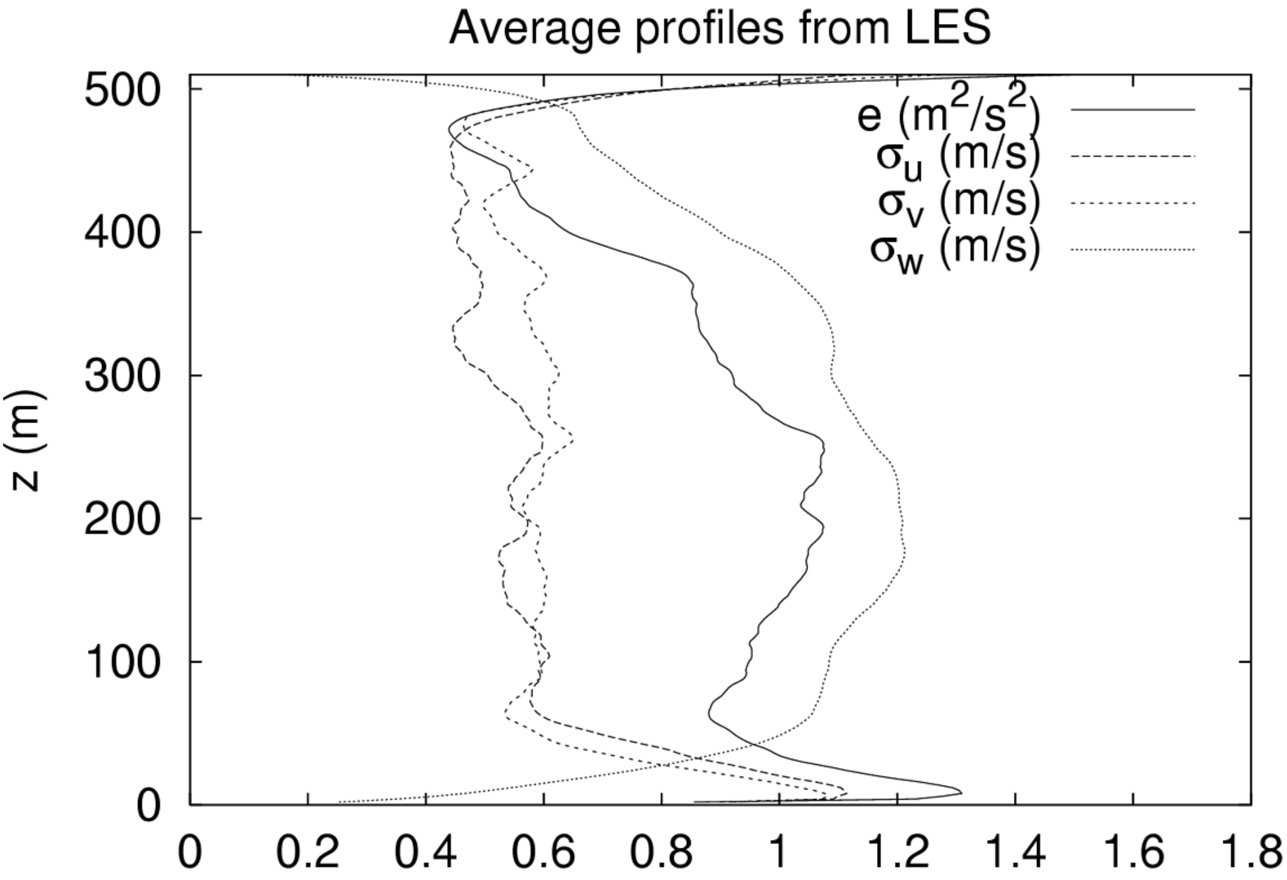

Figure 2: Average meteorological profiles computed from LES data.

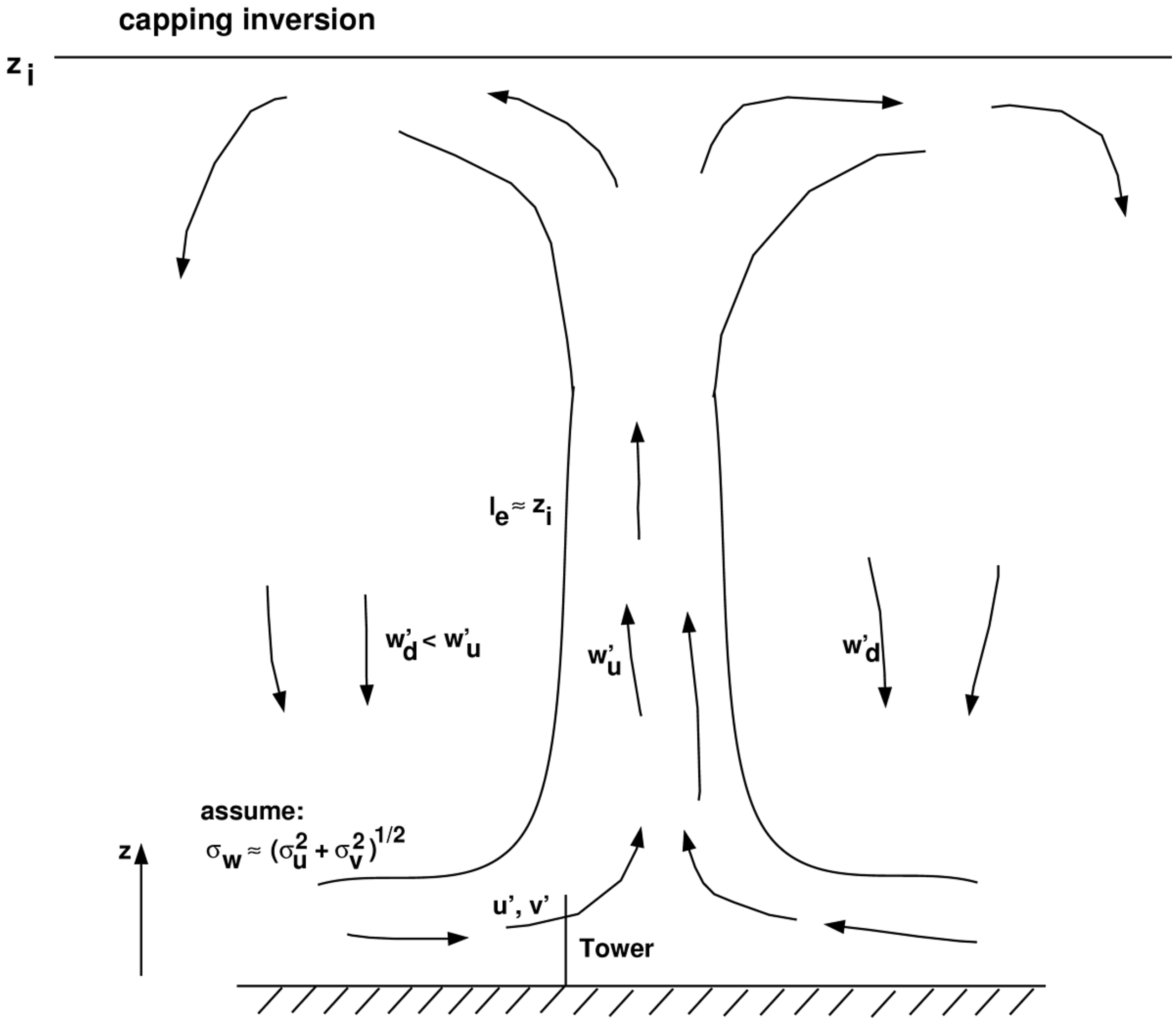

Figure 3: Schematic sketch on assumptions behind the tower approach. w_d **denotes the downward,** w_u **the upward velocity,** l_e **denote scale of the thermal and** z_i **the boundary layer depth.**

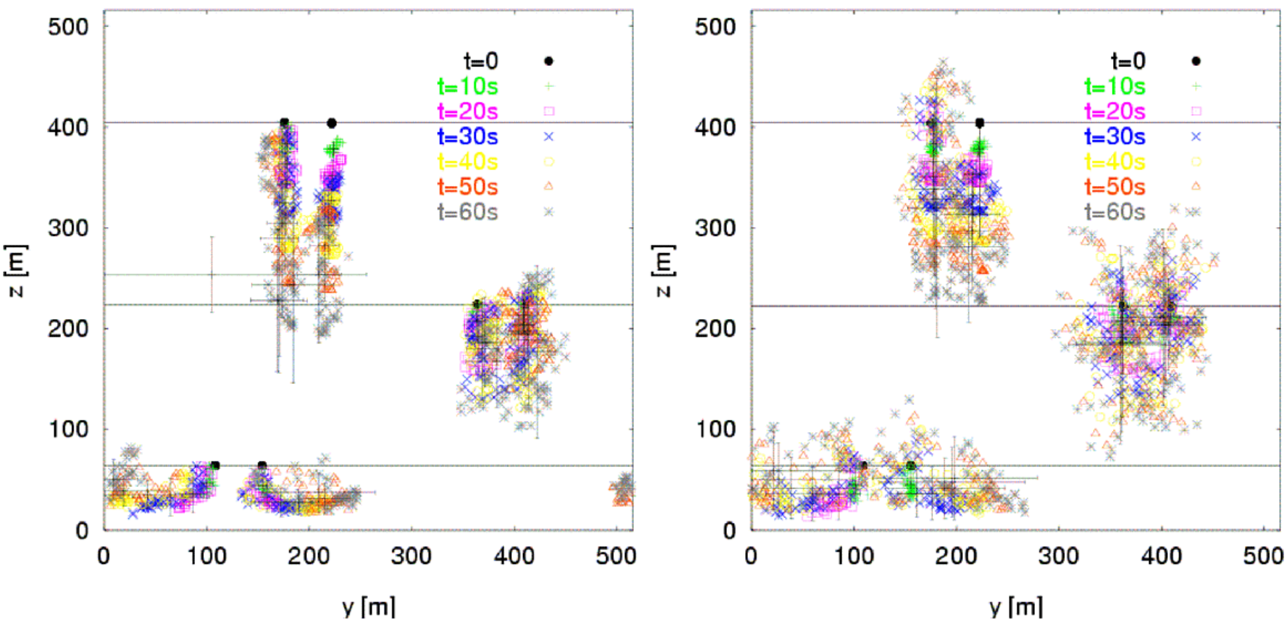

Figure 4: Comparison of the WV positions for different time steps as derived from LES (left) and WV model (right). Crossed error bars denote 2σ of the spread of WVs at different time steps.

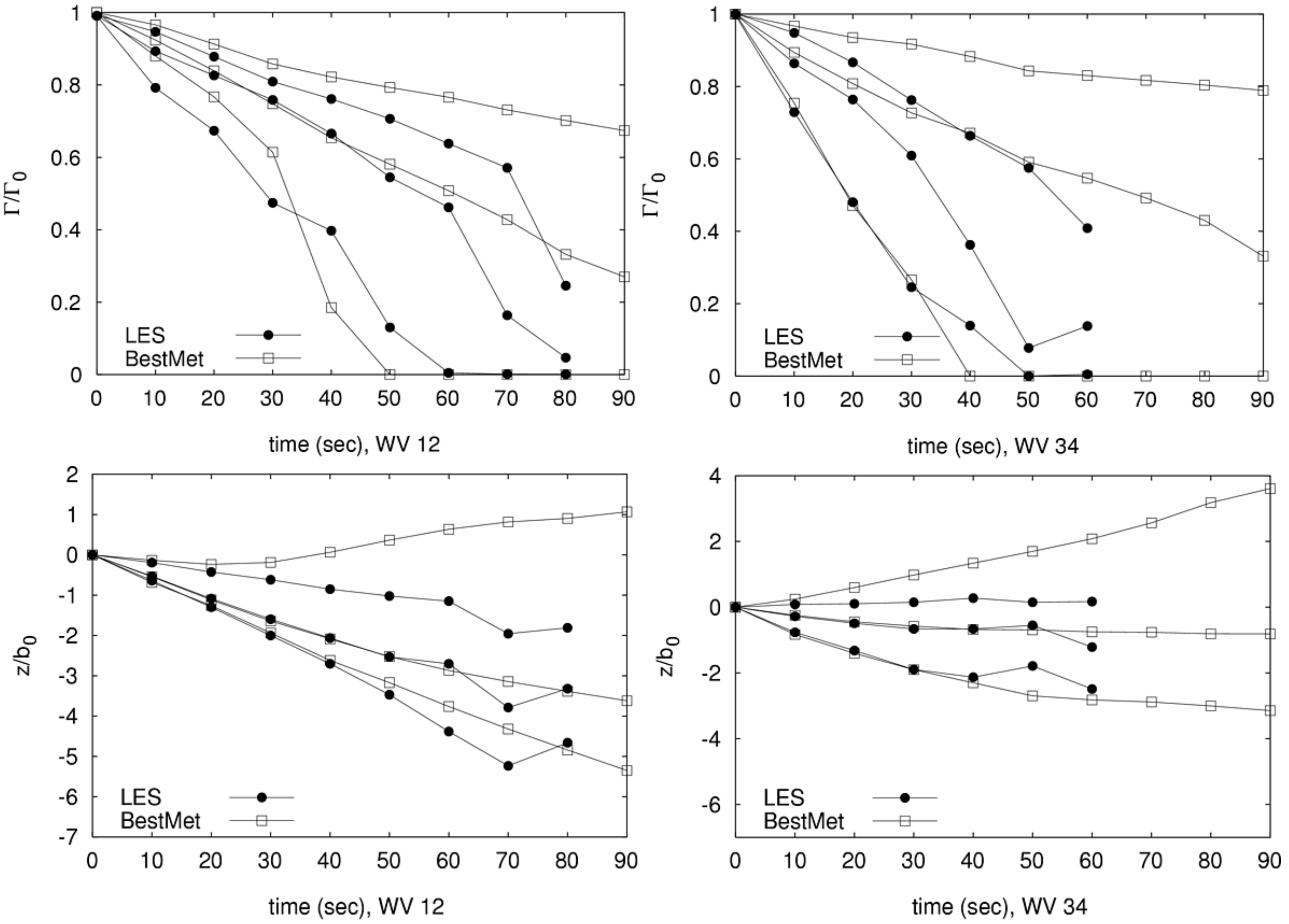

Figure 5: **Predicted circulation and predicted vertical positions of vortex pair 12 and 34 in comparison to LES. The originating level is set to zero and the height is normalized by the initial vortex separation b_0. BestMet denotes the WV model predictions driven by local meteorological data.**

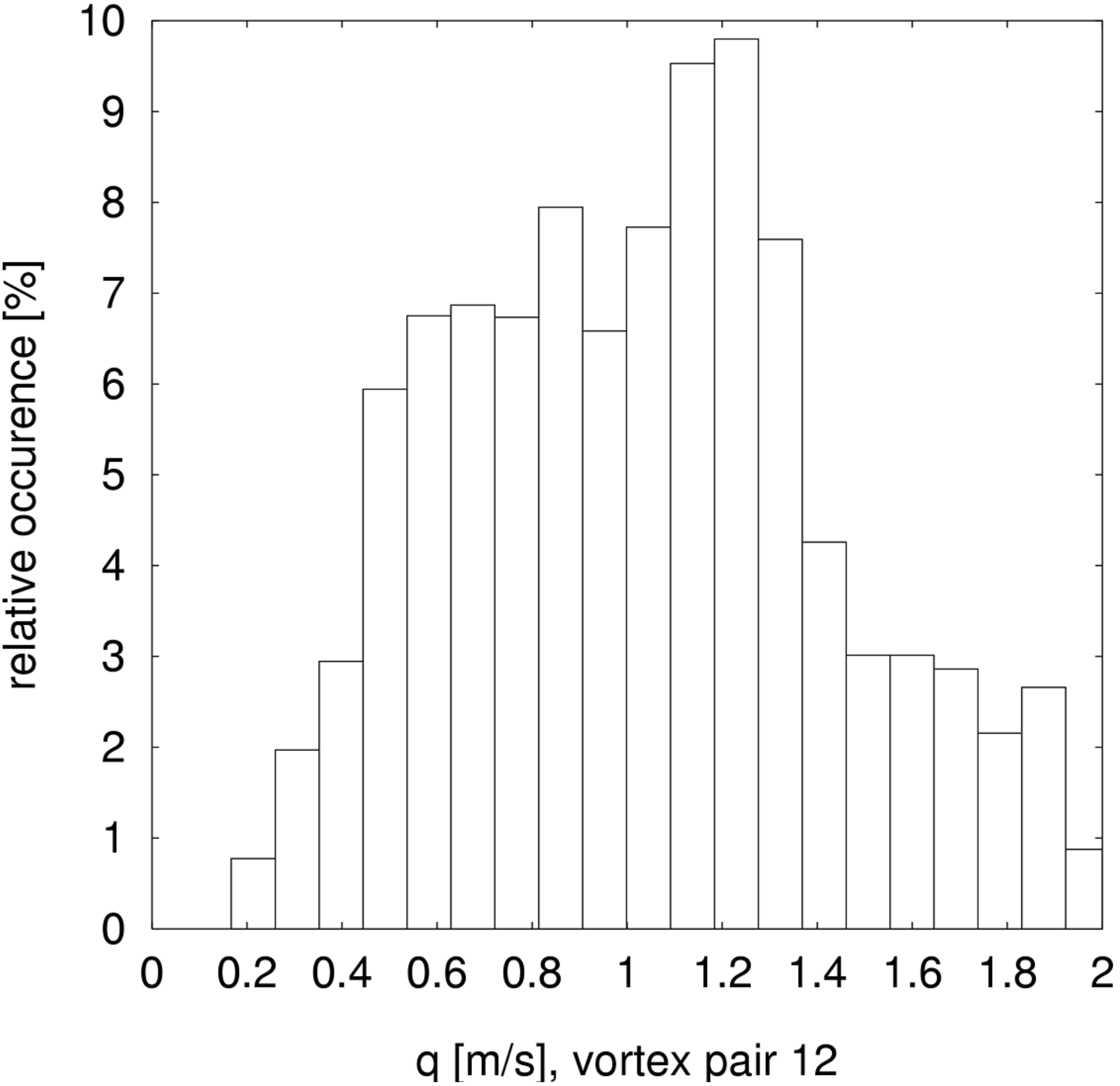

Figure 6: Histogram of q values during the BestMet run for vortex pair 12. q is computed in a volume around the WV pair

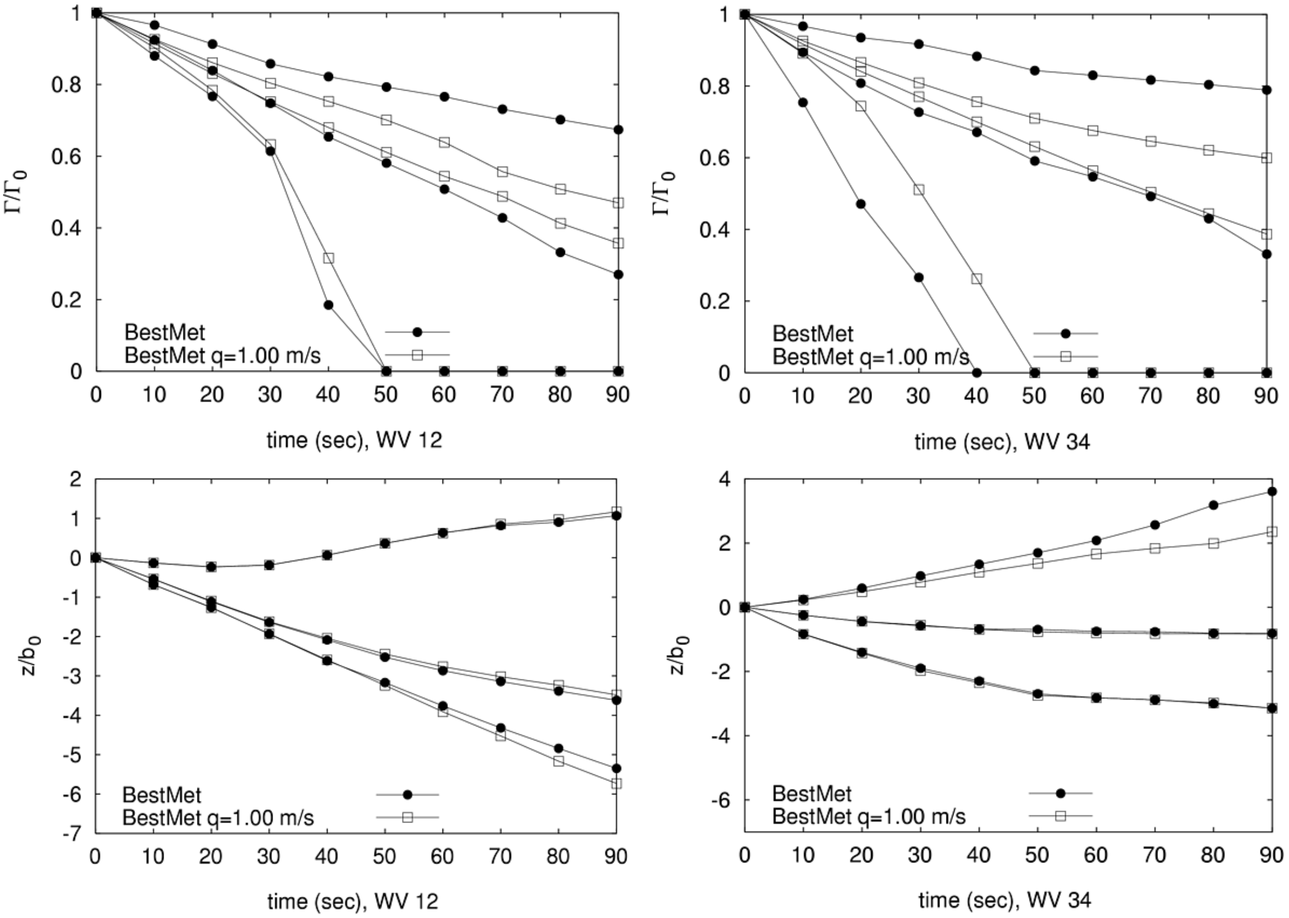

Figure 7: Predicted circulation decay and predicted vertical position of vortex pair 12 and 34 applying the BestMet approach. BestMet denote WV model runs with variable q (as in previous section) and BestMet q=1.00 m/s runs with with constant q.

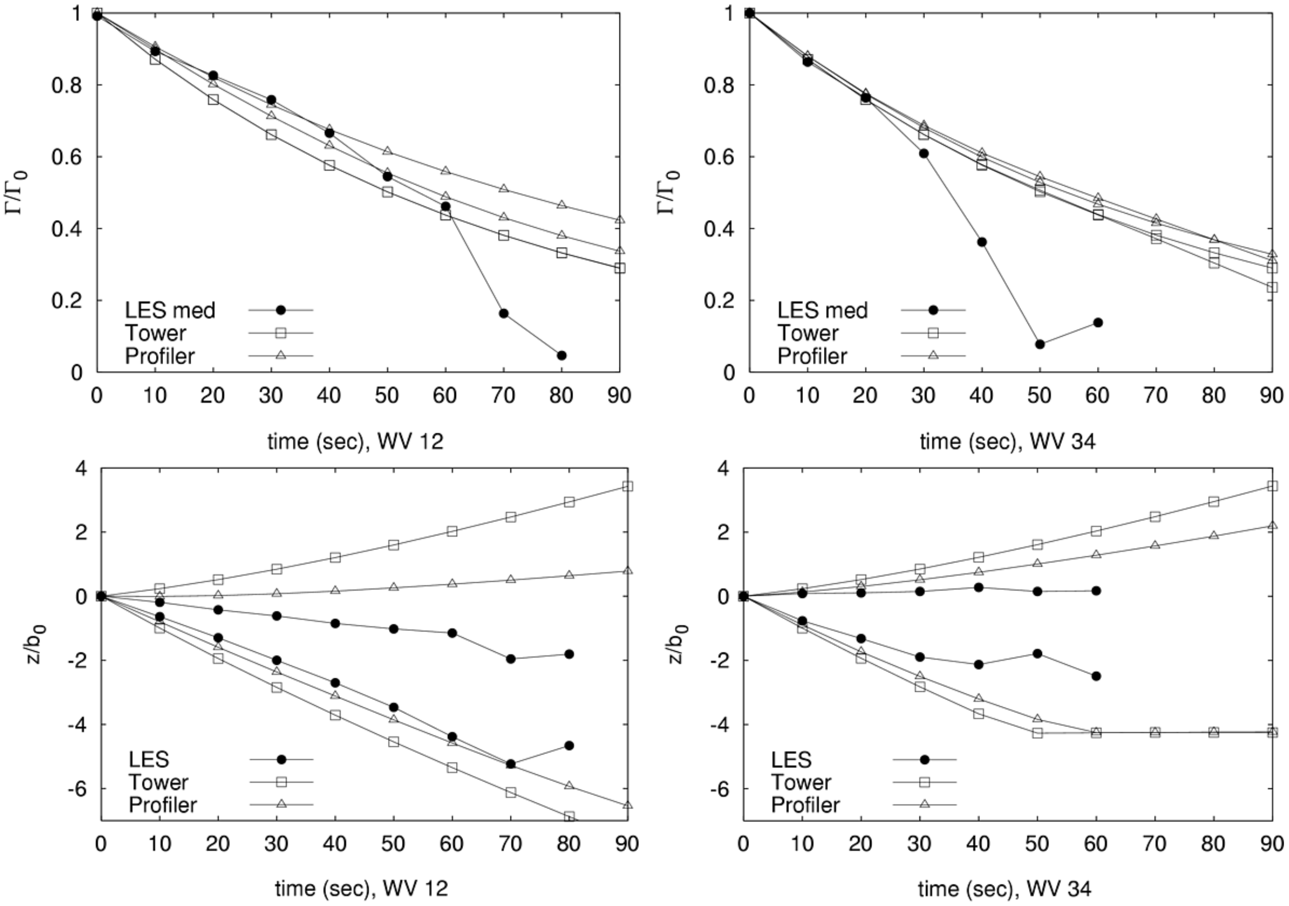

Figure 8: Predicted vertical range of WV position and circulation of WV pair 12 and 34 based on the approaches Tower and Profiler in comparison to LES. Only the median circulation from LES is shown (the ranges can be seen in Figure 5).

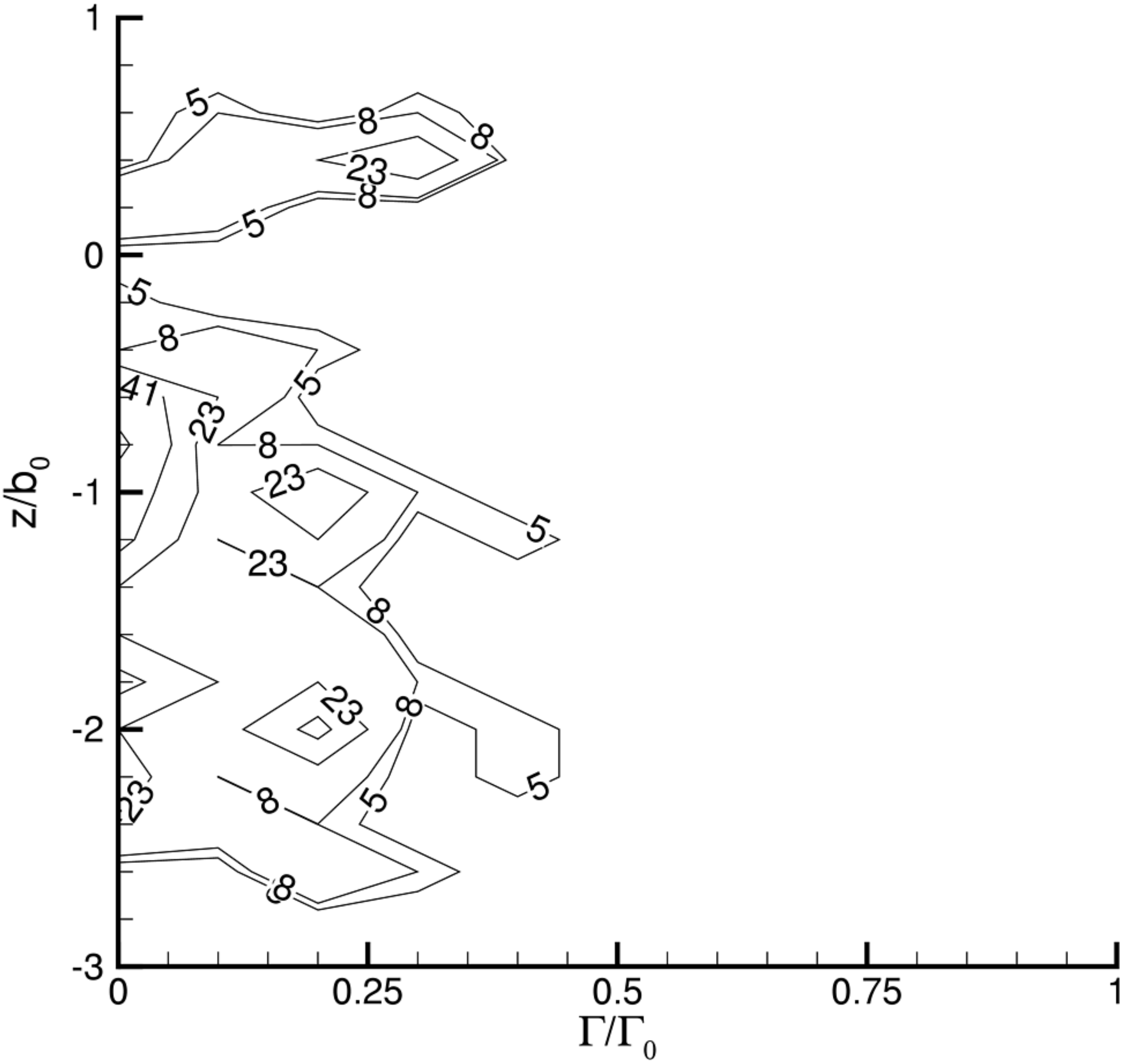

Figure 9: Joint frequency distribution of z and Γ of WV pair 34 at t=60 sec (from LES).

Biography

Dr. rer. nat. Michal Frech graduated with a Masters Degree in Atmospheric Science from Oregon State University, Corvallis, USA in 1993. After joining the Institute of Atmospheric Physics, DLR in Oberpfaffenhofen in 1994, he worked as a boundary layer meteorologist on the analysis of turbulence data and obtained his Phd from the Ludwig-Maximilians University Munich in 1998. Since then he is working in the wake vortex research group at DLR where he is focusing on short term weather prediction, real-time wake vortex modeling and the analysis of field data of wake vortex measurements.

Dr.-Ing. Frank Holzäpfel graduated as mechanical engineer from the University of Karlsruhe (TH) in 1990. He then specialized in multi-hot-wire measurement techniques and turbulence modeling in highly turbulent swirling flows at the Engler-Bunte Institute of the Department of Chemical Engineering, Karlsruhe, where he obtained his Dr.-Ing. in 1996. Since 1997 he is Research Scientist at the Institute of Atmospheric Physics, DLR in Oberpfaffenhofen where he concentrates on wake vortex research which includes large eddy simulations, subgrid scale model and real-time wake vortex model development.