WakeNet3-Europe

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Aircraft Wake Vortex
State-of-the-Art & Research Needs

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5.3 Weather Prediction and Monitoring

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5.3.1 Overview

Wake vortex behaviour strongly depends on the prevailing meteorological conditions. Therefore, most wake vortex concepts and prediction systems (see §3) depend on current meteorological observations and forecasts of conditions for the near future (10 min to next hour) and typically along an aircraft's glide or takeoff path or also along the flight path in cruise. Even tools for risk analysis (see sections 5.5 and 6.2) require appropriate representations of the weather conditions including both the typical weather in a climatological sense and unusual, potentially critical, weather situations.

5.3.2 State-of-the-art

Due to the variability of the meteorological conditions deterministic wake vortex prediction may not represent the variability of the consequential wake vortex behaviour. Probabilistic wake vortex prediction aims to consider all related uncertainties by producing envelopes for wake vortex trajectories and circulation with defined probabilities. For many applications the most important mechanism is the advection of wake vortices out of a flight and runway corridor. Unfortunately, major uncertainties are related to the prediction of crosswind and its fluctuation which are most relevant for lateral vortex transport.

Methods for probabilistic weather prediction appear to have a strong potential to improve probabilistic wake vortex prediction and thus to improve the performance of wake vortex advisory systems. Ensemble weather prediction methods may improve the prediction of average quantities and, additionally, characterize the related forecast uncertainties. However, for short prediction horizons, ensemble prediction may not be the best choice. In contrast, probabilistic nowcasting methods (based on observations) are less time consuming and well suited for a short prediction horizon. Both approaches are faced with interesting developments, yet they have to be adjusted to the requirements of a specific application.

In SESAR WP11.2 "Meteorological Services" the EUMETNET Consortium consisting of several national meteorological services and other partners are preparing the development of systems that shall provide weather data tailored to the needs of Air Traffic Management. The information shall be integrated into a weather database containing meteorological measurement data and prediction data as part of a System Wide Information Management (SWIM). Promising approaches aim at establishing local-area short-range weather prediction models (around airports) employing ensemble prediction techniques and assimilation of weather data at airports. On the other hand, there is an initiative to install common European-wide, high-resolution ensemble prediction systems such that high-quality ensemble prediction data may become available even en route in the future. In relation to this new terminal weather systems are being installed at airports (Evans 1995, Lau 2000). For example, the LLWAS/ITWS (Low Level Wind Shear Alert System/Integrated Terminal Weather System) will be installed at Frankfurt and Munich Airports by the German Weather Service (DWD) and several LIDARs and RADARs will be established at Nice Airport by Meteo France.

In the following the requirements of wake vortex models with respect to their meteorological inputs are discussed. Then a survey on recent developments of weather prediction and monitoring is given. Promising methods are introduced and their potential for wake vortex systems is discussed.

5.3.2.1 Requirements

The meteorological input parameters required by wake vortex prediction models are crosswind, headwind/tailwind, turbulent kinetic energy (TKE), eddy dissipation rate (EDR), and (virtual) potential temperature. Vertical profiles of these variables are needed in the height range where the wake vortices develop, i.e. from the generation height of the vortices down to their lowest descent height.

Ideally, the vertical resolution of the meteorological parameters close to the ground is on the order of 10 m and at higher altitudes not coarser than 50 m. For different applications the temporal prediction horizon may vary from 2 min (warning time needed by airborne wake encounter prevention systems to avoid wake vortices ahead of an aircraft), 6 min (time after which aircraft separation during approach should not be readjusted), 20 min (time to plan sequences of approaching aircraft), 1 hour (time for more comprehensive planning of sequences of approaching aircraft) and up to 6 hours (planning horizon that may already affect aircraft prior to take off).

Most wake vortex encounters occur at flight altitudes below 100 m, because wake vortices cannot further descend below the flight corridor but tend to rebound as a consequence of interaction with the ground. Moreover, the possibilities of a pilot to counteract the imposed moments and forces are restricted due to a low height of the aircraft above ground. Therefore, highest accuracy of the meteorological quantities is needed within a distance of about 1 NM from the touchdown zone or take off position, respectively.

Lateral wake vortex transport driven by crosswind plays a prominent role:

- It is the most important mechanism for many wake vortex advisory systems (in ground proximity, it is the primary mechanism that may clear a flight corridor from wake vortices).
- It is easy to model (crosswind advection can be directly translated into wake vortex transport distances, if the wake vortex residence times during the descent along the crosswind profiles are modelled correctly and if effects of vortex deformation, turbulence, wind shear, and ground proximity can be neglected).
- It introduces the largest uncertainties within the predicted wake vortex properties (lateral transport, vertical transport, and circulation decay). These uncertainties are related to crosswind fluctuations (gusts, turbulence) and spatiotemporal variations of crosswind.
- The knowledge of the remaining meteorological parameters is also important, if highly accurate predictions of wake vortex behaviour are required. EDR is the most important parameter for characterizing wake vortex decay.
- During cruise vortex lifetime and vortex descent are mainly limited by thermal stratification because turbulence typically is very weak.

The uncertainties related to meteorological input parameters contribute significantly to the uncertainties of predicted wake vortex behaviour. Other sources of uncertainty are initial conditions, reference data (typically LiDAR measurements that are closest to the *true* wake vortex behaviour), and the intrinsic variability of wake vortex data. As a consequence, probabilistic predictions of wake vortex behaviour are required. Instead of a deterministic average behaviour, probabilistic predictions yield upper and lower bounds of wake vortex behaviour, ideally with assigned probabilities.

Anticipating that probabilistic weather prediction methods may yield a larger spread for less predictable situations and smaller spread for well predictable situations, wake vortex prediction methods have been developed that utilize spread information for adjusting the probabilistic predictions (Holzäpfel 2010). The ultimate goal of the combination of probabilistic weather and wake vortex prediction methods is to achieve, on average, more compact probabilistic wake vortex predictions resulting in reduced uncertainty allowances. However, initial attempts to exploit ensemble weather prediction have produced little benefit, for reasons that will become clear below.

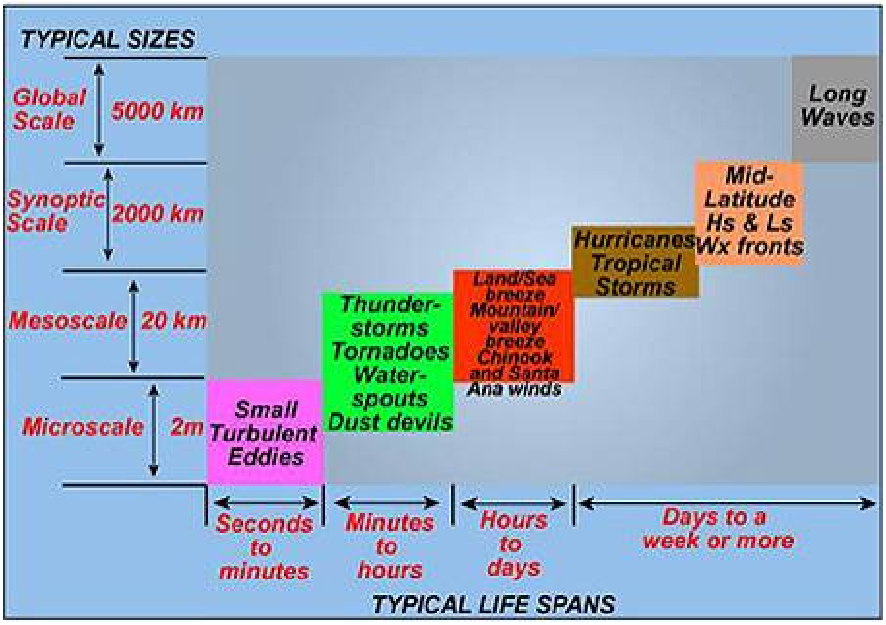

Figure 69: Time and space scales of atmospheric motion (from The Remote Sensing Tutorial, NASA).

5.3.2.2 Features and Opportunities of Weather Prediction Methods

Because of a non-linearity of the underlying transport equations, weather is a chaotic phenomenon. Slightly varying initial conditions may lead to drastically varying outcomes. The predictability of weather phenomena scales with their characteristic length and time scales (see Figure 69). In particular, wind and turbulence scenarios depend on phenomena characterized by a wide range of characteristic length and time scales. This is one reason why the predictability of these parameters may largely depend on the prevailing weather situation.

Basically two approaches for short-term weather prediction are available: nowcasting methods and numerical weather prediction models. Nowcasting is the extrapolation of observed values in space and time. The extrapolation may be based on persistence, Lagrangian approaches, or simple physical or statistical models. Basically, vertical extrapolation is much more restricted than horizontal extrapolation; for example, inversions decouple layers at different altitudes. Also, errors of the underlying measurements are typically smaller than the extrapolation errors. A comprehensive survey on available measurement instrumentation is provided in §5.2.

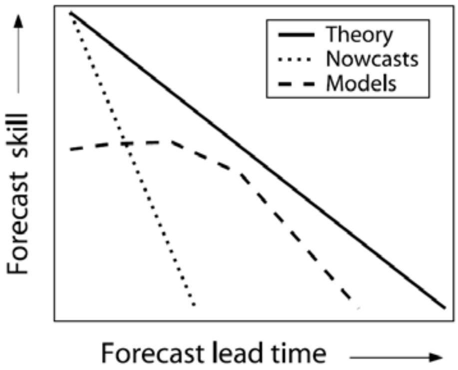

Figure 70: Forecast skill of nowcasting and numerical weather prediction models (from Kober after Lin et al. 2005).

The forecast skill of nowcasting rapidly decreases with forecast lead time. At some forecast lead time numerical weather prediction becomes superior to nowcasting (see Figure 70). The crossover time for prediction skill of these two methods depends largely on the encountered weather conditions and phenomenon of interest. For precipitation forecasts, the crossover time tends to be on the order of 3 to 6 hours (Kober 2010), whereas for wake vortex prediction the crossover time may be around one hour (Frech & Holzäpfel 2008). For convective precipitation forecasts, it has been demonstrated that a smart blending of nowcasting and numerical weather prediction can improve forecast quality (Kober 2010). The blending may be based on weighting functions that depend on the prediction skill of a particular method. This appears to be a promising approach also for wake vortex prediction purposes.

A complete description of the required weather parameters should be stated in terms of appropriate probability density distributions, such as average values and standard deviations. For numerical weather prediction this may be achieved either by basing uncertainty estimates on subgrid scale models used in deterministic numerical weather prediction or by ensemble prediction methods.

For the relatively short prediction horizons required for many wake vortex systems, it is possible that deterministic numerical weather predictions, including assimilation of observations taken in the airport environment, might well capture the average state of the atmosphere. In this case, the subgrid scale variability of weather parameters will make the dominant contribution to the overall uncertainty. Currently, the turbulence parameterization of the COSMO model is being augmented (Raschendorfer 2010). Improved EDR forecasts will consider the effects of horizontal shear, mountain blocking, and convection. The developed turbulence scheme accounts for scale separation of kinetic energy of circulation and turbulence. Further, the EDR output will be calibrated by regression of crucial parameters against EDR measurements.

The above single deterministic approach may be termed *microscale* approach in contrast to the *mesoscale* approach implemented by ensemble prediction methods that are based on a finite number of deterministic integrations. Different classes of ensemble prediction methods have been developed (see Figure 71). The most expensive and powerful approach employs several weather prediction models, combined with perturbed initial and boundary conditions. If properly configured and calibrated (which is not trivial), this approach may likely deliver reasonable spread for short lead times and maintain good prediction skill also for longer lead times. However, such an approach appears way too costly for wake vortex applications at this time. On the other hand, there is an initiative to install common European-wide, high-resolution ensemble prediction systems such that high-quality ensemble prediction data may become available for airport environments in the future.

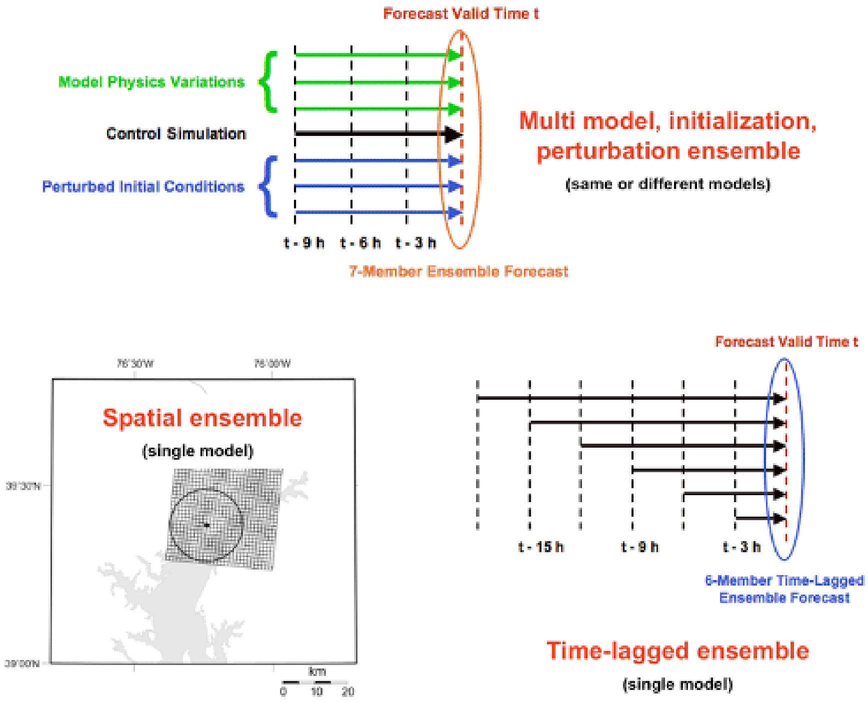

Figure 71: Sketch illustrating different ensemble prediction methods (M. Steiner 2010).

A less expensive approach is the *time-lagged ensemble* forecast that employs a number of overlapping predictions achieved by the same model initialized at different times in the recent past (Lu et al. 2007). For wake vortex applications the most recent members of a time-lagged ensemble may exhibit superior wind prediction skill, whereas turbulence predictions require certain spin-up times. However, experience shows that for short lead times the ensemble spread does not cover the observations in as many cases as desirable.

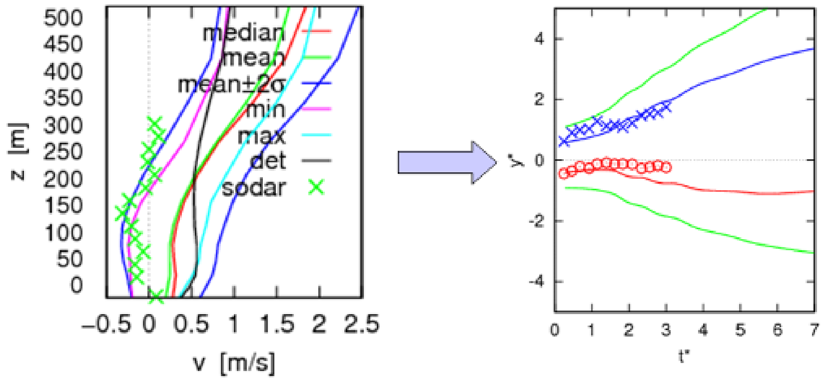

Figure 72: Use of time-lagged ensemble spread for probabilistic wake vortex prediction.

An example of the use of time-lagged ensemble prediction as input for probabilistic wake vortex prediction is shown in Figure 72. The vertical profiles of crosswind (Figure 72, left) have been predicted by the COSMO-FRA weather prediction model (Dengler et al. 2010) employing a time-lagged ensemble with six members and an hourly update rate. The model assimilates local measurement data from SYNOP, TEMP, AMDAR and precipitation Radar. From the six ensemble members averages and the ensemble spread (mean $\pm 2\sigma$) are calculated and are used for the probabilistic predictions of crosswind transport of the wake vortices (Figure 72, right: symbols: LiDAR measurements, red and blue lines: deterministic predictions, green lines probabilistic envelopes, Holzäpfel 2006).

A third approach is the *spatial ensemble* that may be derived from output data of a single model run or, alternatively, from a synthesis of spatial measurements (e.g. radar or LiDAR) with a suite of other observations. The evaluation of neighbouring grid points or measurement data may increase the spread of predictions and, depending on the weather situation, include information of an air mass that is about to be transported to the actual location where predictions are needed.

The described ensemble prediction methods can also be combined, as described above for precipitation prediction. For example, a combination of the time-lagged ensemble and a spatial ensemble may constitute an economical approach for wake vortex prediction purposes.

Experience and analytical considerations suggest that even for a perfect ensemble (one in which all sources of forecast error are sampled correctly) there need not be a high correlation between ensemble spread and prediction skill. The correlation between spread and skill should be larger for meteorological quantities featuring large day-to-day variability of the spread.

Certainly, all types of numerical weather prediction methods may benefit from improved boundary layer physics, parameterizations, and initial conditions. Moreover, weather prediction products can be enhanced by careful calibration which, however, requires sustained predictions and observations over long times.

In conclusion, it is noted that whenever measurement instrumentation may cover the air volumes of interest, short-term predictions based on nowcasting should be preferable. Added value may be achieved from spatial ensembles based on spatial measurements or spatially distributed instrumentation possibly enhanced by 4D data analysis. Utilization of numerical weather prediction becomes necessary, if the air volumes of interest cannot be covered by instrumentation alone. For remote areas and short lead times, the use of available high frequency data using appropriate assimilation schemes will likely increase the forecast skill. Time-lagged ensembles, especially with adjusted data assimilation schemes and possibly combined with spatial ensembles, may economically yield improved prediction skill. Alternatively, uncertainties may be retrieved from models of the subgrid scale variability based on deterministic predictions. Blending of nowcasting and numerical weather prediction has the potential to bridge the gap between the two methods and to improve the overall prediction quality.

5.3.3 Research Needs

5.3.3.1 Sensors

- A generation of new meteorological sensors has emerged (see §5.2). For each of these sensors the spatial and temporal resolutions as well as the weather dependent availability are different. Various sensors have been benchmarked in a three-month measurement campaign in SESAR WP12.2.2. It has to be elaborated which sensors are best suited and how the selected sensors can be combined optimally to provide a consistent weather data base for wake vortex predictions.
- The accuracy of meteorological data measured by standard instrumentation of aircraft should be estimated. The provision of the required parameters with the required resolution transmitted via ADS-B (Automatic Dependent Surveillance – Broadcast) and/or AMDAR (Aircraft Meteorological Data Relay) should be advanced.

5.3.3.2 Numerical Weather Prediction

- Ensemble prediction methods should be employed to improve the prediction skill of average quantities and to quantify the predictability of specific weather situations in terms of the spread of these quantities.
- An economical approach for numerical weather prediction appears the combination of time-lagged ensembles and spatial ensembles enhanced by data assimilation schemes.
- All types of numerical weather prediction may benefit from improved boundary layer physics, parameterizations, and initial conditions.
- Any weather prediction products can be enhanced by careful calibration.

5.3.3.3 Combined Weather Monitoring and Prediction Systems

- Algorithms to deduce robust eddy dissipation rate estimates from various measurement sources and forecast models should be developed.
- Added value from the measurement data can be extracted by the assembly of spatial ensembles. This approach could be enhanced by methods of 4D data analysis.
- Because many applications rely on short-term weather prediction enhanced nowcasting methods employing more sophisticated physical and/or statistical methods should be developed.
- Methods for blending of nowcasting and numerical weather prediction in time may bridge the temporal gap between the methods. Blending of nowcasting and numerical weather prediction in space may improve the prediction skill along the flight path.
- Numerical weather prediction models should assimilate available local measurements in order to improve their forecast skill. It should be investigated which measurements are best suited to improve the prediction skill of the respective required parameters (wind, temperature, turbulence).
- The accuracies achieved by the various measurements sensors (in-situ, remote, and airborne e.g. AMDAR/ACARS), by nowcasting methods, and by weather prediction models should be determined and compared. The respective accuracies (i) should guide the selection of the weather monitoring and prediction methods, (ii) are important inputs for probabilistic wake vortex prediction, and (iii) are critical for the feasibility and success of the different operational concepts.
- Methods for the determination of weather data along the intended flight path of an aircraft are needed for airborne wake vortex prediction. These methods may employ meteorological measurements of the own aircraft and of neighbouring aircraft (provided by ADS-B) and/or may use uplinked ground based weather data. The fusion of weather data from different sources may improve the overall performance of the system.
- For the activities in SESAR WP11.2 “Meteorological Services” and for the new terminal weather systems that are installed at different airports it should be ensured that the developed systems will provide all the parameters needed for wake vortex systems with the required accuracy as well as the required temporal and spatial resolution.