Minutes of the

WakeNet3-Europe-Workshop on Short-Term Weather Forecasting for Probabilistic Wake-Vortex Prediction

10 and 11 May 2010
Institut für Physik der Atmosphäre
Deutsches Zentrum für Luft- und Raumfahrt
Oberpfaffenhofen, Germany

Background and Scope

Wake vortex behaviour strongly depends on the prevailing meteorological conditions. Therefore, most wake vortex prediction systems 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. 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 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. At the same time integrated terminal weather systems are being developed that monitor the weather in the airport terminal area by the combination of multifaceted instrumentation. It is not obvious how and in which form the uncertainty information should be used optimally by the wake vortex predictors. Exploitation strategies may range from Prandtl mixing length approaches to Monte Carlo simulation.

The workshop brought together experts from the meteorological and the wake vortex communities to discuss the most promising methods in their disciplines and how they could be combined meaningfully in order to reduce uncertainties in wake vortex prediction and to potentially adapt the probabilistic predictions to the predictability of the current weather situation.

Organization: Frank Holzäpfel (DLR, frank.holzaepfel@dlr.de, Tel. +49/8153/282529)

Scientific advisors:
George Craig (Lehrstuhl für Theoretische Meteorologie, Ludwig-Maximilians Universität)
Thomas Gerz (DLR)

Participants:

Nash'at Ahmad	NASA Langley Research Center, Hampton, VA, USA
Ludmila Anufrieva	Institute for Meteorology and Climatology (Hannover) , Germany
Nicolas Bourgeois	Université Catholique de Louvain/iMMC, Belgium
George Craig	Ludwig-Maximilians Universität (LMU) München, Germany
Klaus Dengler	DLR, Germany
Caroline Forster	DLR, Germany
Thomas Gerz	DLR, Germany
Ingo Hennemann	DLR, Germany
Frank Holzäpfel	DLR, Germany
Christian Keil	Ludwig-Maximilians Universität (LMU) München, Germany
Kirstin Kober	DLR, Germany
Takashi Misaka	DLR, Germany
Jean-Pierre Nicolaon	National Institute of Aerospace (FAA), USA
Matt Pruise	NorthWest Research Associates, USA
Matthias Raschendorfer	DWD, Germany
Daniel Sacher	MeteoSolutions, Germany
Shanna Schönhals	Technische Universität Braunschweig, Germany
Matthias Steiner	National Center for Atmospheric Research (NCAR), Boulder, USA
Dennis Stich	DLR, Germany
Arnold Tafferner	DLR, Germany
Grégoire Winckelmans	Université Catholique de Louvain/iMMC, Belgium

Contributions of Nigel Roberts (Met Office) have been presented by George Craig.
Andrey Belotserkovskiy (Dorodnitsyn Computing Center RAS, Russia) and Mikhail Kanevskiy (GosNIIAS, Russia) could not attend the workshop because their flights were canceled as a consequence of volcano ash restrictions.

WakeNet3-Europe

Specific Workshop on

Short-Term Weather Forecasting for Probabilistic Wake-Vortex Prediction

Institut für Physik der Atmosphäre, DLR-Oberpfaffenhofen

10/11 May 2010

Workshop Agenda

Monday, 10 May 2010 (1st day)

10:15	**Coffee, informal get-together**
10:45	**Welcome & Introduction** Ulrich Schumann, Director of Institute of Atmospheric Physics Frank Holzäpfel, Coordinator Area Technologies - WakeNet3-Europe, DLR
11:00	**Introduction into Wake-Vortex Aspects for Meteorologists** Thomas Gerz / DLR
11:40	**Introduction into Meteorological Aspects for Wake-Vortex Modelers** George Craig / Ludwig-Maximilians Universität, München
12:20	**Lunch**
13:20	**Predictability and Uncertainty of Meteo Predictions I** Chair: George Craig / Ludwig-Maximilians Universität
13:20	**Short-term Prediction of Wind and Temperature Profiles based on Profiler RADAR data for the use by a Wake Vortex Warning System at Frankfurt Airport** Daniel Sacher / MeteoSolutions
14:00	**Predictability of precipitation determined by convection-permitting ensemble modeling** Christian Keil / Ludwig-Maximilians Universität, München
14:40	**Blending a probabilistic nowcasting method with a high resolution ensemble for convective precipitation forecasts** Kirstin Kober / DLR
15:20	**Break**
15:40	**Predictability and Uncertainty of Wake-Vortex Predictions I** Chair: Thomas Gerz / DLR
15:40	**Investigation of the effect of wind uncertainty/fluctuation on wake vortex transport NGE/IGE** Gregoire WINCKELMANS / UCL/iMMC
16:20	**Methods to establish probabilistic wake vortex models** Frank HOLZÄPFEL / DLR
17:00	**Workshop wrap-up discussion**
17:30	**End of Day 1**
19:30	**Invited Dinner, Andechser Hof, Zum Landungssteg 1, Herrsching, +49-(0)8152-96810**

WakeNet3-Europe

Specific Workshop on

Short-Term Weather Forecasting for Probabilistic Wake-Vortex Prediction

Workshop Agenda

Tuesday, 11 May 2010 (2nd day)

08:40	**Predictability and Uncertainty of Meteo Predictions II** Chair: Matthias Steiner / National Center for Atmospheric Research
08:40	**Towards an improved EDR output of the COSMO model for aviation purposes** Matthias Raschendorfer / DWD
09:20	**Characterization of forecast uncertainty by means of ensemble techniques** Matthias Steiner / NCAR
10:00	**Short Range Time-Lagged-Ensemble Forecasts of COSMO Airport** Klaus Dengler / DLR
10:40	**Break**
11:00	**Predictability and Uncertainty of Wake-Vortex Predictions II** Chair: Gregoire WINCKELMANS / UCL
11:00	**Probabilistic wake vortex predictions using time-based ensemble weather predictions** Frank HOLZÄPFEL / DLR
11:40	**Analysis of the Short-Term Variability of Crosswind Profiles** Matt Pruise / NorthWest Research Associates, USA
12:20	**Lunch**
13:30	**Observability of wake vortex relevant meteorological quantities based on actual wake vortex behaviour** Shanna Schönhals / Technische Universität Braunschweig
14:10	**Open Discussion and Workshop Wrap-up** All **Consolidated view on scientific questions, feasibility, priorities, ...**
16:00	**End of Workshop – Safe Trip Home**

Rather than tracing the course of this workshop, the minutes aim to describe a consolidated view on the state of the art of probabilistic wake vortex prediction and probabilistic weather prediction, related scientific questions, and the feasibility and priorities of different methods with respect to future research.

Requirements of Wake Vortex Models

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 maximum descent height.

Ideally, the vertical resolution of the meteorological parameters close to the ground is on the order of 20 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). The workshop discussions focused primarily on prediction times of tens of minutes up to one hour.

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:

(i) 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).

(ii) 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 modeled correctly and if effects of vortex deformation, turbulence, wind shear, and ground proximity can be neglected).

(iii) 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.

(iv) The knowledge of the remaining meteorological parameters is also important, if highly accurate predictions of wake vortex behavior are required. EDR is the most important parameter for characterizing wake vortex decay.

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

Different methods for probabilistic wake vortex prediction exist. One approach is to derive the spread of wake vortex predictions from Monte Carlo simulations. This requires specifications of the uncertainties of all relevant input parameters. Precise information about meteorological uncertainties is always highly desirable, but in practice hardly feasible. So methods are being developed that represent typical uncertainties of the required parameters. Further, smart methods are available, for example, to minimize the computation effort of Monte Carlo simulations. Alternatively, hybrid empirical probabilistic prediction methods have been developed consisting of empirical static uncertainty allowances that are expanded by dynamic uncertainty allowances considering, for example, effects of turbulence and wind shear. The resulting envelopes of wake vortex behavior can finally be calibrated employing wake vortex field measurement data. A drawback of such an approach is that it represents the peculiarities of a specific experimental/numerical set up. This means that the empirical uncertainty allowances can not readily be transferred to alternative systems.

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. 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. However, initial attempts to exploit ensemble weather prediction have produced little benefit, for reasons that will become clear below.

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. 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.

The forecast skill of nowcasting rapidly decreases with forecast lead time. At some forecast lead time numerical weather prediction becomes superior to nowcasting. 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 6 hours, whereas for wake vortex prediction the crossover time may be around one hour. For convective precipitation forecasts, it has been demonstrated that a smart blending of nowcasting and numerical weather prediction can improve forecast quality. 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 wake vortex encounters, 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 parametrization of the COSMO model is being augmented. 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. 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.

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. 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.

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 radar or lidar measurements 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 improve 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.