Workshop on

WIND PROFILES and MESOSCALE DATA ASSIMILATION
for Numerical Weather Prediction

University of Ljubljana
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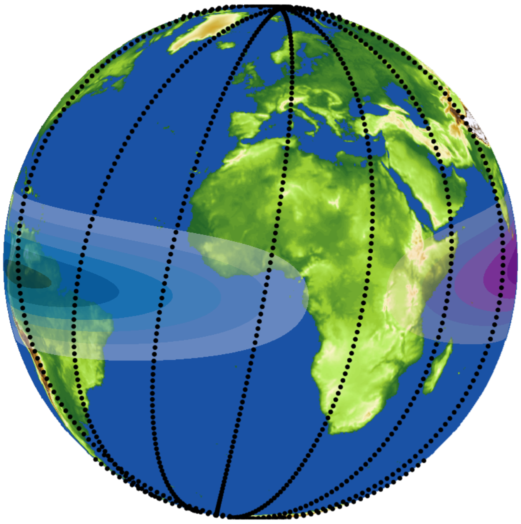

Abstracts

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1. Mesoscale data assimilation and the role of winds: where we stand

Mesoscale data assimilation: 49 years of perspective

Nils Gustafsson
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We have over the last years been busy with trying to improve 4-dimensional variational data assimilation (4D-Var) for high resolution models by using model ensemble information. This was largely successful for models with the order of 10 km grid resolution (for HIRLAM, for example). Ongoing work is devoted to models (HARMONIE - ALADIN/AROME) at the cloud resolving with a grid resolution of a few km. Here the results are still not even pre-mature, while the open and interesting questions are many: We have believed that the cascade process from small scales to the large scales is the dominant process for error propagation, we now think that mainly larger scale forecast errors are responsible for error propagation at the mesoscale. If this is true, to what extent is mesoscale data assimilation meaningful? Can ensemble information be useful for data assimilation at the cloud-permitting scale? Would an ensemble generated by a larger scale model over a larger domain be of any value? Is a priory information in the form of background error statistics based on simplifying assumptions (like stationarity, homogeneity and isotropy) of any value at the mesoscale? According to geostrophic adjustment theory, wind observations (e.g. wind profiles) would be most important source of information for the mesoscale? Is this true also in practise, maybe mass field information related to the forcing from larger scales or from the lower boundary (for example from surface, soil and water surface assimilation) and/or moisture information (clouds) equally important? The answers to these questions go in many directions at present, and a review will be attempted during the talk.

Mesoscale wind data assimilation and global OSE results

Ad Stoffelen
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The International Winds Working Group (IWWG) discusses the requirements and capabilities of satellite wind observations, the assimilation of mesoscale winds (e.g., at https://groups.ssec.wisc.edu/groups/iwwg/activities/high-resolution-winds-1/nwp-data-assimilation) and convened this summer in Monterey, USA, at the IWW13 to discuss wind products and wind Observing System Experiment (OSE) results. Progress that was reported at the IWW13 on mesoscale data assimilation will be presented and recent OSE results discussed.

Challenges in mesoscale data assimilation

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Data assimilation (DA) has proven beneficial for numerical weather prediction (NWP) in global and limited area hydrostatic models. However, demonstrating positive impact from assimilating observations (both conventional and from satellites) in non-hydrostatic mesoscale models appears quite a challenge. Observing System Experiments (OSE) have been conducted with the high-resolution limited area model HARMONIE, which is operational at KNMI and most other weather centres which are part of the European HIRLAM consortium. The default assimilation system used at most HIRLAM centres is 3D-VAR. So far, the added value of observations for forecasts is limited to a couple of hours, which is disappointing. This presentation aims to address challenges of mesoscale data assimilation and possible directions for solutions are discussed.

It is found that the additional variance brought into the model through increased energy on small spatial scales does not verify with observations. A dense network of observations in all four dimensions is needed to correctly initiate the evolution of rapidly evolving small-scale weather phenomena, deterministically. Lacking observation density on spatial scales that the model resolves and on time scales of, e.g., convective processes induces phase errors, i.e., incorrect positioning of weather systems. Additional errors are introduced by the discrepancy between observation time and analysis time for satellite observations, but also aircraft observations, which is inherent for 3D-VAR.

From the notice that mesoscale data assimilation is an inherent deterministic methodology, it is argued that DA should be limited to model spatial scales governed by the density of the observation network. This is facilitated by the use of a background error covariance matrix (shortly denoted **B** matrix) with broad structure functions which is expected to yield improved skill relative to the use of sharp structure functions as suggested by the high resolution of the model. Model smaller spatial scales should be treated in probabilistic sense. It is shown that passive observations can be used to assess the effect of the used **B** matrix through the increments.

Observation-minus-background statistics from ocean surface winds measured from space using scatterometer indicate that time interpolation in model space to the observation measurement brings the model state parameter closer to the observed quantity. Moving to 4D-VAR is then expected to yield a better use of observational information for the simulated model state. In addition, the use of more advanced observation operators, taking into account instrument footprints, will improve observation usage.

Assumptions behind background error statistics and the evolution of uncertainty on mesoscale

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The number of observations is several orders of magnitude smaller than the number of the model state variables. For this reason the background error and the observation error statistics are used to spread the observed values in space and time constructing the initial model state. The climatological background error statistics of the Harmonie meso-scale forecasting system are derived using a multivariate linear regression approach. The statistics are derived from the averaged in time data aset imposing a number of simplifying assumptions. This approach has been successfully applied for synoptic scale data assimilation, while it was more difficult to demonstrate a positive impact of data assimilation for convection-permitting models with a grid-resolution of few km.

In the current study we try to better understand reasons for these problems. Using a LAM ensemble of high resolution of the model states we provide an insight into the error propagation mechanism and impact of the imposed balance constraints on it. We demonstrate that relaxing certain balance constraints in mass-wind-humidity interactions leads to improved forecast quality in wind and precipitation that is measurable in standard verification scores.

2. Mesoscale observations: what needs to be initialized

Near-surface wind variability: impacts on wind energy applications

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Knowing the three-dimensional velocity field properties from global to micro scales, and between a few minutes and 20 years and longer, is fundamental for planning and performance evaluation of individual wind turbine generators (WTG) on existing and future wind farms. Besides, accurate forecasting of every weather parameter which may affect wind energy production is required for optimal integration of wind-produced electricity into the power grid. Both of the above rely on precise and complete observations, and assimilation of these observations into the atmospheric model chain.

A collection of examples will be presented in an attempt to give a holistic picture of challenges and opportunities related to the diagnosis and prediction of atmospheric variability and relevant in the wind energy business. Wherever meaningful, we will assign financial value to the reduced uncertainty, potentially achieved with improved accuracy of atmospheric models as a consequence of mesoscale (and microscale) data assimilation. We will also give an overview of the use of data, collected at the nacelle anemometers, for understanding of the microscale wind characteristics, and for improving the short-term forecast of power production.

Atmospheric internal gravity waves - Observations versus numerical predictions by the ECMWF Integrated Forecast System

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Numerical predictions of the middle atmospheric circulation are regularly used to guide aircraft and ground-based field campaigns aiming to observe the deep vertical propagation of internal gravity waves. Most of the observations are based on backscatter or Rayleigh lidars covering altitude ranges from ground to about 30 km and from 30 to about 80 km, respectively. The temporal and spatial resolutions are high and mesoscale features as up- and downward propagating waves can be clearly identified in the middle atmosphere. The temperature measurements by the Rayleigh lidars provide an independent source for validating numerical predictions. Here, we present examples from recent field campaigns which prove the ability of the ECMWF IFS first to resolve mesoscale mountain waves and, secondly, to accurately reproduce the stratospheric temperatures up to an altitude of about 40 ... 45 km.

3. Impact of wind observations in NWP models: recent results

Mode-S analysis and assimilation at KNMI

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We present the beneficial impacts of high-resolution (in space and time) wind and temperature observations from aircraft on very short-range numerical weather forecasting. The observations are retrieved using the tracking and ranging radar from the air traffic control facility at Schiphol Airport, Amsterdam, the Netherlands, but while the network of Mode-S is expanding in Europe. This Schiphol surveillance radar tracks all aircraft in sight every 4 s, generating one million wind and temperature observations per day in a radius of 270 km around the radar. Nowcasting applications will benefit from improved three-dimensional wind fields.

When these observations are assimilated into a numerical model with an hourly update cycle, the short-range three-dimensional wind field forecasts match the observations better than those from an operational forecast cycle, which is updated every 3 h. The positive impact on wind in the first hours of the forecast gradually turns into a neutral impact, when compared to other wind and temperature observations. The timeliness of the forecasts combined with the high resolution of the observations and the extent of their coverage are the main reasons for the observed nowcasting benefits. All in all, the assimilation of high-resolution wind (and temperature) observations is found to be beneficial for nowcasting and short-range forecasts up to 2–3 h. Further work to analyse the quality of Mode-S winds using triple collocation will be presented.

Introduction of Mode-S wind and temperature profiles into ALADIN model

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Mode-S Meteorological Routine Air Report (MRAR) observations are new aircraft temperature and wind observations derived through air-traffic surveillance systems. These observations are assimilated in the ALADIN mesoscale model. I present data smoothing, thinning and results of data assimilation experiments for different seasons. A special focus is given on the initialization of humidity fields (humidity is not observed in Mode-S) through multivariate background error covariances.

Assimilation of the high resolution wind data with the ensemble Kalman filter

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Using perfect model experiments with mass, total energy and momentum conserving 2D shallow water model that also conserves enstrophy for non-divergent flow, we first illustrate the importance of assimilation of the wind data. The data assimilation uses the local ensemble transform Kalman filter (LETKF) with varying localization radius, thinning interval, observed variable and inflation. During assimilation, the total mass remains consistent with that of the nature run and the total energy of the analysis mean converges towards the nature run value. However, enstrophy, divergence, as well as energy spectra are strongly affected by localization radius, thinning interval, and inflation and depend on the variable which is observed. Only observations of wind are able to at least control unrealistic enstrophy increase in one hour data assimilation updates. In this idealized setup, we test the effects on prediction depending on the type of errors in the initial condition. By measuring nonlinear energy cascade through scalar, domain averaged, noise term, we show that the accumulated noise during assimilation and the analysis RMSE are good indicators of quality of the prediction.

Although one can argue that these results might not be applicable to the convective scales applications, we show two applications of assimilation of wind data in the Consortium for Small-Scale Modeling Kilometre-scale Ensemble Data Assimilation (COSMO-KENDA), which couples an ensemble Kalman filter to a 40-member ensemble of the convection permitting COSMO-DE model. First example assimilates aircraft observations of wind and temperature collected by airport surveillance radars [Mode-S Enhanced Surveillance (Mode-S EHS)]. With the high density of Mode-S EHS observations, a reduction of temperature and wind error in forecasts of 1 and 3 hours was found mainly in upper levels and less near the surface. Forecast kinetic energy spectra indicated that the reduction in error is related to analysis updates on all scales resolved by COSMO-DE. In the second example, in addition the radar data were assimilated. We show that assimilation of radial wind data reduces the noise during assimilation. It remains to be seen whether this can be related to better control of enstrophy or divergence.

Results from experiments assimilating densely sampled aircraft wind data in the ECMWF model

Michael Rennie
European Centre for Medium-Range Weather Forecasts (ECMWF)

OSEs were performed using Global Aircraft Data Set (GADS) wind observations (from early 2011) using a recent cycle of the ECMWF global model. GADS provides densely sampled (along the flight-track) observations from British Airways long-haul flights. The observations were assimilated as if Aeolus HLOS winds. We found the need for bespoke QC to stop spurious GADS observations entering the assimilation. O-B statistics for the GADS dataset are found to be consistent with AMDAR data (which are effectively the same observations but much less densely spaced). Some interesting discrepancies e.g. around jet streams, can be found between the ECMWF model and the GADS observations. The analysis increments are investigated along the flight-tracks - the analysis pulls very strongly to the GADS data. Assimilating the densely sampled data with a diagonal R matrix with wind component standard deviation of 2.5 m/s leads to negative impact in the OSEs. This is suspected to be due to not accounting for correlated represenativeness error. Ways to mitigate the assumed problem are investigated. Note that these investigations are not complete and this is presented for discussion purposes.

4. ADM-Aeolus and Mesoscale NWP

Aeolus Level-2B wind products

Michael Rennie
European Centre for Medium-Range Weather Forecasts (ECMWF)

An introduction to ADM-Aeolus Level-2B wind retrievals and their application in NWP will be given. This talk will present the Aeolus L2B processing software, its algorithms and examples of real L2B HLOS wind products from a realistically simulated atmosphere. Details on ECMWF's operational L2B production, which is part of ESA's Ground Segment will be given. The option to download and apply the L2Bp for research in your own research environment, allowing users to tune the L2Bp settings to their own application will be discussed. Using up-to-date realistic simulations of Aeolus we investigate the effect of varying the horizontal averaging length on the L2B HLOS wind errors and then discuss which length-scale may be optimal for mesoscale data assimilation.

Aeolus error characteristics in heterogeneous atmospheric conditions

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The European Space Agency Aeolus mission aims to measure wind profiles from space. A major challenge is to retrieve high quality winds in heterogeneous atmospheric conditions, i.e. where both the atmospheric dynamics and optical properties vary strongly within the sampling volume. In preparation for launch we aim to quantify the expected error of retrieved winds from atmospheric heterogeneity, particularly in the vertical, and develop algorithms for wind error correction, as part of the level-2B processor (L2Bp).

We demonstrate that high-resolution data from radiosondes provide valuable input to establish a database of collocated wind and atmospheric optics at 10m vertical resolution to simulate atmospheric conditions along Aeolus' lines of sight. The database is used to simulate errors of Aeolus winds retrieved from the Mie and Rayleigh channel signals. The non-uniform distribution of molecules in the measurement bin introduces height assignment errors in Rayleigh channel winds up to 2.5% of the measurement bin size in the stratosphere which translates to 0.5m/s bias for typical atmospheric conditions, if not corrected. The presence of cloud or aerosol layers in the measurement bin yields biases in Mie channel winds which cannot be easily corrected and mostly exceed the mission requirement of 0.4m/s. The results show that Aeolus L2Bp, under development, can be improved by the estimation of atmosphere optical properties to correct for height assignment errors and to identify wind solutions potentially detrimental when used in Numerical Weather Prediction.

Assimilation of line-of-sight winds and balance issues: from the tropics to the mid-latitude mesoscale

Nedjeljka Žagar
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Global analysis fields are characterized by significant uncertainties in the tropical analysis fields. Furthermore, the largest spread of global ensemble forecasts in the short range on all scales is in the tropics. Examples for this are presented from the ECMWF ensemble prediction system. The ADM-Aeolus winds are therefore expected to be most valuable in the tropics, where the wind profiles are missing and the mass field adjusts to the wind field. On the other hand, recent results suggest that even with a globally homogeneous network of wind and temperature profiles and using the ensemble Kalman filter data assimilation in the perfect model framework, tropics remain the region of largest analysis uncertainties.

In the talk, I will discuss reasons for this result by applying a scale-dependent decomposition of analysis and forecast uncertainties associated with the balanced and inertio-gravity dynamics. It will be shown that the peak efficiency of data assimilation is on the synoptic scales in the mid-latitudes that are associated with quasi-geostrophic dynamics. In contrast, the variance associated with the inertia–gravity modes, that dominate in the tropics, is less successfully reduced on all scales. Based on previous work, I will suggest that the wind-mass couplings of large-scale inertia-gravity modes may benefit the global assimilation and numerical weather prediction. Furthermore, examples from mid-latitude mesoscale models will be used to raise a similar argument for the mesoscale data assimilation.

Results from mesoscale OSSE with simulated ADM-Aeolus winds and EnKF

Matic Šavli and Nedjeljka Žagar
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In this presentation we discuss the potential impact of the space-borne Doppler wind lidar (DWL) observations expected from the ESA ADM-Aeolus mission in a mesoscale data assimilation system for numerical weather prediction (NWP). The limited-area NWP model is Weather Research and Forecasting (WRF) model that is applied with the ensemble adjustment Kalman filter (DART/WRF). We shall present the new modelling framework developed in the last few years for the observing system simulation experiments (OSSE) with the DART/WRF system nested into the ensemble prediction system of ECMWF.

This is the study addressing the impact of ADM-Aeolus winds with limited-area OSSEs. A number of studies addressed the potential impact of ADM-Aeolus wind profiles in the global ECMWF model and they showed significant benefits of new wind data in the tropics. The impact of new observations in short-term forecasts for Europe has been more challenging to demonstrate.

The ADM-Aeolus measurements will provide wind profiles along the horizontal line of sight (HLOS). The HLOS wind observations need to be combined with prior wind information in order to construct the wind vector. This step crucially depends on data assimilation, especially the background-error covariances. In contrast to the variational data assimilation with static covariances applied in global studies, the application of EnKF in the present study provides the flow-dependent covariances that may show profitable the HLOS observations.

The presentation will focus on the relative value of HLOS observations compared to the two wind components, wind vector and temperature observations. Data assimilation cycling experiments of OSSE type over a Euro-Atlantic domain are carried out for September 2015. The 50-memebr ensemble applies the lateral boundary conditions from the operational ensemble prediction system of ECMWF. The assimilation frequency is 6 hours. Simulated HLOS winds have azimuth 60 degree (clockwise from North) and the same observation error as radio-sonde winds. The results suggest that the HLOS winds are on average more beneficial for assimilation than any of the two components. Reasons for this are discussed on examples of baroclinic development in the northern Atlantic.

5. Mesocale dynamics and data assimilation

Improved mesoscale analyses with 2DVAR

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The two-dimensional variational ambiguity removal (2DVAR) method provides a spatial analysis of the sampled ocean vector winds to resolve the local Advanced Scatterometer (ASCAT) dual wind vector ambiguity. Like other variational meteorological data assimilation systems in numerical weather prediction (NWP), 2DVAR combines ASCAT observations with prior NWP background information, in this case from the European Centre for Medium-range Weather Forecasts (ECMWF). Although 2DVAR is generally effective, it may select the wrong ambiguity under certain conditions, e.g. when the background mislocates frontal areas or low-pressure centres, or when it misses convective systems. The relative influence of the ASCAT and ECMWF wind fields in the resulting 2DVAR analysis field can be controlled by adjusting the background error spatial correlation structure, and the background and/or observation error variances.

In this article an adaptive 2DVAR approach is proposed to improve ASCAT ambiguity removal, using background error spatial correlations estimated from the autocorrelation of observed scatterometer wind components minus ECMWF forecasts, and using observation and background errors estimated from triple collocation analysis on collocated buoy, ASCAT and ECMWF data. The triple collocations are segregated into several categories according to the ASCAT-derived parameters that have proven to be effective in detecting the correct position of frontal lines and low-pressure centres.

Verification using a typical cyclone case and collocated ASCAT and buoy winds shows that the 2DVAR analysis as well as the ASCAT ambiguity removal is improved significantly by putting more weight on the ASCAT observations, using empirically determined spatial background error structure functions, and by incorporating situation-dependent observation/background error variances.

Dynamics of winds and aerosols in four-dimensional variational assimilation

Žiga Zaplotnik and Nedjeljka Žagar
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An ever-increasing amount of remotely sensed data in recent years includes also atmospheric trace constituents. This trend is going to continue with the launch of the ADM-Aeolus that will provide also aerosol profiles along the line-of-sight wind profiles. In spite of new wind profiles, the gap between the available mass-field and wind-field information will remain large. The initialization of wind field will thus often strongly depend on the specification of the data assimilation modeling, especially the representation of the background-error covariances.

This study deals with the potential of the four-dimensional variational data assimilation (4D-Var) to retrieve the unobserved wind field from the observations of atmospheric tracers through the internal model dynamics and the multivariate background-error covariances. It can be argued that some aerosol tracers can be used to describe the transport properties through 4D-Var on short time scales as the advection-diffusion processes are the main cause of their temporal variability and their feedback on the dynamics is weak. However, the presence of non-linear moist dynamics makes this task very difficult.

We investigate the potential of aerosol concentrations to describe transport properties (wind) by assimilating their distribution patterns involving sharp horizontal gradients. For this purpose, we have developed an intermediate complexity model including non-linear interactions between the wind, aerosols and moisture with their sinks and sources. The model is now been using for 4D-Var assimilation studies of OSSE type to address the ability of 4D-Var to extract unobserved wind field from mass-field observations in the tropics. Some preliminary results will be presented including the role of flow nonlinearity, the observations density and the length of the assimilation window.

The growth of forecast uncertainties in mesoscale NWP models due to lateral boundary perturbations

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Forecast uncertainties grow due to initial uncertainties, due to model uncertainties, their combinations and chaotic properties of the system described by the model. In the case of the limited area models, additional source of uncertainties is associated with the update of the prognostic variables by the host model at the lateral boundaries (LBs).

In the ensemble data assimilation and ensemble forecasting, uncertainties associated with lateral boundaries are taken into account in a number of ways, some of which are rather ad hoc. Availability of the 50-member ECMWF ensemble prediction system (ENS) in Europe makes the application of the ensemble Kalman filter for data assimilation relatively straightforward. This work evaluates the contribution of the LBs from the ENS system to the ensemble spread in a limited-area model as a function of the domain size and horizontal resolution.

The two mesoscale models for numerical weather prediction (NWP) are the WRF model and the preoperational version of the AROME at the Slovenian Environmental Agency. The WRF model is applied on a Euro-Atlantic domain that is larger than domains typically used for NWP in Europe and with a resolution similar to that of the coupling ECMWF model. In contrast, the domain of AROME covers western and central Europe with a grid spacing 2.5 km. The two models are used to run 50-member forecast ensemble for selected cases in 2016. Three sensitivity experiments allow to differentiate between the growth of forecast uncertainty due to uncertainties in initial conditions, due to uncertainties at LBs and due to uncertainties in both initial conditions and LBs. We show average results from the three experiments and selected weather situations.