WAsP-CFD Validation Report

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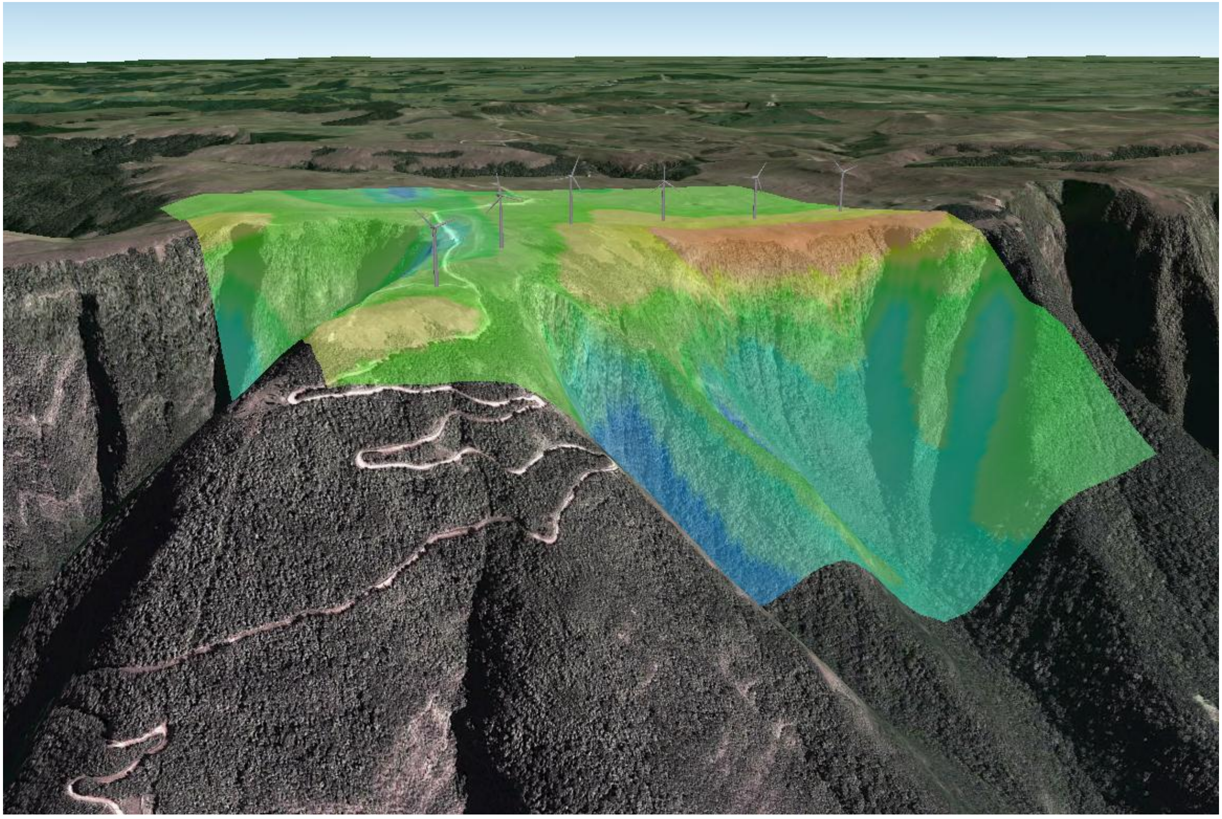

Visualization of WAsP-CFD speed-up at 100m agl. for easterly winds. View is from East.

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Executive summary

EMD has performed a thorough validation of WAsP-CFD. A number of test cases were selected and grouped as “Classical” cases and “Reference” cases.

The results of the classical case “Speed-up versus slope” show that WAsP-CFD speed-ups are consistent with WAsP at low terrain inclinations up to around 5°. At larger inclinations WAsP over predicts speed-ups compared to WAsP-CFD. A maximum in speed-up is found for WAsP-CFD around a slope of 20° where WAsP over-predicts speed-up by roughly 15%. No substantial cross-over of WAsP-CFD and WAsP speed-up is found in contrast to claims in an often cited study.

For the classical case “Original Delta RIX site” (Aveiro-Viseu site) WAsP shows cross prediction errors up to 38%, strongly correlated (R^2=0.95) with Delta-RIX. Using WAsP-CFD cross-prediction errors are within 9% and do not correlate with Delta-RIX (R^2=0.00).

For the classical case “Askervein hill experiment” WAsP-CFD reproduces speed-ups significantly better than WAsP. RMS errors reduce to 1/3, both along the horizontal transect across the Askervein hill and for vertical profile at the hill top. In particular speed-up factors at the lee side of the hill and closest to the ground of the hill top profile are superiorly predicted by WAsP-CFD.

For the six reference cases cross-predictions were performed between the masts on each site. Using top anemometers only, which have the highest data quality, results show a significant and very consistent reduction in RMS cross prediction errors (RMSE) of 0.31±0.04m/s for WAsP-CFD relative to WAsP. On average the RMSE is more than halved and corresponds to a reduction of prediction errors of 4.0±0.5% on mean wind speed or 6-8% on annual energy production. Using measurements at lower heights WAsP-CFD results also show a consistent but smaller improvement relative to WAsP.

WAsP-CFD does not seem to improve predictions of observed wind profiles using standard stability settings on the 15 masts within the six reference sites. Profile RMSEs show a large scatter both for WAsP and WAsP-CFD, but averages are comparable. This suggests that WAsP-CFD performance should not be evaluated solely by means of profile-fit.

WAsP-CFD performance shows a minor dependence on the 2x2km tile configuration. In three of the six reference sites all masts fit in just one tile. RMSE improvements compared to WAsP worsened by averagely 0.04m/s compared to the (optimal) tile configuration with each mast centred in a separate tile.

Conclusions:

- **Validation results document that in complex terrain WAsP-CFD is a significant improvement compared to WAsP.**
- **WAsP-CFD reduced prediction errors on mean wind speed by 4% compared to WAsP, translating to a 6-8% error reduction on AEP predictions.**
- **The reference cases suggest that profile fit alone is not a good overall indicator of WAsP-CFD’s improvement of accuracy in complex terrain.**

Contents

WAsP-CFD Validation Report

This report summarizes and analyses the results of the WAsP-CFD validation effort at EMD. The integration of WAsP-CFD in the general WAsP model framework is briefly described in following.

The basis of the traditional WAsP model [1] is a superposition of four sub models:

1) a model to calculate terrain speed-ups (IBZ),
2) a model to calculate the effect of roughness transitions,
3) a model that predicts the vertical flow perturbations due to non-neutral stability,
4) a model to predict reductions caused by obstacles.

In the WAsP-CFD solution flow perturbations of model components 1) and 2) are replaced by the combined terrain and roughness flow perturbations predicted by the non-linear Ellipsys3D CFD solver running in the "cloud" on EMD's Cerebrum cluster. WAsP model components 1+2 assume neutral stability; this is also the case for the flow perturbations predicted by the WAsP-CFD counterpart. The CFD flow perturbations are relative to an upstream average roughness named "reference" or "mesoscale" roughness which defines the inlet profile for the CFD solver for each of the 36 model sectors.

1 WAsP-CFD validation

The main focus of this study is to evaluate the performance of the WAsP-CFD model, with emphasis on the CFD-based model components. Model performance has been evaluated both by direct evaluation of speed-up factors, and at a higher level using cross-predictions of observed wind climatologies.

In a cross-prediction, observations of the wind climate at one position are used in WAsP-CFD to predict the wind climate at another position which also has observations. Model performance is then characterized by the cross prediction error of the predicted mean wind speed or annual energy production. In case of multiple masts on a site an overall performance measure is the Root-Mean-Square-Error (RMSE) of a set of cross-predictions.

In all cases of this study the performance of WAsP-CFD has been benchmarked against WAsP, which is the current de facto industry standard in wind energy.

A number of test cases have been selected as basis for this study. The test cases are grouped in "Classical" cases and "Reference" cases. The classical cases are cases which are well known and which have already been analysed thoroughly in the literature. The selected classical cases are:

- Speed-up versus terrain slope (theoretical)
- Aveiro-Viseu site, Portugal (original Delta RIX site)
- Askervein hill experiment (1983 experiment)

First classical case "Speed-up versus terrain slope" refers to reproduction of a Japanese theoretical study [2] of speed-up factors for different terrain slopes. This study is important as it has been strongly referenced and used by one of the leading providers of CFD calculation tools for wind energy applications.

Second classical case "original Delta RIX site" is a well-studied site, which was originally used to establish the correction measure named Delta RIX to correct WAsP modelling errors in complex terrain.

Third classical case is the "Askervein hill" atmospheric experiment conducted in 1982-83 in Scotland. This experiment has probably had a larger impact on the wind energy industry, than any other meteorological experiment.

The "Reference" cases were selected as sites with complex terrain, multiple masts and with acceptance of use by the project owner. A large geographical spread was also prioritized. Eventually, just six projects turned out to fulfil these criteria. These six reference projects are named as follows according to their region:

- Oceania
- Central Europe
- North-West Europe
- East Asia
- Central America
- South America

2 Classical cases

2.1 Speed-up versus slope

The classical case "Speed-up versus terrain slope" refers to the Japanese study [2] of speed-up factors for different mean terrain slopes. This study has been widely referenced and used by one of the leading providers of CFD calculation tools for wind energy applications.

Terrain files for five hills shaped as squared cosines have been established with mean slopes: 5%, 10%, 20%, 40% and 80%, defined as the ratio of maximum hill elevation divided by half the total base length of the hill. These slopes correspond to slopes of 3°, 6°, 11°, 22° and 39°.

All hills are 200m high and speed-ups were predicted at 50m agl., 1/4 of the hill height above the hill top as in [2]. The paper uses a roughness length-to-hill-height ratio of 133, equivalent to a roughness length of 1.5m (class 4). In our study we reproduce the calculations for the five hills using all four roughness classes 1 (0.03m), 2 (0.1m), 3 (0.4m) and 4 (1.5m). A total of 20 calculations have been performed both in WAsP and in WAsP-CFD.

The figure below shows the original result from the [2] on the left. Note the cross-over effect around 10° slope. At slopes below 20° MASCOT CFD produces higher speed-ups than WAsP whereas above 20° WAsP produces much higher speed-ups than CFD.

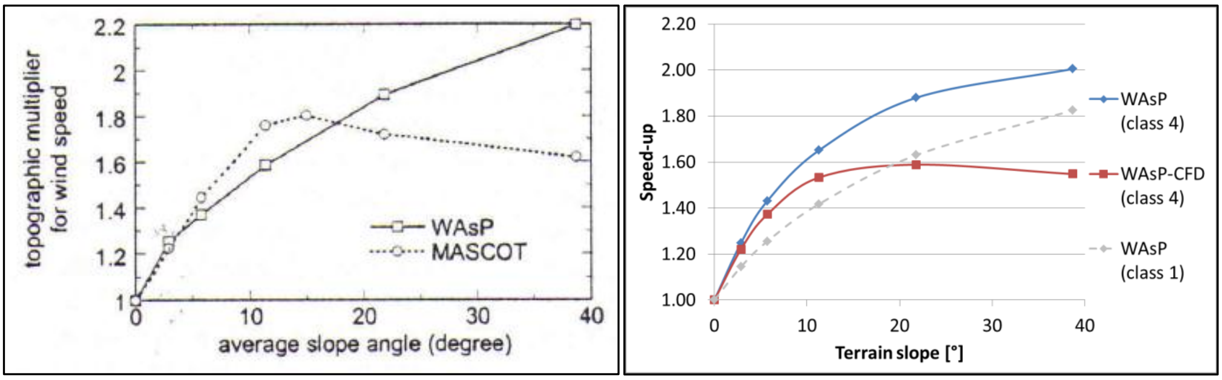

Figure 1: *Left: original results from [2] comparing WAsP and MASCOT CFD. Right: results of this study comparing WAsP and WAsP-CFD.*

The right side of Figure 1 shows the results of this study using the roughness-to-hill-height ratio specified in [2]. Our results do not produce the cross-over effect. Instead WAsP and WAsP-CFD speed-ups are consistent at low slopes as expected for a linearized and a non-linear model – this is the regime where the linear terms dominate and they should be consistent. At larger slopes WAsP-CFD speed-ups behave consistently with MASCOT CFD speed-ups.

The only way to obtain a cross-over as shown in Figure 1 on the left is to compare WAsP-CFD with WAsP results at a wrong roughness class. Using roughness class 1 for WAsP and class 4 for WAsP-CFD, a cross-over of similar shape is reproduced as illustrated with the grey dashed curve in Figure 1. It seems likely that the authors of [2] were not aware that also the speed-ups of WAsP depend on roughness and hence may have used an arbitrary or default roughness.

Figure 2 (below) shows the complete results of speed-up versus slope for the 20 "squared cosine terrain" runs using WAsP and WAsP-CFD including all four roughness classes.

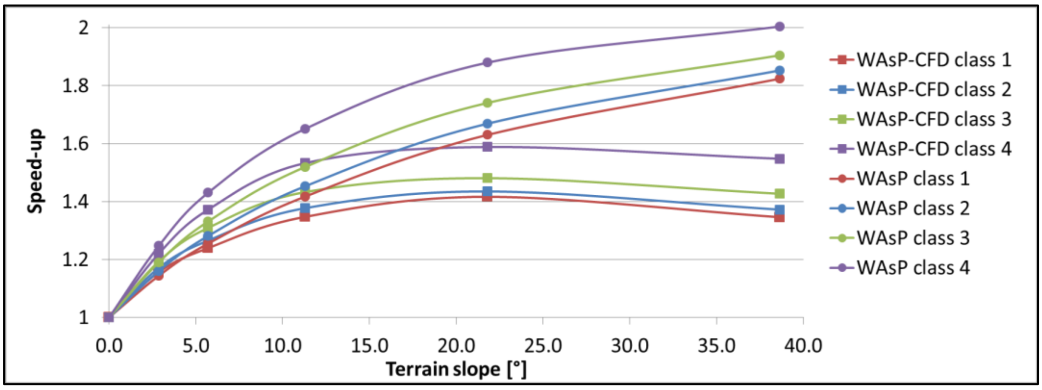

Figure 2: *Speed-up results for all hill slopes and roughness classes.*

Figure 3 shows a sub-set of the runs, showing the speed-up as a function of roughness class for two slopes (5.7° and 21.8°). Notice the relatively strong increase of speed-up with roughness and that WAsP and WAsP-CFD speed-ups have almost identical variation with roughness, but at different levels for 21.8°.

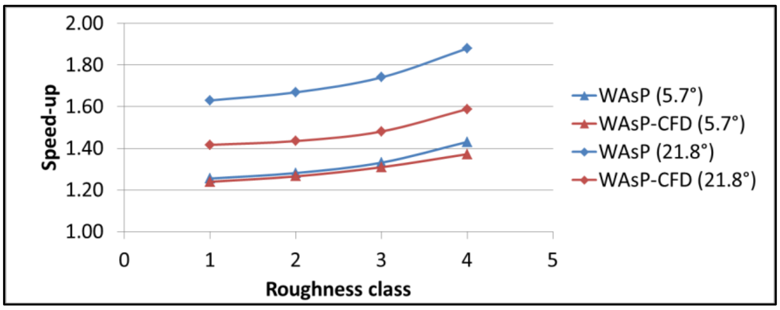

Figure 3: *Speed-up as function of roughness class for two values of hill slope.*

Conclusion

WAsP-CFD speed-ups are consistent with WAsP at low terrain inclinations up to around 5° and both are roughness dependent. At larger inclinations WAsP over-predicts speed-ups compared to WAsP-CFD. A maximum in speed-up is found for WAsP-CFD around a slope of 20° where WAsP over-predicts speed-up by roughly 15%. No substantial cross-over of WAsP-CFD and WAsP speed-up is found in contrast to claims in an often cited study.

2.2 Original Delta-RIX site (Aveiro-Viseu site)

The Delta RIX analysis and correction method for WAsP in complex terrain was developed in [3] and earlier publications. The analyses were based on data from the Aveiro-Viseu site, typically including the five masts M06-M10 measuring at 10m agl..

Delta RIX analysis for WAsP cross-predictions between the five masts M06-M10 is illustrated in Figure 4 as the blue points and trend line. The X-axis shows mast-to-mast differences in “Ruggedness IndeX” (Delta RIX) and the Y-axis a logarithmic measure of the prediction error. Note the strong correlation (R^2=0.95) of Delta RIX and the logarithmic prediction error. The maximum prediction error is 38% when mast M10 predicts mast M06. The cross-prediction results using WAsP-CFD are shown in Figure 4 in red. Logarithmic prediction errors and Delta RIX show no correlation (R^2=0.00) and prediction errors are within 9%.

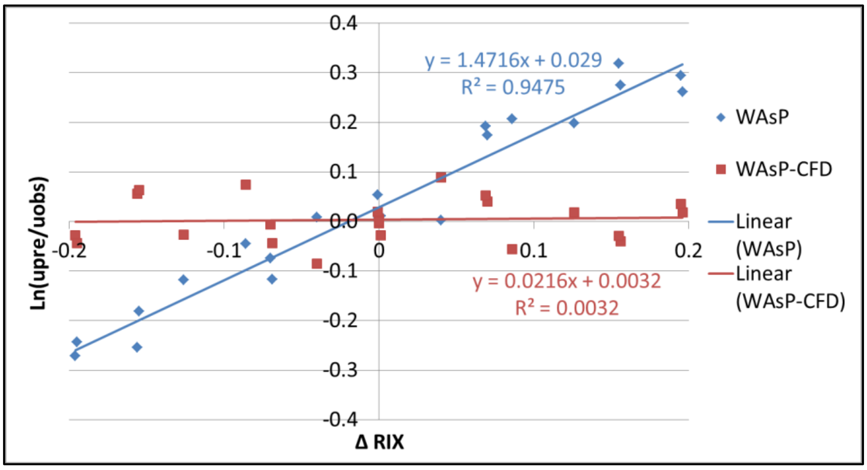

Figure 4: *Delta RIX plot and fit for WAsP (blue) and WAsP-CFD (red).*

Conclusion
For the original Delta RIX site WAsP-CFD reduces the maximum prediction error to 1/4 relative to WAsP. In addition the strong correlation of WAsP prediction errors with Delta RIX is fully removed using WAsP-CFD.

2.3 Askervein hill

In this study two of the key data runs from the 1983 Askervein hill experiment [4] have been modelled. The SW-NE transect across the hill top measured at 10m agl. and the vertical profile measured at the hill top measuring at 3, 5, 8, 15, 24 and 34m agl.. During measurement of these data the atmospheric stability was near neutral and the mean wind direction was 210°.

Figure 5 below shows the results for the horizontal transect on the left. Measurements have been normalized to show the speed-up as the relative deviations from the measurement at an up wind reference mast. Model results for WAsP and WAsP-CFD have been normalized in a similar way to show the relative deviation to the speed-up at the reference mast. Note the strong similarity of the measurements and the WAsP-CFD speed-up curves, in particular for the right part, the leeside of the hill. The total RMS prediction error for all points on the transect reduce to 1/3 for WAsP-CFD compared to WAsP.

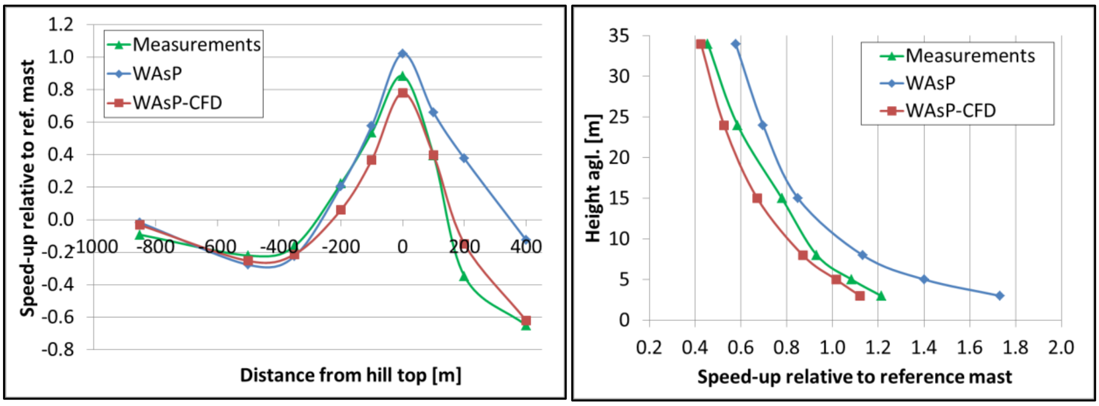

Figure 5: *Left: data and modelling results for the 10m transect. Right: vertical profile at the hill top. In both cases data and predictions are normalized to show fractional speed-up relative to an up-wind reference mast measuring both at 10m and each of the heights in the profile.*

The right part of Figure 5 shows the results for the vertical profile at the hill top. Again measurements and predicted speed-ups are shown as relative deviations for measurements or predicted speed-ups at the same level of the reference mast. Also for the profile WAsP-CFD seems to capture the shape of the measurements better, in particular near the ground. Again the RMS prediction error is reduced to 1/3 compared to WAsP.

For both the horizontal transect and the vertical profile, the data and model predictions may instead be (re-)normalized to a point on the transect or profile itself. Generally, such re-normalisations seem to emphasize the superior performance of WAsP-CFD even more.

Conclusion

For the Askervein horizontal transect and for the hill top wind profile, WAsP-CFD clearly captures the variations in observed speed-ups more accurately. In both cases the total RMS prediction error reduces significantly to 1/3 compared to WAsP.

3 Reference cases

The reference sites were selected prior to any evaluations using WAsP-CFD so the selection procedure does not bias the results. The analysis of model performance is decomposed into lateral cross-predictions between observations at same height and in prediction of the vertical profile at each mast. The former is the most direct evaluation of the actual CFD-solution as the WAsP stability model will not influence this performance. The latter on the other hand is strongly influenced by the settings of the WAsP stability model. In all runs default stability settings have been employed, hence, profile fit could be further optimized by tuning the WAsP/WAsP-CFD stability parameters for each site. However, as the stability model is a post processing and is identical for WAsP and WAsP-CFD such analysis would not contribute to the validation of the actual CFD solution for terrain and roughness in WAsP-CFD.

3.1 Same height mast-to-mast cross predictions

For a prospect wind energy site the top level anemometers generally provide the highest data quality, as often double anemometry is employed or carefully top mounted instruments. These set-ups limit the mast disturbance effects or allow compensation of such biases by always using the upwind instrument. In addition the majority of present day sites collect measurements at or near the expected hub height. Hence, the most critical modelling error is that associated with predicting the wind climate at other lateral positions on a site at the same height as the top-level anemometers.

Top-level same height cross-predictions have been performed for the masts at the six reference sites and the results are illustrated in Figure 6 below. The blue curve shows the RMS cross-prediction errors for WAsP at each site and the red curve shows RMS errors for WAsP-CFD. For all sites the RMS error is significantly lower for WAsP-CFD as shown by the green curve which is the reduction in RMS error of WAsP-CFD versus WAsP. The green curve varies consistently around 0.3 m/s with a mean of 0.31±0.04m/s.

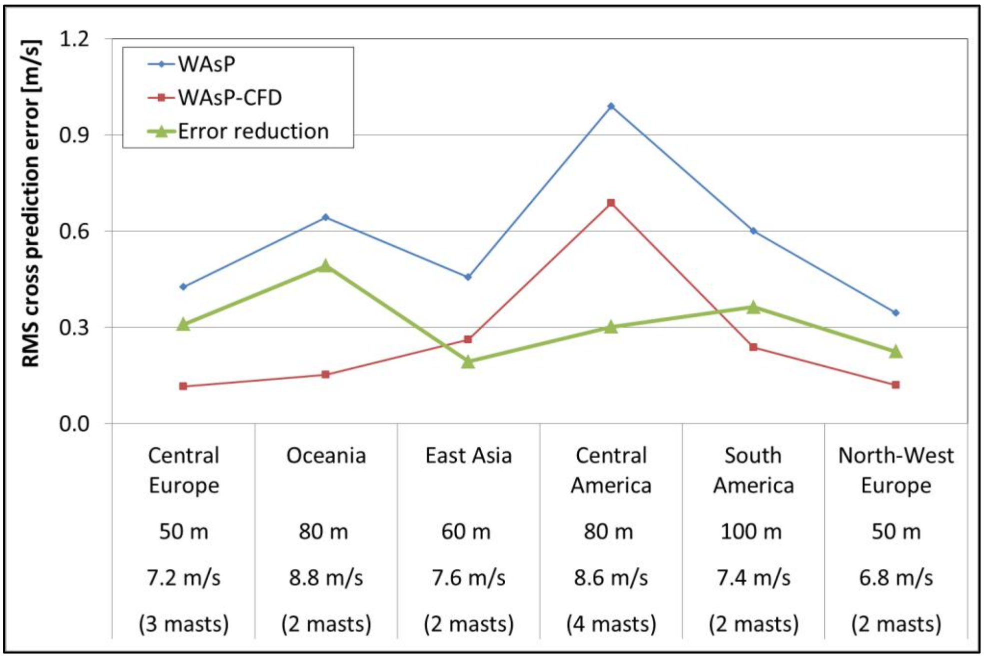

Figure 6: *RMS cross-prediction errors between top level anemometers for each of the six reference sites. RMS errors are shown for WAsP and WAsP-CFD as well as the reduction obtained using WAsP-CFD.*

Relative to WAsP the WAsP-CFD RMS prediction errors are more than halved. In per cent of observed mean wind speed at the six sites RMS error reductions average to 4.0±0.5%, which corresponds to a 6-8% reduction of error on annual energy production.

When all relevant heights are compared in the same height cross-prediction analysis the results still show a consistent WAsP-CFD improvement for all heights and sites (see Figure 7).

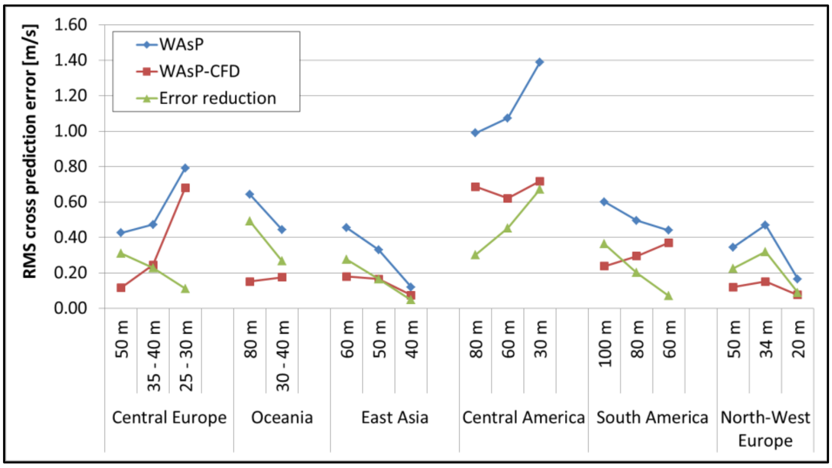

Figure 7: *RMS cross-prediction errors at same height (approximately), shown for all sites and heights analysed.*

However, for heights below the top levels the improvement of WAsP-CFD is less pronounced as indicated by the decreasing trend of the green curves showing WAsP-CFD RMS error reduction. Only the Honduras site shows larger error reductions at lower heights, which is the expected behaviour. The remaining five sites behave contrary to what would be expected, and contrary to what is seen for the Askervein hill profile, which shows largest improvements for the lower heights.

Possible explanations for this behaviour could be limited resolution of the terrain description. In case the contour map is too smooth and does not accurately describe the fine scale terrain complexity, these effects will naturally be underestimated by WAsP-CFD. As we have seen already WAsP would overestimate the effects and perhaps (for the wrong reasons) balance the slightly underestimated terrain effects closest to the surface.

Another contribution could be the lower quality of the lower measuring heights, with more pronounced mast effects and larger uncertainty. However, this does not explain the systematic decreasing trend of the green curves in Figure 7, which remains to be fully understood.

3.2 Vertical profile predictions at each mast

In total, there are 15 masts on the six reference sites, and each mast has multiple measuring heights. Using the top level measurement, how well are the other measuring heights on the same mast predicted? Figure 8 answers this question using WAsP (blue curves) and WAsP-CFD (red curves). For both models the variation is large even within each site, and no clear improvement is seen using WAsP-CFD. On average the RMS profile prediction-errors are very close: 0.18±0.04m/s (WAsP-CFD) and 0.19±0.05m/s (WAsP), suggesting that WAsP-CFD does not significantly improve the profile fits.

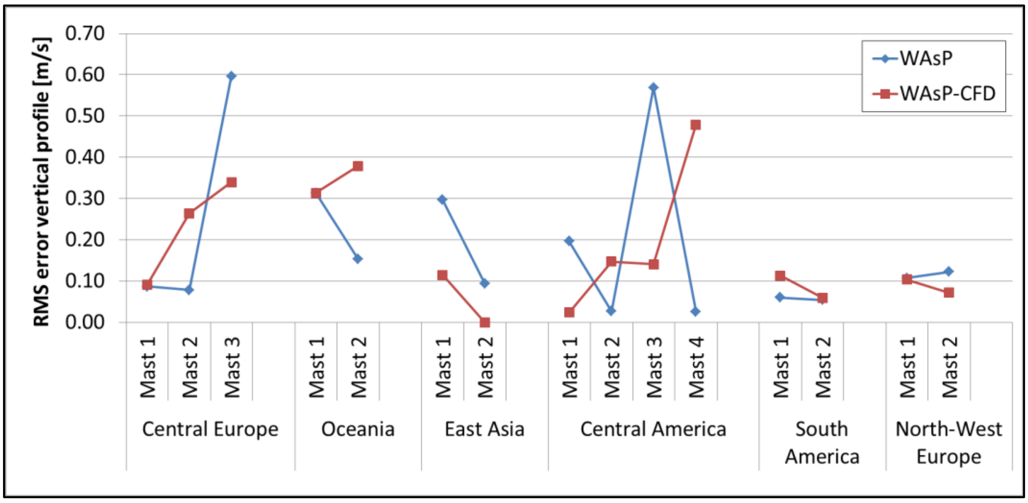

Figure 8: *RMS error for the vertical profile fit using the top level anemometer as predictor.*

These (disappointing?) results may be explained by the following two effects:

1) For both models the vertical profile is strongly controlled by the WAsP stability model, which is a post-processing added after the actual flow calculation. Improvements due to the WAsP-CFD solution may for the vertical profile be relatively small compared to the perturbations of the stability model and hence less significant. For consistency all WAsP and WAsP-CFD runs are done using default WAsP stability settings. Site specific adjustments to the stability settings could likely improve the profile fits and further emphasize/improve the significance of the WAsP-CFD improvements also for the profile fit. This is indeed seen for several sites run using neutral or site specific stability, but is beyond the scope of this study.

2) In section 3.1 the six reference sites show a general decreasing WAsP-CFD improvement closer to the ground. This height dependent effect may explain a smaller part of the apparent insignificant improvement of profile fits using WAsP-CFD.

Conclusion

In conclusion, the overall significant improvements in the WAsP-CFD results seen for the six reference sites are not reflected in improved predictions of the vertical profile at the 15 masts within the sites. This suggests that evaluation of WAsP-CFD improvements should not be based solely on profile fit, which will not reflect the large improvements in cross predictions seen with multiple masts.

3.3 Dependence on tile configuration

The WAsP-CFD solution requires a site area to be modelled as a number of 2 km x 2 km tiles. Each tile is run as a separate CFD calculation. Hence, tiles may be placed in many different configuations. For three of the six referene sites all masts could fit within one tile. For these sites the WAsP-CFD calculations were also run using one common tile in addition to the general setup used for all reference sites with a tile contered on each mast. Results using the two tile configurations are presented in Figure 9.

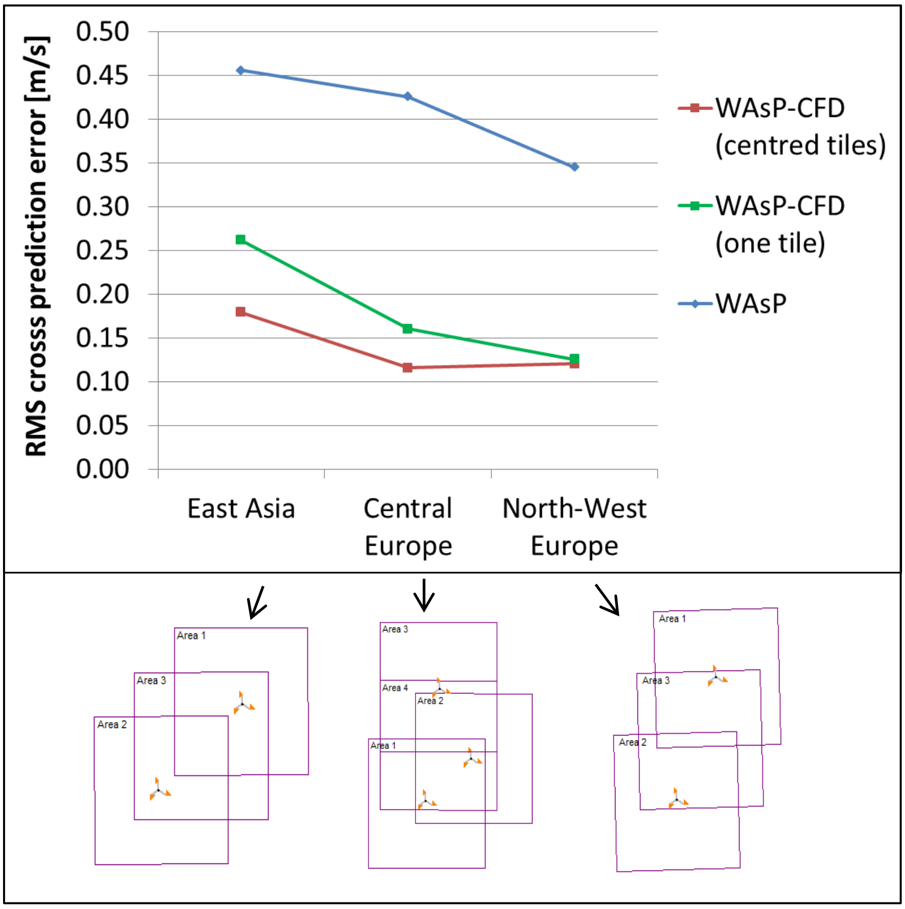

Figure 9: *Top: RMS cross-prediction errors for WAsP (blue) and for WAsP-CFD using two different tile configurations (green and red) for three of the six reference sites. The green curve represents all masts within same tile and the red curve the results when all masts are centred in their own tile. Bottom: tile configurations for each of the sites.*

The all-in-one-tile run shows higher RMSEs and, thus, a smaller improvement to WAsP when compared to the each-mast-centred-in-a-tile run. Averagely, the RMSEs deterioate by 0.04m/s.

Conclusion

A minor dependence on tile configuration must be expected with WAsP-CFD. Results for the reference sites suggest that this error on average is <0.05m/s. Improvements of WAsP-CFD are still fully significant for non-optimal tile configurations with target areas near the edge or corner of a tile.

4 References

[1] Troen, I. and Petersen, E. L., 1989, European Wind Atlas, ISBN 87-550-1482-8, Risø National Laboratory, Roskilde. 656 pp.

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[4] Taylor, P. A, and Teunissen, H. W., 1984, The Askervein Hill Project: Report on the sept/oct 1983, main field experiment. Technical report, Atmospheric research.