



10 Appendix

10.1 Appendix 1

SKILL SCORE PARAMETERS											
Skill A. Model parameters	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
A1. Mathematical model - what is the complexity of the underlying aerodynamic equations?	0%	10% - linear / conservation of mass	20%	30%	40% - RANS	50% - RANS	60% - URANS	70%	80% - DES	90% - LES	100% - DNS
A2. Mathematical model - what is the complexity of the underlying thermodynamic equations (including temperature and coriolis force modelling)?	0% - none	10%	20%	30%	40%	50% - medium	60%	70%	80%	90%	100% - high
A3. Time step - how well does your chosen time step conform to the recommendations for your model and set-up?	0% - not at all	10% - partly	20% - partly	30% - partly	40% - partly	50% - partly	60% - mostly	70% - mostly	80% - mostly	90% - mostly	100% - completely (or not applicable)
A4. Simulation period - how well does the simulation period reflect the entire measurement period?	0% - not all	10%	20% - poorly	30%	40% - reasonably	50%	60% - fairly well	70%	80% - very well	90%	100% - all effects are fully captured
A5. Grid quality - how well are the software recommendations regarding orthogonal quality, skewness and aspect ratio fulfilled?	0% - not at all	10% - partly	20% - partly	30% - partly	40% - partly	50% - partly	60% - mostly	70% - mostly	80% - mostly	90% - mostly	100% - fully (or not applicable)
A6. Grid quality - has grid independency been proven via a grid study?	0% - no	10%	20%	30% - yes, but with major problems	40%	50%	60%	70% - yes, with some minor problems	80%	90%	100% - yes (or not relevant)
A7. Grid quality - are the estimated y+ values within the software recommendations of the applied boundary layer model?	0% - not at all	10% - partly	20% - partly	30% - partly	40% - partly	50% - partly	60% - mostly	70% - mostly	80% - mostly	90% - mostly	100% - fully (or not applicable)
A8. Domain size - how well do the domain dimensions allow the flow to be properly captured?	0% - not at all	10% - partly	20% - partly	30% - partly	40% - partly	50% - partly	60% - mostly	70% - mostly	80% - mostly	90% - mostly	100% - fully
A9. Convergence - how well does your model convergence meet the required convergence criteria?	0% - not at all	10% - partly	20% - partly	30% - partly	40% - partly	50% - partly	60% - mostly	70% - mostly	80% - mostly	90% - mostly	100% - fully
A10-A12. Operating envelope - if you are using WAsP or a linear model, what is the average dRIX value for all wind sectors at the validation mast 1?	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%

Appendix 1(a). Comparison Metrics parameters: Skill A.



SKILL SCORE PARAMETERS

SKILL SCORE PARAMETERS											
Skill B. Input data quality											
B1. Measurement data - how do you assess the general quality of wind data you have been provided with?	0% - no data	10%	20%	30% - simulation / reanalysis data	40%	50%	60% - non-IEC-conform met mast(s)	70%	80% - one IEC-conform met mast	90%	100% - multiple IEC-conform met masts
B2. Measurement data - how well did you filter the measurement data?	0% - no filtering	10%	20%	30%	40%	50% - some basic filtering	60%	70%	80%	90%	100% - all unrealistic points were removed
B3. Quality of terrain data - what is the ratio of horizontal resolution as a % of your domain length?	0% - 0.05% or lower	10%	20% - 0.2%	30%	40% - 0.4%	50%	60% - 0.6%	70%	80% - 0.8%	90%	100% - 1% or higher
B4. Quality of land cover data - how well does the land cover data you have been provided with depict the real situation?	0% - not at all	10%	20% - poorly	30%	40%	50% - reasonably well	60%	70%	80% - very well	90%	100% - extremely well (or not relevant)
B5. Quality of atmospheric data - how do you assess the general quality of atmospheric data you have been provided with?	0% - none	10%	20% - poor	30%	40%	50% - not bad	60%	70%	80% - good	90%	100% - excellent (or not relevant)
Skill C. Wind model calibration and validation											
C1. Validation of model - If you have previously validated the wind model for other sites, what was the average deviation between simulations and measurements for a site of similar complexity?	0% - no validation	10%	20%	30%	40% - deviation > 10%	50%	60%	70%	80%	90%	100% - deviation < 5%
C2. Wind speed calibration quality - which wind speed calibration method did you use? (please describe in detail in the model description)	0% - none	10%	20% - linear scaling of average wind speed at one height	30%	40% - linear scaling of average wind speed at one height for all wind sectors	50%	60% - linear scaling of average wind speed at many heights	70%	80% - linear scaling of average wind speed at many heights for all wind sectors	90%	100% - direct input of data at calibration mast
C3. Wind speed calibration quality - how well does your input data method capture the wind profile actually measured at the calibration mast?	0% - very poorly	10% - poorly	20% - poorly	30% - poorly	40% - not bad	50% - not bad	60% - fairly well	70% - fairly well	80% - very well	90% - very well	100% - very well

Appendix 1(b). Comparison Metrics parameters: Skill B and Skill C.



SKILL SCORE PARAMETERS

Skill D. AEP calculations											
D1. Wind sectors - which wind sector extrapolation method are you applying?	0%	10%	20% - results of one wind direction and speed scaled with wind rose	30%	40% - results of two wind directions scaled with wind rose	50%	60% - results of three wind directions scaled with wind rose	70%	80% - results of six wind directions scaled with wind rose	90%	100% - all wind sectors were simulated
D2. Wind sectors - how are different wind speeds in different sectors taken into account?	0% - wind speed kept constant	10%	20%	30%	40%	50% - some sectors were simulated with its average wind speed	60%	70%	80%	90%	100% - each sector was simulated with its average wind speed (or we showed this wasn't necessary)
D3. How well did you account for flow turning?	0% - no turning	10%	20%	30%	40%	50% - turning accounted for in half the sectors simulated	60%	70%	80%	90%	100% - turning accounted for in each simulated sector
D4. Long-term AEP - which long-term extrapolation method is applied?	0% - none	10%	20% - low quality reference data and correlation	30%	40%	50% - reasonable quality reference data and correlation	60%	70%	80% - high quality reference data and correlation	90%	100% - the calibration mast data was 20 years long
D5. Rotor area extrapolation - which rotor area extrapolation method is applied?	0% - hub-height wind speed only	10%	20%	30%	40% - rotor equivalent wind speed with 3 heights	50%	60%	70% - rotor equivalent wind speed with 10 heights	80%	90%	100% - entire disc area
Skill E. Other parameters											
E1. Skill of user - how many years of experience do you have with the applied model?	0%	10%	20% - less than one year	30%	40% - 1-2 years	50%	60%	70%	80% - 3-4 years	90%	100% - 5+ years
E2. Skill of user - on a scale of 0-100%, how do you rate your own ability to apply the chosen model correctly?	0% - very poor	10%	20%	30%	40%	50% - not bad	60%	70%	80%	90%	100% - world-leading
E3. Robustness of model - what is the status of the applied model?	0% - no validation or experience	10%	20% - first user experience gained	30%	40% - initial validation reached and positive user feedback received	50%	60% - multiple successful validations and user experience reports	70%	80% - new industry tool	90%	100% - well-established industry tool

Appendix 1(c). Comparison Metrics parameters: Skill D and Skill E.



10.2 Appendix 2

Step 1: processing of the wind data

The actions carried out in this step consist of:

- **Data preparation:** the provided data is checked for feasibility, the calibration of the sensors is examined, the data is cleaned and filtered, resulting in a new set of cleaned data for each sensor provided.
- **Choice of "calibration" data sensor:** this sensor is used to provide input data for the simulations, either directly (as for *WindPro* and *WindSIM*) or indirectly (as for *Fluent* and *CFX*) as discussed in Step 7.
- **Choice of "validation" data sensor:** a second dataset at a different location (preferably far away from the reference position) is required in order to validate the data, i.e. to quantify the accuracy of the simulations, as discussed in Step 8.
- **Choice of overlapping time period:** the validation of the simulations can only be carried out using calibration and validation data over the same time period. Therefore if a validation is carried out, an overlapping time period must be chosen and both data sets filtered accordingly. The longest overlapping time period possible should be chosen in this step, in order to ensure that the data sets are representative of a full year.
- **Long-term extrapolation of calibration and validation data:** if the results are to be used to estimate the long-term Annual Energy Production (AEP), the measurement data needs to be extrapolated for a 20-year period. This includes the choice of the long-term data source(s) (e.g. MERRA data, weather station data, a second met mast at the site, etc.) and of the method (e.g. MCP).
- **Classification of data into pre-defined wind direction sectors:** for some tools (such as *WindPro* and *WindSIM*), this step is carried out within the tool itself. For *CFX* and *Fluent*, however, this step has to be carried out as part of Step 1. In wind energy, twelve sectors of 30° size are commonly defined and the data classified accordingly.

In this project, this step was carried out together to ensure that the same input data was used for the simulations.

Step 2: processing of the site data

In this step, the following actions are carried out:

- **Read in and convert terrain data:** the provided terrain data is read in and converted to the correct format for creating raster data.
- **Read in and convert roughness data:** the provided roughness data is read in and converted to the correct format for creating raster data.
- **Combine data into raster:** the converted terrain and roughness data is combined into raster data for the next step.

This step is carried out in *WindPro* and *WindSim* automatically. For *Fluent*, *CFX* and *PALM*, this step was carried out via in-house scripts as described in Section 3.1.4.

Step 3: Creating a 3D digital model.

In this step, the following actions are carried out:



- **Define model domain extent and model height:** Depending on the dimensions of the site, the computational power available and the accuracy of results required, the dimensions are chosen.
- **Create model for each wind direction to be simulated:** For some tools, only one model is needed and the inflow direction is changed (*WindPro*, *WindSim*, *CFX*). For *Fluent*, the geometry is rotated and the inflow direction is kept constant.

This step is carried out in *WindPro* and *WindSim* automatically. For *Fluent*, *CFX* and *PALM*, this step was carried out via in-house scripts as described in Section 3.1.4.

Step 4: Creating the mesh

In this step, the following actions are carried out:

- **Choose mesh type (structured / unstructured):** The type of mesh is chosen.
- **Define cell size (horizontal/vertical):** The horizontal and vertical cell sizes are chosen.
- **Define main domain expansion factor:** The main domain expansion factor is defined.
- **Define boundary layer cell size and expansion rate:** The boundary layer cell size and expansion rate is defined.
- **Create mesh:** The mesh is created.

This step is carried out automatically by *WindPro* and *WindSim*. In *Fluent*, the surface model is transferred to the meshing programme *Pointwise*, which automatically generates a structured mesh with the desired resolution using a *Glyph2* script, which then projects it onto the surface model. A structured mesh up to the defined maximum height is then generated and optimised using internal functions. Boundary conditions such as inlet and outlet are assigned to the resulting 3D domain and exported as a *Fluent* setup file (.cas). The time needed for mesh generation can therefore be reduced to a minimum. In *CFX*, a fully automatised in-house mesh generator is used to generate a hexahedral mesh within the user-specified volume. The land cover as well as the digital elevation model are read in dxf- and grid-file format, respectively, and cut along the boundaries of the computational domain. The extent of the computational domain, the horizontal and vertical cell sizes are set in an input text file. The mesh resolution in the vertical direction, especially near the wall, can be well controlled by defining distances of grid lines or growth factors. For a defined ground layer thickness the cells are extruded perpendicular to the ground surface as far as possible. The tool reliably produces high quality meshes in CGNS-format within seconds.

Step 5: Setting up the simulation domain

In this step, the following actions are carried out:

- **Enter boundary conditions (wind speed and profile, other factors):** the wind speed profile and other factors such as turbulence intensity are entered.
- **Enter turbulence model:** The chosen turbulence model is entered.
- **Choose number of iterations/time interval:** The number of iterations/time interval is chosen.
- **Define other simulation parameters:** Any other simulation parameters such as stability factors are defined.

This step is carried out in *WindPro* and *WindSim* automatically. For *Fluent*, *CFX* and *PALM*, this step was carried out via in-house scripts as described in Section 3.1.4.



Step 6: Running the simulations

In this step, the following actions are carried out:

- **Define processor speed, number of cores, etc.:** The processor speed and number of cores are defined.
- **Create run script:** A run script is created.
- **Run simulation:** The simulations are run.

This step is carried out automatically by *WindPro* and *WindSim*. In *Fluent*, a scheme script merges the automatically generated inputs and important parameters such as time step length and turbulence model. Monitoring points and lines are created for the assessment of wind conditions at pre-defined locations. The script currently works in a way that in a first step a stationary RANS simulation is performed. This data is then used as initialisation for a transient SBES simulation. For *CFX*, the ANSYS *CFX5PRE* software is used for the build-up of the numerical set-up. Solver settings, roughness lengths and functions implementing the anelastic formulation, Coriolis force as well as the canopy model are defined for all the computed cases. They are used for all the cases computed and therefore only the boundary conditions coming from the Python pre-processing tools have to be initialised.

Step 7: processing of the results

In this step, the following actions are carried out:

- **Classification of measured calibration time series into wind direction sectors:** the measurement time series from the "calibration" data defined in step 1 are classified into the wind direction sectors that were also defined in step 1. In this project, 12 sectors of 30° size starting at 0° (meaning a bin containing all wind directions between -15° and 15°) are used.
- **Averaging of measured calibration and validation wind speed and direction time series per sector:** for each sector, the measurement time series data for both the "calibration" and "validation" sensor is averaged over the overlapping time period chosen in step 1.
- **Calculation of calibration factor = simulated/measured wind speed at calibration location:** the calibration factor is calculated for each sector by dividing the average simulated wind speed at the calibration location by the average measured wind speed at the same location.
- **Calibration of simulated wind speeds:** the simulation results for each sector are all multiplied by this calibration factor, ensuring that the simulated average wind speed at the calibration location is equal to the measured average wind speed.
- **Export of calibrated simulated wind speed and direction data per sector at calibration and validation locations:** this calibrated data is then exported at the calibration and validation locations, as well as for any other locations that are being examined (e.g. wind turbine locations).
- **Export of other flow details:** any other flow details to be examined, such as wind speed contours of a plane at a fixed distance above the ground, are exported for further analysis.
- **Calculation and comparison of speed-up factors and turning per sector for validation location from each simulation:** the speed-up factor at the validation location is defined as the ratio of wind speed at the validation location to the wind speed at the calibration location. The turning is the difference in wind direction between the validation and calibration location.



- **Correction of sector definitions due to flow turning between inflow and calibration mast:** if the flow has turned more than $\pm 15^\circ$ between the inflow and the calibration location, the sector definitions have to be corrected, otherwise the incorrect speed-up factors will be defined.
- **Calculation of wind speed and direction time series at validation location from calibration time series from speed-up factors and turning:** the speed-up factors and turning are used to generate a new time series at the validation location. Each wind speed is multiplied by the simulated speed-up factor for the sector in which it is located. The turning is added to the wind direction to get the expected wind direction at the validation location.
- **Calculation of power at each data point using calculated wind speed and the power curve:** for each data point, the new wind speed is converted to power by interpolating the provided power curve.
- **Sum all power time series and multiply by time:** The total energy production over the overlapping time period is obtained by summing all the powers and multiplying this by the total number of hours.
- **Multiplication of energy with the ratio of measured time to time in a year per sector:** The Annual Energy Production (AEP) is then obtained by multiplying the total energy over the overlapping time period with the ratio of measured time to the total time in one year for each sector.

For all models, this step is carried out using a combination of in-house post-processing tools and a shared Excel sheet to summarise and unify the results.

Step 8: Checking the quality of the data

In this step, the following actions are carried out:

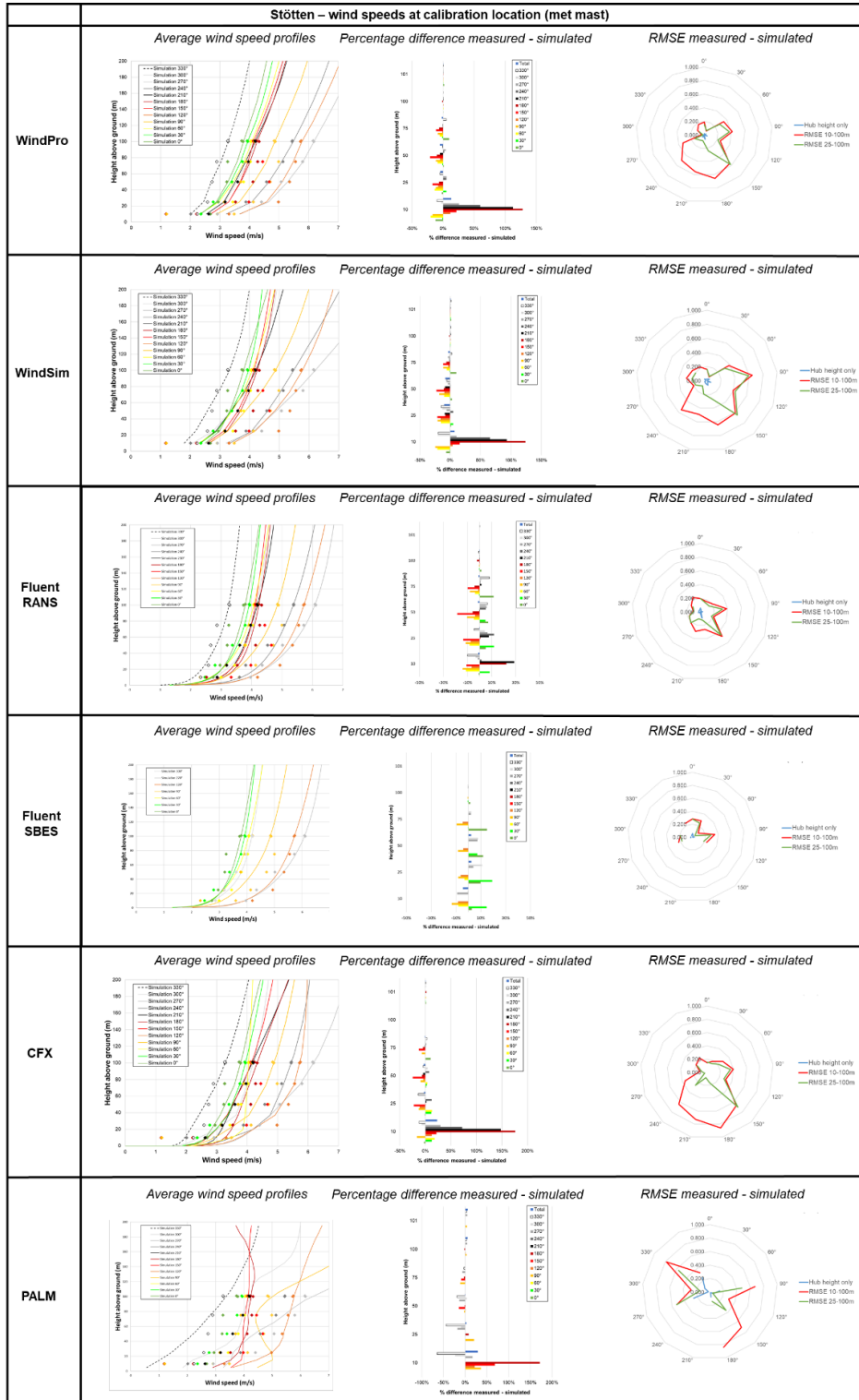
- **Calculate absolute differences in wind speed and direction per sector:** For each sector, the absolute difference between average measured and simulated wind speeds and directions are calculated. If the validation data contains more than one height, the differences are calculated for each height.
- **Calculate wind speed Root Mean Square Error between measurements and simulations per sector:** For each sector, the RMSE between measurements and simulations is carried out. If the validation data contains more than one height, RMSE values are calculated for (a) the entire profile, (b) only the rotor area, and (c) only hub-height (then the RMSE value is the same as the absolute difference).
- **Calculate theoretical AEP that would be ideally produced using the validation wind speed time series:** for comparison purposes, the validation sensor time series wind speed data is used in combination with the power curve to obtain the expected AEP using the method from Step 7.
- **Calculate percentage difference in total AEP between simulations and measurements:** the percentage difference between the theoretical AEP and the simulated AEP is calculated.
- **Collect and summarise Comparison Metrics estimations and complex terrain classification:** the Comparison Metrics and complex terrain classification results that have been entered in the Google Forms as described in Section 3.1.2 are collected and summarized for each model in an Excel file.



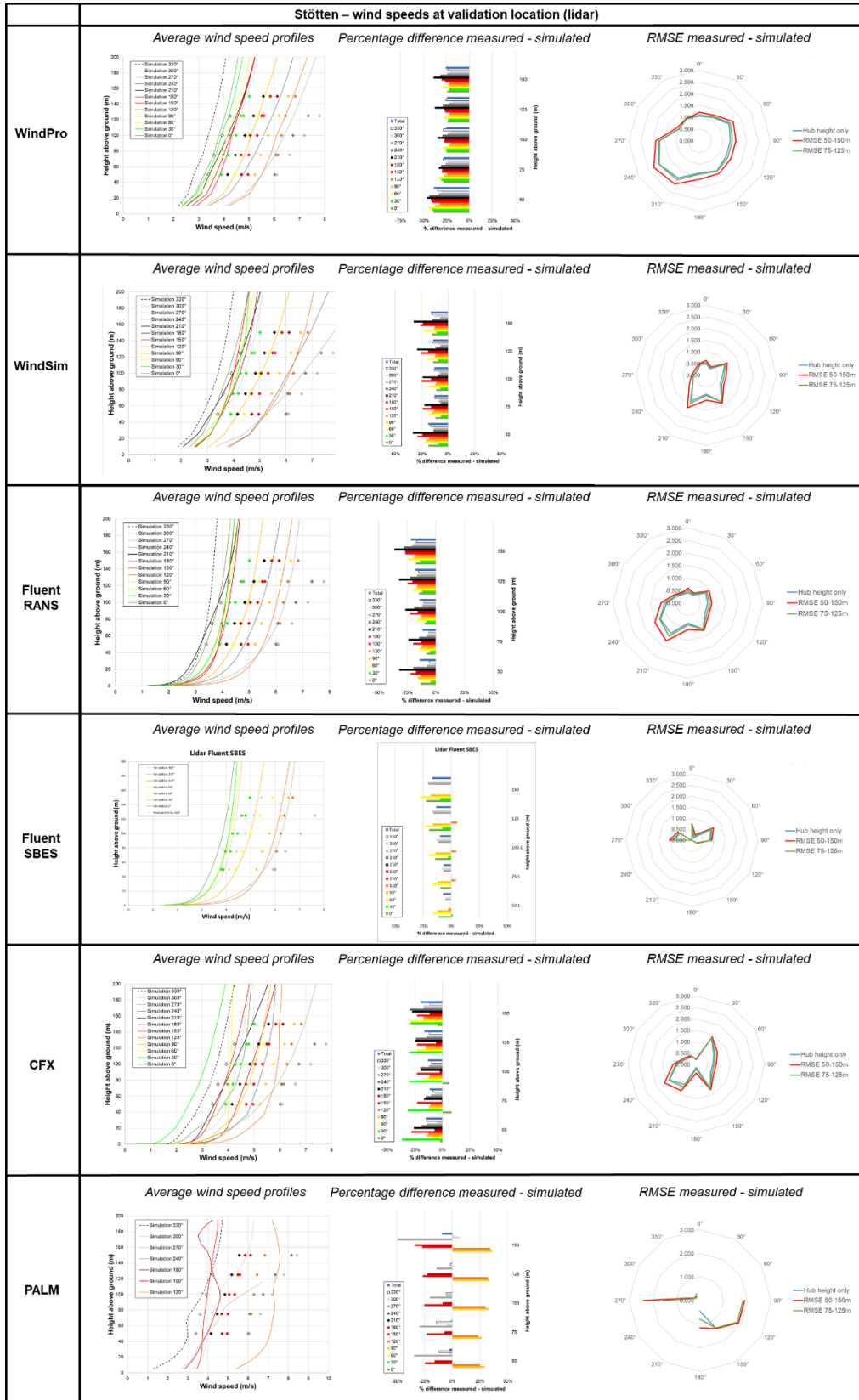
- **Combine results and produce Comparison Metrics charts:** the RMSE wind speeds and percentage difference in AEPs are entered into the summary Excel, and the Comparison Metrics charts are created.

This step is carried out in a combined Excel summary sheet.

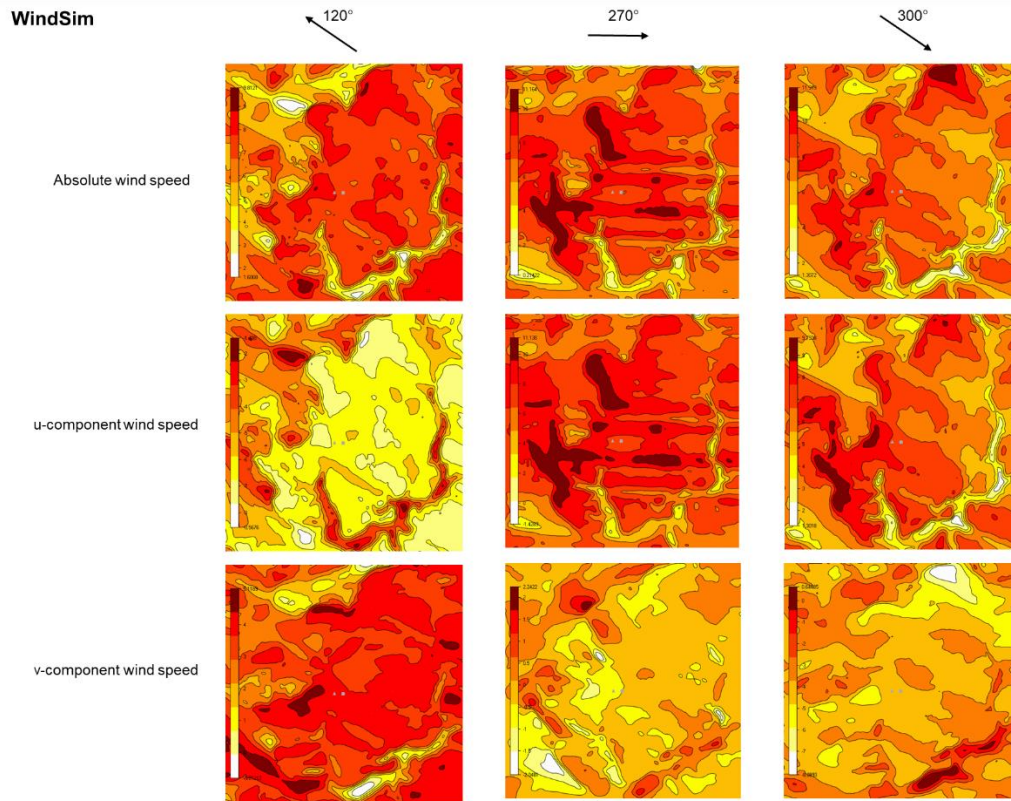
10.3 Appendix 3



Appendix 3(a). Stötten wind speed profiles for calibration location (met mast).



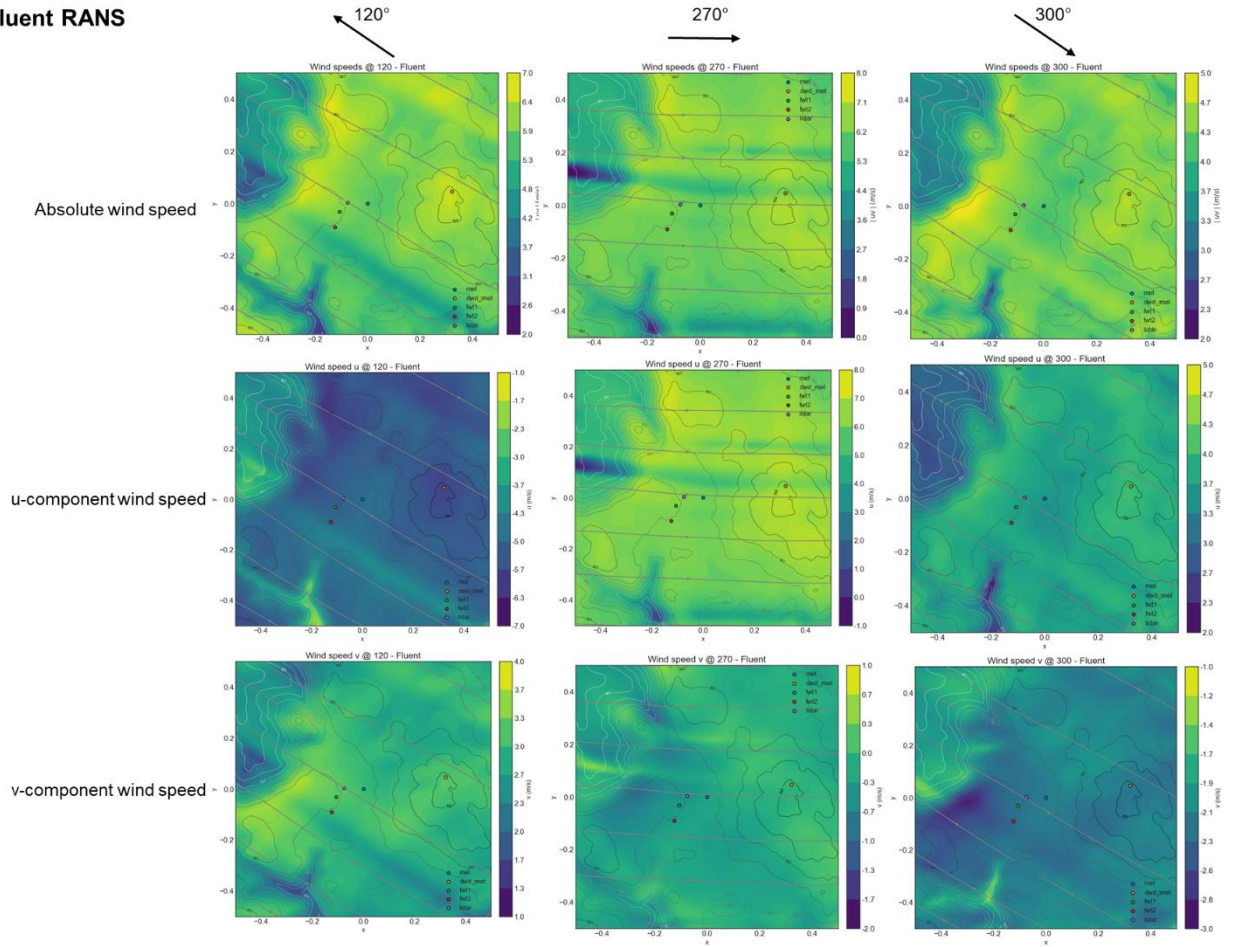
Appendix 3(b) Stötten wind speed profiles for validation position (lidar).



Appendix 3(c) Stöten wind speed contours for the three most frequent wind directions (*WindSim*).



Fluent RANS



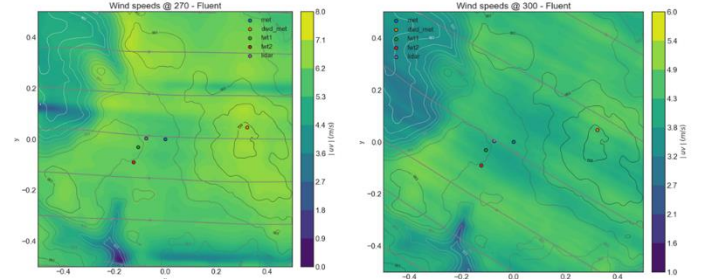
Appendix 3(d) Stöten wind speed contours for the three most frequent wind directions (*Fluent RANS*).



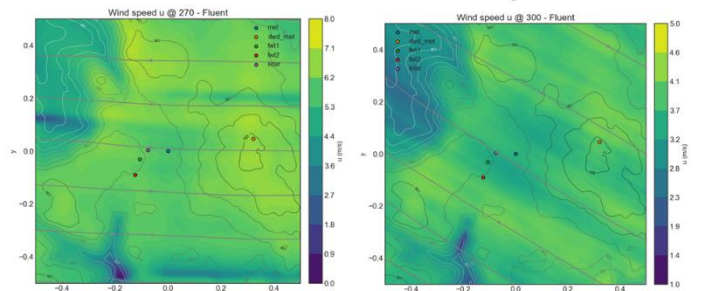
Fluent SBES



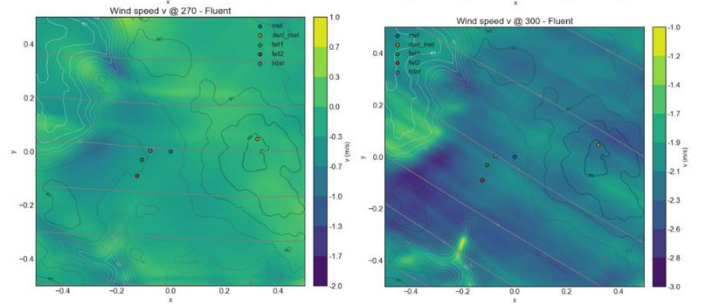
Absolute wind speed



u-component wind speed



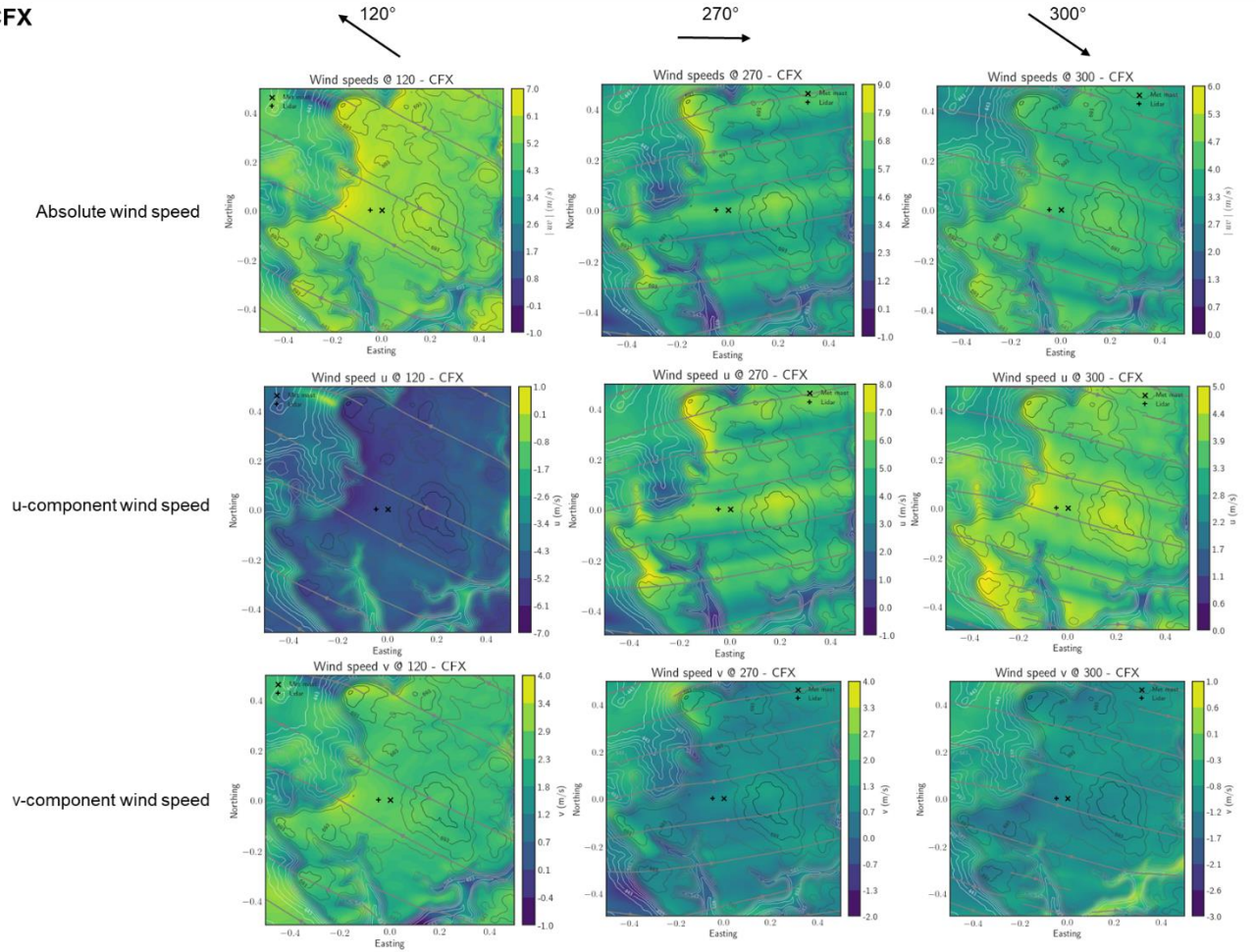
v-component wind speed



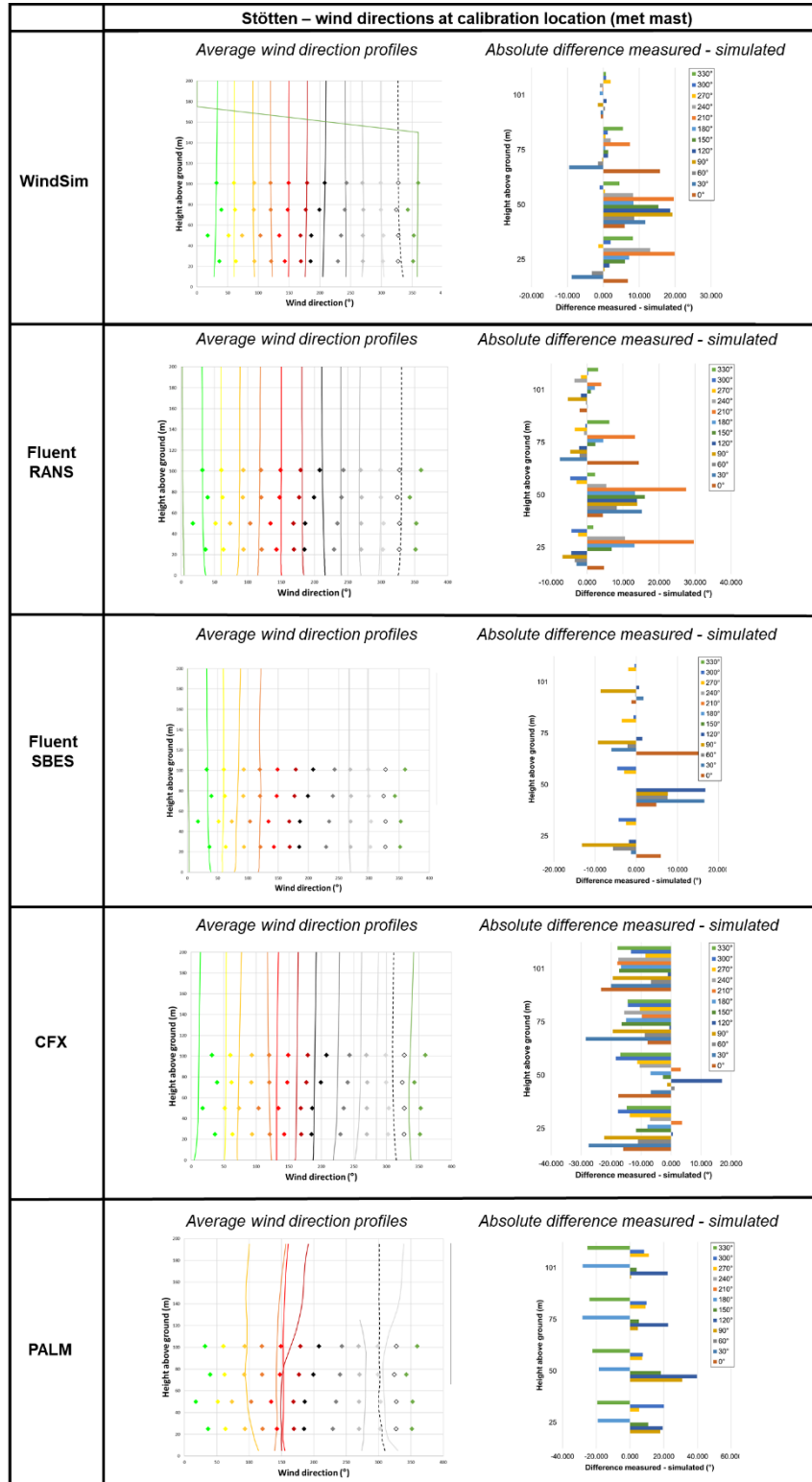
Appendix 3(e) Stötten wind speed contours for the three most frequent wind directions (*Fluent SBES*).



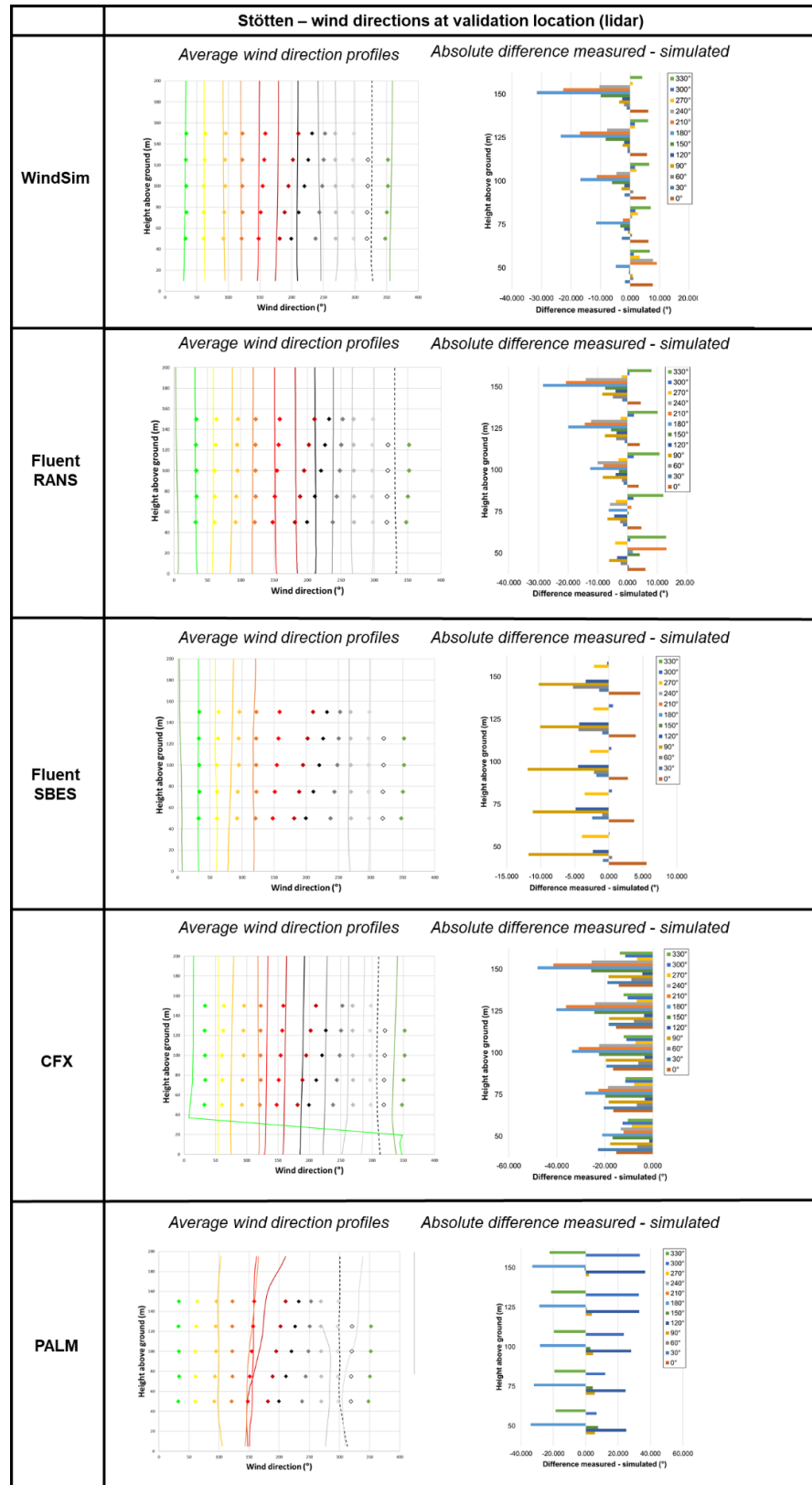
CFX



Appendix 3(f) Stöten wind speed contours for the three most frequent wind directions (CFX)



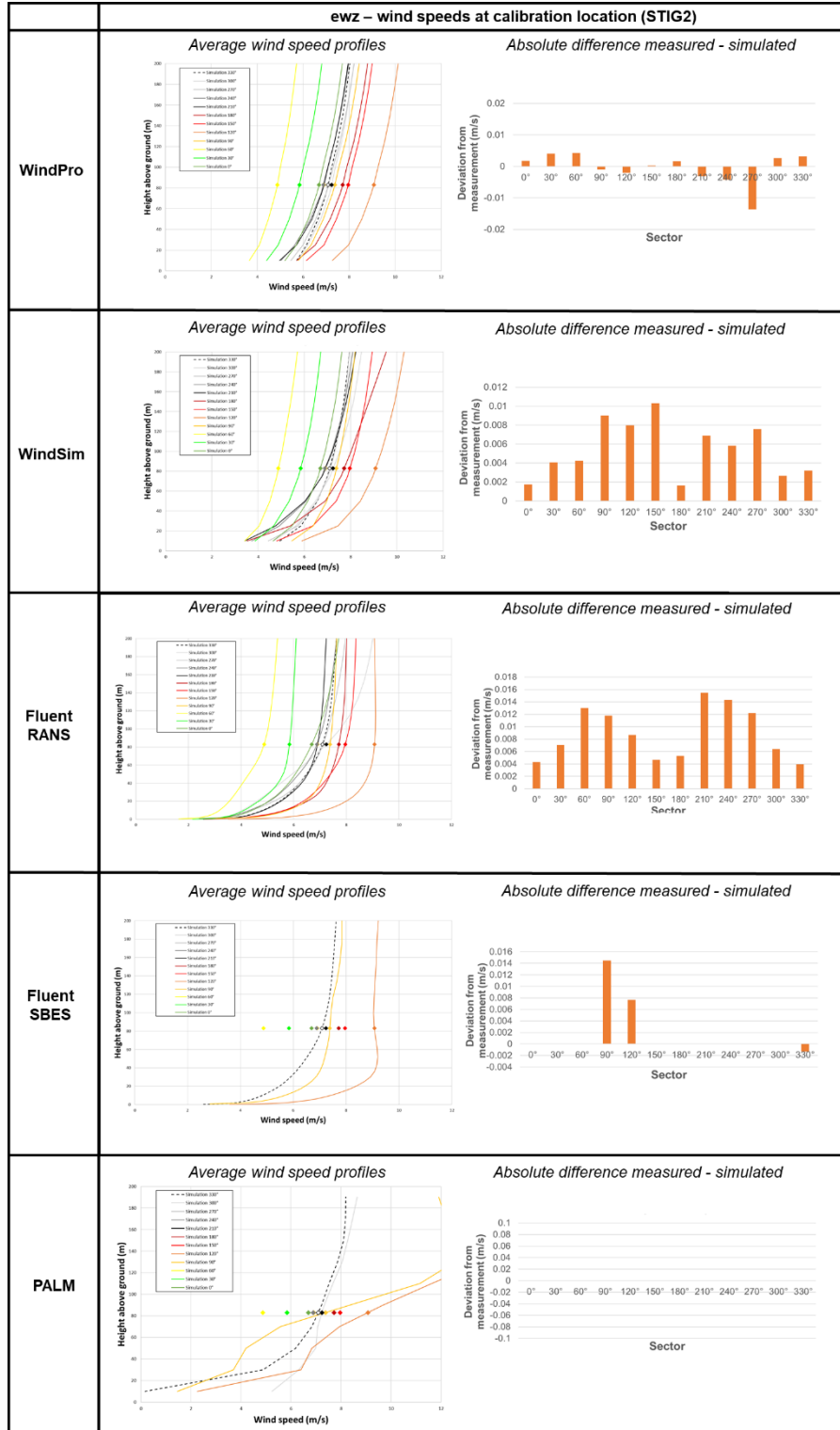
Appendix 3(g) Stötten wind direction profiles for calibration location (met mast).



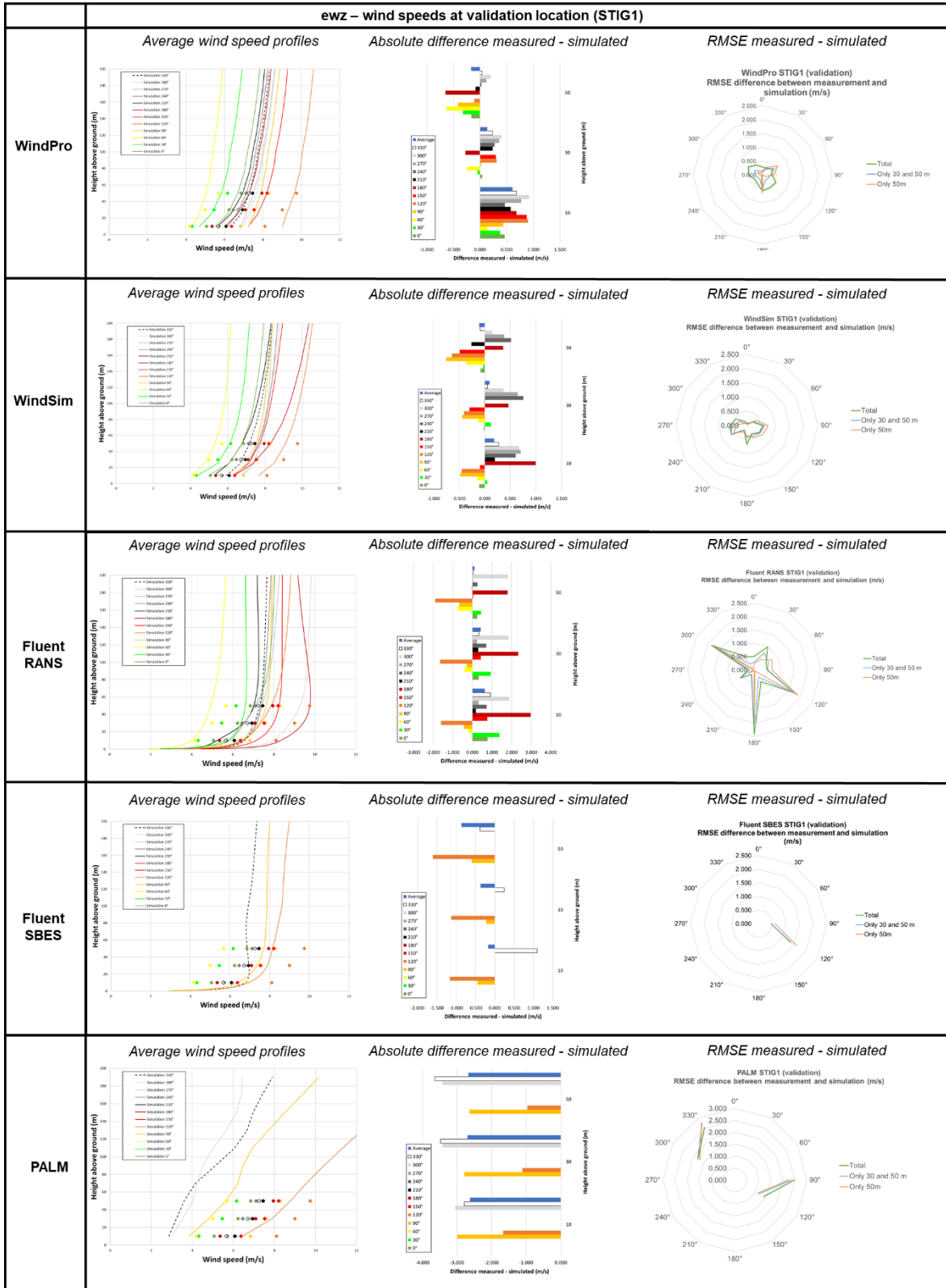
Appendix 3(h) Stötten wind direction profiles for validation location (lidar).



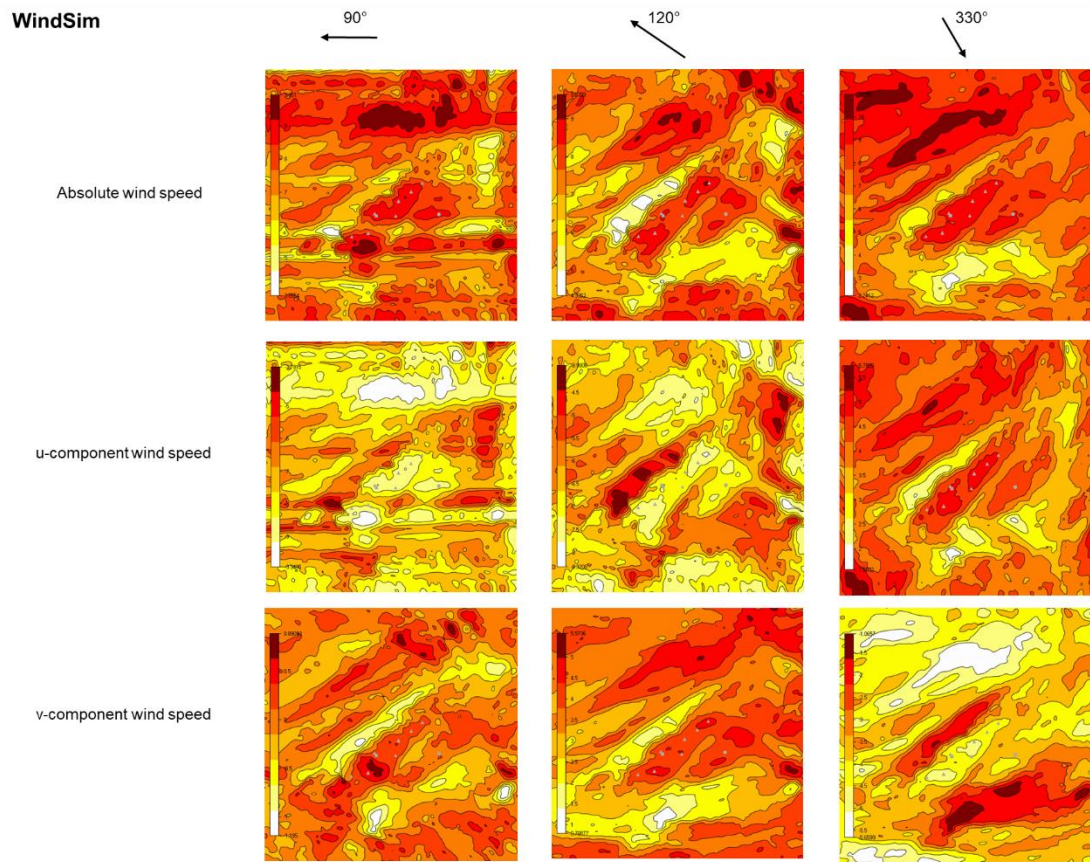
10.4 Appendix 4



Appendix 4(a). ewz wind speed profiles for calibration location (STIG2).



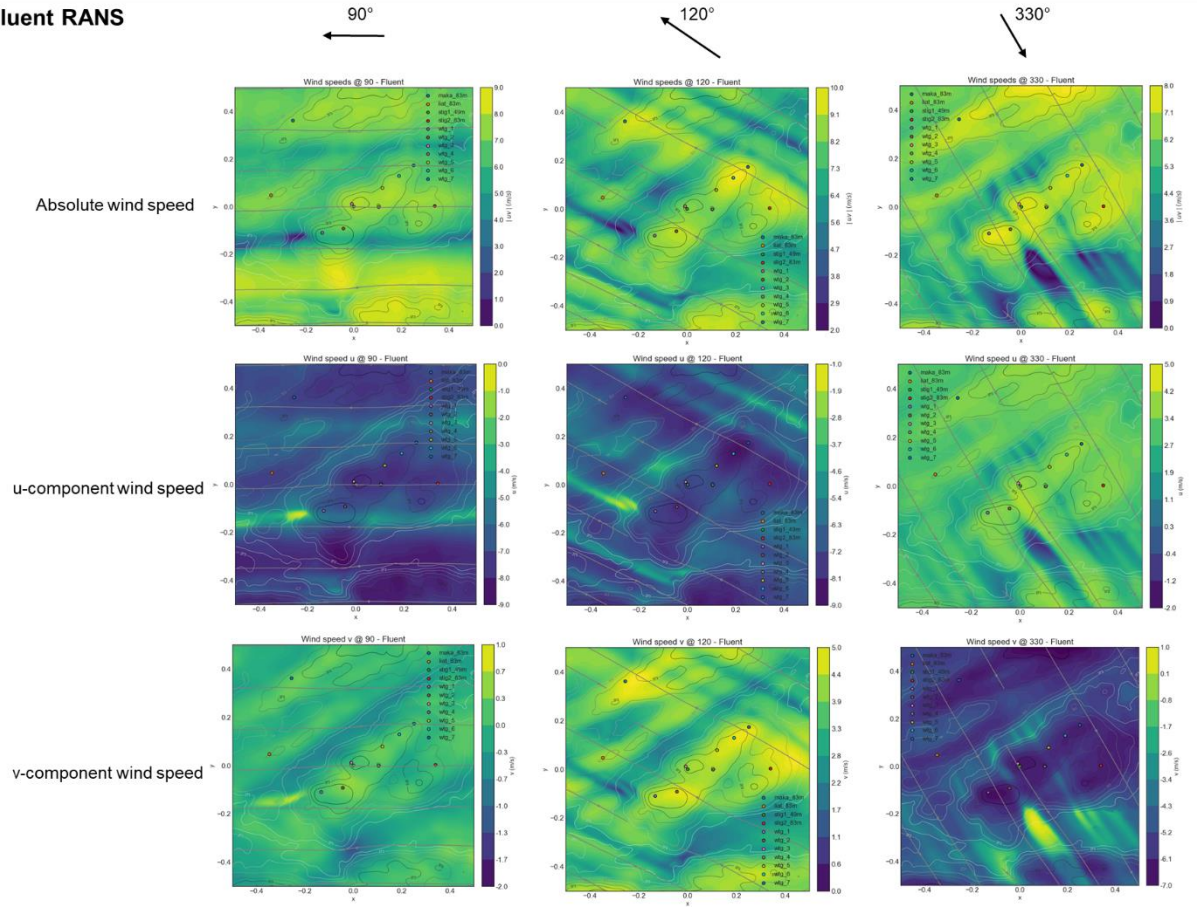
Appendix 4(b). ewz wind speed profiles for validation location (STIG1).



Appendix 4(c) ewz wind speed contours for the three most frequent wind directions (*WindSim*).



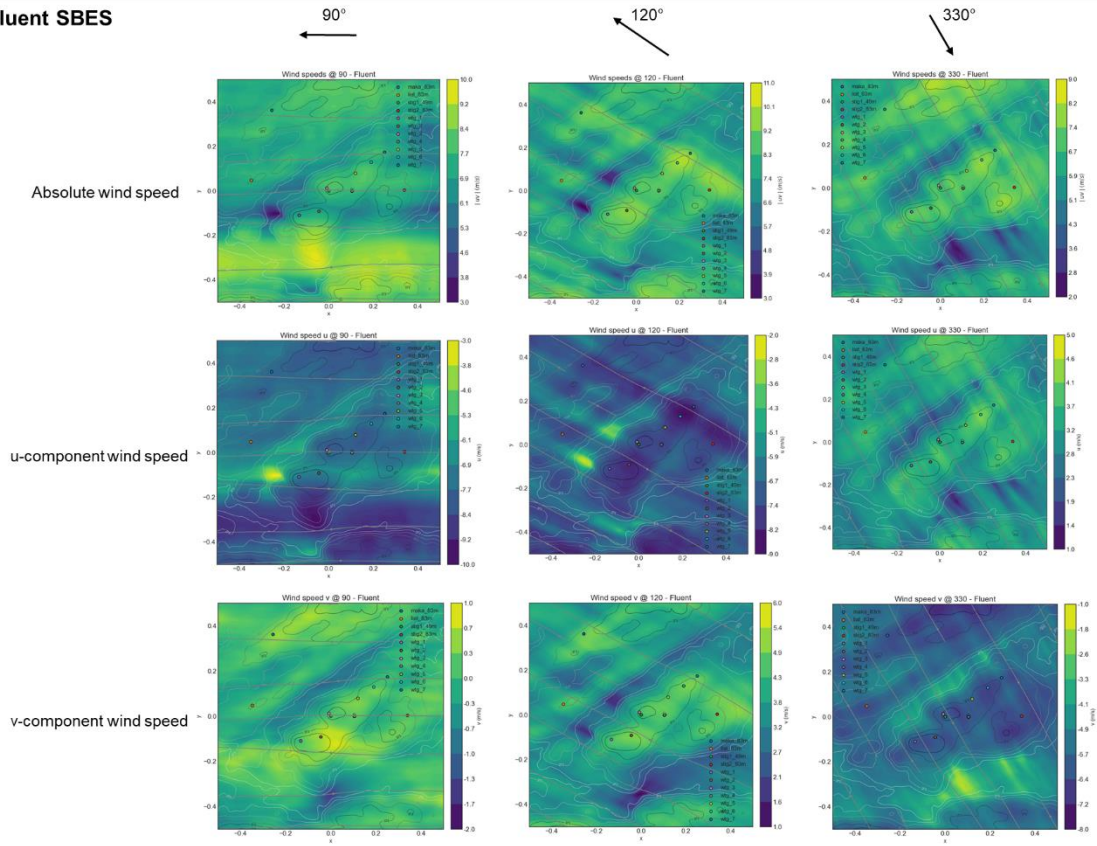
Fluent RANS



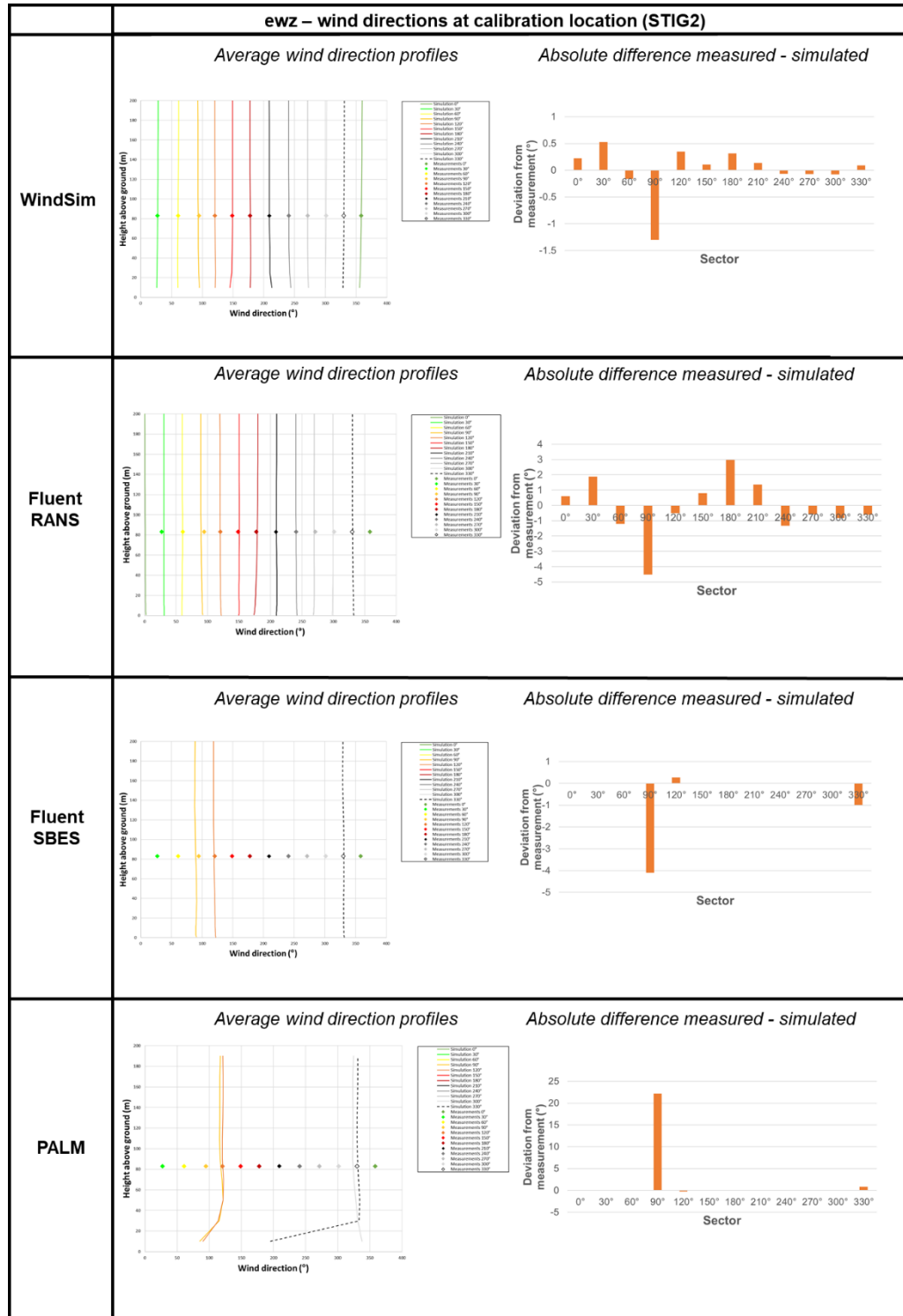
Appendix 4(d) ewz wind speed contours for the three most frequent wind directions (*Fluent RANS*).



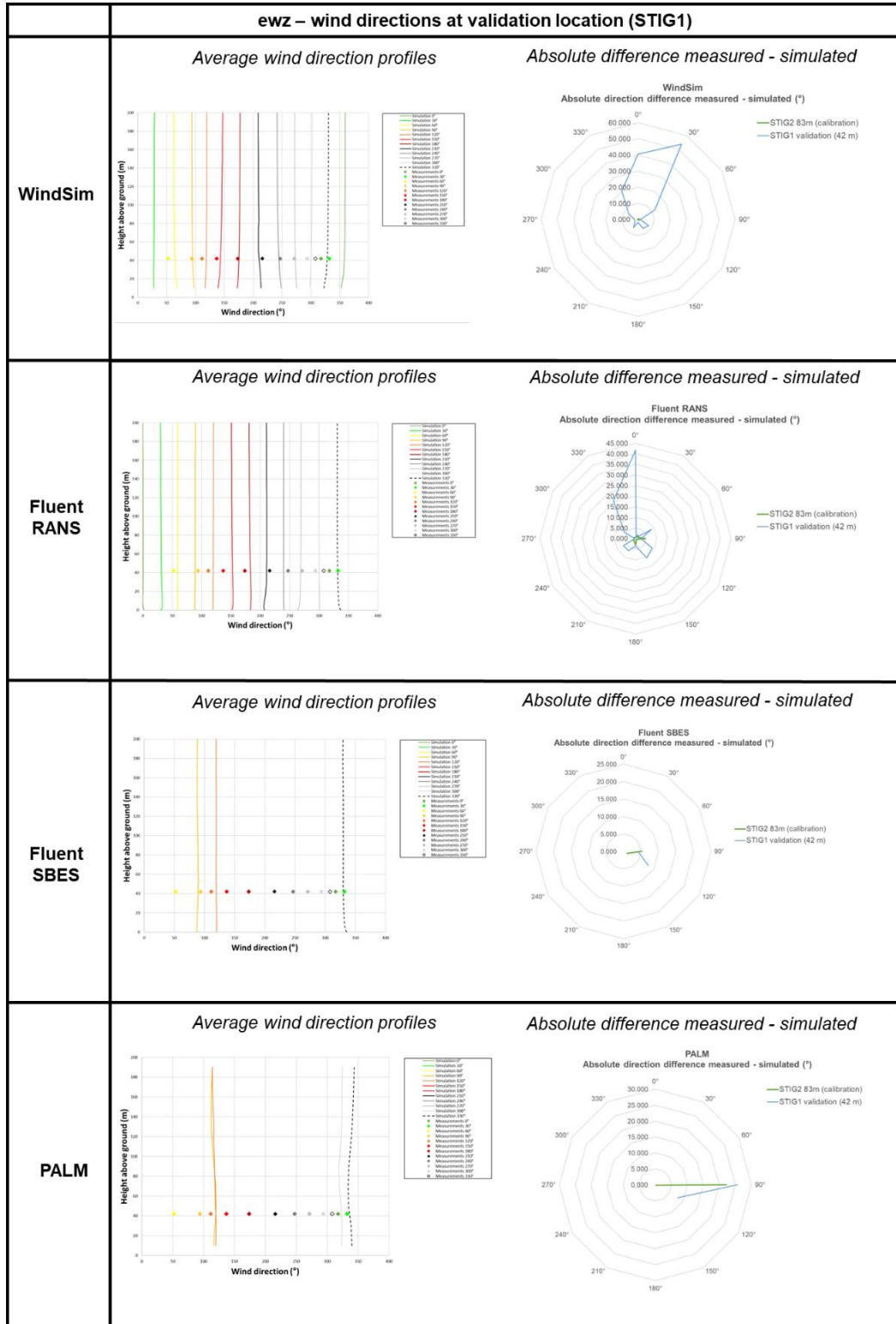
Fluent SBES



Appendix 4(e) ewz wind speed contours for the three most frequent wind directions (*Fluent SBES*).

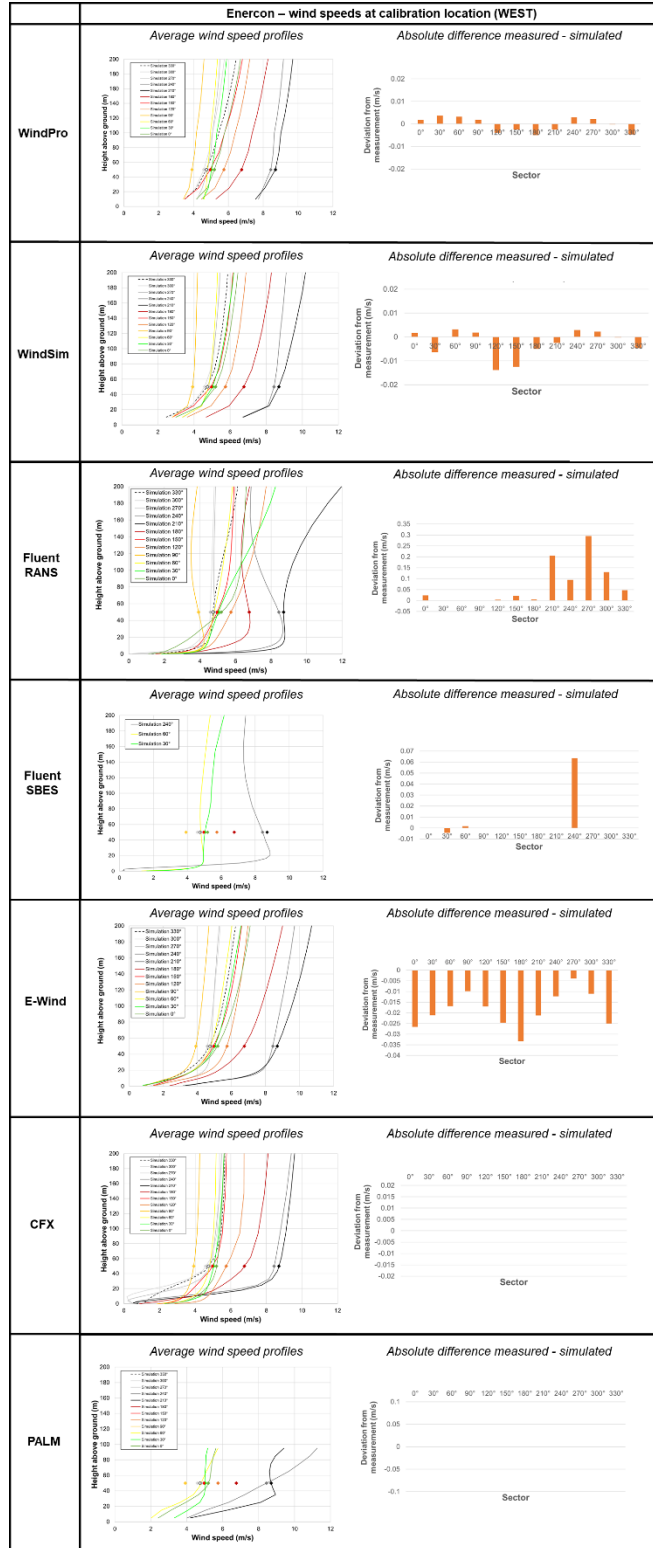


Appendix 4(f) ewz wind direction profiles for calibration location (STIG2).

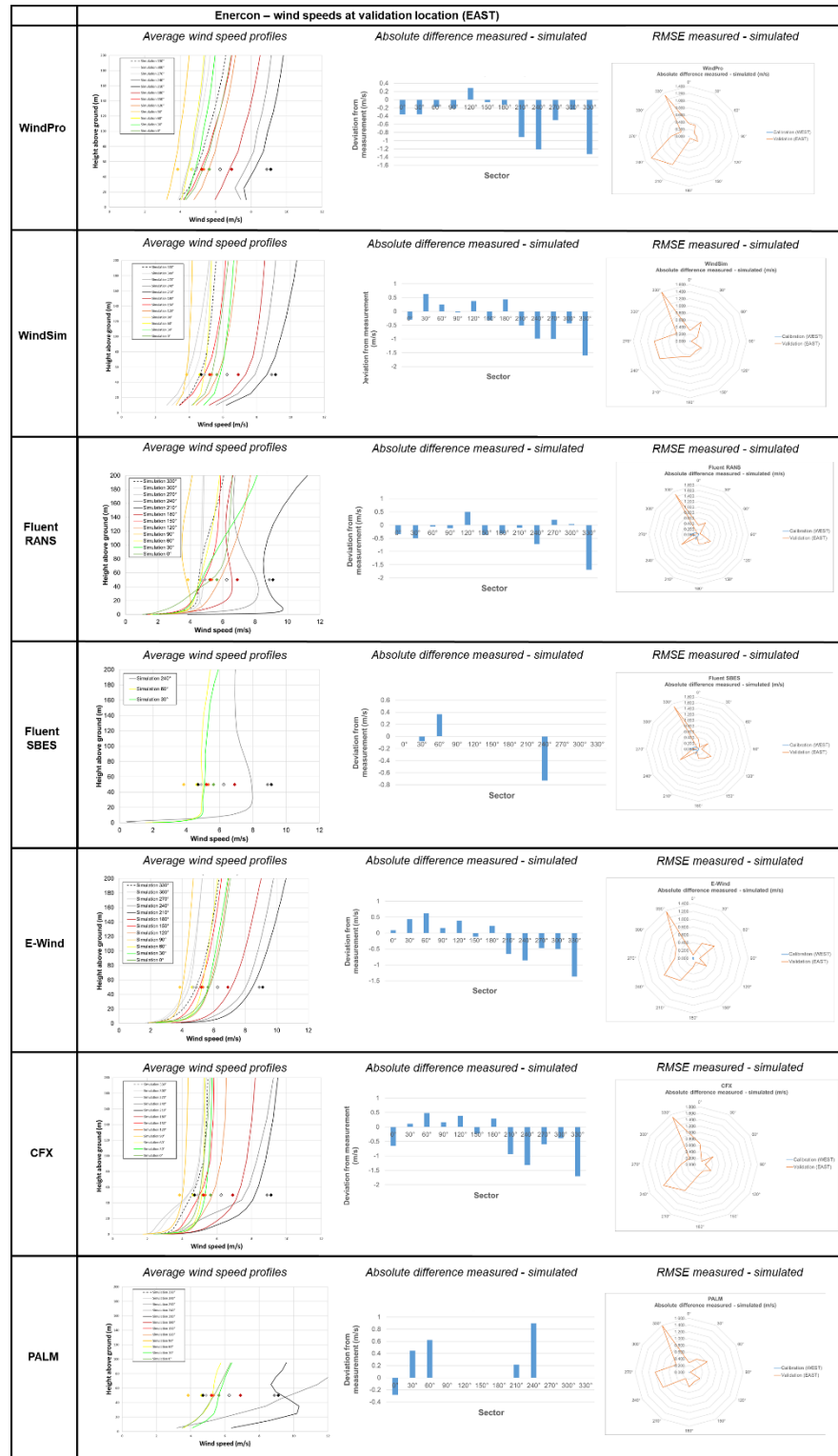


Appendix 4(g). ewz wind direction profiles for validation location (STIG1).

10.5 Appendix 5



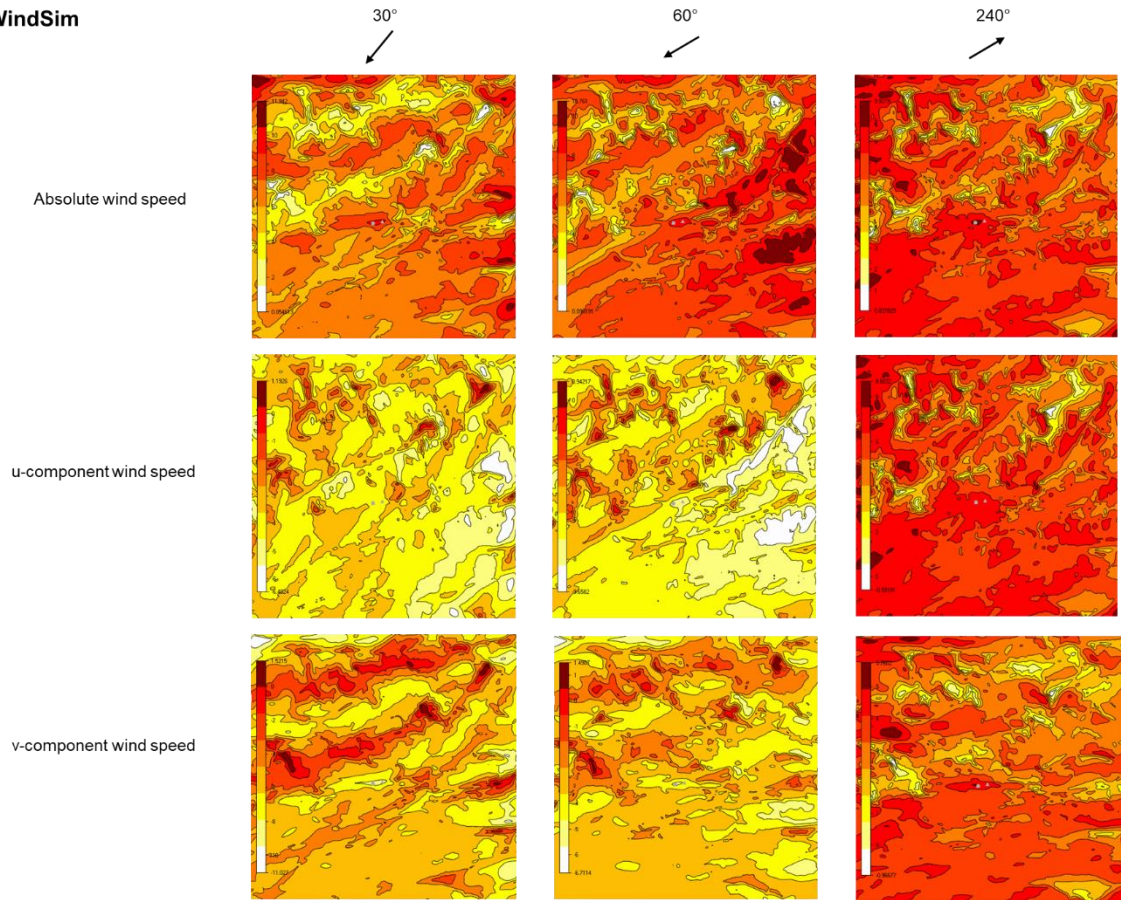
Appendix 5(a). Enercon wind speed profiles for calibration location (EAST).



Appendix 5(b). Enercon wind speed profiles for calibration location (WEST).



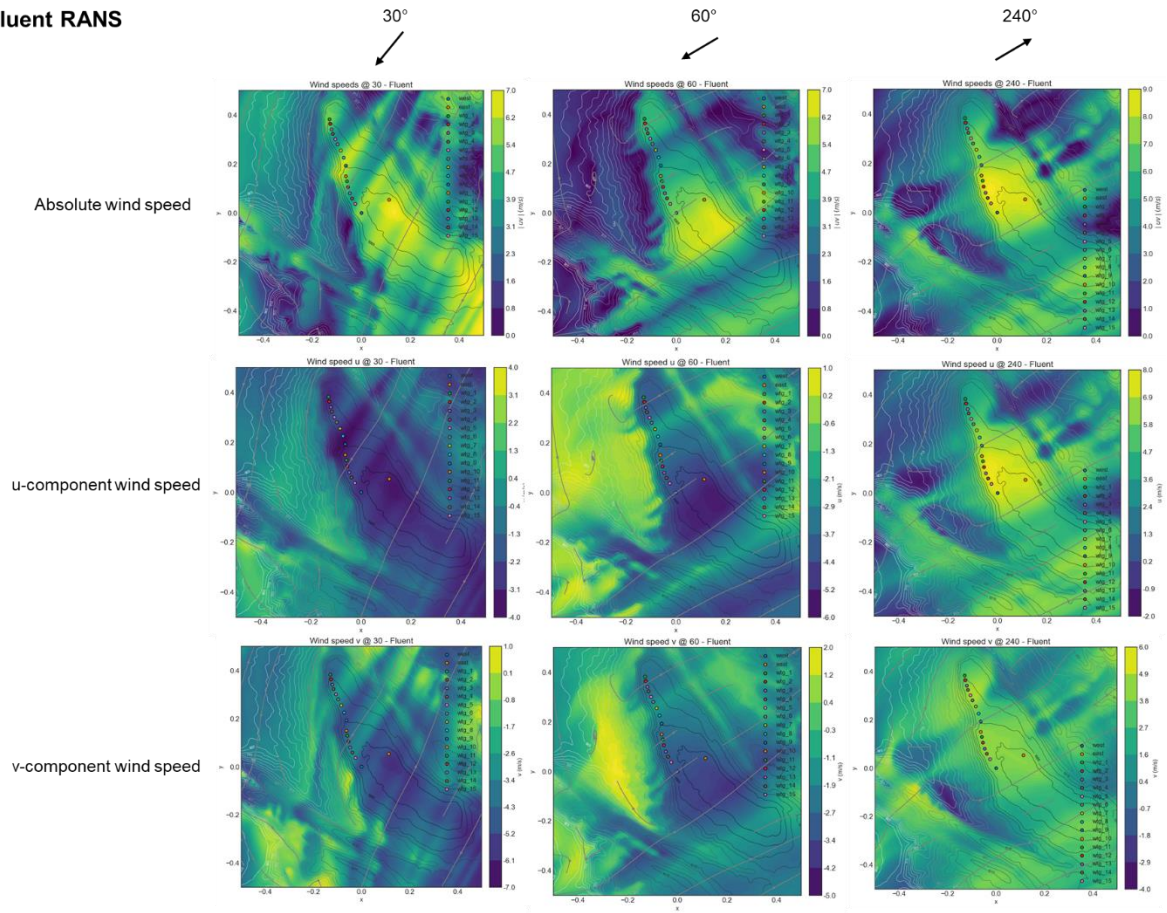
WindSim



Appendix 5(c) Enercon wind speed contours for the three most frequent wind directions (*WindSim*).



Fluent RANS



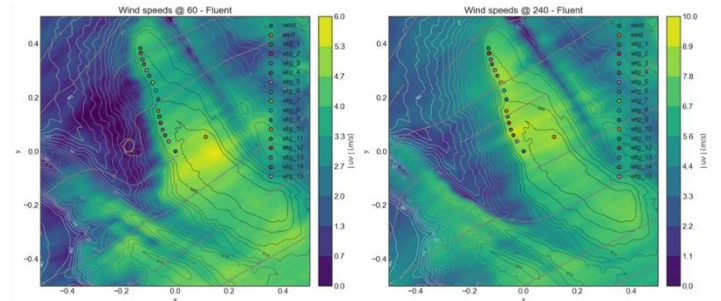
Appendix 5(d) Enercon wind speed contours for the three most frequent wind directions (*Fluent RANS*).



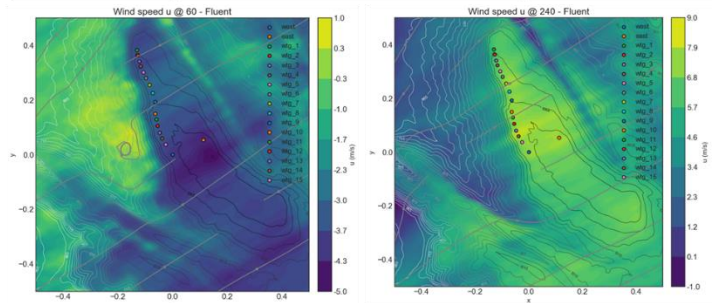
Fluent SBES



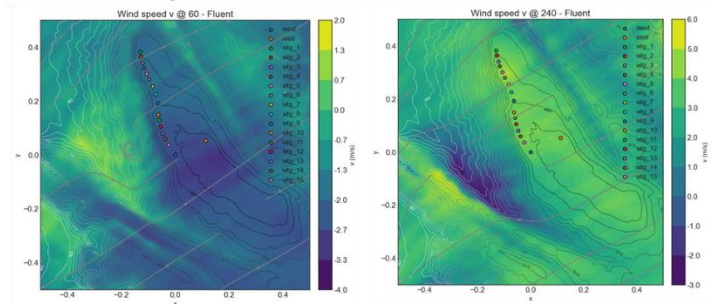
Absolute wind speed



u-component wind speed



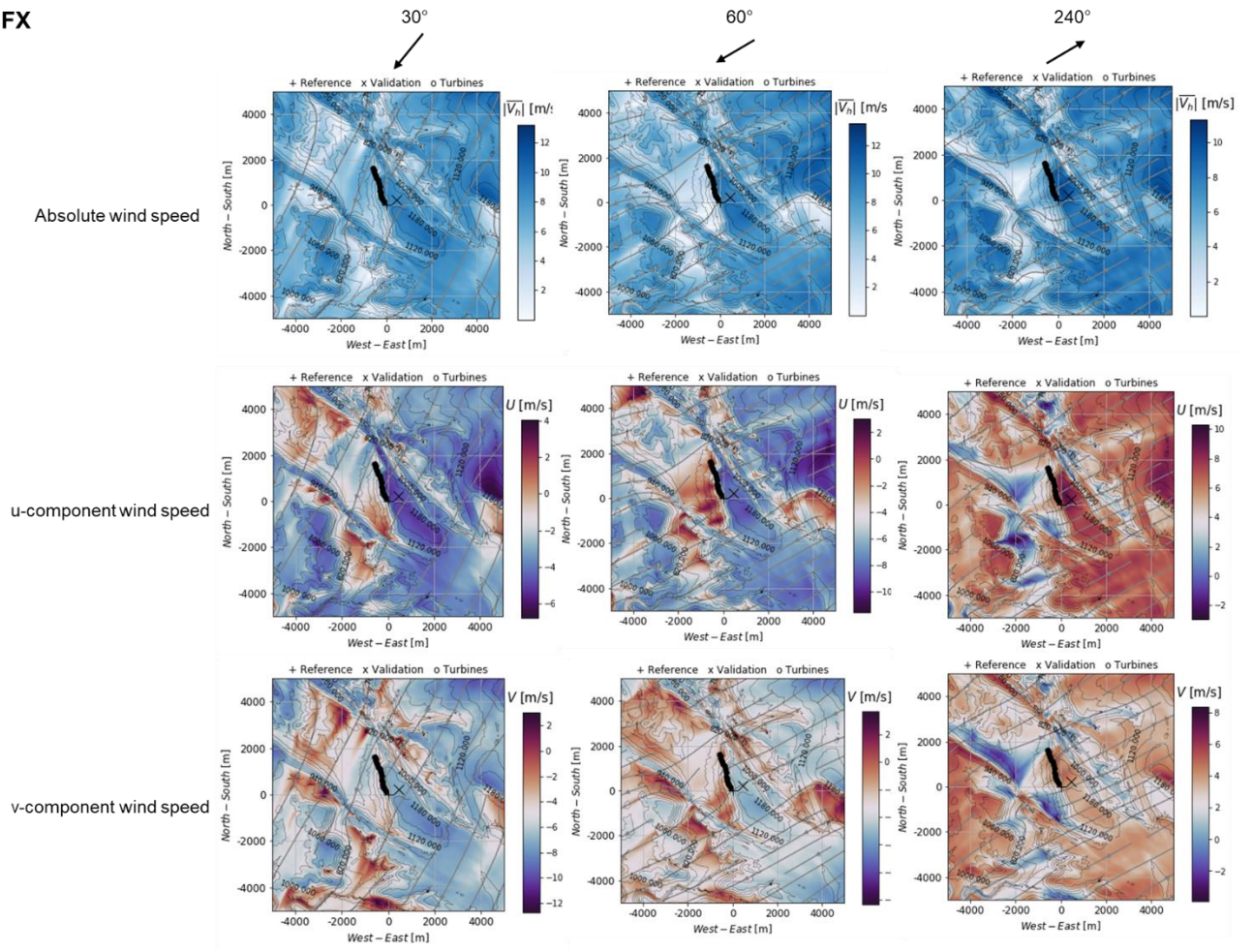
v-component wind speed



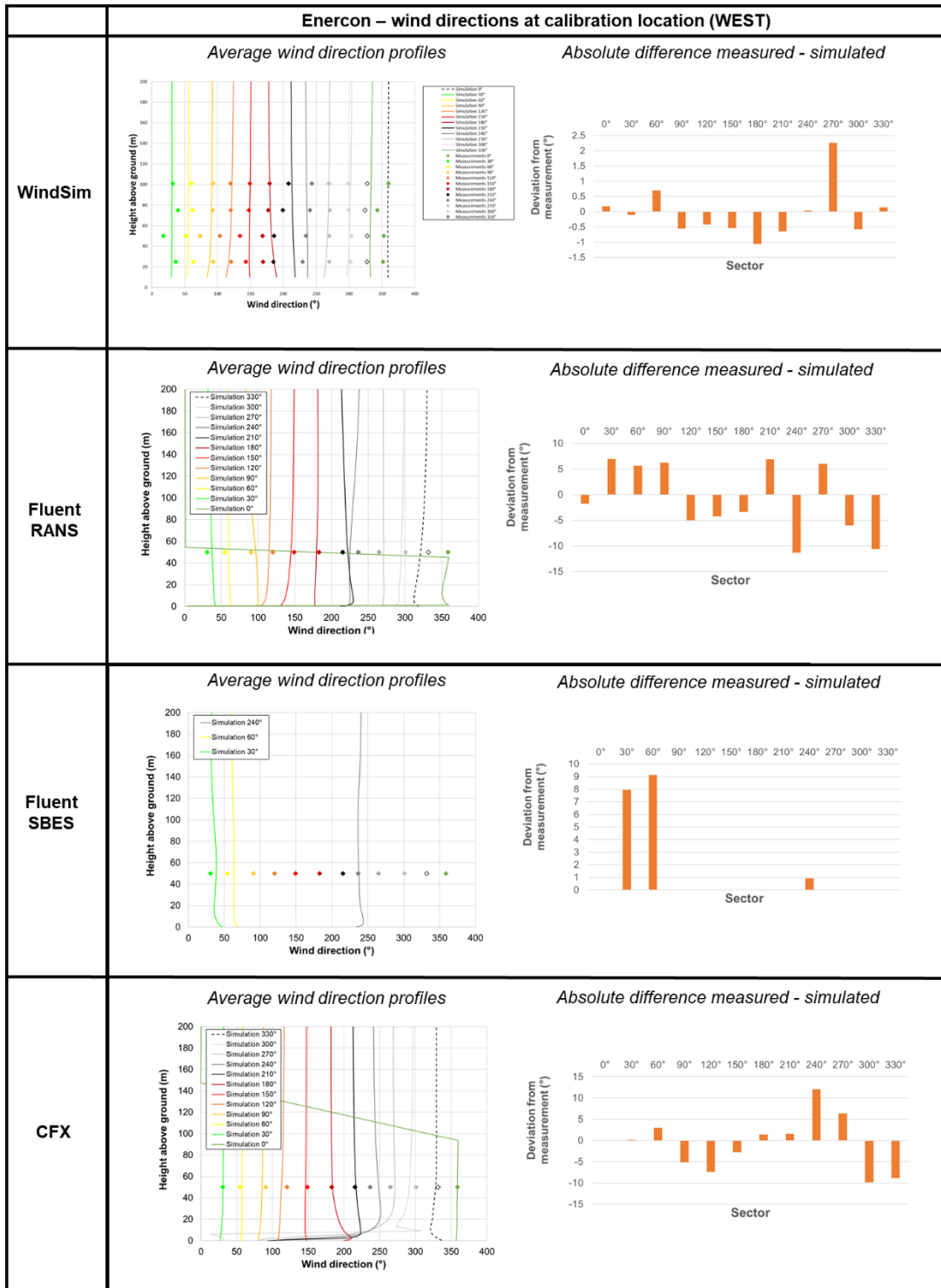
Appendix 5(e) Enercon wind speed contours for the three most frequent wind directions (*Fluent SBES*).



CFX



Appendix 5(f) Enercon wind speed contours for the three most frequent wind directions (CFX).



Appendix 5(g). Enercon wind direction profiles for calibration location (WEST).

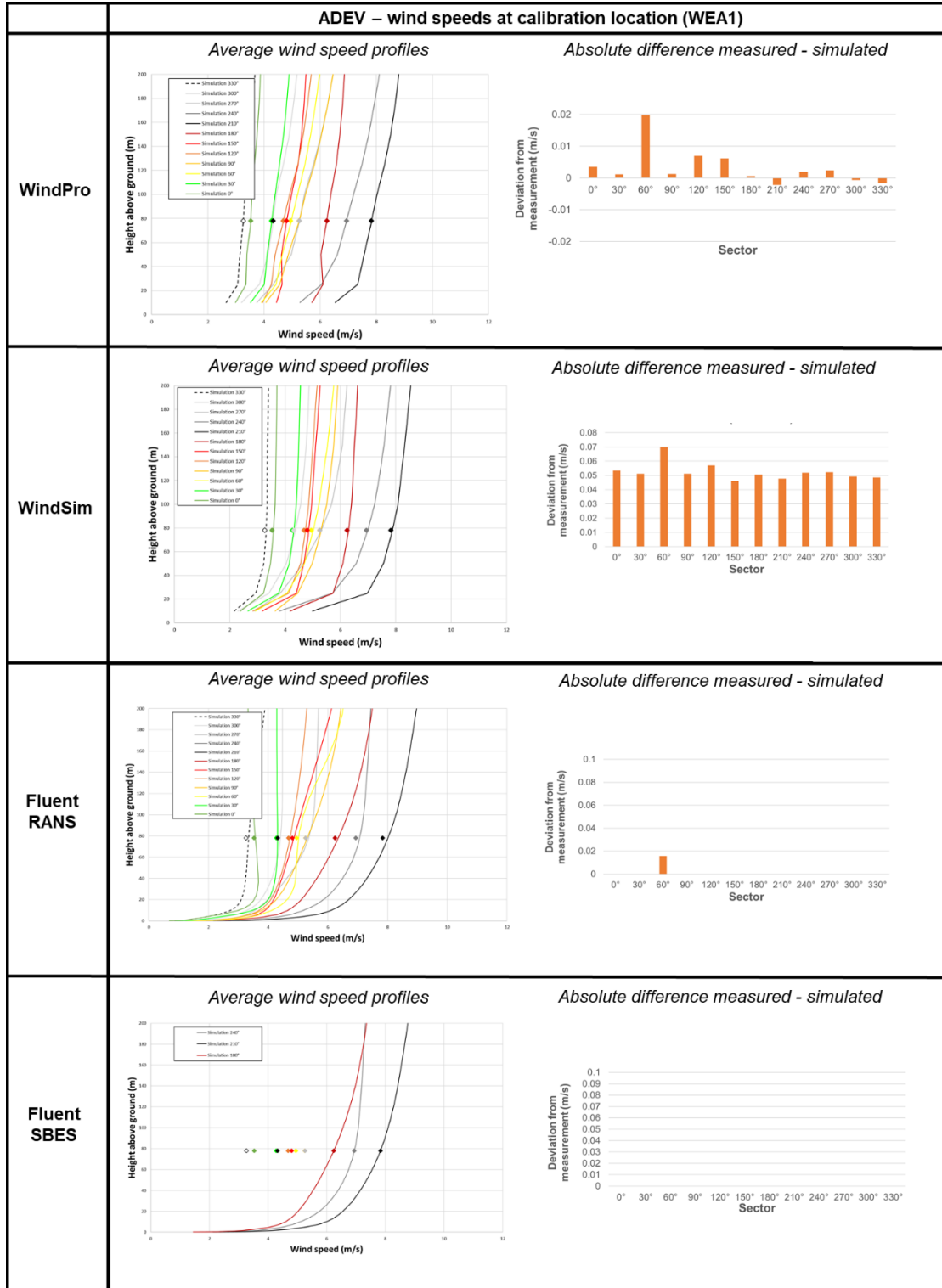


Enercon – wind directions at validation location (EAST)	
WindSim	<p><i>Average wind direction profiles</i></p> <p><i>Absolute difference measured - simulated</i></p>
Fluent RANS	<p><i>Average wind direction profiles</i></p> <p><i>Absolute difference measured - simulated</i></p>
Fluent SBES	<p><i>Average wind direction profiles</i></p> <p><i>Absolute difference measured - simulated</i></p>
CFX	<p><i>Average wind direction profiles</i></p> <p><i>Absolute difference measured - simulated</i></p>

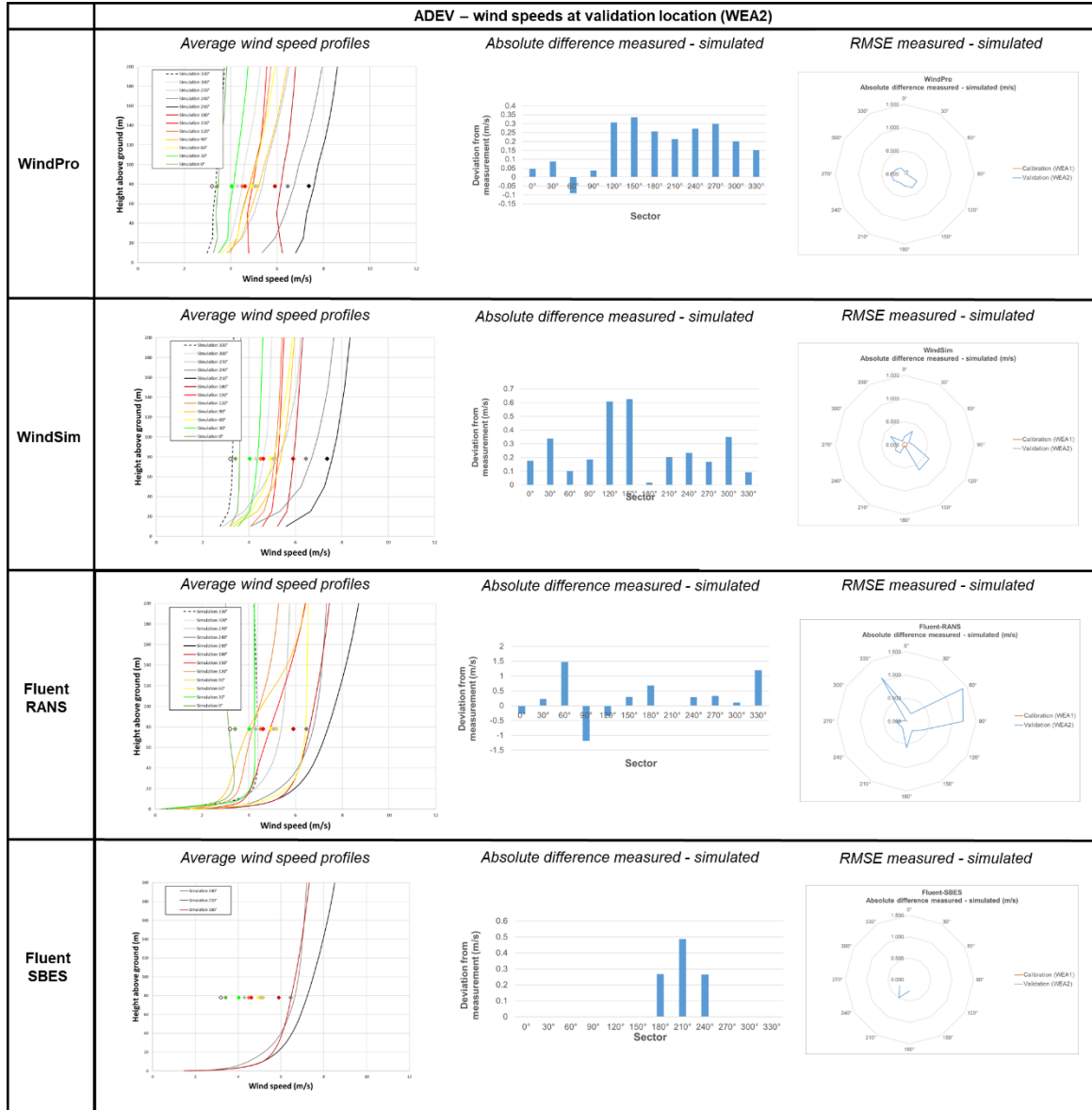
Appendix 5(h). Enercon wind direction profiles for validation location (EAST).



10.6 Appendix 6



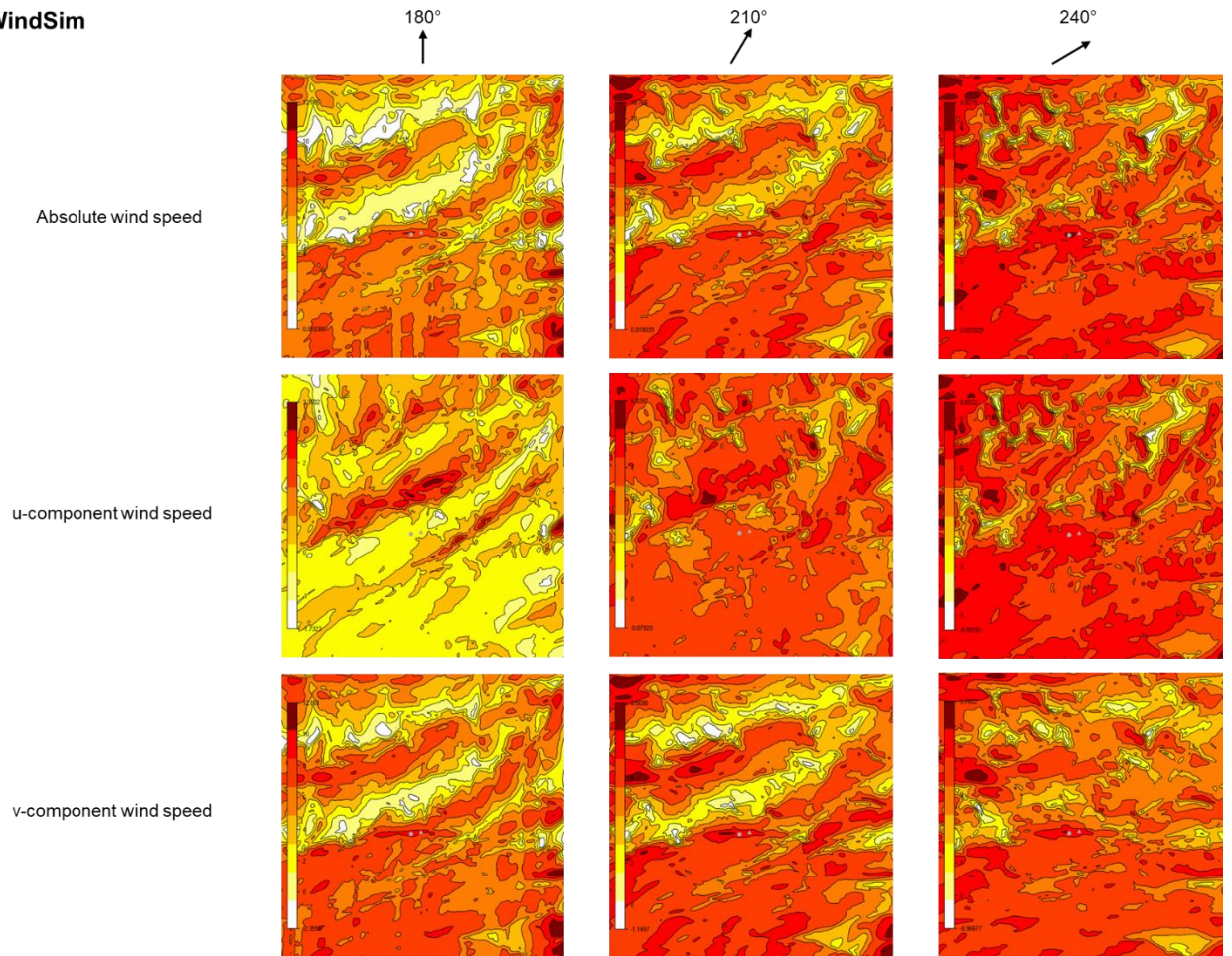
Appendix 6(a). ADEV wind speed profiles for validation location (WEA1).



Appendix 6(b). ADEV wind speed profiles for validation location (WEA2).



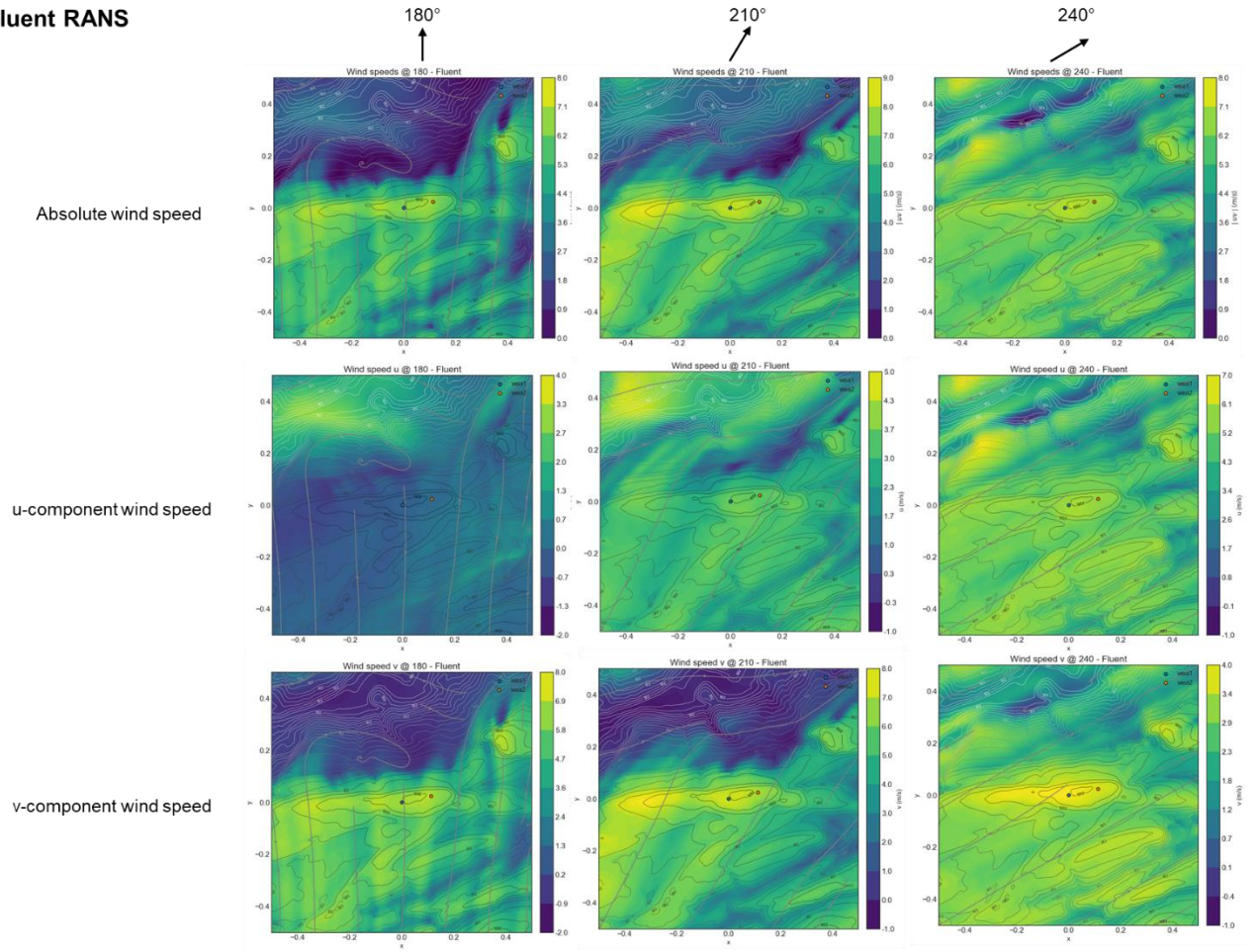
WindSim



Appendix 6(c) ADEV wind speed contours for the three most frequent wind directions (*WindSim*).



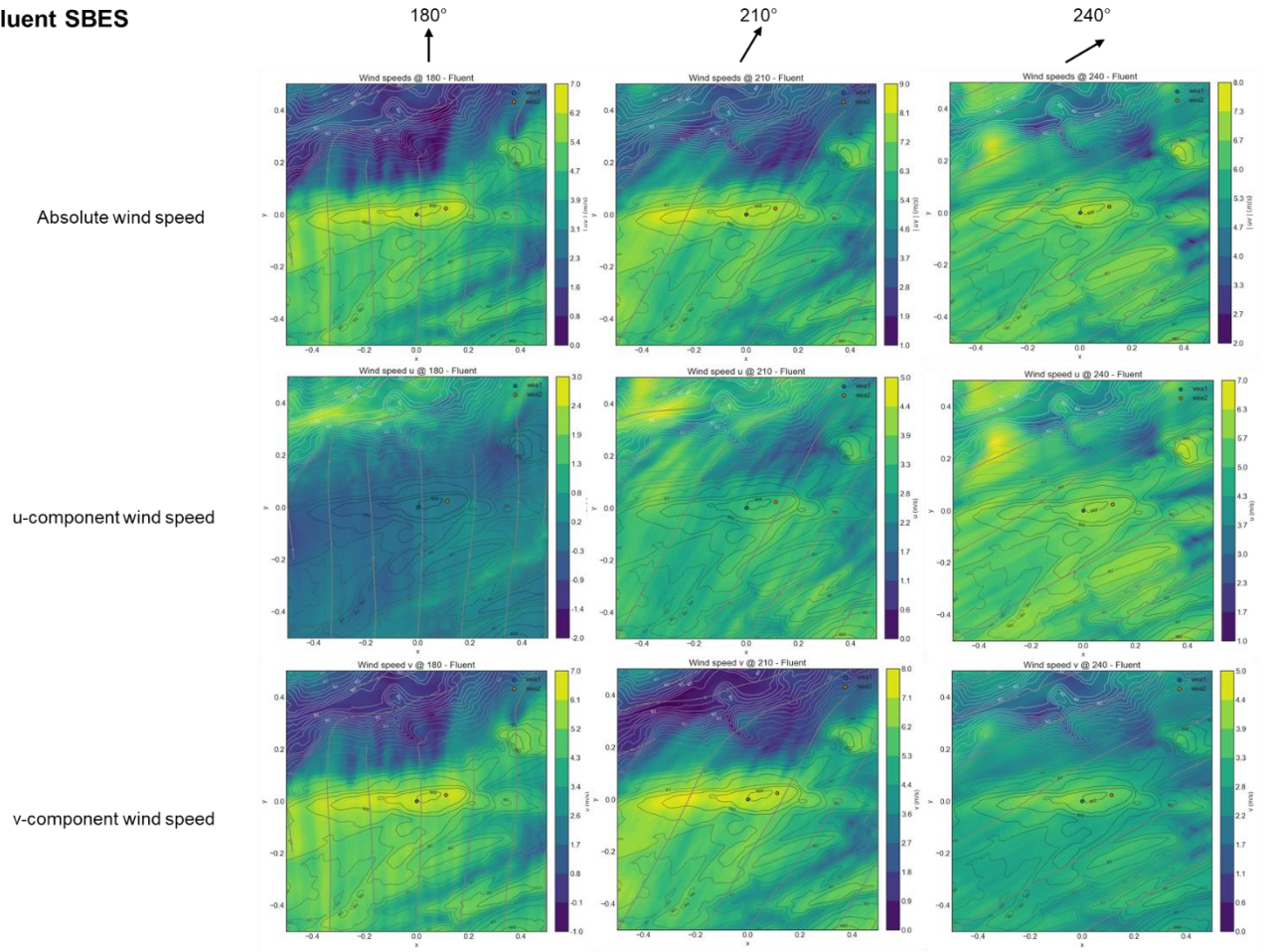
Fluent RANS



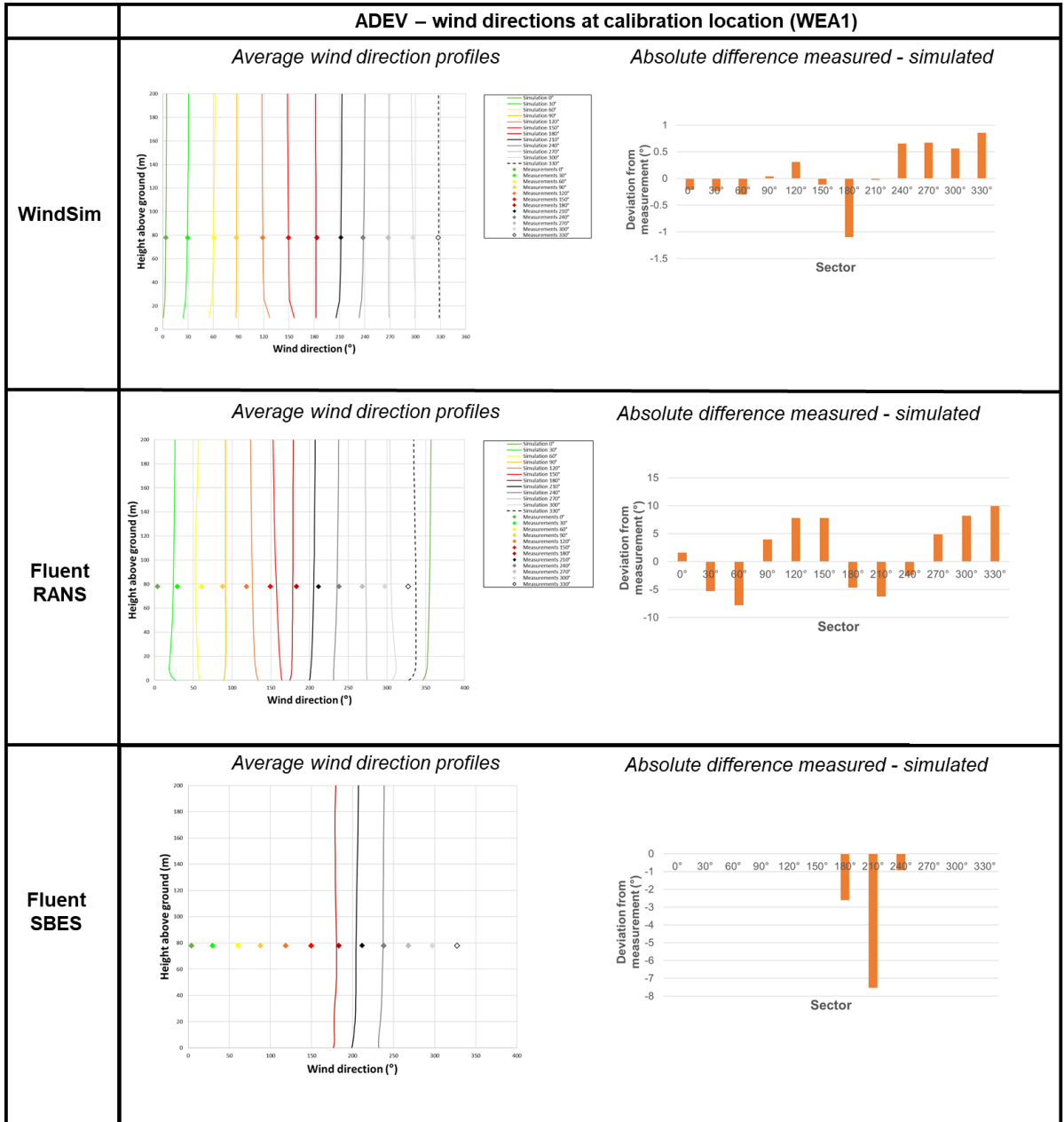
Appendix 6(d) ADEV wind speed contours for the three most frequent wind directions (*Fluent RANS*).



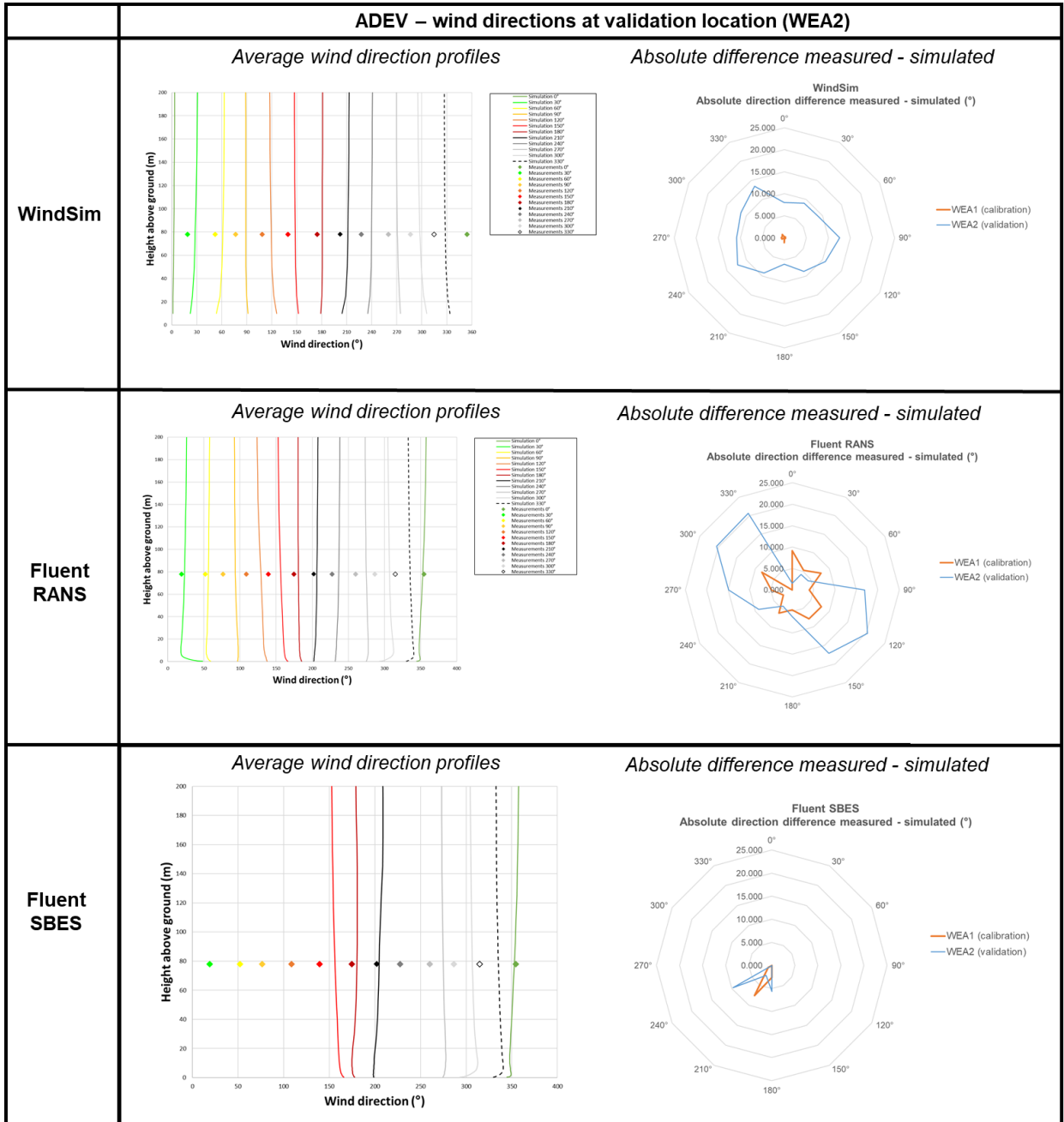
Fluent SBES



Appendix 6(e) ADEV wind speed contours for the three most frequent wind directions (*Fluent SBES*).



Appendix 6(f). ADEV wind direction profiles for calibration location (WEA1).



Appendix 6(g). ADEV wind direction profiles for validation location (WEA2).