# Turbulence Measurements – Theory – Models

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# Turbulence Application in Wind Energy Background and Facts

juwi SENVION wind energy solutions

**Turbulence Estimates:**

**Without Measurements**

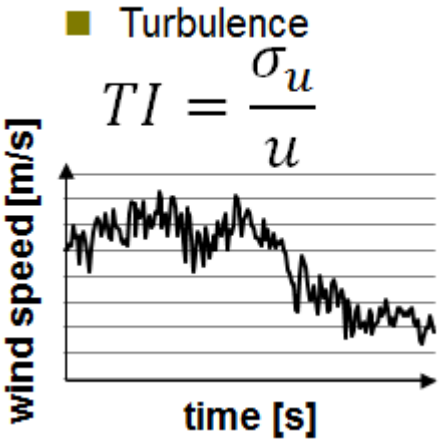
→ General estimation of TI from surface roughness and theoretical interpolation to hub height

**Met Tower Measurements**

→ "Measured TI" and theoretical interpolation to hub height

**Lidar Measurement**

-> "Measured" TI up to hub height, no interpolation necessary, different values compared to cup anemometers due to different measurement systems



# Turbulence Application in Wind Energy Questions

- How do practical TI measurements from Lidars compare to those from cup anemometers?

- How is measured TI and its decrease with height in comparison values estimated from analytical derived values from z0?

- How can vertical shape of TI profile and horizontal TI variations be represented in theoretical Models?

→ Can CFD close some gaps?

# Measurement basis

- 12 different sites
  - 6 flat + simple
  - 2 hilly + partly forested
  - 4 hilly + forested
- WindCubes only
- Co-located masts (cup anemometers)
  - 3 WindCube v1
  - 9 WindCube v2
- 2-9 months of deployment
- 2.000-14.000 valid data samples after filtering
  - Concurrent time series
  - Wake-free sectors
  - Availability (all heights)

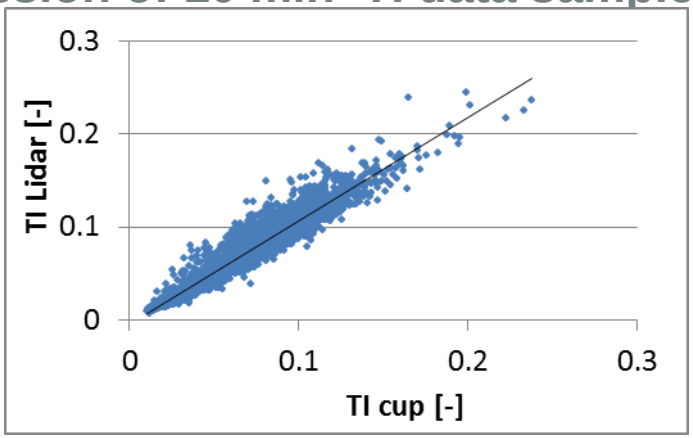
# Questions Part 1

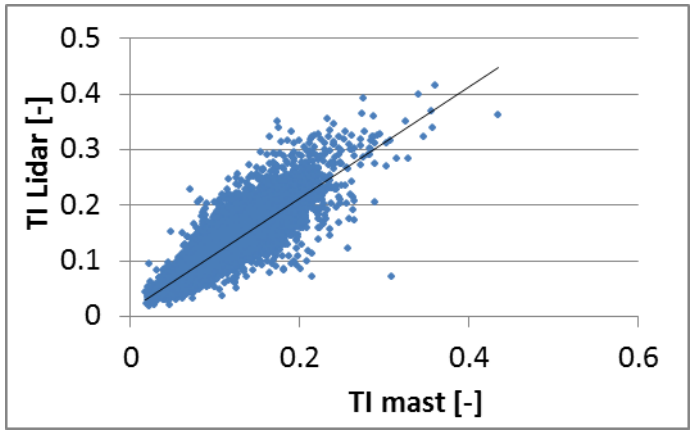
- How do practical TI measurements from Lidars compare to those from cup anemometers?
- How is measured TI  and its decrease with height in comparison values estimated from analytical derived values from z0?
- How can vertical shape of TI profile and horizontal TI variations be represented in CFD?

# Lidar vs. cup anemometers

## Regression of 10 min TI data samples – different sites

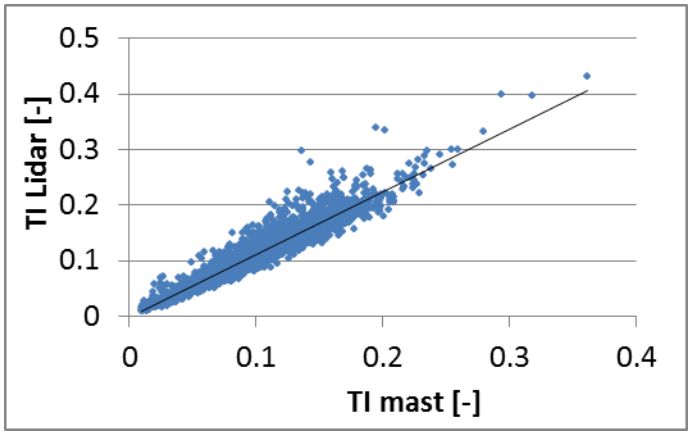
y = 1.116x - 0.006
$R^2$ = 0.925

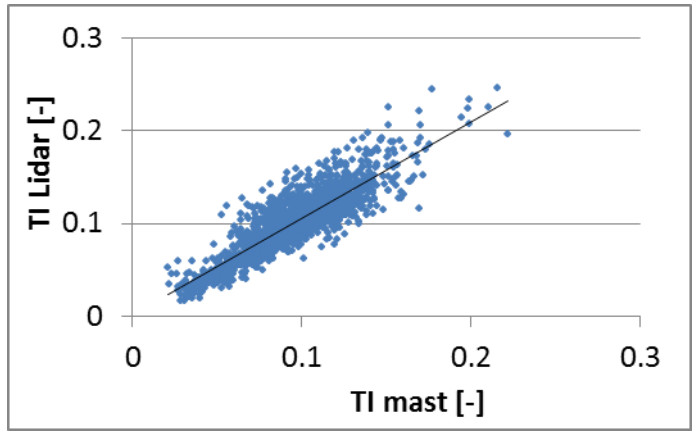



y = 1.001x - 0.012
$R^2$ = 0.71

y = 1.131x - 0.002
$R^2$ = 0.906



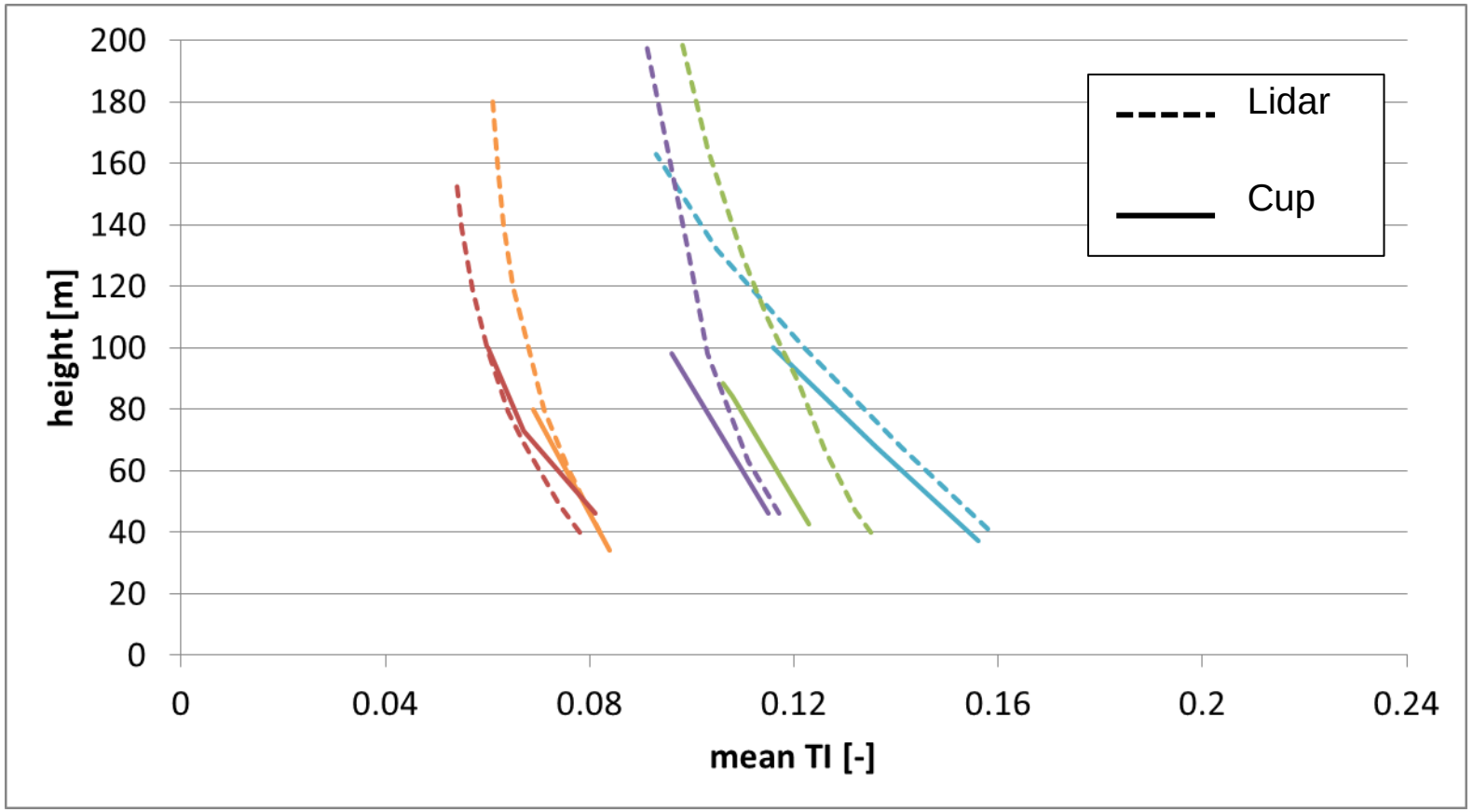




y = 1.045x + 0.002
$R^2$ = 0.76

- quality of regression varies significantly
- Lidar more conservative with high TI

# Lidar vs. cup anemometers

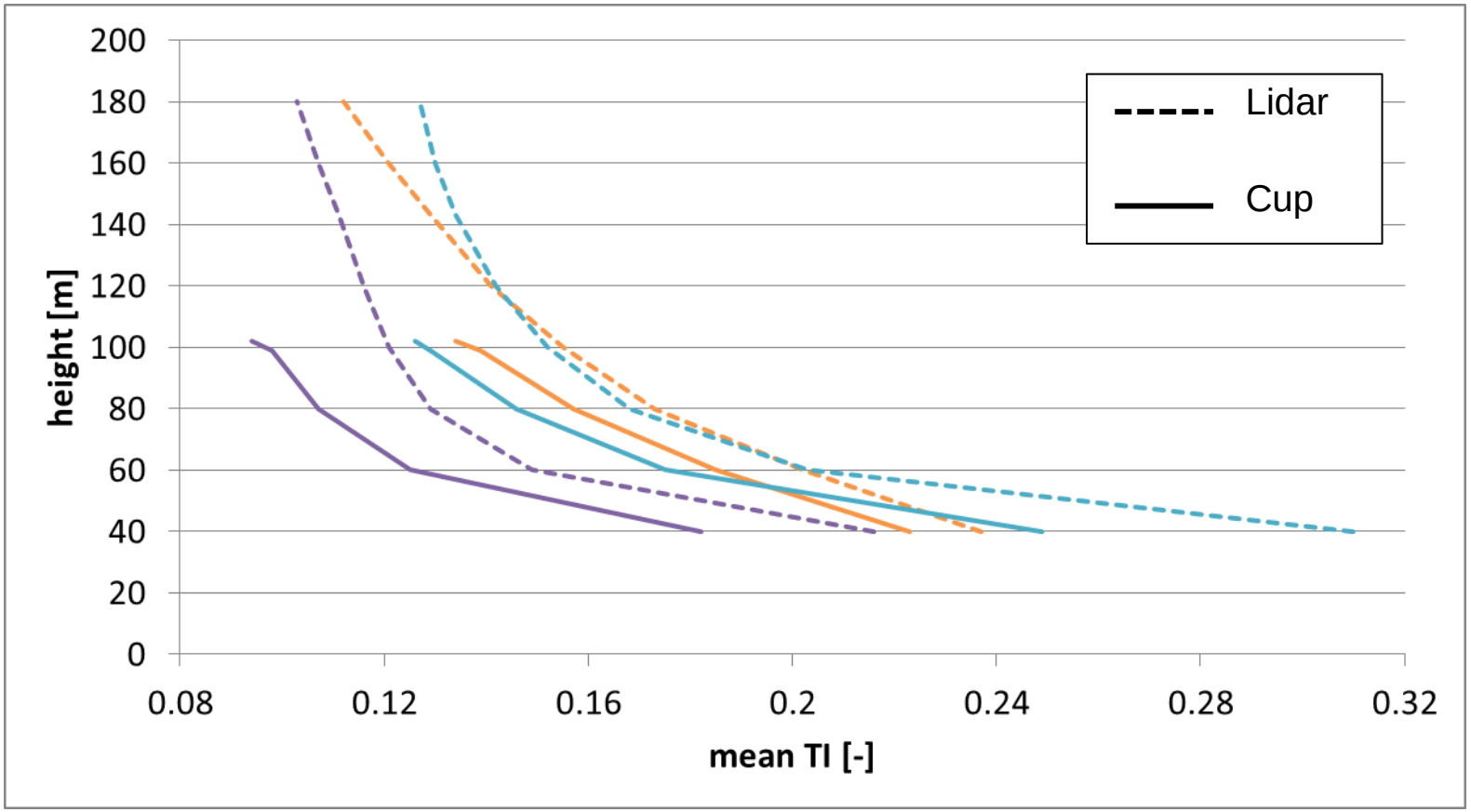
## Mean TI over height – simple sites




- Lidar slightly conservative over all heights (around 0.5-1% pts.)

# Lidar vs. cup anemometers

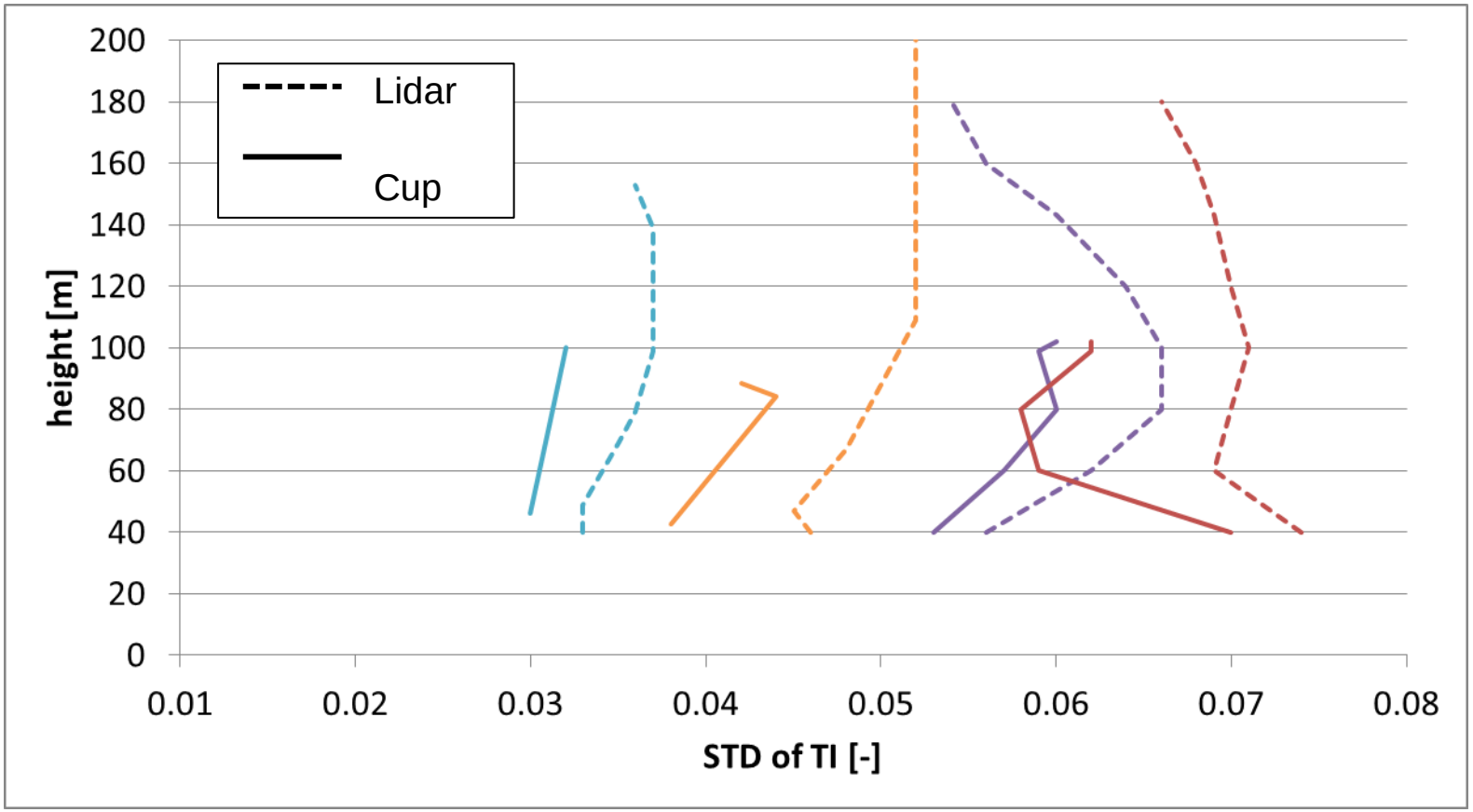
## Mean TI over height – complex sites




- Lidar strictly conservative over all heights (around +2% pts.)

# Lidar vs. cup anemometers

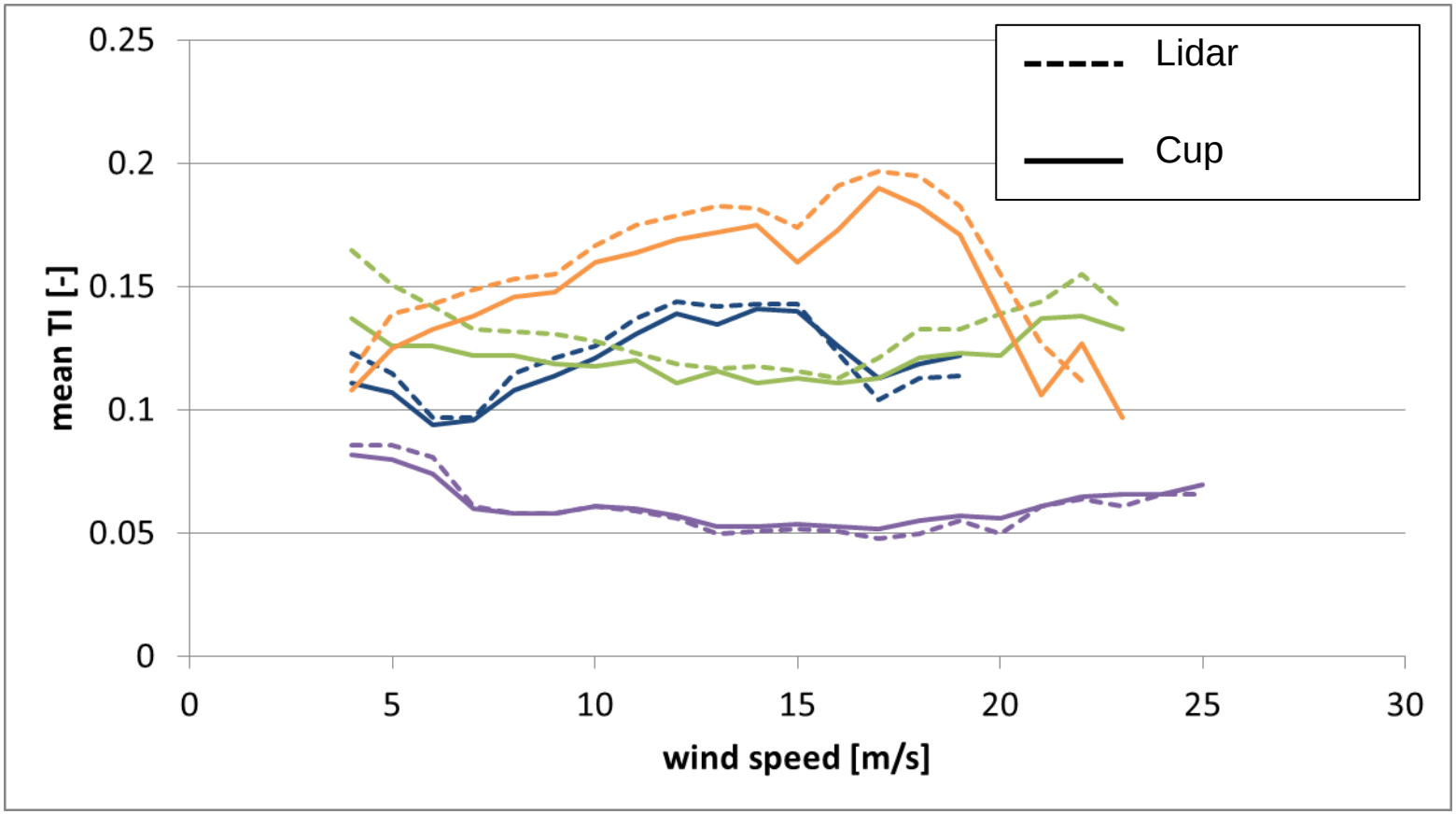
## Standard deviation of TI over height




- Lidar in all cases conservative for STD of TI (around 1% pts.)

# Lidar vs. cup anemometers

## Distribution over wind speed




- Performance quite stable over wind speed

# Questions Part 2

- How do practical TI measurements from Lidars compare to those from cup anemometers?

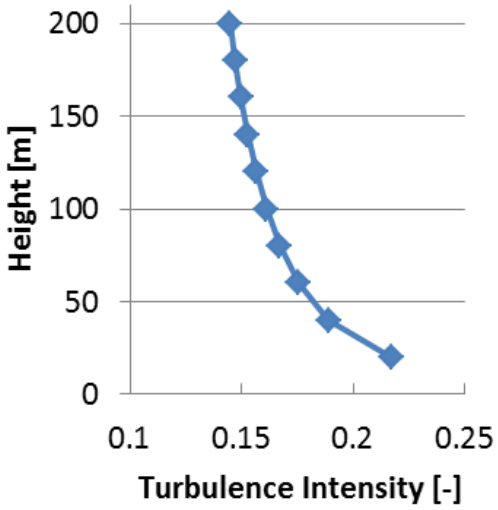
- **How is measured TI  and its decrease with height in comparison values estimated from analytical derived values from z0?**

- How can vertical shape of TI profile and horizontal TI variations be represented in CFD?

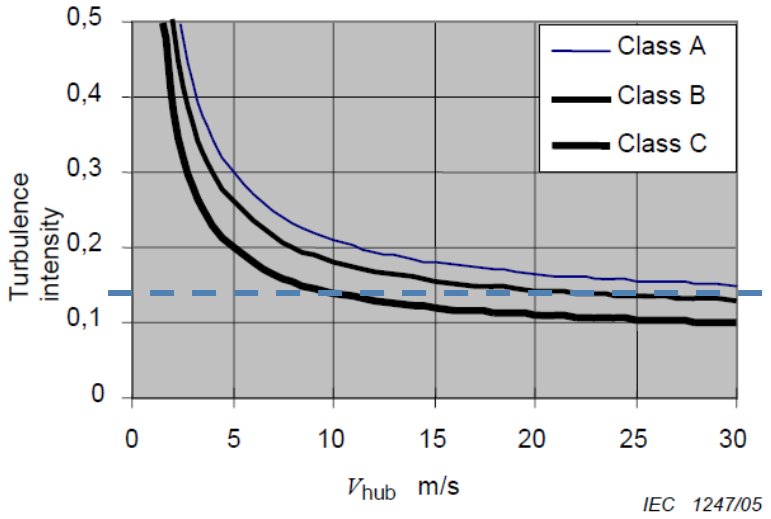
# Analytical methods

**Theory for neutrally stratified ABL**

$$TI(z) = \frac{1}{\ln\left(\frac{z}{z_0}\right)}$$



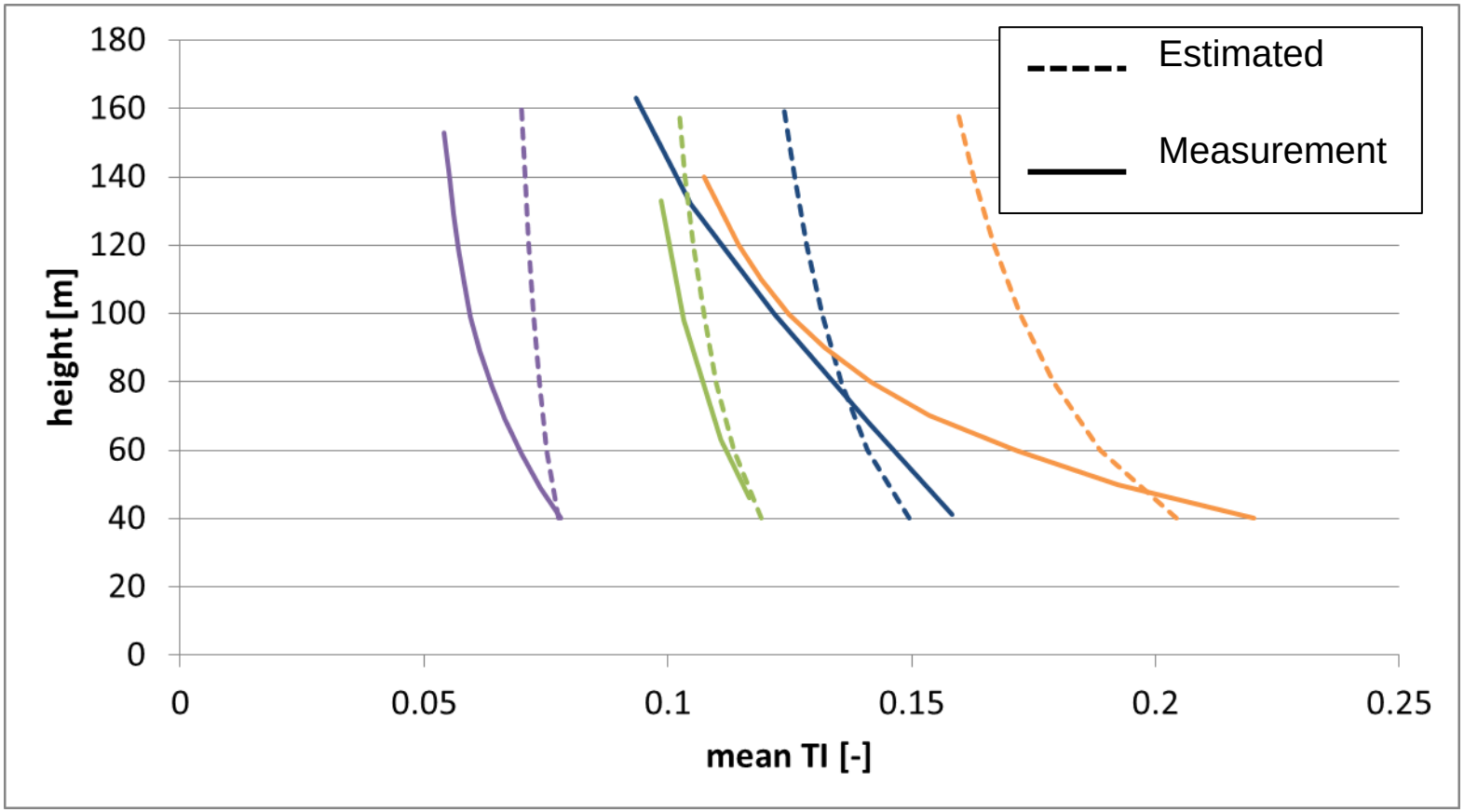

**IEC – distribution over wind speed**




- Approaches used in expert's reports on estimated TI

# Real measurements – vertical profile

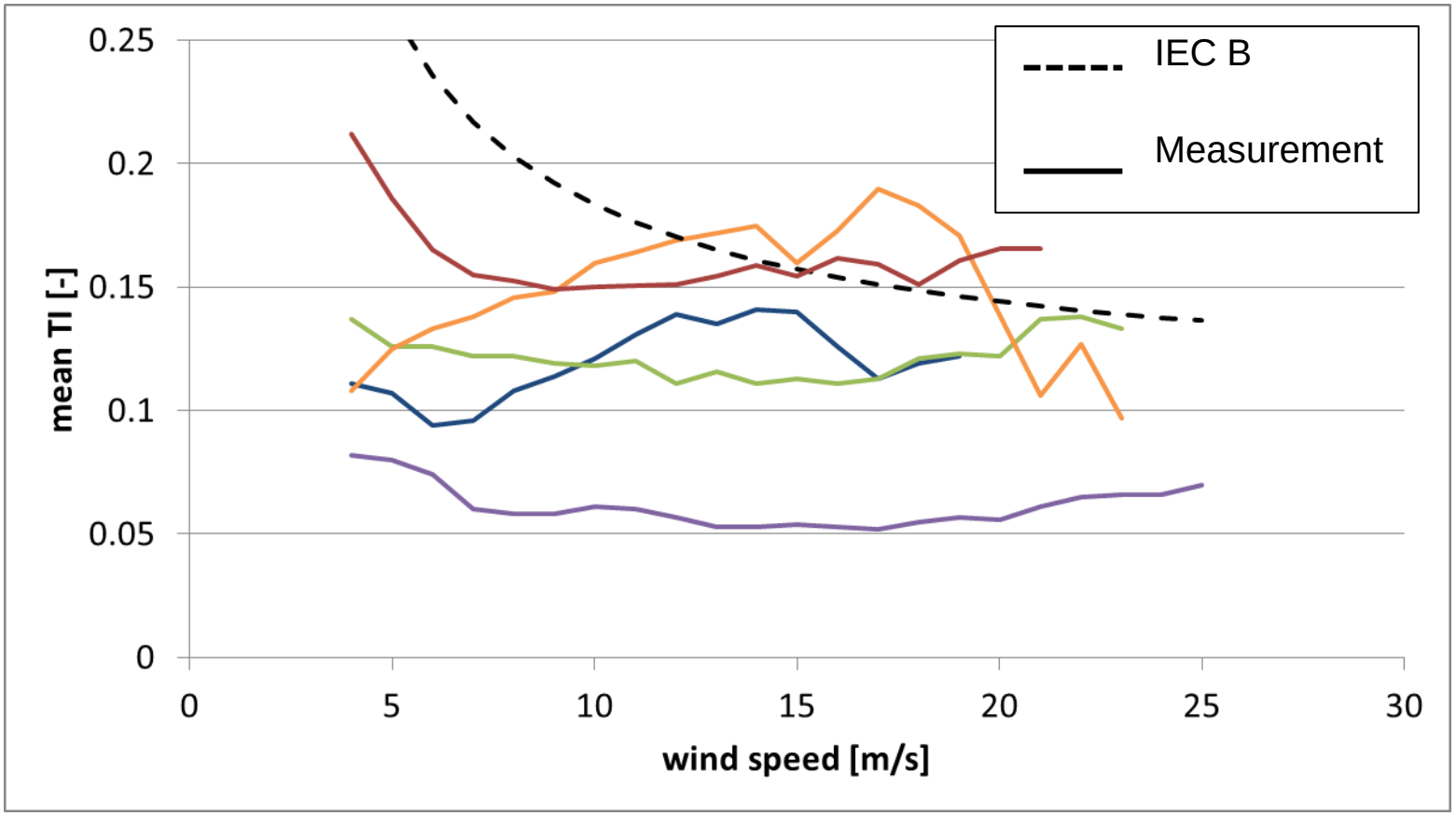
## Lidar measurements vs. estimated profiles




- Turbulence decay with height: Stronger than suggested by theory

# Real measurements – distribution over wind speed

## Lidar measurements vs. IEC distributions




- IEC-like distribution may not be representative, even of simple sites

# Questions Part 3

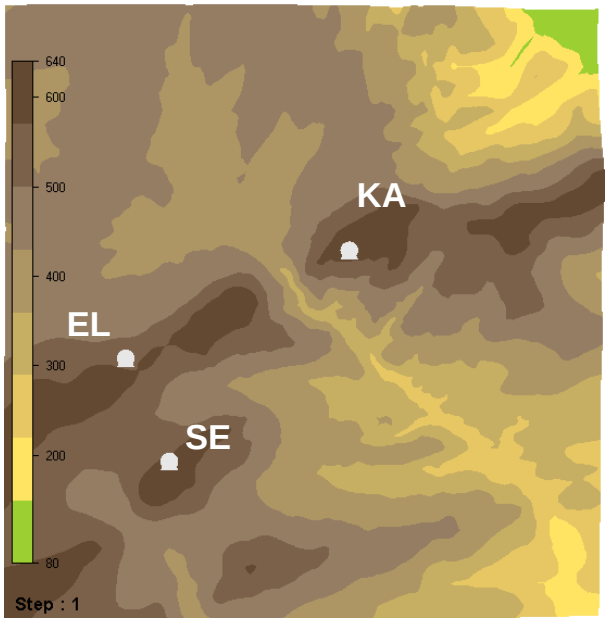
- How do practical TI measurements from Lidars compare to those from cup anemometers?

- How is measured TI  and its decrease with height in comparison values estimated from analytical derived values from z0?

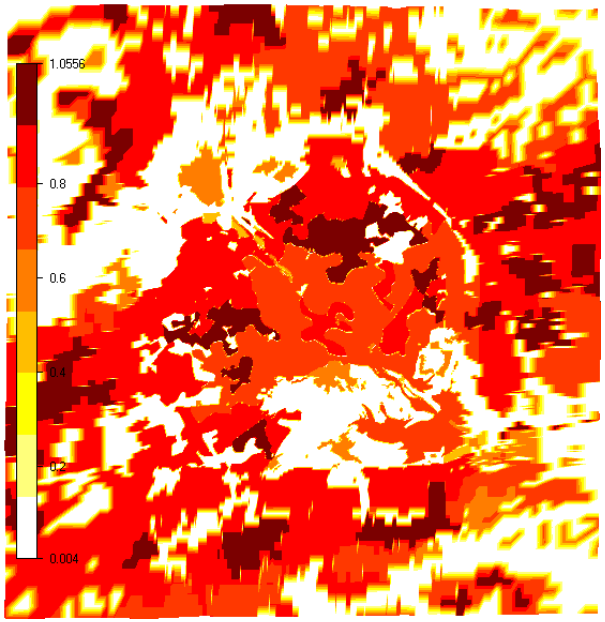
- **How can vertical shape of TI profile and horizontal TI variations be represented in CFD?**

# CFD Model Area

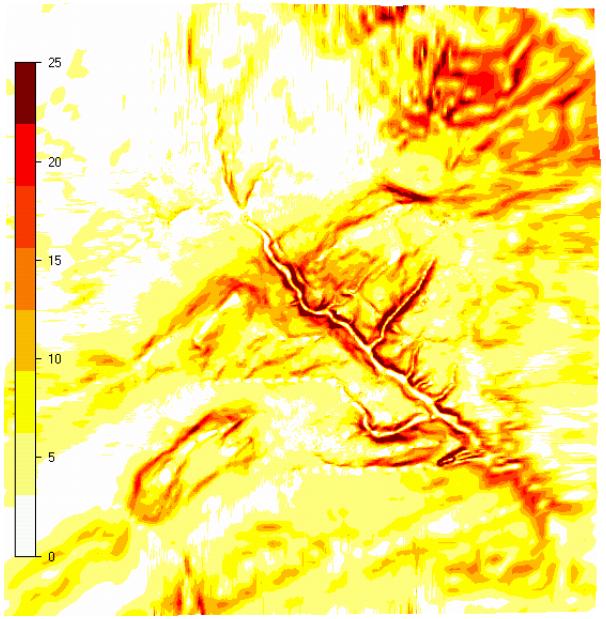
## Elevation




## Roughness/Forest



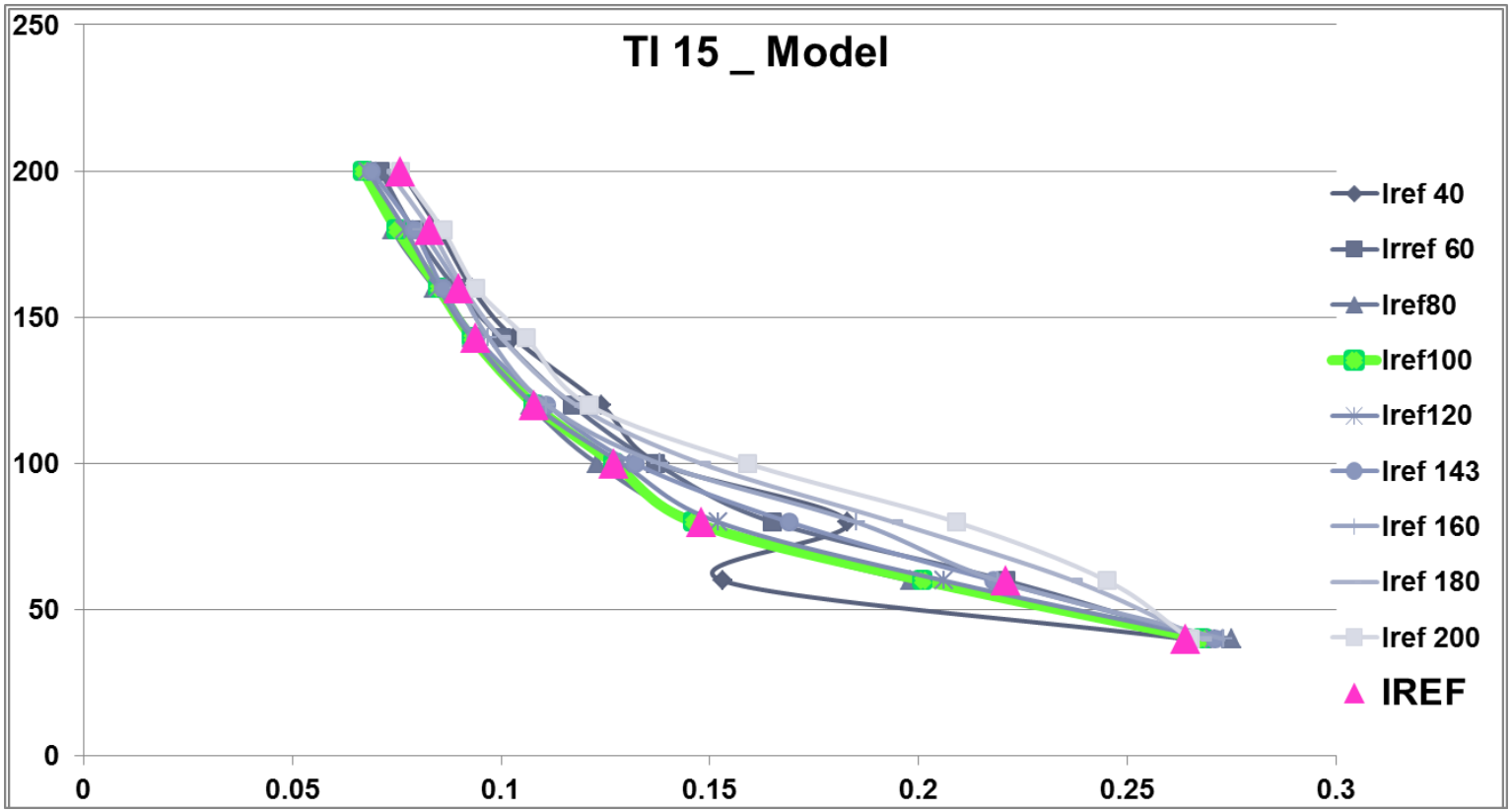

## Inclination




- Complex Terrain, all z0 values > 0.6 forest
- 3 synchronous Lidar measurements, 1 Met tower

# Vertical distribution vs. CFD

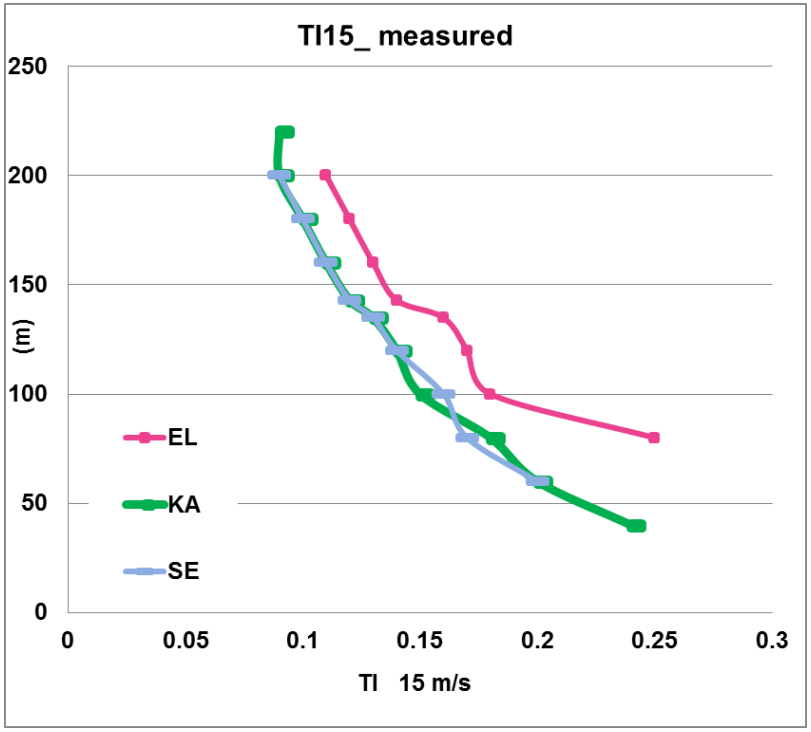
## TI (15 m/s) over height modelled from different measurement heights

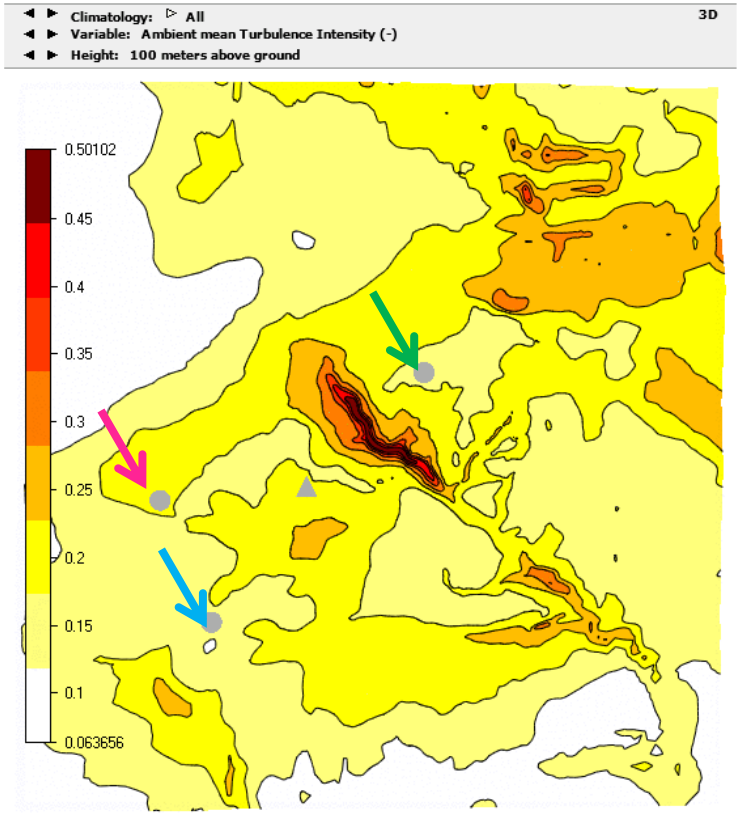



- Depending on quality of CFD, range 100m up to HH can be represented, good for “normal” Site setup with 100m tower and HH around 140m, problems with lower heights/TI values

# Horizontal distribution vs. CFD

## Regional Distribution of TI_amb (15 m/s) from measurement and model

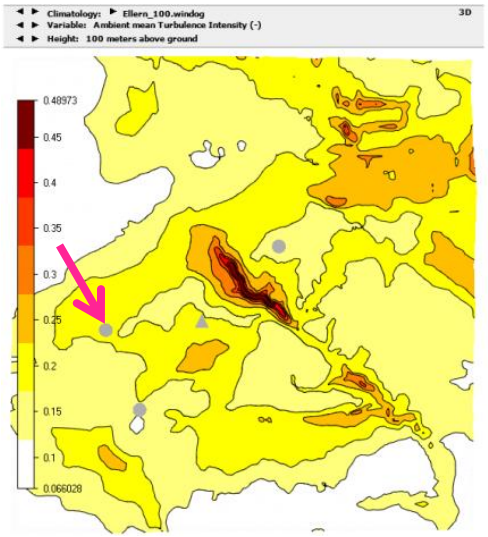


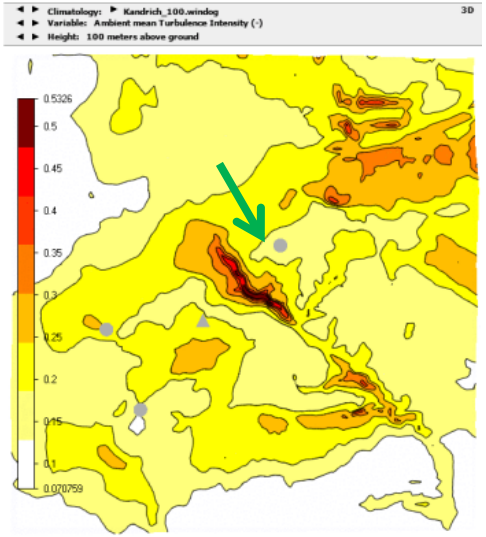



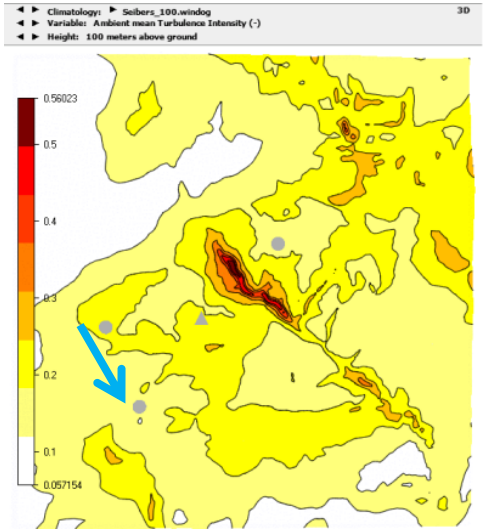

- Horizontal differences in TI are good represented when including ALL climatologies

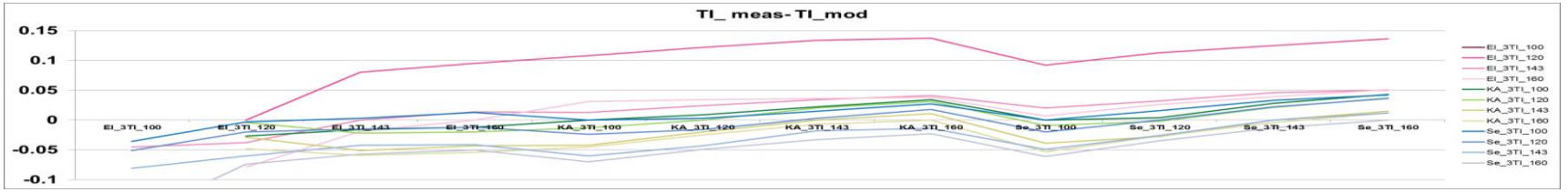
# Horizontal distribution vs. CFD

## Differences TI (15 m/s) modelled with only 1 climatology




- Even with forcing from only one climatology, the horizontal differences can be captured and represented by the model; differences here below 0.05

# Summary & Conclusions

**1. Lidar TI (WindCube) vs. cup anemometer TI**

- Lidars provide a conservative measure of TI and its standard deviation
- Overestimation increases with TI (complex sites)
- Stable performance over all wind speeds

**2. Lidar TI vs. analytical estimates**

- Analytical model and IEC profiles not necessarily representative
- Vertical profile: decay stronger in reality
- Distribution over wind speed: decay may be weaker / non-existent in reality

**3. Representation in CFD Models**

- Vertical decay and horizontal variations can be reproduced
- Quality depending on model accuracy

# Thanks for your Attention

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# Field Campaign

## Exemplary Site Layout and Requirements