



## WKN AG – renewable energies for today and tomorrow



# Forest Modeling inside WindSim 7.0 – interim report

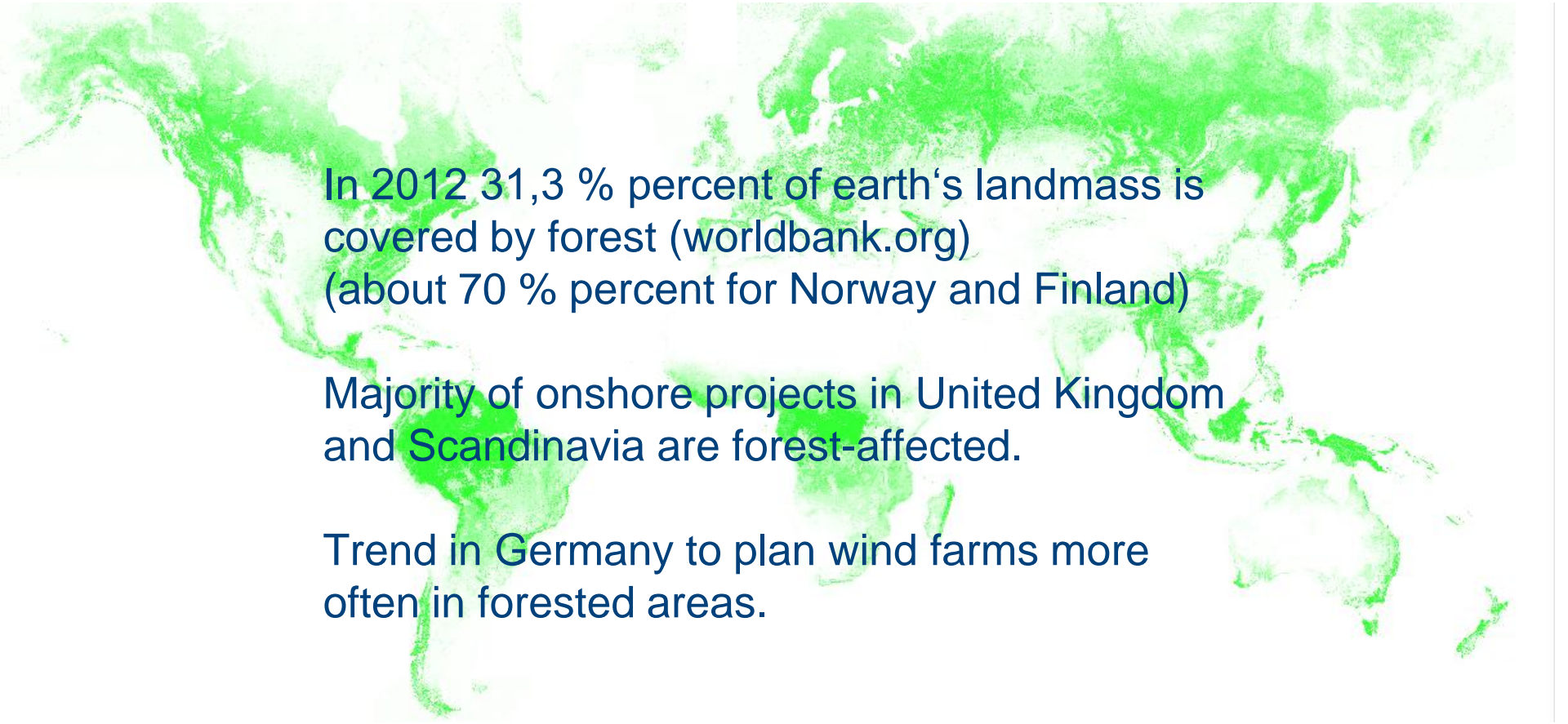
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[karsten.busch@uni-oldenburg.de](mailto:karsten.busch@uni-oldenburg.de)

- Motivation
- Theory
- Sensitivity/“Stability“ Analysis  
GCV and Segregated
  - Forest porosity
  - Forest resistive force  $C_2$  ( $\sim u^2$ )
  - Forest Turbulence Sources ( $\beta_p$ ,  $\beta_d$ ,  $C_{\epsilon 4}$ ,  $C_{\epsilon 5}$ )
  - Forest cell count in Z direction
- GCV + turbulence source models
  - First results from virtual wind tunnel
  - First results from real terrain (if time left)



In 2012 31,3 % percent of earth's landmass is covered by forest (worldbank.org)  
(about 70 % percent for Norway and Finland)

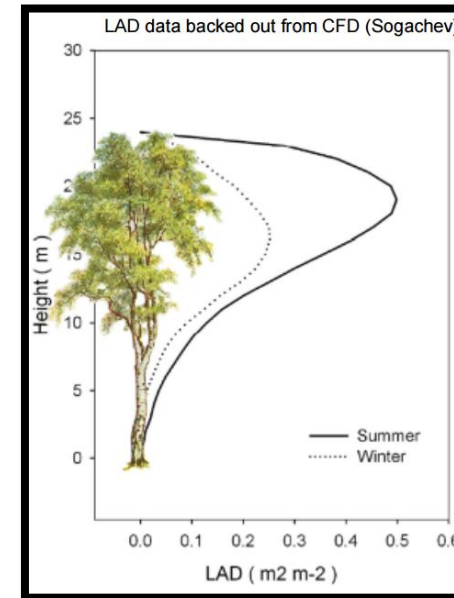
Majority of onshore projects in United Kingdom and Scandinavia are forest-affected.

Trend in Germany to plan wind farms more often in forested areas.

Source: Landsat Vegetation Continuous Fields (VCF) tree cover, world wide data (via Global Mapper)

But...

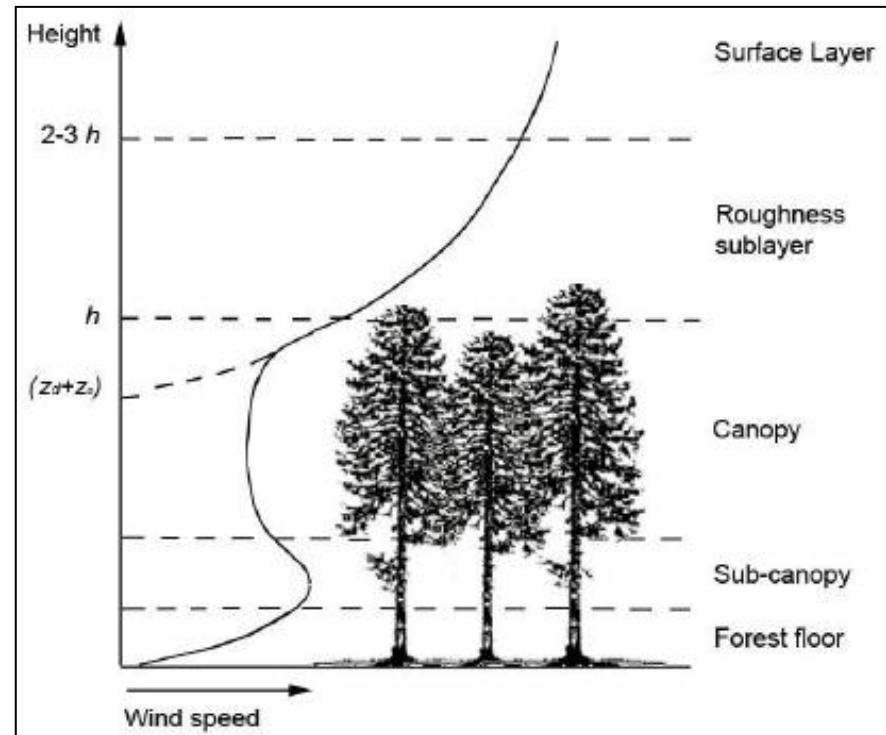
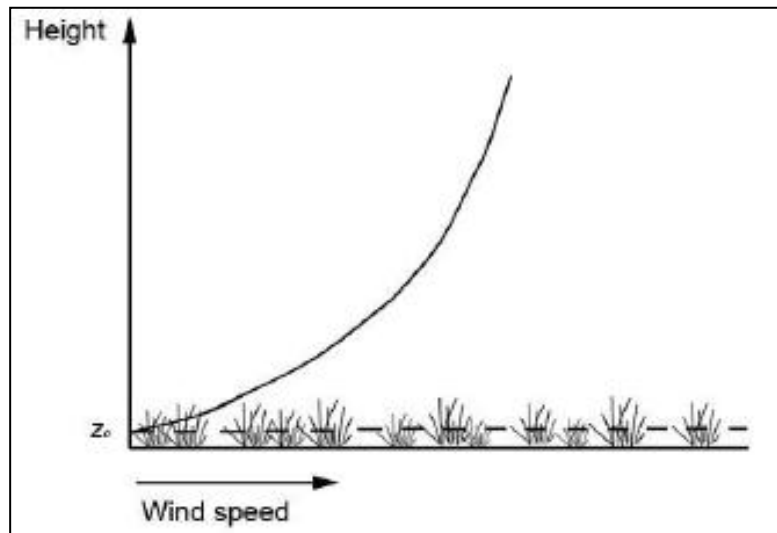
- No industry consensus on models
- Large modeling uncertainties
- Information from site
  - often inaccurate
  - seasonal depending
  - evolves over time
- Need further analyzes in flow modeling in forest-affected areas
- Forestry increases turbulence
  - Increases uncertainties e.g. because of imperfect turbulence models



- “Real life” needs:
  - few parameters,
    - with acceptable necessary effort to determine
    - with sufficient correct results
- “Real life” is
  - No idealized and homogeneous forest
    - Spatial variance of forest height
    - Spatial variance of forest density
    - Seasonal variance

## Vertical wind profiles for low vegetation (left) and forest (right).

Source:  
Junge „Estimation of Zero Displacement Heights in the Vicinity of a Forest“  
Gardiner (2004) „Airflow over forest and forest gaps“ BWEA Tree Workshop  
Forestry Commission.



Applied forests models in WindSim neglects sub canopy bulges.  
Possible influences along the edges of forests.  
Few influence on vertical profile above canopy.

## Segregated solver Porosity plus momentum sinks $C_1$ and $C_2$

$$\beta = \frac{\text{volume of voids}}{\text{total volume}}$$

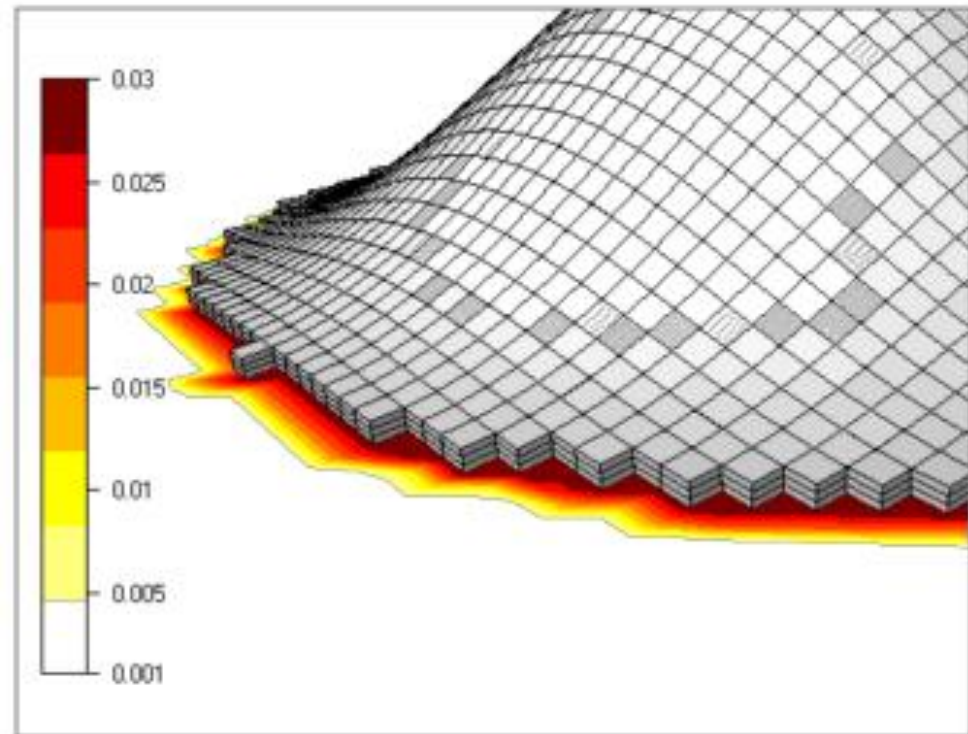
$$S_j = -\rho C_1 U_j - \rho C_2 \sqrt{U_i U_i} U_j$$

sink  $U$   
proportional

sink  $U^2$   
proportional

$$[C_1] = \frac{1}{s}$$

$$[C_2] = \frac{m^2}{m^3}$$



## Segregated solver Porosity plus C1 ( via permeability k) 2005

$$\beta = \frac{\text{volume of voids}}{\text{total volume}}$$

$$k^* = C \frac{\beta^2}{1-\beta^2} \quad [\text{m}^2]$$

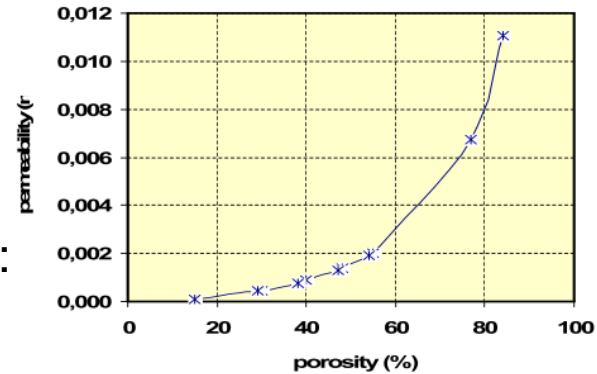
$$C1 = \frac{v}{k^*} = \frac{v}{C} \frac{1-\beta^2}{\beta^2} \quad [1/\text{s}]$$

$$S_j = -\rho C1 U_j$$

sink U  
proportional
sink U<sup>2</sup>  
proportional

$$[C1] = \frac{1}{\text{s}} \quad [C2] = \frac{\text{m}^2}{\text{m}^3}$$

Wei Li et al.:  
permeability  
C2=0



original proposal (2005)

| Species of tree | porosity [%] | C <sub>1</sub> [1/s] |
|-----------------|--------------|----------------------|
| <b>Fluid</b>    | <b>100</b>   | <b>-</b>             |
| Beech           | 84           | 1,394E-03            |
| Black cherry    | 77           | 2,294E-03            |
| Birch           | 55           | 7,703E-03            |
| Lime            | 54           | 8,116E-03            |
| Ash             | 48           | 1,116E-02            |
| Mature maple    | 47           | 1,178E-02            |
| Scots pine      | 38           | 1,980E-02            |
| Firs            | 30           | 3,378E-02            |
| Spruce          | 29           | 3,638E-02            |
| Cypresses       | 15           | 1,451E-01            |
| <b>Solid</b>    | <b>0</b>     | <b>-</b>             |

## Segregated solver Porosity plus momentum sinks C<sub>1</sub> and C<sub>2</sub>

$$\beta = \frac{\text{volume of voids}}{\text{total volume}}$$

Today suggestion:  
high value of porosity  
and tune C<sub>2</sub> coefficient

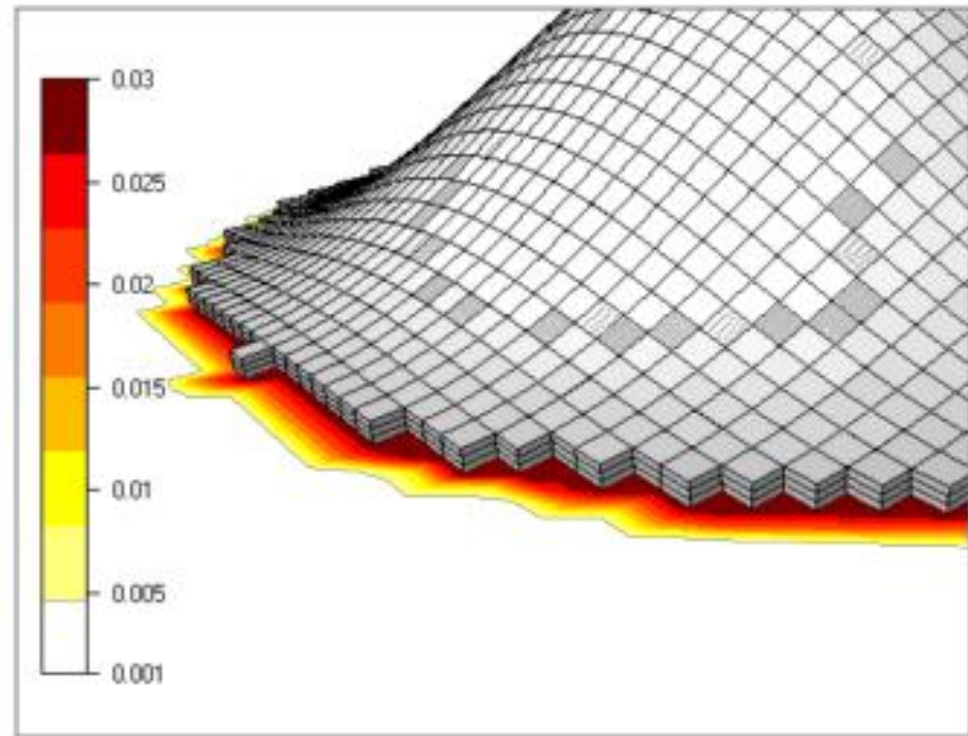
$$S_j = -\rho C_2 \sqrt{U_i U_i} U_j$$

sink U  
proportional

sink U<sup>2</sup>  
proportional

$$[C_1] = \frac{1}{s}$$

$$[C_2] = \frac{m^2}{m^3}$$



## RANS forest modeling terms

Forest Model, David Hilbert, UM 2012

$$S_j = -\rho C_1 U_j - \rho C_2 \sqrt{U_i U_i} U_j$$

$$S_k = C_D a (\beta_P |U|^3 - \beta_D |U|k)$$

$$S_\varepsilon = C_D a \left( C_{\varepsilon 4} \beta_P \frac{\varepsilon}{k} |U|^3 - C_{\varepsilon 5} \beta_D |U| \varepsilon \right)$$

- momentum absorbed
  - decrease in wind speed ←
- turbulence generated and absorbed
  - + Wake-induced turbulence ←
  - TKE spectral short-cut ←

### Model sets

| $\beta_P$ | $\beta_D$ | $C_{\varepsilon 4}$ | $C_{\varepsilon 5}$ | Ref.                             |
|-----------|-----------|---------------------|---------------------|----------------------------------|
| 1.0       | 6.51      | 1.24                | 1.24                | Sanz 2003 / Katul 2004 (adapted) |

Modified slide!

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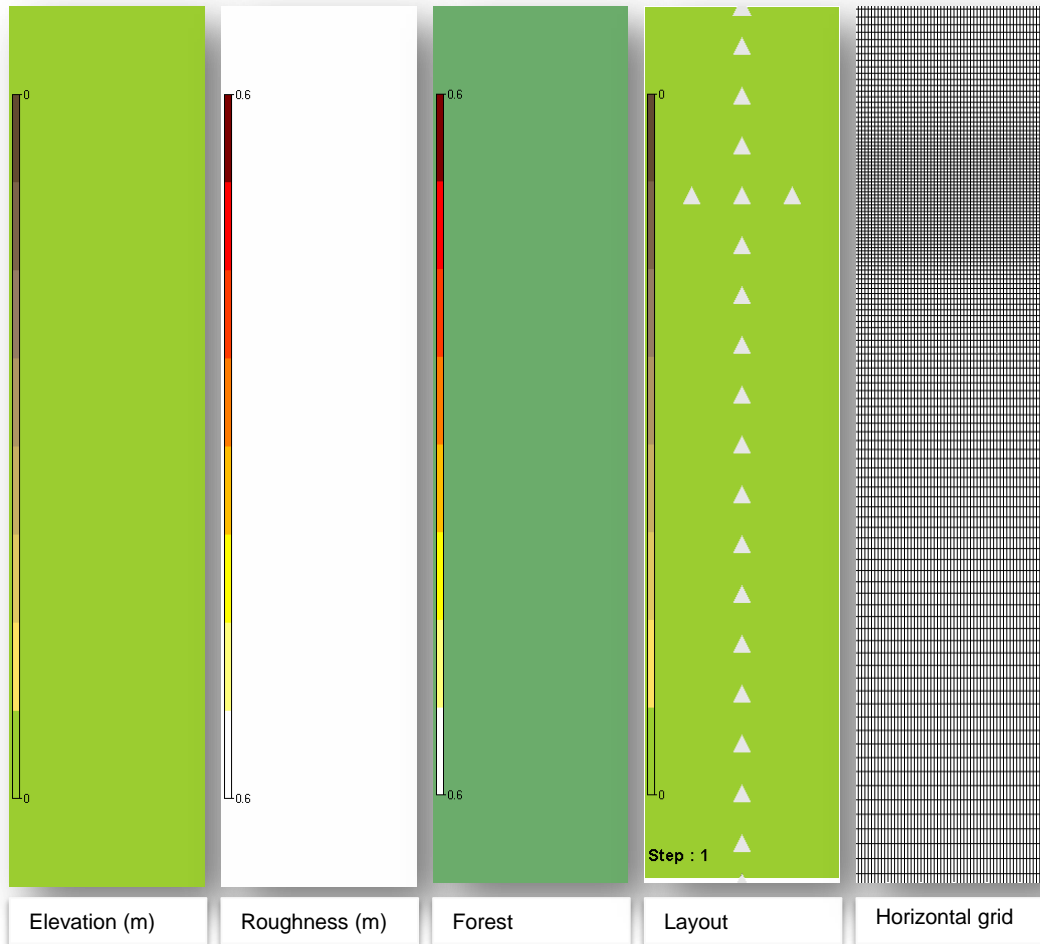
### Model sets

|           | $\beta_P$ | $\beta_D$ | $C_{\varepsilon 4}$ | $C_{\varepsilon 5}$ | Ref.                                     |
|-----------|-----------|-----------|---------------------|---------------------|--|
| model 'A' | 0.0       | 0.0       | 0.0                 | 0.0                 | Gravdahl et al. 2006 (WindSim, modified) |
| model 'B' | 0.17      | 3.37      | 0.9                 | 0.9                 | Lopes da Costa 2007                      |
| model 'C' | 1.0       | 0.0       | 1.8                 | 0.0                 | Mochida et al. 2010 (Svensson adaption)  |
| model 'D' | 1.0       | 6.51      | 1.24                | 1.24                | Sanz 2003 / Katul 2004 (adapted)         |

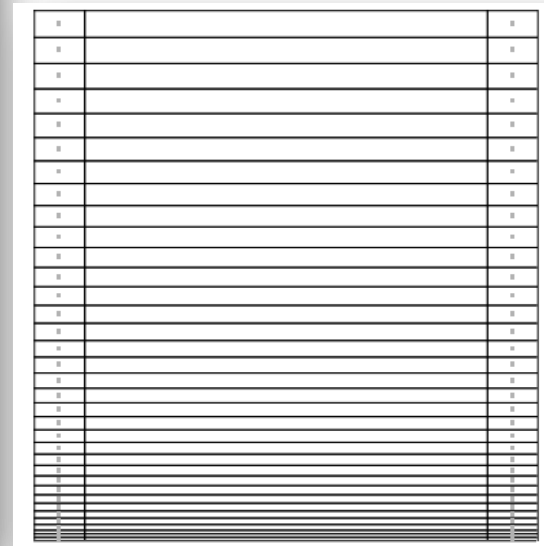
Further model(s) will be tested.

| Solver  | Segregated                 | GCV   |
|---|----------------------------|---|
| Forest height   | average forest height      | average forest height   |
| <i>Forest porosity</i>  | <i>0.3 (tested [0..1])</i> | <i>n/a<br/>(not applicable)</i>   |
| Forest resistive force C1 (~u)  | negligible                 | negligible  |
| Forest resistive force C2 (~u <sup>2</sup> )  | 0.005                      | 0.005 (tested [0..1])<br>("models forest")                              |
| <i>Forest Turbulence Sources<br/>(β<sub>p</sub>, β<sub>d</sub>, Cε<sub>4</sub>, Cε<sub>5</sub>)</i> | <i>n/a</i>                 | <i>Sanz /Katul (2003/2004),<br/>da Costa (2007),<br/>Mochida (2010)</i> |
| Forest cell count in Z direction  | 3 (tested [2..10])         | 3 (tested [1..10])  |

# Forest Model - Sensitivity analysis



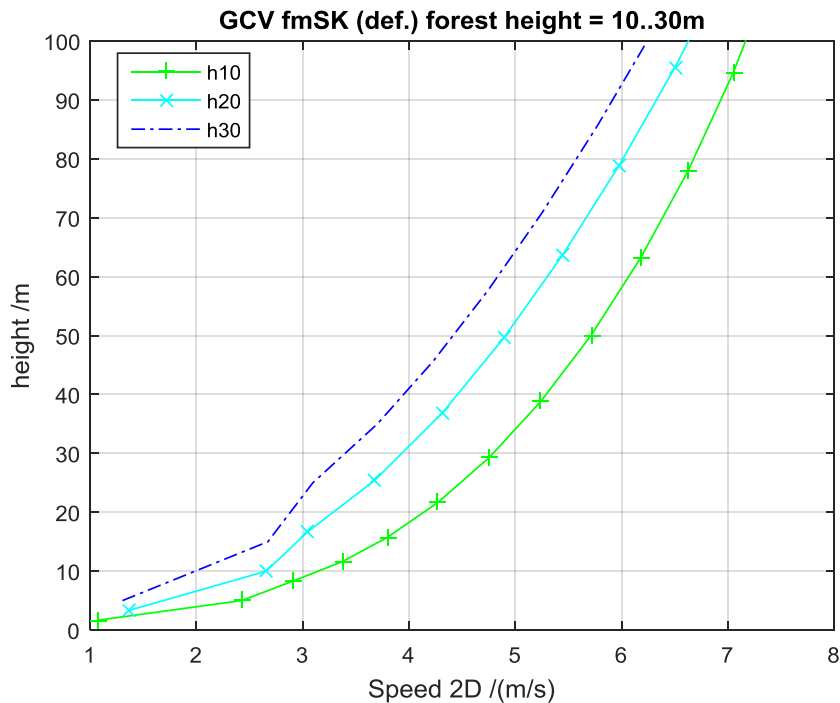
**Fully forested**  
**Flat plane ~narrow wind tunnel**  
**UBC: no friction wall**  
**“Canopy Modeling with a CFD code”**  
**(Gravdahl, Crasto et al, EWEC 2006)**



|                  | Easting     | Northing        | z          | Total          |
|------------------|-------------|-----------------|------------|----------------|
| Grid spacing (m) | 33.3 - 33.4 | 33.3 - 155.1    | Variable   | 2000-9000-1000 |
| Number of cells  | 60          | 125             | 35         | 262500         |
|                  | Sectors     | Simulation time | Iterations | Status         |
|                  | 000         | 02:20:51        | 6976       | C              |

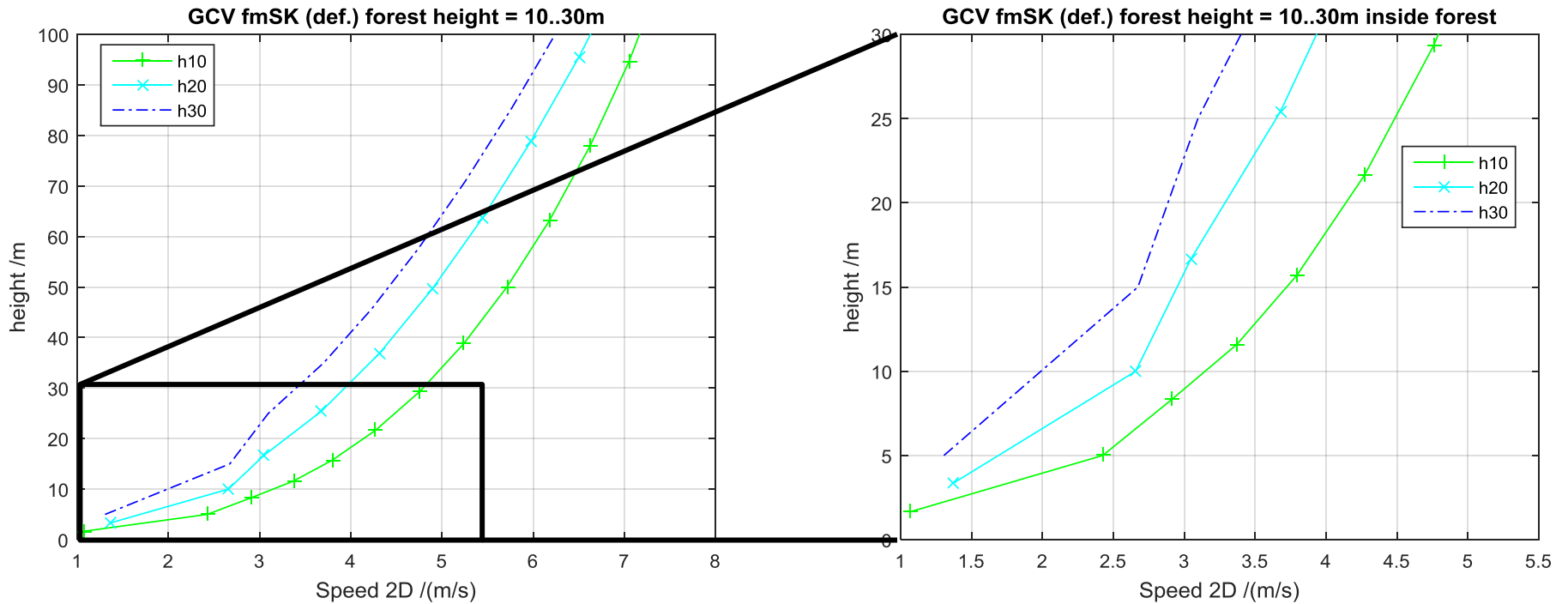
|                 | 1   | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10    |
|-----------------|-----|------|------|------|------|------|------|------|------|-------|
| z-dist. max (m) | 3.3 | 10.0 | 16.7 | 25.4 | 36.9 | 49.6 | 63.7 | 79.0 | 95.6 | 113.4 |
| z-dist. min (m) | 3.3 | 10.0 | 16.7 | 25.4 | 36.9 | 49.6 | 63.7 | 79.0 | 95.6 | 113.4 |

## GCV solver *Speed 2D* with varying *forest heights*



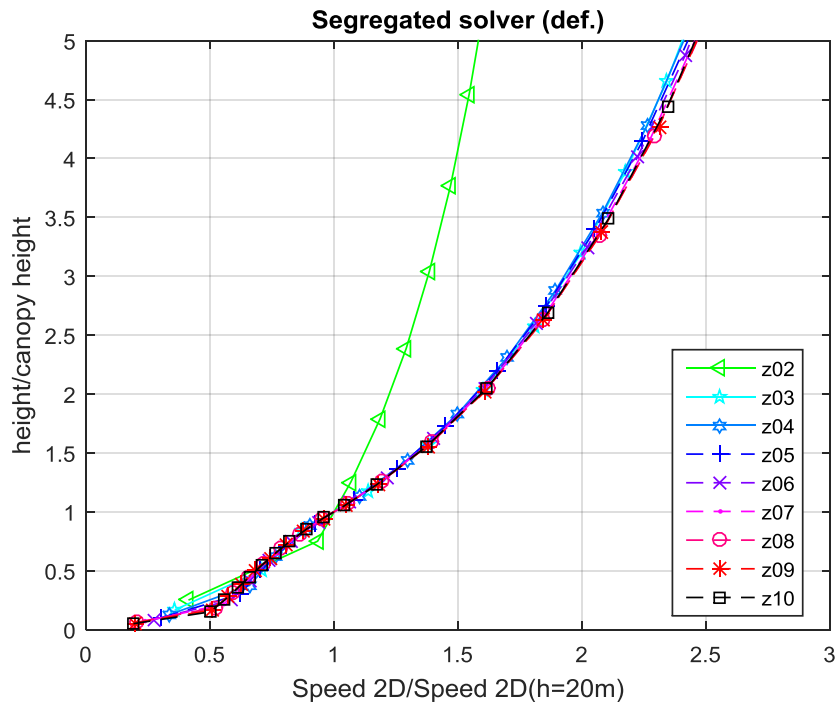
Forest height is obviously a very crucial parameter.

## GCV solver Speed 2D with varying forest heights



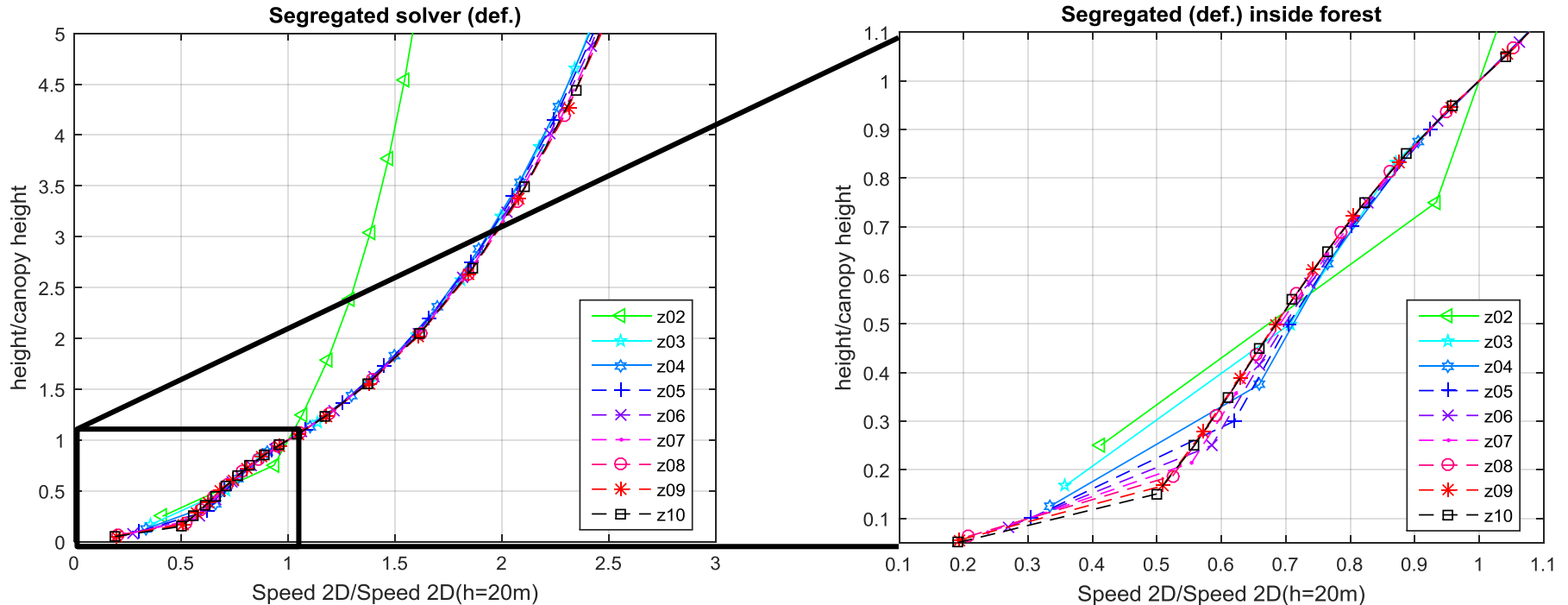
Forest height is obviously a very crucial parameter.

## Segregated: *Speed 2D* with *forest vertical cell count z*



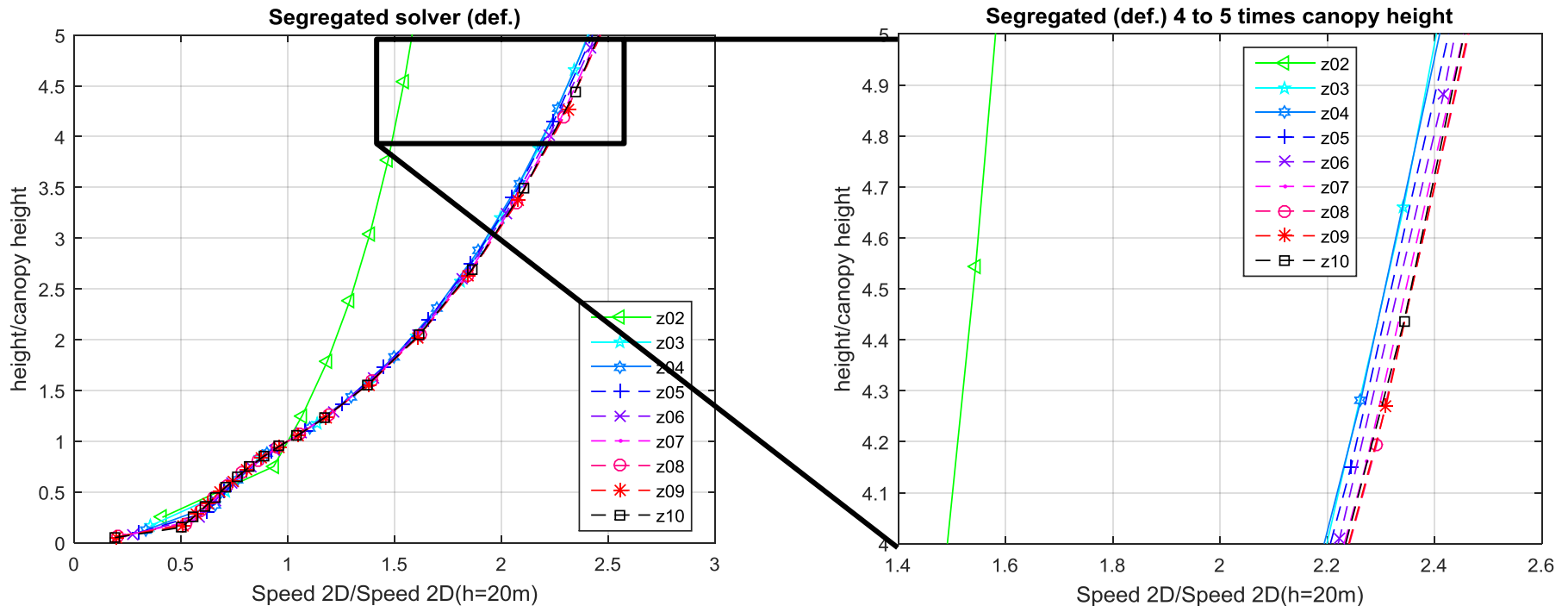
Default setting ( $z=3$ ) for Segregated solver regarding Speed 2D solver is good.

## Segregated: Speed 2D with forest vertical cell count z



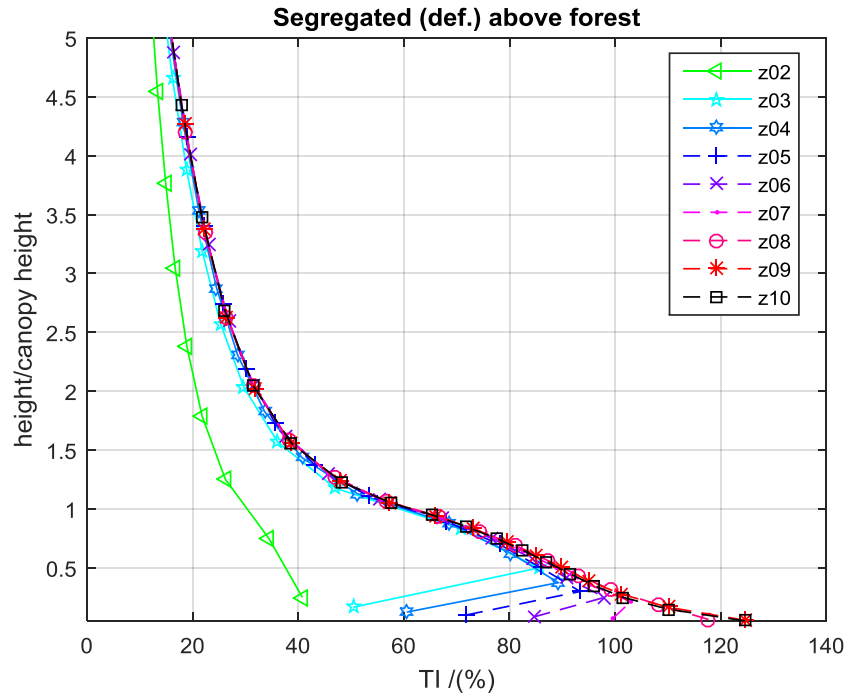
Default setting (z=3) for Segregated solver regarding Speed 2D solver is good.

## Segregated: Speed 2D with forest vertical cell count z



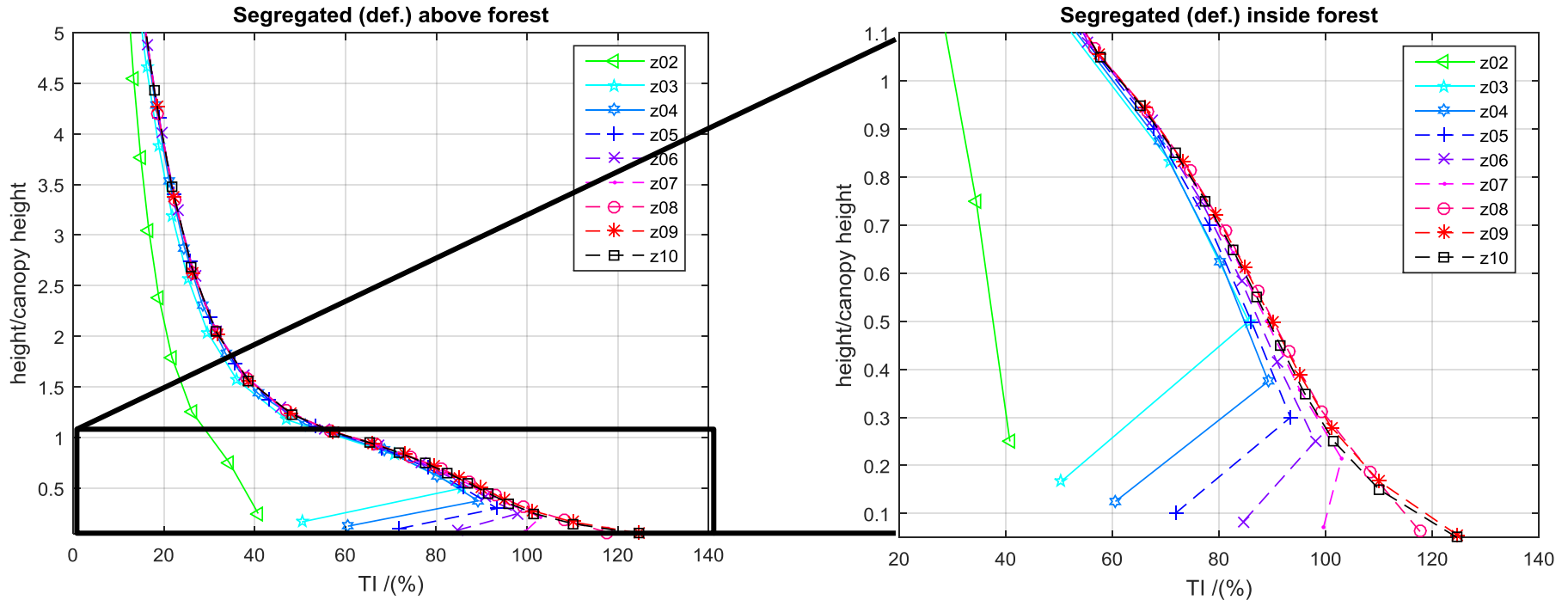
Default setting (z=3) for Segregated solver regarding Speed 2D solver is good, but might be better (z>8).

## Segregated: $TI$ with forest vertical cell count $z$



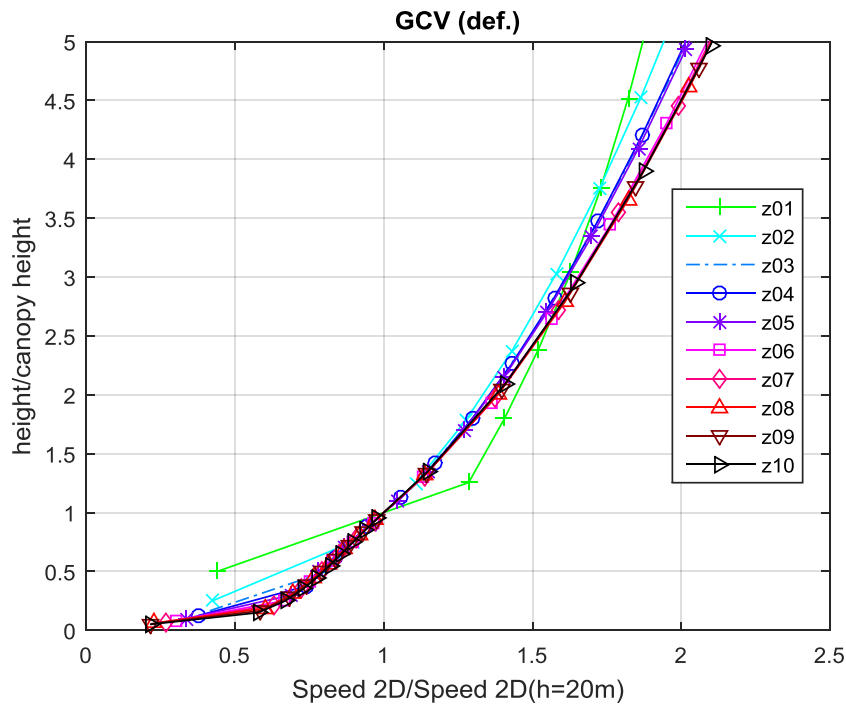
Default setting for Segregated solver ( $z=3$ ) looks good.

## Segregated: $TI$ with forest vertical cell count $z$



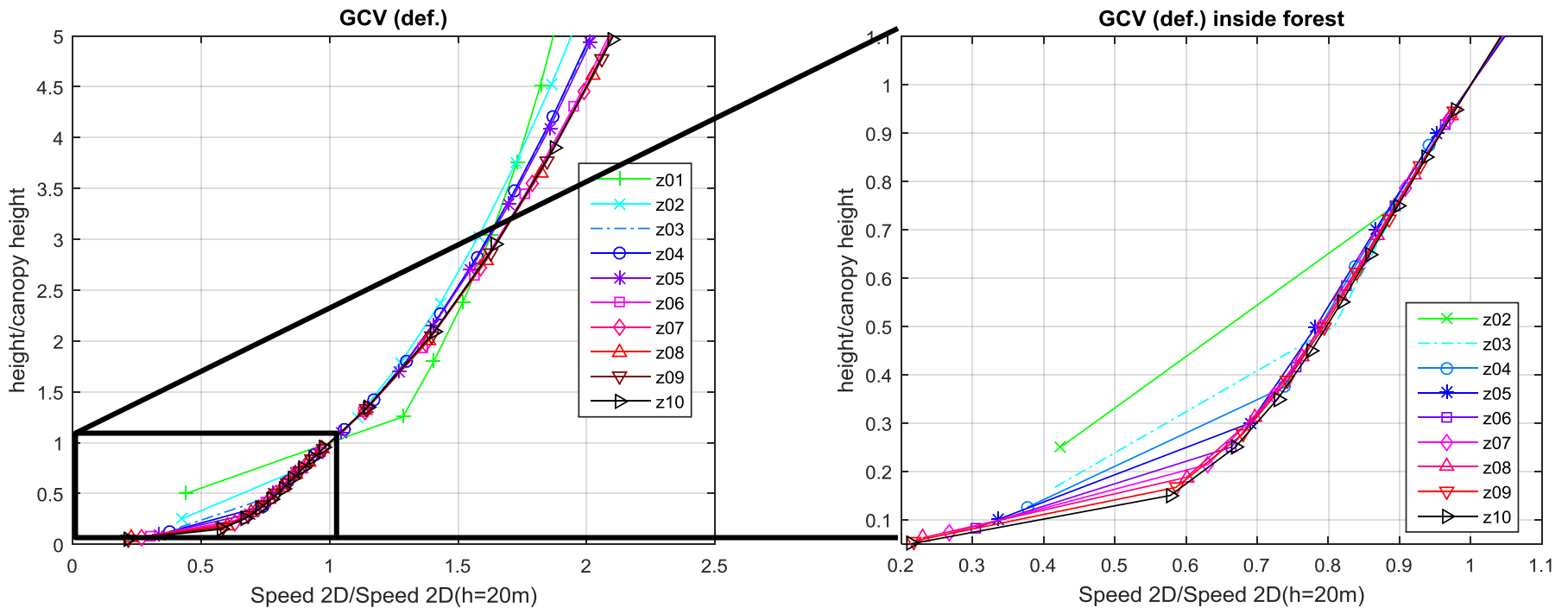
Default setting for Segregated solver ( $z=3$ ) looks good, but  $TI$  profile inside forest becomes stable for  $z>9$ .

## GCV: Speed 2D with forest vertical cell count z



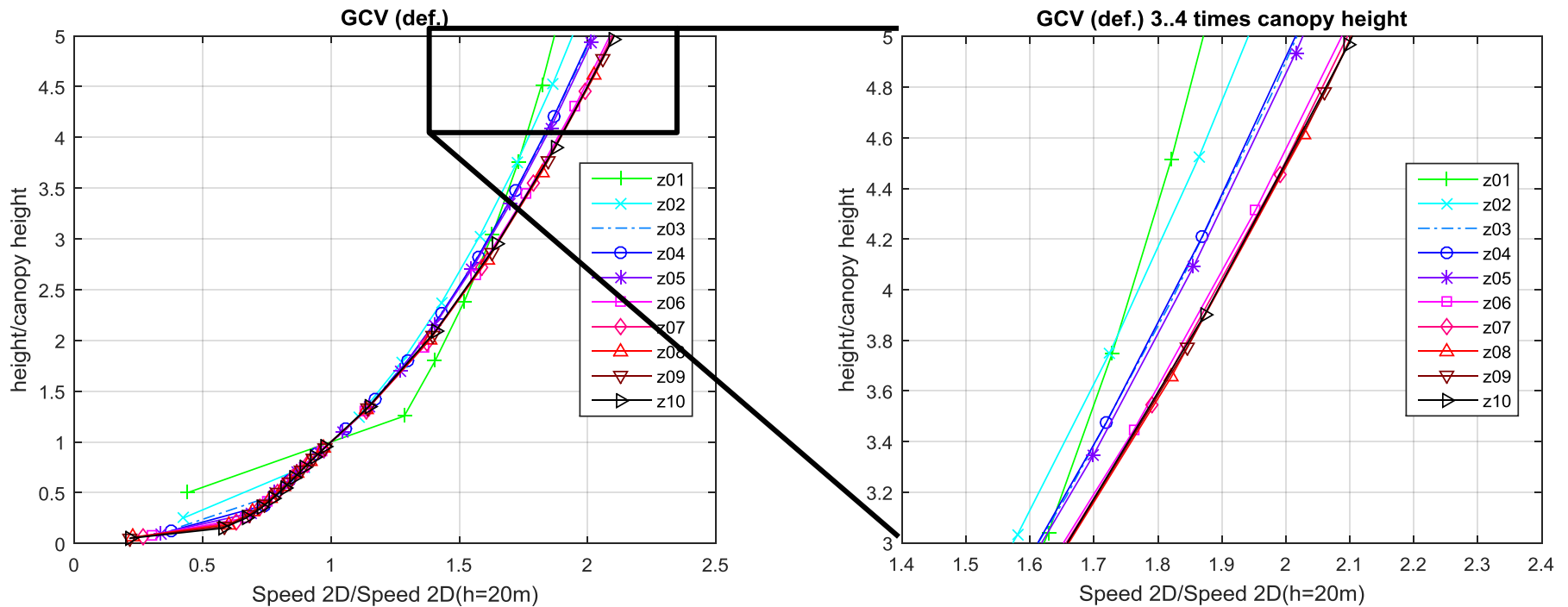
GCV solver regarding Speed 2D is stable with small z inside forest.

# GCV: Speed 2D with forest vertical cell count z



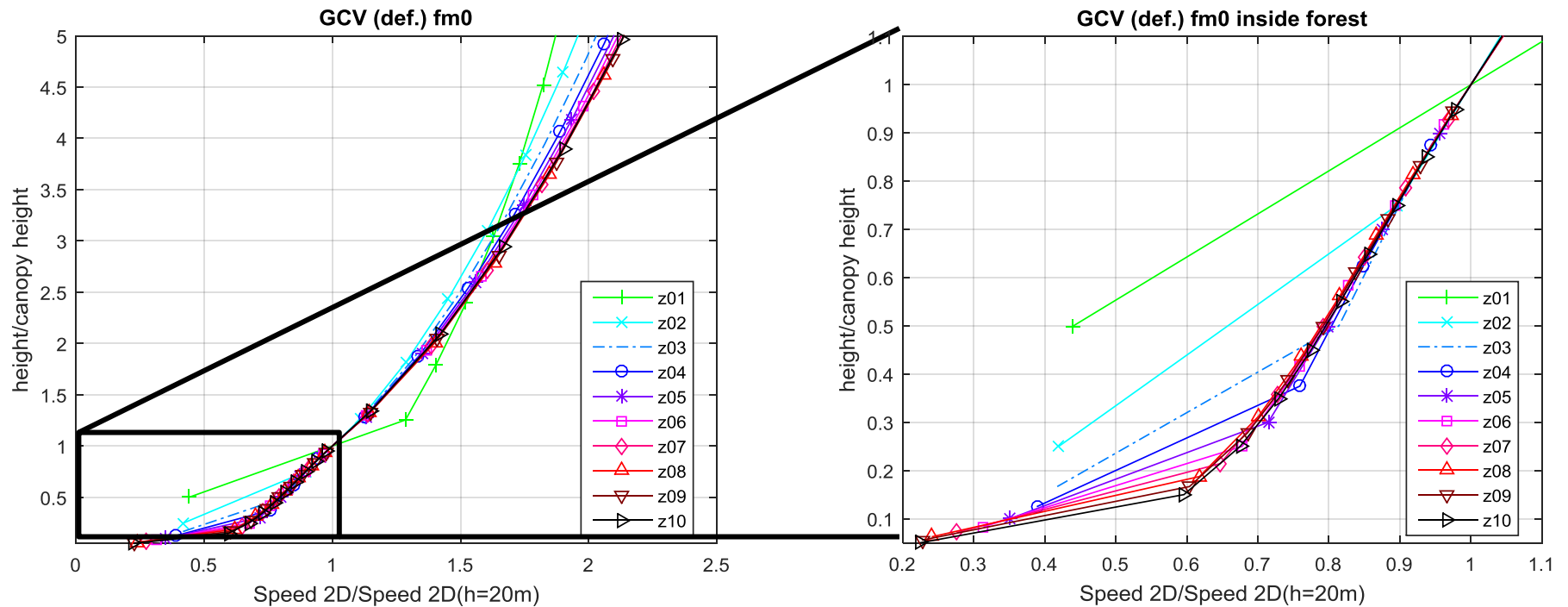
GCV solver regarding Speed 2D is stable with small z inside forest.

## GCV: Speed 2D with forest vertical cell count z



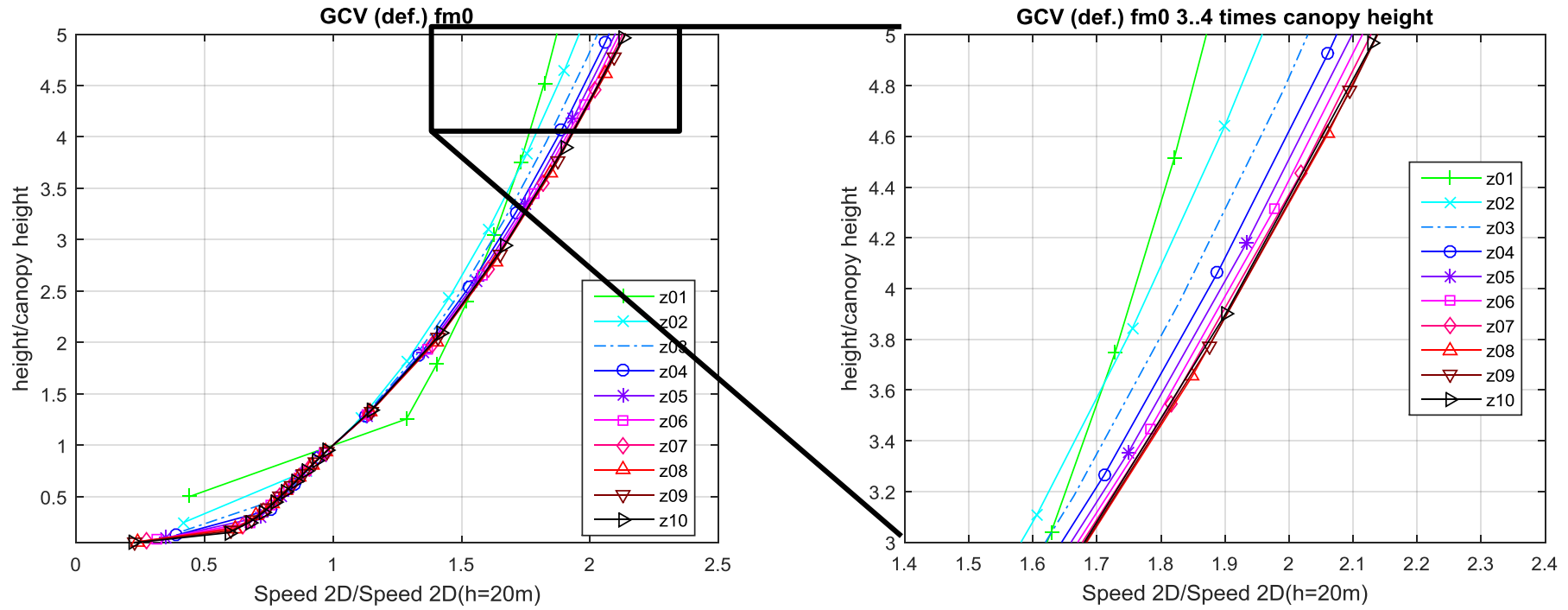
GCV solver regarding Speed 2D is stable with small z inside forest, but needs  $z > 6$  to stabilize above canopy.

# GCV fm0: Speed 2D with forest vertical cell count z



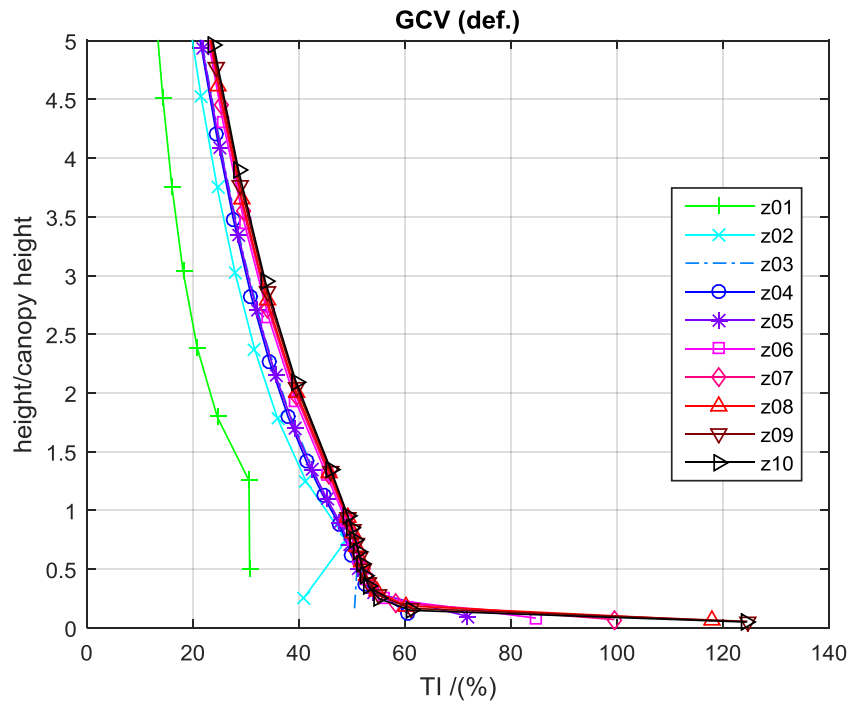
GCV solver regarding Speed 2D is stable with small z inside forest.

# GCV fm0: Speed 2D with forest vertical cell count z



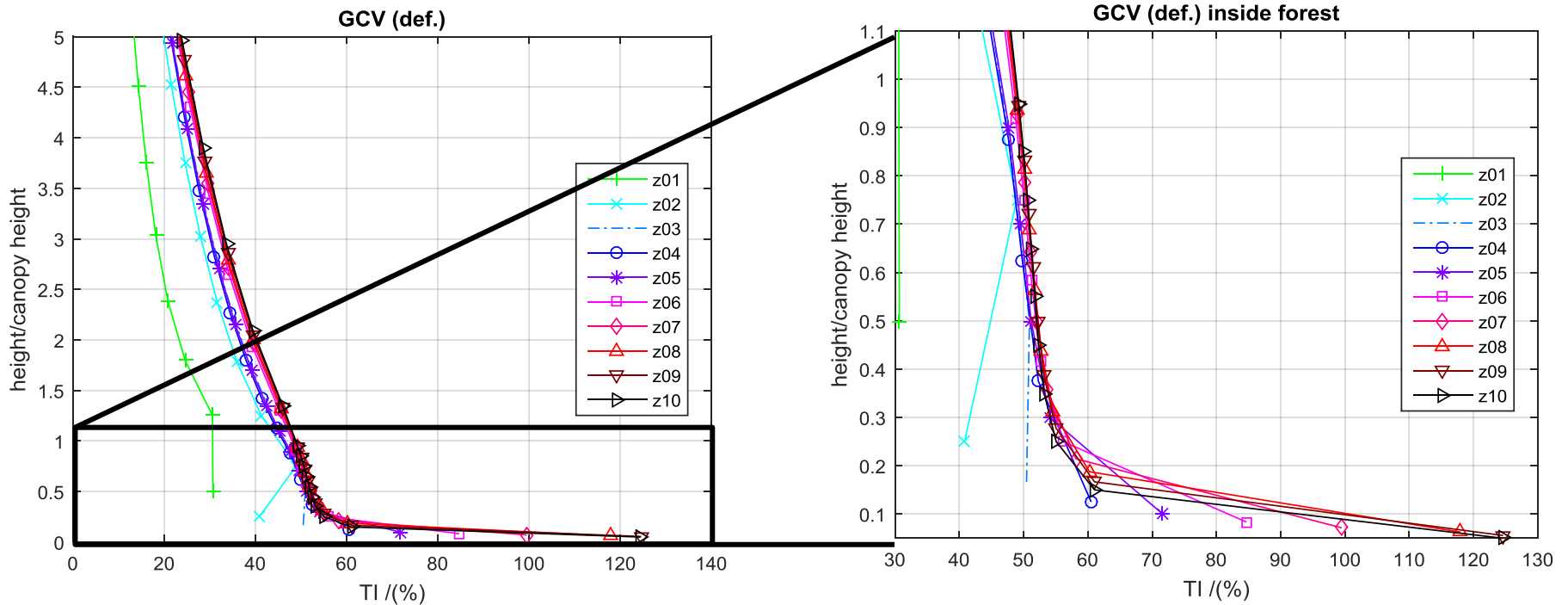
GCV solver regarding Speed 2D is stable with small z inside forest, but needs  $z > 6$  to stabilize above canopy.

## GCV: *TI* with forest vertical cell count



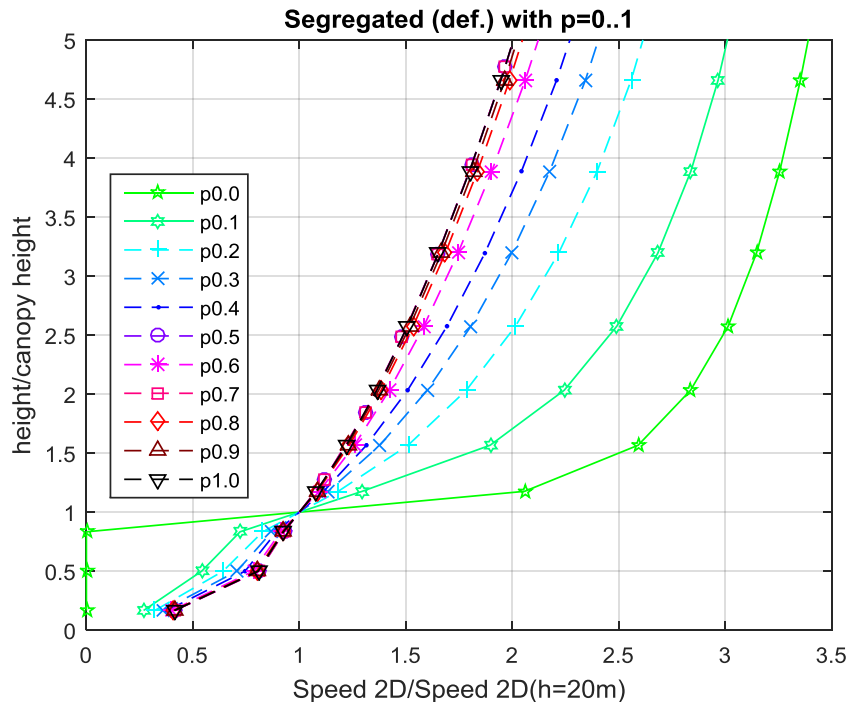
GCV solver regarding TI needs  $z > 6$  for stable behaviour.

## GCV: TI with forest vertical cell count

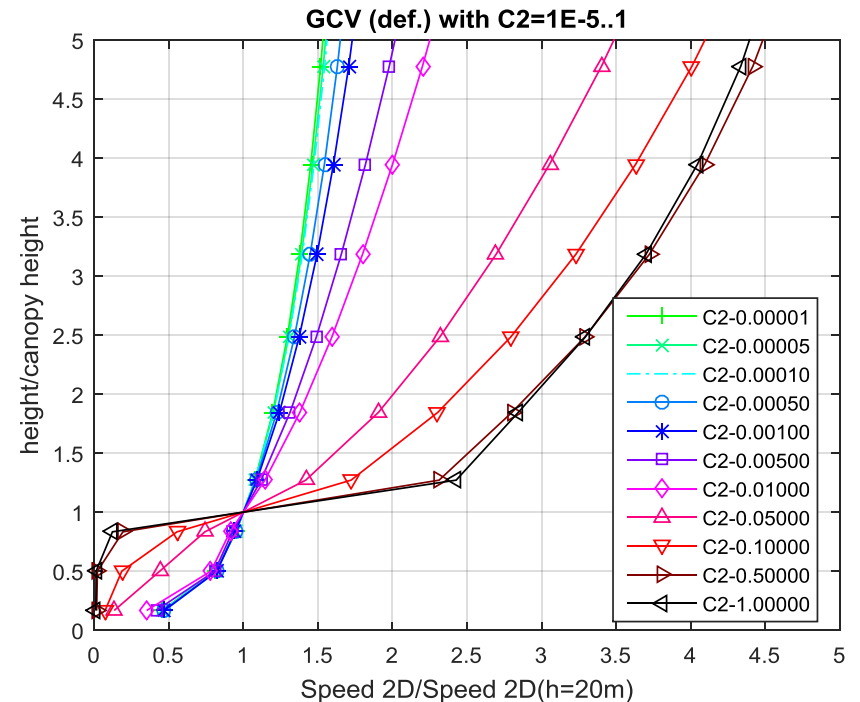


GCV solver regarding TI needs  $z > 6$  for stable behaviour.

## Segregated Solver: Speed 2D with porosity

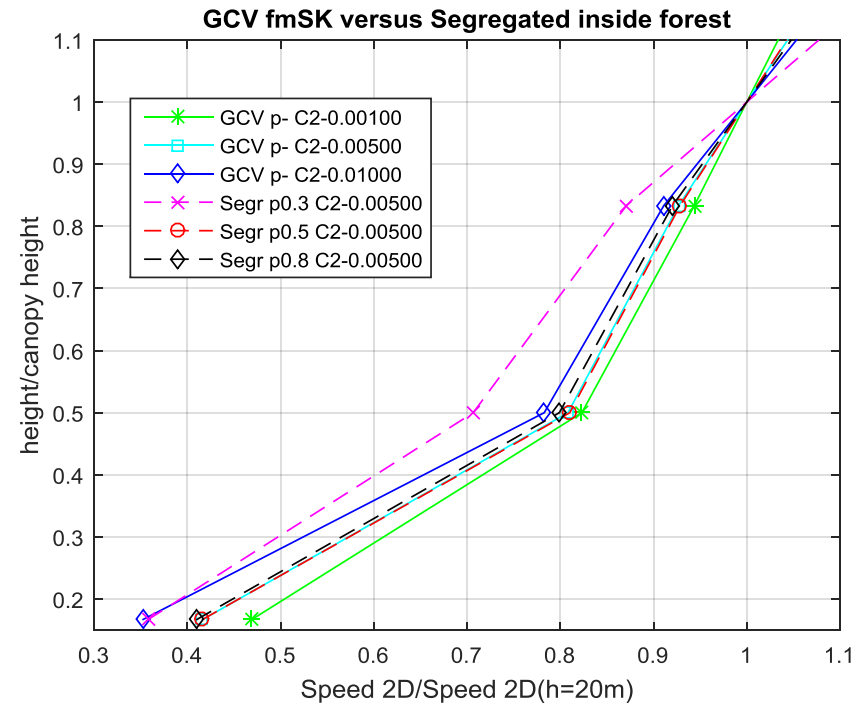
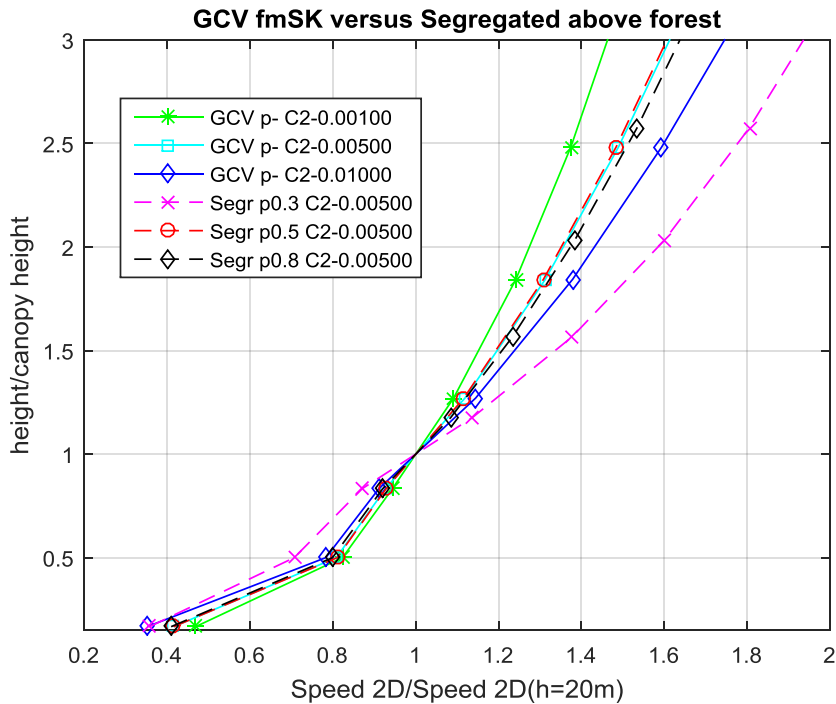


## GCV solver: Speed2D with $C_2$



Both approaches seem to deliver suitable profiles. ← need to be validated.  
Segregated  $0 < p < 0.7$  | GCV  $0.0001 < C_2 < 1$

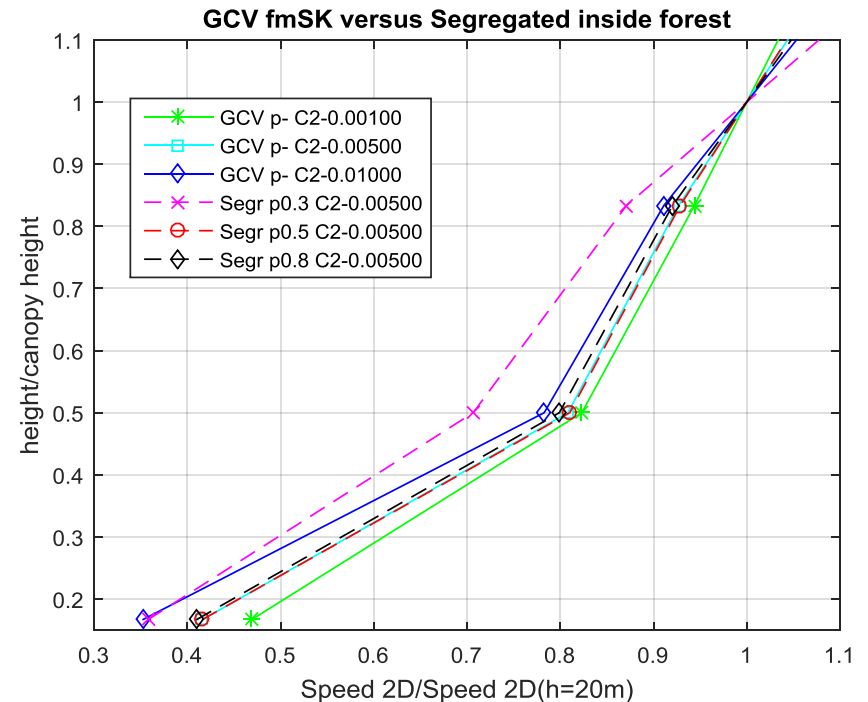
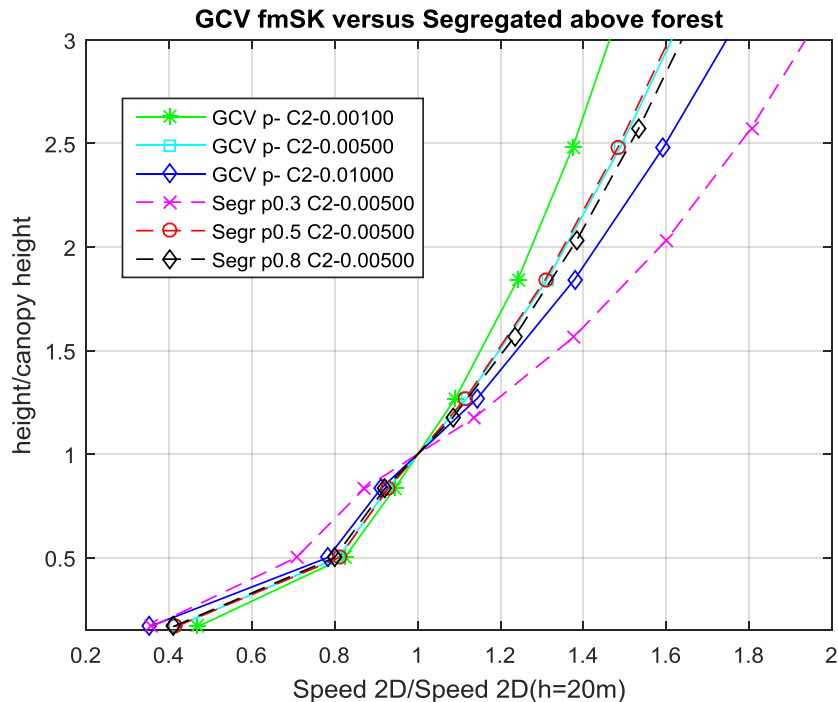
## Try to match both forest approaches:



Good match with GCV (def.) with Segregated set to higher porosities than 0.5.

## Segregated solver - porosity

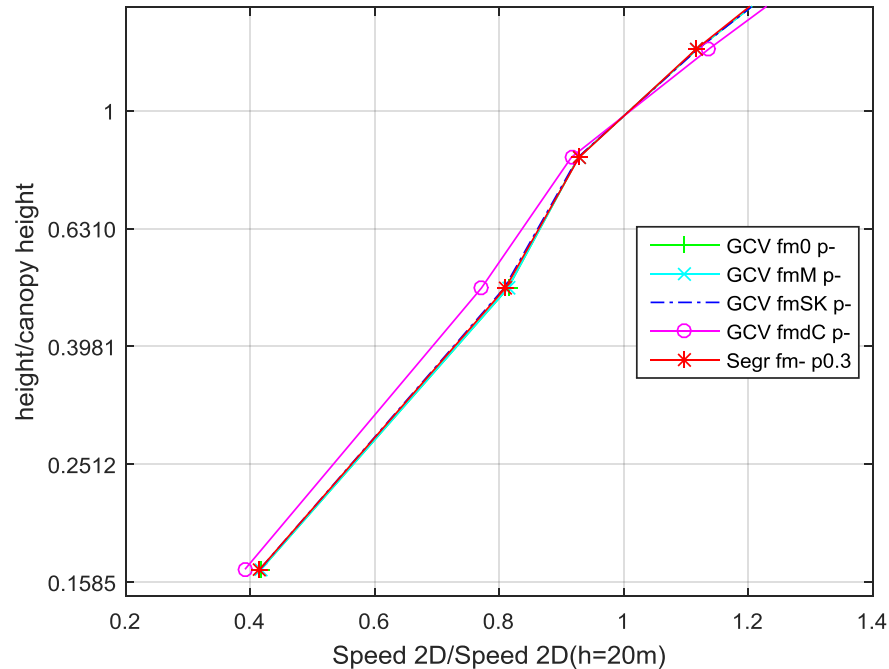
## GCV solver – C2



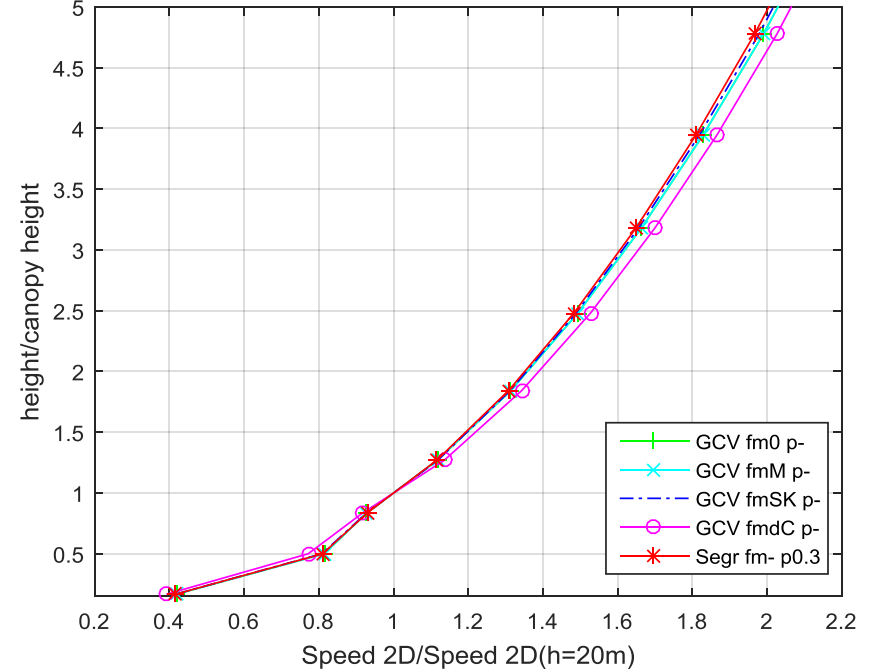
A real comparison of both solvers would be done with Segregated solver with porosity 1.0 and same C2.

## First results: Performance of different GCV forest models

GCV forest models versus Segregated (def.)



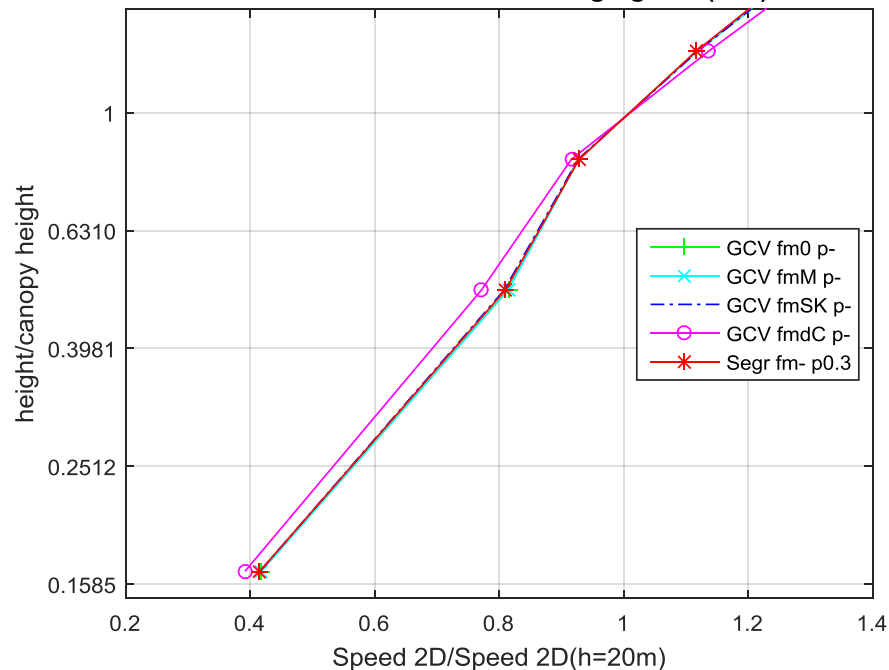
GCV forest models versus Segregated (def.)



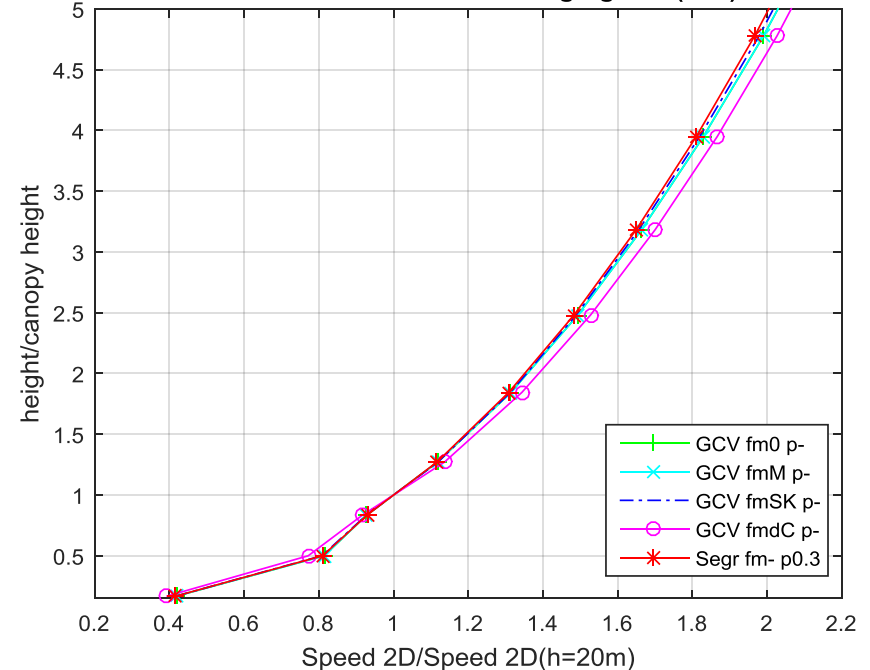
„fm0“ = no forest turbulent source model

## First results: Performance of different GCV forest models

GCV forest models versus Segregated (def.)



GCV forest models versus Segregated (def.)



„fm0“ = no forest turbulent source model

GCV forest models except daCosta show similar results as well as

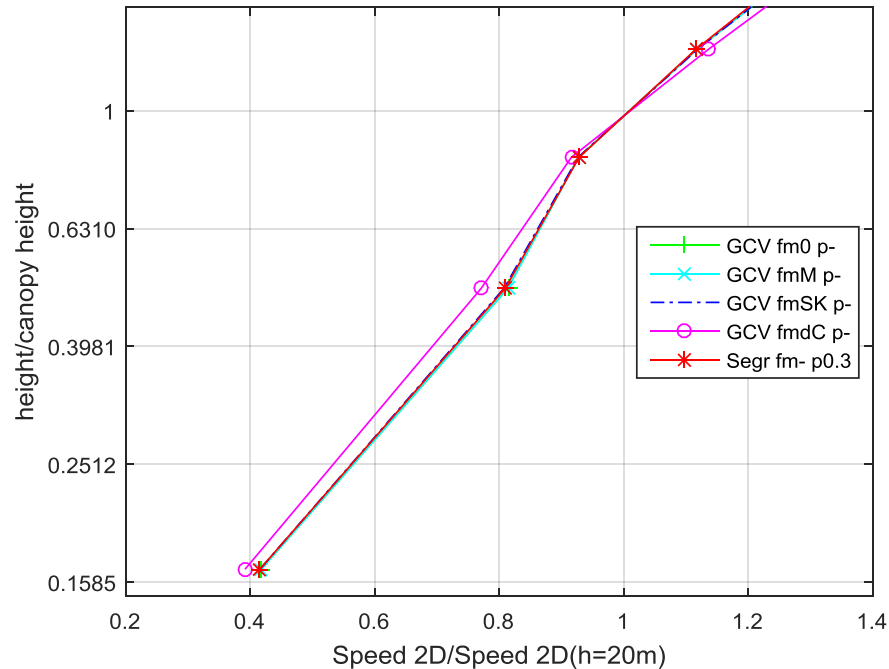
Segregated solver (def.) ← profiles need to be validated with measured data

## Forest Model – diff

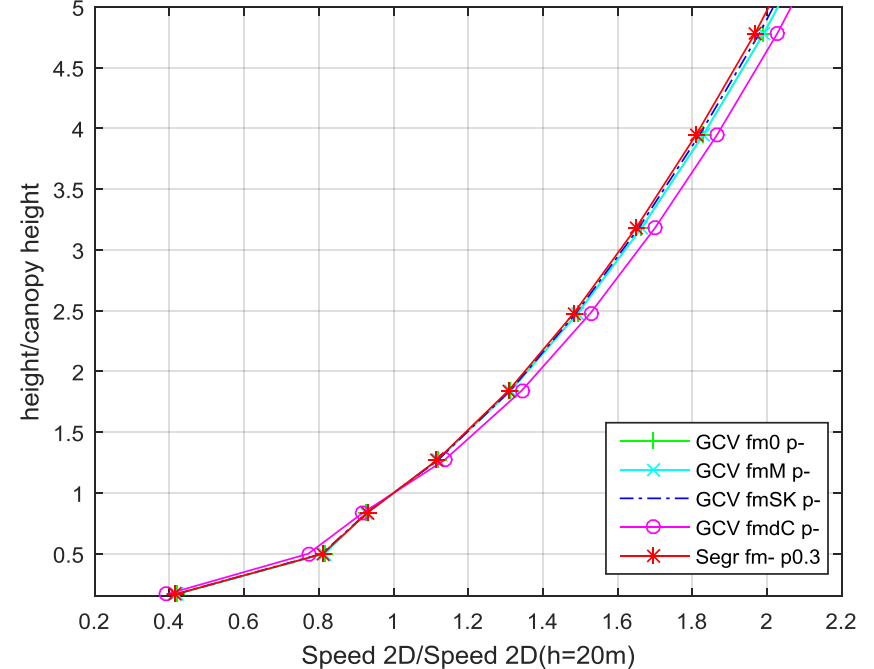
| $\beta_P$ | $\beta_D$ | $C_{\varepsilon 4}$ | $C_{\varepsilon 5}$ | Ref.                                     |
|-----------|-----------|---------------------|---------------------|--|
| 0.0       | 0.0       | 0.0                 | 0.0                 | Gravdahl et al. 2006 (WindSim, modified) |
| 0.17      | 3.37      | 0.9                 | 0.9                 | Lopes da Costa 2007                      |
| 1.0       | 0.0       | 1.8                 | 0.0                 | Mochida et al. 2010 (Svensson adaption)  |
| 1.0       | 6.51      | 1.24                | 1.24                | Sanz 2003 / Katul 2004 (adapted)         |

## First results: F

GCV forest models versus Segregated (def.)



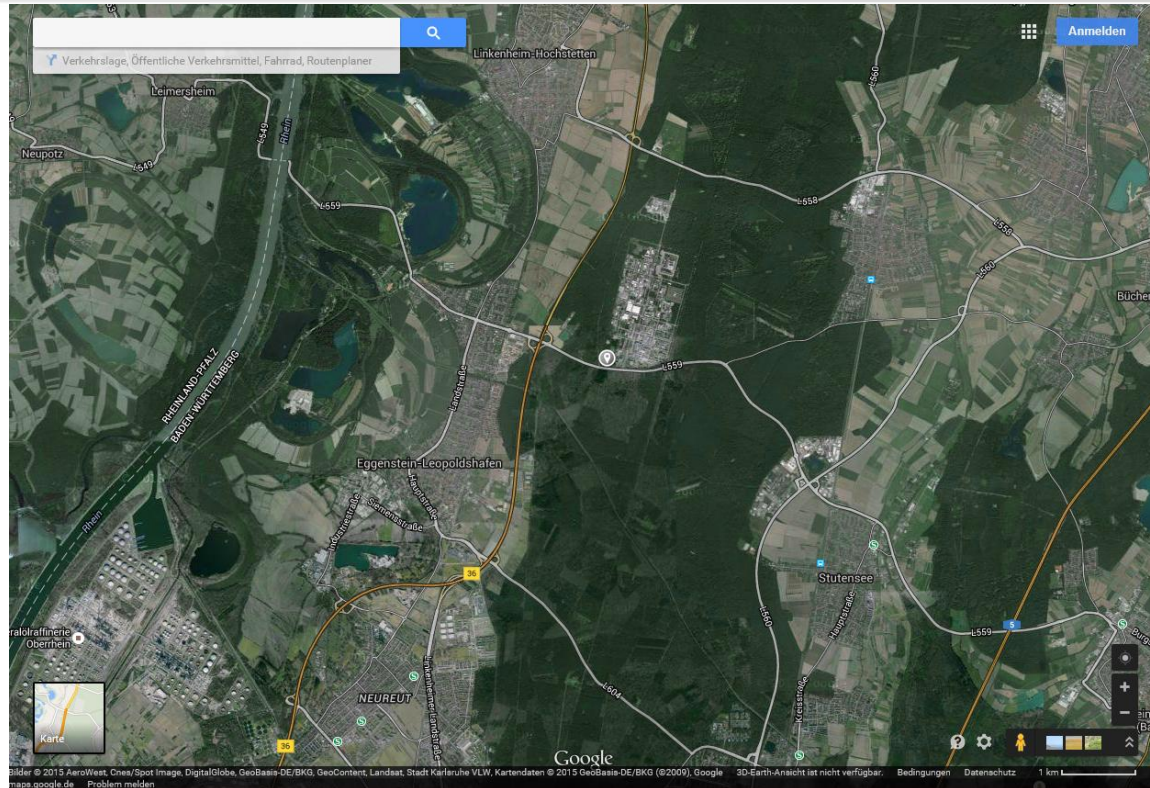
GCV forest models versus Segregated (def.)



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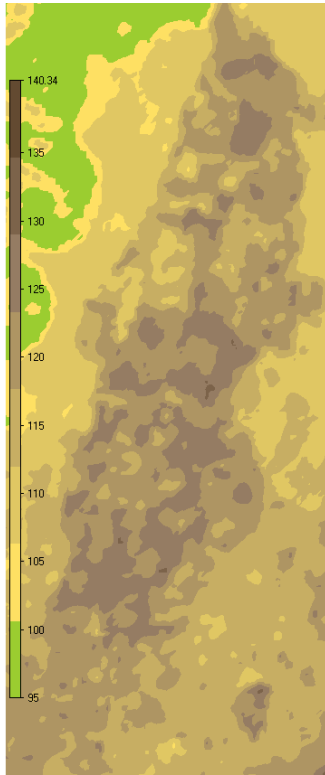
Segregated solver (def.) ← profiles need to be validated with measured data



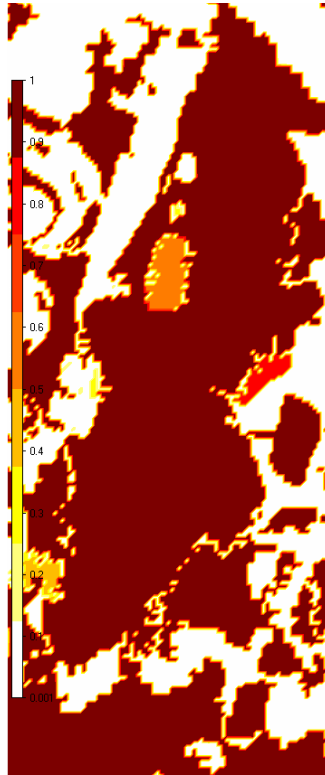
## K.I.T Karlsruhe Met Mast 200m

Positioned directly at K.I.T. campus inside forest edge

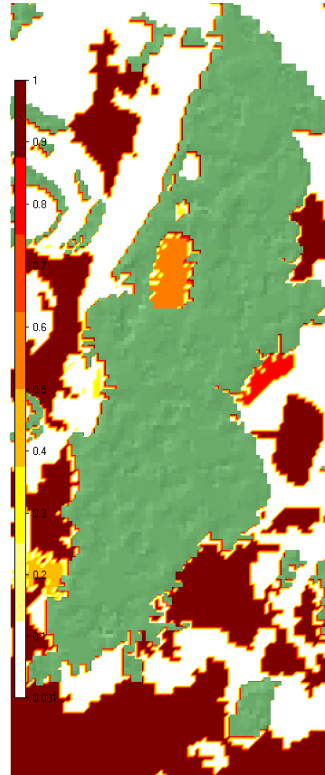
Main wind direction upwind with wind flow along about 2 km forest



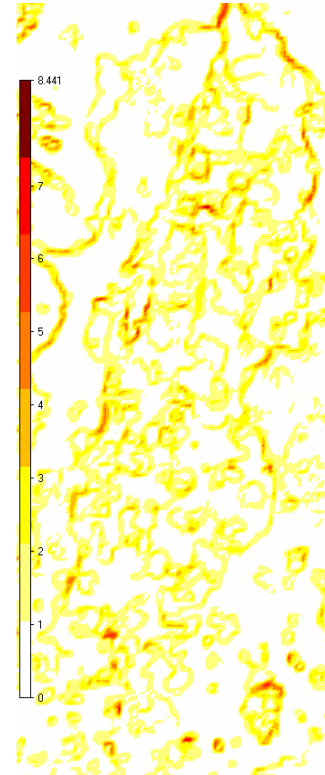
Elevation (m)



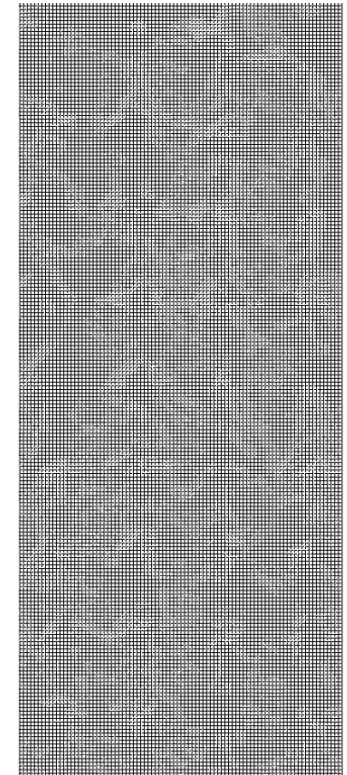
Roughness (m)



Forest



Inclination



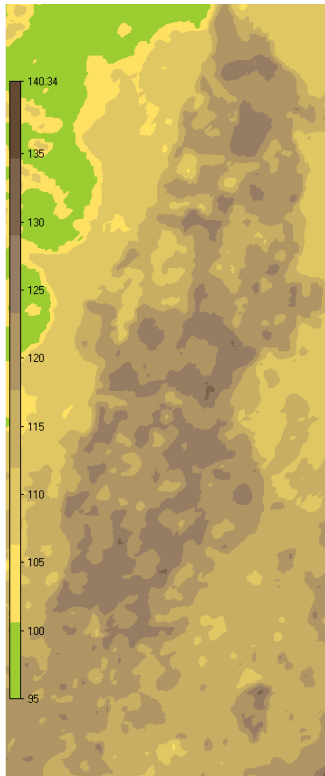
Horizontal grid

|                  | Easting     | Northing        | z          | Total            |
|------------------|-------------|-----------------|------------|------------------|
| Grid spacing (m) | 40          | 40              | Variable   | 10040-13040-3000 |
| Number of cells  | 251         | 326             | 30         | 2454780          |
|                  | Sectors     | Simulation time | Iterations | Status           |
|                  | 72 (0..355) | ~3,2h           | 185        | C                |

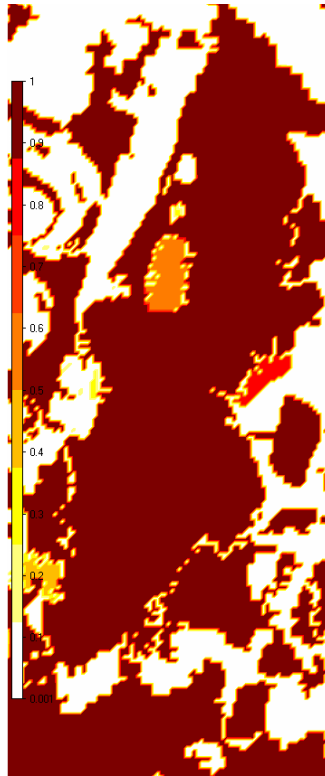
|                 | 1   | 2   | 3    | 4    | 5    | 6    | 7    | 8     | 9     | 10    |
|-----------------|-----|-----|------|------|------|------|------|-------|-------|-------|
| z-dist. max (m) | 3.0 | 9.0 | 15.0 | 21.0 | 27.0 | 40.8 | 66.5 | 100.2 | 142.0 | 192.0 |
| z-dist. min (m) | 3.0 | 9.0 | 15.0 | 21.0 | 27.0 | 40.9 | 66.9 | 101.0 | 143.4 | 193.9 |

All sectors converged with default settings.

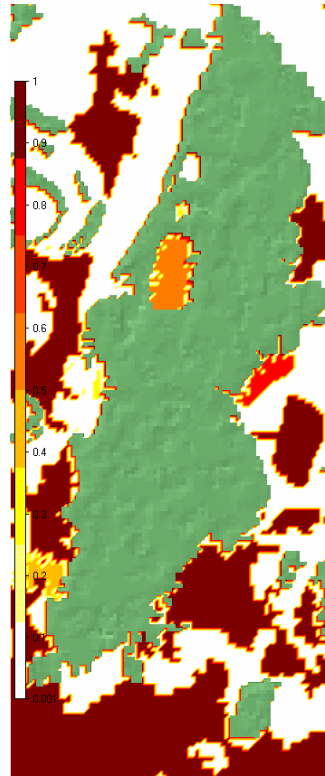
# Forest Model – K.I.T. met mast 200m



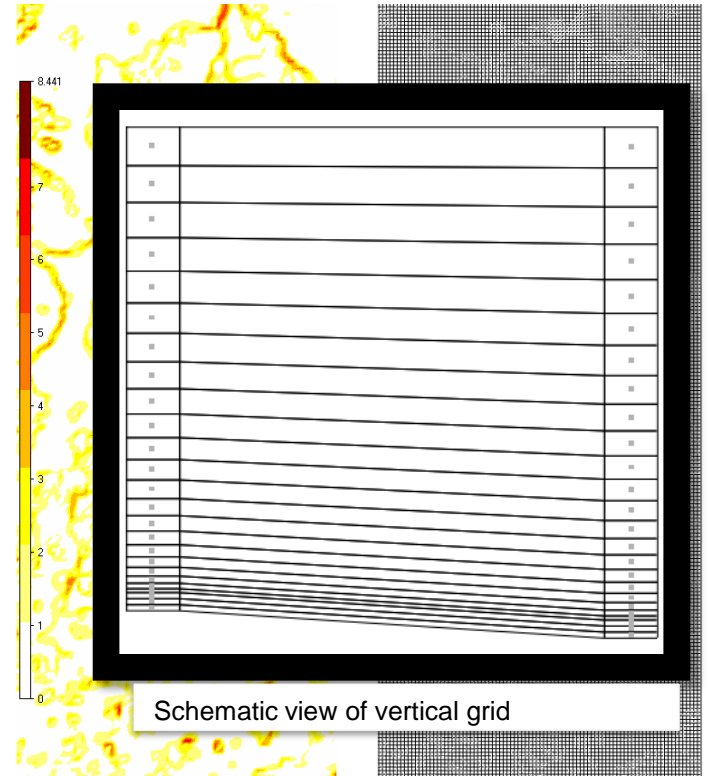
Elevation (m)



Roughness (m)



Forest



Inclination

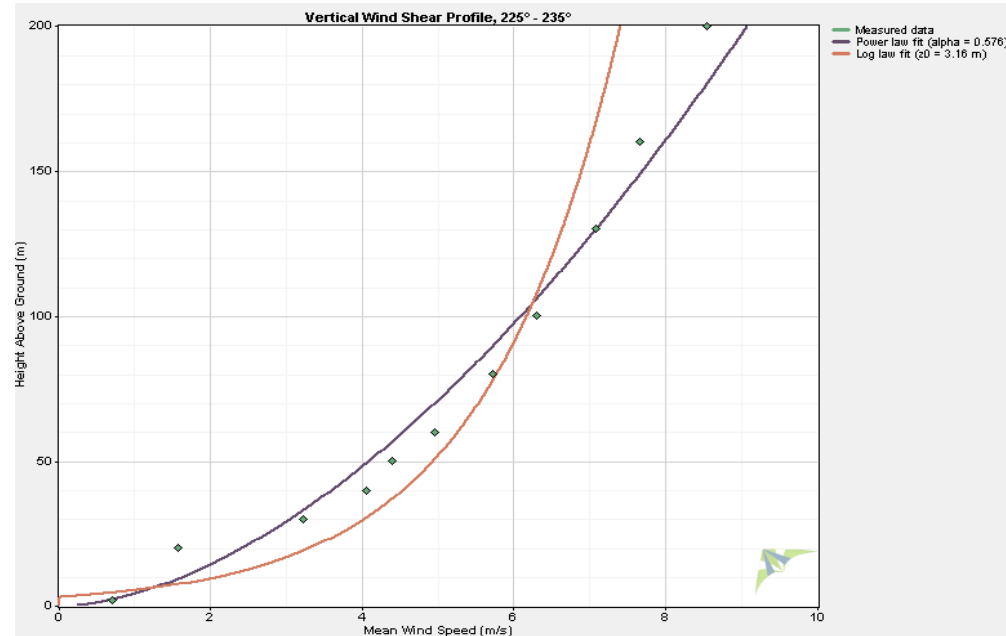
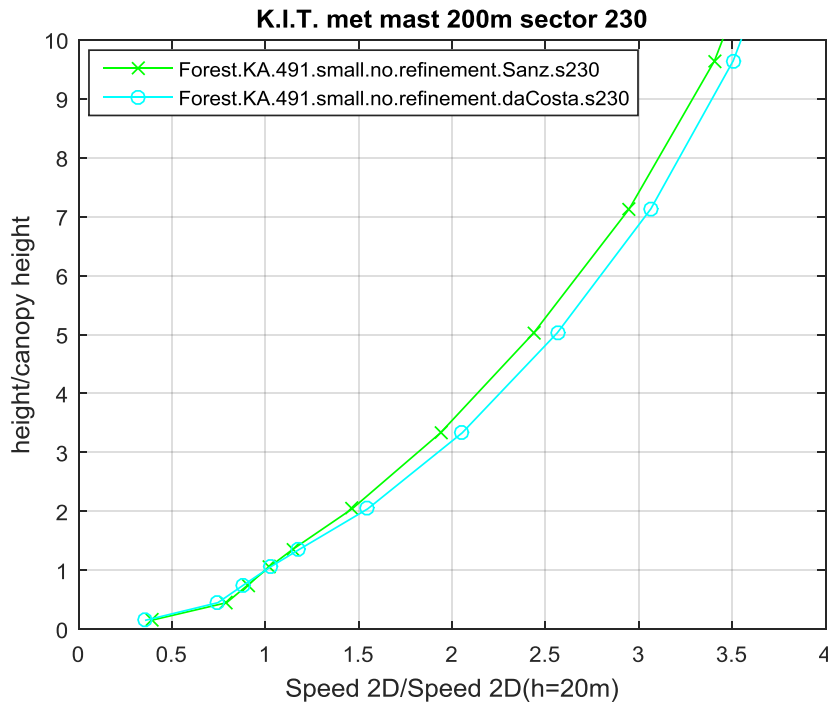
Horizontal grid

|                  | Easting     | Northing        | z          | Total            |
|------------------|-------------|-----------------|------------|------------------|
| Grid spacing (m) | 40          | 40              | Variable   | 10040-13040-3000 |
| Number of cells  | 251         | 326             | 30         | 2454780          |
|                  | Sectors     | Simulation time | Iterations | Status           |
|                  | 72 (0..355) | ~3,2h           | 185        | C                |

|                 | 1   | 2   | 3    | 4    | 5    | 6    | 7    | 8     | 9     | 10    |
|-----------------|-----|-----|------|------|------|------|------|-------|-------|-------|
| z-dist. max (m) | 3.0 | 9.0 | 15.0 | 21.0 | 27.0 | 40.8 | 66.5 | 100.2 | 142.0 | 192.0 |
| z-dist. min (m) | 3.0 | 9.0 | 15.0 | 21.0 | 27.0 | 40.9 | 66.9 | 101.0 | 143.4 | 193.9 |

All sectors converged with default settings.

## Performance of different GCV forest models Sector 230

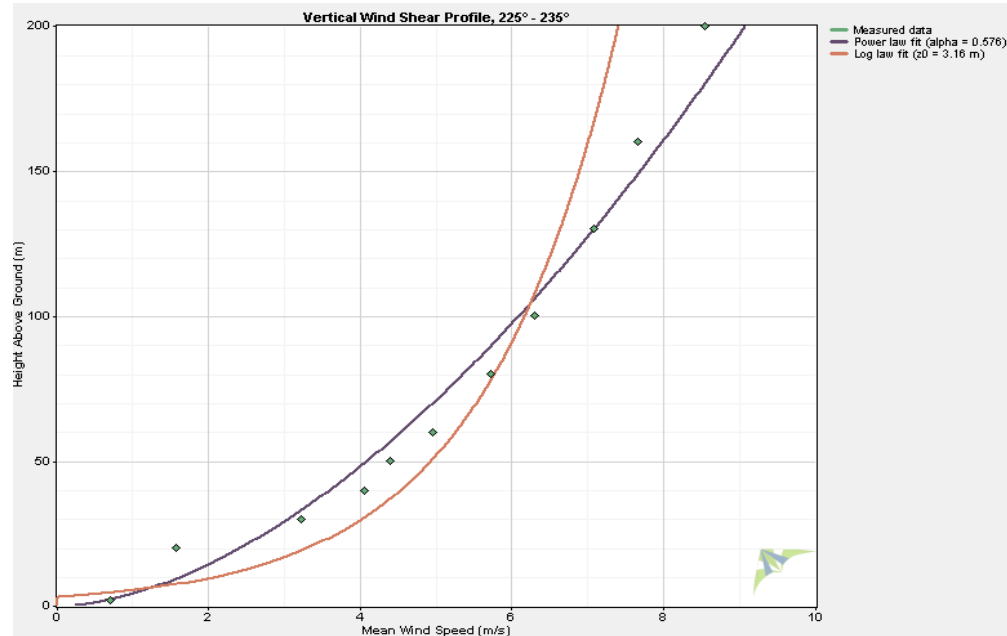
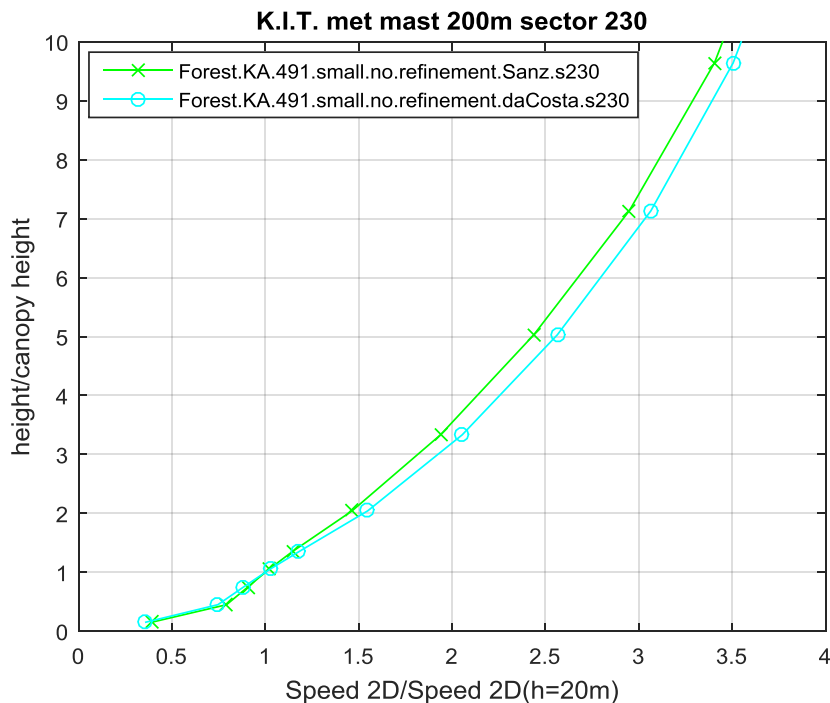


First results: GCV fm (0,SK,C,M) show similar results as Segregated solver with default settings.  
Mistake in implementation ? (obstacles\_vol.log OK).

## Forest Model – K.

| $\beta_P$ | $\beta_D$ | $C_{\varepsilon 4}$ | $C_{\varepsilon 5}$ | Ref.                                     |
|-----------|-----------|---------------------|---------------------|--|
| 0.0       | 0.0       | 0.0                 | 0.0                 | Gravdahl et al. 2006 (WindSim, modified) |
| 0.17      | 3.37      | 0.9                 | 0.9                 | Lopes da Costa 2007                      |
| 1.0       | 0.0       | 1.8                 | 0.0                 | Mochida et al. 2010 (Svensson adaption)  |
| 1.0       | 6.51      | 1.24                | 1.24                | Sanz 2003 / Katul 2004 (adapted)         |

## Performance of



First results: GCV fm (0,SK,C,M) show similar results as Segregated solver with default settings.  
Mistake in implementation ? (obstacles\_vol.log OK).

- Current proposal for segregated solver with high porosity value ( $p > 0.8$ ) and tuning C2 delivers similar results as GCV.
- Segregated: effective porosity  $0 < p < 0.8$
- GCV: effective C2 setting  $0.0001 < C2 < 1$
- A higher number of vertical cells than proposed lead to more stable results of the model.  
Segregated ( $z > 8$ ) – GCV ( $z > 6$ )
- Forest turbulence source models for GCV still need to be validated.

- Test of different forest models
- Test of different closures (k- $\omega$ , RNG)
- Tests of sensitivity on
  - Forest outlet
  - Forest inlet
  - (overflow of raised cos or Gaussian hill)if suitable wind tunnel experiment data
- Test of „lab“ experience on different sites. Hard to get data. Any projects?



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