Stability classification for CFD simulations in complex terrain

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Outline

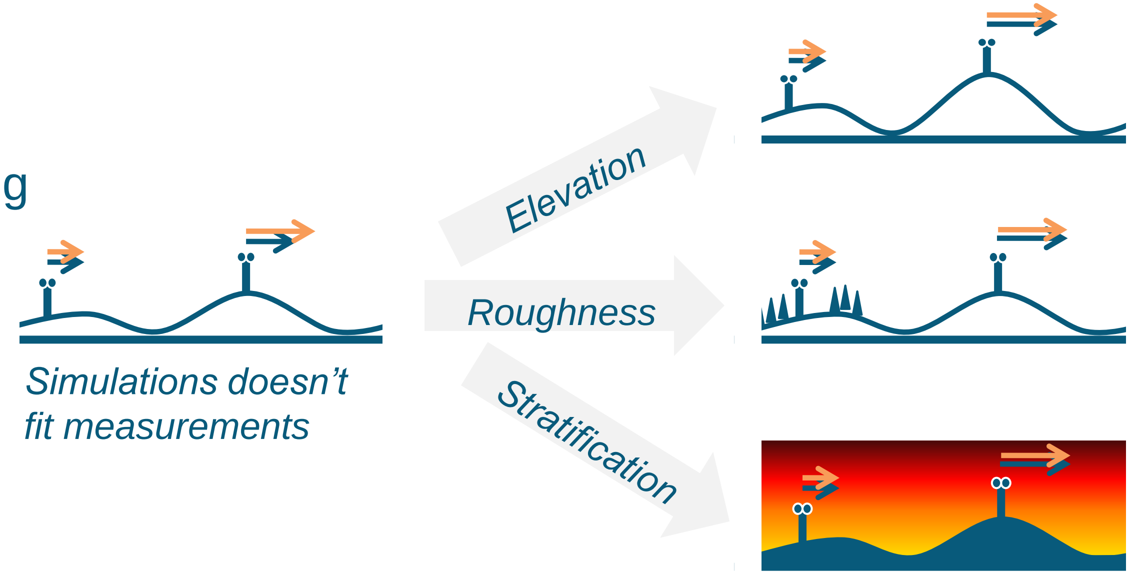
- General Aspects of Atmospheric Stability
- Effects of Stability on Wind Fields – Theory, Measurements and Modelling
- Stability Parameters in Measurement and MERRA Data
- Examples from Different Sites
- CFD Modelling Capabilities
- Conclusions and Outlook

General Aspects of Atmospheric Stability

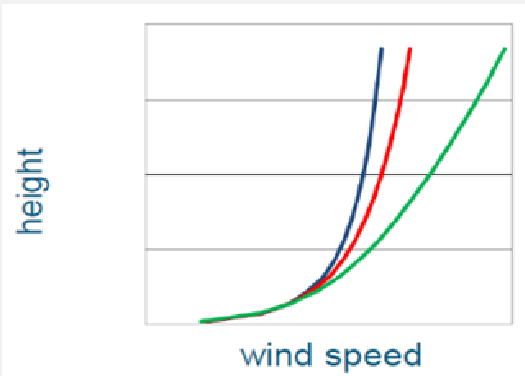
- Atmospheric Stability
  - Resistance of the atmosphere to vertical motion depend on different stratification parameters

- Application and Importance for Wind Energy
  - Site suitability and power curve performance
  - Vertical, Horizontal
  - Energy yield

- Integration in CFD Modelling



Effects of Stability on Wind Fields



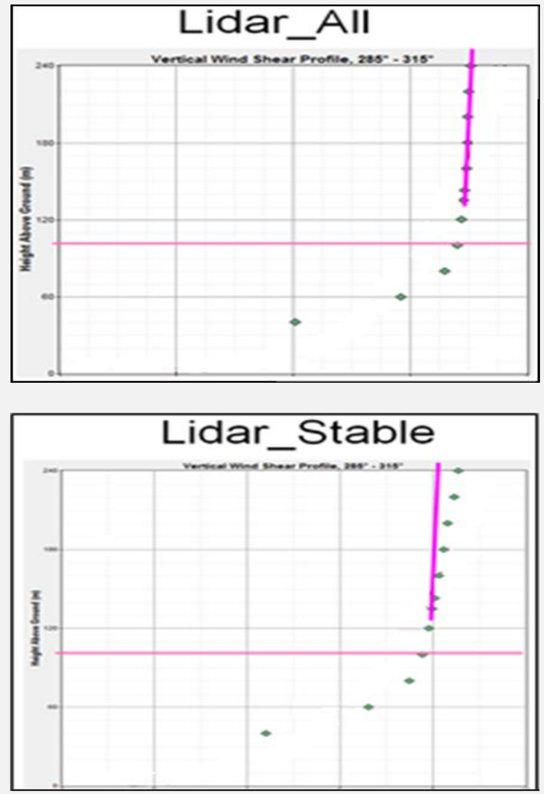
Neutral case

$$\bar{u}(z) = \frac{u_*}{\kappa} \, ln\left(\frac{z}{z_0}\right)$$

Non-neutral case

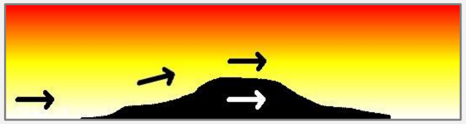
$$\bar{u}(z) = \frac{u_*}{\kappa}\left[ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right)\right]$$

Vertical wind profiles: Theory

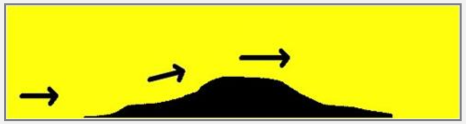


Vertical wind profiles: Measurements

Effects of Stability on Wind Fields



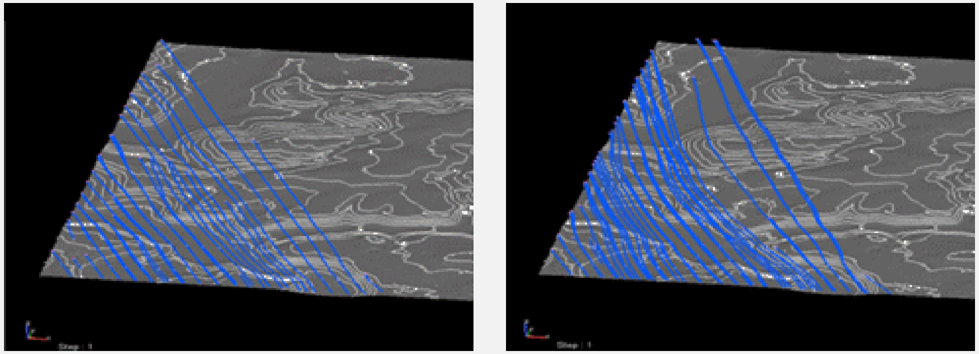
Stable



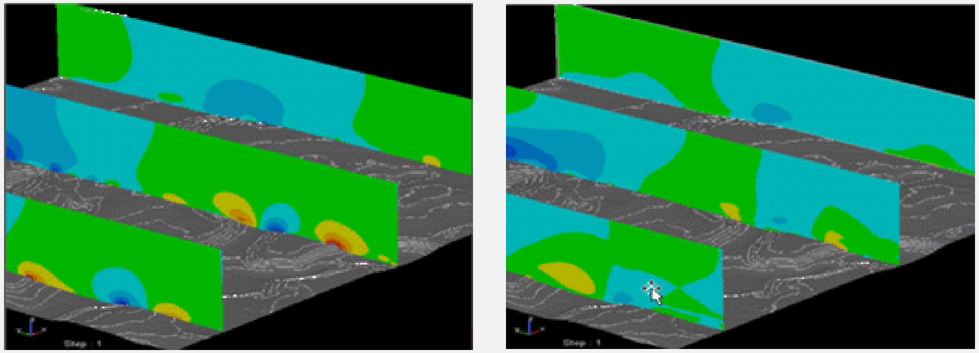
Neutral

Unstable

Stratification: Theory



Streamlines, neutral (left) and stable (right) stratification



Vertical speed, neutral (left) and stable (right) stratification

Stratification: Modelling

Stability Parameters in Measurement and MERRA Data

- Challenges
  - Reality vs Equation
  - Captured by measurement
  - Model methods and parameters

- Atmospheric Stability Model Methods
  - Temperature Gradient
  - Richardson
  - MOL (Monin–Obukhov Length)
  - Pasquill Classes
  - ...

Stability Parameters in Measurement and MERRA Data

Measurement Limitations:

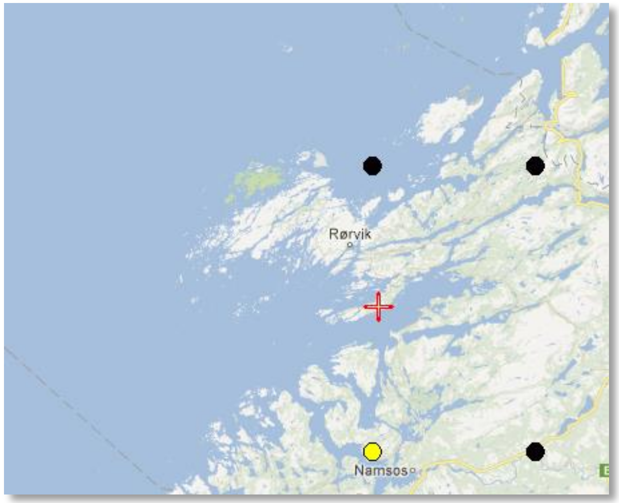
- Met tower
  - No flux measurement
  - Sensor accuracy/mounting for gradient method
  - Short period not representative
- LIDAR
  - No temperature gradient measured
  - Short period not representative
  - Approaches like Pasquill not yet validated

Stability Parameters in Measurement and MERRA Data

- MERRA Data Possibilities
  - Available for free
  - MOL can be calculated

$$L = -u^3 * T_{vlml} * cp * \rho_0/(k * g * shtfl)$$

- MERRA Data Challenges
  - Four surrounding MERRA data points
  - Could be far away

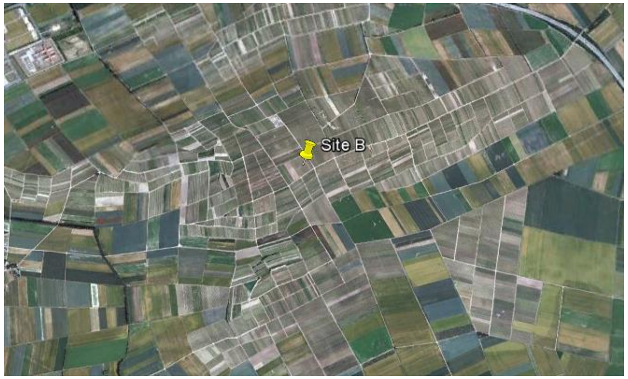


Source: Modern-ERA Retrospective Analysis for Research and Applications http://gmao.gsfc.nasa.gov/merra/

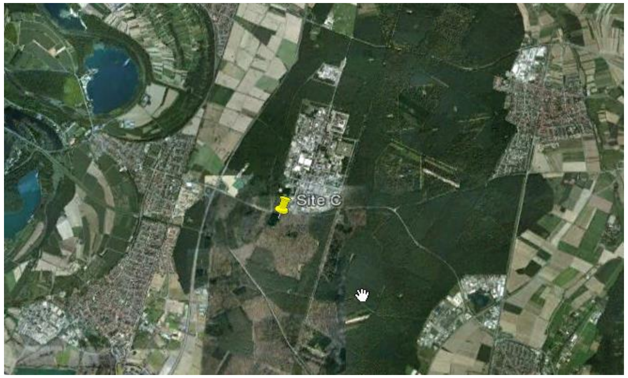
Examples from different Sites

All sites with one or more met towers, A and B also with LIDAR measurements

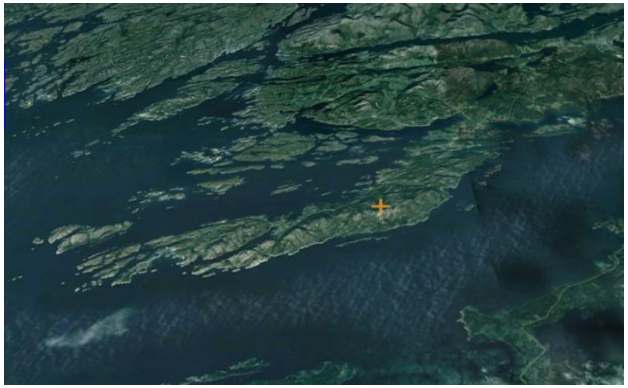
Site A - Complex, forest



Site B - Medium, no forest



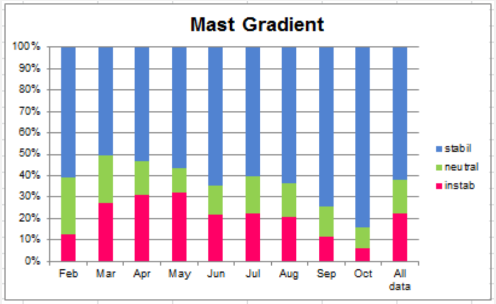
Site C - Flat, forest

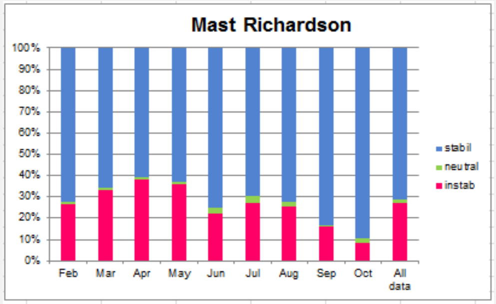


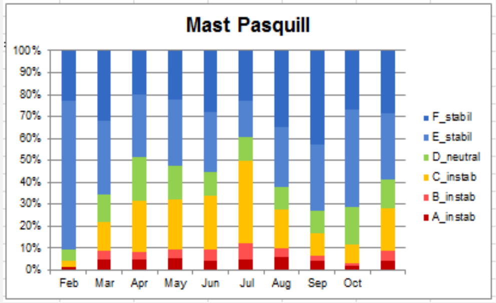
Site D - Complex, coastal, no forest

Site A – Stability Distribution

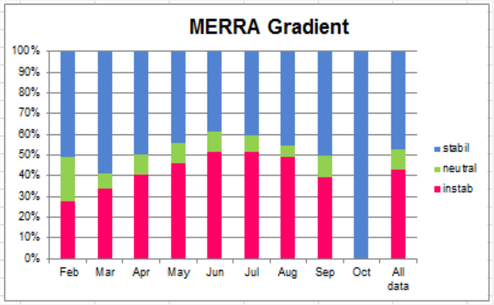
Stability Classifications for Monthly Distribution

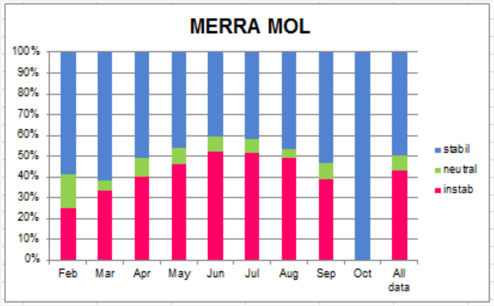






Measurement Data

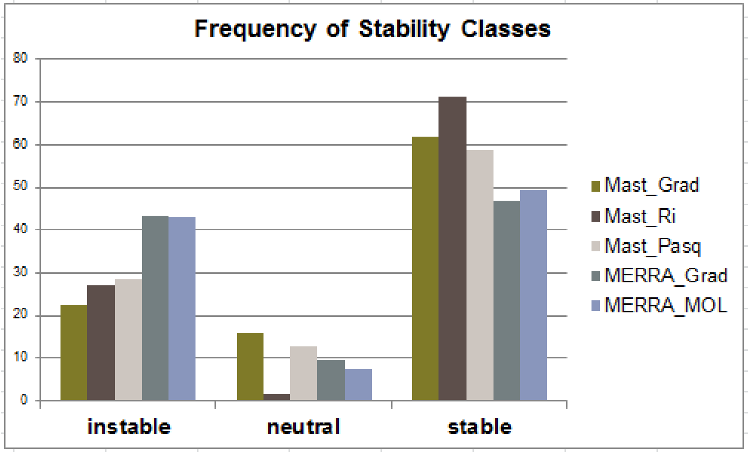




MERRA Data

- Similar average ratio of stable cases over the year
- Ratio neutral/instable depends on classification scheme
- Monthly variability smoothed by MERRA

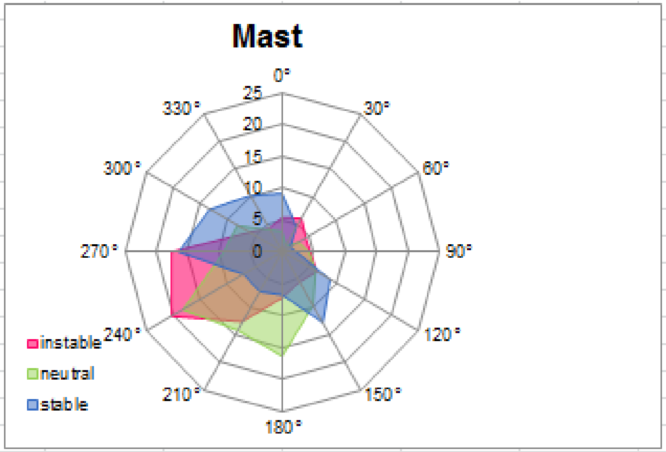
Site A – Quality

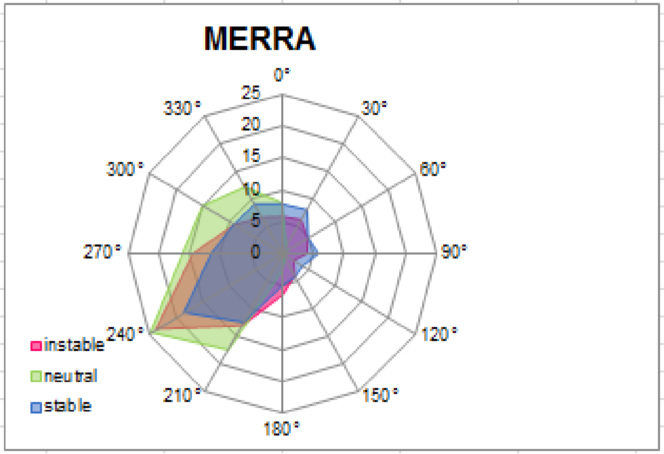


- ✘ *Over estimated instable*
- ✘ *Under estimated stable*

	Speed	Dir	Temp
ρ hour	0.62	0.45	0.98
ρ day	0.83	0.46	0.99

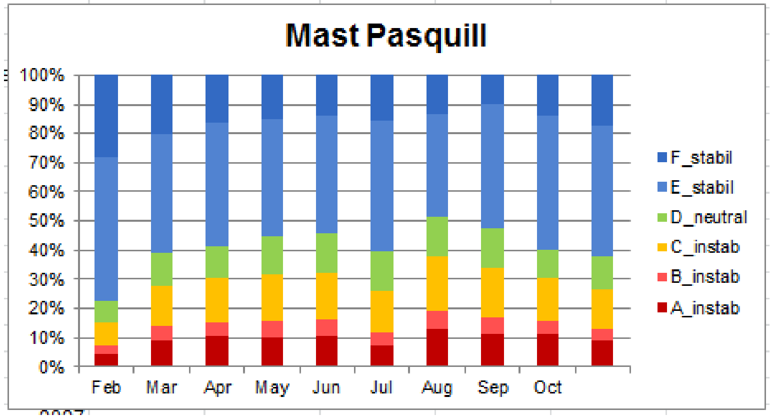
- ✓ *Good correlation of speed and temperature*



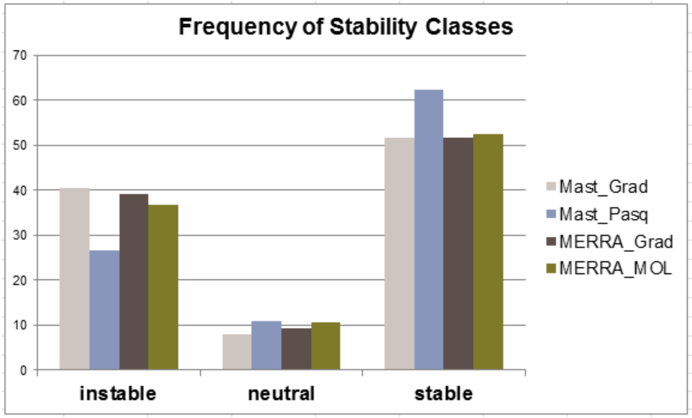


- ✘ *Stable directions*

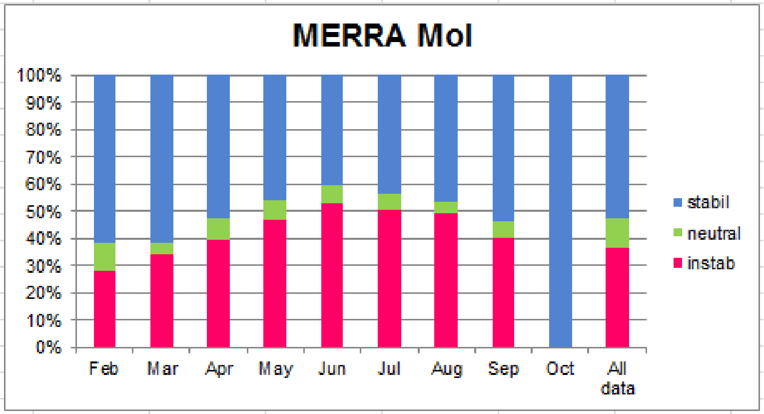
Site B – Stability Distribution and Quality



Measurement Data



✓ *Mast Gradient vs MERRA Gradient/MOL*



MERRA Data

	Speed	Dir	Temp
ρ hour	0.69	0.31	0.98
ρ day	0.89	0.34	0.99

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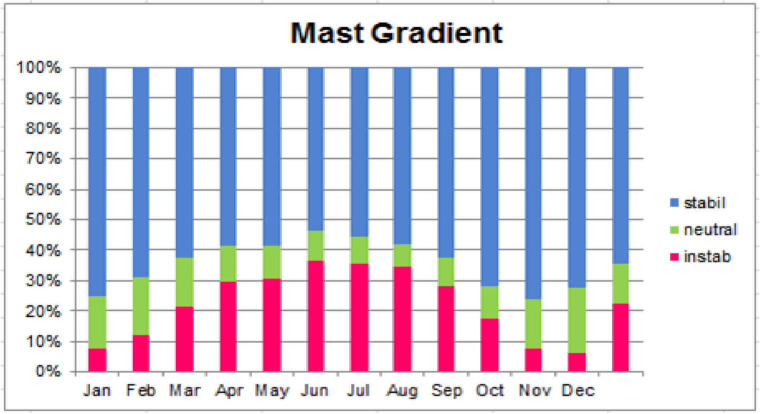
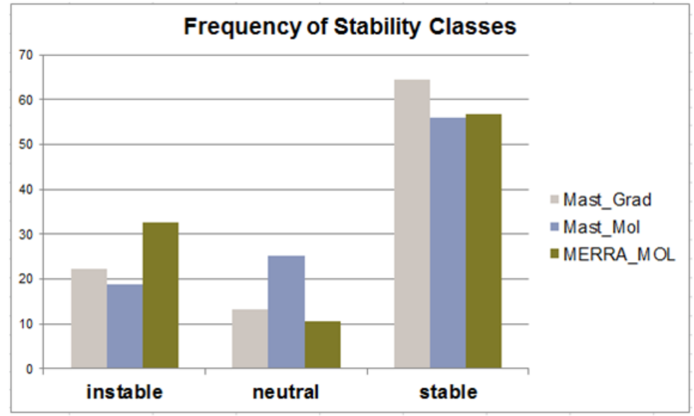
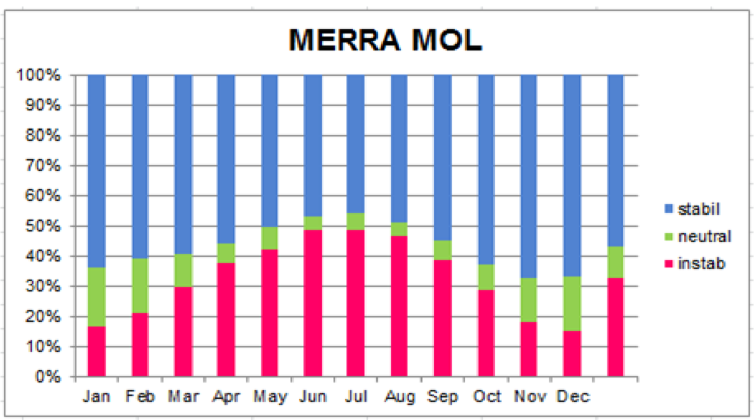
Site C – Stability Distribution and Quality



Measurement Data



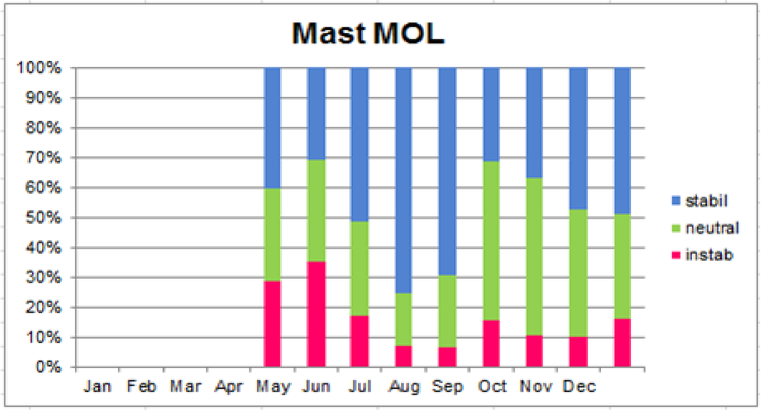
✓ Mast MOL vs MERRA MOL at stable



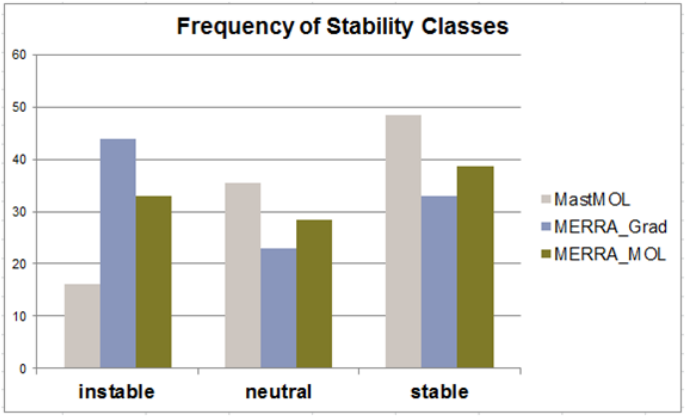
MERRA Data

	Speed	Dir	Temp
ρ hour	0.63	0.44	0.96
ρ day	0.79	0.67	0.98

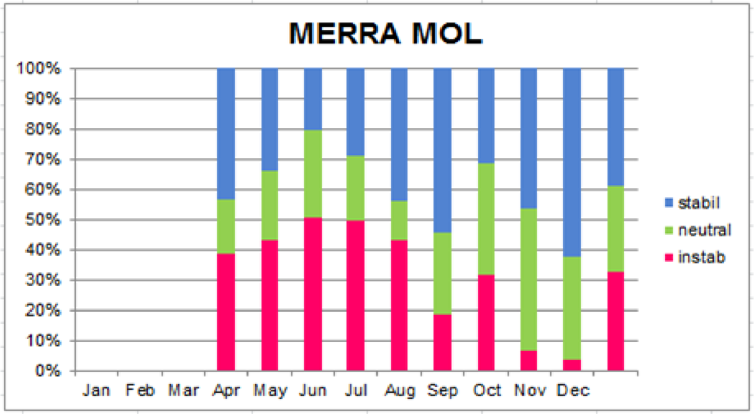
Site D – Stability Distribution and Quality



Measurement Data



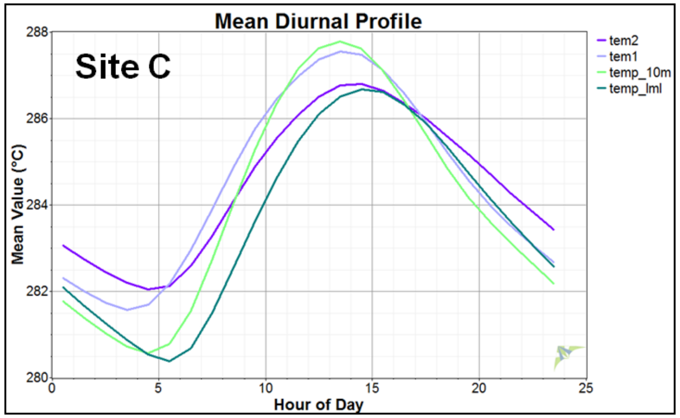
- *Over estimated instable*
- *Under estimated stable*



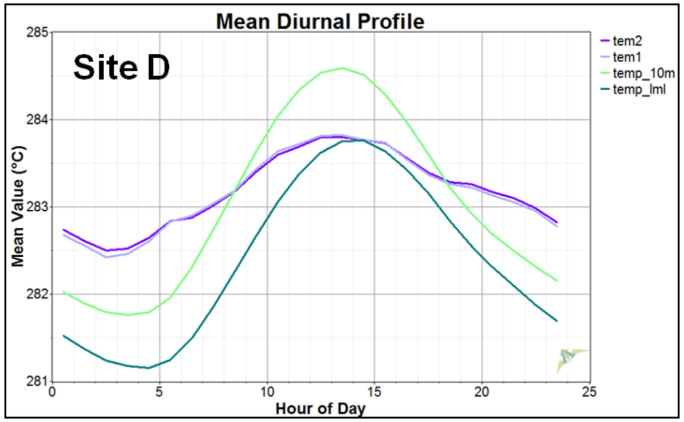
MERRA Data

	Speed	Dir	Temp
ρ hour	0.70	0.44	0.89
ρ day	0.83	0.53	0.96

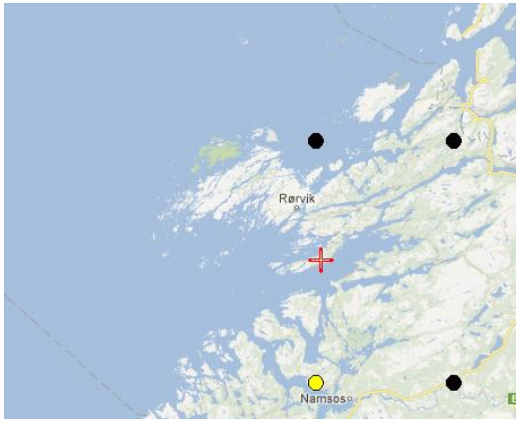
Comparison Temperature Cycle C and D



Site C - Flat, forest



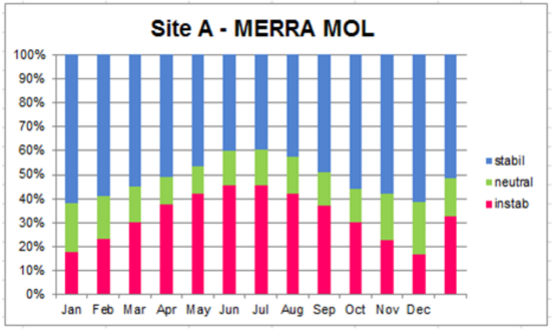
Site D - Complex, coastal, no forest



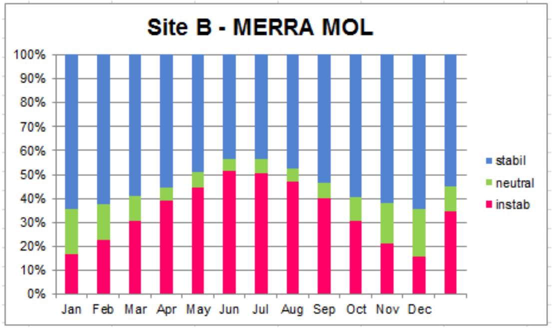
- Land/sea surface distribution

All Sites – longterm MERRA MOL

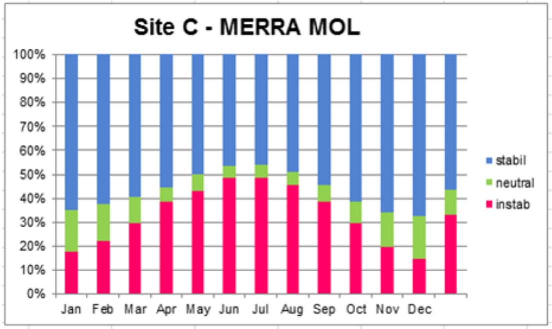
MOL stability values and distribution (sector-wise) in CFD model setup



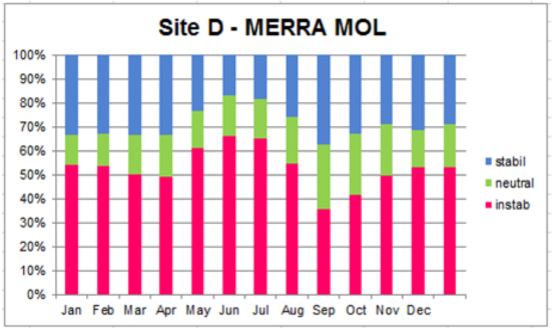
Site A - Complex, forest



Site B - Medium, no forest



Site C - Flat, forest



Site D - Complex, coastal, no forest

MOL	I	N	S
A	-113	500	132
B	-95	-700	119
C	-83	-600	118
D	-124	2500	231

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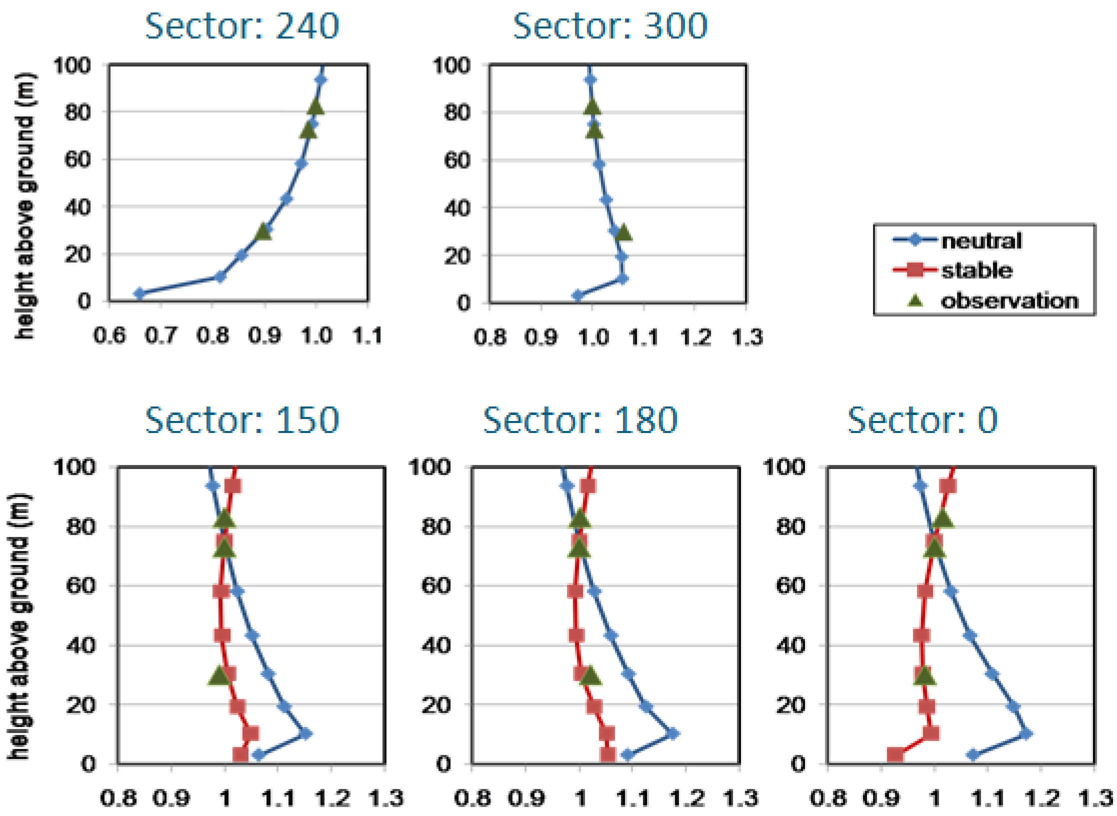
CFD Modelling Capabilities

Results Site D: Sector-wise Normalized Wind Profiles

Sector (°)	Stability
0	s
30	s
60	s
90	s
120	s
150	s
180	s
210	n
240	n
270	n
300	n
330	s



Conclusions and Outlook

• Local atmospheric stability plays an important role in the wind flow behavior

• Measurements of stability are necessary

• MERRA has proven to be a valuable dataset for the determination of the monthly overall stability conditions of a site, as long as the surrounding grid points are representative for the site

• The MERRA wind direction distribution can be misleading, for complex terrains and coastal sites with land/sea mixing. Often the use of measured wind direction might improve the results

• Application of MERRA MOL helps with proper setup of CFD Modeling and results in better representation of wind profiles

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Thank you

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Determination and Application of Parameters

Stability Classification Calculation

- Temperature gradient — T0 – gamma*z

- Monin-Obukhov length

$$L = -\frac{u_*^3 \bar{\theta}_v}{kg(\overline{w'\theta'_v})_s}$$

$$L = -\frac{v_*^3}{k\frac{g}{\theta}\left(\frac{Q_0}{\rho c_p}\right)}$$

- Richardson

$$Ri_g = \frac{\frac{g}{\theta}\frac{\partial \theta}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2}$$

$$Ri = \frac{g}{T(z_1)}\frac{\left[\frac{T(z_1)-T(z_2)}{z_1-z_2}\right]}{\left[\frac{u(z_1)-u(z_2)}{z_1-z_2}\right]^2}$$

- Many more…

MERRA Data

MERRA data is free available in the internet. The MOL is not given directly but can be calculated by the variables given in the data set.

$$L = -u^3 * T_{v_{lml}} * cp * \rho_0 / (k * g * shtfl)$$

karman = 0.40, g = 9.81, cpl = 1005.
Tv_lml = tt_lml * (1. + 0.61 * spfh_lml)
Tv_2m = tt_2m * (1. + 0.61 * spfh_2m)
cp = (1. + 0.87 * spfh_2m) * cpl

k= karman

g = gravity

cpl/cp = heat capacity (dry/wet)

Tv = virtual temperature

tt = temperature

spfh = specific humidity

shtfl = surface heat flux

lml = lowest model level