Analysis of offshore turbulence intensity – comparison with prediction models

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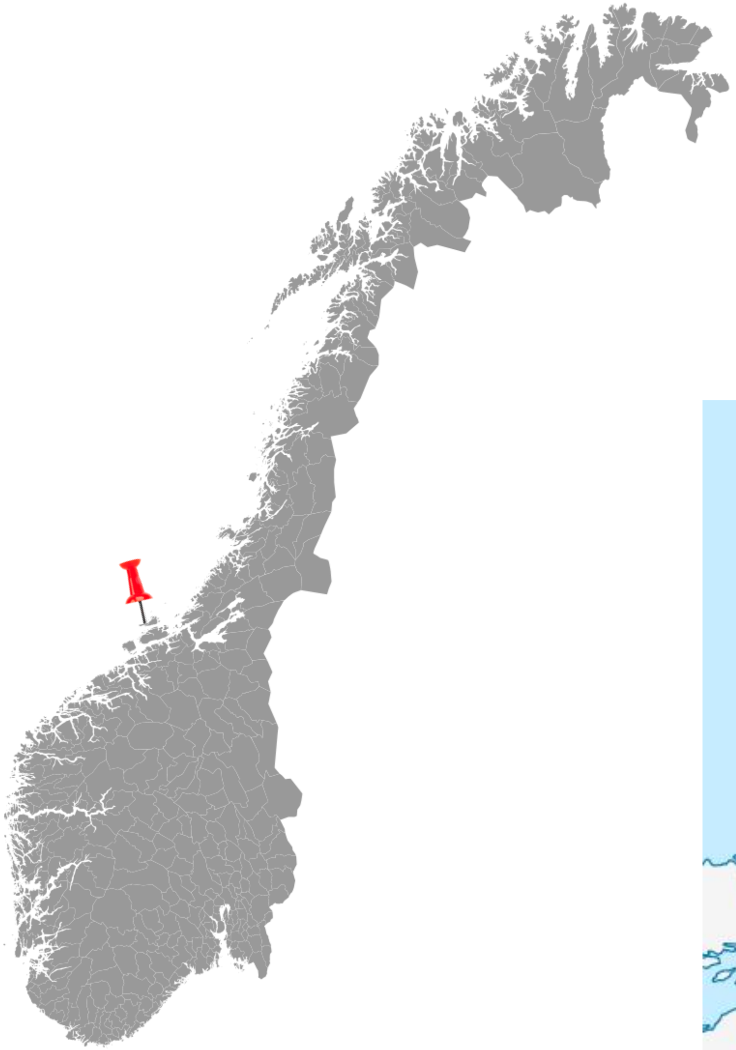
Agenda

1. Site description and methodology
2. Atmospheric stability
3. Models in neutral conditions
4. Models in stable conditions
5. Models in unstable conditions
6. Conclusions
7. Bibliography

Site of Skipheia measurement station

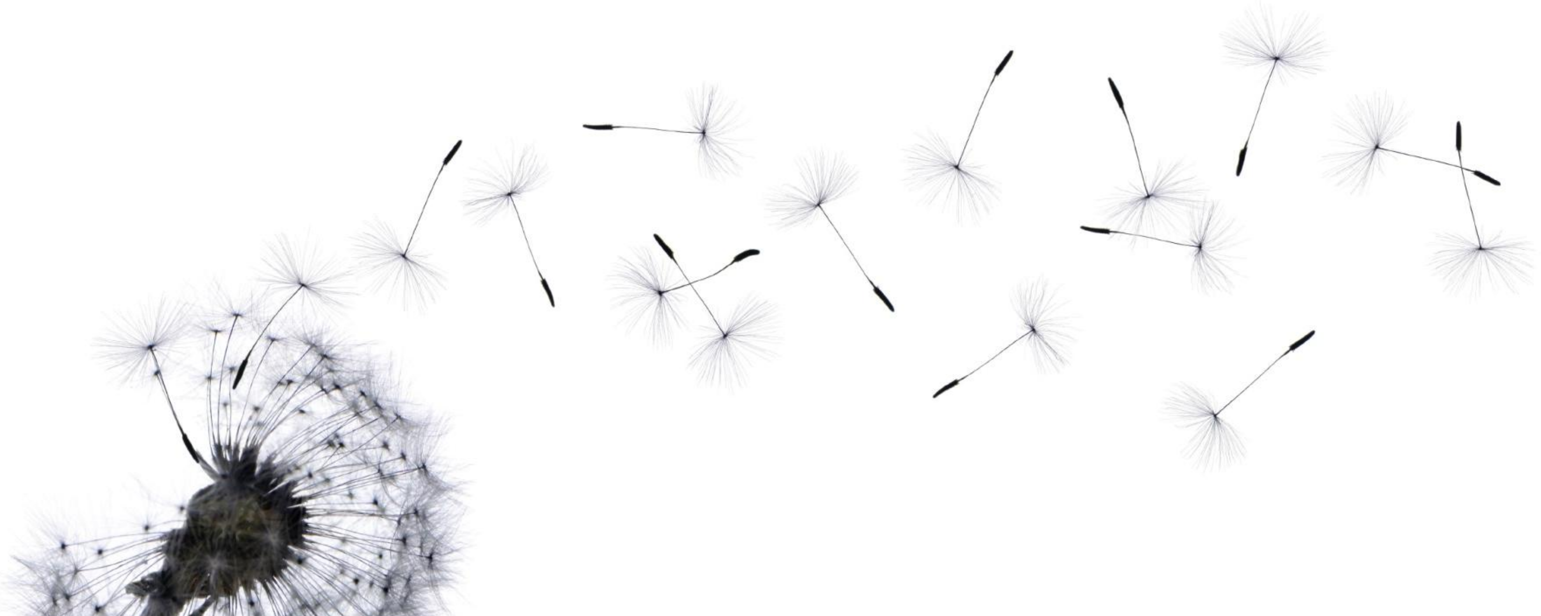


Titran on Frøya island,
Sør-Trøndelag region in mid-Norway

100 m high Mast-2 is located
63.66638 N, 8.34251 E

Equipment and methodology

- Mast-2: six pairs of 2D ultrasonic wind sensors (Gill Wind Observer); seven temperature sensors
- Sampling frequency: 1Hz
- Investigated heights: 16, 25, 40, 70 and 100 m
- Pressure from Sula Weather Station, 20 km north from Mast-2
- Average surface roughness: 0.00308 m
- Most frequent wind velocity at 100 m: 9.05 m/s
- Observations time: 18.11.2009 — 31.12.2014
- Filter: 10 min. subsamples of wind data only with 100% covering 600 s interval
- Coverage: 44.2% i.e. 360 870 000 one-second-samples



Atmospheric stability class calculation

The Monin-Obukhov length (L) is computed from bulk Richardson number.

$$Ri_b = \frac{g}{\bar{\theta}_v} \frac{\frac{\Delta\theta_v}{\Delta z}}{\left(\frac{\Delta u}{\Delta z}\right)^2}$$

If bulk Richardson number is 0, assuming L=∞ [3]

$$L = \begin{cases} \dfrac{z_{ref}}{Ri_b}, & Ri_b \leq 0 \\ \dfrac{z_{ref}(1 - 5Ri_b)}{Ri_b}, & 0 < x < 0.2 \end{cases}$$

where $$z_{ref} = \frac{z_2 - z_1}{\log\left(\frac{z_2}{z_1}\right)}$$

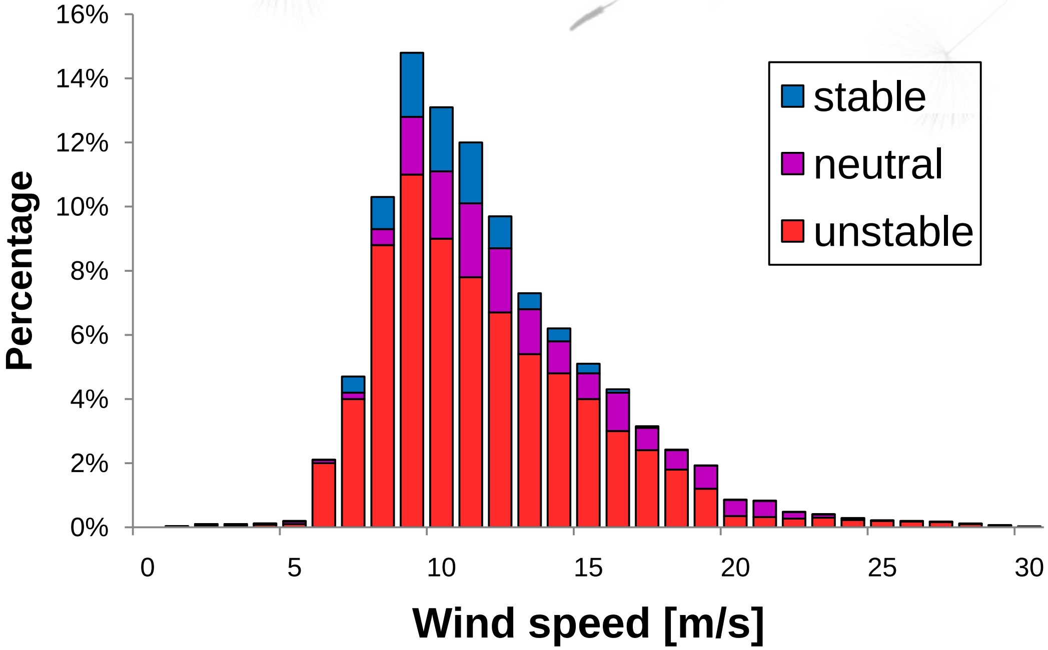
Three **atmospheric stability classes**

Stability classifications according to the
Monin-Obukhov length:

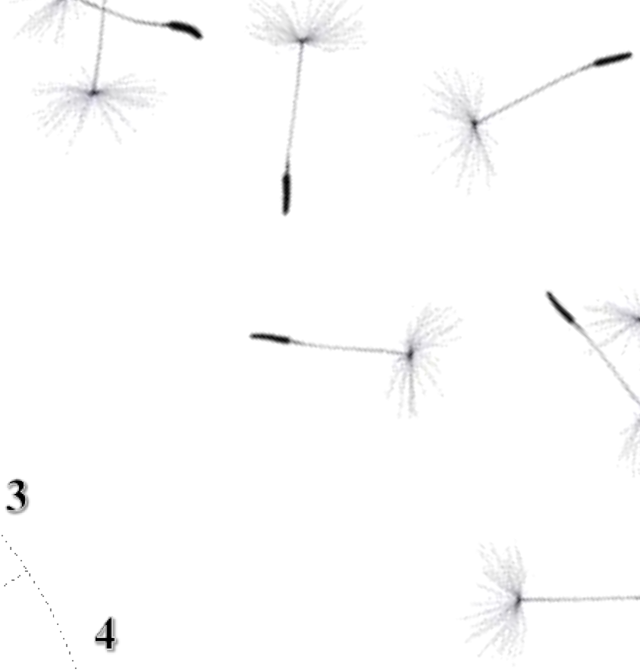
Monin-Obukhov length [L]	**Atmospheric stability class**	
-200 m <L< 0 m	very unstable	unstable
-1000 m< L<-200 m	unstable	
|L| > 1000 m	neutral	
200 m < L< 1000 m	stable	stable
0 m < L < 200 m	very stable	

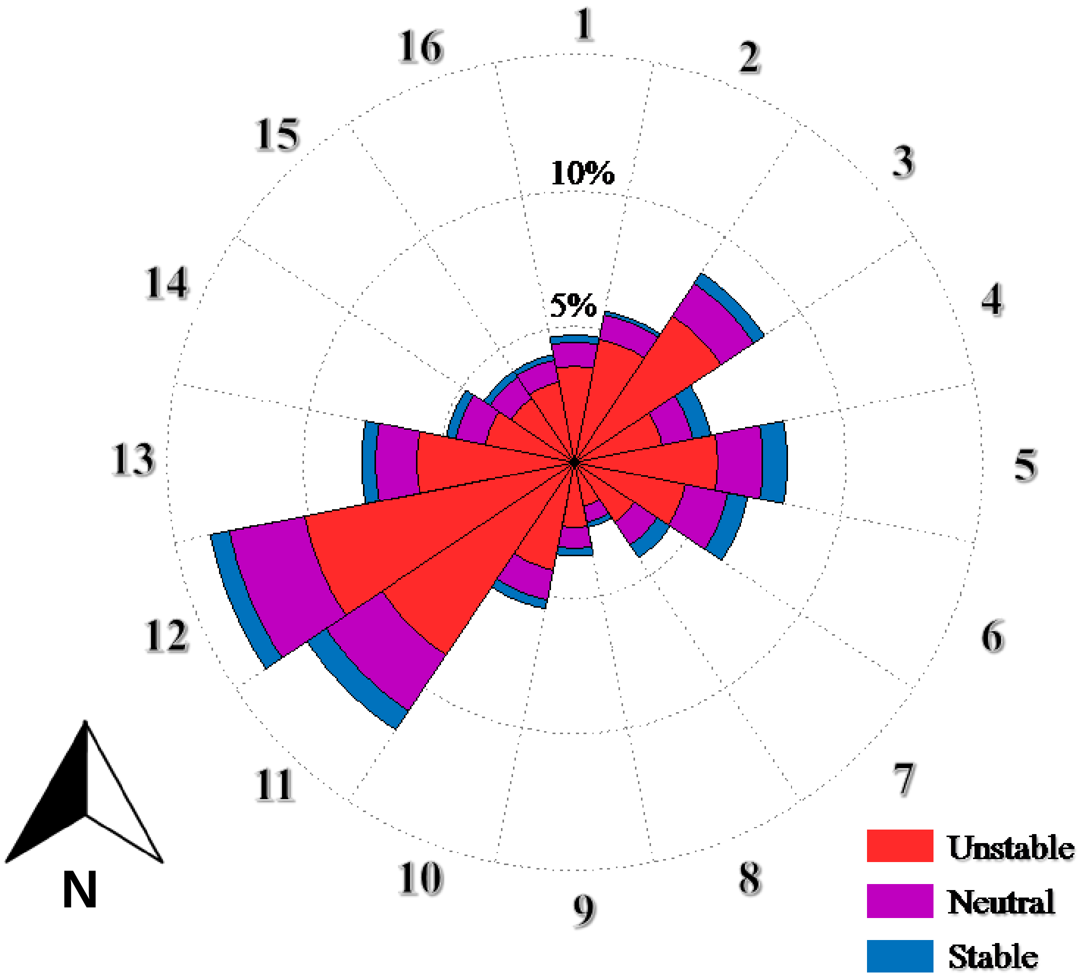
Stability **of the atmosphere**

Distribution of atmospheric stability for all investigated heights

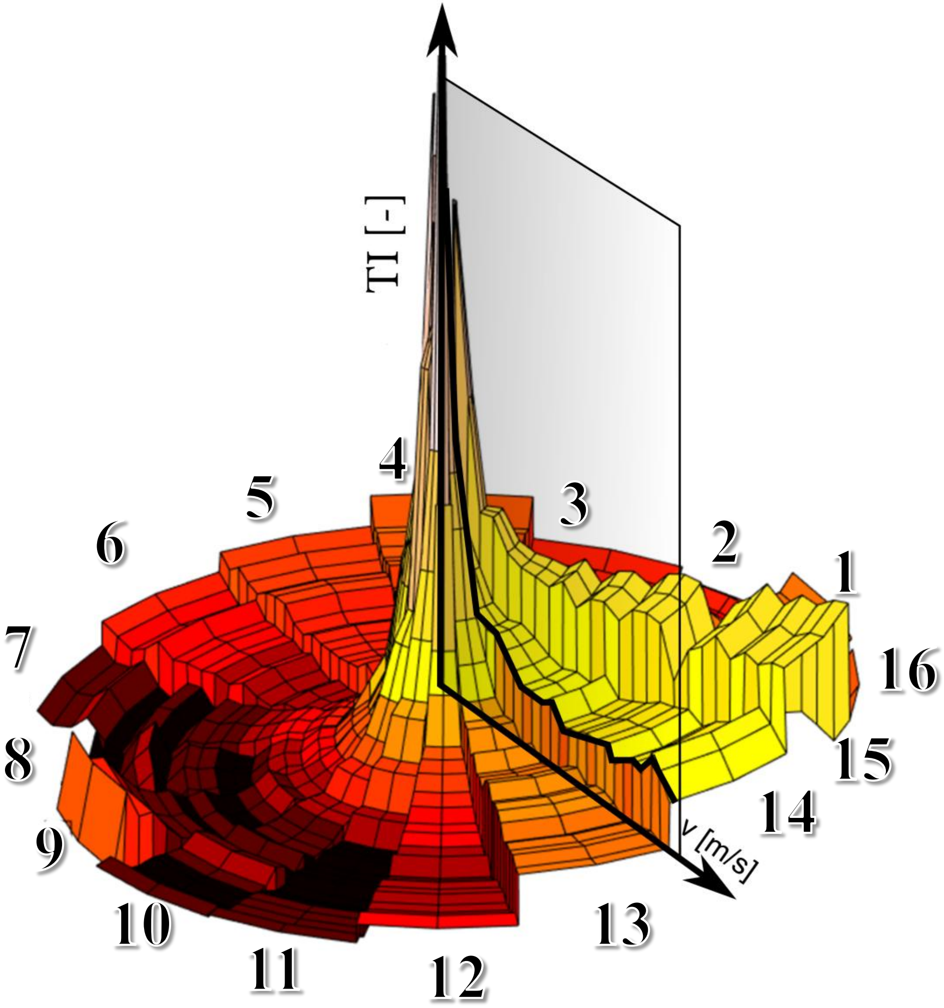


Stability class frequency in 16 sectors

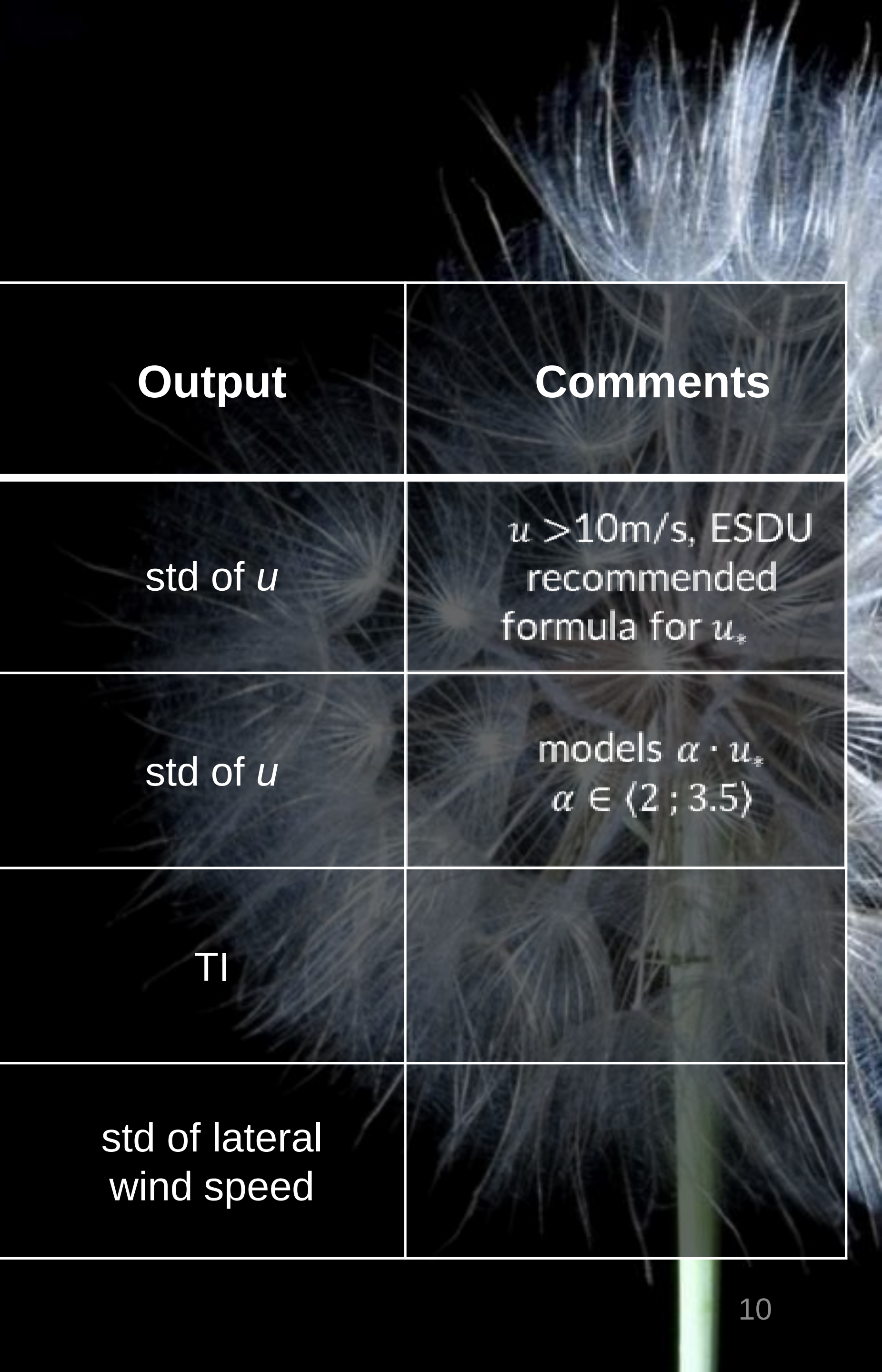




Longitudinal TI in neutral class

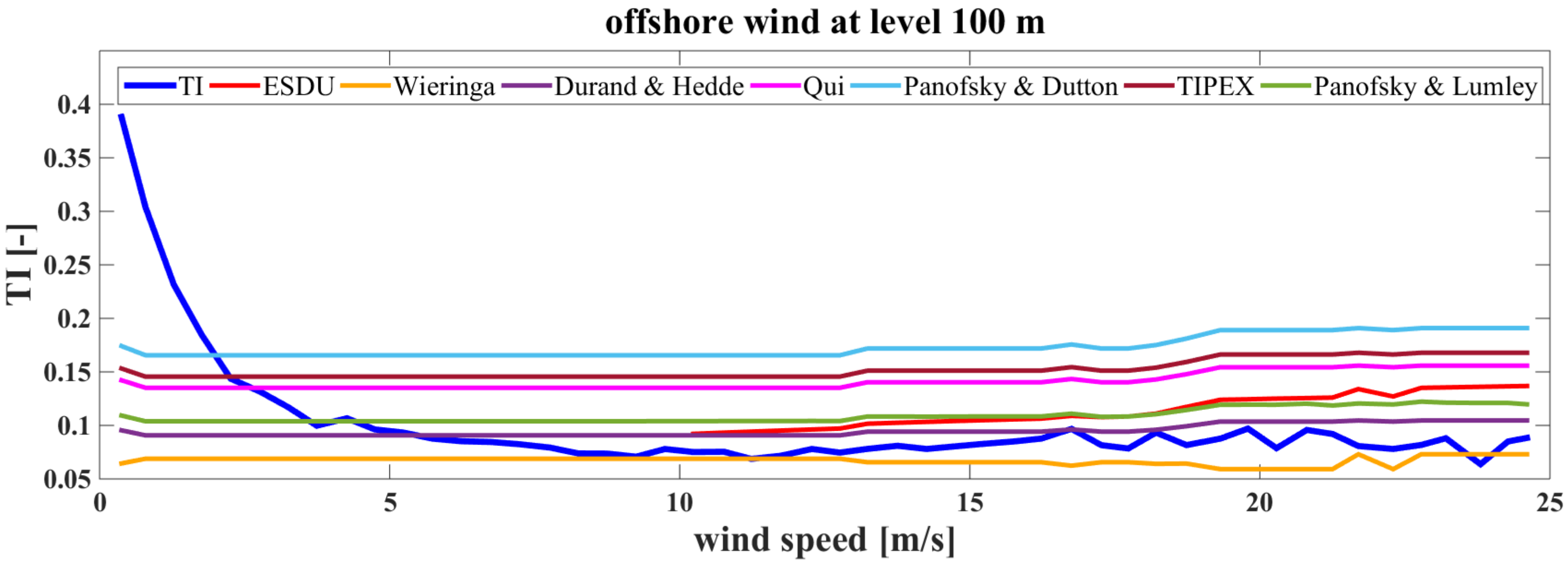


Neutral conditions



Source	Input	Output	Comments
ESDU 85020	f, z, u, z_0, u_*	std of *u*	u >10m/s, ESDU recommended formula for u_*
TIPEX, Zhou, Panofsky, Emeis et al.	u_*	std of *u*	models $\alpha \cdot u_*$ $\alpha \in \langle 2 ; 3.5 \rangle$
Wieringa	z, z_0	TI	
Hanna, Wyngaard	f, z, z_0	std of lateral wind speed	

Average TI from 5 years



ESDU in equilibrium conditions, where $\eta = 1 - 6fz/u_*$ and h can be taken as $u_*/(6f)$. [7]

$$\frac{\mathrm{std}(u)}{u_*} = \frac{7.5\eta[0.538 + 0.09\ln(\frac{z}{z_0})]^{\eta^{16}}}{1 + 0.156\ln(\frac{u_*}{fz_0})}$$

Zhou et al. (2000) [9]

$$\mathrm{std}(u) = 3.4u_*$$

Qi et al. (1996) [9]

$$\mathrm{std}(u) = 2.98u_*$$

Hedde & Durand [15]

$$\mathrm{std}(u) = 2u_*$$

TIPEX [9]

$$\mathrm{std}(u) = 3.45u_*$$

Panofsky & Dutton (1984) for surface layer only. [9]

$$\mathrm{std}(u) = 2.65u_*$$

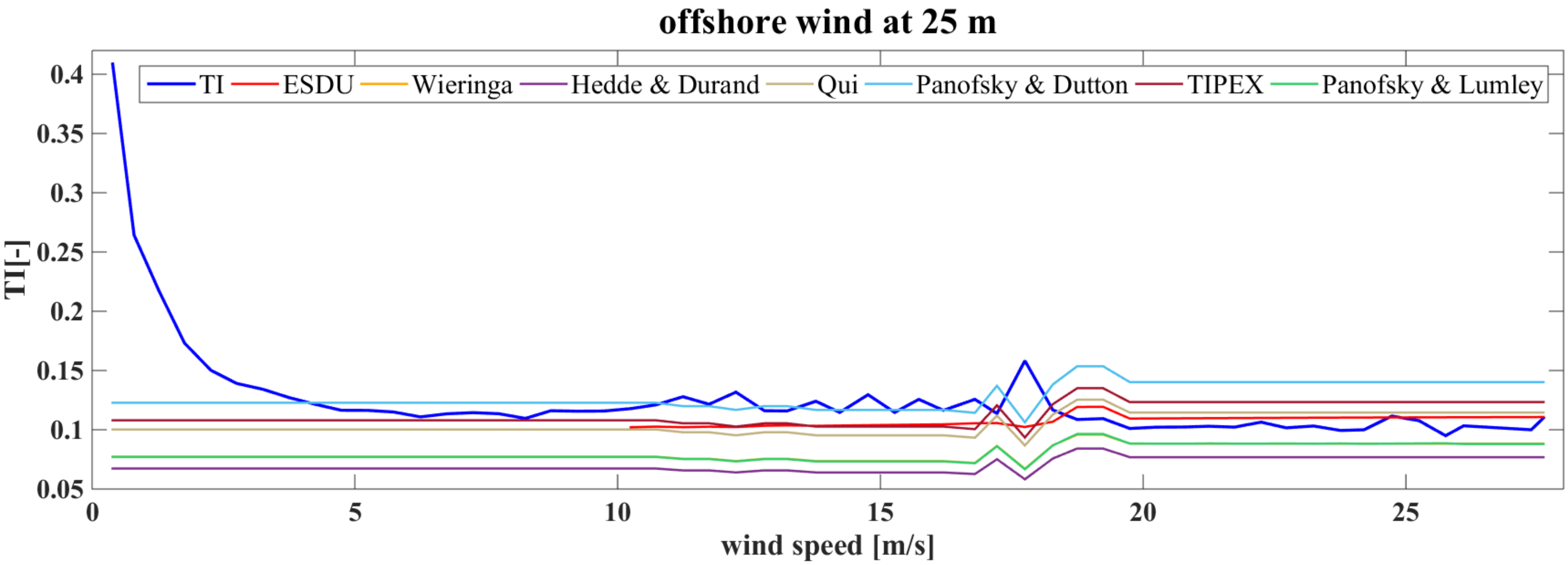
Couniham [18], Emeis [4]

$$\mathrm{std}(u) = 2.5u_*$$

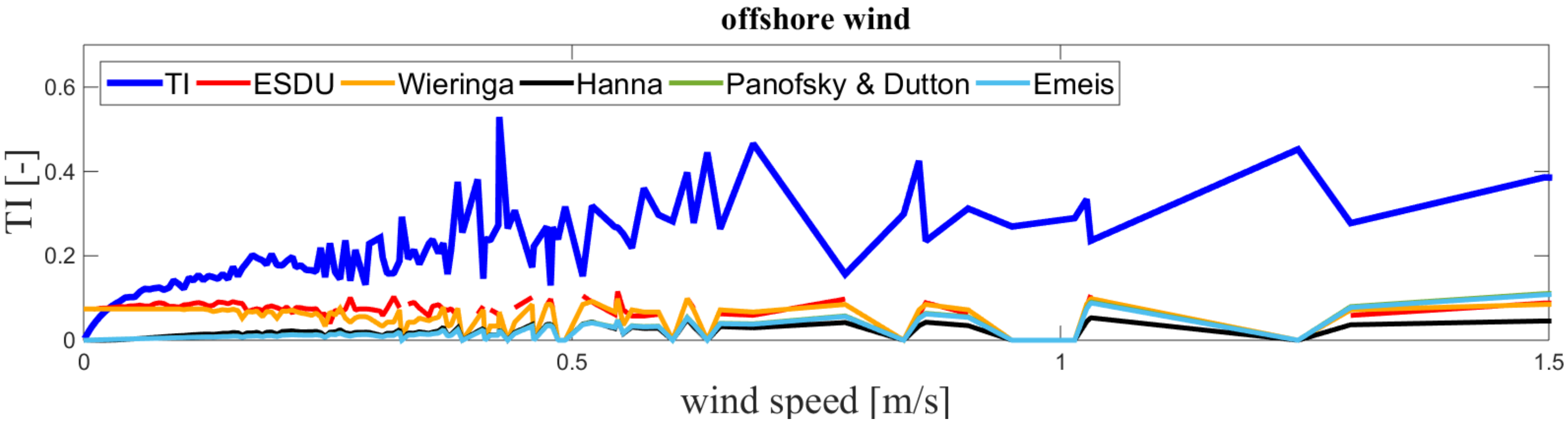
Wieringa (1973) [14]

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

Accuracy change with altitude



TI in normal direction



ESDU in equilibrium conditions [7]

$$\mathrm{std}(v) = \mathrm{std}(u)\left[1 - 0.22\cos^4\left(\frac{\pi}{2}\frac{z}{h}\right)\right]$$

Hanna(1982) based on Wyngaard (1974) for the surface layer only. [16]

$$\mathrm{std}(v) = 1.3u_* \exp(-2\frac{fz}{u_*})$$

Panofsky & Dutton (1984) for surface layer only. [9]

$$\mathrm{std}(v) = 1.92u_*$$

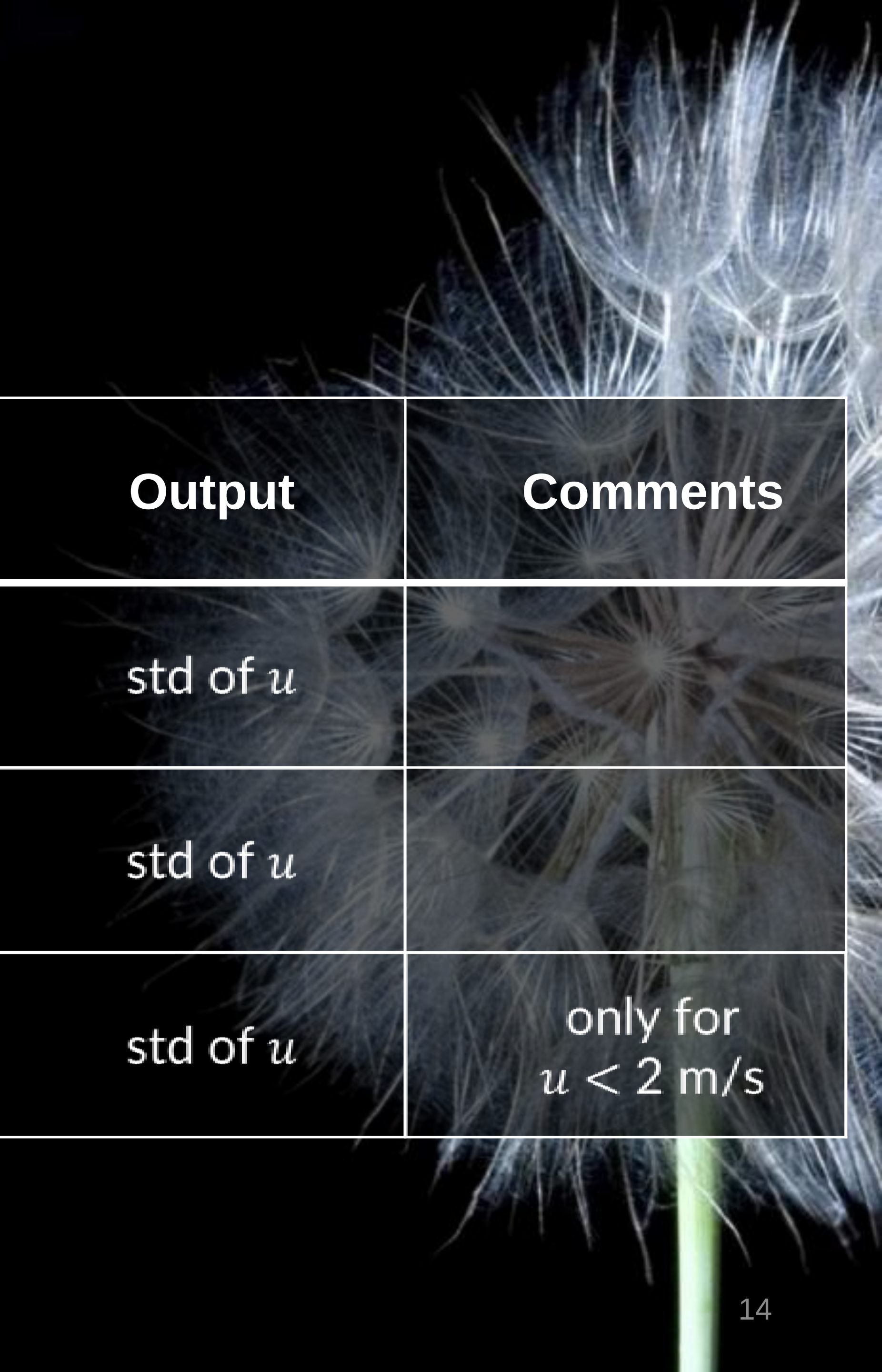
Couniham [18], Emeis [4]

$$\mathrm{std}(v) = 1.875u_*$$

Wieringa (1973) [14]

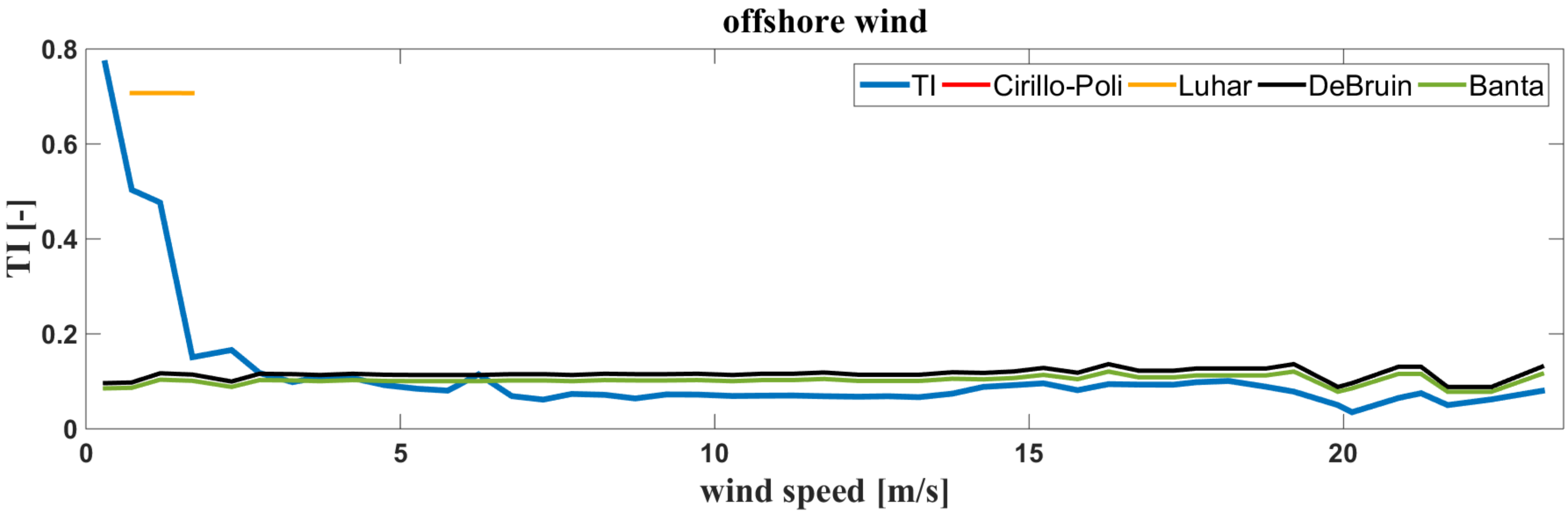
$$TI = \frac{1}{\ln(z/z_0)}$$

Stable conditions



Source	Input	Output	Comments
Gryning et al. Paumier	z, h, u_*	std of u	
Banta, De Bruin	u_*	std of u	
Pasquill, Luhar, Cirillo&Poli	std of wind direction, u	std of u	only for $u < 2$ m/s

Stable atmospheric class



Average from 5 years for offshore wind at level 100 m

Banta et al. [11]

$$\mathrm{std}(u)^2 = 4.9u_*^2$$

De Bruin, Kohsiek, Van Den Hurk (1992) [5]

$$\mathrm{std}(u) = 2.5u_*$$

Formulas only for low wind ($u < 2\frac{m}{s}$):

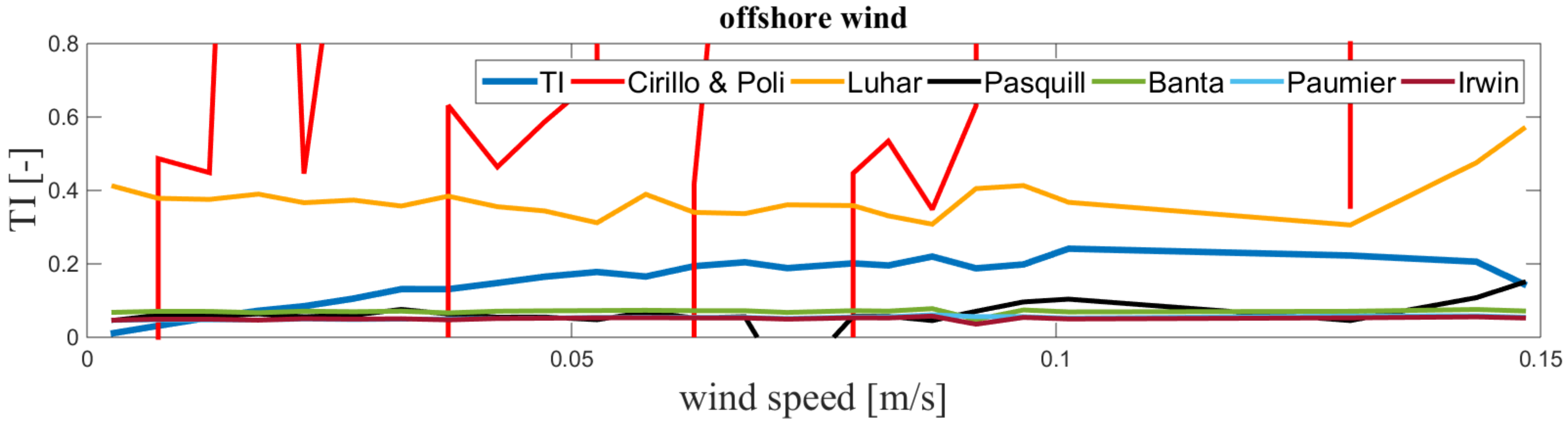
Cirillo and Poli (1992)[17]

$$\mathrm{std}^2(u) = \overline{u}^2[\cosh(\sigma_\theta^2) - 1]$$

Luhar (2010) [10]

$$\mathrm{std}^2(u) = \overline{u}^2\exp(-\sigma_\theta^2)[\cosh(\sigma_\theta^2) - 1]$$

Diagrams of TI in normal direction during stable conditions



Offshore wind from 5 years at level 70 m

Gryning, Holtslag, Irwin and Sivertsen (1987) [8]

$$\frac{\mathrm{std}(v)}{u_*} = \left[2\left(1-\frac{z}{h}\right)\right]^{1/2}$$

Banta et al. [11]

$$\mathrm{std}(v)^2 = 3.4u_*^2$$

Paumier. Formula from COST 710 [6]

$$\mathrm{std}(v) = 1.643u_* \frac{1-\frac{z}{h}}{(1+2.8\frac{z}{h})^{\frac{1}{3}}}$$

Formulas only for low wind ($u < 2\frac{m}{s}$):

Pasquill (1974) (in article of Steven Hanna (1983)) [9]

$$\frac{\mathrm{std}(v)}{\overline{u}} = \mathrm{tg}\,\sigma_\theta$$

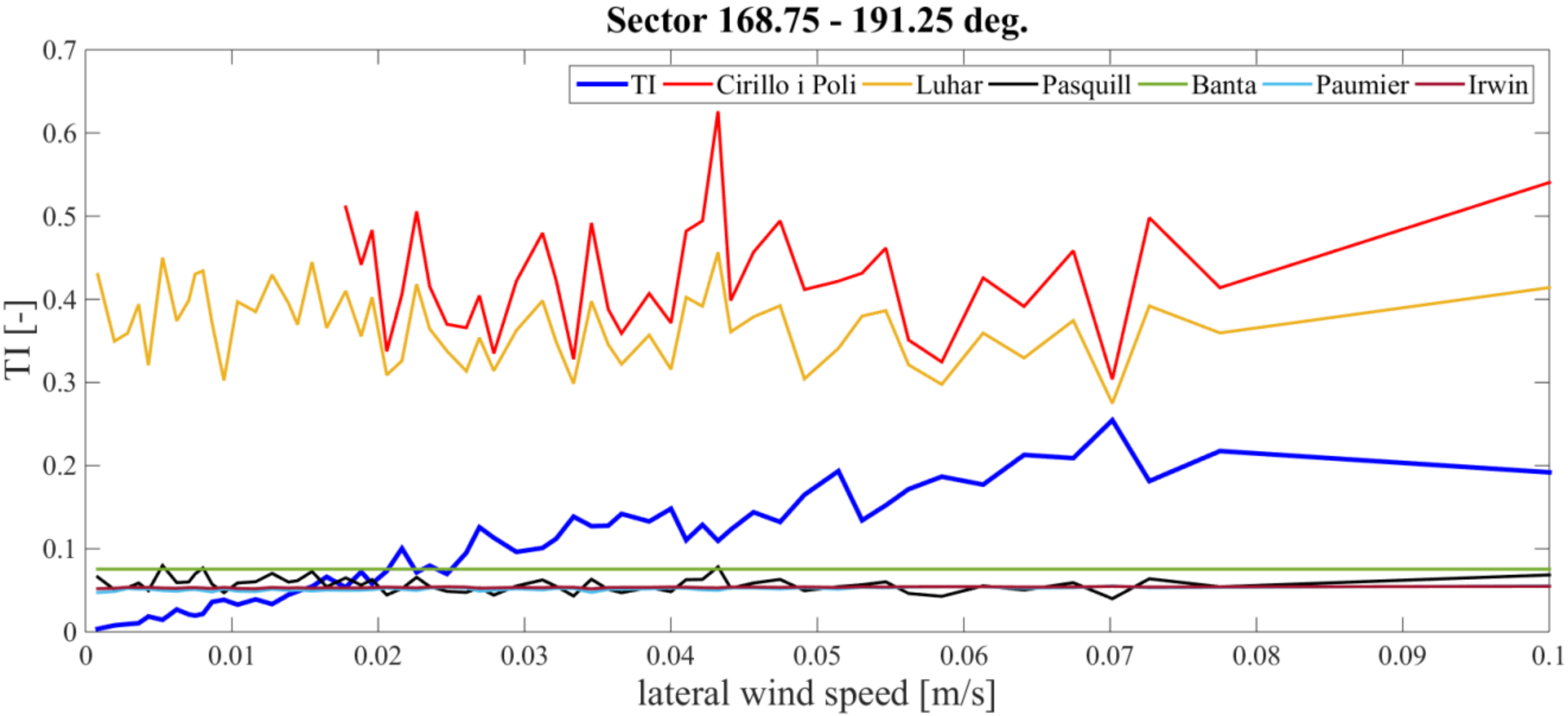
Cirillo and Poli (1992)[17]

$$\mathrm{std}^2(v) = \overline{u}^2 \sinh(\sigma_\theta^2)$$

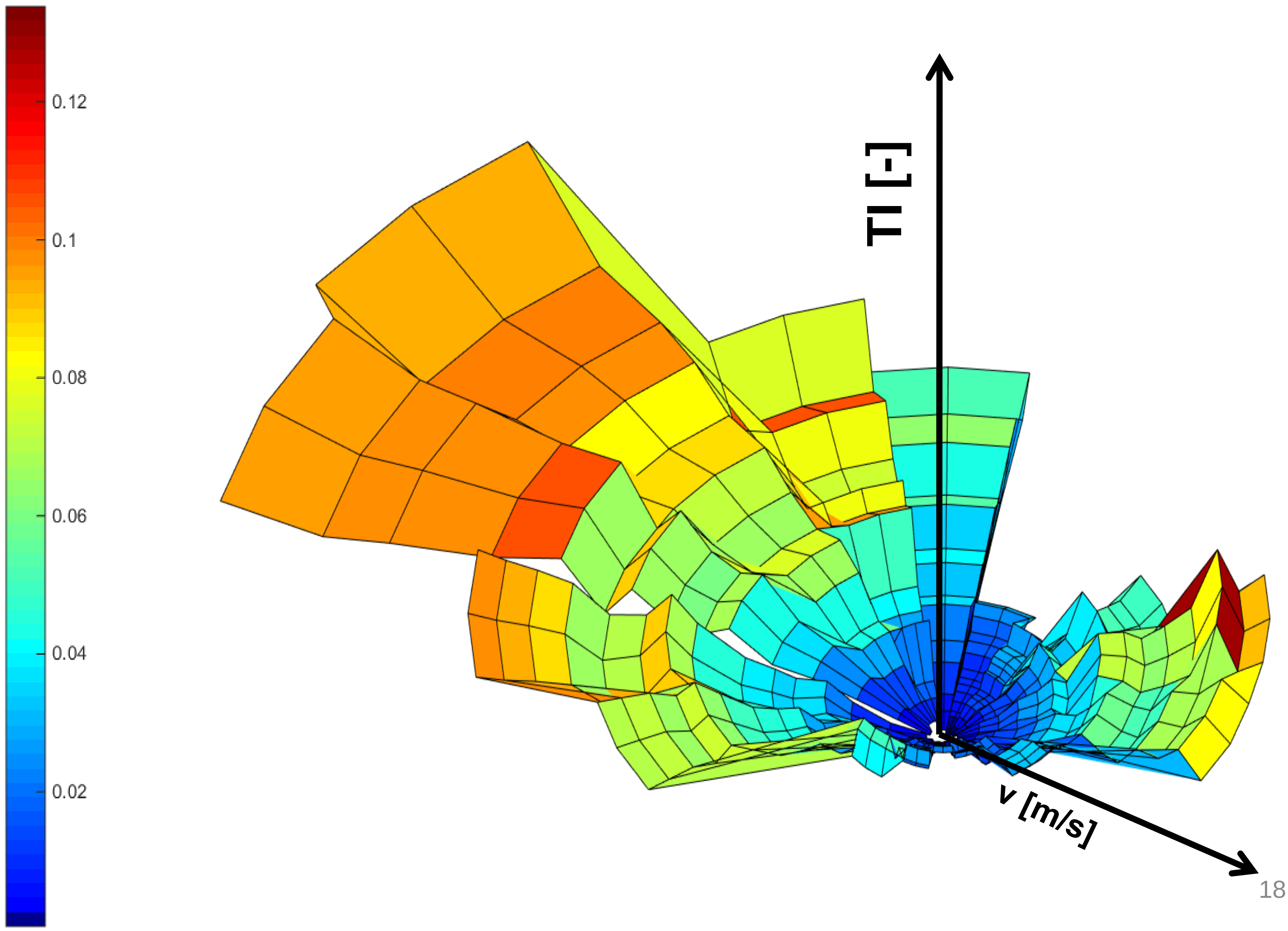
Luhar (2010) [10]

$$\mathrm{std}^2(v) = \overline{u}^2 \exp(-\sigma_\theta^2)\sinh(\sigma_\theta^2)$$

Model’s behavior in sector 9



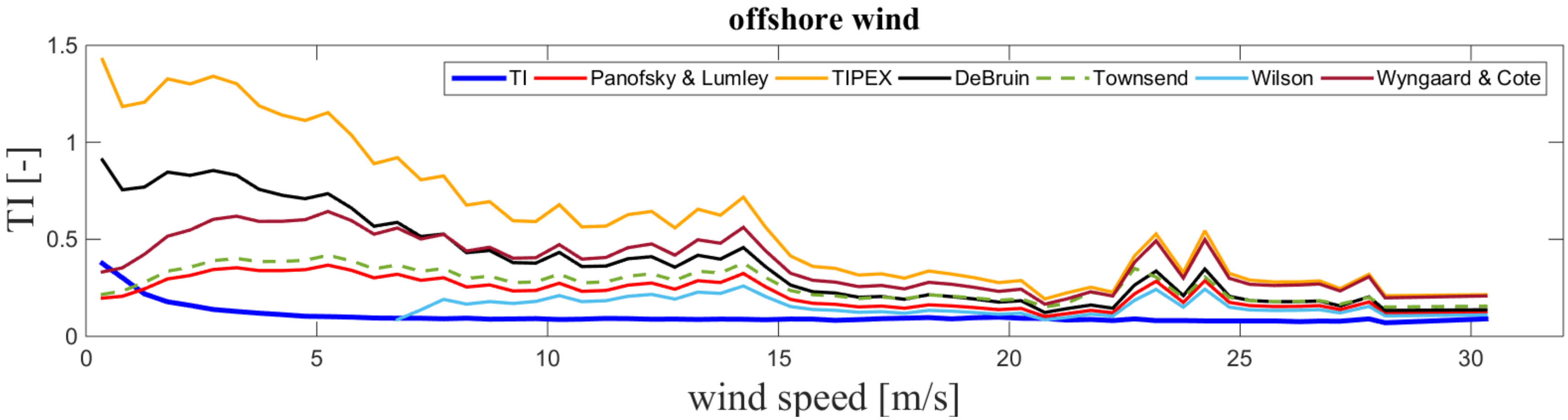
Normal TI in stable atmospheric class



Unstable conditions

Source	Input	Output	Comments
Townsend	L, z, h, u_*, u	std of u	
Wilson	L, z, h, u_*, u	std of u	$z \ll h$
Wyngaard, Cote Panofsky, Arya	L, h, u_*	std of u	formulas good also for near neutral conditions
TIPEX **De Bruin et al.**	L, z, u_*	std of u	
Gryning et al.	L, z, h, u_*, k	std of u	k is von Karman constant

TI in longitudinal direction



Offshore wind from 5 years at level 70 m

Models in use:

Townsend (1976), where Towsend & Perry recomended $A_1 = 1.26$ [12]

$$\frac{\mathrm{std}^2(u)}{u_*^2} = 4 + 0.6\left(\frac{h}{-L}\right)^{2/3} - A_1 \ln\left(\frac{z}{h}\right)$$

Wilson with parameters $b = 3/4 \quad c = 1/4, \; z \ll h.$[12]

$$\frac{\mathrm{std}^2(u)}{u_*^2} = \left[4 + b\left(\frac{h}{-L}\right)^{2/3}\right]\left[1 - \left(\frac{z}{h}\right)^{c}\right]$$

Wyngaard & Cote (1974) [13]

$$\frac{\mathrm{std}(u)}{u_*} = \left[4 + 0.6\left(\frac{h}{-L}\right)^{2/3}\right]^{1/2}$$

Panofsky & Lumley (1964) [13]

$$\frac{\mathrm{std}(u)}{u_*} = \left(12 + 0.5\frac{h}{-L}\right)^{1/3}$$

De Bruin, Kohsiek, Van Den Hurk (1992) [5]

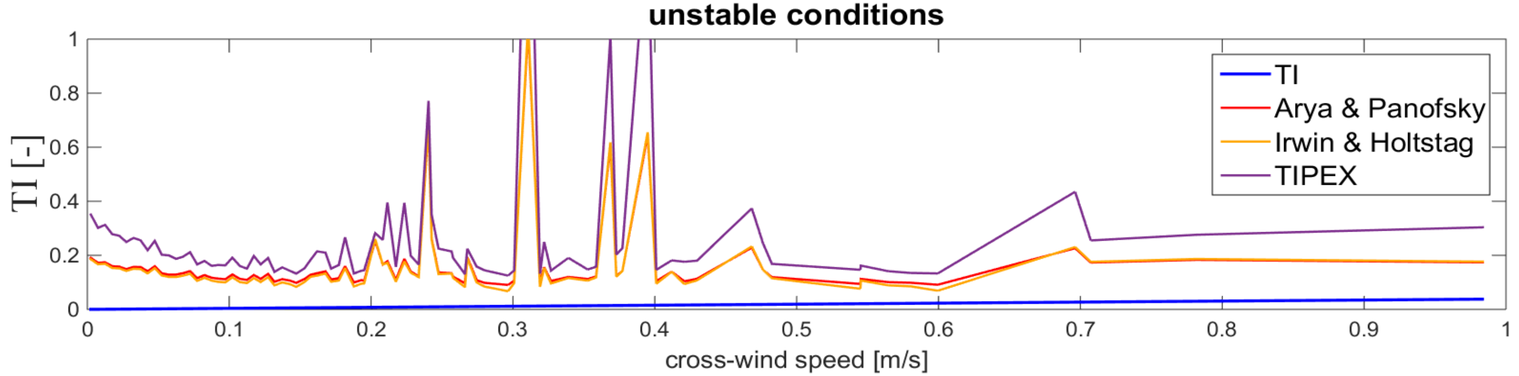
$$\frac{\mathrm{std}(u)}{u_*} = 2.2\left(1 + 3\frac{z}{-L}\right)^{1/3}$$

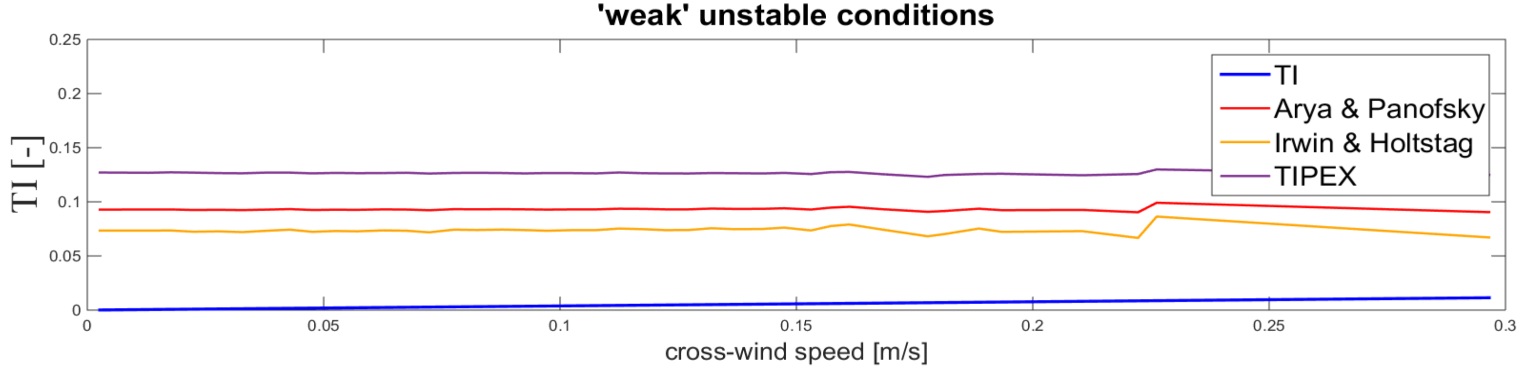
Bian, Xu, Lu and others, TIPEX (2002) [9]

$$\frac{\mathrm{std}(u)}{u_*} = 3.45\left(1 + 3\frac{z}{-L}\right)^{1/3}$$

Only for the weak?

Crosswind components of wind velocity during unstable conditions


unstable conditions


'weak' unstable conditions

Panofsky (1977), Arya(1995) [6]

$$\frac{\mathrm{std}(v)}{u_*} = \left(12 + 0.5\frac{h}{-L}\right)^{1/3}$$

Gryning, Holtstag, Irwin and Sivertsen (1987) [8]

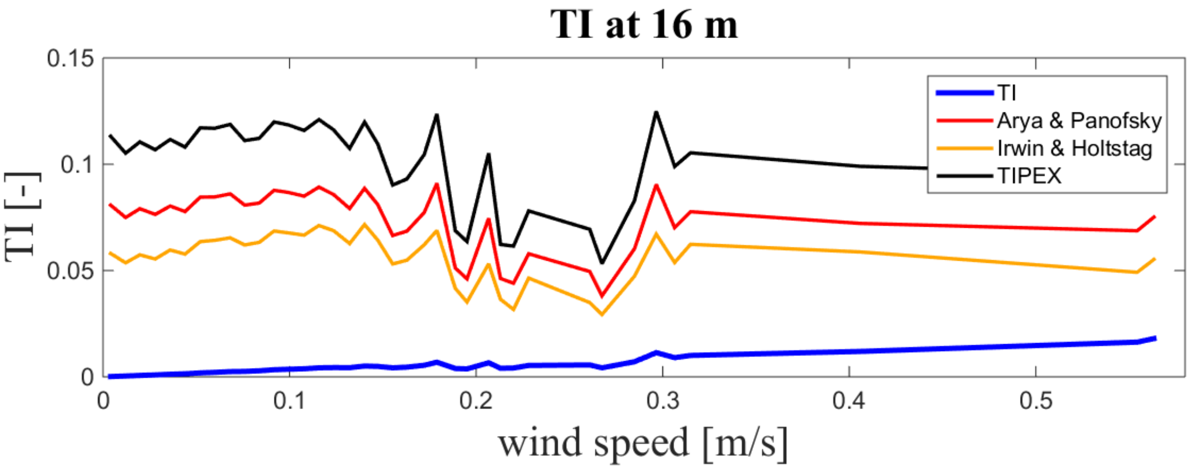
$$\frac{\mathrm{std}(v)}{u_*} = \left[2\left(1 - \frac{z}{h}\right)\right]^{1/2}$$

Bian, Xu, Lu and others, TIPEX, at Tibetan Plateau (2002) [9]

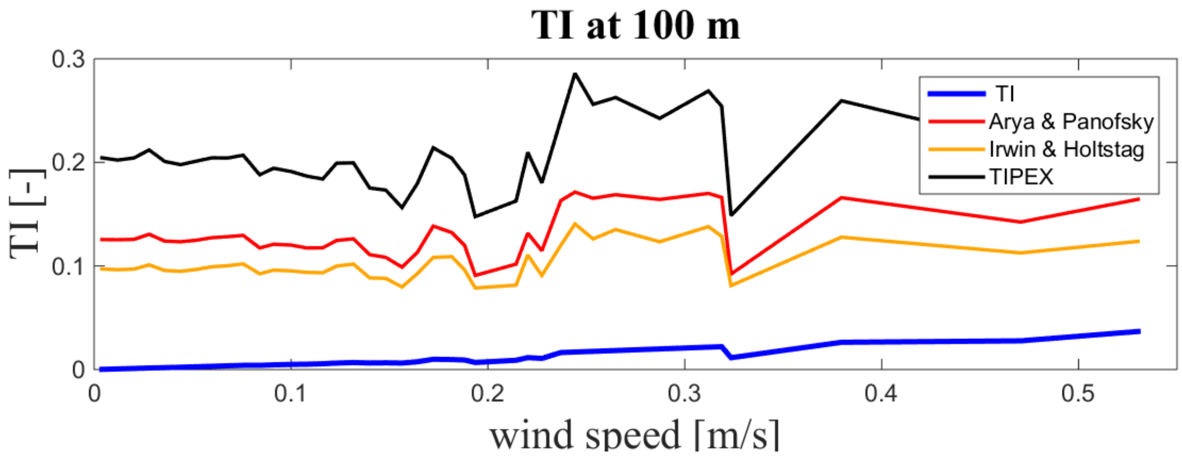
$$\frac{\mathrm{std}(v)}{u_*} = 3.15\left(1 + 3\frac{z}{-L}\right)^{1/3}$$

Weak unstable condition

Model's accuracy
at level 16 m


TI at 16 m

Model's accuracy
at level 100 m


TI at 100 m

Conclusions

- **Neutral** atmospheric stability class**:** the strong influence of height on the models accuracy. Longitudinal TI at the level **100** m: **Wieringa, Hedde & Durand**, but with level the accuracy change.
  Best, regardless of the height: **ESDU**.
  Normal TI: **none**.
- **Stable** conditions, longitudinal TI: both **De Bruin et al.** and **Banta** models.
  Normal TI: model of **Luhar**.
- **Unstable** class of atmospheric stability, longitudinal TI: model of **Wilson.**
  TI in normal direction: **Irwin & Holstag** .

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