CHARACTERIZING TURBULENCE ANISOTROPY, COHERENCE, AND INTERMITTENCY AT A PROSPECTIVE TIDAL ENERGY SITE

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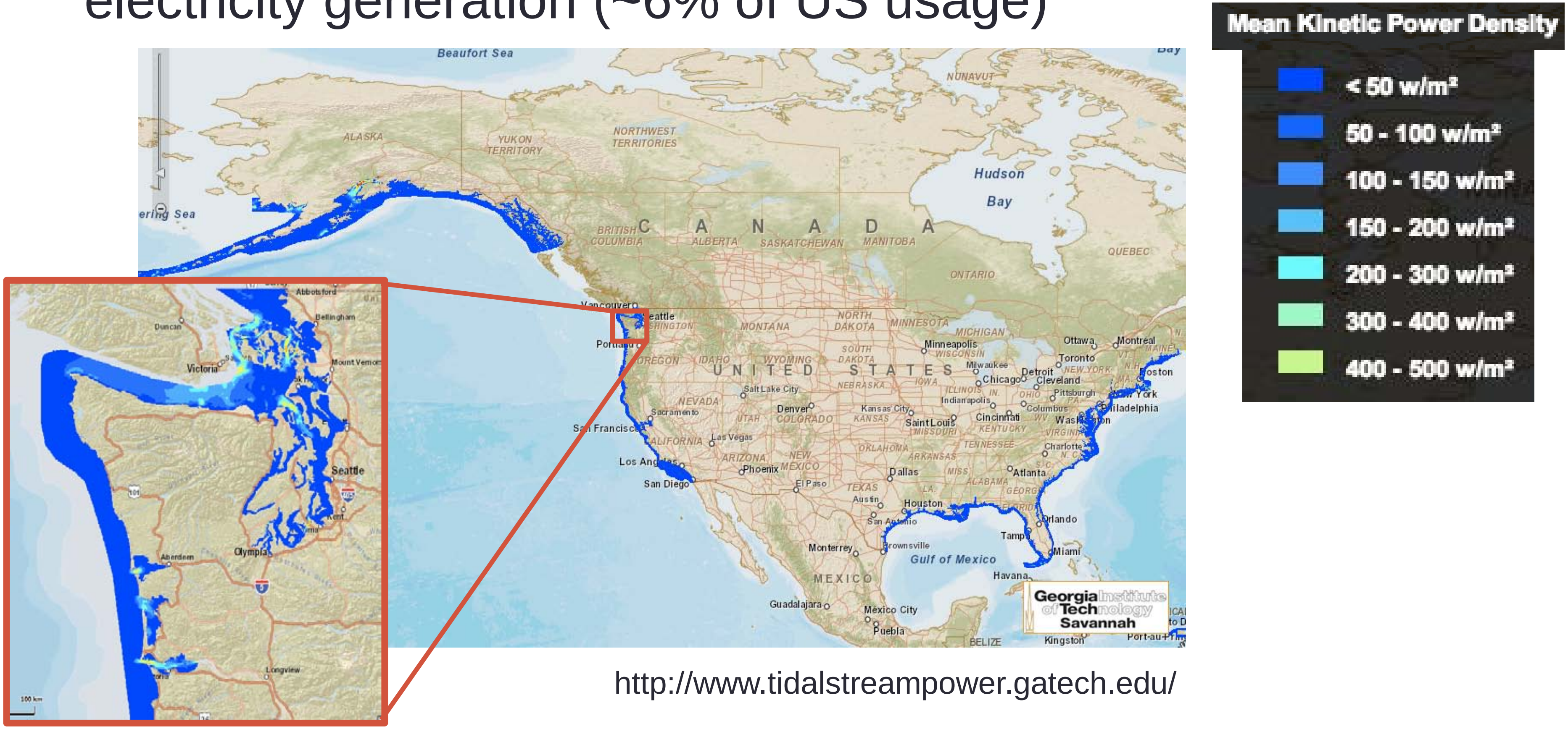
Outline

- Introduction to Tidal Energy
- Introduction to the Problem
- Anisotropy, Coherence, and Intermittency
  - Observations and Metrics
  - Parameterization Results
- Preliminary Statistical Model Results

Tidal Energy Resource

- Clean, renewable, predictable energy source; close to population centers
- DOE Resource Assessment: potential 250 TWh/year electricity generation (~6% of US usage)

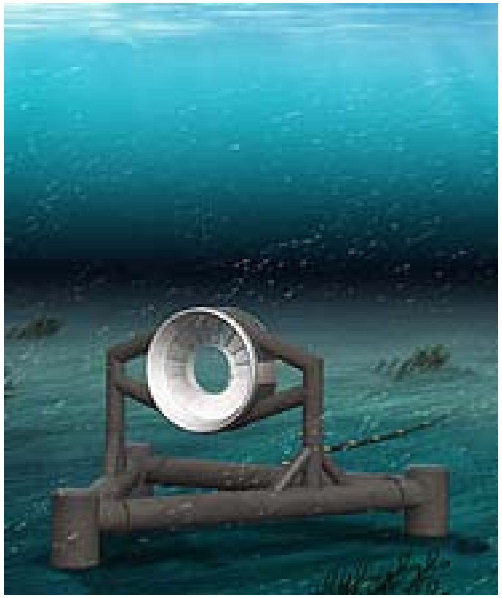


http://www.tidalstreampower.gatech.edu/

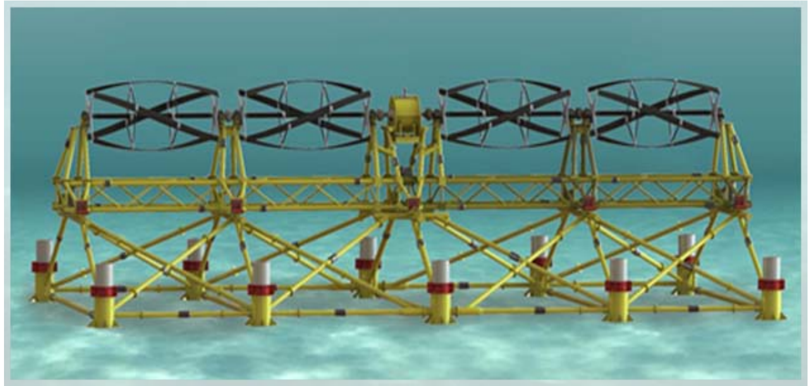
Tidal Energy Conversion Technology

- In-Stream Turbine – in the flow, invisible from surface
- Similar technology to a wind turbine, though with many different designs

http://www.infoniac.com/environment/world-s-biggest-tidal-turbine-to-be-built-in-scotland.html



http://www.openhydro.com/technology.html

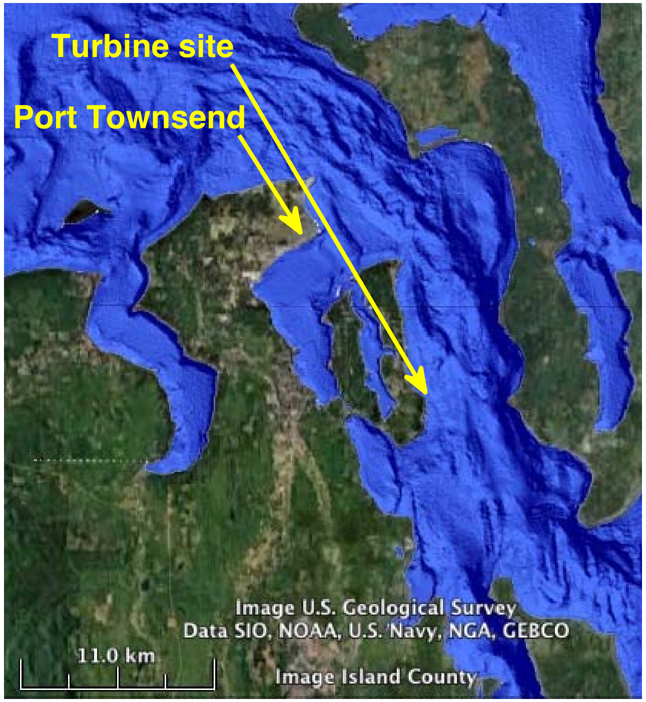


http://www.orpc.co/orpcpowersystem_tidgenpowersystem.aspx

Goals

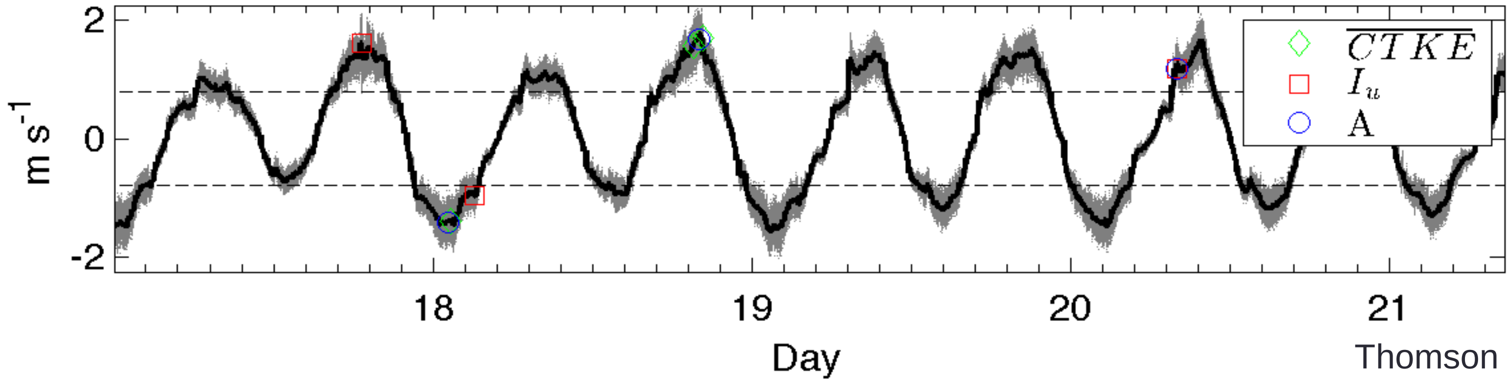
- Take the knowledge and experiences of the wind energy industry to further the development of tidal energy, focusing on turbulence.
- Do a thorough physical description of the turbulence that will affect a tidal turbine
  - Site classification for decision-making
  - Describe realistic turbulence with metrics that can be used to improve models
    - Turbulent in-flow generators: National Renewable Energy Laboratory’s TurbSim/pyTurbSim
    - Turbine-scale dynamical models: LES

Nodule Point, Puget Sound, WA



Acoustic Doppler Velicometer

Latitude	N 48 01.924’
Longitude	W 122 39.689’
Depth	22m
Dates	Feb 17-21, 2011
Sampling Frequency	32 Hz
Noise	0.02 m/s
Proposed Hub Height	4.7m
Hub Height Max. Velocity	1.8 m/s



Thomson et al, 2012

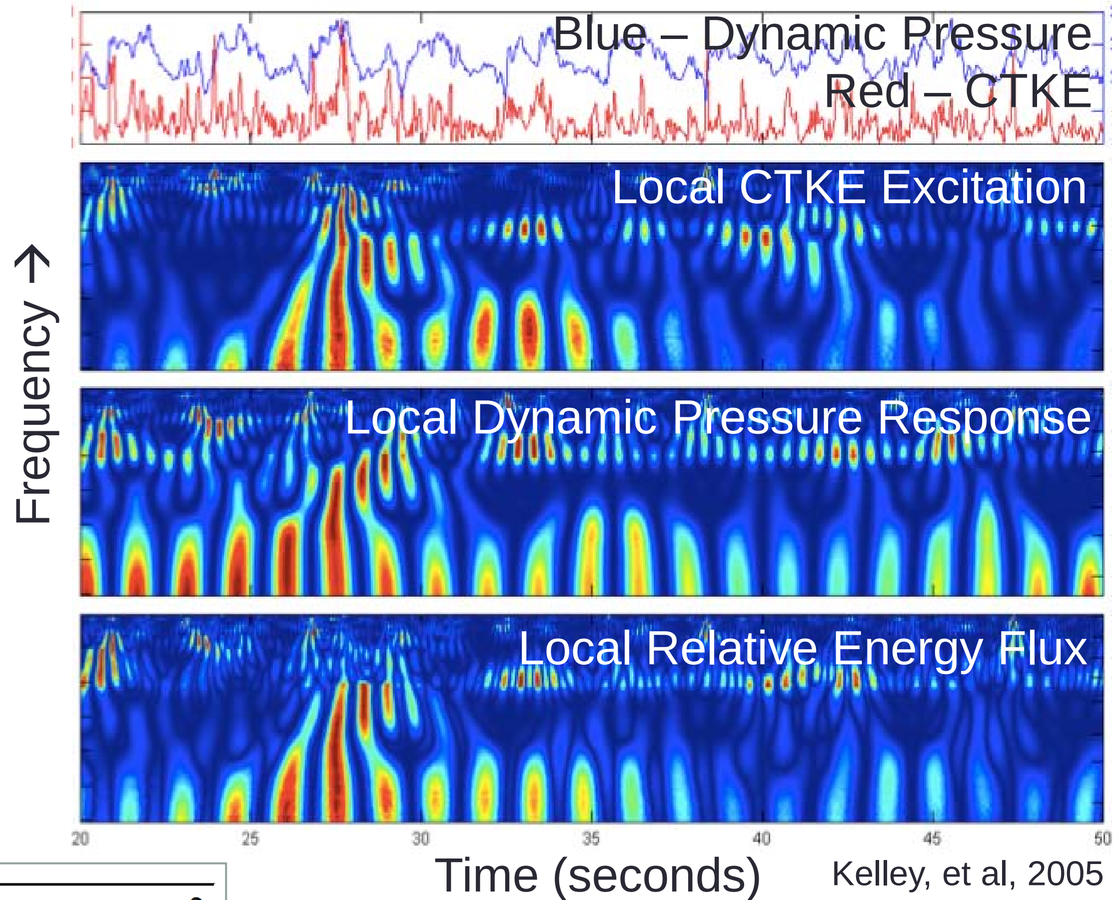
Turbulence Metrics

- Turbulence effects on power production: **turbulence intensity**

$$I_u = \frac{\sigma_u}{\langle u \rangle} = \frac{\sqrt{\langle u'^2 \rangle - n^2}}{\bar{u}}$$

- Turbulence effects on turbine mechanics (loads and subsequent gear box failures): **coherent turbulent kinetic energy**

$$CTKE = \frac{1}{2}\sqrt{(u'v')^2 + (u'w')^2 + (v'w')^2}$$



Kelley, et al, 2005

Thomson et al, 2012

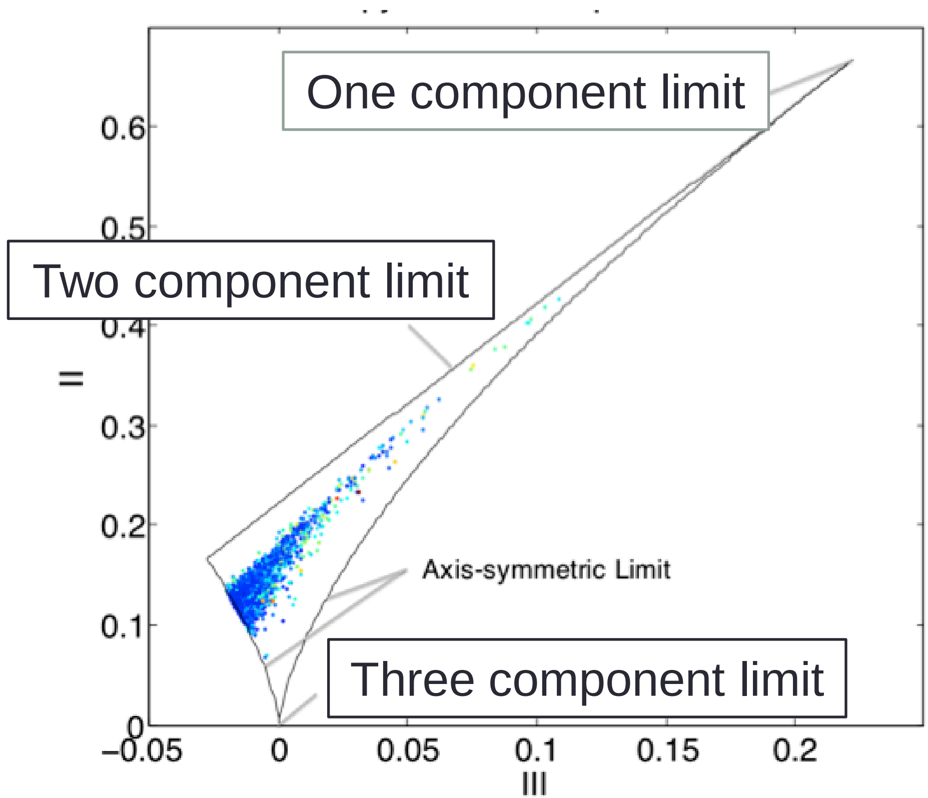
Turbulence Metrics

- Anisotropy Tensor

$$a_{ij} = \frac{\overline{u'_i u'_j}}{2k} - \frac{\delta_{ij}}{3}, \quad k = \frac{\overline{u'_i u'_i}}{2}$$

Invariants:

$$I = a_{ii}$$
$$II = a_{ij} a_{ji}$$
$$III = a_{ij} a_{in} a_{jn}$$



- Anisotropy Magnitude
  - CTKE-like, but built from invariants
  - Independent of chosen coordinate system
  - Captures anisotropy from shear *and* normal Reynolds stresses

$$A = k\sqrt{II}$$

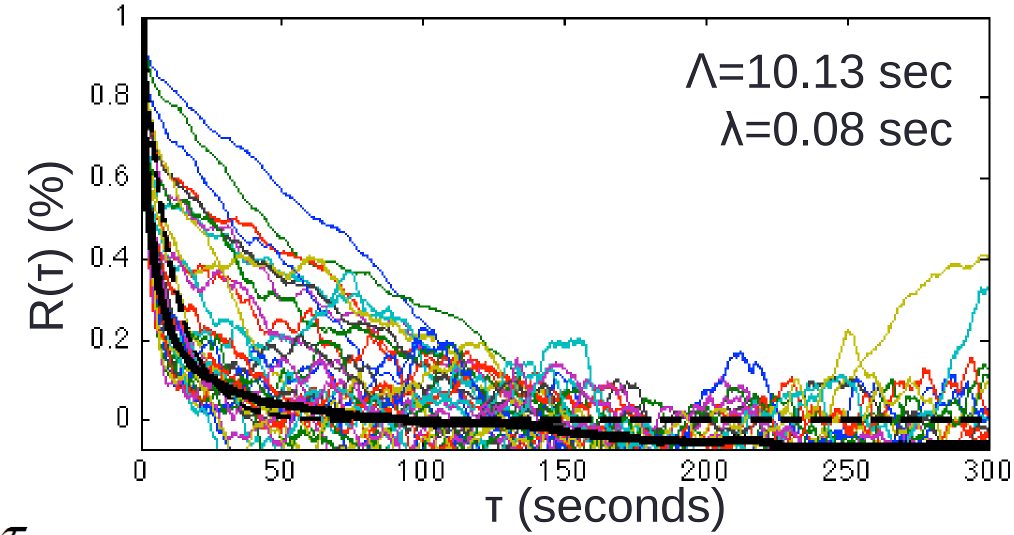
Coherence & Intermittency

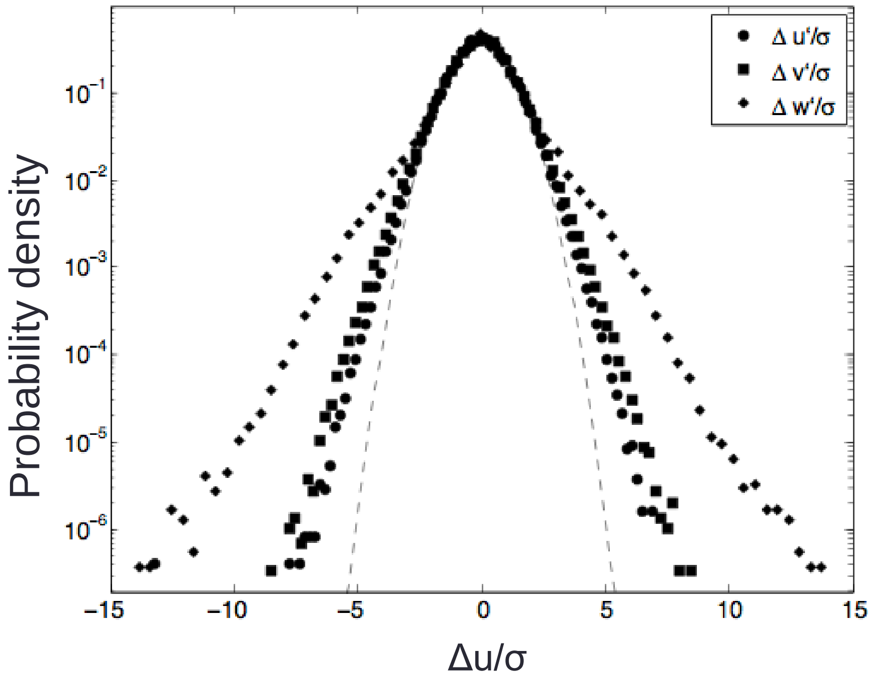
- Temporal Autocorrelation

$$R(\tau) = \frac{\overline{u'(t)u'(t+\tau)}}{\overline{u'^2}}$$

  - Integral Scale $\Lambda_t = \int_0^\infty R(\tau)\,d\tau$
  - Taylor Scale $\lambda_t = -2\left[\frac{d^2 R}{d\tau^2}\right]^{-1}$

- Probability density function





Turbulence isn't always constant; "events" occur.

Anisotropy

- Improvement to the anisotropy analysis: For eigenvalues, λ_i, of the anisotropy tensor, a_{ij}, ordered from greatest to least, the barycentric coordinates are defined by:

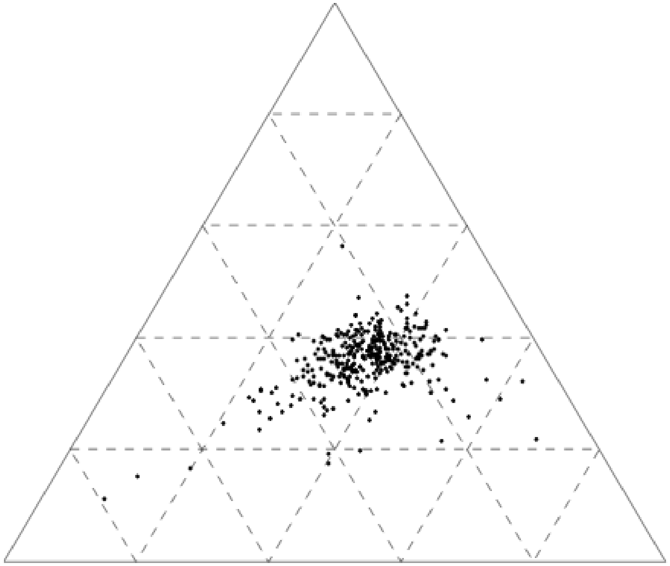
$$C_{1c} = \lambda_1 - \lambda_2$$
$$C_{2c} = 2(\lambda_2 - \lambda_3)$$
$$C_{3c} = 3\lambda_3 + 1$$

C_{1c} : one-component limit – linear

C_{2c} : two-component limit – planar

C_{3c} : three-component limit – isotropic

Three component limit



One component limit

Two component limit

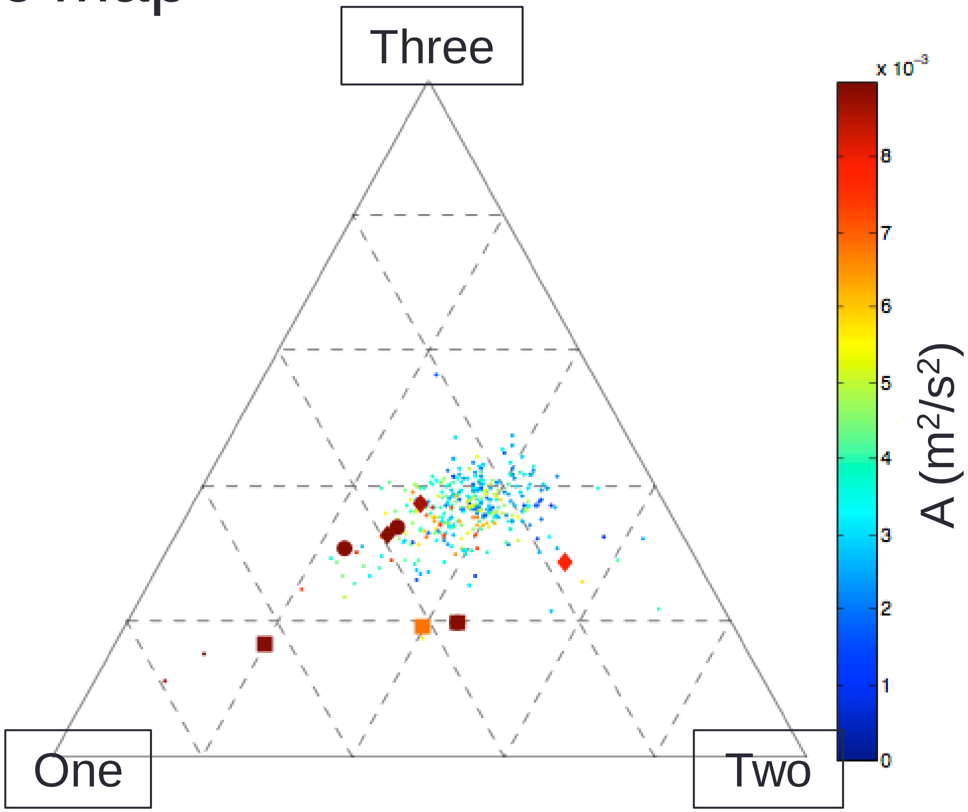
Banerjee et al 2007

Parameterization

The anisotropy magnitude, *A*, captures the:

- behavior of *CTKE*
- coherence of the correlation function.
- shape from the barycentric map
- intermittency in the pdf

	λ	Λ
I_u	0.596	0.450
CTKE	0.680	0.017
A	**0.884**	0.317



Next step: How well do models generate realistic turbulence?

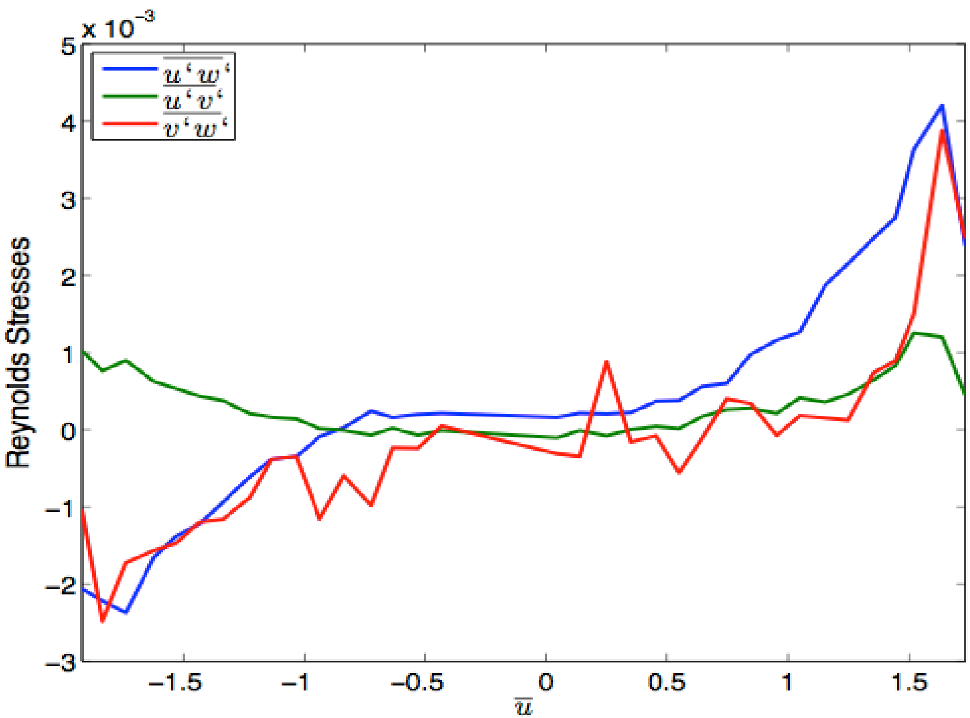
How do the statistics calculated from the model output compare to those from the observations?

- **The NREL pyTurbSim (or "HydroTurbSim") model (Jonkman & Kilcher) creates stochastic turbulence for tidal energy applications.**
- The NCAR LES model (Sullivan, McWilliams & Moeng) is a dynamical atmospheric model adapted for tidal flow (Alexander & Hamlington, in progress).

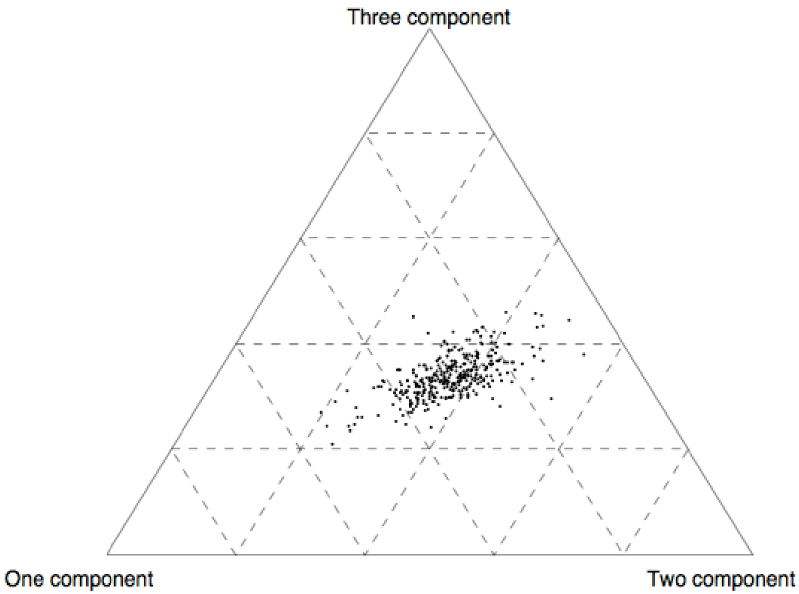
Introduction to pyTurbSim

- Inputs:
  - Background mean flow profile
  - Turbulent spectral density curve based on observations
  - Turbulence intensity standard
  - Reynolds stresses
- Method:
  - Inverse fast Fourier transform
  - Spatial correlation function
- Outputs:
  - Two-dimensional snapshots in time, and through Taylor's hypothesis (L~U*t), the third dimension

Latitude	$\overline{u'w'}$
Depth (RefHt)	$\overline{u'v'}$
U_{RefHt}	$\overline{v'w'}$
Time step ("Sampling Frequency")	TIDAL Turb Model based on observations
Hub Height	Mean Profile – H_2O log

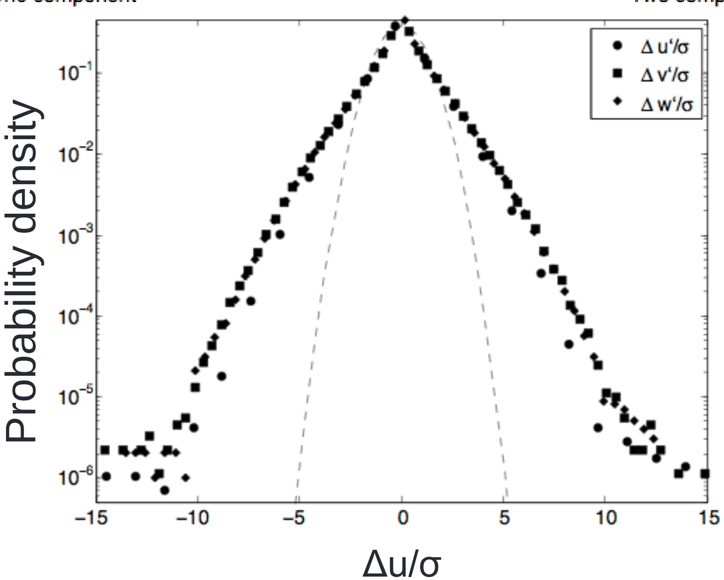


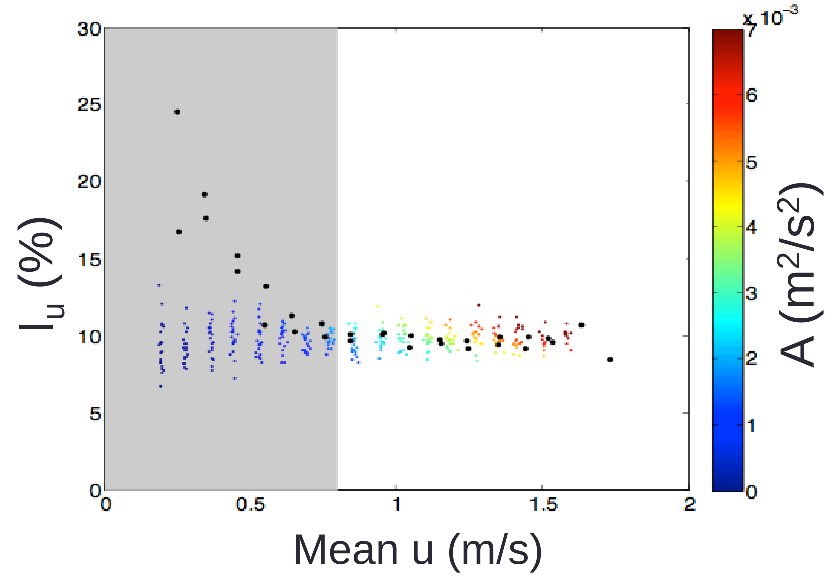
TurbSim Results



Barycentric map is correct, but the turbulence intensity is not, and pdfs show no anisotropy.

To examine: how is the anisotropy captured in the normal stresses versus shear stresses?





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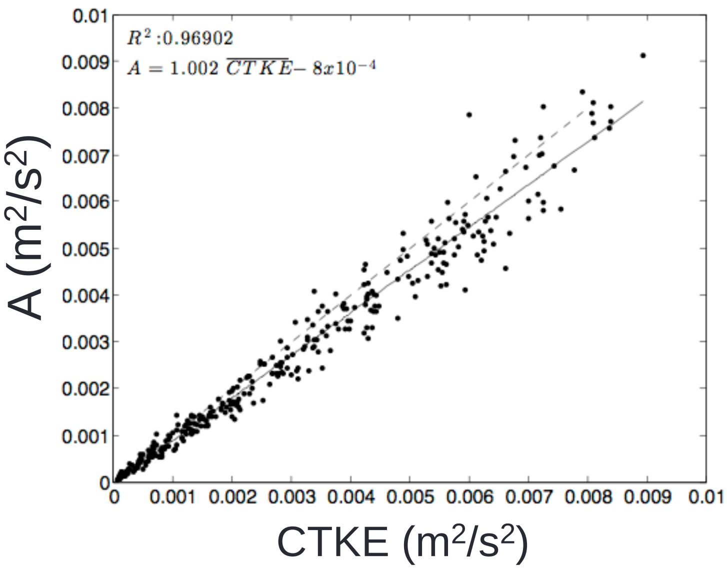
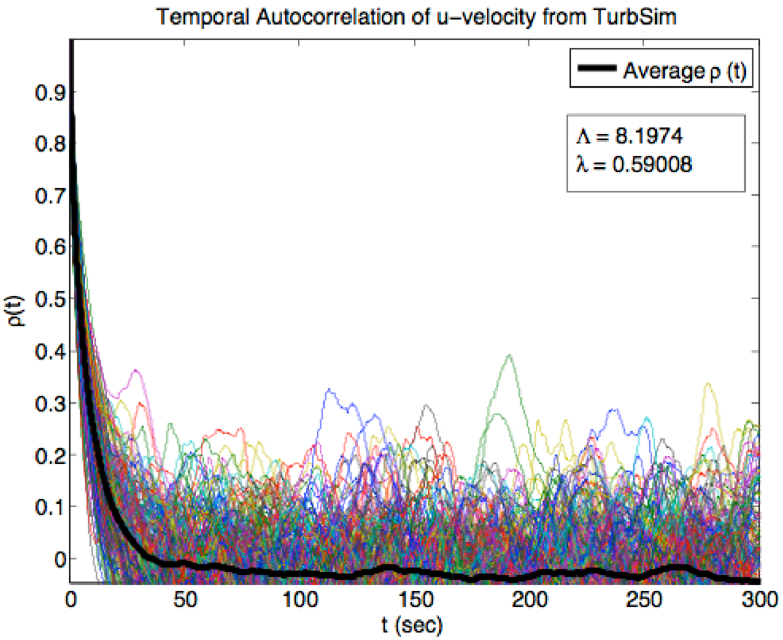


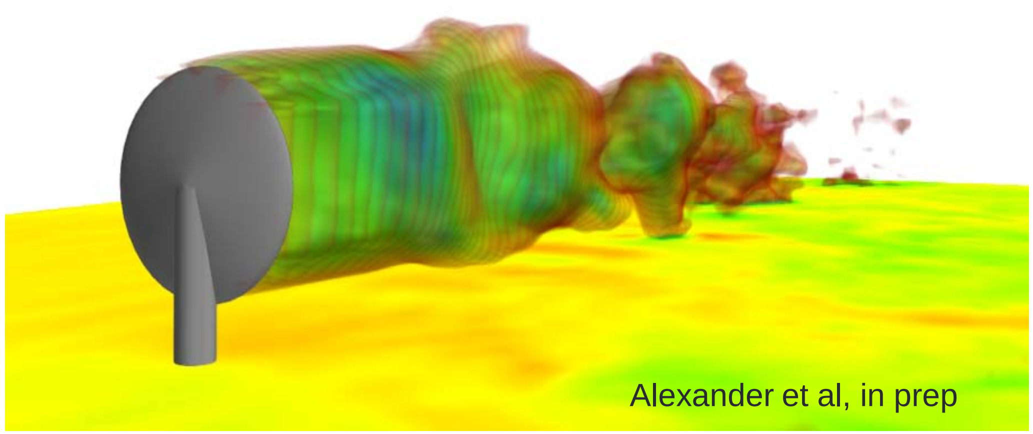


Extreme events seen in observations are not evident in A, CTKE, or autocorrelations.

Is it possible for a stochastic model to contain these anomalous events?

Large-Eddy Simulations

- With these inherent problems with a stochastic model, can a large-eddy simulation create more realistic turbulence?
  - The NCAR LES model (Sullivan, McWilliams & Moeng) is a dynamical atmospheric model adapted for tidal flow (Alexander & Hamlington, in preparation).
- Can LES create the turbulent events, and capture the anisotropy



Alexander et al, in prep

Conclusions

- A new, tensor-invariant metric, the anisotropy magnitude, is introduced to physically describe turbulence from ADV measurements.
- The anisotropy magnitude does a better job at representing intermittency, coherence, and anisotropy than the previously-used turbulence intensity and CTKE.
- pyTurbSim captures the anisotropy in a tidal flow in the shear stresses (defined by input), but not normal stresses (defined in model).

- Current work: How statistics calculated from LES model data compare to those from the observations?

Thank you!

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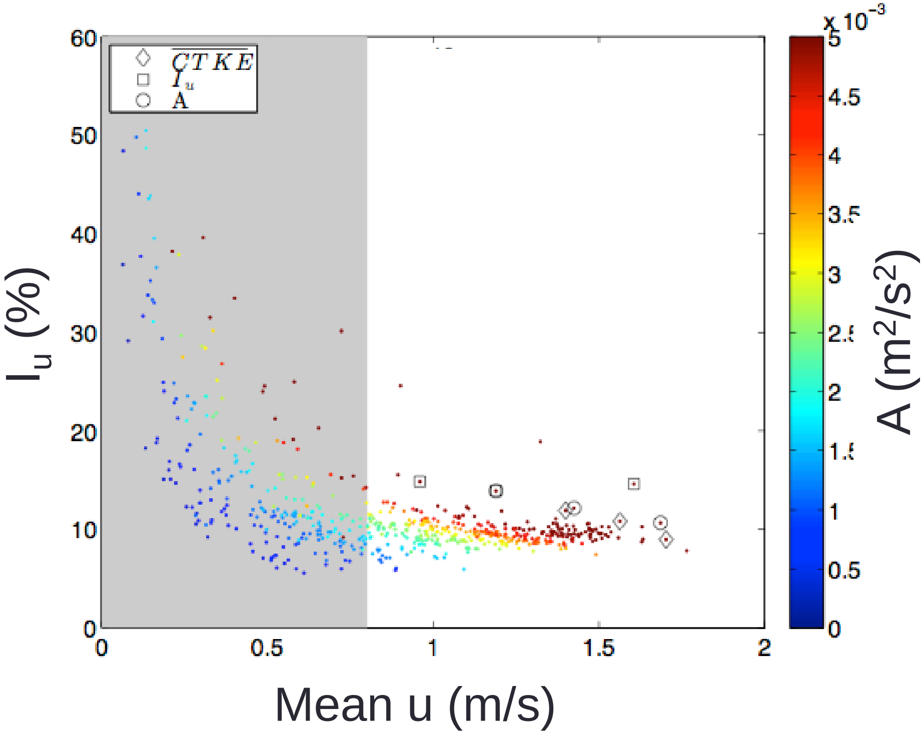
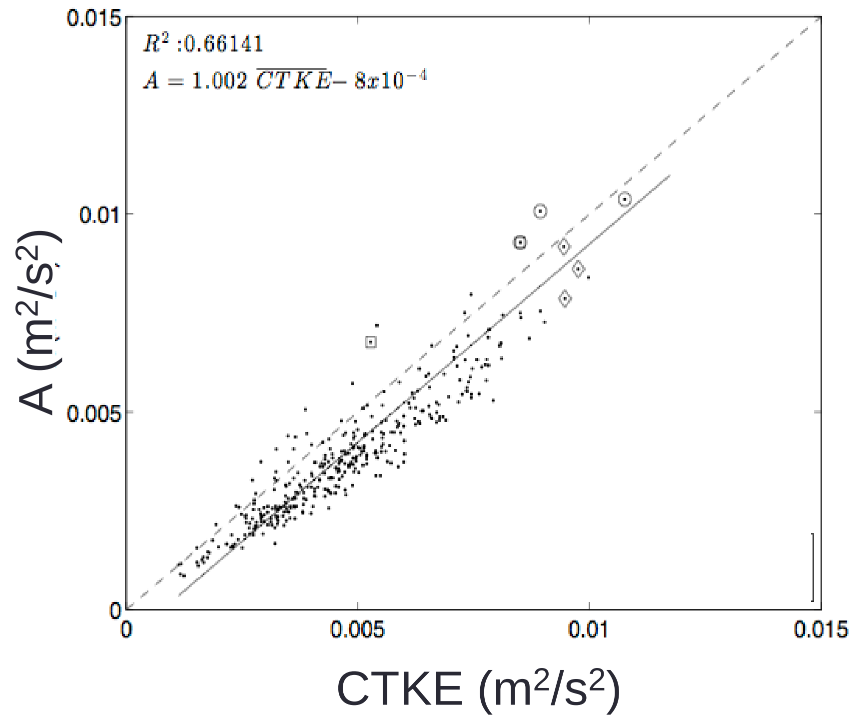
Parameterization

- How do we represent how “turbulent” a location is?
  - Is I_u, CTKE, or A better at representing intermittency, coherence, and anisotropy?

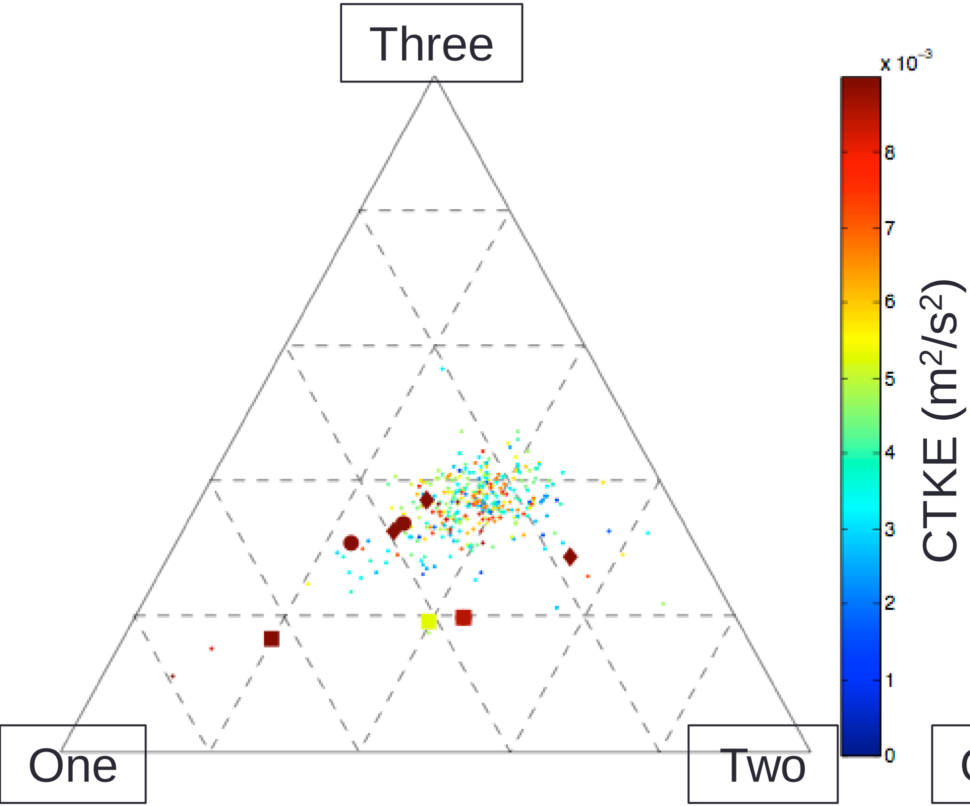


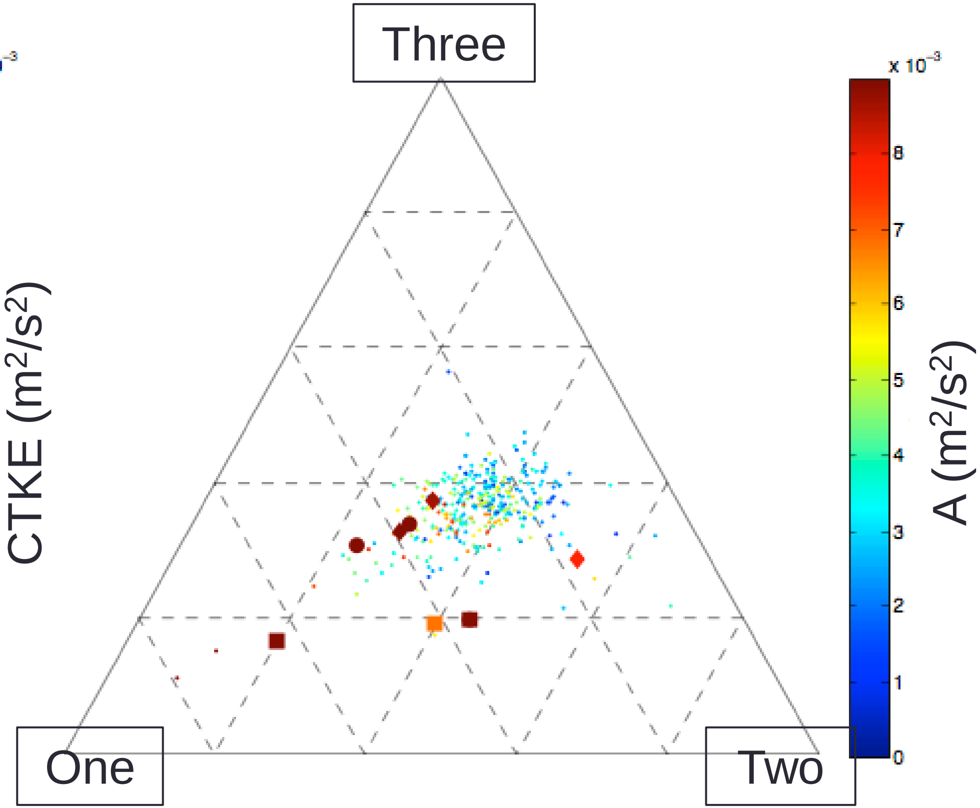


Parameterization: Shape

The highest instance of each parameter (large shapes) is close(r) to the one-component limit.

- I_u only measures one component (*u*)
- *A* is better than *CTKE*





Parameterization

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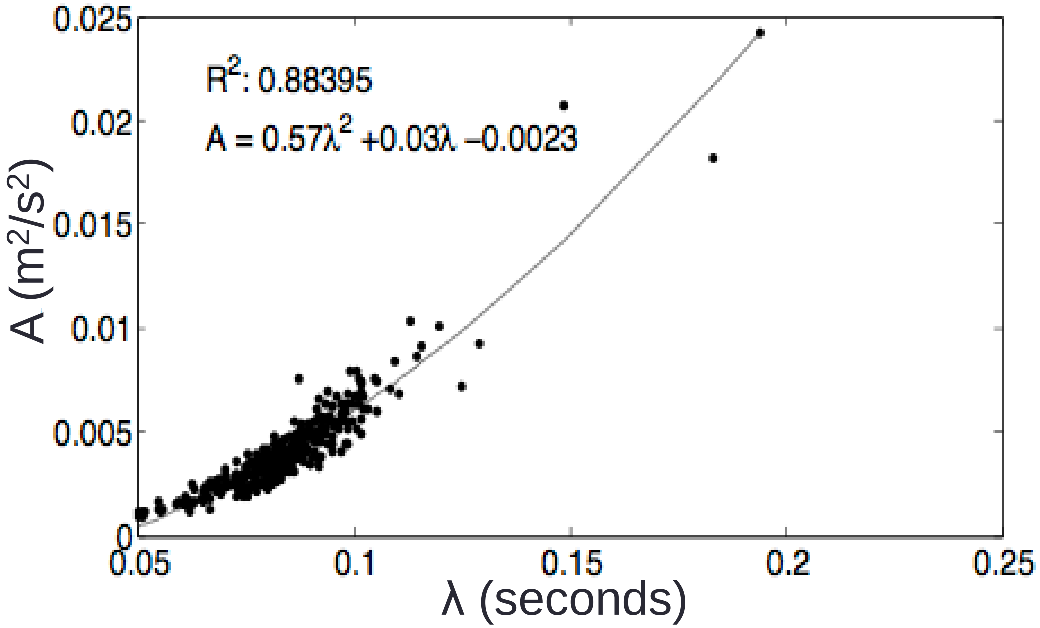

- The anisotropy magnitude, *A*, captures:
  - the behavior of *CTKE*
  - the intermittency in the pdf
  - the shape from the barycentric map
  - the coherence of the correlation function.