Extreme acceleration events:

towards better understanding of wind-driven fatigue & ultimate loads

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Herning, DK

Motivation / justification

- Hiperwind: want extreme loads offshore
- what events drive extreme loads offshore?   (flow / meteorology)
  - long-term statistics of load-driving events
  - allowance for different turbine sizes and control-systems

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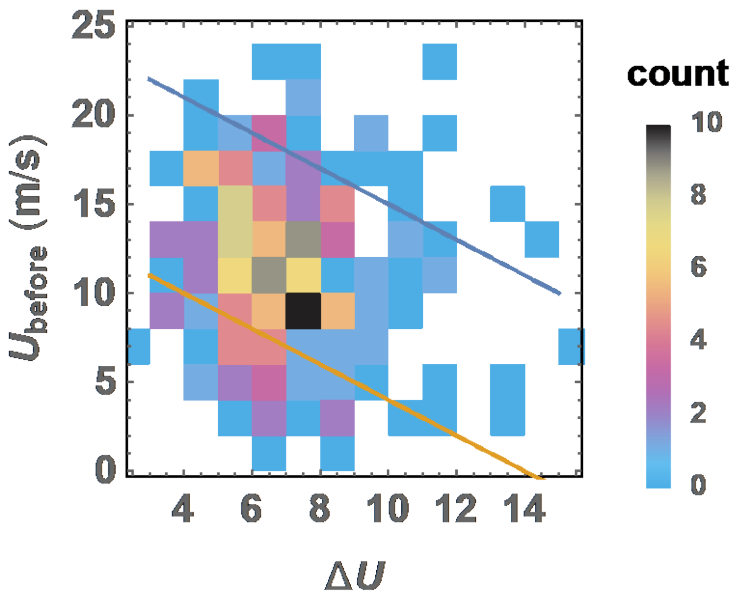
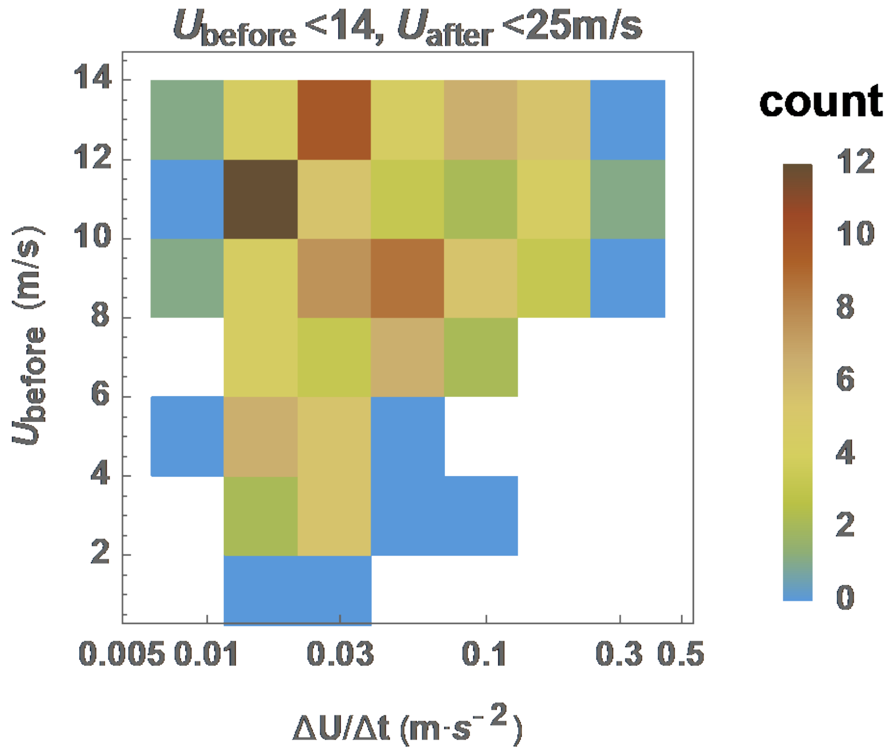
Previously :

- wind speed ramps results (OWA project, 2019, Kelly *et al.* 2021)
  - large features: highest variance >1km
  - most missed by 10-minute stats (need fast data)
  - persist throughout wind farm
  - large increase in thrust-based loads

background / previous results

- offshore wind ramps through farms (Kelly *et al.* 2021)
  - statistical climatology: $P\left(\Delta U, \Delta t, \frac{\Delta U}{\Delta t}, \frac{\Delta U}{\Delta z}\right)$
  - effect on loads, via coupled Mann-model+LES+Flex5
    - » flap-wise, tower-base (3% per 0.1 m/s^2)





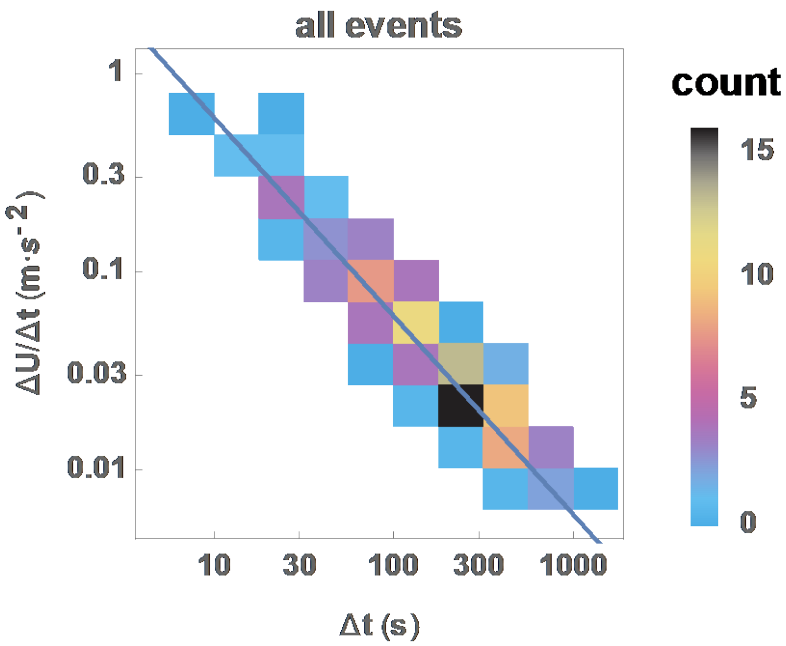
Beyond ramps

- Find load-inducing flow perturbations
  - "fast data" (10Hz, 20Hz)
  - lighting mast: heights 100–160 m $(z > h_{\mathrm{IBL}})$
- Calculate ***accelerations***
  - streamwise & crosswind/direction
  - in Fourier space (finite-difference not enough)
  - appropriate filtering
    - Low-pass: consider turbine response
      - » O(2) Butterworth
      - » $f_c = (30s)^{-1}, (10s)^{-1}, (3s)^{-1}$

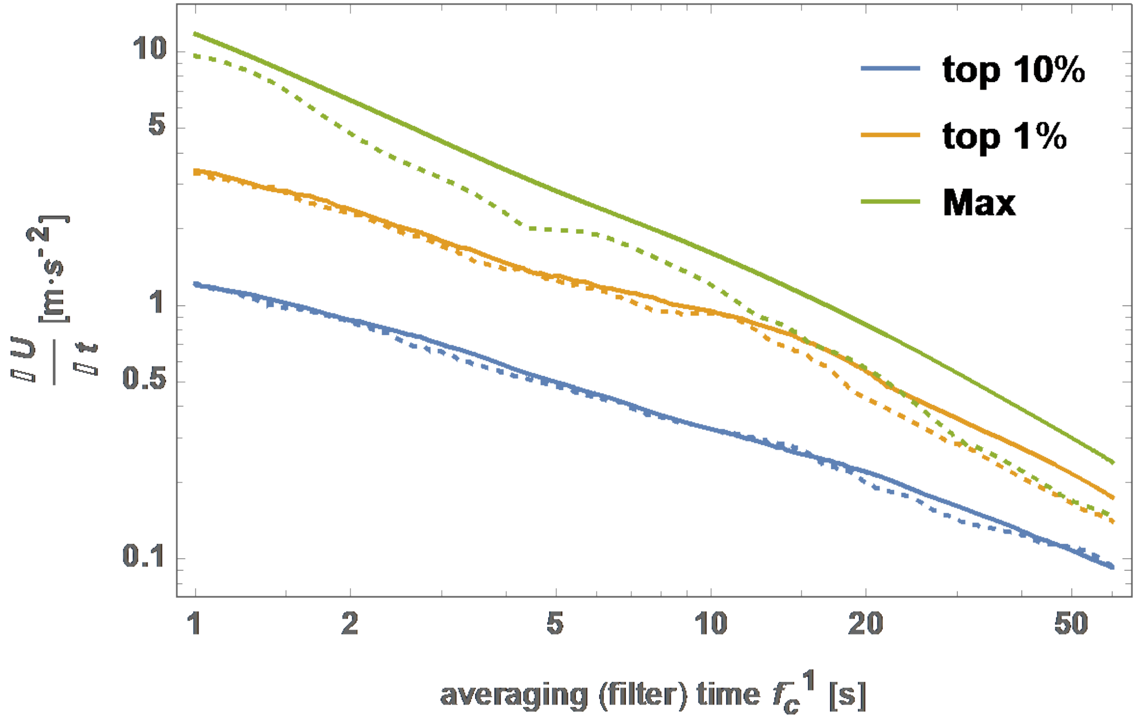
(ramp detection had HP/LP $k_c^{-1} = 2$ km)

(filtered) wind accelerations

- filtering is essential



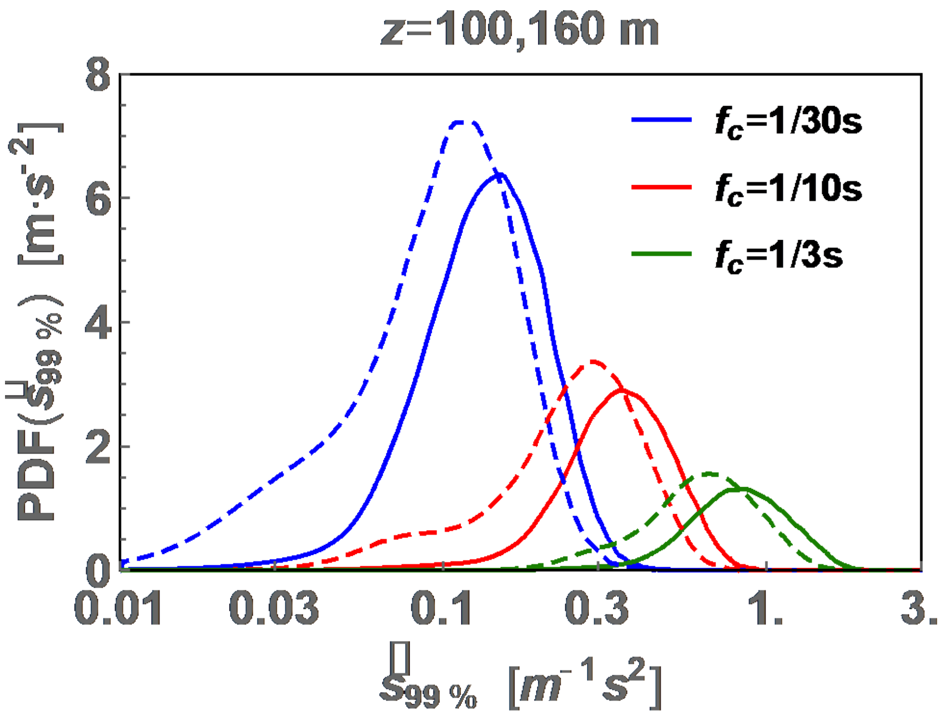
OWA: all ramps



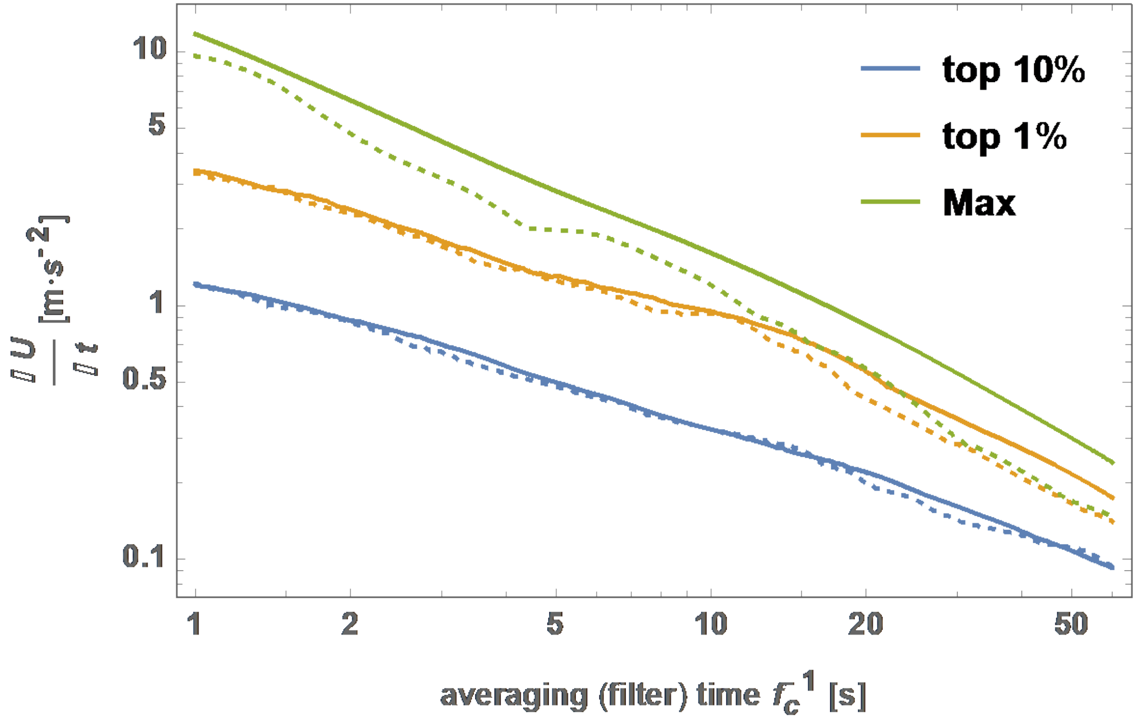
now: a strong 10-minute period

(filtered) wind accelerations

- filtering is essential



top dS/dt from all data



now: a strong 10-minute period

can we guess du/dt stats from 10-min. obs.?

streamwise (or horizontal):

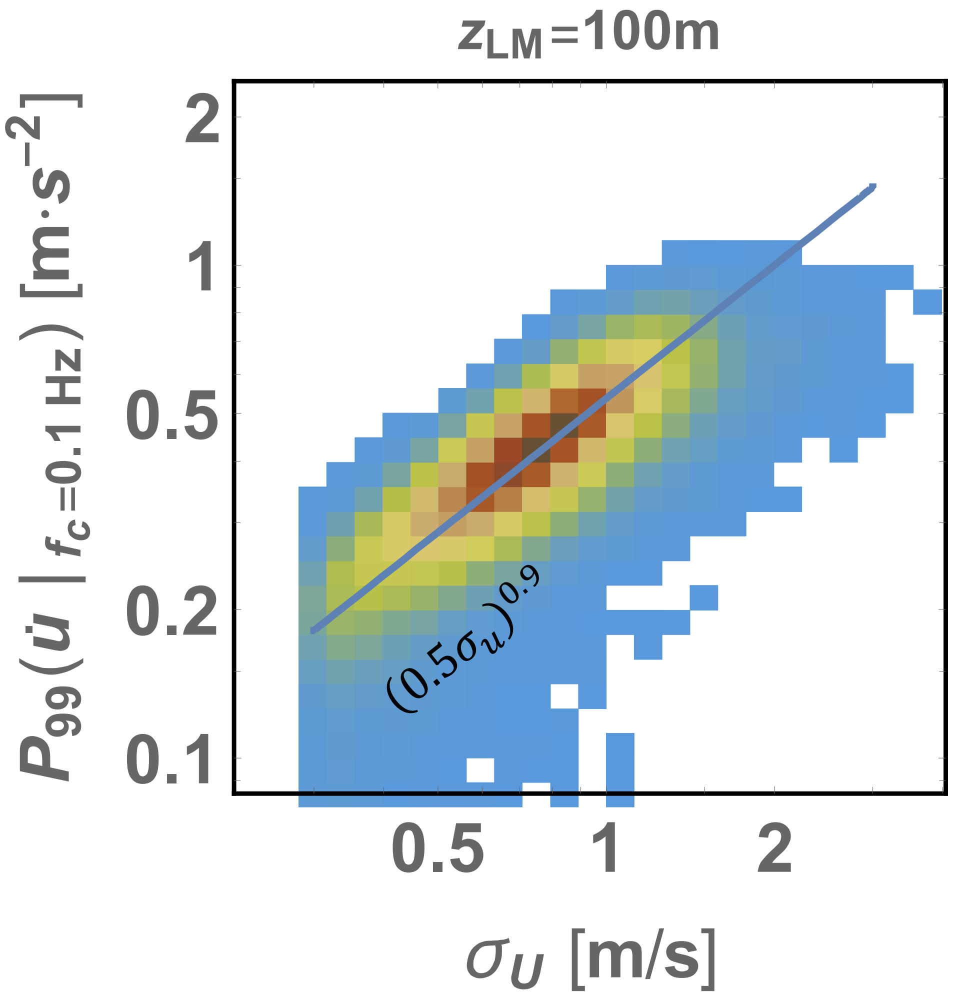
significant a_u at sub-meso scales (<~3km)

- most common Max{a_u}: YES
  - a_u maxima follow σ_u
- extreme Max{a_u} : NO
  - extreme {a_u , σ_u} <u>not correlated</u>
    - » (though at larger σ_u)

shown: filter O(2) BW, $f_c = 0.1$ Hz

– can "slide" plot up/down

per turbine response/filter

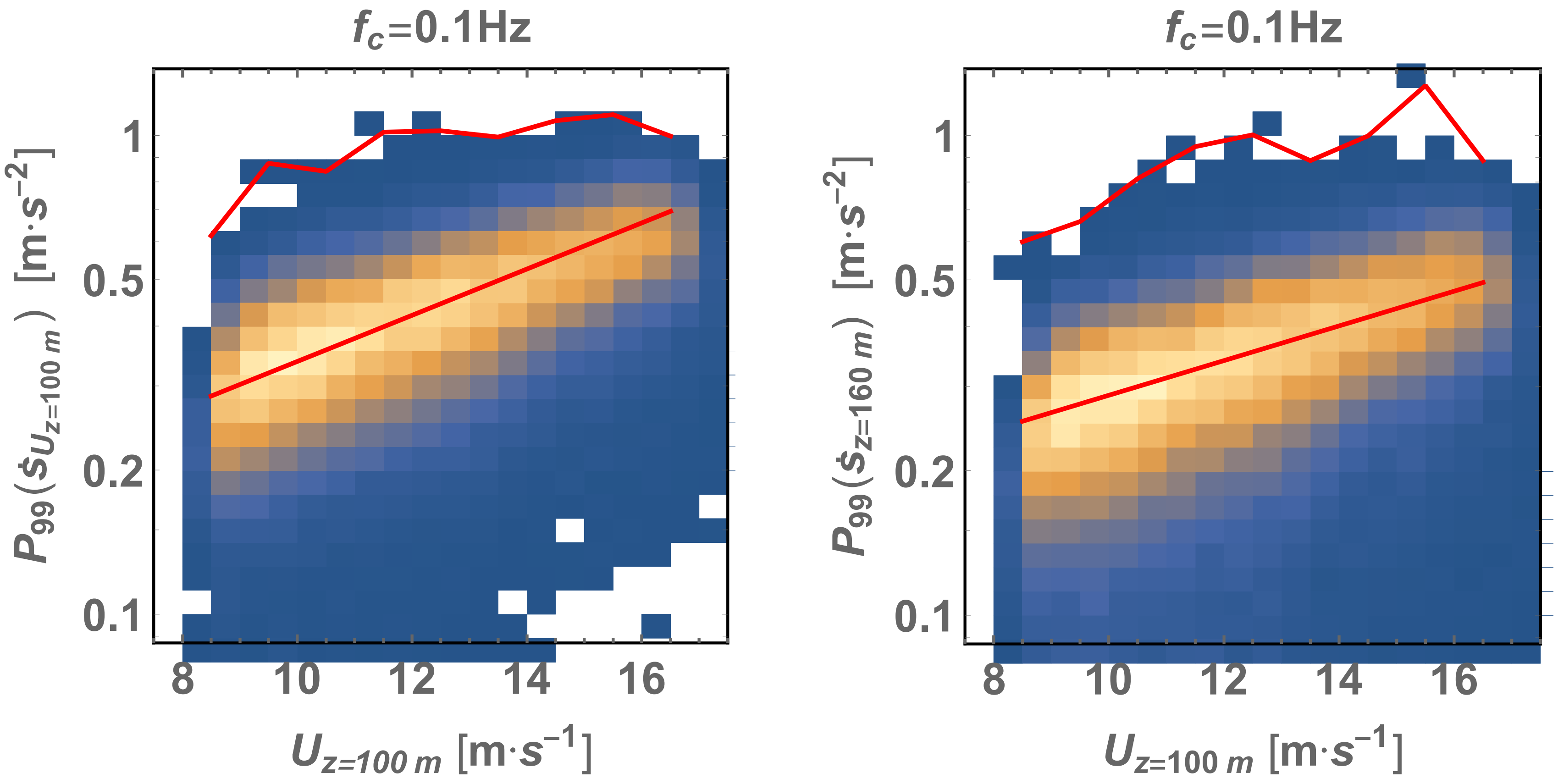


speed dependence of 10-min. max[ds/dt] ?

- most common $\dot{s}_{\max} \propto U$
- extremes ~ independent of *U*

- many extremes cross typical V_{rated}

  → larger loads!



extreme events

$u(t)$ at 100m, 160m for

- largest du/dt at z=100 m
  - per wind speed bin (1 m/s)
- LP-filter/response: 10 s

(red, green: u_{100}, u_{160})

(blue, gold: s_{100}, s_{160})

extreme events

$u(t)$ at 100m, 160m for

- largest du/dt at z=100 m
  - per wind speed bin (1 m/s)
- LP-filter/response: 10 s

(red, green: u_{100}, u_{160})

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extreme events

$u(t)$ at 100m, 160m for

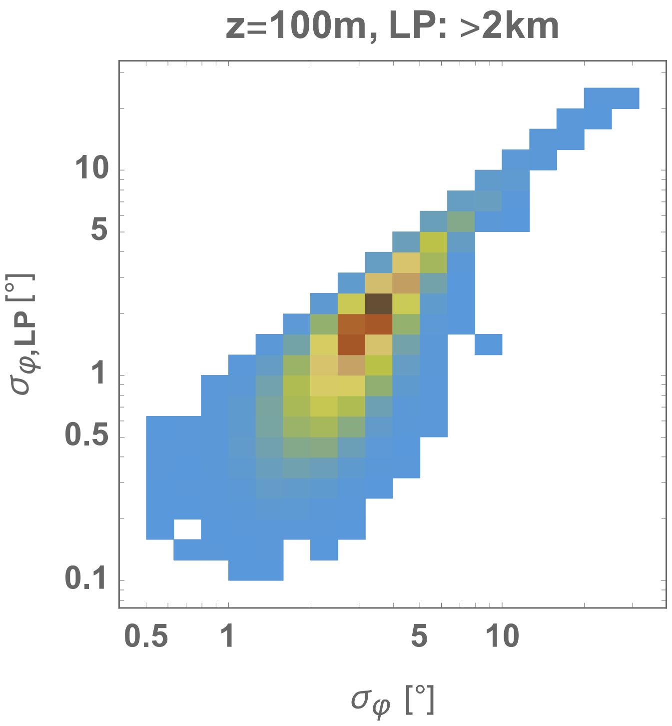
- largest du/dt at z=**160** m
  - per wind speed bin (1 m/s)
- LP-filter/response: 10 s

(red, green: u_{100}, u_{160})

(blue, gold: s_{100}, s_{160})

lateral / directional accelerations

- biggest lateral variability due to large-scale (>2km) motions
  - mostly frontal passages (different propagation angles)
  - check individual events against WRF, etc.



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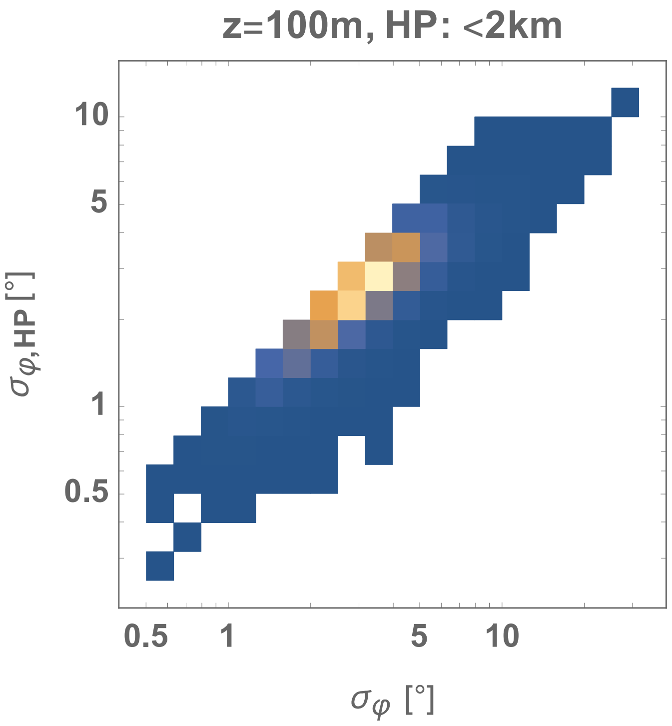
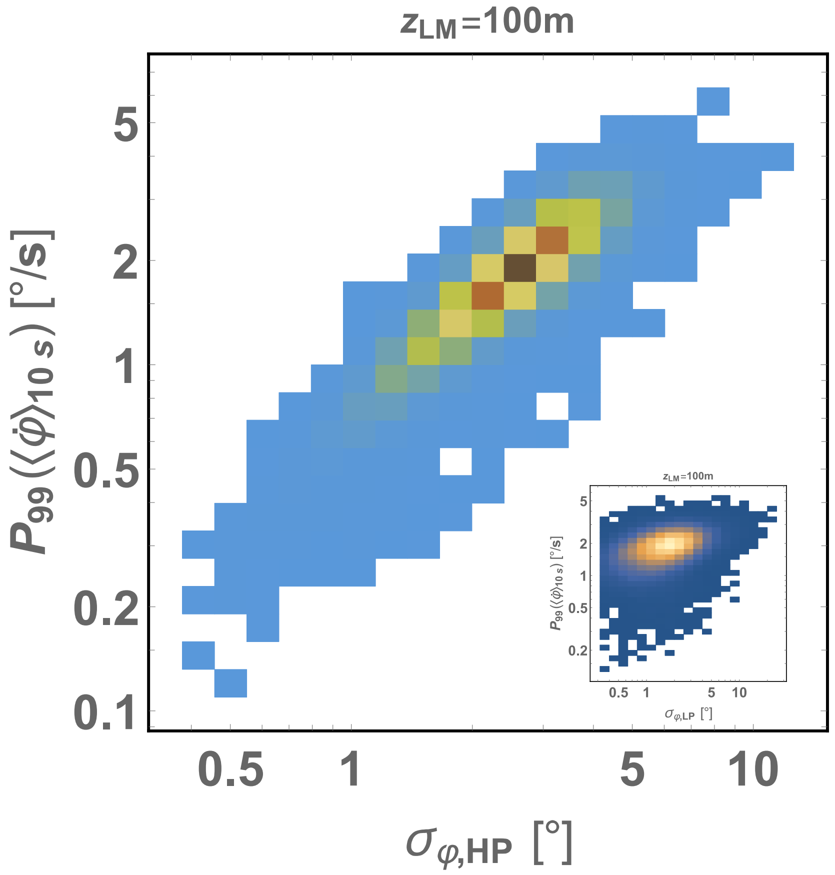
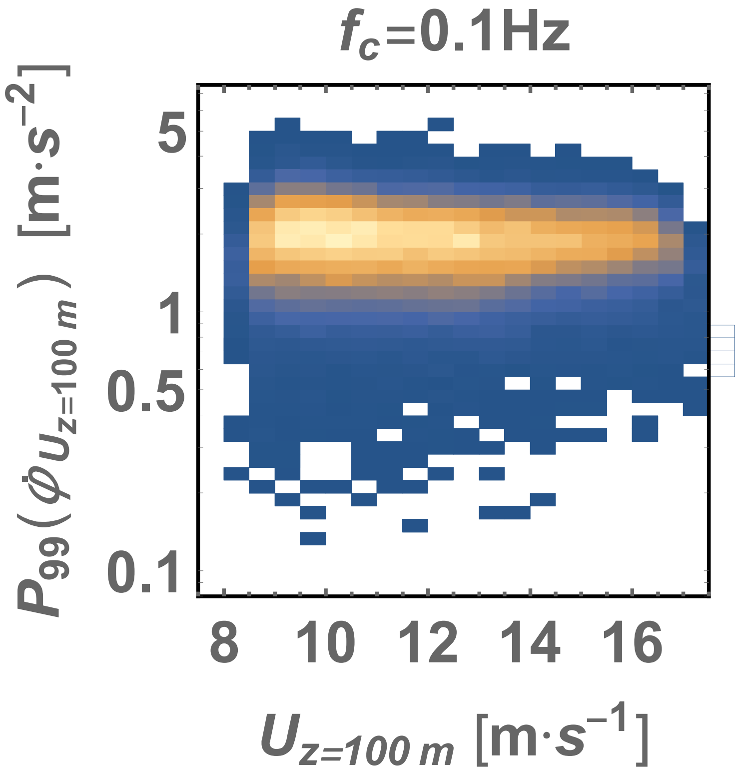


lateral / directional accelerations

- biggest lateral variability due to low-frequency motions (fronts)
  – but <2km (HP) stats are better for common/fatigue-inducing
- similar relation between $\{\dot{\varphi}, \sigma_\varphi\}$ as for $\{\dot{u}, \sigma_u\}$ → but no U-dependence



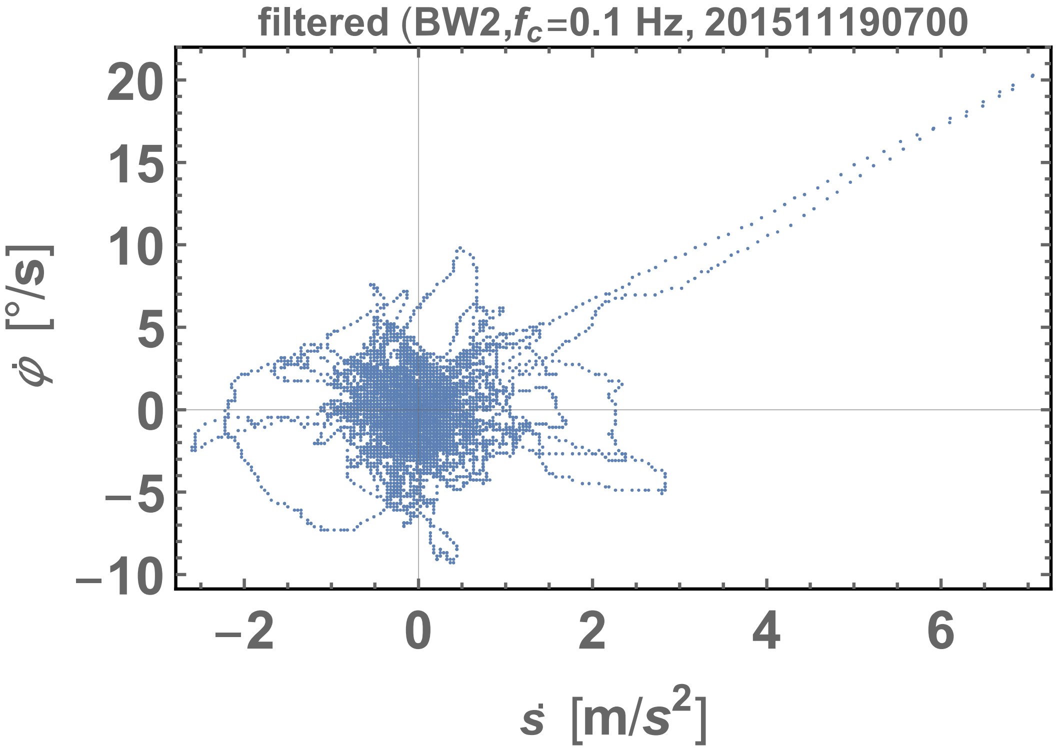
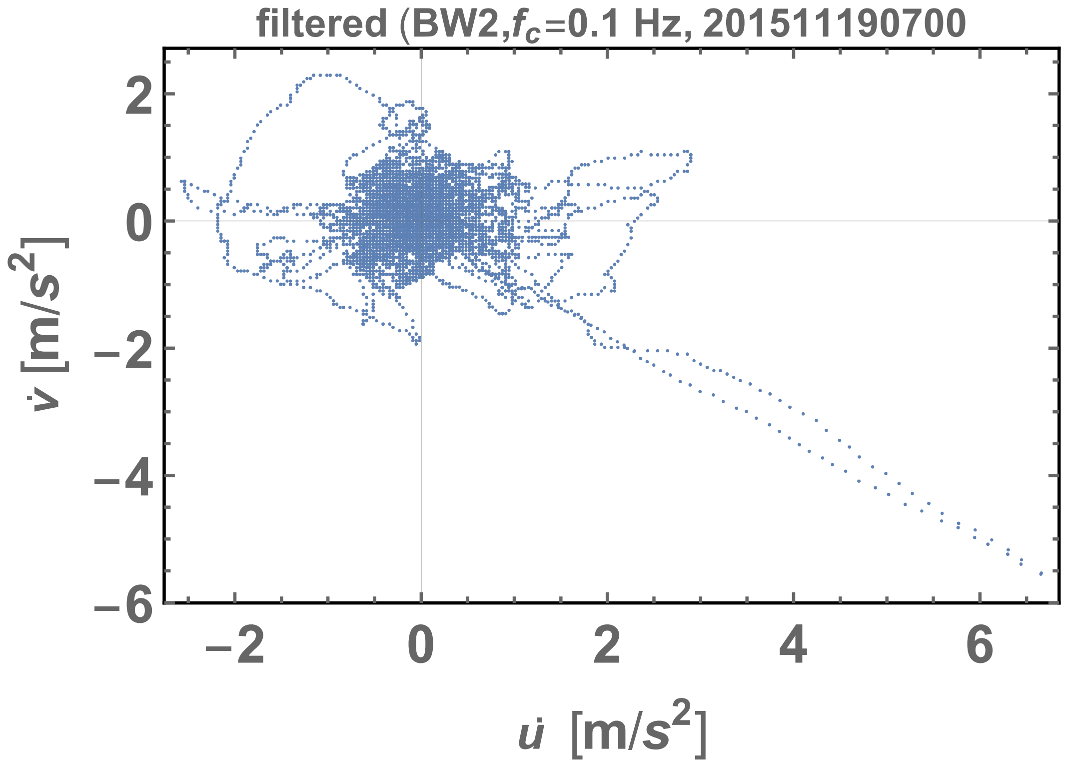


extreme events

$\varphi_{100}(t)$, $\varphi_{160}(t)$ for

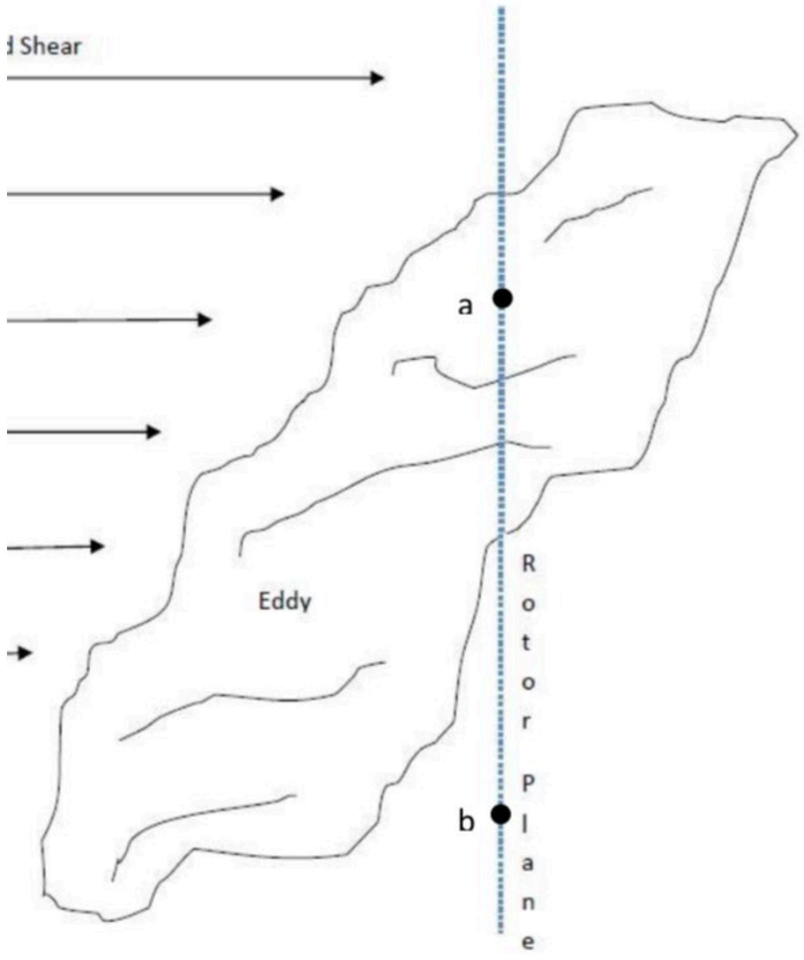
- largest $d\varphi_{100}/dt$ (solid)
- also $d\varphi_{160}/dt$ (dashed)
  - per wind speed bin (1 m/s)
- LP-filter/response: 10 s

‘anatomy’ of an event

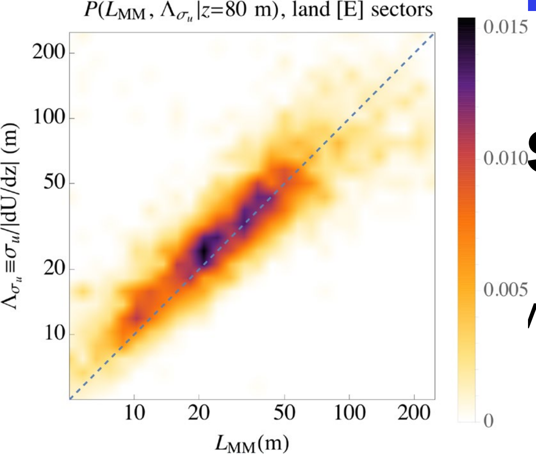
- accelerations:
  (directional vs. horizontal  , or lateral vs. streamwise component) 

scale information…

- associated L_z ?
- correlation across rotor
- ‘lag’ in time



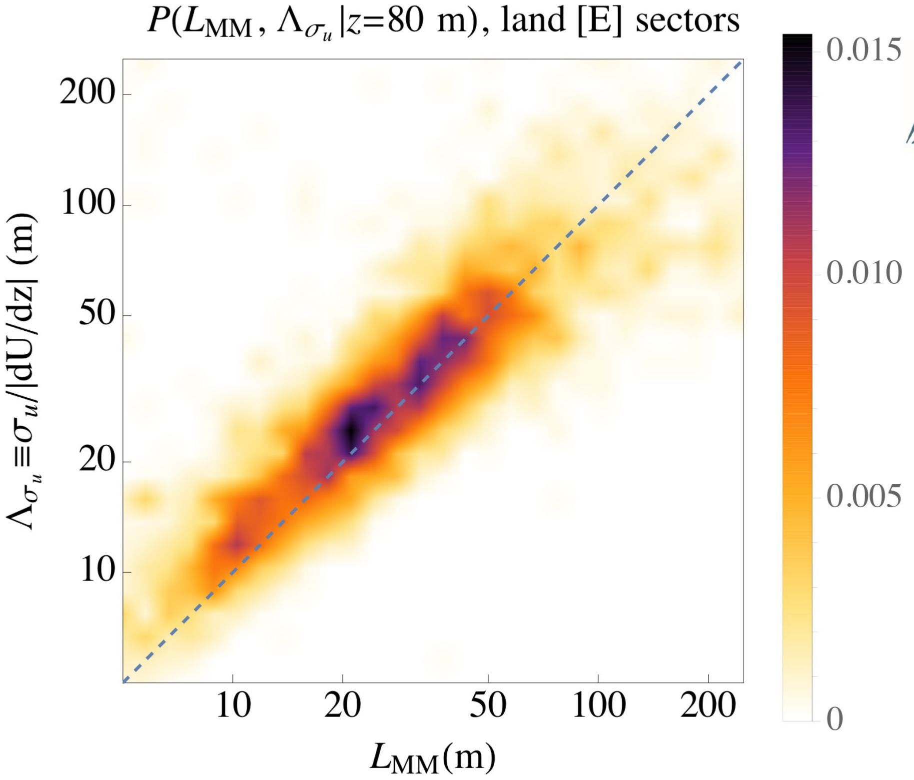
from Chougule *et al.*, 2014



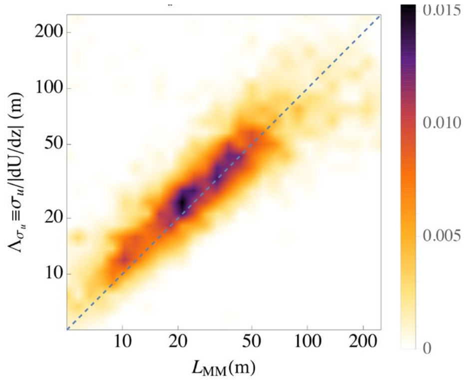
scale info in practice

/e cup anemometers (not 3-d)

8): $L = \dfrac{\sigma_u}{\Delta U/\Delta z}$



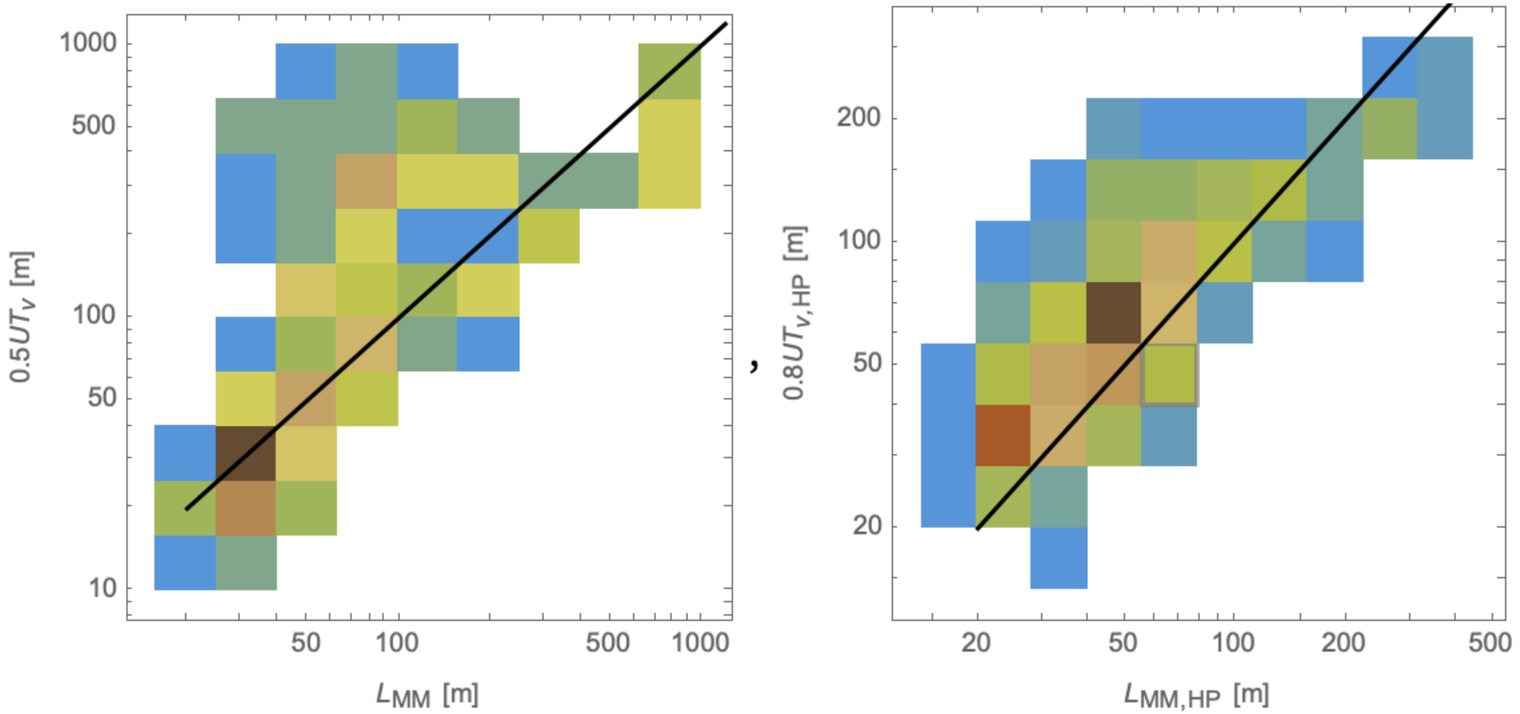
getting scale info in practice



- typically have cup anemometers (not 3-d)
  - Kelly (2018): $L = \dfrac{\sigma_u}{\Delta U/\Delta z}$

- what about extreme events?
  - many extremes have “ambiguous” L
    - » event-scale
    - » background

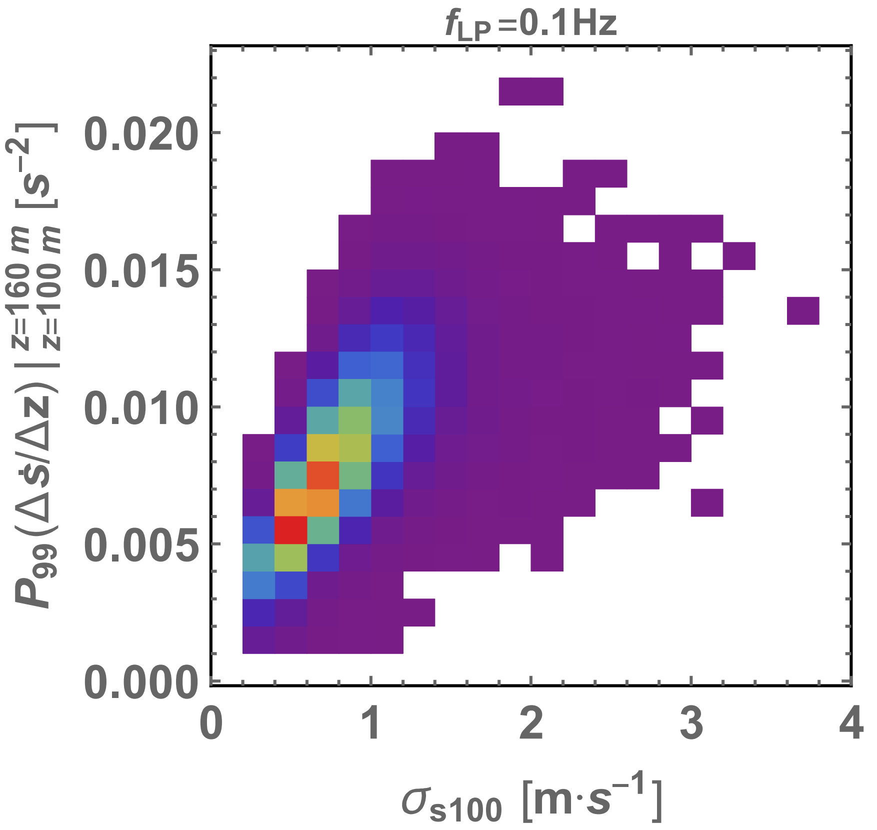
→ use integral time scales & Taylor’s hyp.



direct: implicit scale info

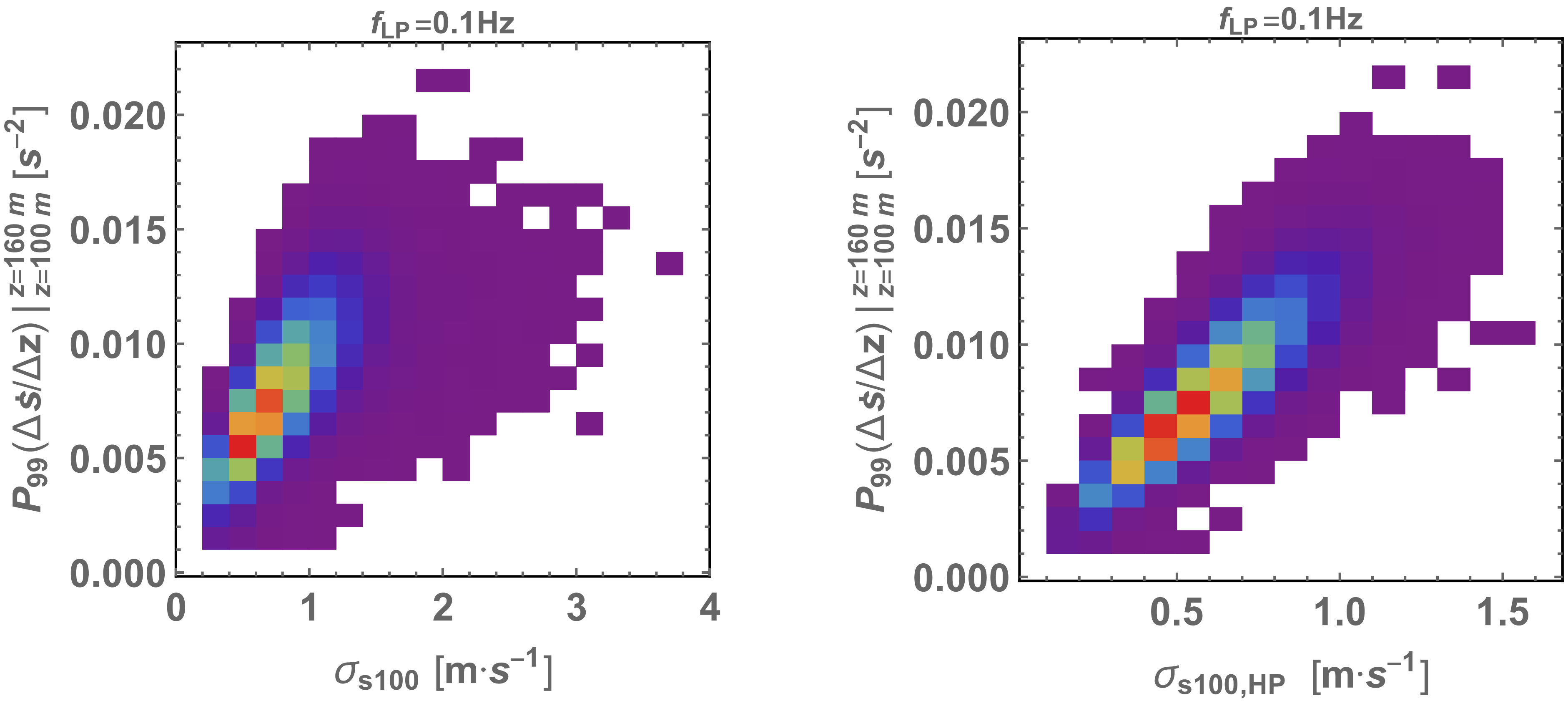
- can we use typical stats?

- direct: $\Delta\dot{s}/\Delta z$



direct: implicit scale info

- can we use typical stats? → yes (common/fatigue), IF we use only sub-meso part
- direct: $\Delta\dot{s}/\Delta z$



Summary & Outlook

- Can exploit universal behavior to find accelerations
  – filter according to turbine response
- typical 10-min. data can give fatigue-inducing accelerations
  – most common ds/dt, dφ/dt : trends with σ_s , S
  – sub-mesoscale statistics work best
- extremes require fast data (unavailable from 10-minute averages)
- big directional changes mostly due to large structures (cold fronts)
- mostly different extreme events, for streamwise and lateral
  – can use speed or streamwise *u* in these cases
- multiple characteristic scales for extreme events
  – 'background' turbulence & coherent event

Outlook / next:

- timeseries + Mann-model parameters for constrained turbulence→loads simulations

Acknowledgements

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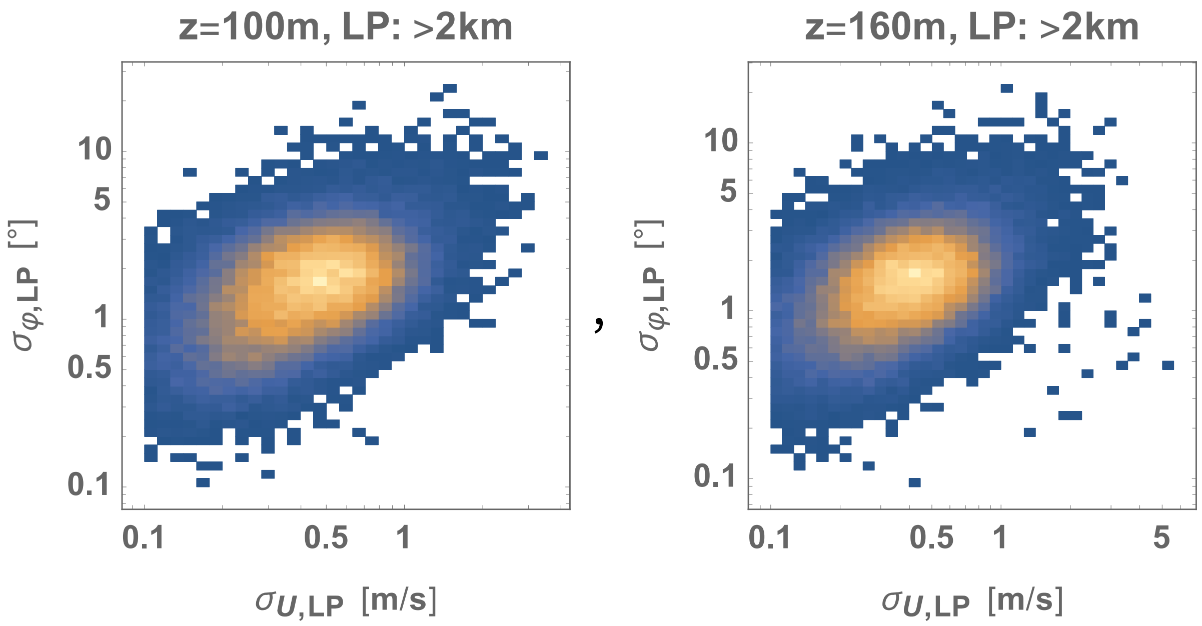
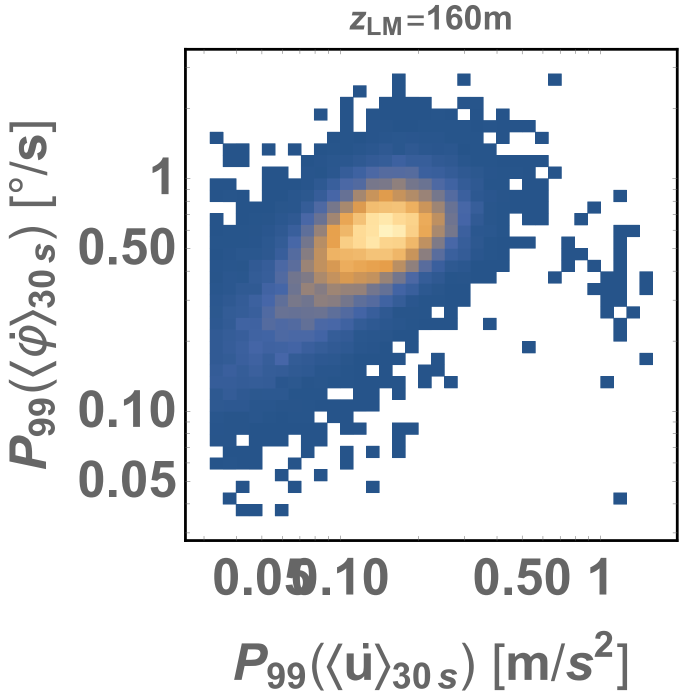
Preliminary results

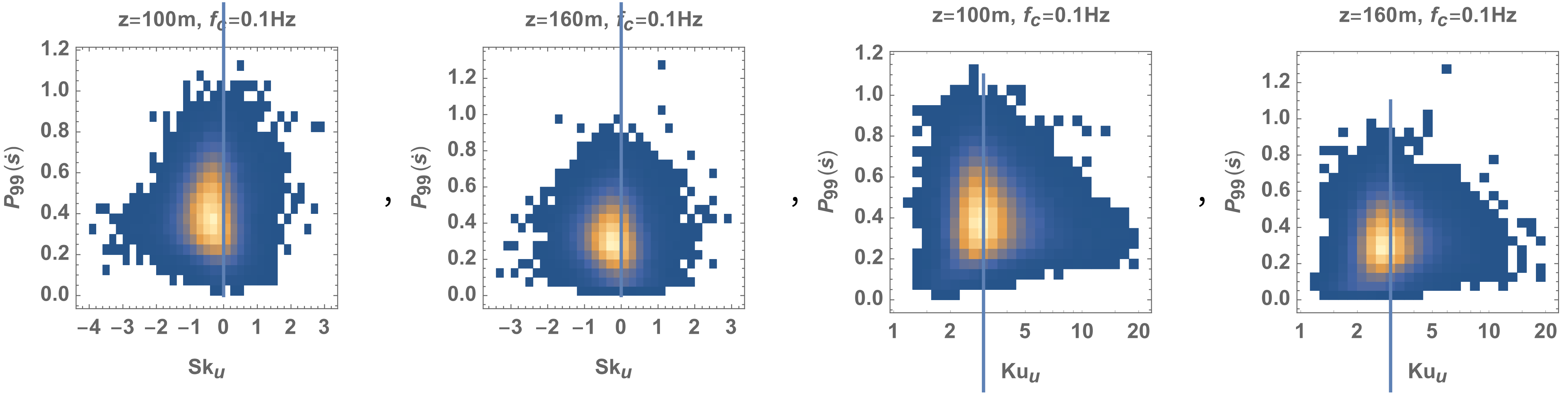
- lateral extremes uncorrelated with streamwise





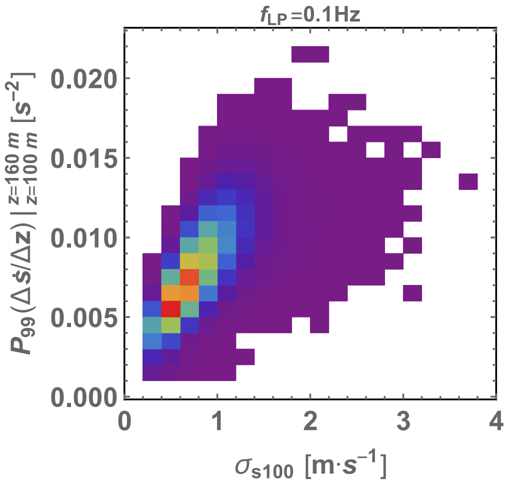
largest accelerations per 10-min:

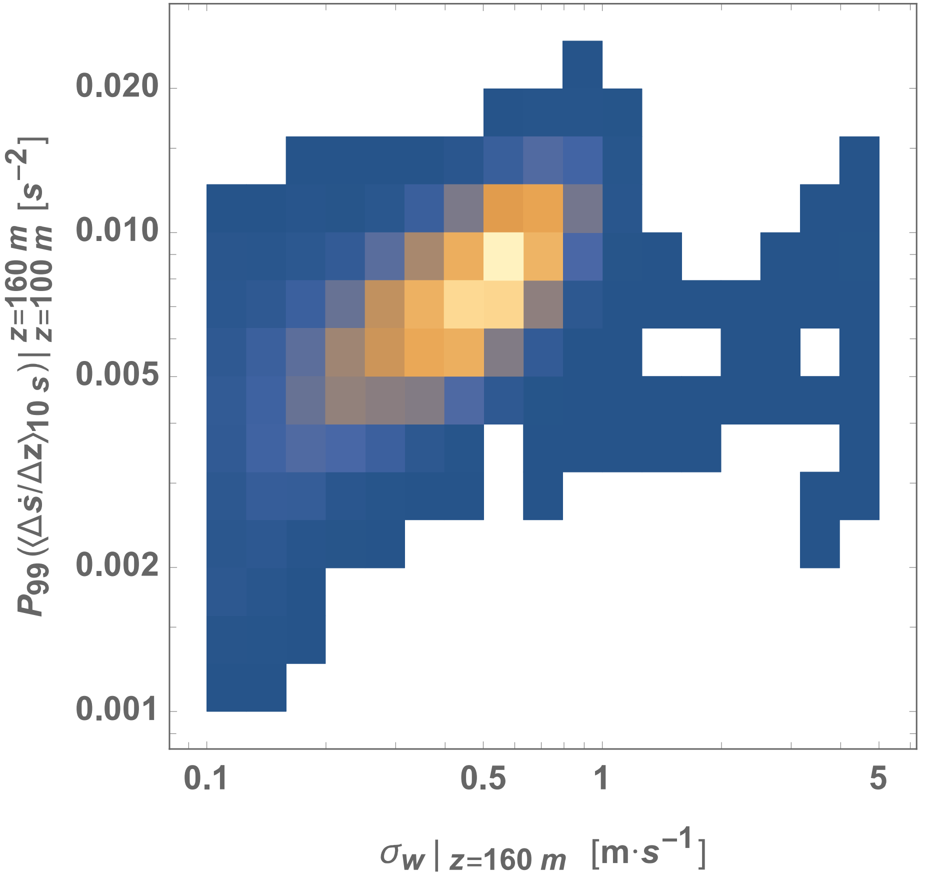
- Gaussian ?
  - Skewness, kurtosis

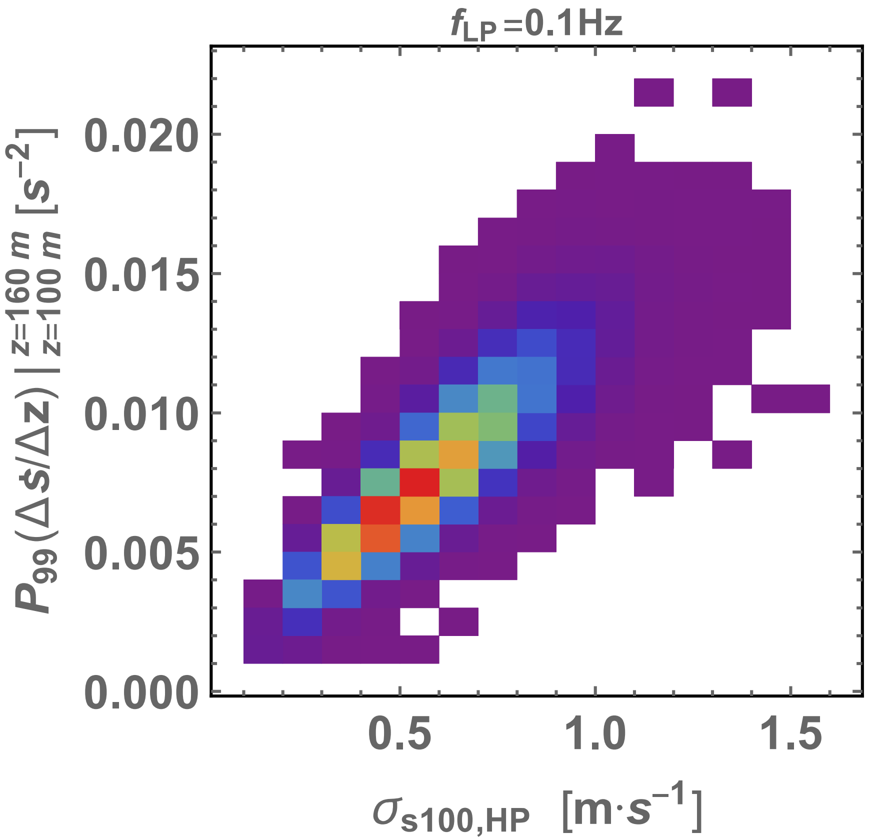


direct: implicit scale info

- can we use typical stats? → yes, IF we use only sub-meso part
- direct: $\Delta\dot{s}/\Delta z$







Site / data

- Høvsøre coastal masts
  - offshore sectors
  - lighting mast: heights 100–160 m $(z > h_{\mathrm{IBL}})$
- “fast data” (10Hz, 20Hz)