Turbulence Modeling in a Numerical Model for Tidal Hydrokinetic Turbine Siting

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Outline

Outline

Tidal Hydrokinetic Energy

Like wind energy

http://windeis.anl.gov/guide/photos/photo7.html

Tidal Hydrokinetic Energy

Like wind energy
... but under water

http://verdantpower.com

Differences between Wind and Tidal Energy

- $P = \frac{1}{2}\rho s^3 A_c$, ρ density, s speed, A_c area
- Wind: $s \approx 7$ m/s; tidal: $s \geq 1$ m/s
- $\rho \approx 1$ kg/m^3 in air and $\rho \approx 1000$ kg/m^3 in water
- Limited space underwater in constricted channels
- Wind turbine has larger cross-sectional area

Tidal Hydrokinetic Energy

Pros:

- Near large population center (in Puget Sound)
- No carbon output
- Predictable
- Potential for low environmental impacts
- No visual impact

Cons:

- Not consistent resource
- Possible effects on marine mammals and fish
- Additional stress on coastal ocean environments

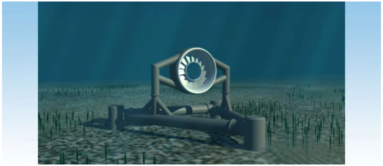
Various Tidal Turbine Designs

Verdant turbine

http://verdantpower.com

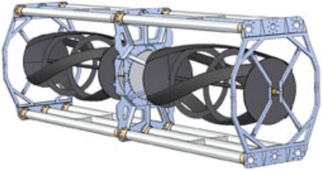
Marine Current Turbines turbine

http://www.marineturbines.com



Open Hydro turbine

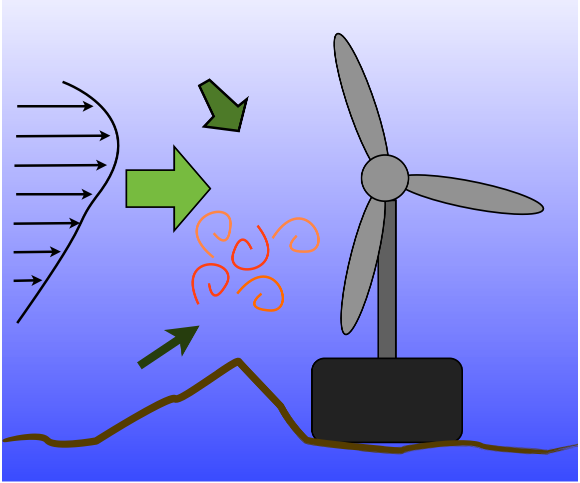
http://www.openhydro.com



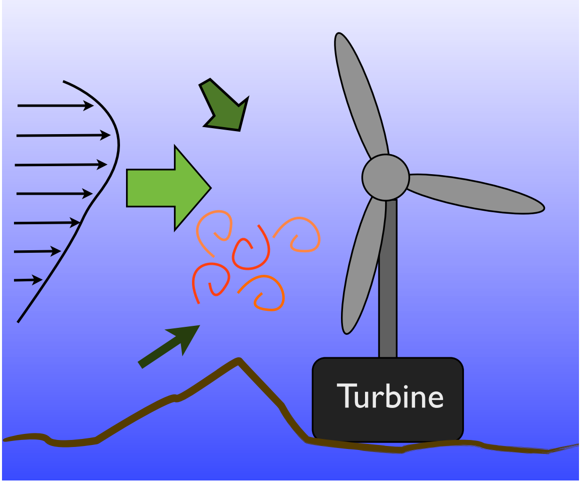
ORPC turbine

http://www.oceanrenewablepower.com/

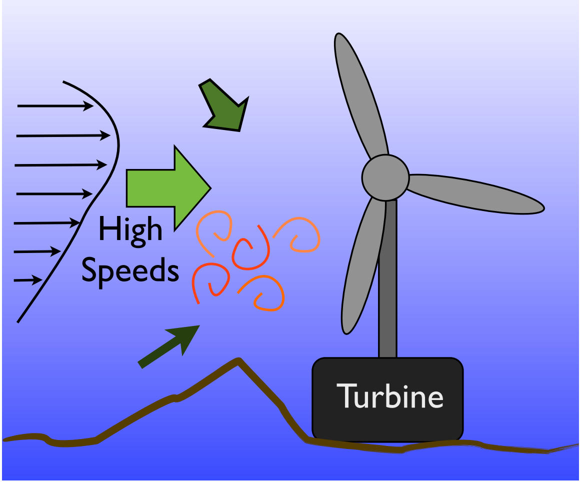
Turbine Siting Considerations



Turbine Siting Considerations



Turbine Siting Considerations



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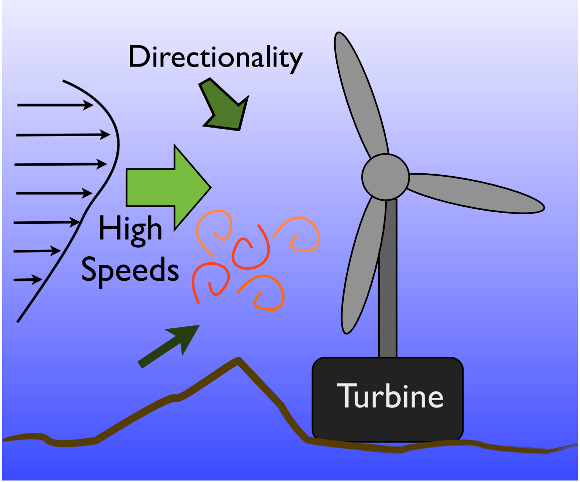
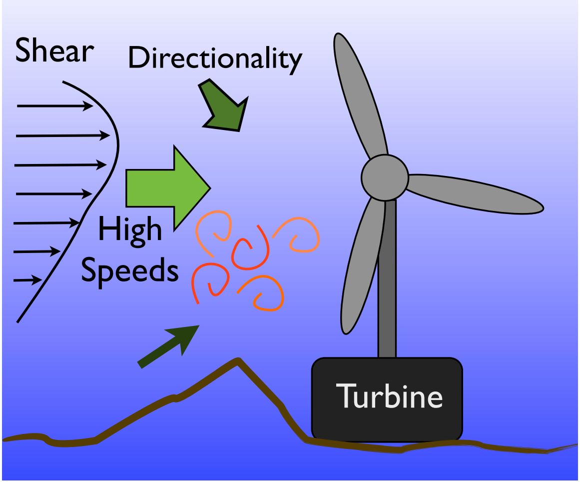
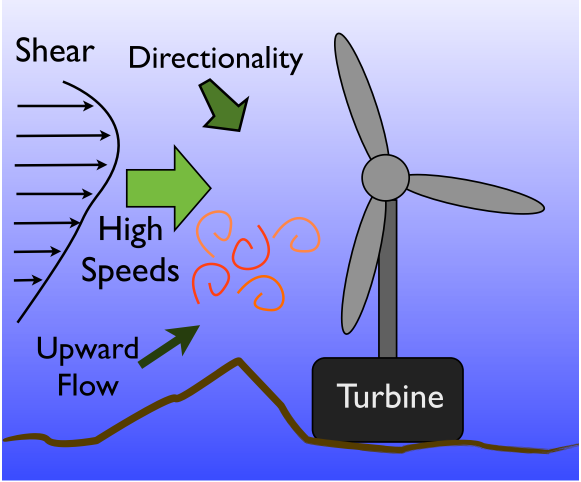


Turbine Siting Considerations



Turbine Siting Considerations



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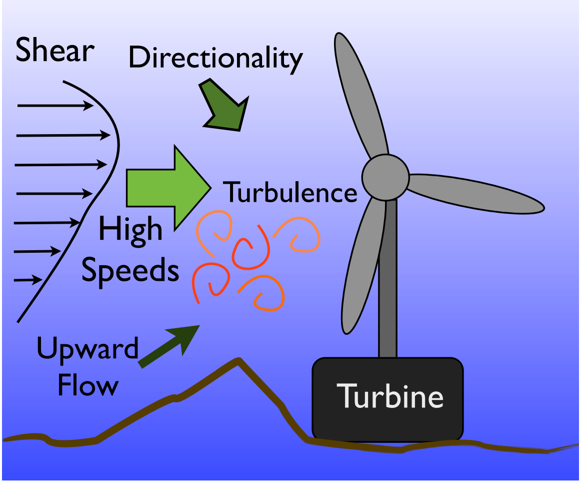
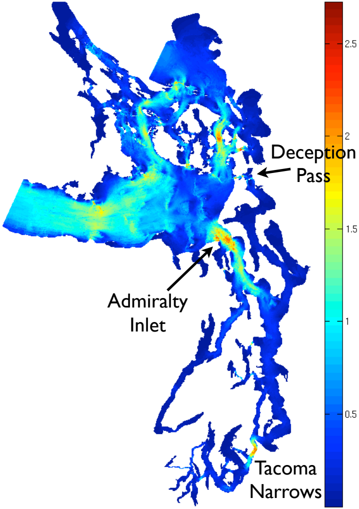
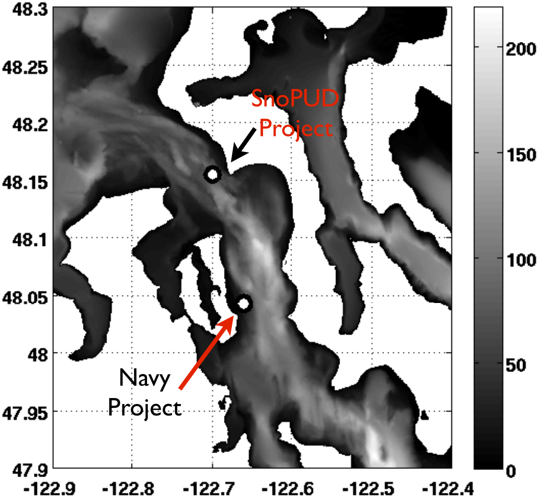


Speeds in Puget Sound



Kawase, M, and K.M Thyng. *IET Renewable Power Generation*, 2010

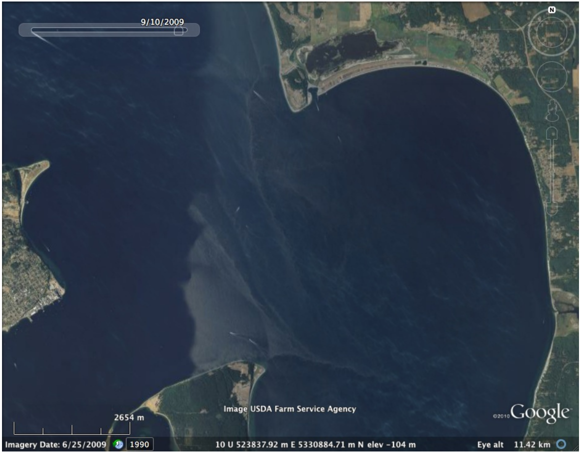
Tidal Projects in the Puget Sound: Admiralty Inlet



Flow Features in Admiralty Inlet: Eddies

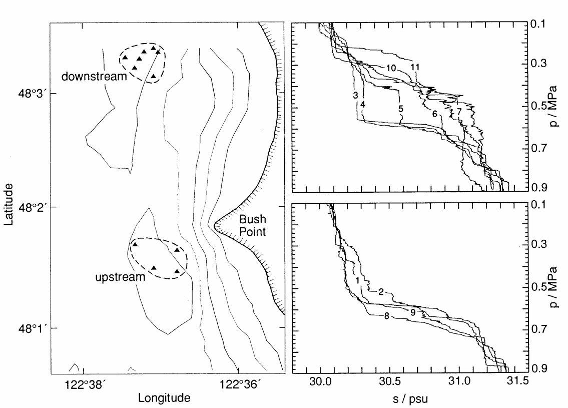
Google Earth

Flow Features in Admiralty Inlet: Fronts



Google Earth

Flow Features in Admiralty Inlet: Hydraulic Control



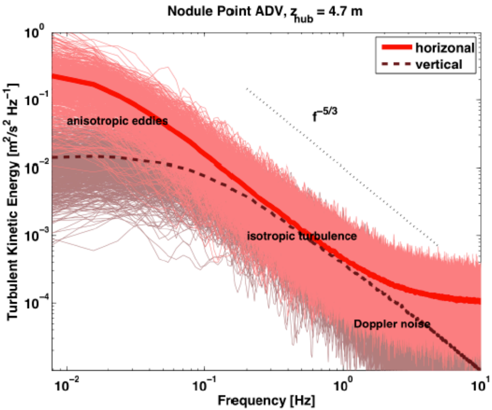
Harvey Seim's thesis at UW, 1993

Flow Features in Admiralty Inlet

- Turbulent kinetic energy (TKE) is present in these features
- A metric used by turbine developers regarding level of TKE is called *turbulent intensity:* $I = \frac{\sqrt{<u'^2>}}{\bar{u}}$
- Use numerical model to see features
- How well does model simulate TKE?

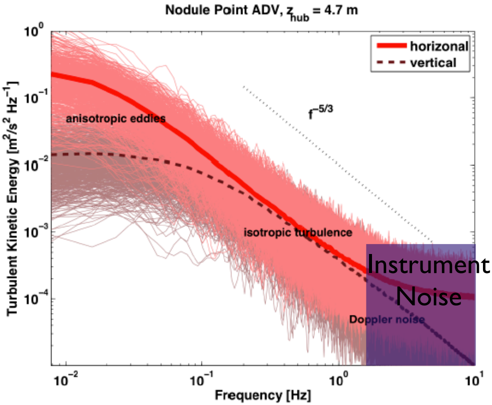
Outline

Data TKE Spectrum



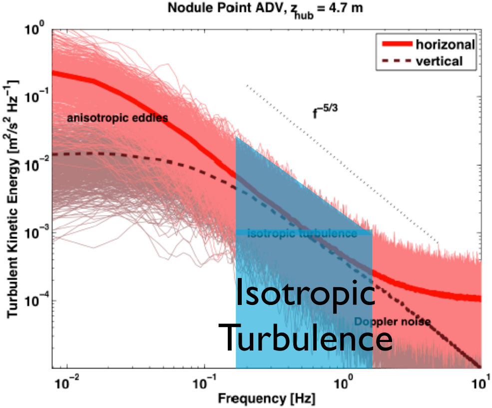
- Frequencies are above cut-off for turbulent averaging time (5 minutes)
- Spectrum follows Kolmogorov's $f^{-5/3}$ relationship

Data TKE Spectrum



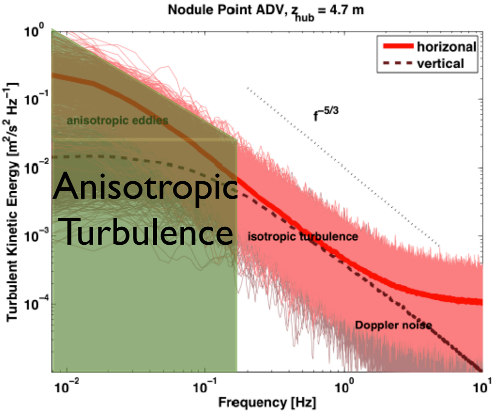
- Data diverges from $f^{-5/3}$ at high frequencies due to instrument noise

Data TKE Spectrum



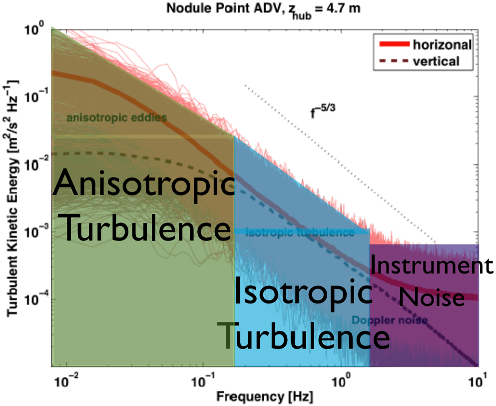
- Classical turbulence assumes all 3 directions are roughly identical, or isotropic
- $0.2 < f < 2$ Hz

Data TKE Spectrum



- Horizontally dominant; much more energy than classical turbulence
- Includes larger length scales than typical TKE
- $f < 0.1$ Hz

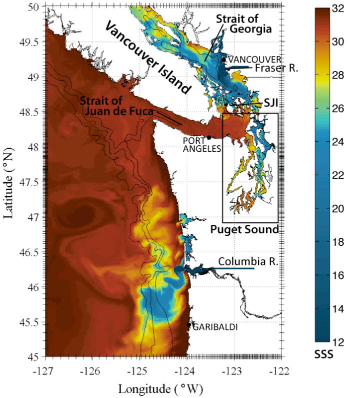
Data TKE Spectrum



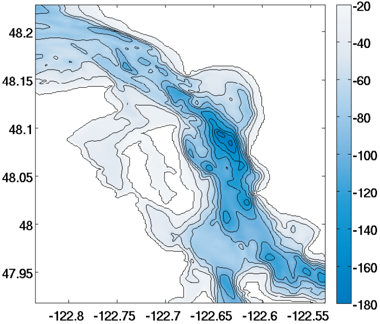
- Length scales included here: $.5, 10 < L < 300$ m
- All potentially matter for turbine performance and fatigue
- This is the range we take for TKE in this application for model too

Outline

Realistic Model Domain



Surface salinity of regional model

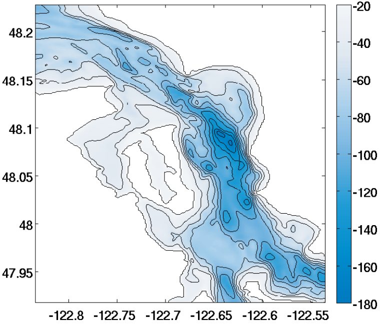


Bathymetry of nested model of Admiralty Inlet.

http://faculty.washington.edu/pmacc/MoSSea
D. Sutherland, *J. Phys. Ocean*, 2011

Realistic Model Domain

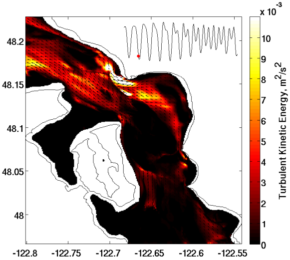
- Run in ROMS: hydrostatic, 3D, parallelized, large user community
- Horizontal resolution of 65 meters
- 20 vertical layers
- $k - \epsilon$ turbulence closure scheme
- Boundary and initial conditions from regional model



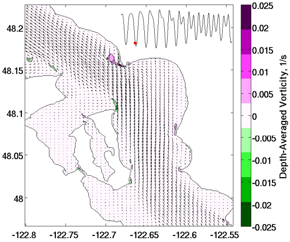
Bathymetry of nested model of Admiralty Inlet.

Surface Speed

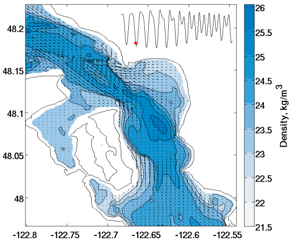
Snapshots



(a) TKE



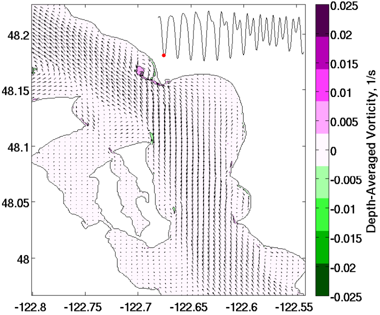
(b) Vorticity



(c) Density

Surface Vortex

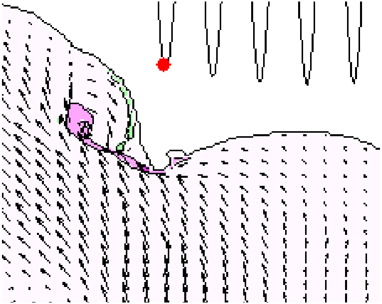
Google Earth



Vorticity Snapshot

Surface Vortex

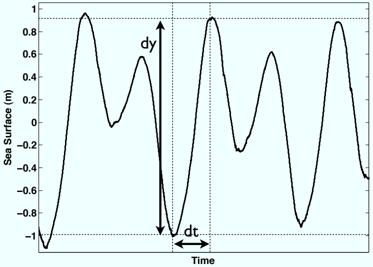
Google Earth



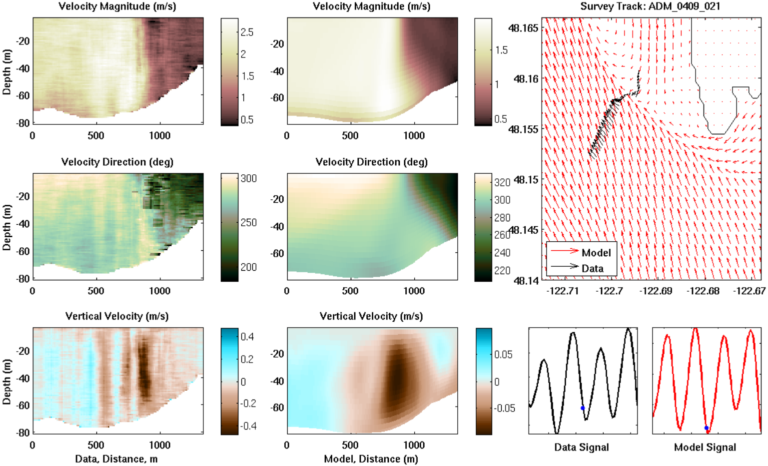
Vorticity Snapshot

How to Compare Non-Coincident Time Series

- Compare two sea surface signals at an (x, y) location
- Want consecutive tidal half-cycles that are close to each other in range and duration

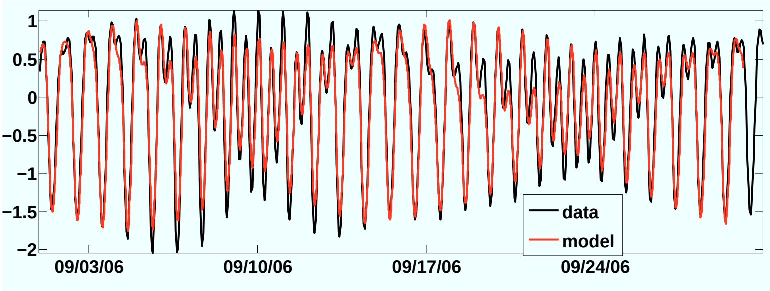


Vortex in Depth: OTS Data



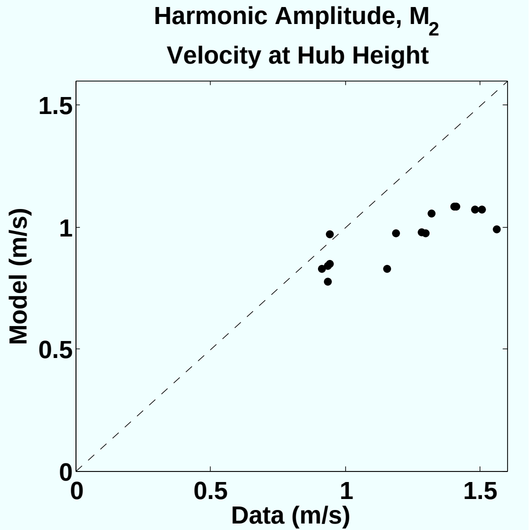
Free Surface

Free surface comparison with NOAA tide gauge station



Similar behavior as in regional model

Velocities

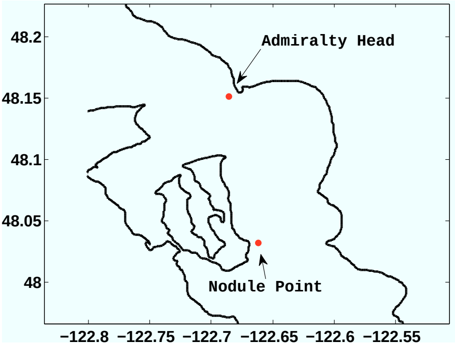


Similar behavior as in regional model

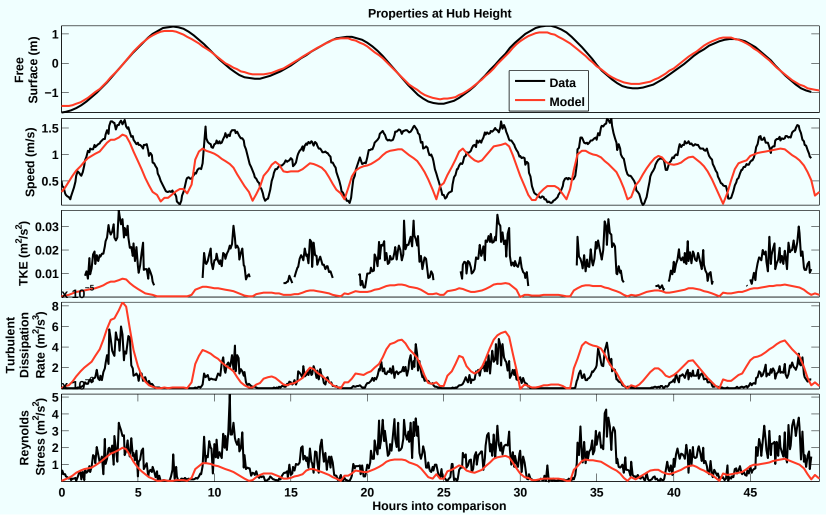
Turbulence Data Comparison Locations

High quality field data set:

- Multiple instruments (ADV, ADCP, AWACs) were deployed at two locations
- Focus of data collection was on high frequencies for turbulence calculations
- Data has been corrected for Doppler noise and analyzed
- All data from J. Thomson et al, *J. Ocean Eng*, submitted

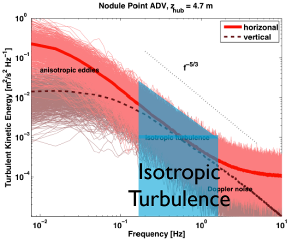


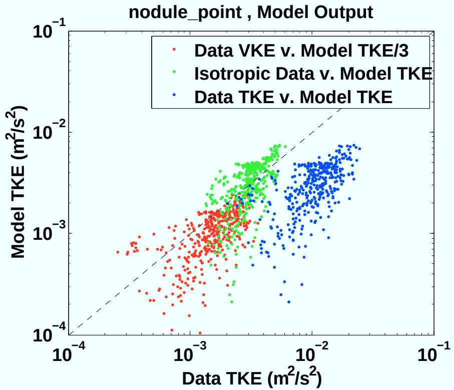
Initial Data-Model Comparison: Nodule Point



Decent matching - except in TKE

Model TKE is Classical Turbulence Only



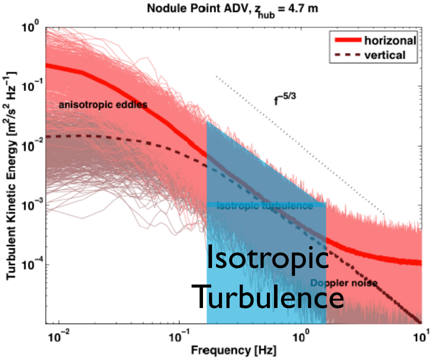


- Full TKE data is much larger than model TKE
- Model TKE matches isotropic data TKE well
- 1/3 model TKE (vertical TKE) matches vertical TKE data well

Outline

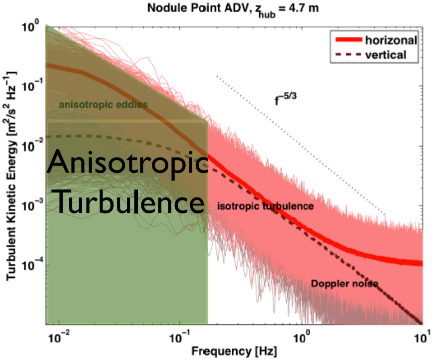
Approximate TKE Spectrum Given Data Behavior

- Kolmogorov approximation holds typically in classical turbulence range



Approximate TKE Spectrum Given Data Behavior

- Appears to hold in lower frequency range as well

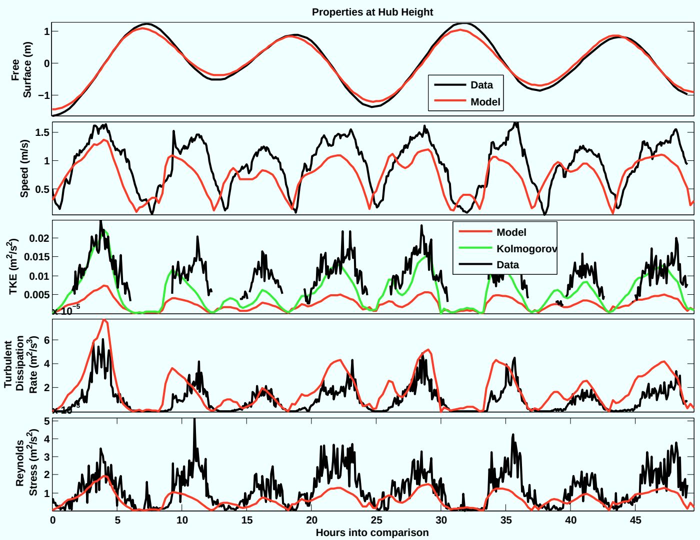


Kolmogorov Approximation of TKE

- Kolmogorov approximation in isotropic range:
  $TKE(k) = \alpha\epsilon^{2/3}k^{-5/3}$, k is wavenumber
- This appears to hold over a wide range of frequencies in data
- Using Taylor's frozen field assumption: $L = u/f$
- k in terms of frequency: $k = 2\pi f/u$
- After integration over k for the 5-minute averaging range of the data:
  $TKE = C\epsilon^{2/3}u^{2/3}$

$\Rightarrow$ We can approximate the "full" model TKE from the model u and ϵ using the observed data behavior

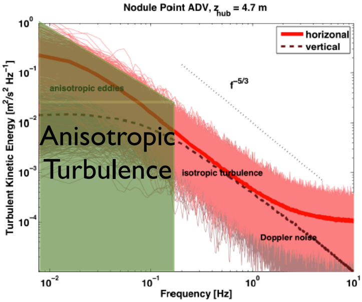
Revised Data-Model Comparison for Kolmogorov



Approximation of Numerical Horizontal Mixing

- Model does isotropic range well
- But most energy is in larger length scales
- Can we account for energy lost this way with effective numerical mixing present in the discretized equations?

⇒ Look at discretization errors in advection of horizontal momentum



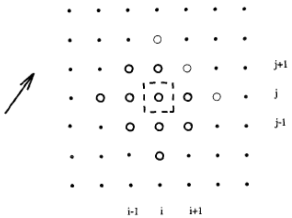
Truncation Error Analysis

- When a physical equation, $\mathcal{F}$, is numerically discretized as F, errors are introduced: $\mathcal{F} = F + \epsilon$
- To find the form of these errors:
    - $\epsilon = \mathcal{F} - F$
    - Discretized terms will have forms like $\frac{1}{2h}(u_{i+1} - u_{i-1})$, where h is the grid spacing
    - Use Taylor series to expand around the mean state $u(\bar{x} + h)$
    - *E.g.* $u_{i+1} = u + hu_x + \frac{1}{2}h^2 u_{xx} + \frac{1}{6}h^3 u_{xxx} + \mathcal{O}(h^4)$
- We typically assume that these terms are small

Upstream Scheme for Advection of Momentum

- Used upstream momentum advection scheme
- Based on UTOPIA
- Uses polynomial interpolation assuming an upstream direction to approximate the flux into a grid cell
- Under the best circumstances, this can be a third-order scheme
- Can be as low as first-order.

P.J. Rasch, *Mon. Weather Rev.*, 1994.



Scheme uses information at bold nodes for the indicated flow direction. From Rasch 1994.

Form for Truncation Error in Energy Form

$$\epsilon = -\frac{h}{4}\left(\left(u^2 v\right)_y + \left(u u_y v\right)_y - \left(u_y\right)^2 v + u u_y v_y\right) + \mathcal{O}(h^2)$$

Form for Truncation Error in Energy Form

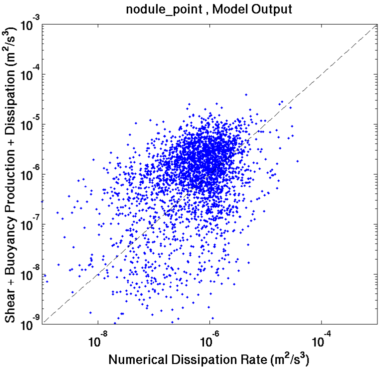
$$\epsilon = -\frac{h}{4}\left(\left(u^2 v\right)_y + \left(u u_y v\right)_y - \left(u_y\right)^2 v + u u_y v_y\right) + \mathcal{O}(h^2)$$

Conservative terms: can be ignored since they just move the flow around without dissipating it

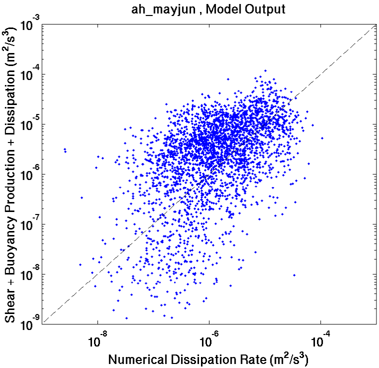
Form for Truncation Error in Energy Form

$$\epsilon = -\frac{h}{4}\left(\left(u^2 v\right)_y + \left(u u_y v\right)_y - \left(u_y\right)^2 v + u u_y v_y\right) + \mathcal{O}(h^2)$$

Size of Numerical Dissipation Rate



(d) Nodule Point



(e) Admiralty Head

Numerical Horizontal Mixing

- Horizontal dissipation rate is same order of magnitude as other turbulence terms
- Next: find contribution to TKE from this mixing

Outline

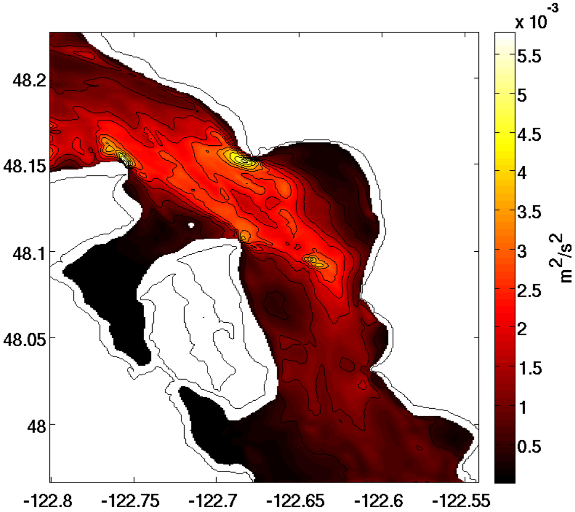
Summary

- Using a numerical model in ROMS of Admiralty Inlet for tidal turbine siting
- Model performs well in many areas, but the "full" TKE is not well-represented by model TKE
- Examined two possible ways of improving this field
    - Approximate numerical horizontal mixing due to truncation error in the discretized equations for momentum advection
    - Extend Kolmogorov's $f^{-5/3}$ relationship beyond isotropic, high frequency range to lower frequencies, based on data behavior
- So far, the Kolmogorov approximation has helped to improve the model behavior in relation to data

Conclusions

- ROMS captures real dynamic flow features such as fronts and eddies, which in turn have effect on tidal hydrokinetic turbine siting
- ROMS simulations can be used to approximate some turbulence parameters
- There is evidence that adjustments can be made to improve performance of the model-predicted turbulent kinetic energy

Current Mean TKE Map... To Be Improved!



Future Work

- Find horizontal viscosity TKE contribution
- Find TKE changes and improvements with depth
- More outputs in time to see how good comparison can be using only model output. Since my time step is 5 seconds, there may be a lot more information available that is being aliased with my 15-minute output.

Thank you!

This work was done as part of the Northwest National Renewable Energy Center at the University of Washington
http://depts.washington.edu/nnmrec/

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Additional support came from the PACCAR chair.