C2SM Center for Climate Systems Modeling
Hurricane Research Division
Atlantic Oceanographic & Meteorological Laboratories
National Oceanic & Atmospheric Administration
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

3-D to 2-D Turbulence Transition in the Hurricane Boundary Layer

David Byrne and Jun A. Zhang

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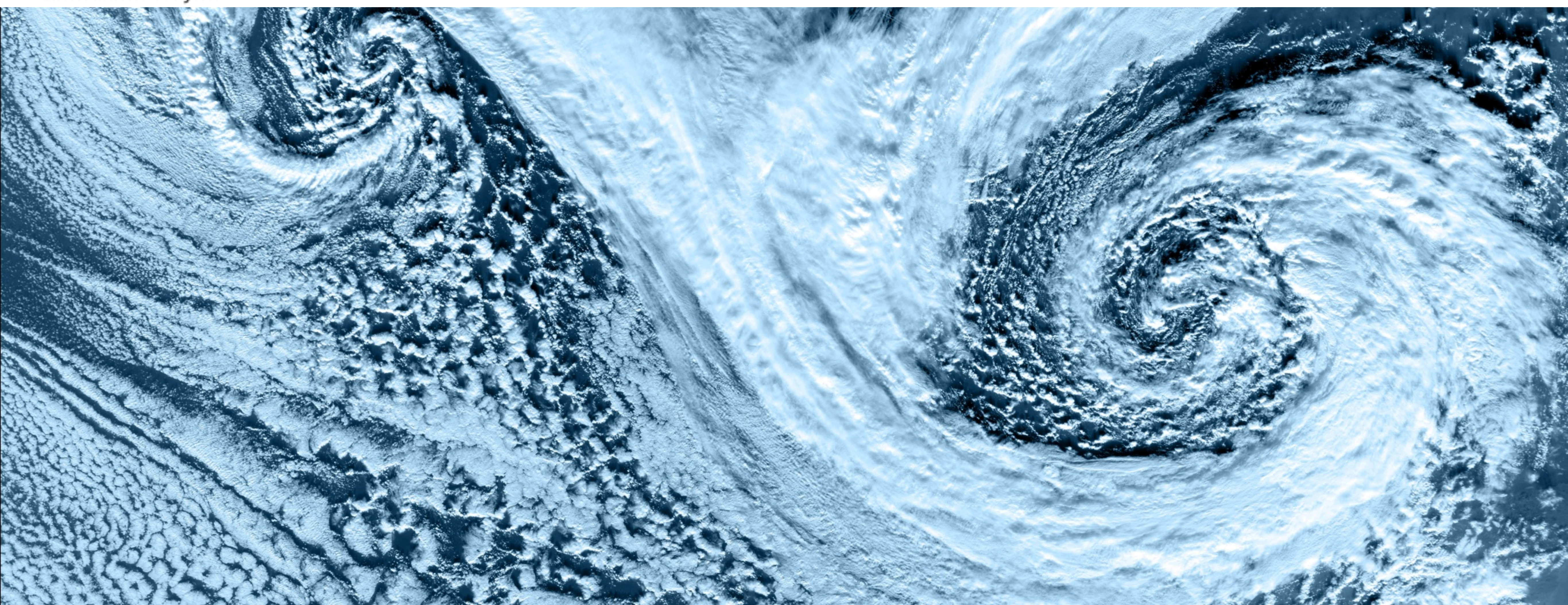
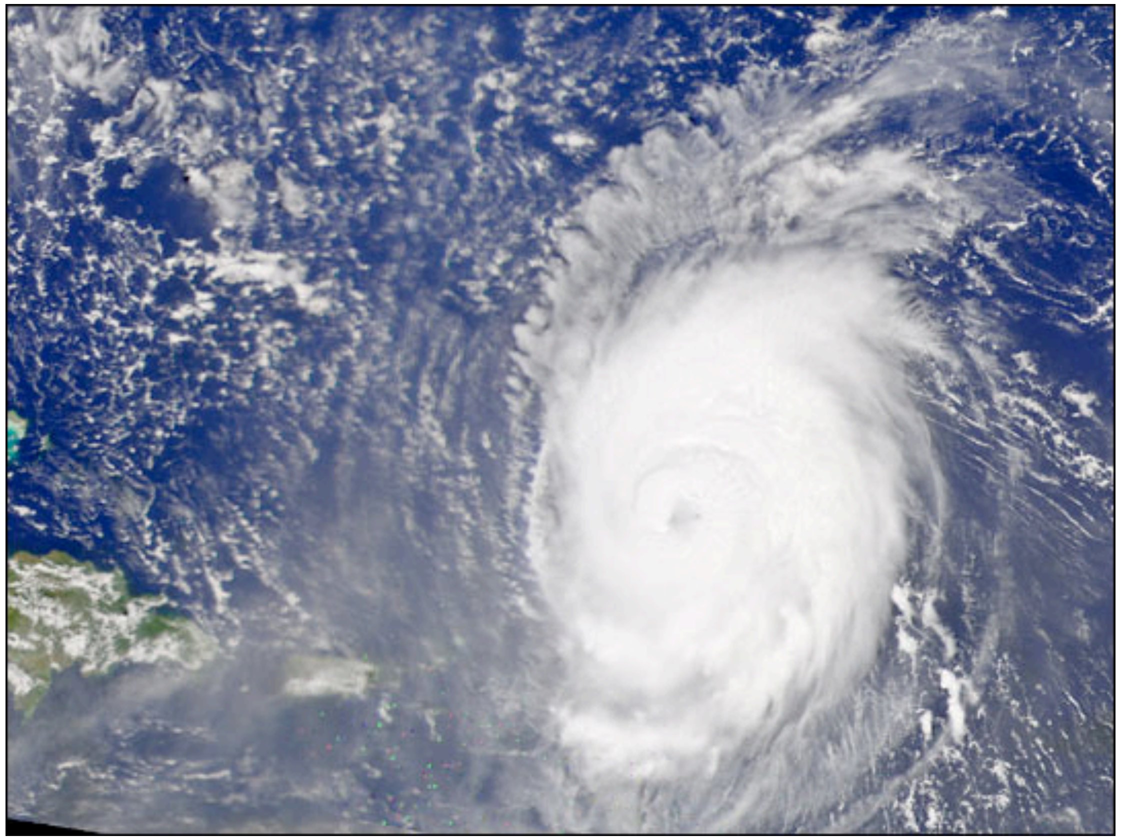
Environmental Physics



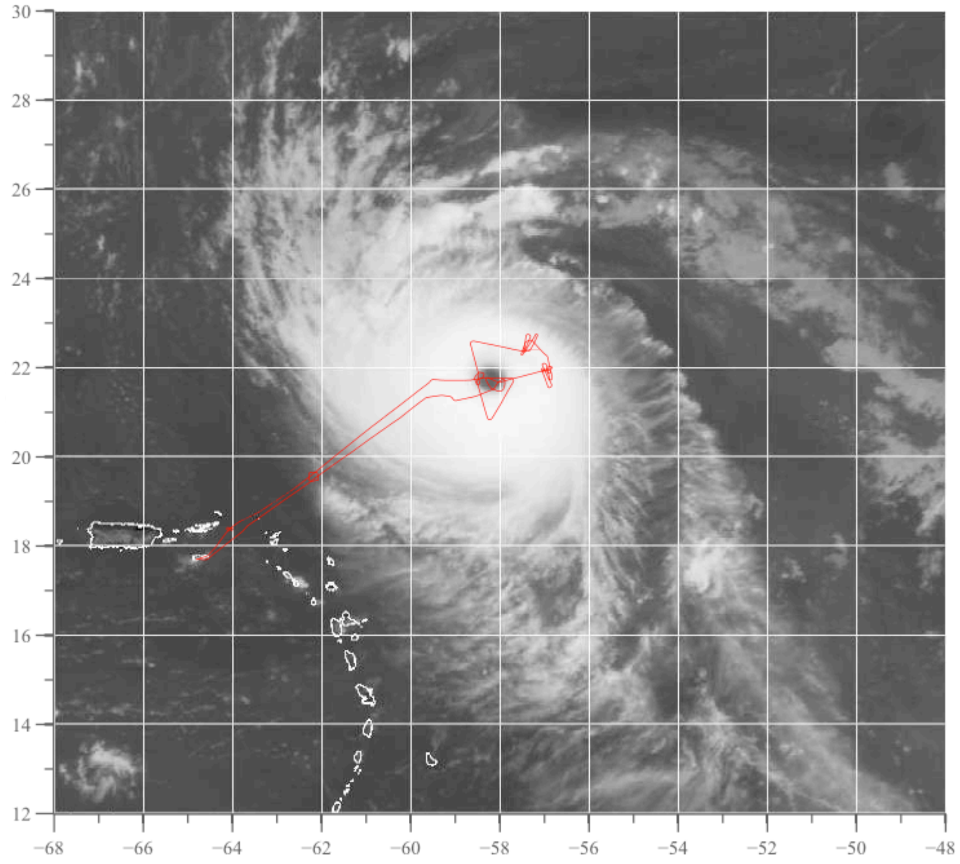
Hurricanes Isabel and Fabian

Isabel

Fabian

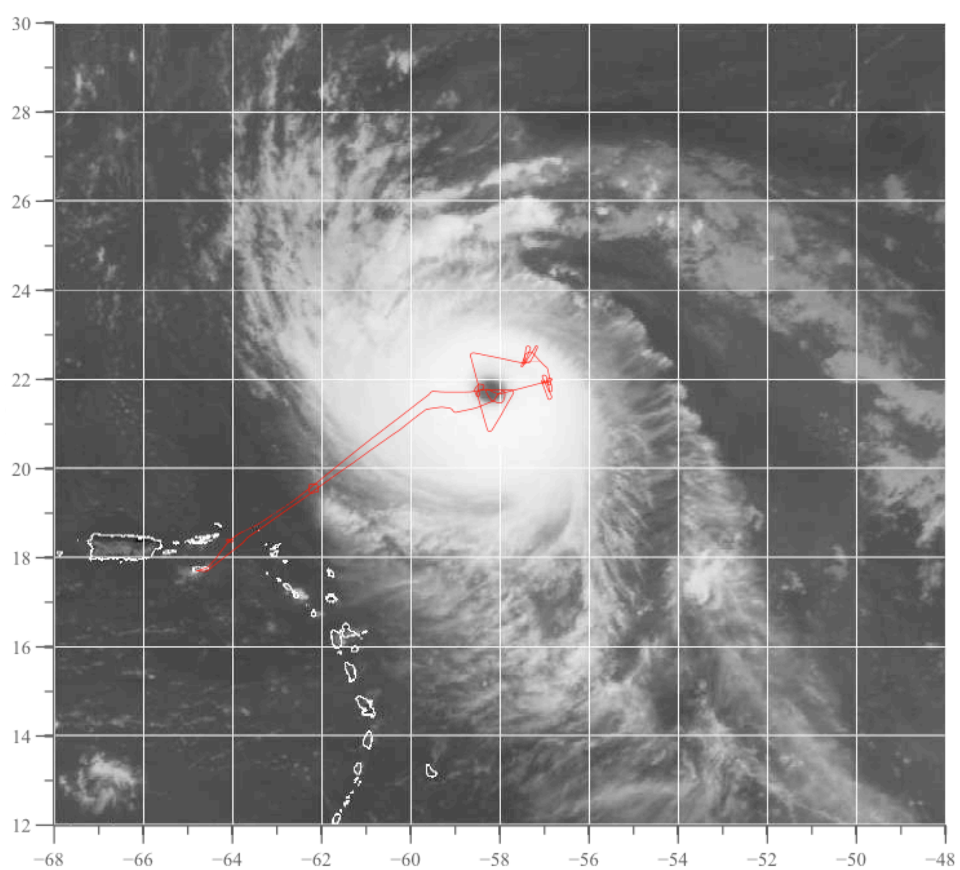


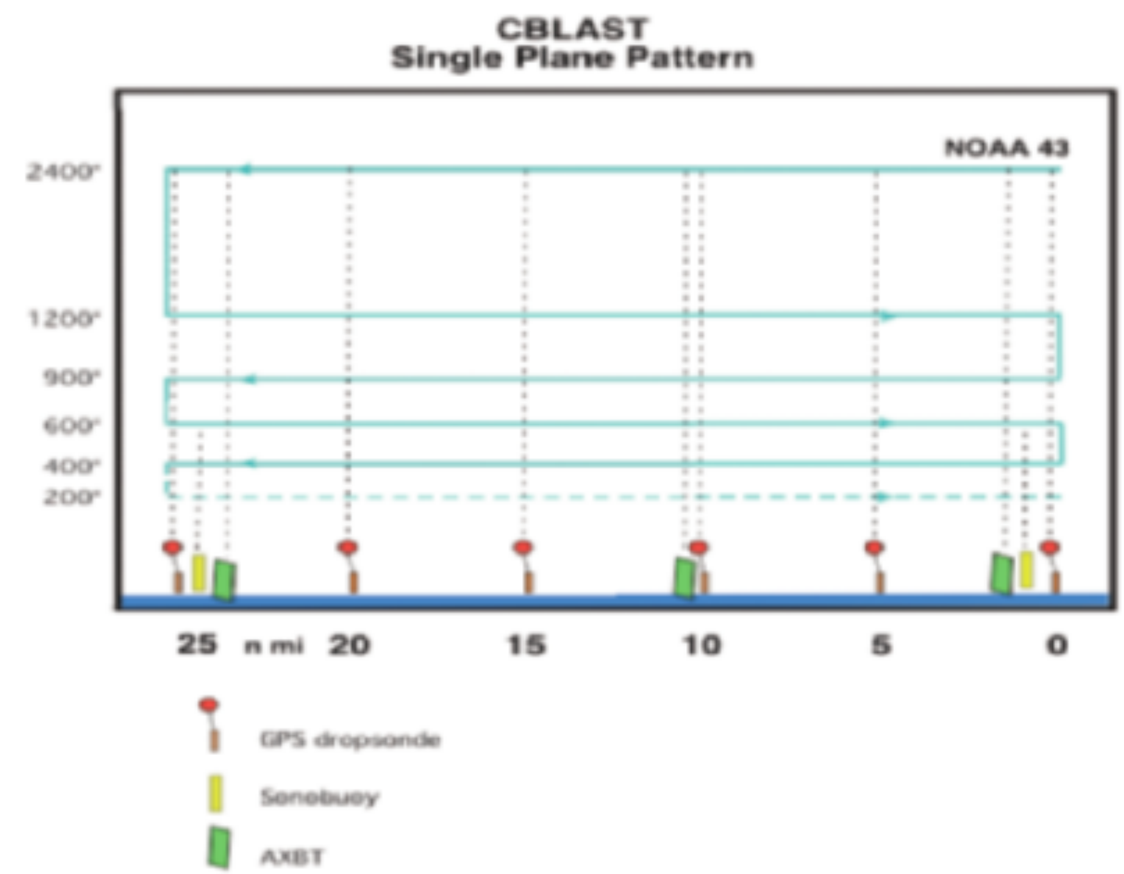
Hurricanes Isabel and Fabian



P.G. Black, et. al, Bulletin of the American Meteorological Society (2007)

Hurricanes Isabel and Fabian





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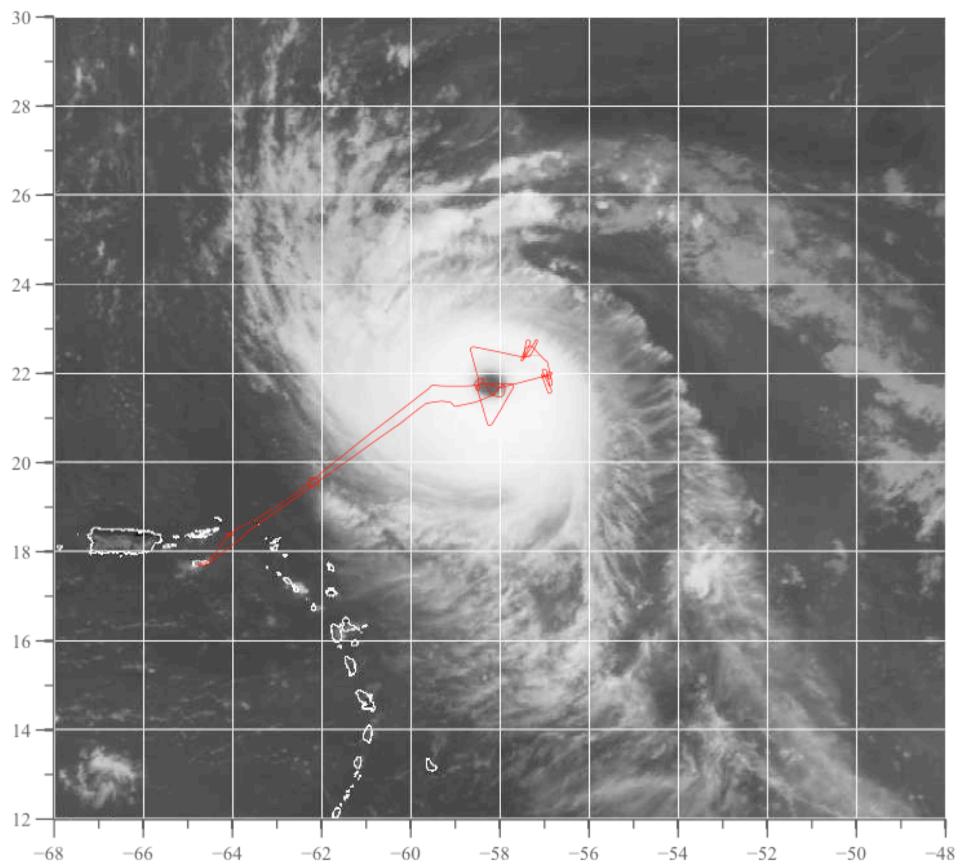
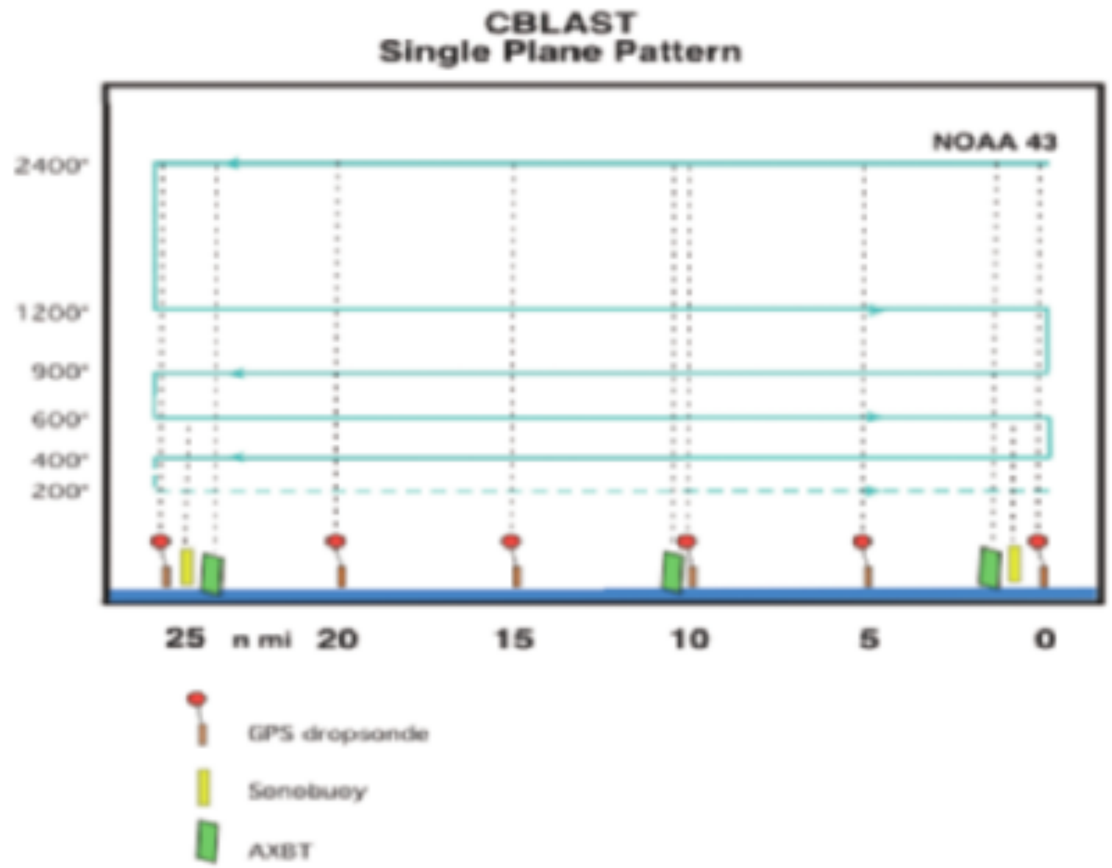
Hurricanes Isabel and Fabian

2-D or 3-D?





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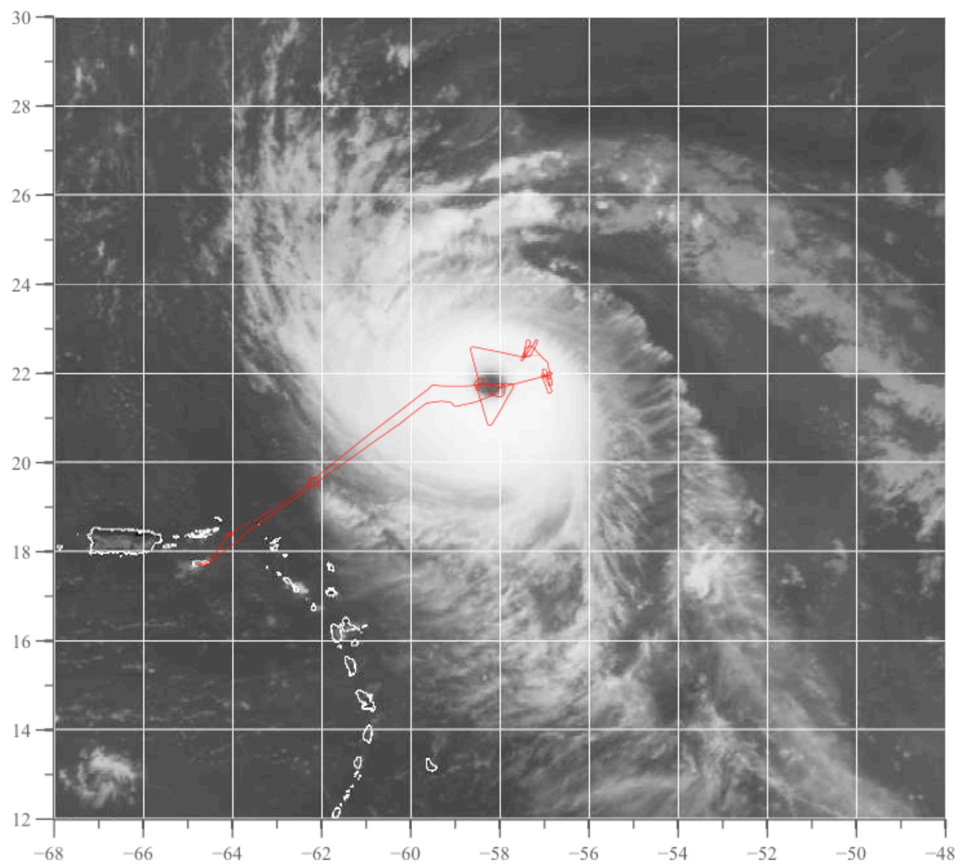

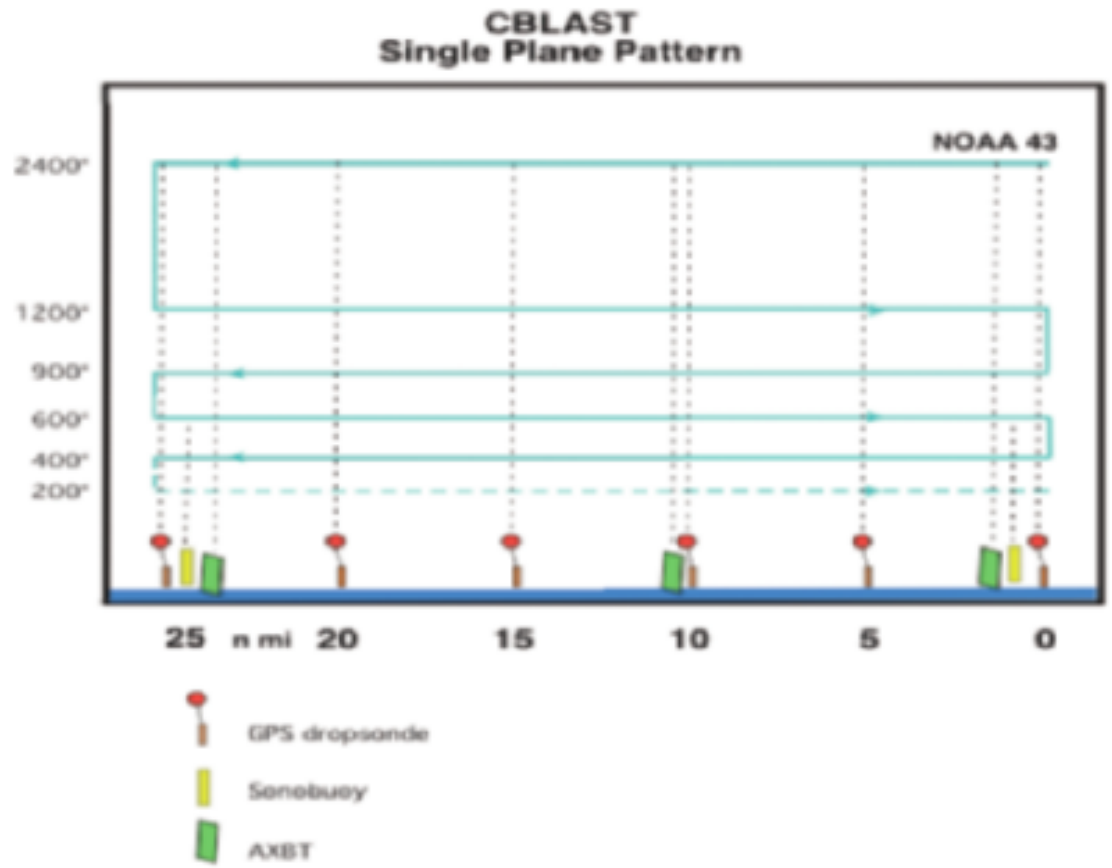

Parent vortex - Large aspect ratio width/depth. 2-D?

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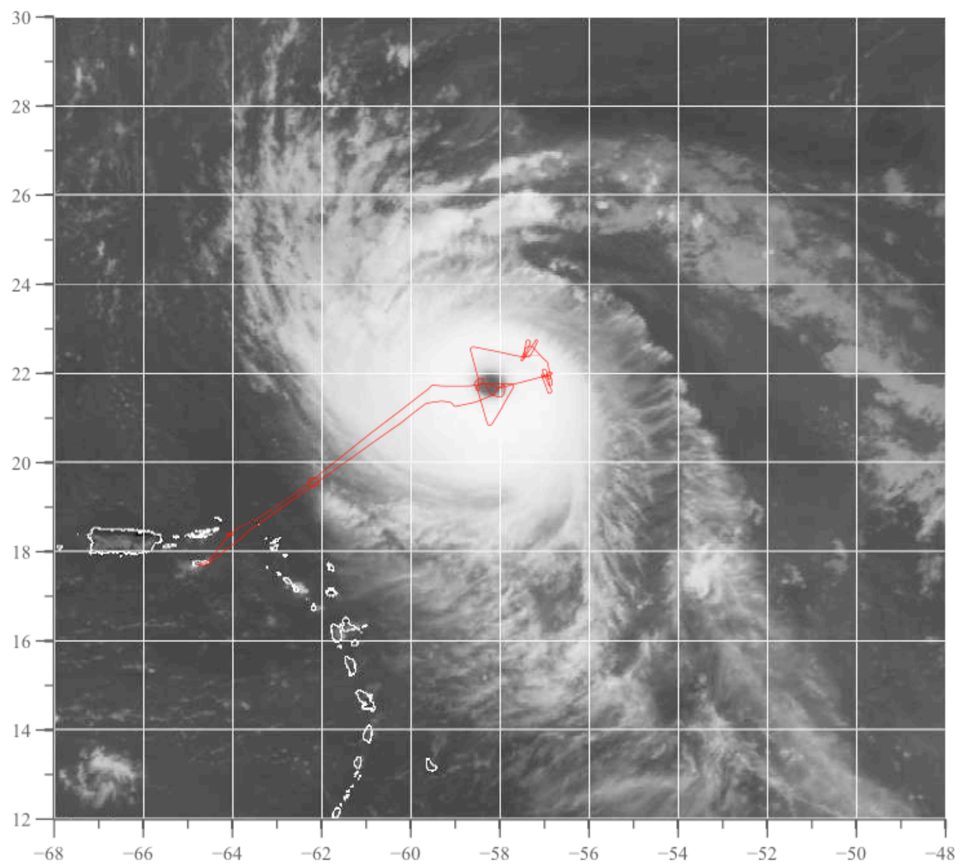
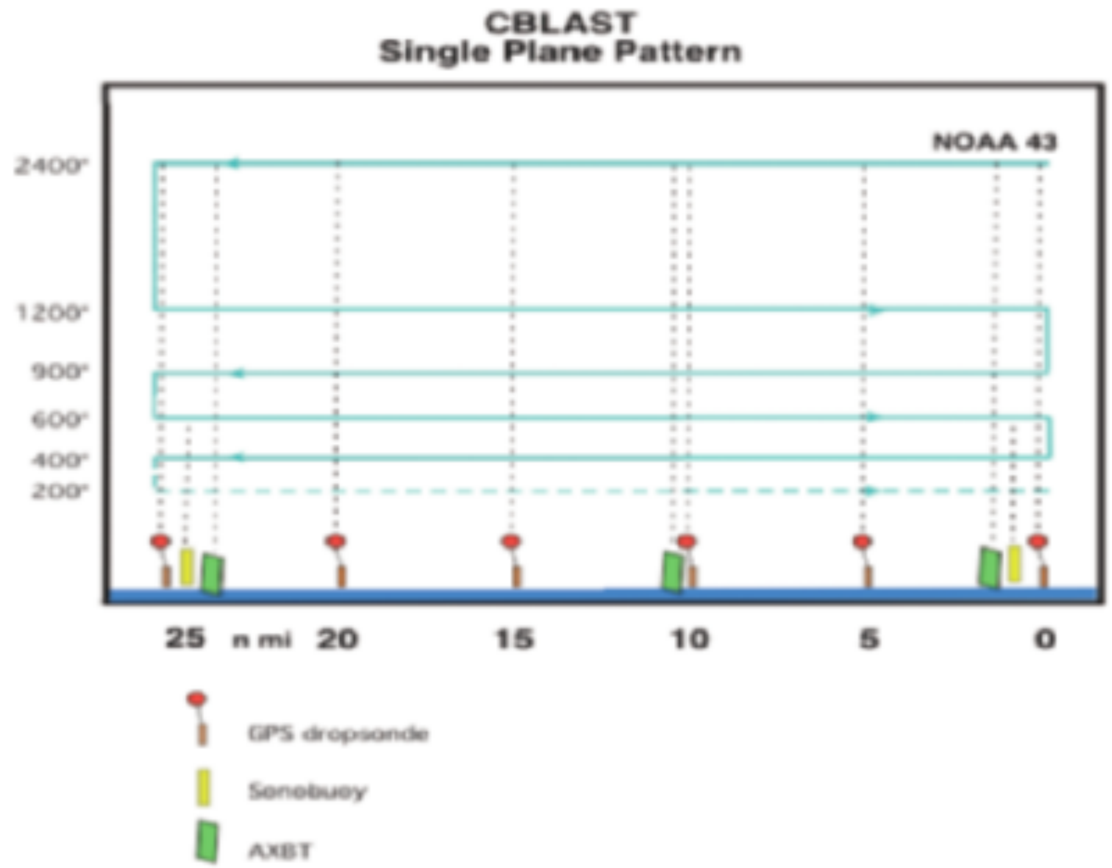
Hurricanes Isabel and Fabian

2-D or 3-D?





Parent vortex - Large aspect ratio width/depth. 2-D?

Smaller scales - Aspect ratio smaller 3-D?

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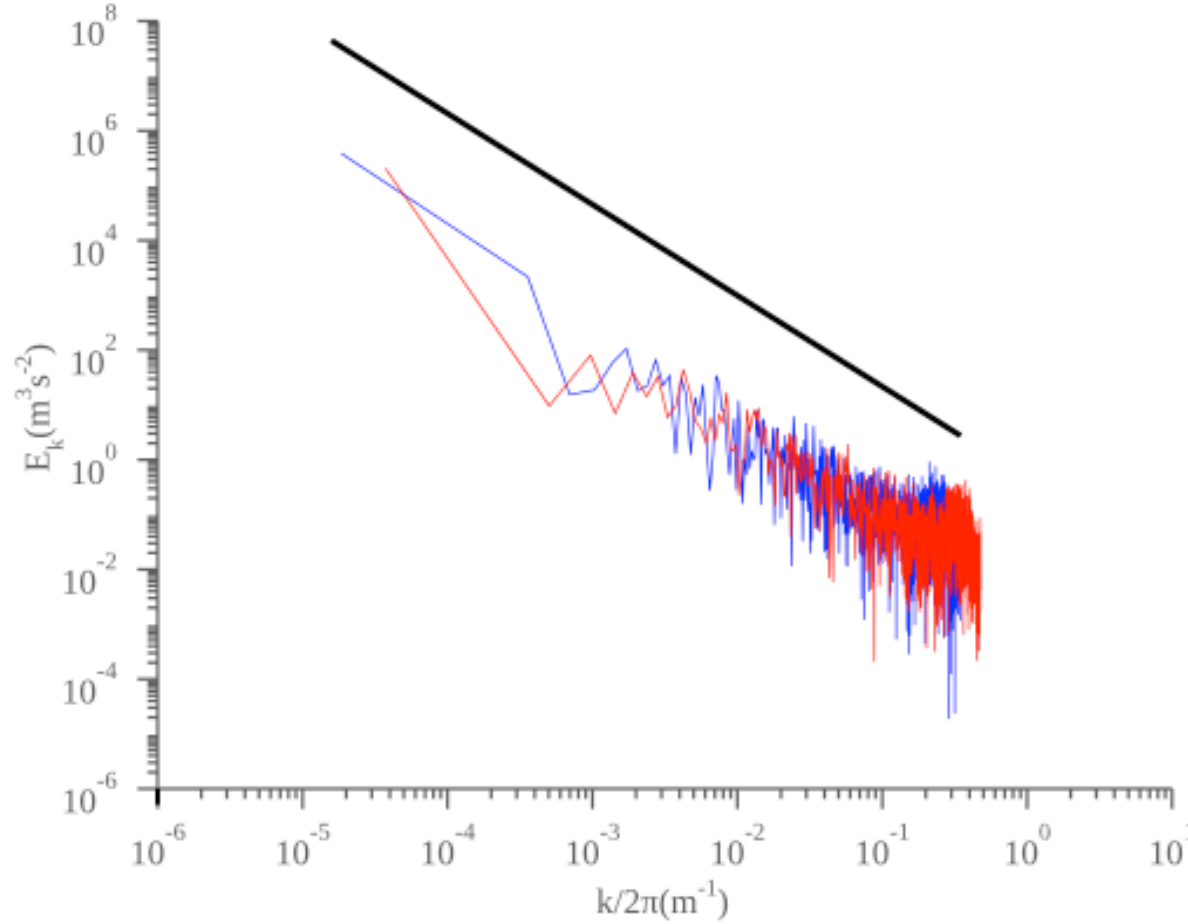
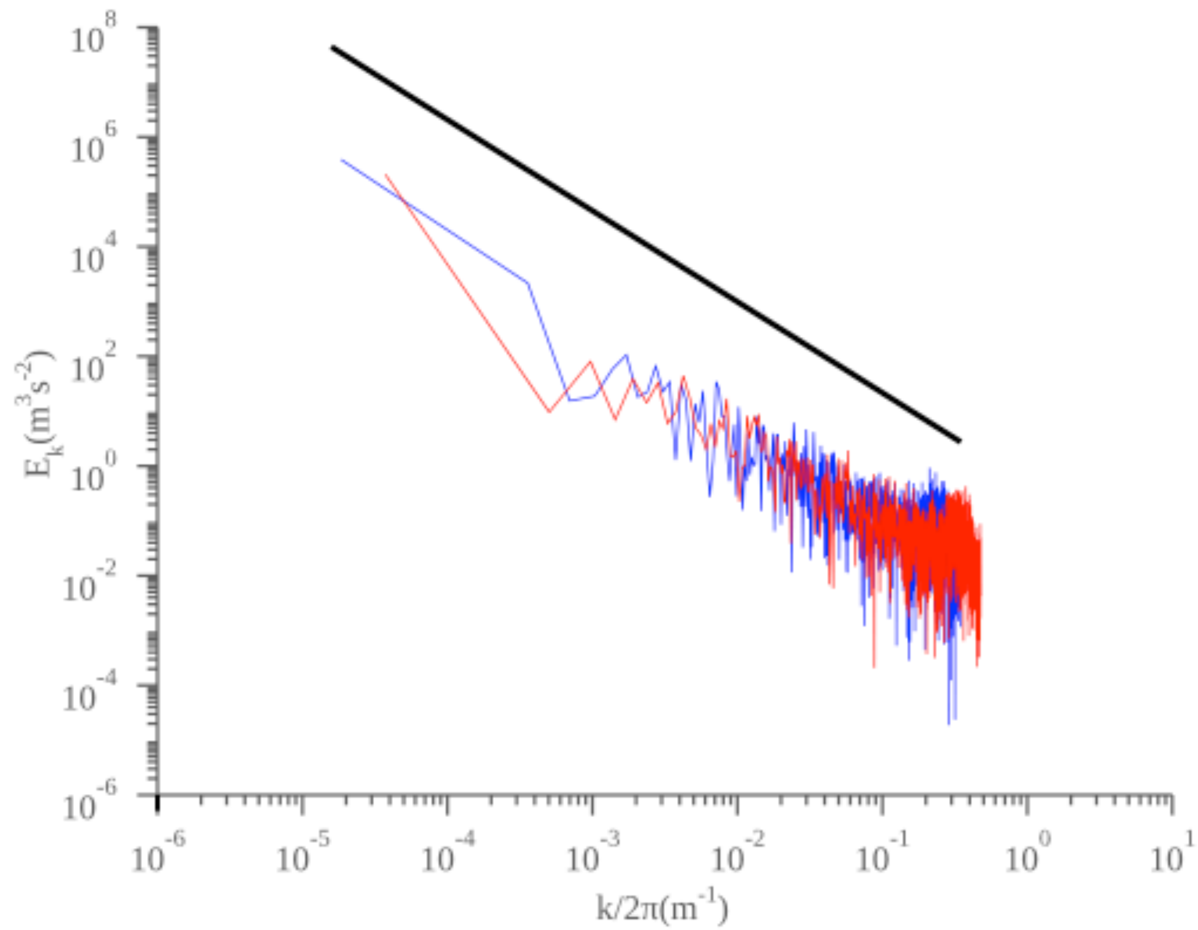
Dimensionality of Turbulence

Dimensionality of Turbulence



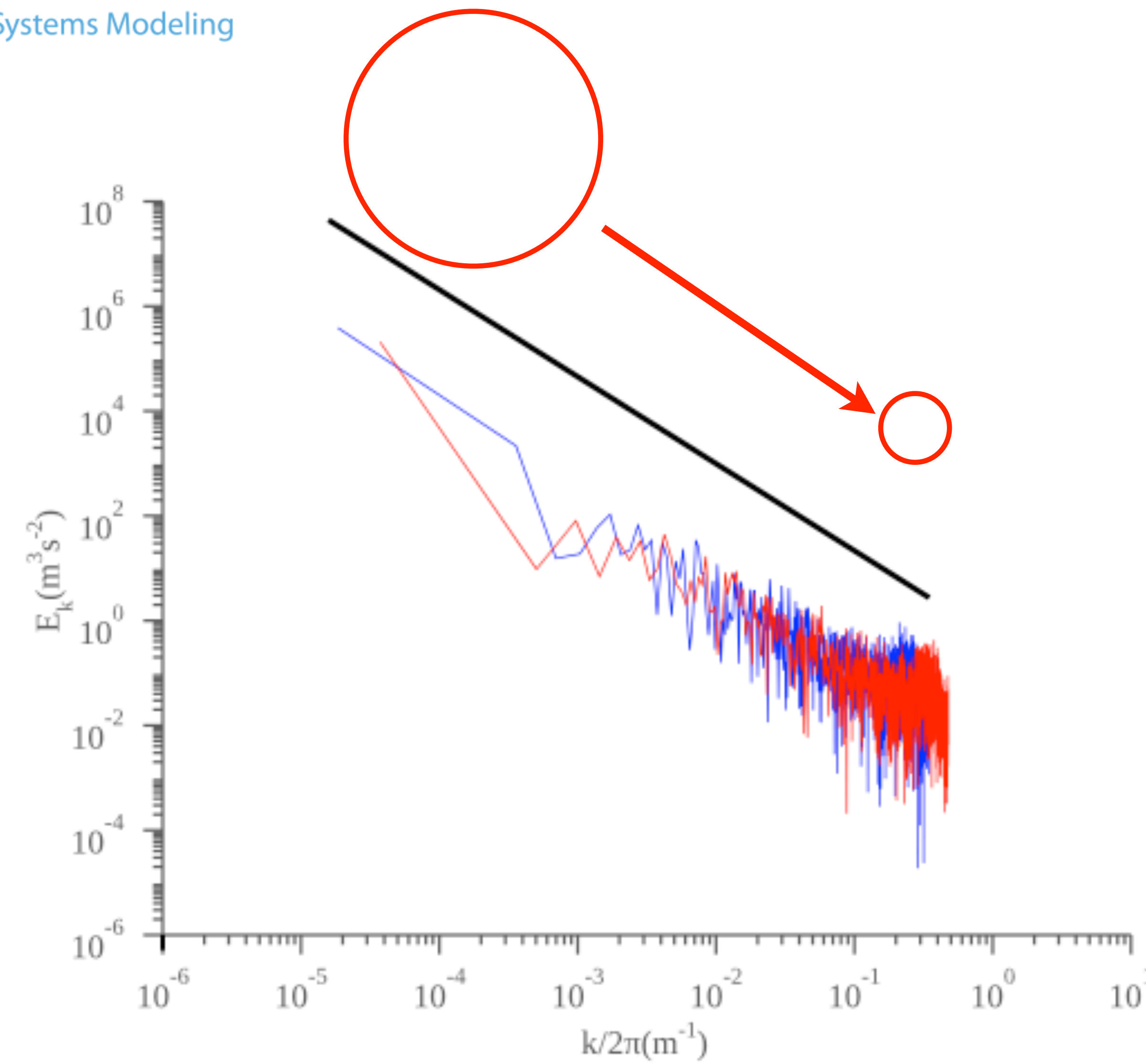
- **Broad range of scales (10m-60km)**

Dimensionality of Turbulence



- **Broad range of scales (10m-60km)**
- **-5/3 Scaling is in good agreement with turbulence theory**

Dimensionality of Turbulence



- **Broad range of scales (10m-60km)**
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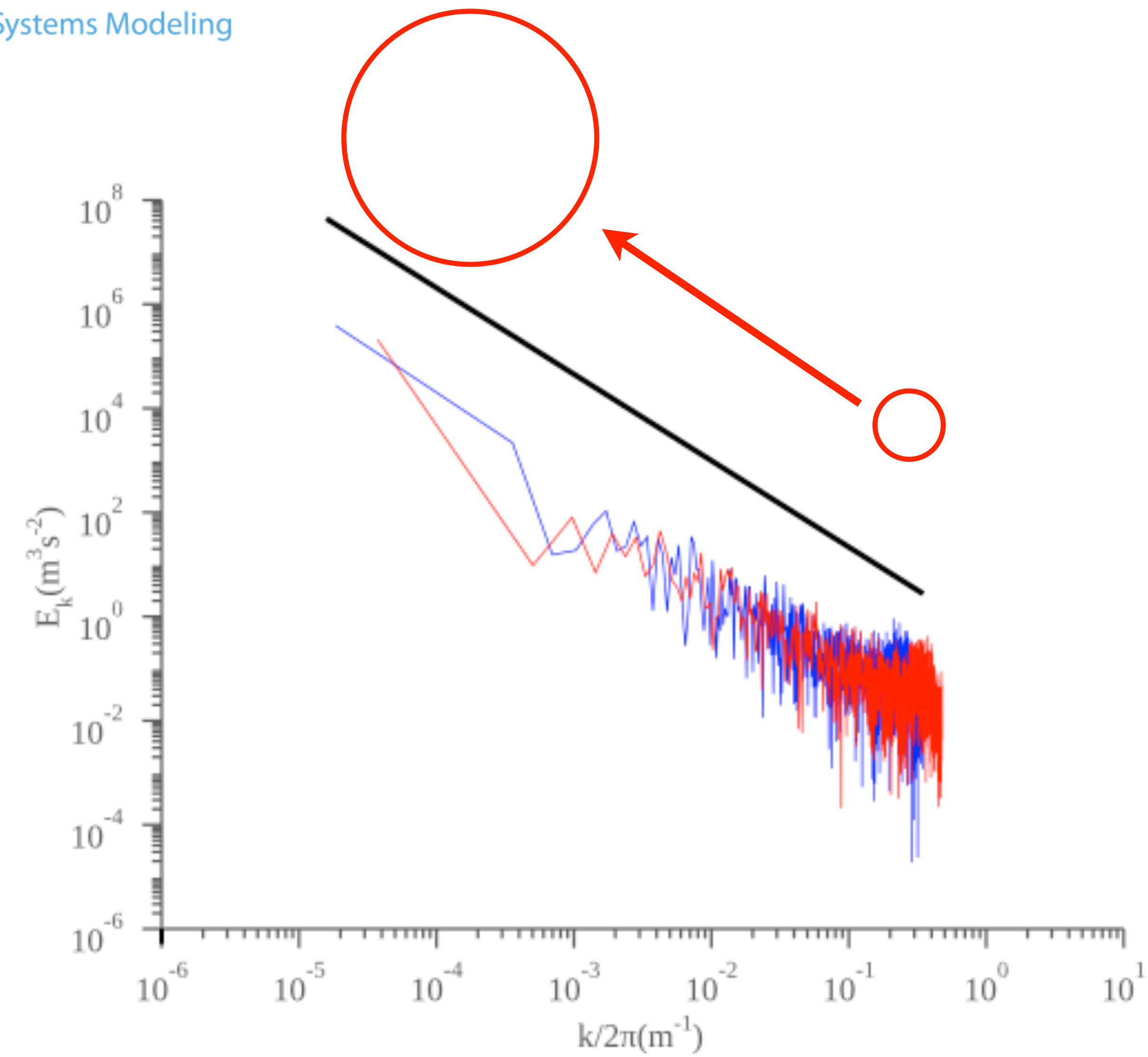
3-D - Energy flows from large to small scales

Dimensionality of Turbulence



- Broad range of scales (10m-60km)
- -5/3 Scaling is in good agreement with turbulence theory

3-D - Energy flows from large to small scales

2-D - Energy flows from small to large scales

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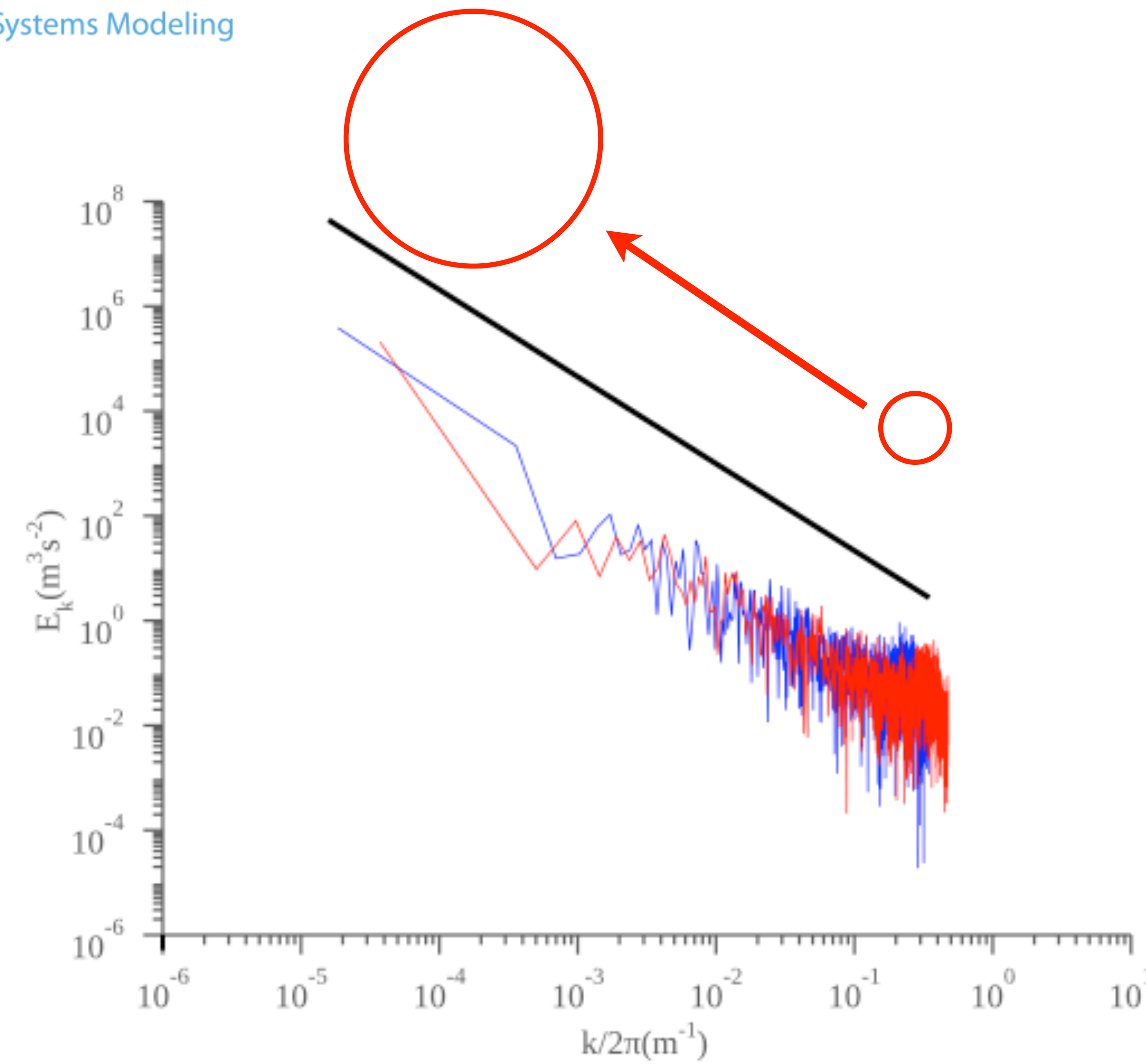
Dimensionality of Turbulence



- **Broad range of scales (10m-60km)**
- **-5/3 Scaling is in good agreement with turbulence theory**
- **Spectra gives no indication of direction of energy flux**

3-D - Energy flows from large to small scales

2-D - Energy flows from small to large scales

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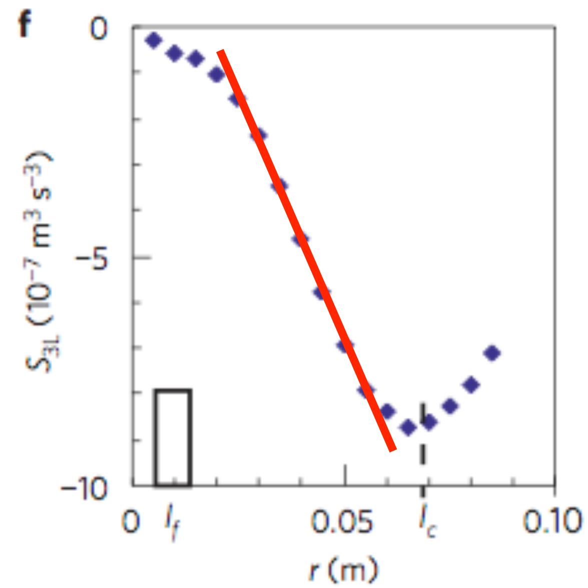
Structure Functions - Dimensionality of Turbulence

$$\delta \mathbf{v}(\mathbf{r}) = (\mathbf{v}(x+\mathbf{r}) - \mathbf{v}(x)).$$

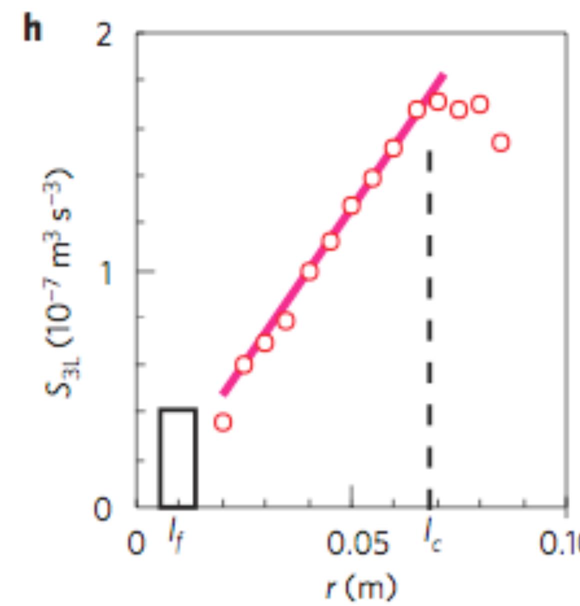
$$S_{3\mathrm{L}} = \langle (\delta V_{\mathrm{L}})^3 \rangle$$

$$\varepsilon = -(2/3) S_{3\mathrm{L}}/r$$

3-D

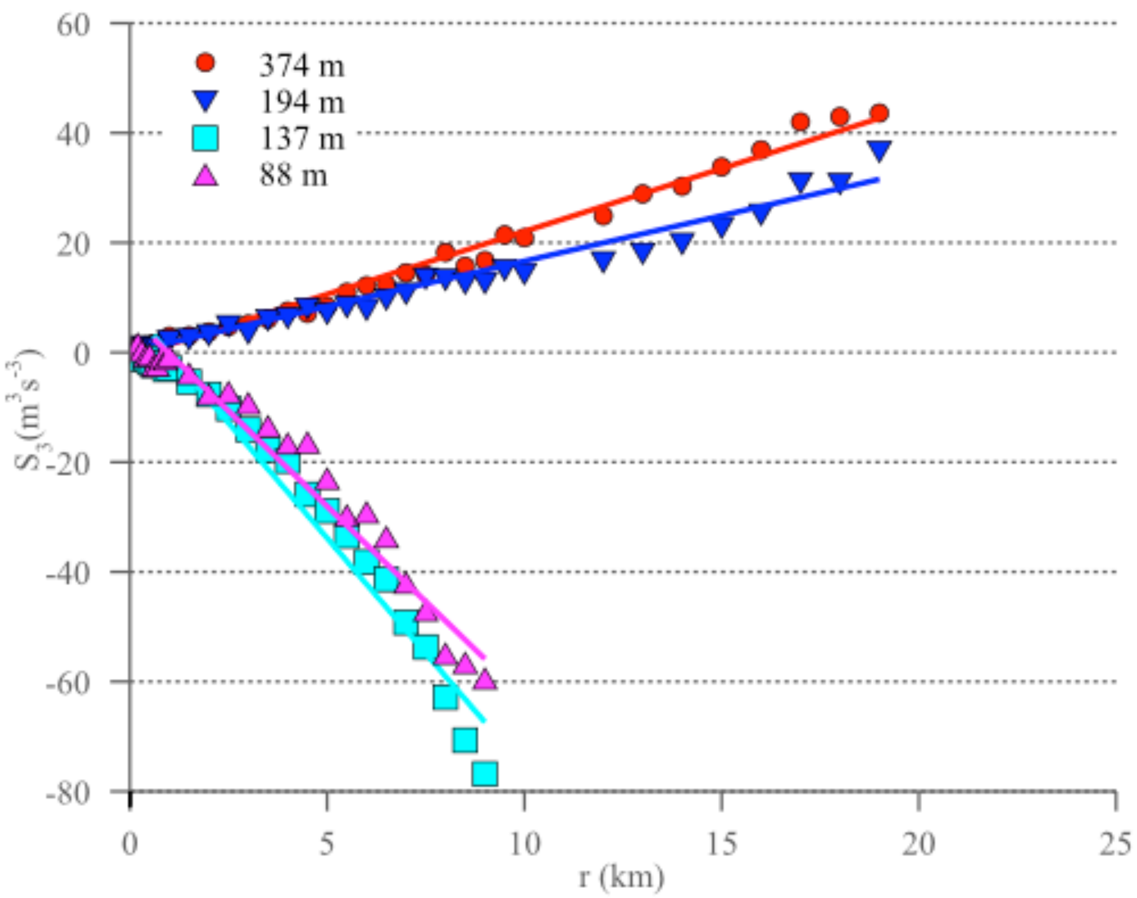


2-D



CBLAST - Hurricanes Isabel and Fabian

Isabel



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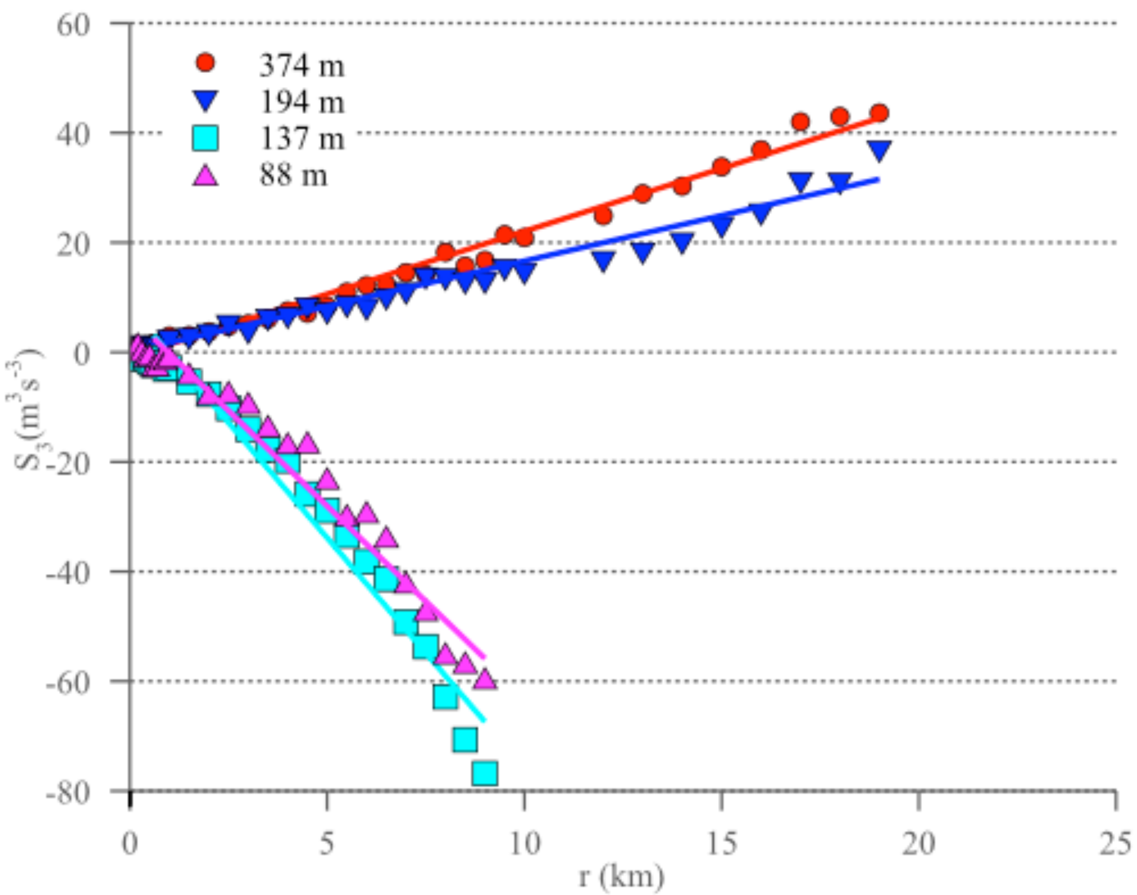
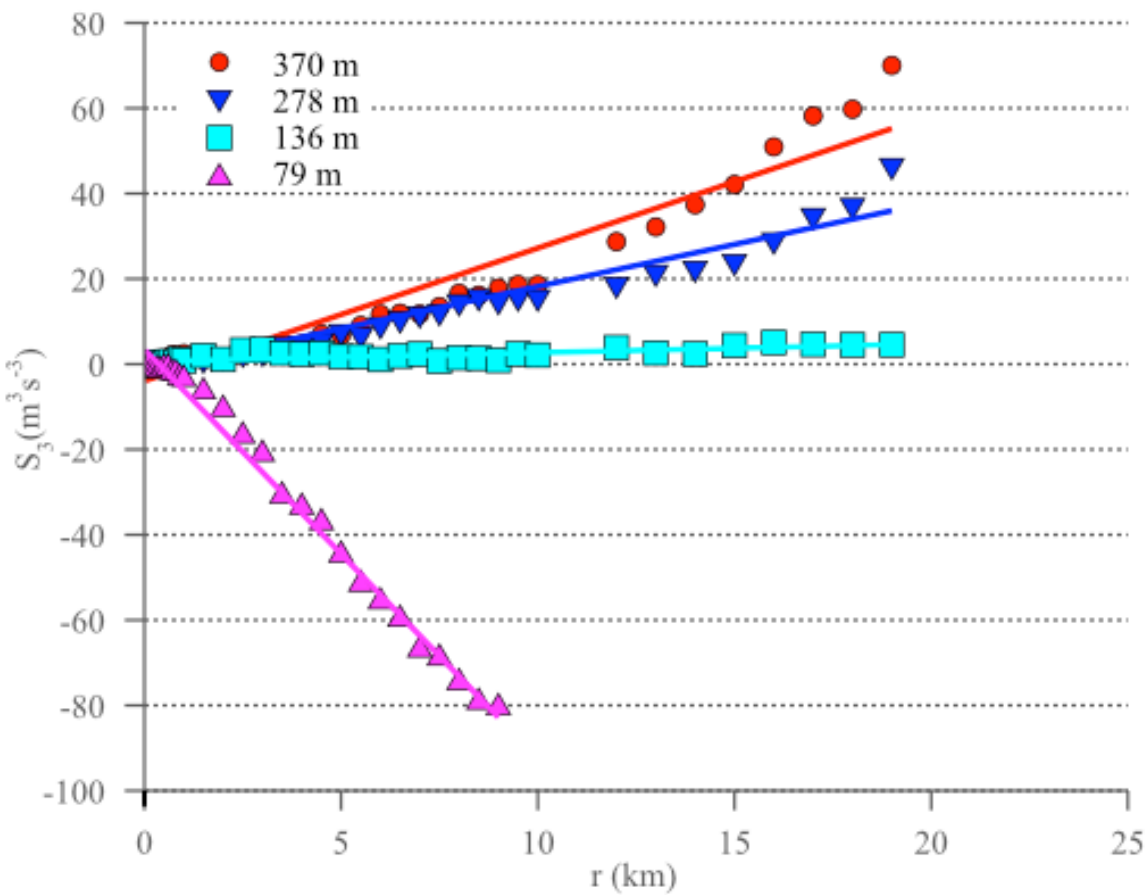


Fabian



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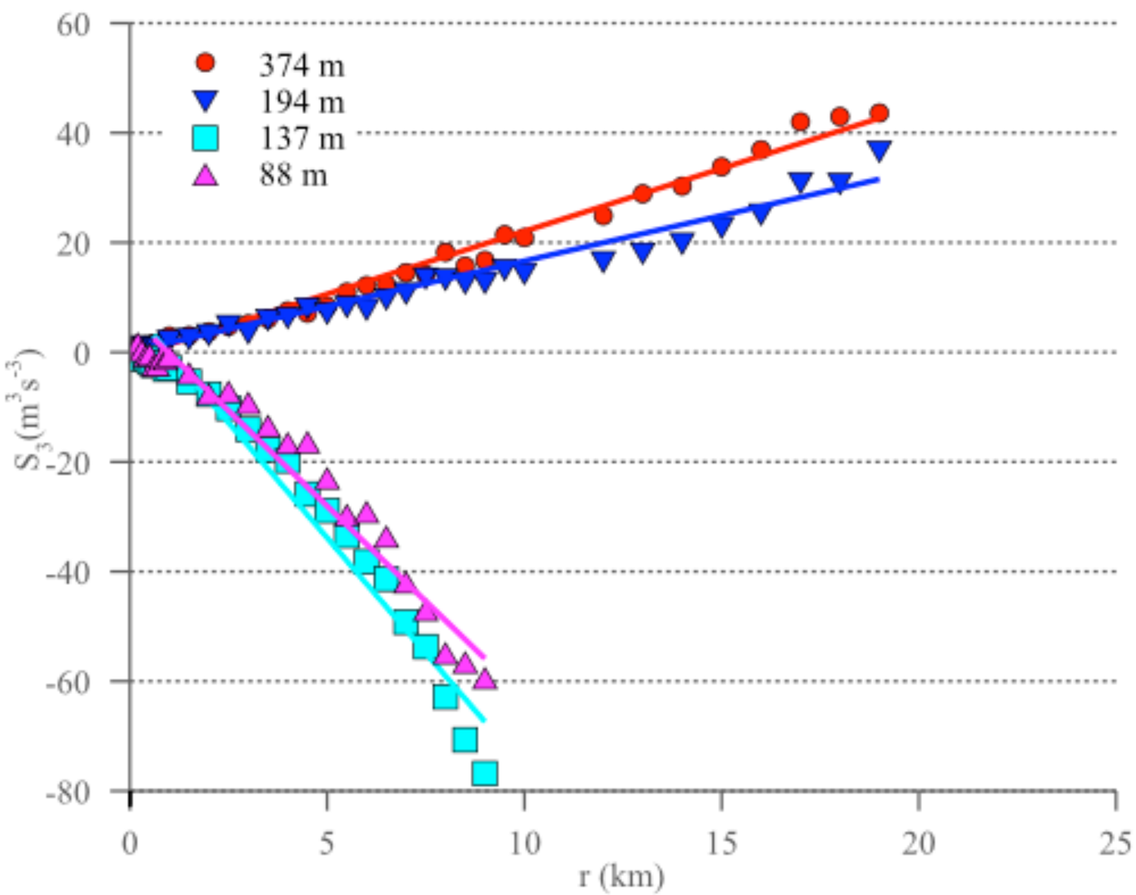
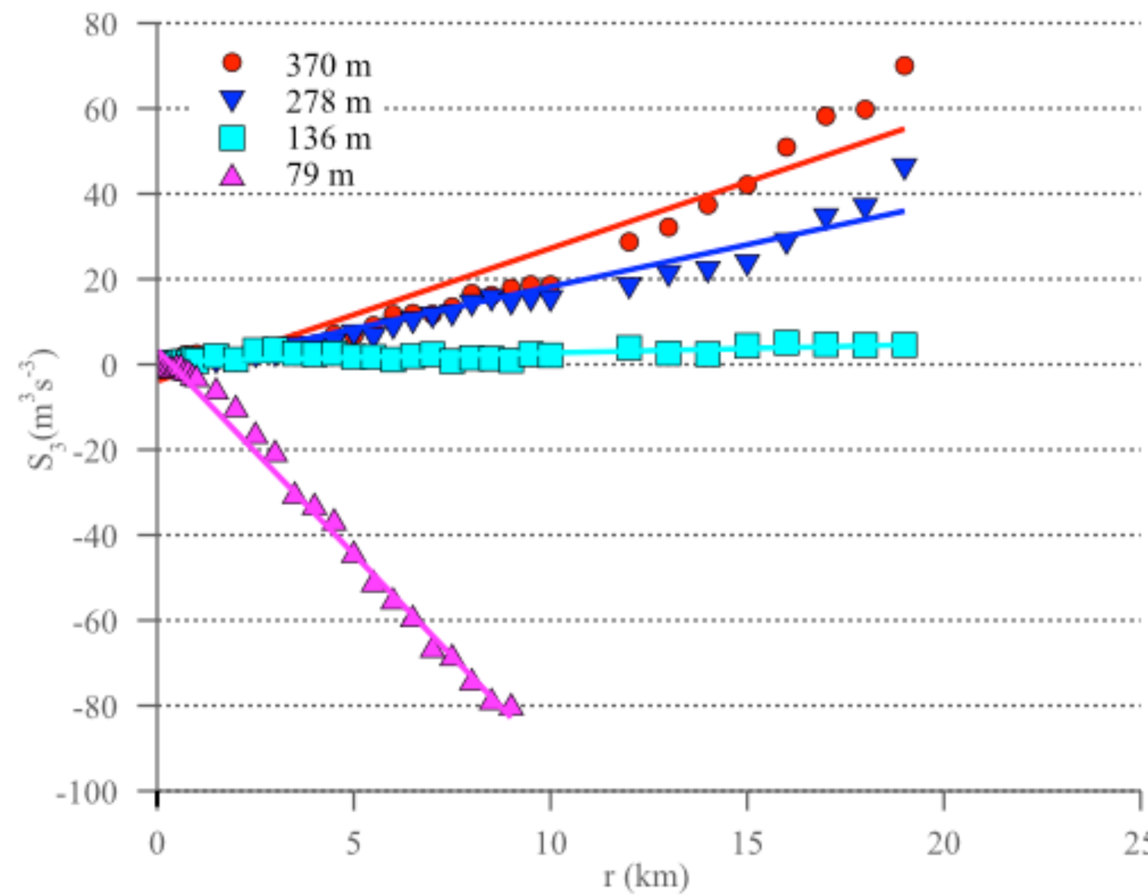
Isabel



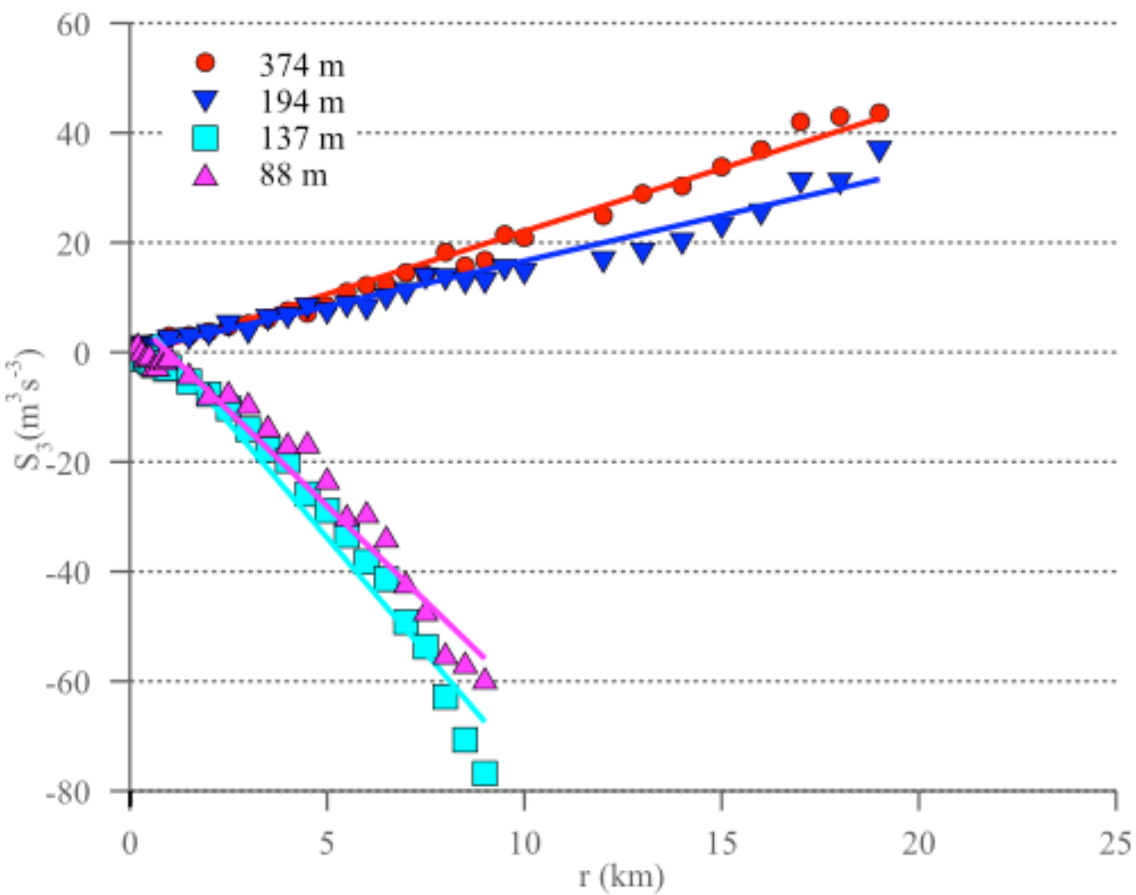
Fabian



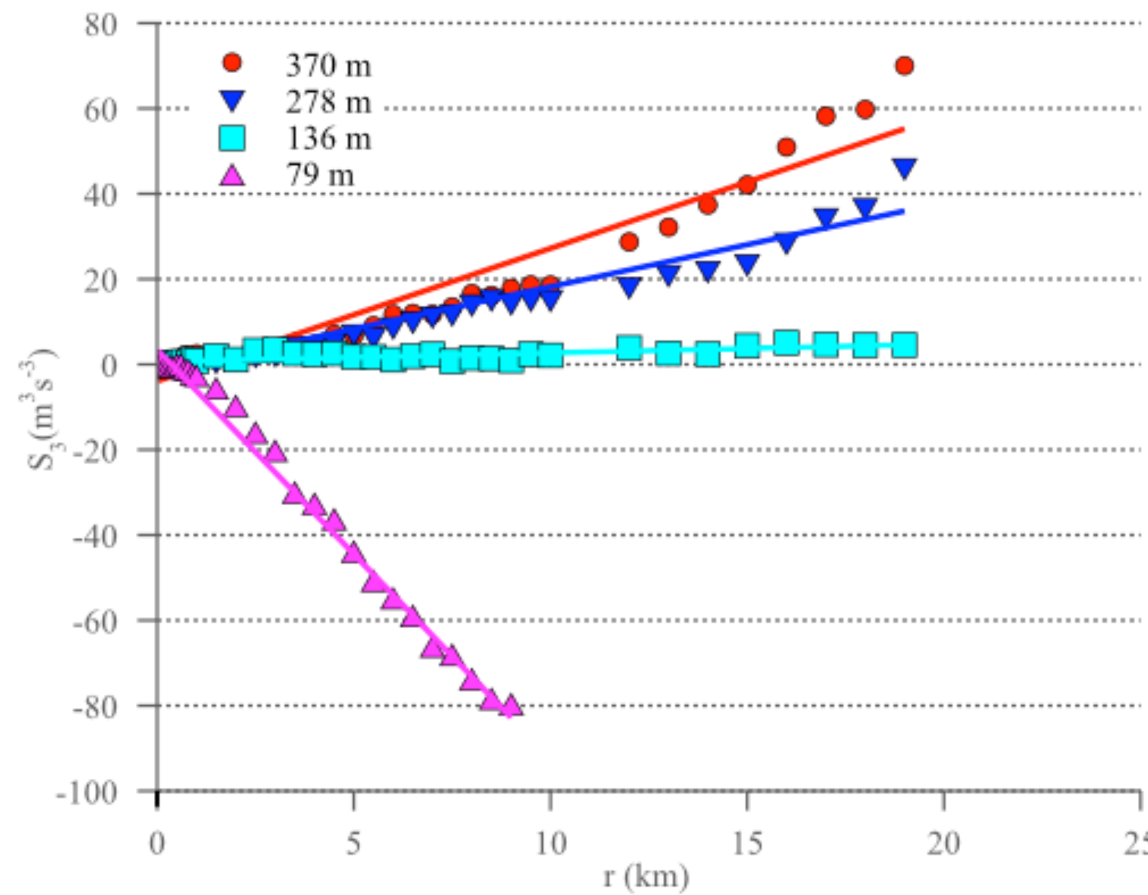
Data verified with energy balance estimates - Shear production and dissipation estimated K parameterization.

CBLAST - Hurricanes Isabel and Fabian

Isabel



Fabian



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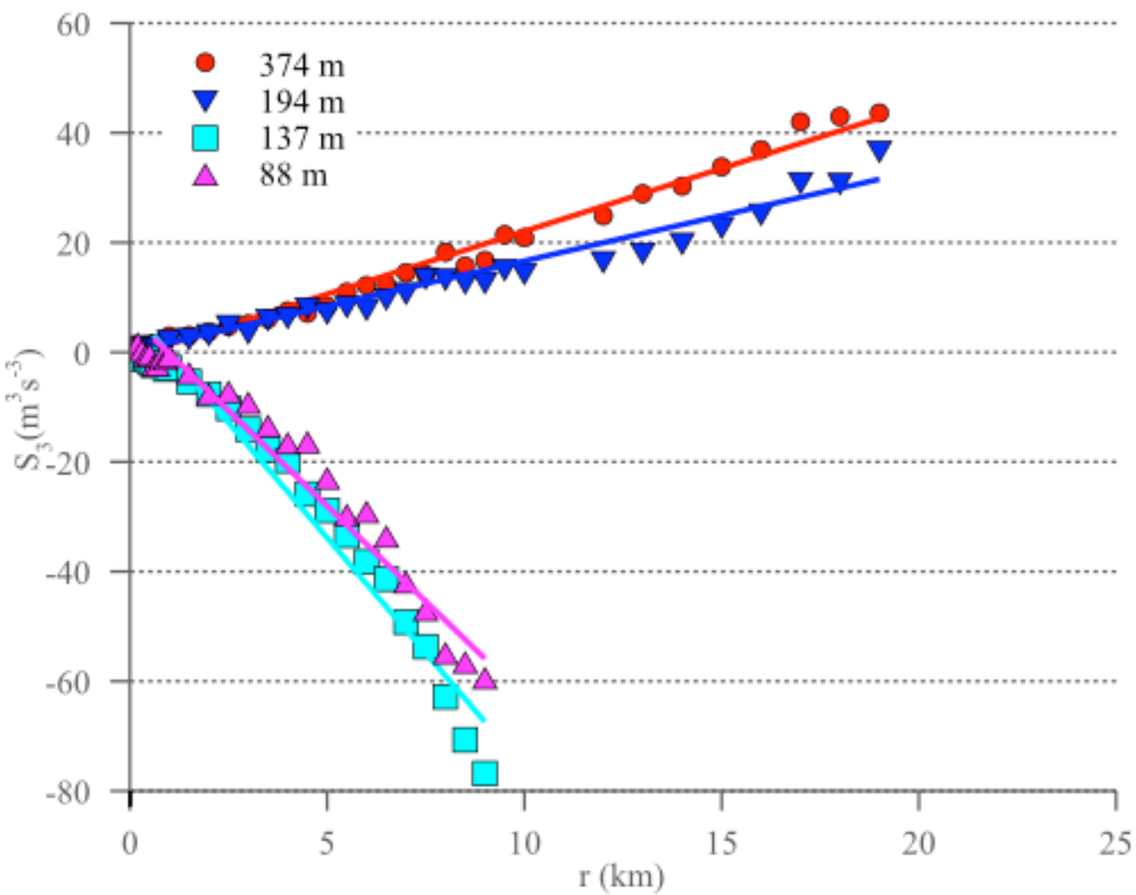
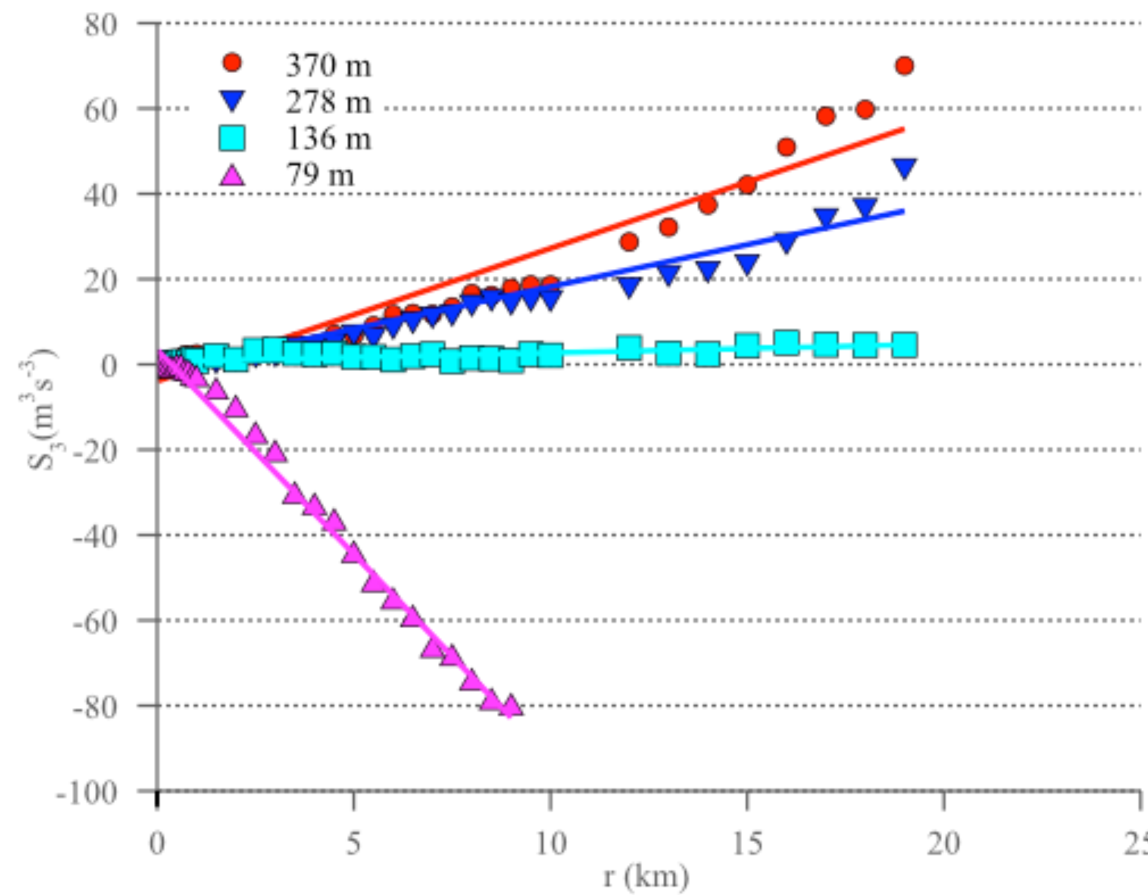
Further details - (D.Byrne, J. Zhang (2013) GRL, DOI:10.10002/grl.50355)

CBLAST - Hurricanes Isabel and Fabian

Isabel



Fabian



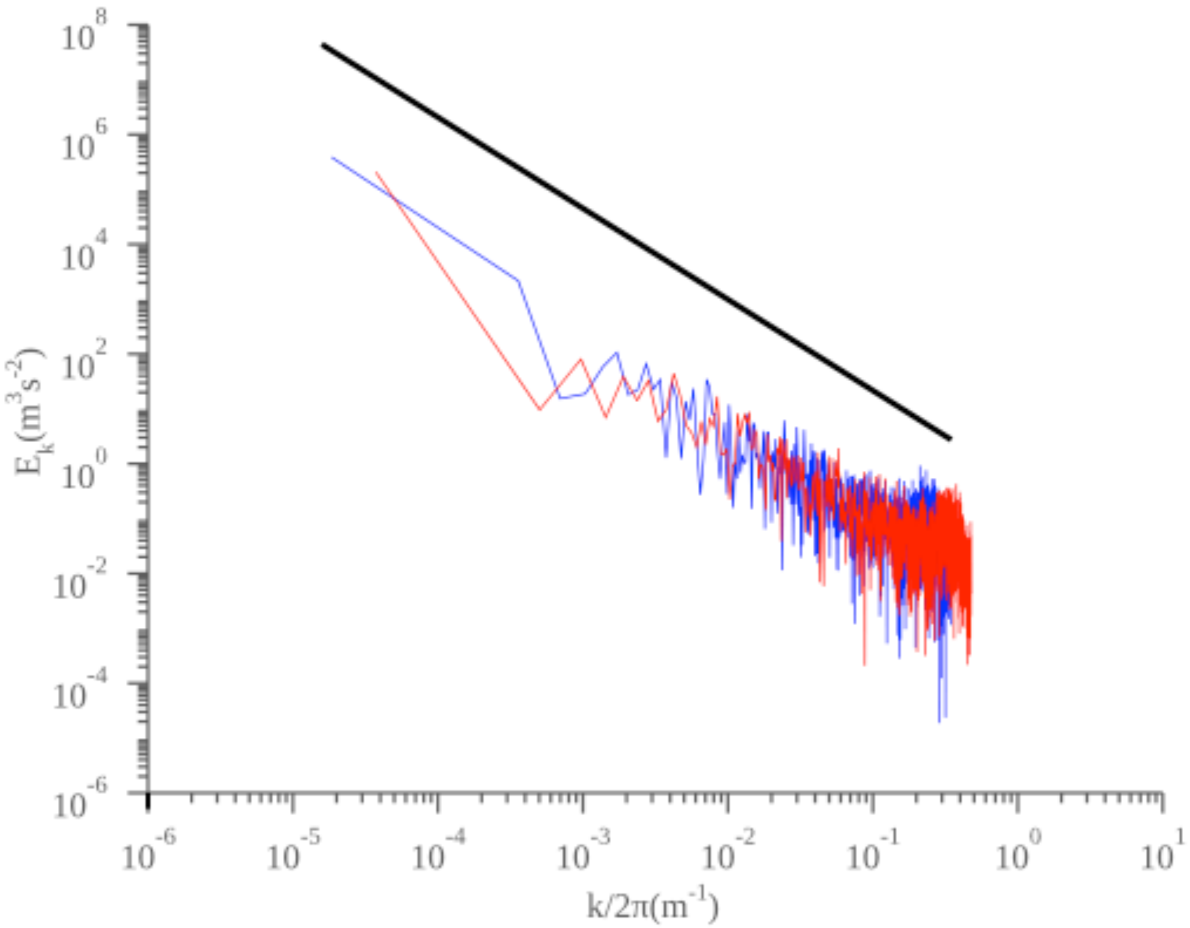
Data verified with energy balance estimates - Shear production and dissipation estimated K parameterization.

2D - Very good closure for both Isabel and Fabian.
3D - Discrepancy where estimated dissipation outweighs production 50%.

Further details - (D.Byrne, J. Zhang (2013) GRL, DOI:10.10002/grl.50355)

Internal Consistency

$$C = E_k \epsilon^{-2/3} k^{5/3}$$



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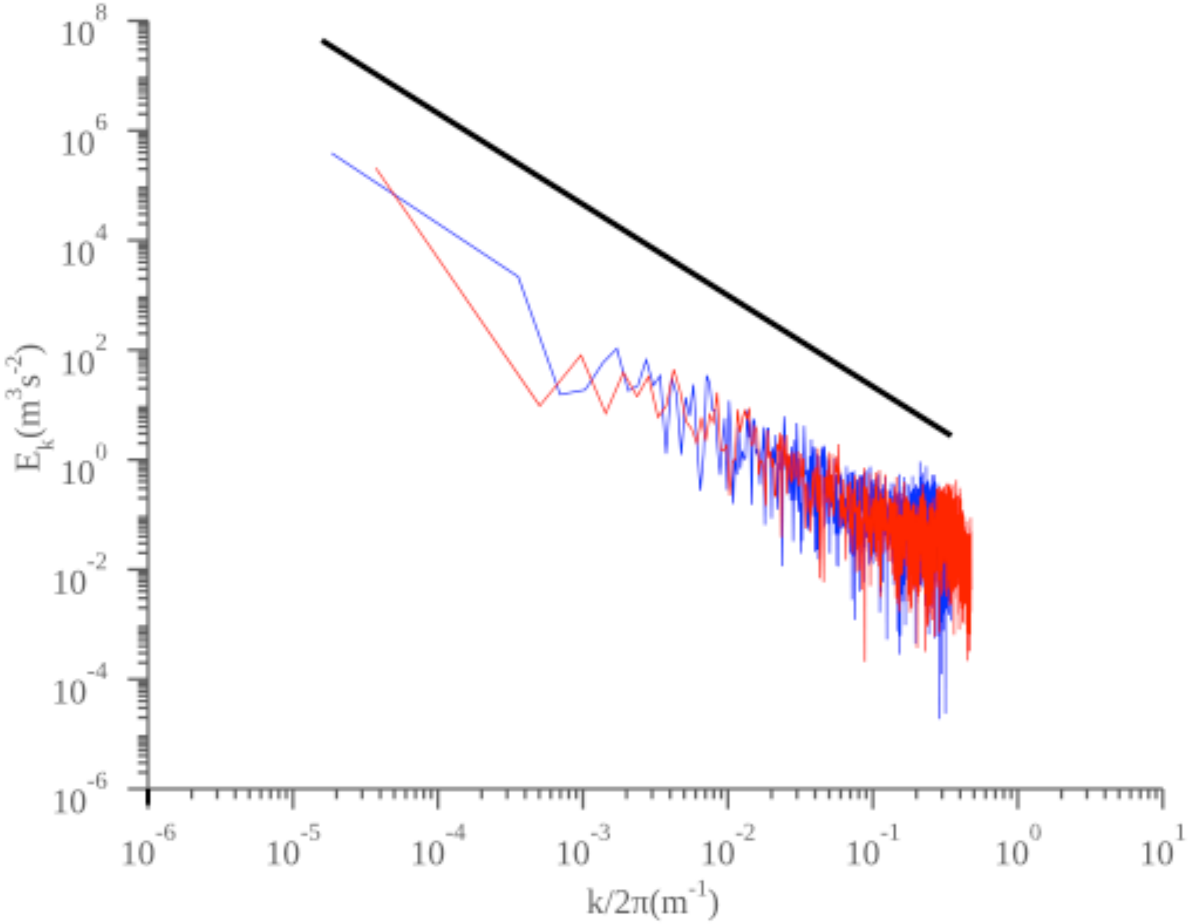

3D ~ 0.5

2D ~ 5-7

Internal Consistency

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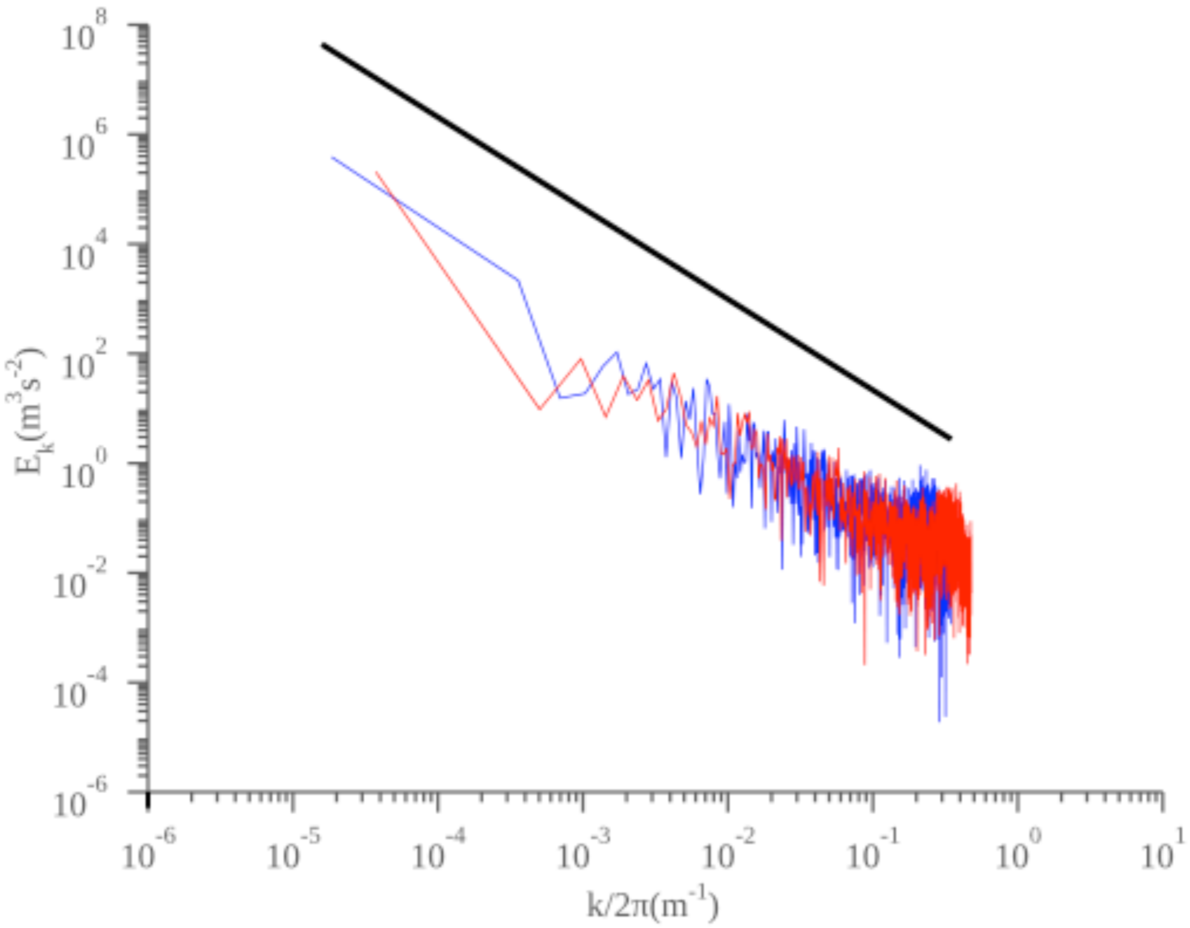


3D ~ 0.5

2D ~ 5-7

Computed for each flight leg -

3D ~ (0.5-1.0)

2D ~ (2.0-5.5)

All fall within agreed values with experimental uncertainty

Cause of transition - 2D constraints

Cause of transition - 2D constraints

- **Aspect Ratio**

Cause of transition - 2D constraints

- Aspect Ratio
- Rotation

Cause of transition - 2D constraints

- Aspect Ratio
- Rotation
- Stratification

Cause of transition - 2D constraints

- Aspect Ratio
- Rotation
- Stratification
- Vertical Shear

Cause of transition - 2D constraints

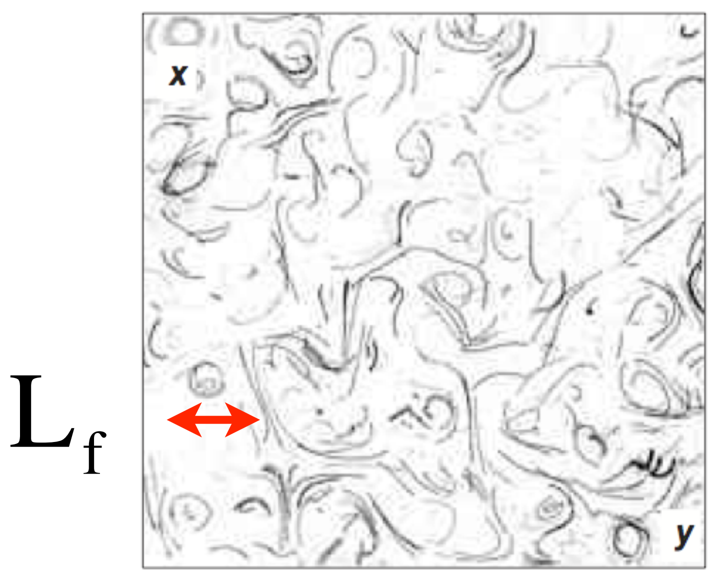
- Aspect Ratio
- Rotation
- Stratification
- Vertical Shear

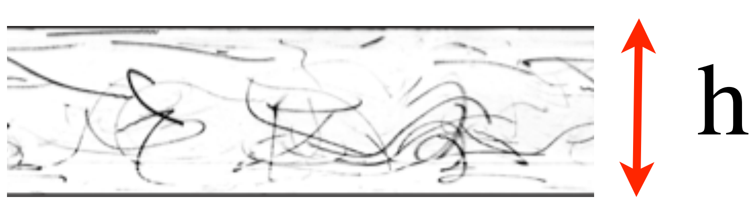
Transition 2-D to 3-D - Recent Progress

Transition 2-D to 3-D - Recent Progress

Aspect Ratio

$$h\,/\,L_f$$





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Transition 2-D to 3-D - Recent Progress

Direct Numerical Simulations (Celani et. al. (2010))

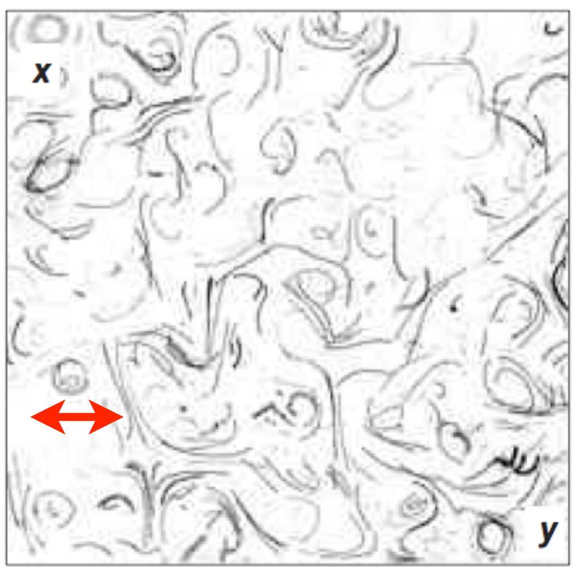
2-D $h / L_f < 0.5$

3-D $h / L_f > 0.5$

Aspect Ratio

$$h / L_f$$

L_f



h

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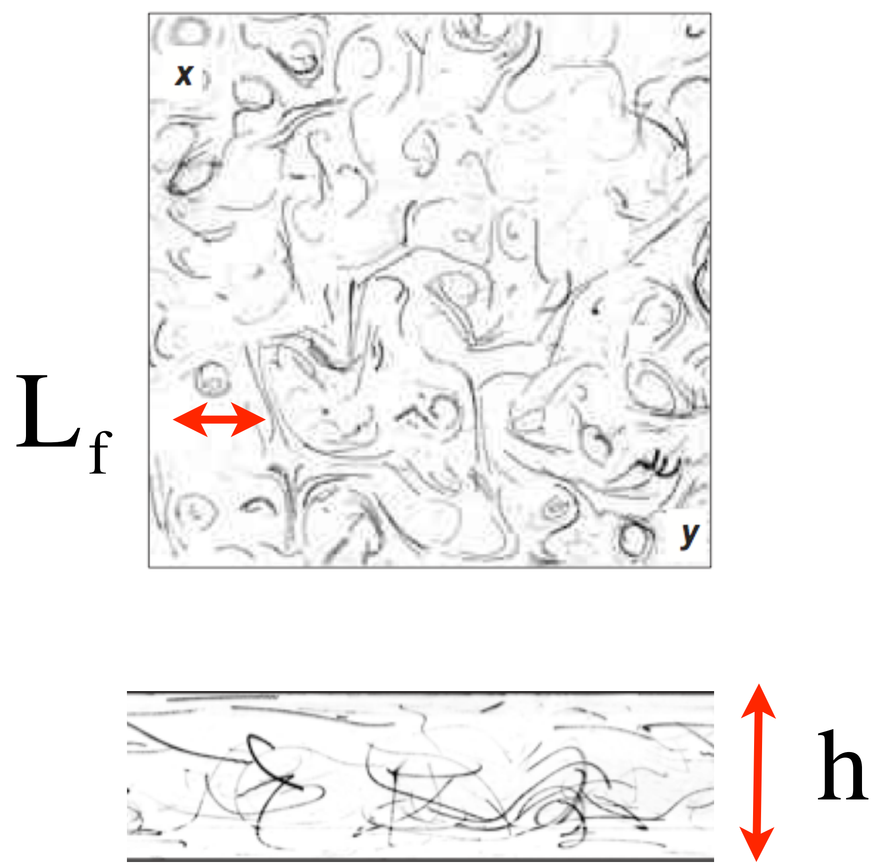
Transition 2-D to 3-D - Recent Progress

Aspect Ratio

$$h / L_f$$



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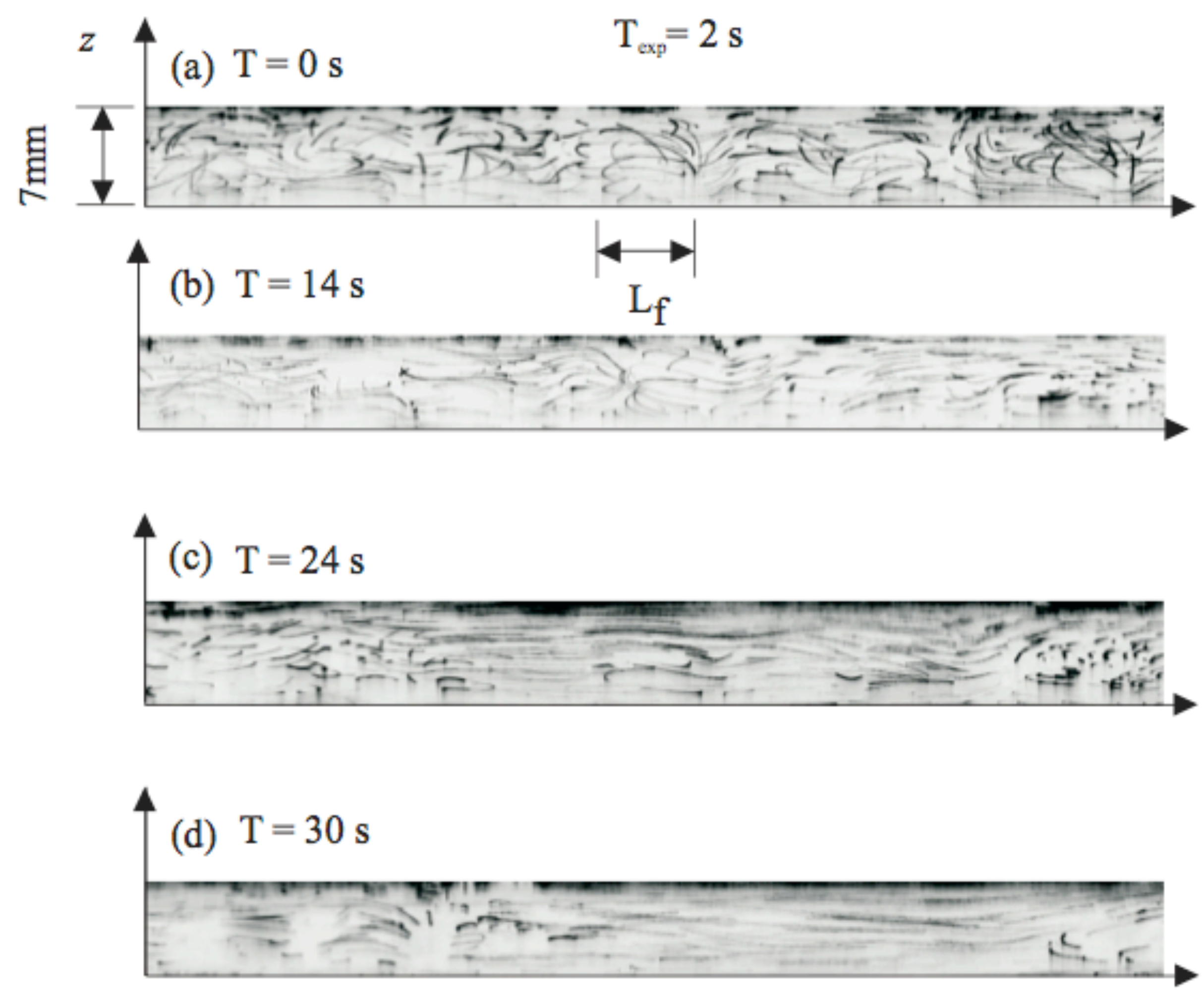

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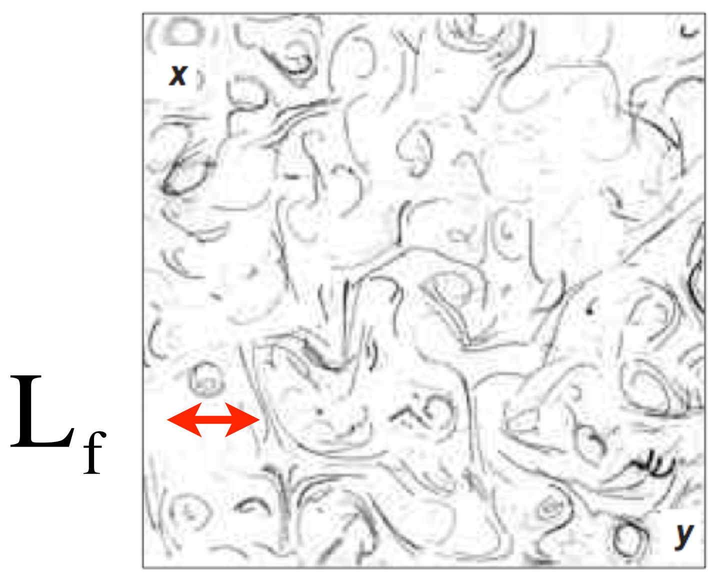

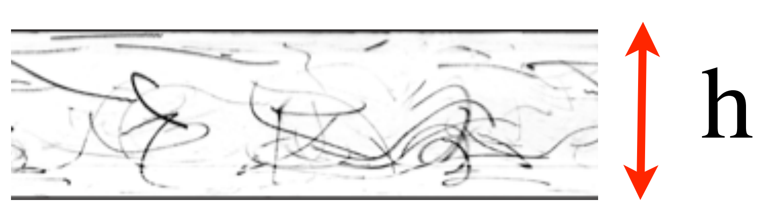

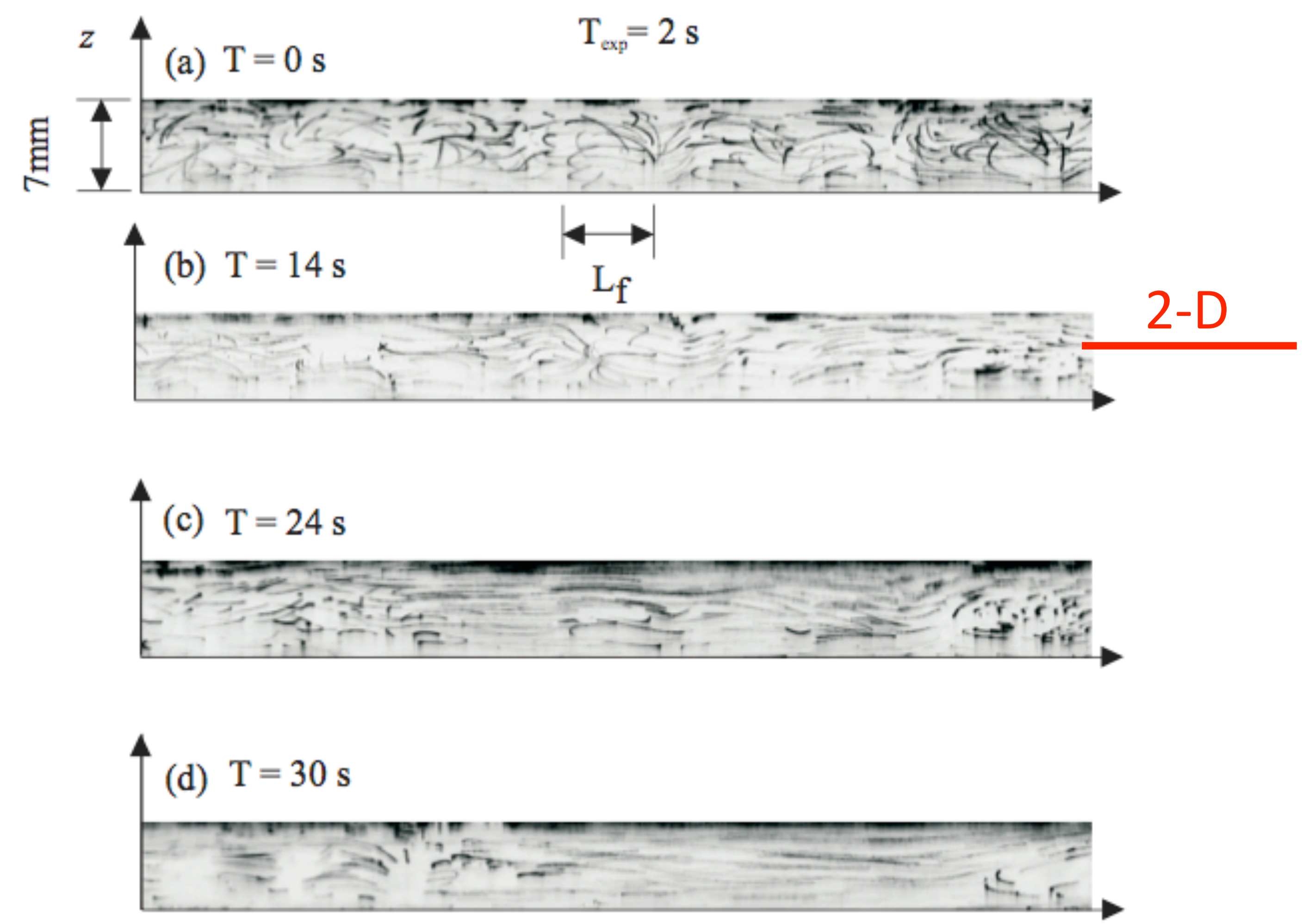

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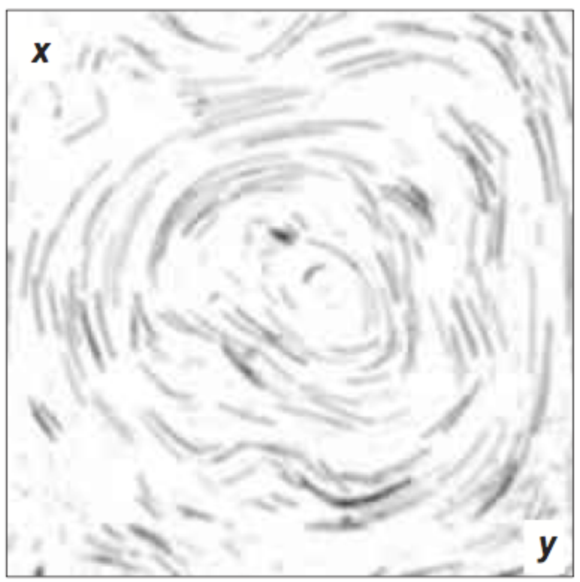
Experiments in Fluid Layers (Byrne et. al (2012))

L_f



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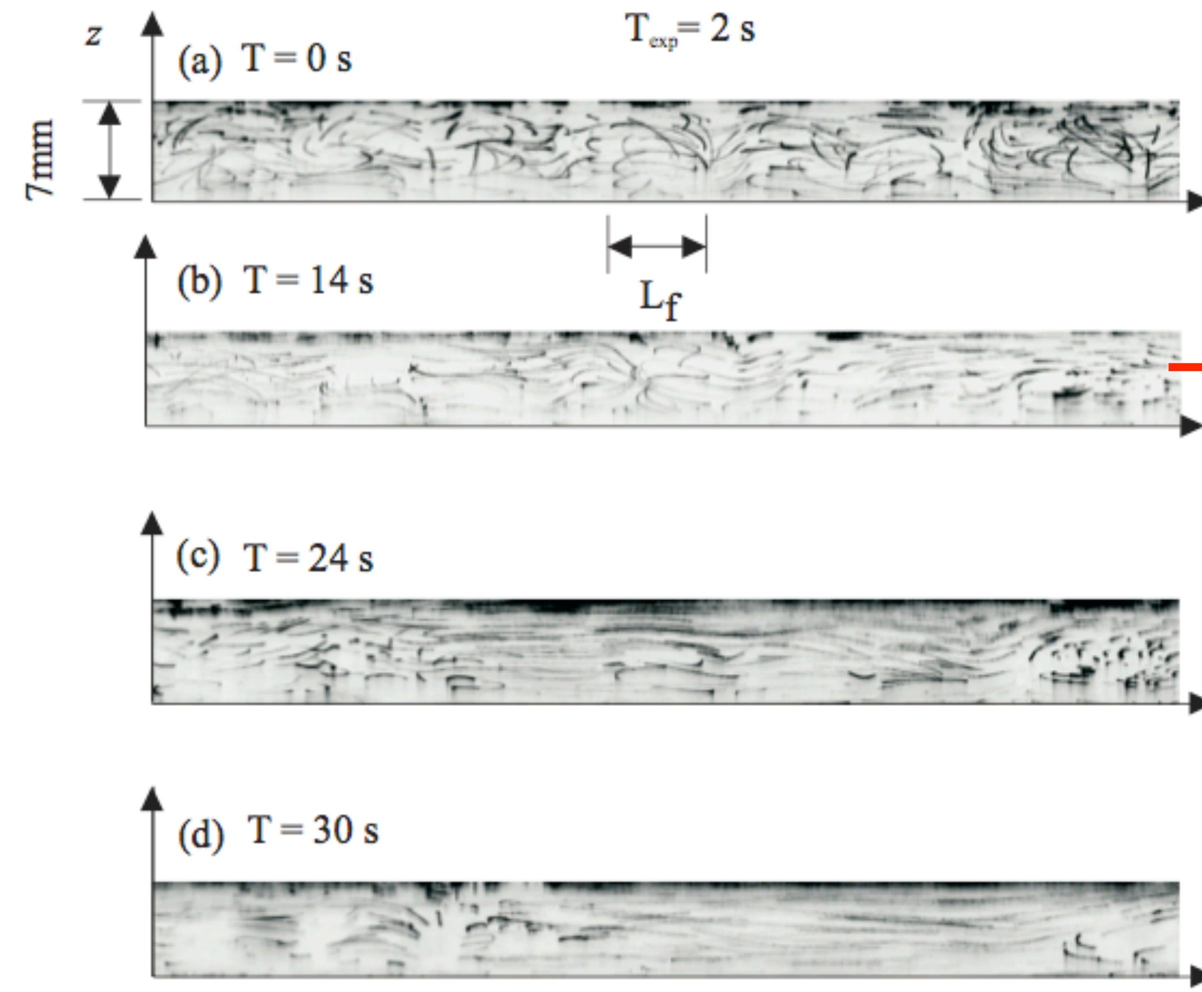

2-D

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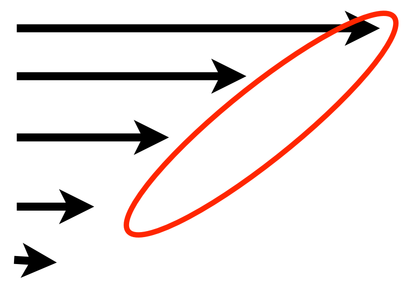
Transition 2-D to 3-D - Recent Progress

Transition 2-D to 3-D - Recent Progress

Shear

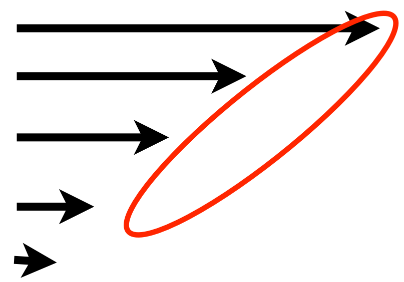


$$\Omega_{LS} = \frac{d < V_{xy} >}{dz} \quad \textbf{>} \quad \Omega_{3d} = < V_z >_{rms} / h$$

H. Xia et. al. Nature Physics 7 (4), 321-324 (2011)

Transition 2-D to 3-D - Recent Progress

Shear



$$\Omega_{LS} = \frac{d < V_{xy} >}{dz} \quad > \quad \Omega_{3d} = < V_z >_{rms} / h$$

Dissipation

$$\alpha = (\nu + K)\pi^2 / 2h^2$$

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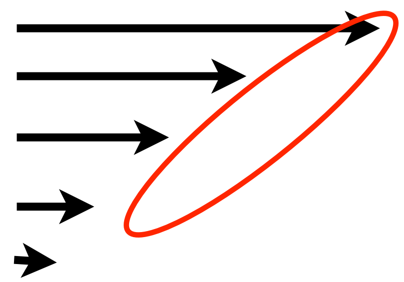
Transition 2-D to 3-D - Recent Progress

Shear

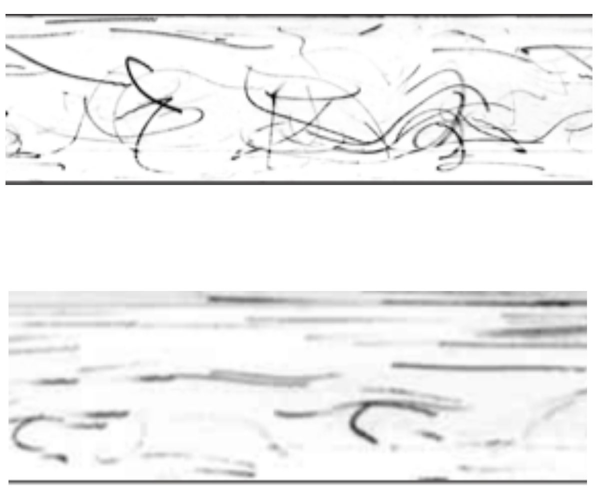


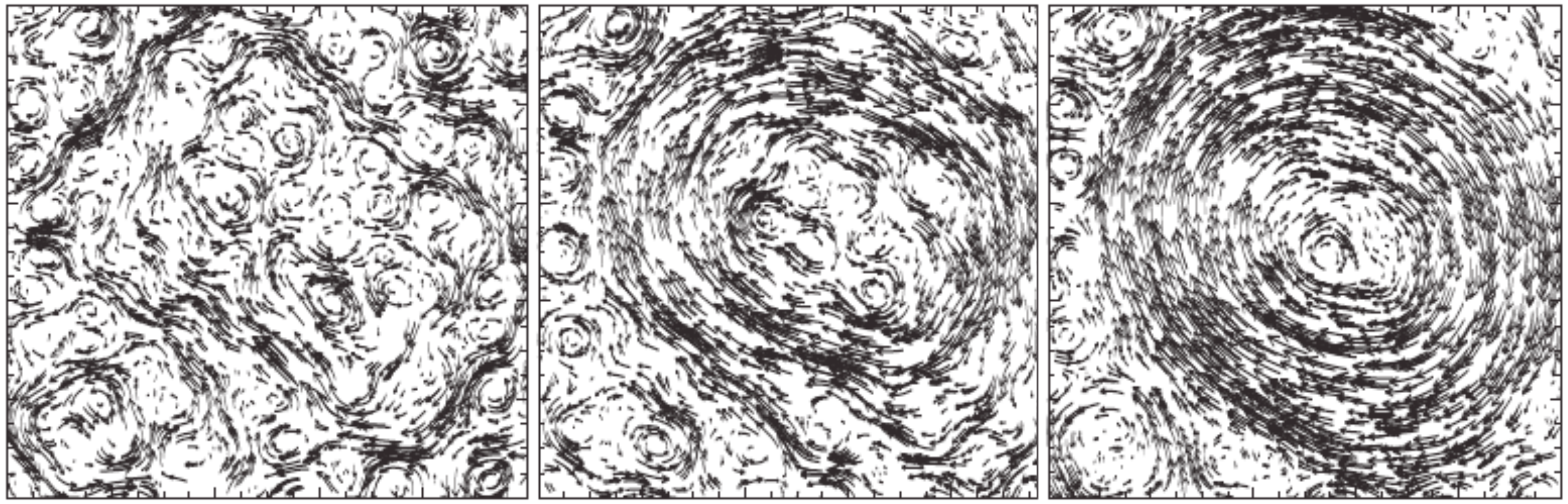
$$\Omega_{LS} = \frac{d < V_{xy} >}{dz} \quad > \quad \Omega_{3d} = < V_z >_{rms} / h$$

Feedback Loop

Dissipation

$$\alpha = (\nu + K)\pi^2 / 2h^2$$





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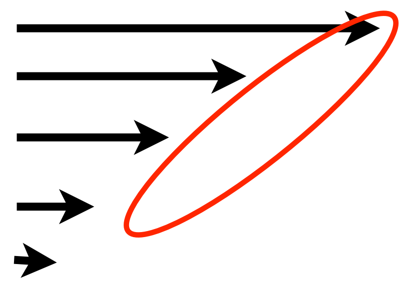
Transition 2-D to 3-D - Recent Progress

Shear

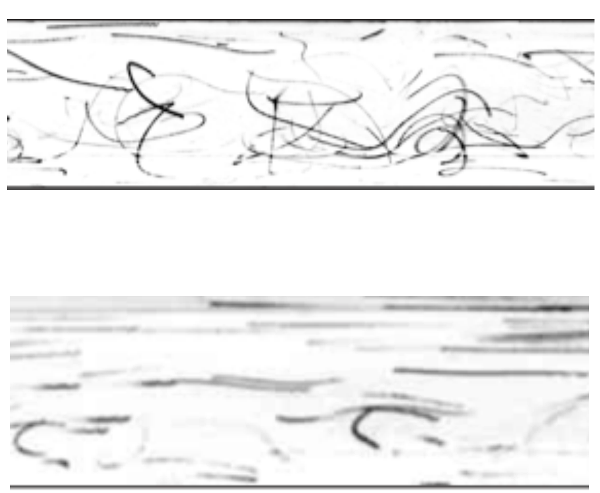


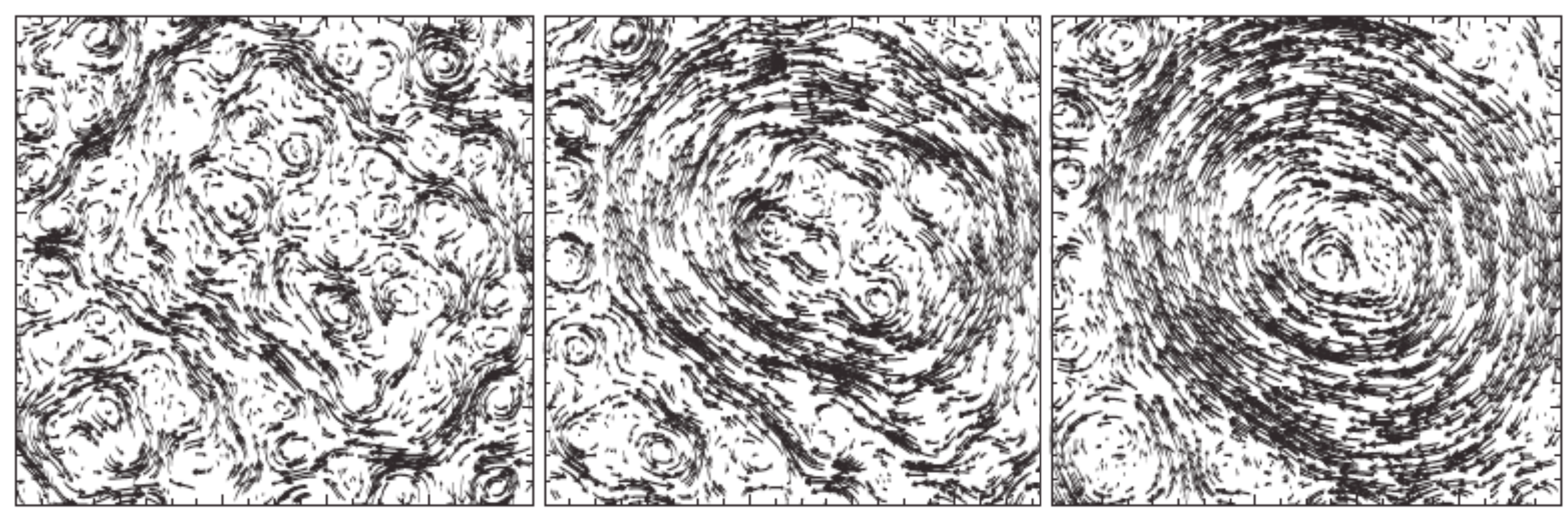
$$\Omega_{LS} = \frac{d < V_{xy} >}{dz} \quad > \quad \Omega_{3d} = < V_z >_{rms} / h$$

Feedback Loop

Dissipation

$$\alpha = (\nu + K)\pi^2 / 2h^2$$





Self Generated - Small scale forcing

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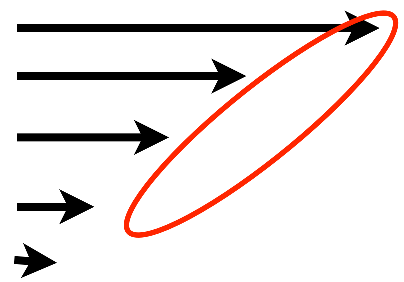
Transition 2-D to 3-D - Recent Progress

Shear

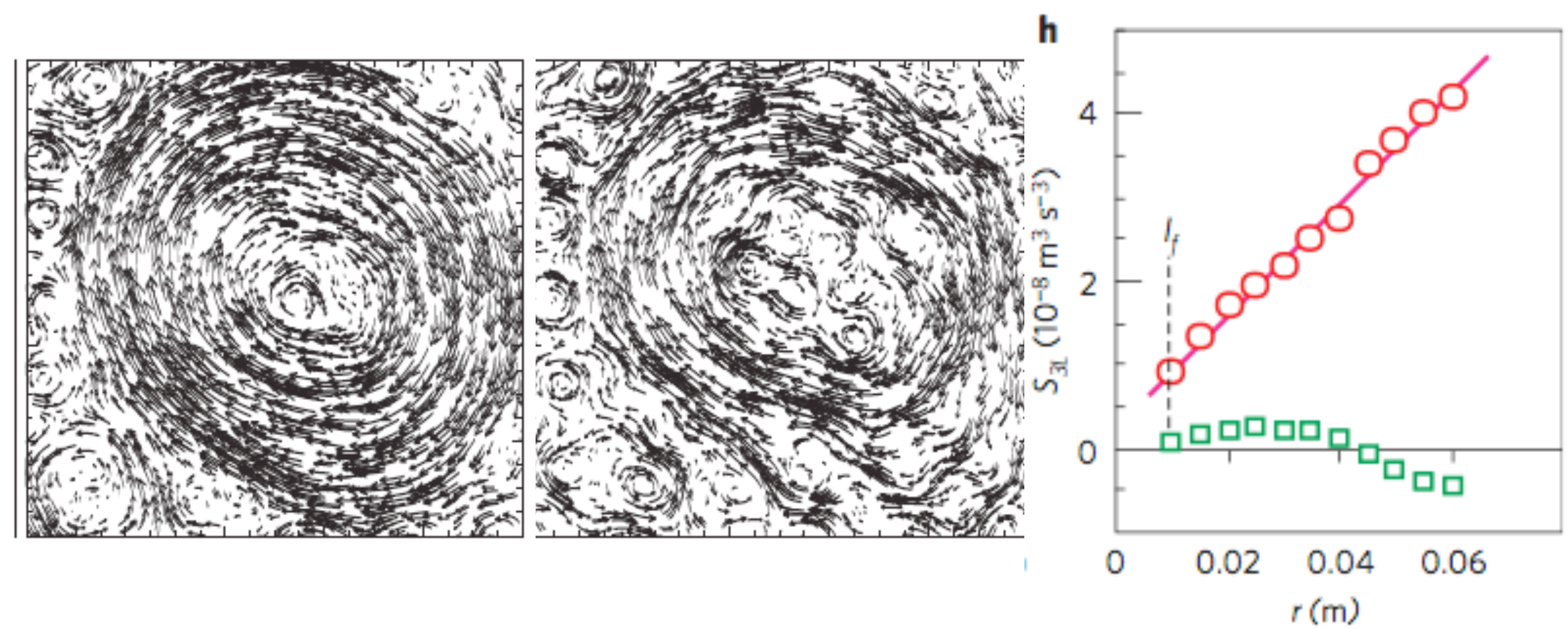


$$\Omega_{LS} = \frac{d < V_{xy} >}{dz} \quad > \quad \Omega_{3d} = < V_z >_{rms} / h$$

Dissipation

$$\alpha = (\nu + K)\pi^2 / 2h^2$$

Feedback Loop



Externally Forced - Forcing at large scale and small scale

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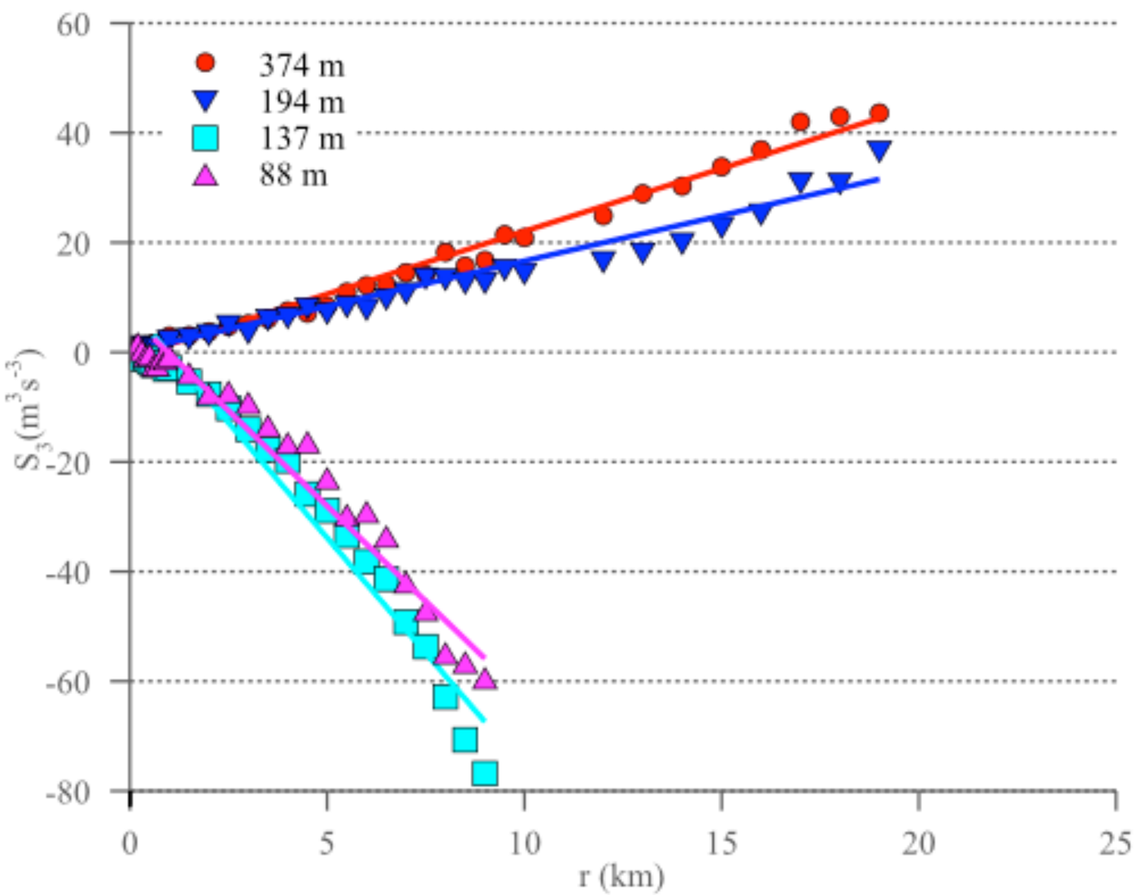
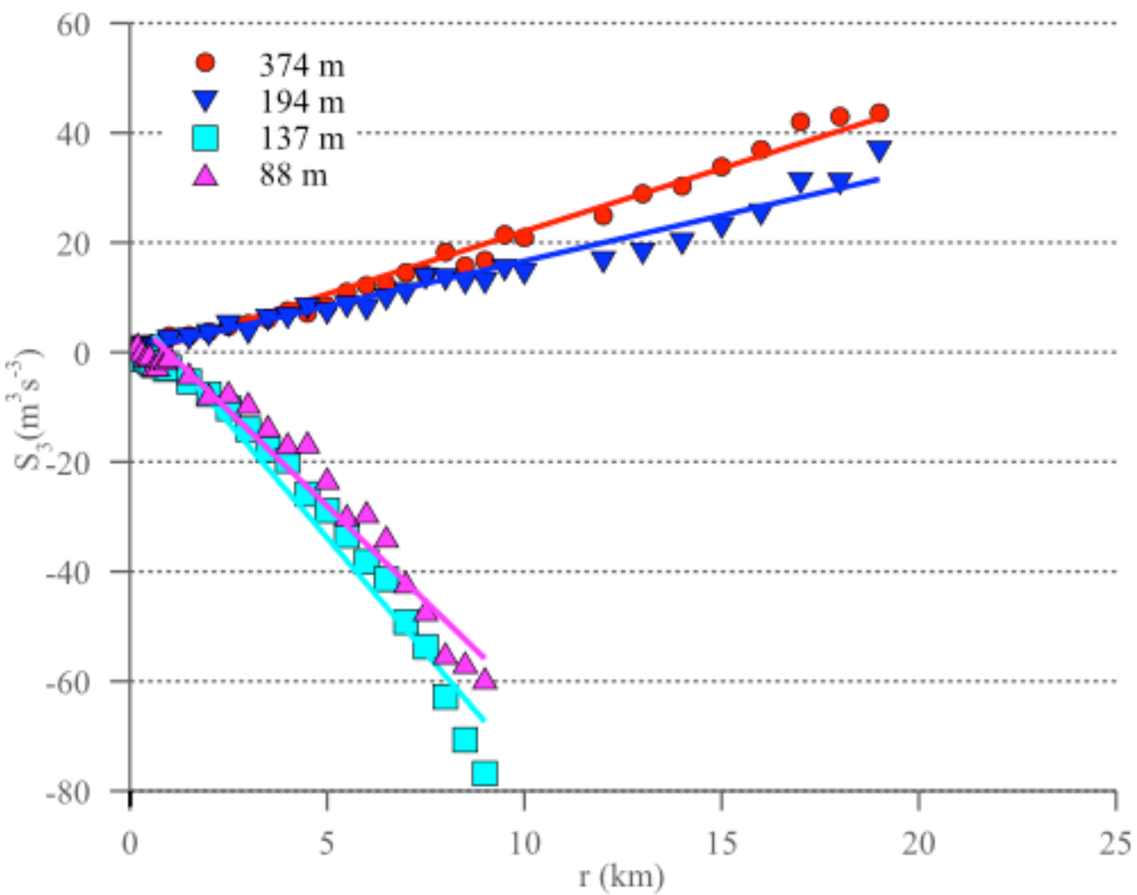
Potential cause of Transition



Potential cause of Transition

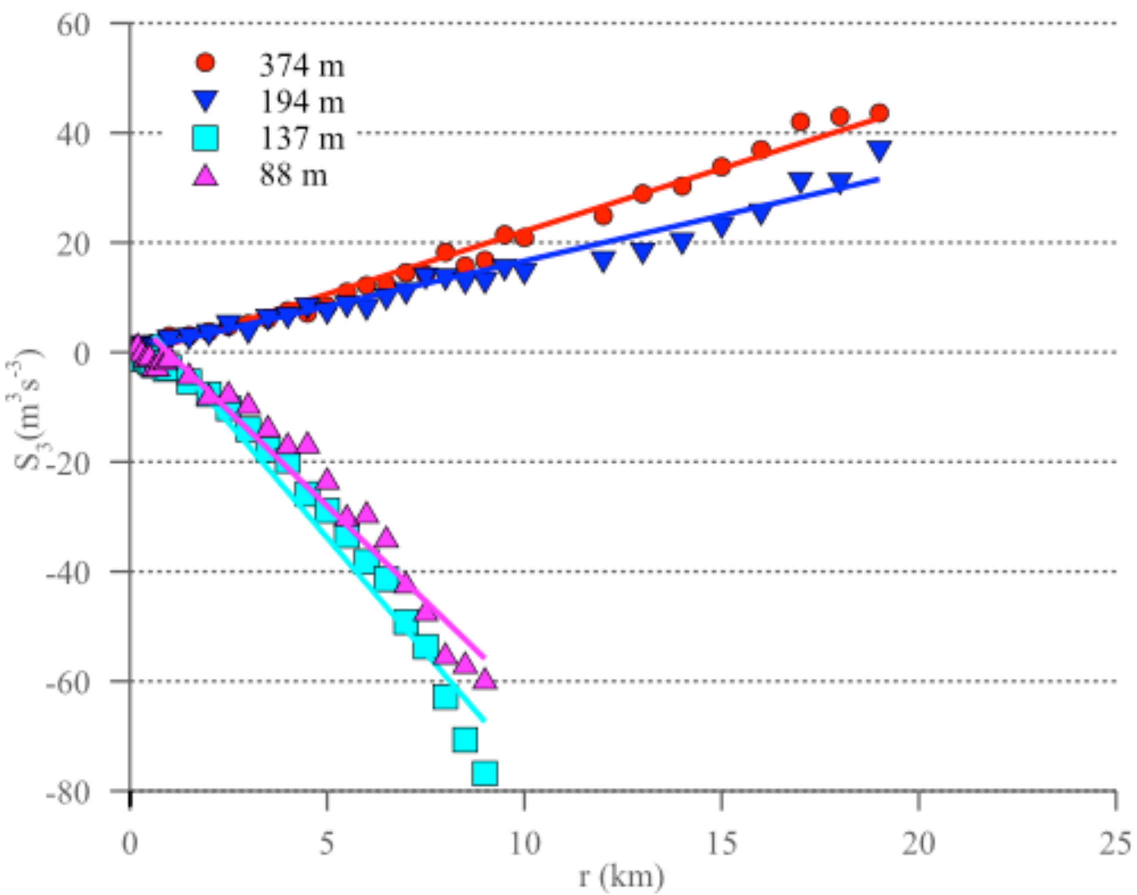


Shear Produces 3D eddies but also limits their size.

$$\Omega_{LS} = \frac{d < V_{xy} >}{dz} \quad > \quad \Omega_{3d} =< V_z >_{rms} /h$$

$h < 150m$

Potential cause of Transition



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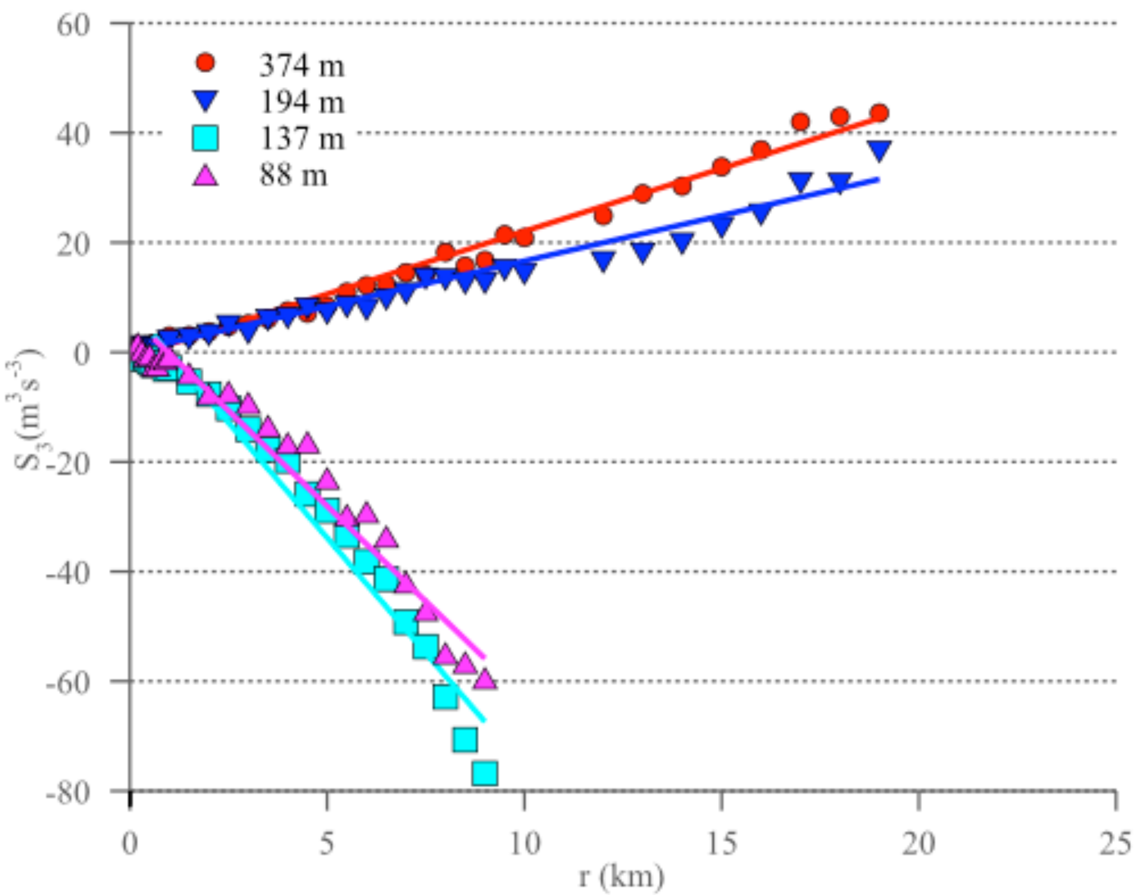

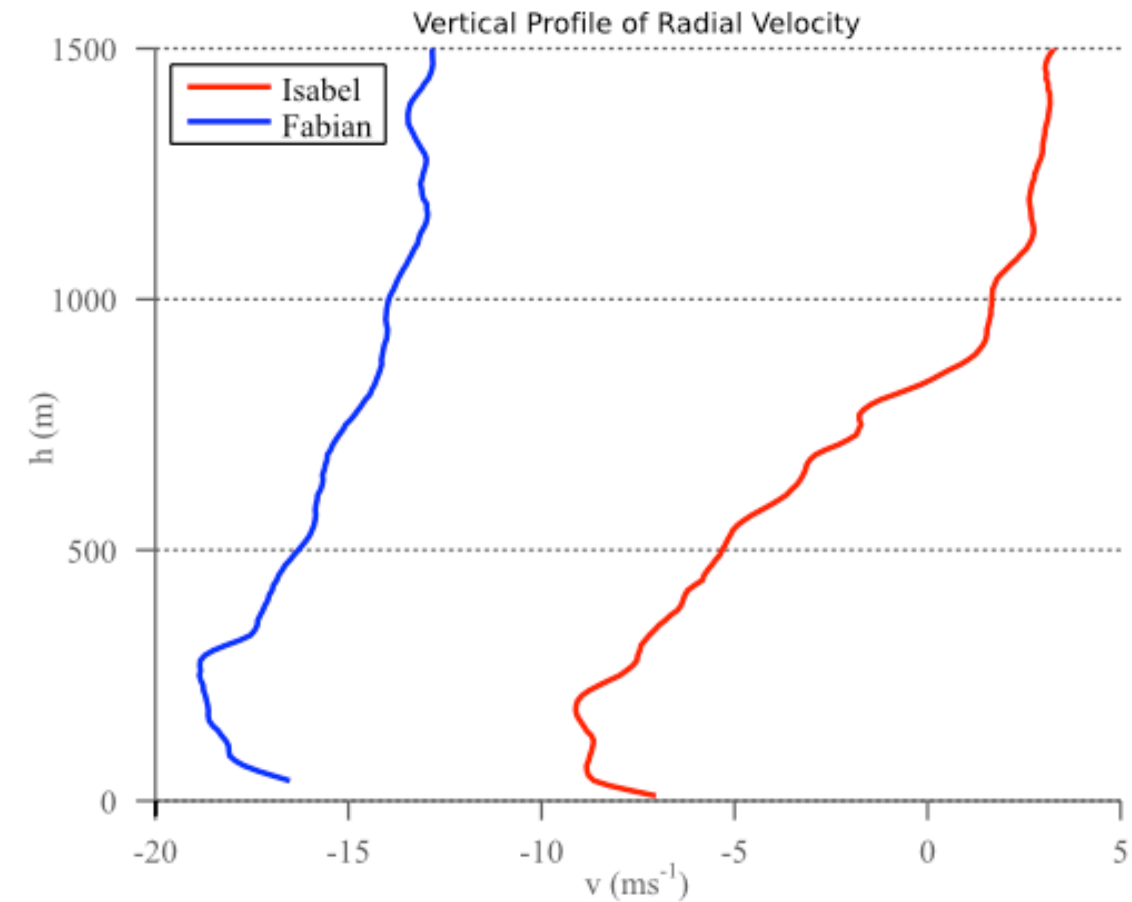

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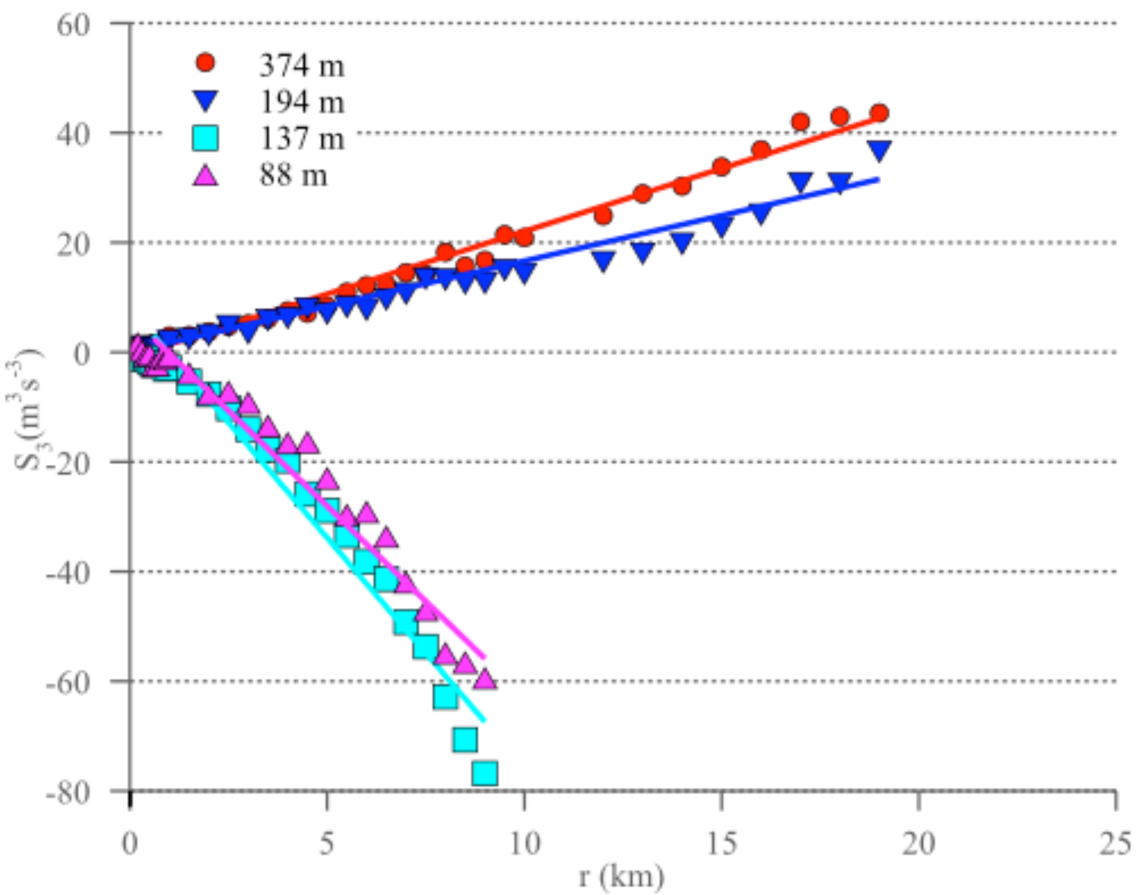

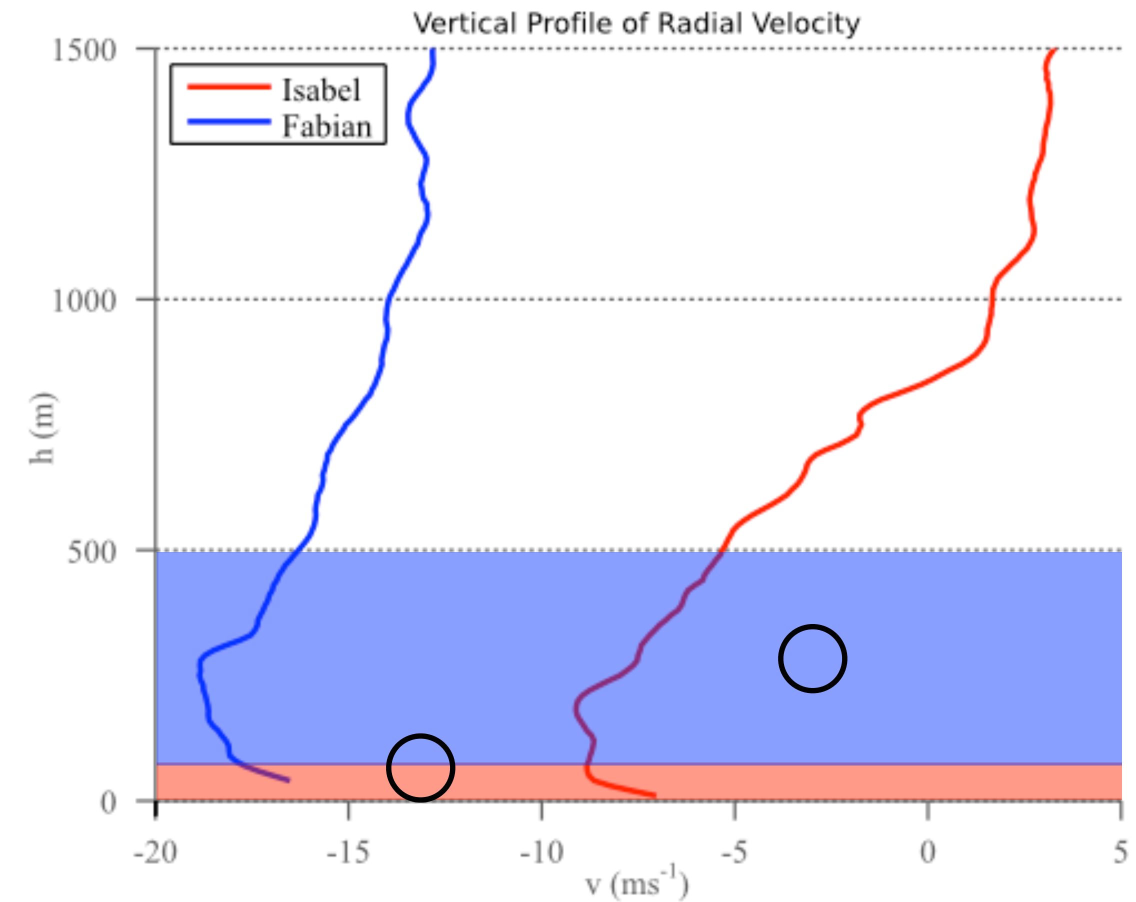

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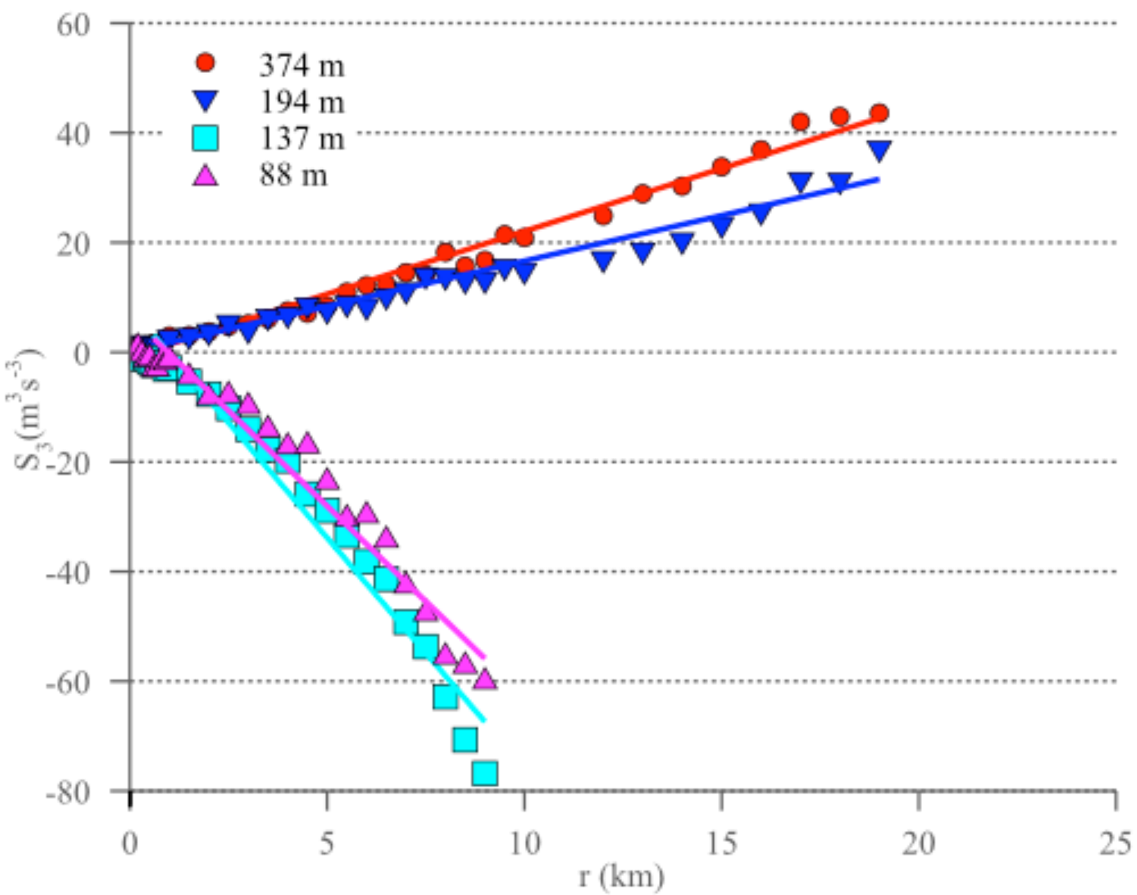

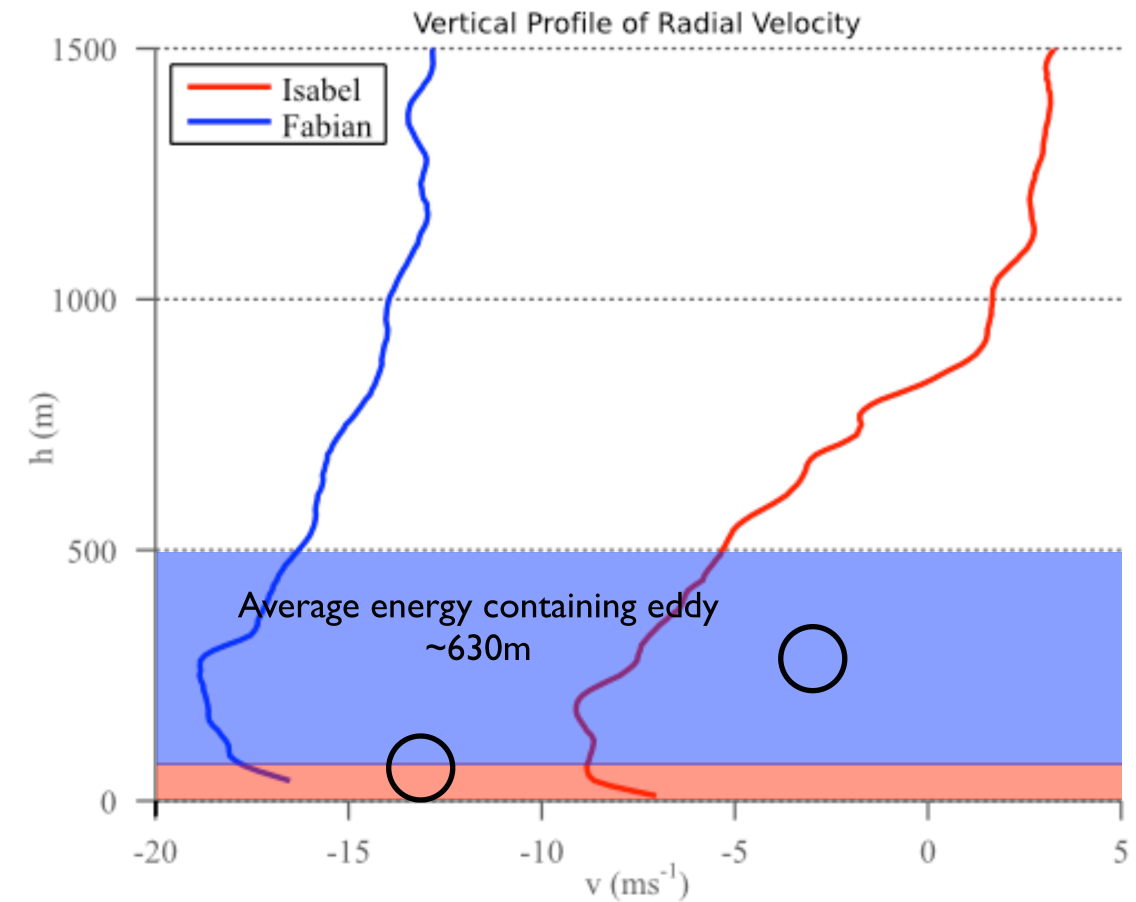

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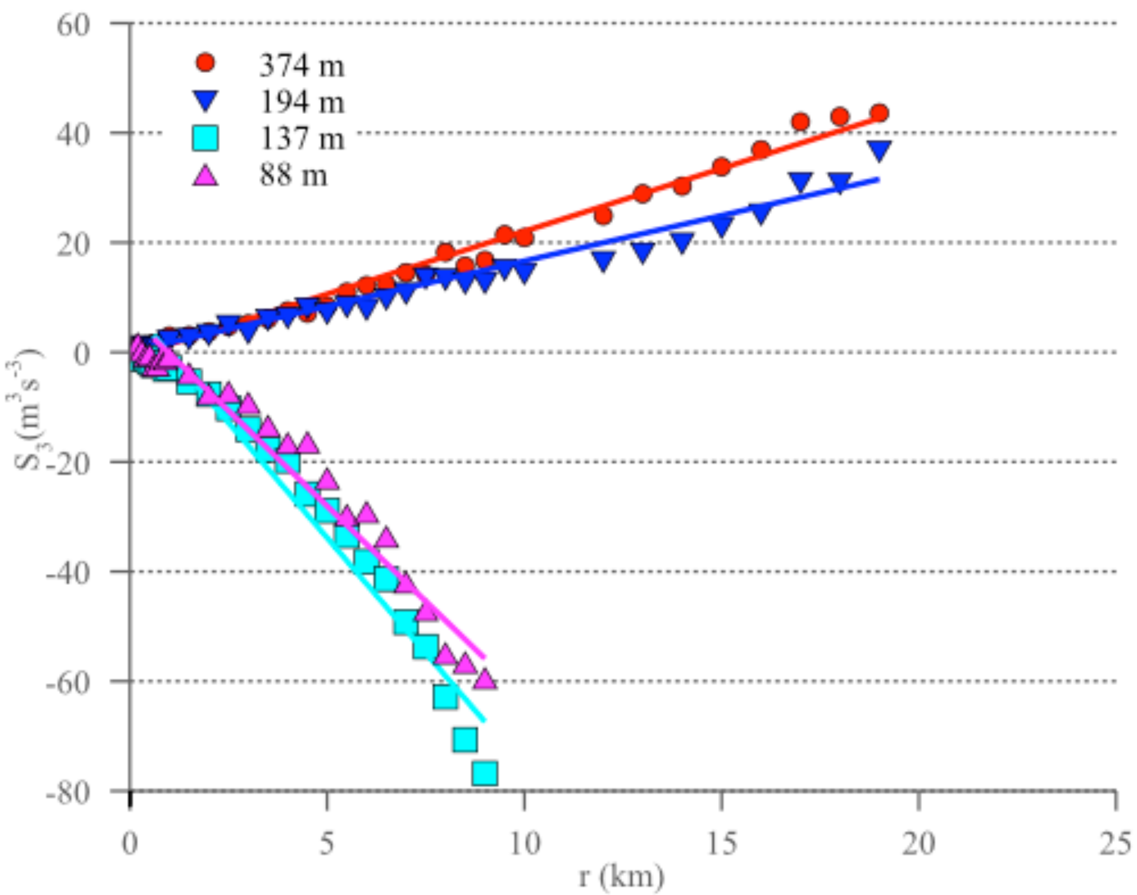

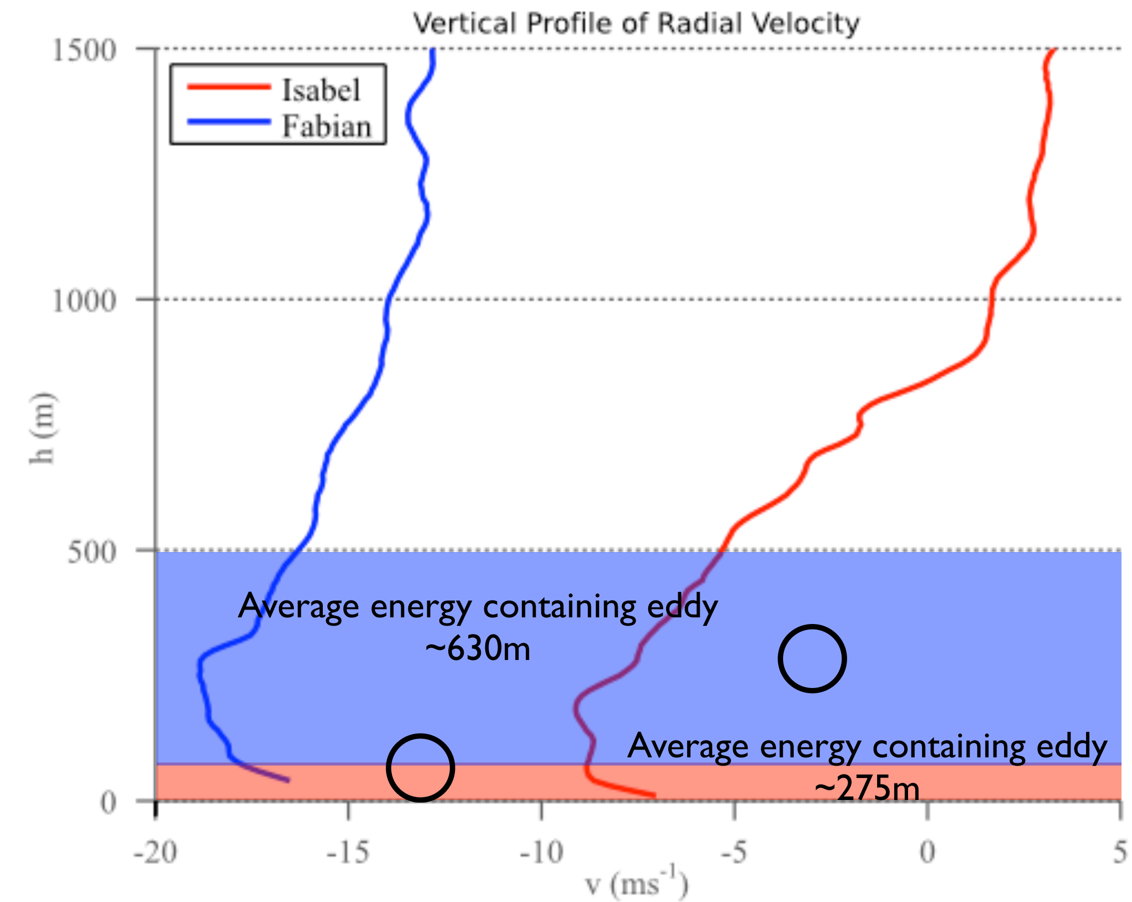

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- Boundary layer rolls are commonly observed, however from spectral analysis, Isabel and Fabian show no boundary layer rolls present. The effect on the transition of such phenomena remains to be seen.

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- Agrees with picture formed from results in fluid experiments and numerical simulations.

C2SM Center for Climate Systems Modeling

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Eidgenössische Technische Hochschule Zürich
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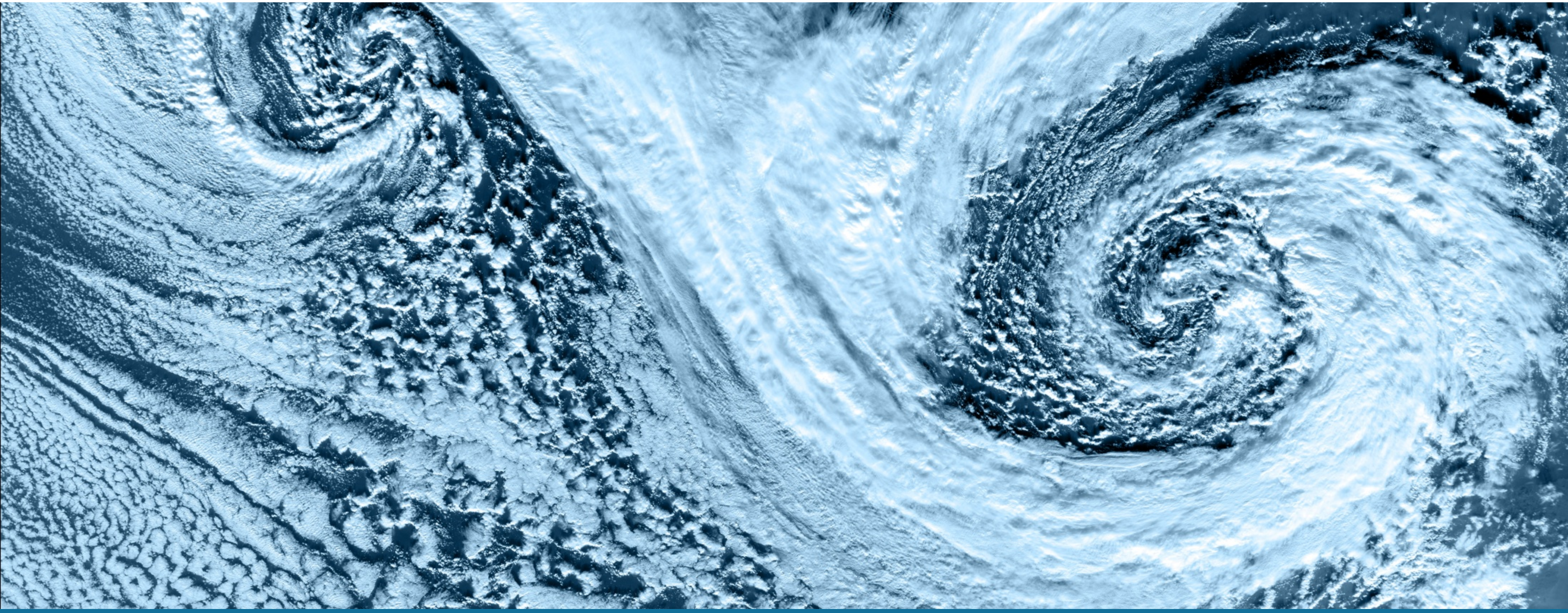
3-D to 2-D Turbulence Transition in the Hurricane Boundary Layer

David Byrne and Jun A. Zhang

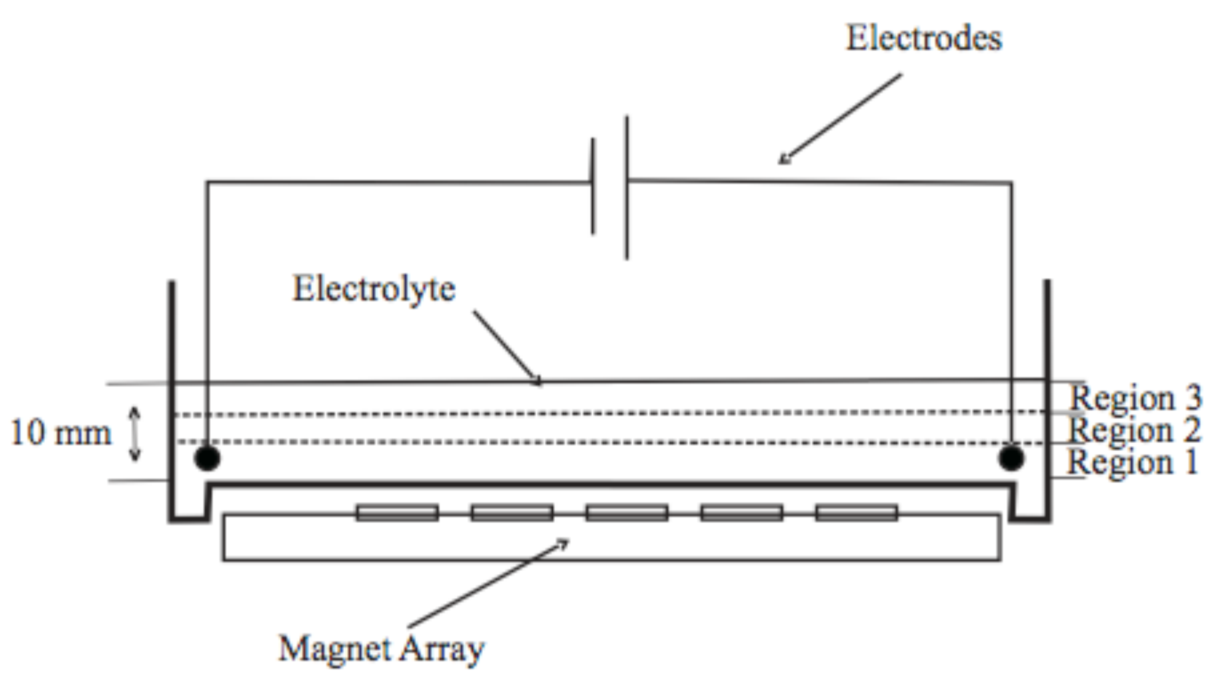
UP
Environmental Physics



Transition 2-D to 3-D - Recent Progress

Height Dependence

Experiments in Fluid Layers (Byrne et. al (2012))



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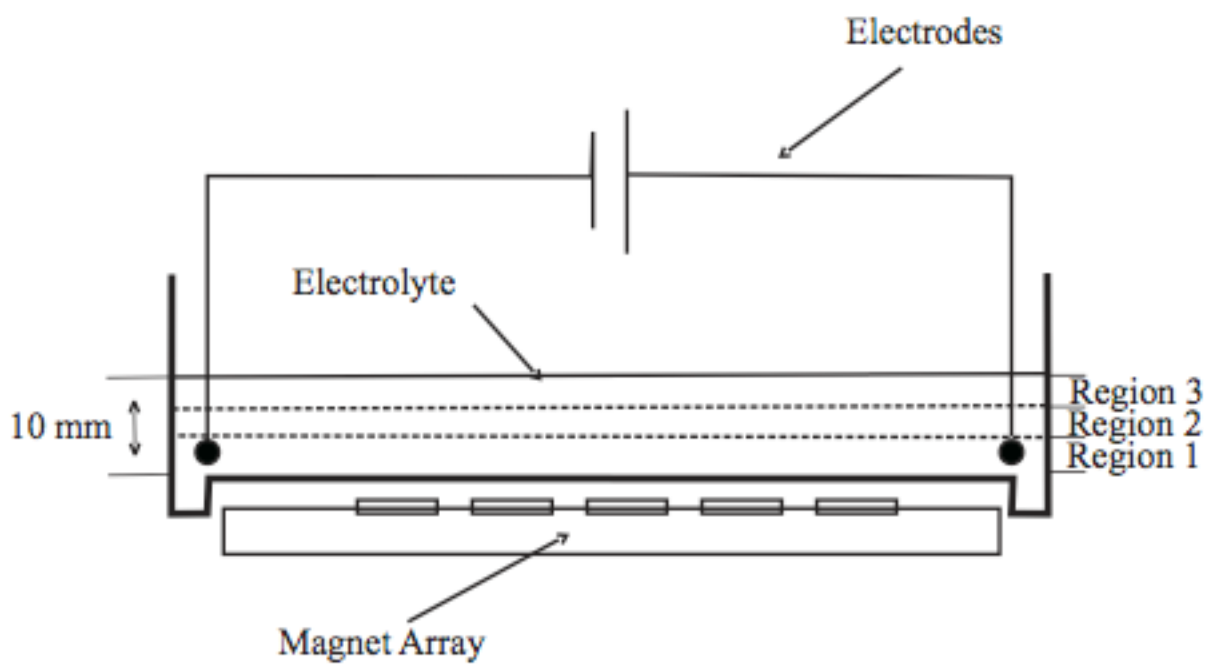

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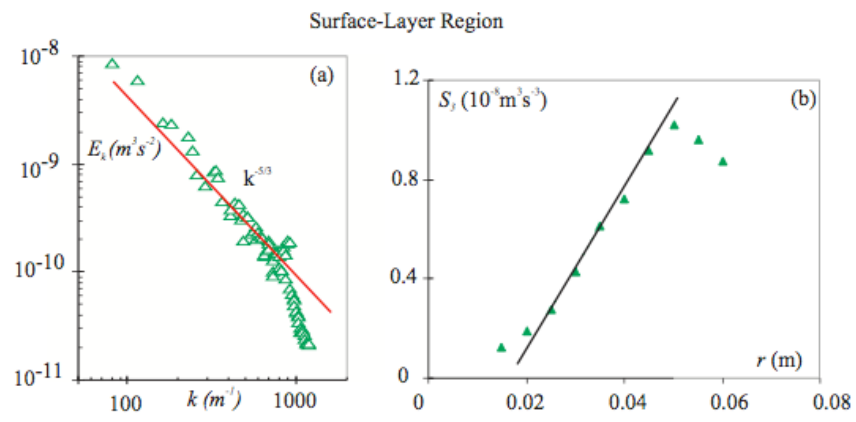

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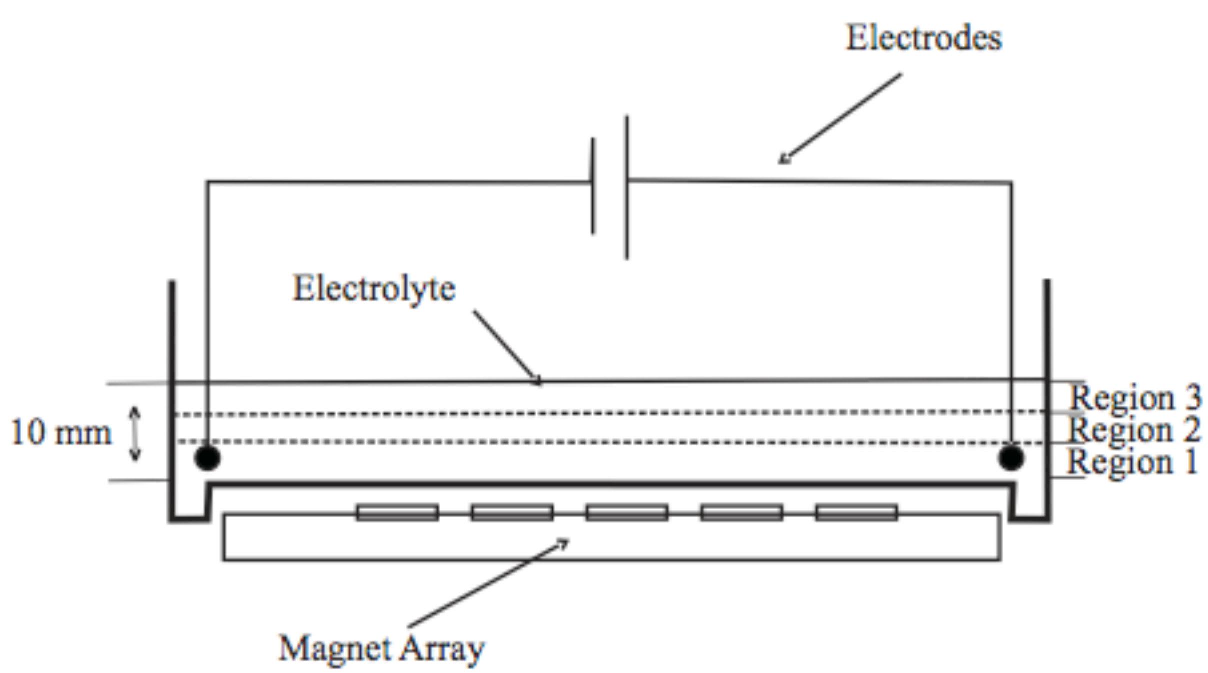

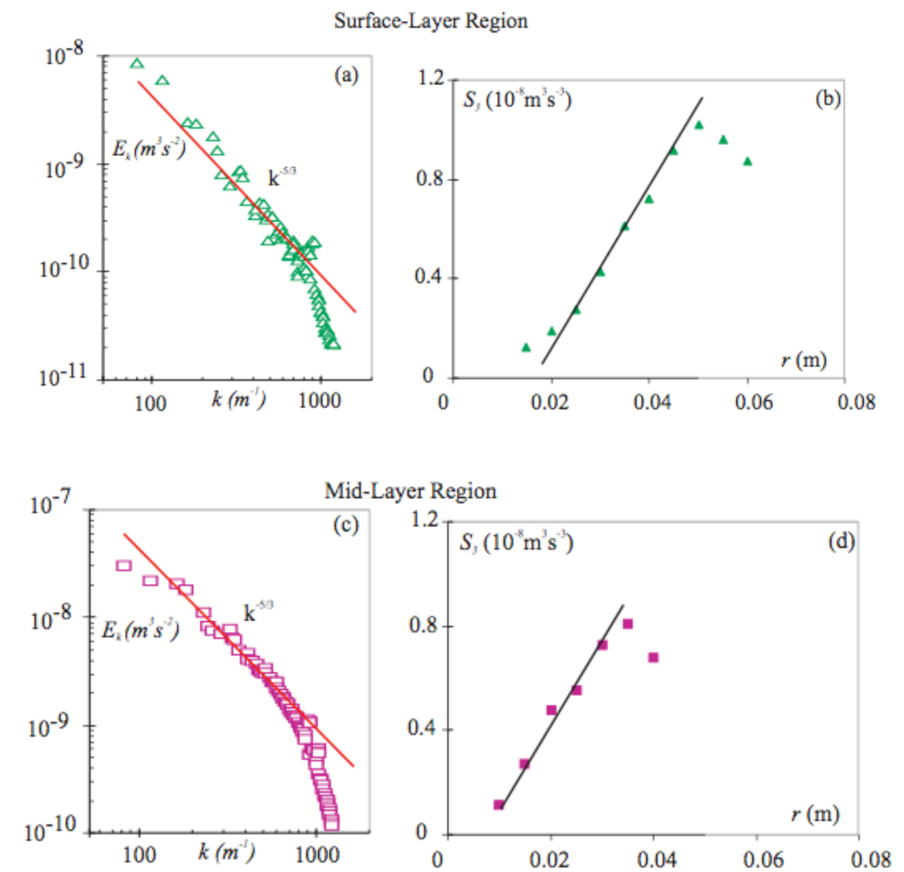

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