MISR Observations and Numerical Modeling of Kármán Vortex Streets

Á. Horváth  
TROPOS, Leipzig

K. Mueller  
JPL, Pasadena

C. Nunalee  
NCSU, Raleigh

Pico do Fogo, Cape Verde  
12 June 2014

@astro_reid: Volcanoes make great artists
@astro_alex: Fascinating! Another good example that sometimes you have to take a step back to see the big picture...

IWW12, 15-20 June 2014, Copenhagen
aspect ratio: \( h / l = 0.28 \) (Kármán and Rubach [1912])

dimensionless width: \( h / d = 1.20 \) (Tyler [1930])
VKVSs form when a mountain penetrates a strong thermal inversion, below which the boundary layer is well-mixed [Etling, 1989]
Research Questions

Science
- How do atmospheric VKVSs compare to classical VKVS theory?
  - Shedding rate
  - Influence of added vertical dimension
  - Impact of island shape and roughness
- Can we formulate new physical relationships between environmental parameters and vortex characteristics?

Application
- What kind of wind shears do they induce?
- How do they influence scalar transport and dispersion?
Global Distribution of Kármán Vortex Streets From MERIS

M. Paperin, Cloud Structures, Brockmann Consult, Germany
Kármán Vortex Streets From MISR
Kármán Vortex Streets From MISR

P215_O006672
Kármán Vortex Streets From MISR

- Height-resolved stereo winds
- Operational resolution: 17.6 km (old)
Vorticity Field
Idealized Large Eddy Simulation

Heinze et al. [2012], Meteorol. Z.
Mean Vorticity vs. Distance From Island

Sample number: MISR = 88, LES = 333
WRF Simulation of Madeira, 9 July 2010

- **Initial/Boundary Conditions**
  - ERA-Interim Reanalysis

- **3-D Domain**
  - 1 km x 1 km horizontal resolution
  - 50 vertical grid points

- **30-hour simulation (Δt = 10 min)**
  - 8 July 18:00 to 9 July 24:00 (MISR at 10:30, 9 July)

- **Default Physics Schemes**

  Peak Elevation = 1862 m
WRF DEM Peak Elevation = 1318 m
Madeira, 9 July 2010: MISR P209_O056155
Madeira, 9 July 2010: Meteosat-9 IR
Madeira, 9 July 2010: Meteosat-9 VIS

Vortex shedding frequency 4-5 hours
Madeira, 9 July 2010: WRF simulation

Streamlines at level 10 (~400 m)
Madeira, 9 July 2010: WRF simulation

Wind speed at level 10 (~400 m)
Madeira, P209_O056155: wind vector comparison

level = 10
Madeira, P209_O056155: streamlines comparison
level = 10

MISR

WRF
Madeira, P209_O056155: wind speed comparison
level = 10

MISR

WRF
Madeira, P209_O056155: U component comparison
level = 10

MISR

WRF
Madeira, P209_O056155: V component comparison
level = 10
Madeira, P209_O056155: wind speed comparison using MISR absolute heights
Madeira, P209_O056155: wind speed comparison using MISR relative heights

MISR

WRF
Madeira, P209_O056155: U component comparison using MISR absolute heights
Madeira, P209_O056155: U component comparison using MISR relative heights
Madeira, P209_O056155: V component comparison using MISR absolute heights
Madeira, P209_O056155: V component comparison using MISR relative heights
Madeira, P209_O056155: U component comparison using MISR relative heights vs. WRF levels.
Madeira, P209_O056155: V component comparison using MISR relative heights and WRF levels
Madeira, P209_O056155: streamlines comparison using MISR relative heights ±3 WRF levels
Madeira, P209_O056155: wind vector comparison using MISR relative heights ±3 WRF levels.
Madeira, P209_O056155: wind direction comparison using MISR relative heights ±3 WRF levels
Madeira, P209_O056155: wind field comparison statistics using MISR relative heights ±3 WRF levels
Madeira, P209_O056155: wind field comparison statistics using MISR relative heights. WRF levels, outside wake.
Madeira, P209_O056155: wind field comparison statistics using MISR relative heights with WRF relative wind wake
Summary

- Downstream decrease of vorticity measured by MISR agrees well with idealized LES simulations

- WRF simulations of specific cases: accurately representing topography is crucial

- Using relative (to the mountain peak) heights and accounting for uncertainty in MISR height retrievals yields decent agreement between measured and modeled wind fields

- WRF-modeled vortex streets are shorter and narrower (stronger dissipation, problems with representing topography)

- Next steps: runs with different boundary layer parameterizations, increased horizontal resolution
Backup Slides
aspect ratio: \( \frac{h}{l} = 0.28 \)  
(Kármán and Rubach [1912])

dimensionless width: \( \frac{h}{d} = 1.20 \)  
(Tyler [1930])
Vortex Geometry Analysis

vortex centers

intervortex midpoints

3rd order polynomial centerline

H,L,D calculate ratios H / L and H / D

(02)  P217_O007808
Analyzed Cases

(01) P215_O006672
03/20/2001

(02) P217_O007808
06/06/2001

(03) P214_O023812
06/09/2004

(04) P213_O024875
08/21/2004

(05) P216_O028210
04/07/2005

(06) P217_O028778
05/16/2005

(07) P218_O033540
04/08/2006

(08) P213_O051903
09/20/2009

(09) P218_O051947
09/23/2009

(10) P213_O065417
04/05/2012

(11) P040_O002569
11/06/2000

(Guadalupe Island)
### Measured Vortex Geometry

<table>
<thead>
<tr>
<th>Path_Orbit</th>
<th>H / L (aspect ratio)</th>
<th>H / D (dimensionless width)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(01) P215_O006672</td>
<td>0.47</td>
<td>1.54</td>
</tr>
<tr>
<td>(02) P217_O007808*</td>
<td>0.36</td>
<td>0.94</td>
</tr>
<tr>
<td>(03) P214_O023812*</td>
<td>0.38</td>
<td>1.60</td>
</tr>
<tr>
<td>(04) P213_O024875</td>
<td>0.32</td>
<td>1.29</td>
</tr>
<tr>
<td>(05) P216_O028210</td>
<td>0.30</td>
<td>0.62</td>
</tr>
<tr>
<td>(06) P217_O028778*</td>
<td>0.37</td>
<td>0.91</td>
</tr>
<tr>
<td>(07) P218_O033540*</td>
<td>0.39</td>
<td>1.11</td>
</tr>
<tr>
<td>(08) P213_O051903*</td>
<td>0.37</td>
<td>1.56</td>
</tr>
<tr>
<td>(09) P218_O051947</td>
<td>0.12</td>
<td>0.46</td>
</tr>
<tr>
<td>(10) P213_O065417</td>
<td>0.46</td>
<td>1.38</td>
</tr>
</tbody>
</table>

**Kármán and Rubach [1912]**

**Tyler [1930]**

**Young and Zawislak [2006] (MODIS, 30 cases)**

- straight centerline: 0.36 - 0.47
- curved centerline: 0.30 - 0.43

*well-developed vortices, extensive cloud sheets, clear centers*
Sr-Re Similarity Theory

- Studies over the past 20-30 years have solely focused on the lower Re end of the spectrum, leaving the higher Re side (i.e. $>10^7$) largely unexplored.

- Atmospheric VKVSs provide the opportunity to study the behavior of N at very high Reynolds number (i.e. $10^7 - 10^{10}$)
Strouhal-Reynolds Number Similarity Theory

2D flow around a cylinder with convergence (blue) and prarticle divergence (red).
Credit: American Physical Society/Jens Kasten, Christoph Petz, Ingrid Hotz, Gilead Tadmor, Bernd R. Noack, Hans-Christian Hege

Still no universal equation for vortex shedding frequency (N)!

However, laboratory studies have proved similarity relationships between Reynolds number and dimensionless shedding frequency (Sr)...
PBL-Parameterization Sensitivity: cloud cover

MYJ-scheme  QNSE-scheme  ACM2-scheme

observation
Real Case Study: Madeira and the Canary Islands

MODIS

WRF Simulated Clouds

Shedding frequency ~5.5 hours
Madeira, P209_O056155: WRF U-wind time-height plot
Madeira, P209_O056155: WRF V-wind time-height plot
Madeira, P209_O056155: WRF full wind time-height plot
Madeira, P209_O056155: wind speed comparison using MISR relative heights ±3/9 WRF levels.
Madeira, P209_O056155: U component comparison using MISR relative heights vs. WRF levels.
Madeira, P209_O056155: V component comparison using MISR relative heights ±3 WRF levels
Madeira, P209_O056155: wind field comparison statistics using MISR relative heights 3/3 WRF levels