MISR Observations and Numerical Modeling of Kármán Vortex Streets

Á. Horváth
TROPOS, Leipzig

K. Mueller
JPL, Pasadena

C. Nunalee
NCSU, Raleigh

@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...

TROPOS
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IWW12, 15-20 June 2014, Copenhagen

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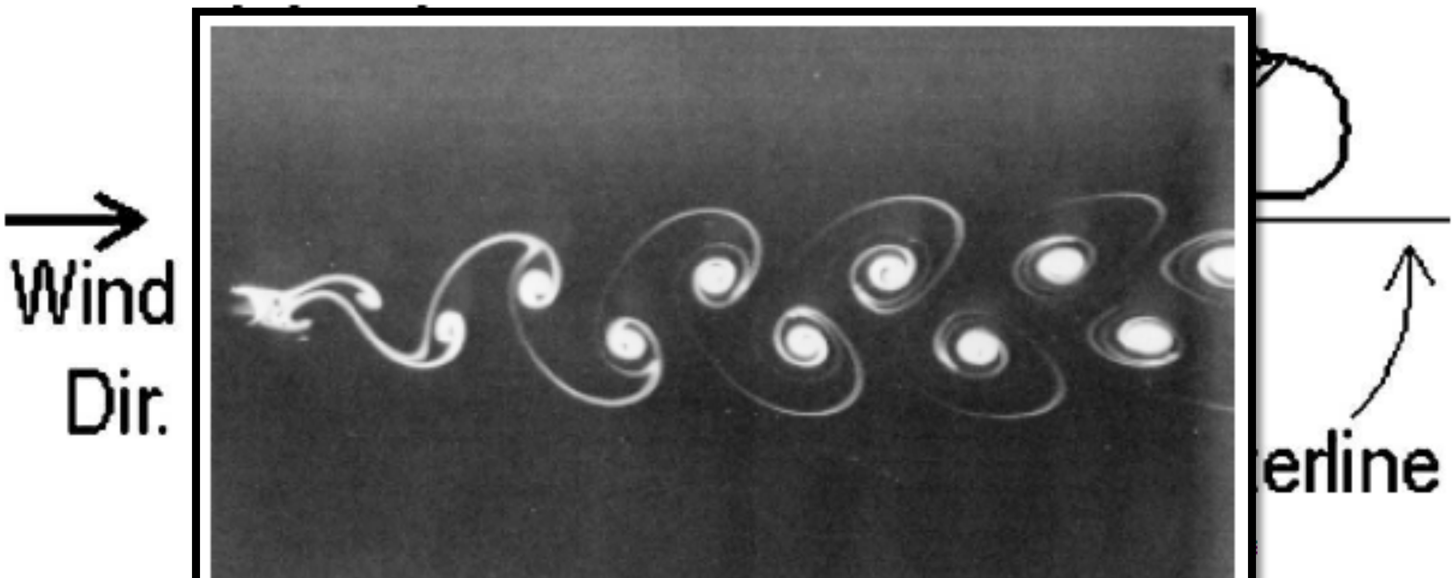
Classic von Kármán Vortex Street



Karman vortex street behind a cylinder placed in uniform flow. Re ~ 300 [Courtesy: Sadotoshi Taneda; from An Album of Fluid Motion by Van Dyke (1982)]

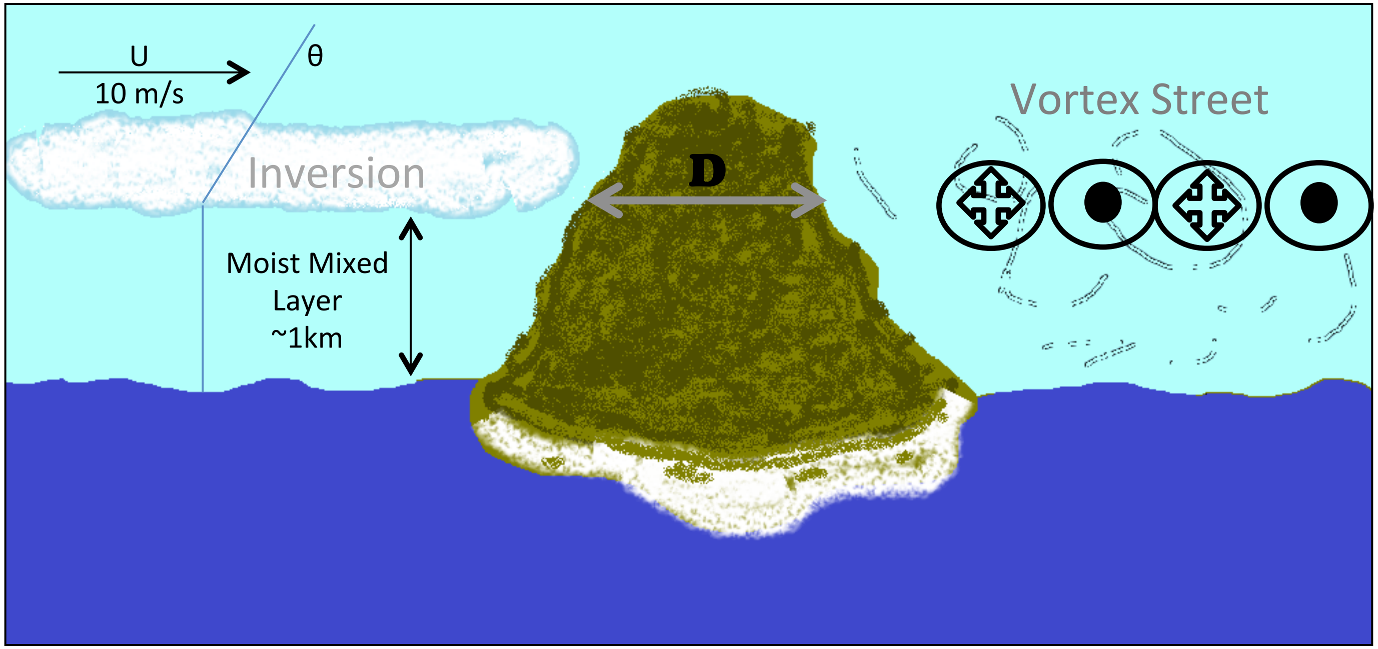
aspect ratio: *ubach* [1912])

dimensionless width: **h / d = 1.20** (*Tyler* [1930])

Cesareo de la Rosa Siqueira, University of Sao Paulo, Brazil

Atmospheric von Kármán Vortex Street (VKVS)

VKVSs form when a mountain penetrates a strong thermal inversion, below which the boundary layer is well-mixed [Etling, 1989]



Research Questions

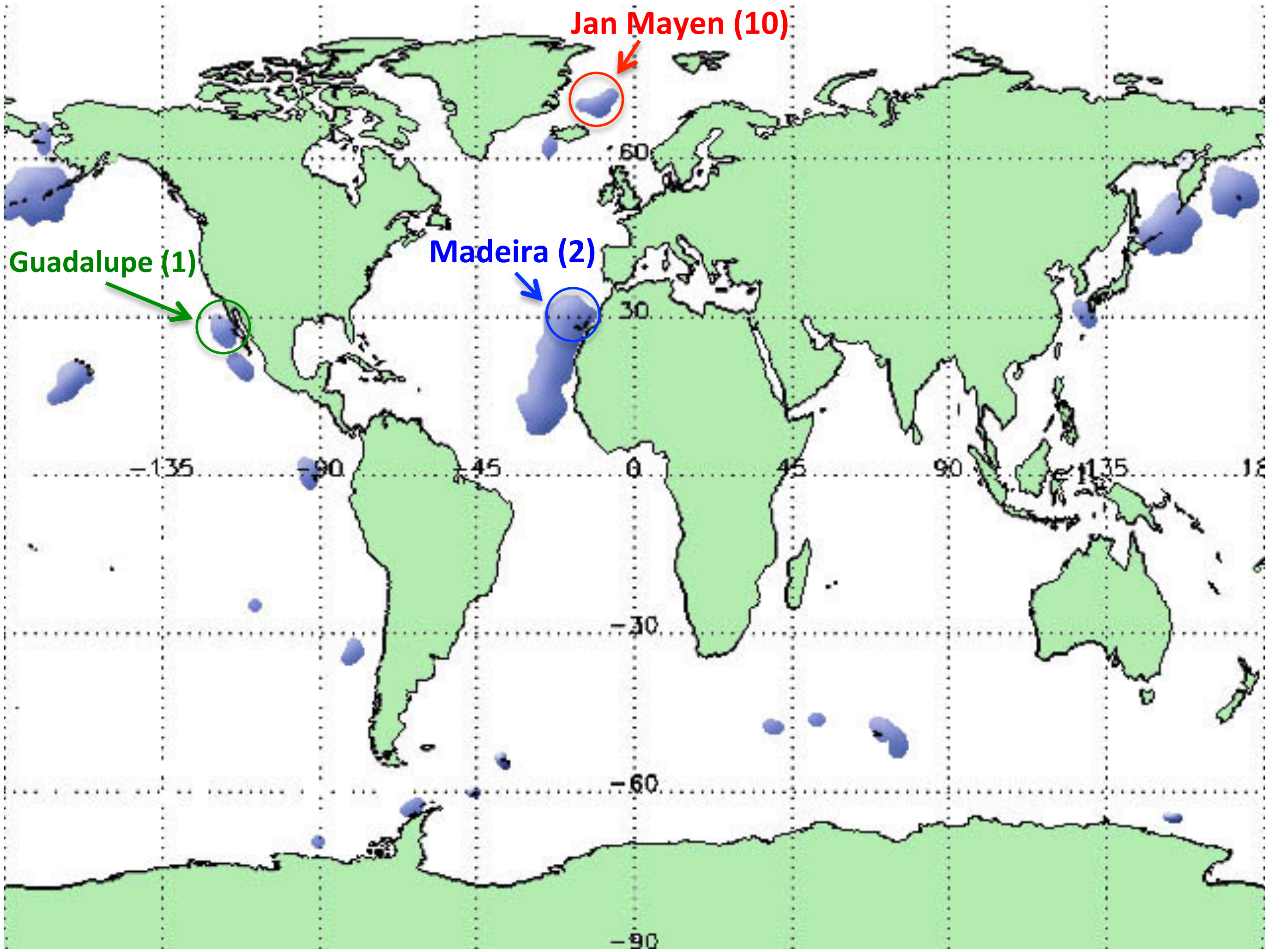
Science

- ❖ 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?

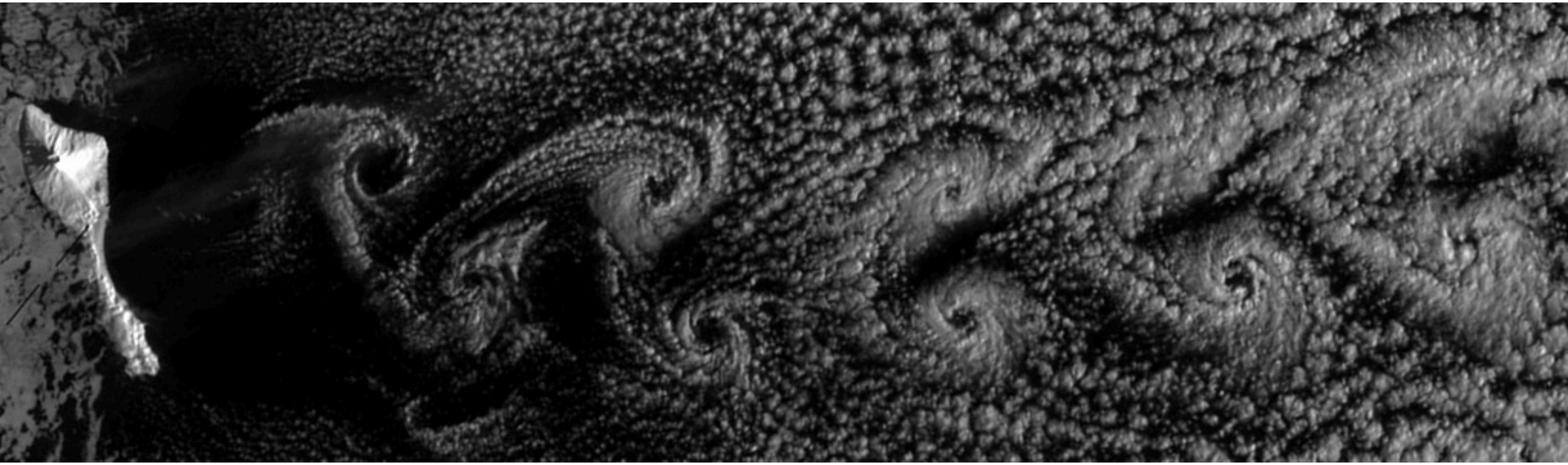
Global Distribution of Kármán Vortex Streets From MERIS



M. Paperin, Cloud Structures, Brockmann Consult, Germany

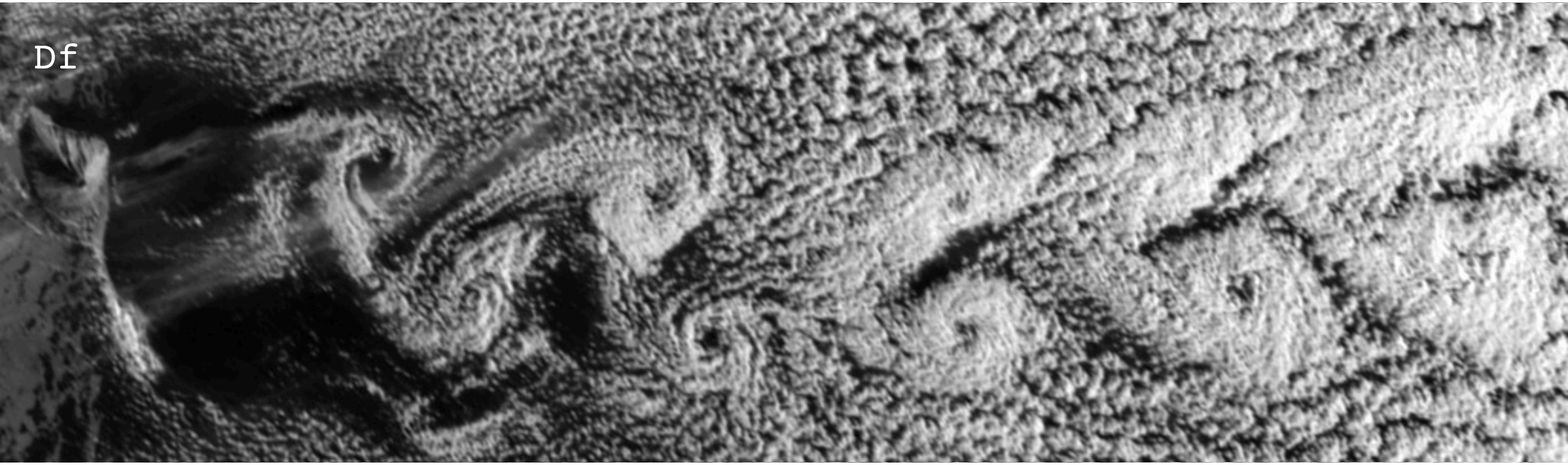
Kármán Vortex Streets From MISR

P215_O006672



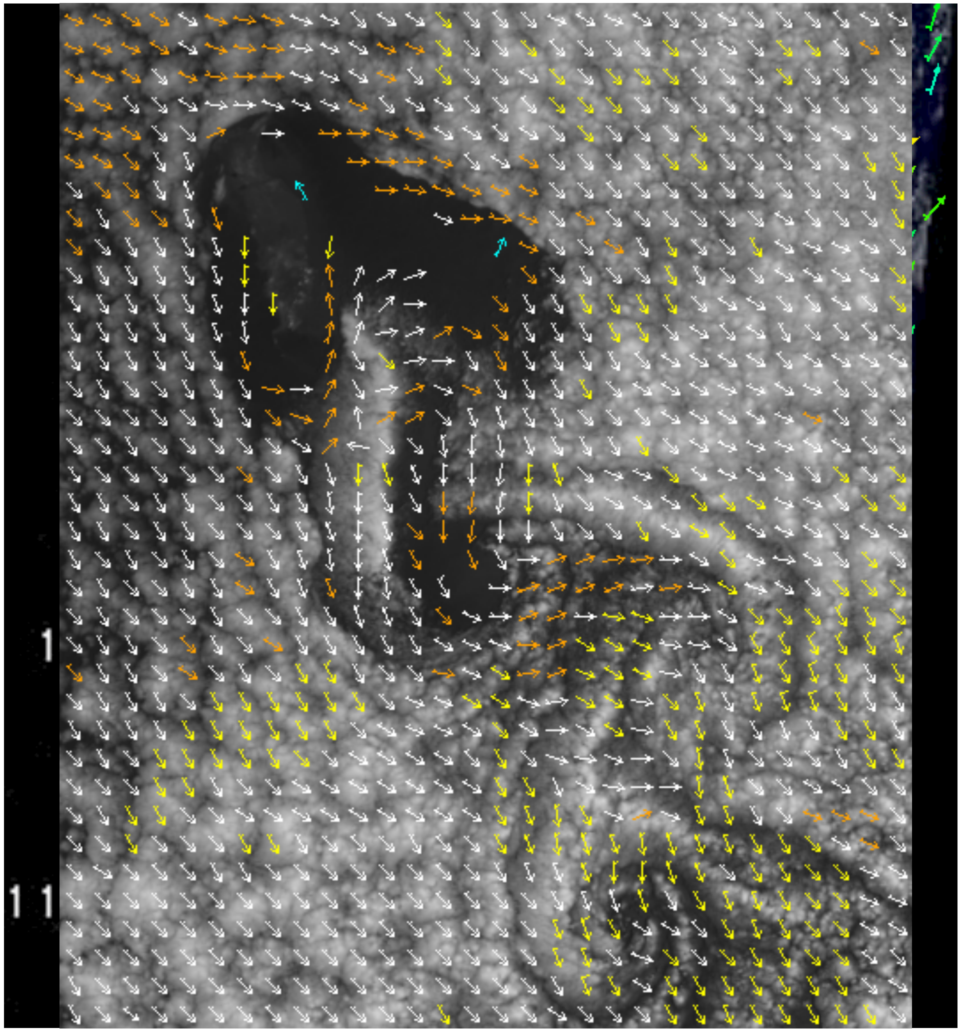
Kármán Vortex Streets From MISR

P215_O006672

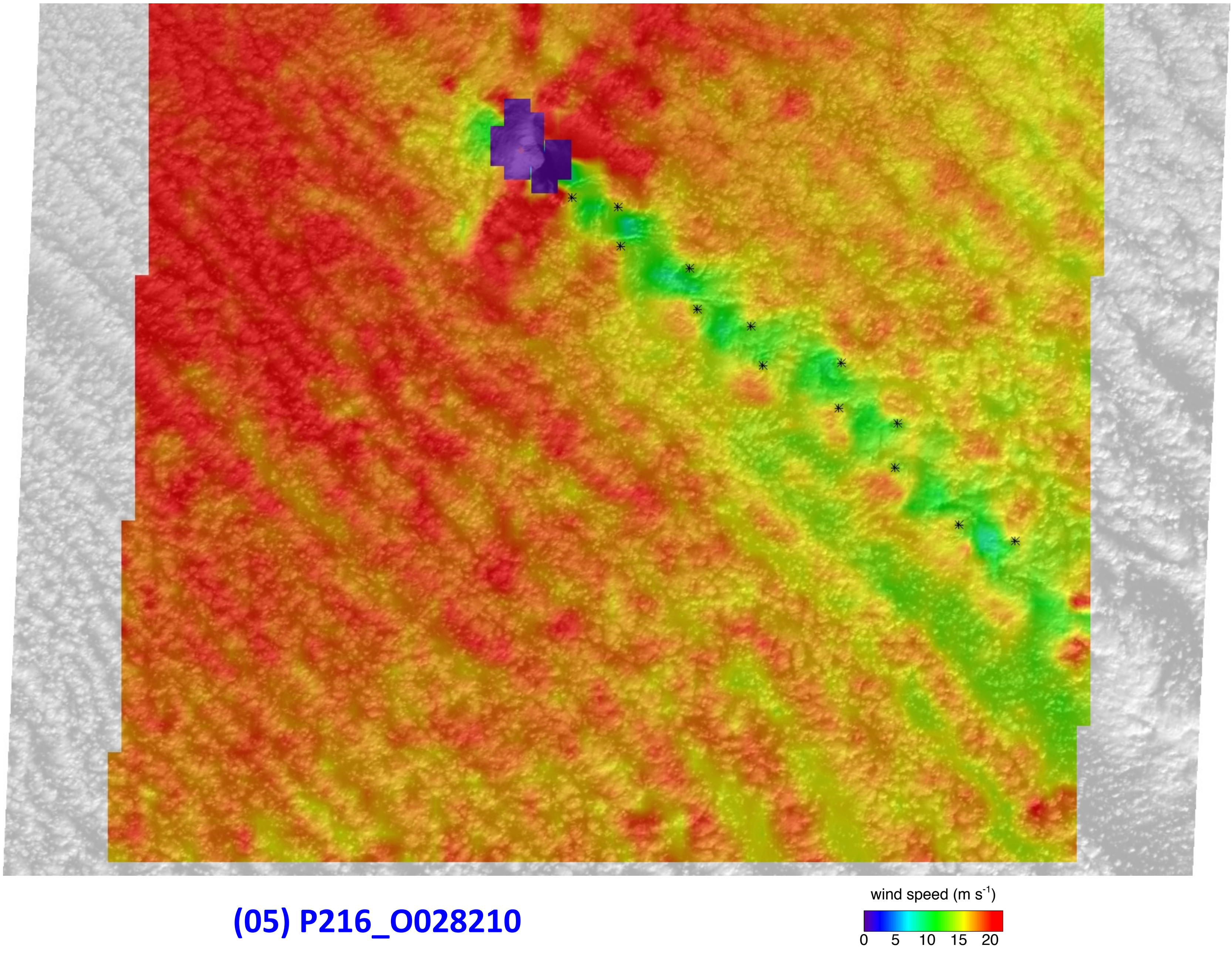


Kármán Vortex Streets From MISR

- Height-resolved stereo winds
- Research code: 4.4 km (new)
- Operational resolution: 17.6 km (old)

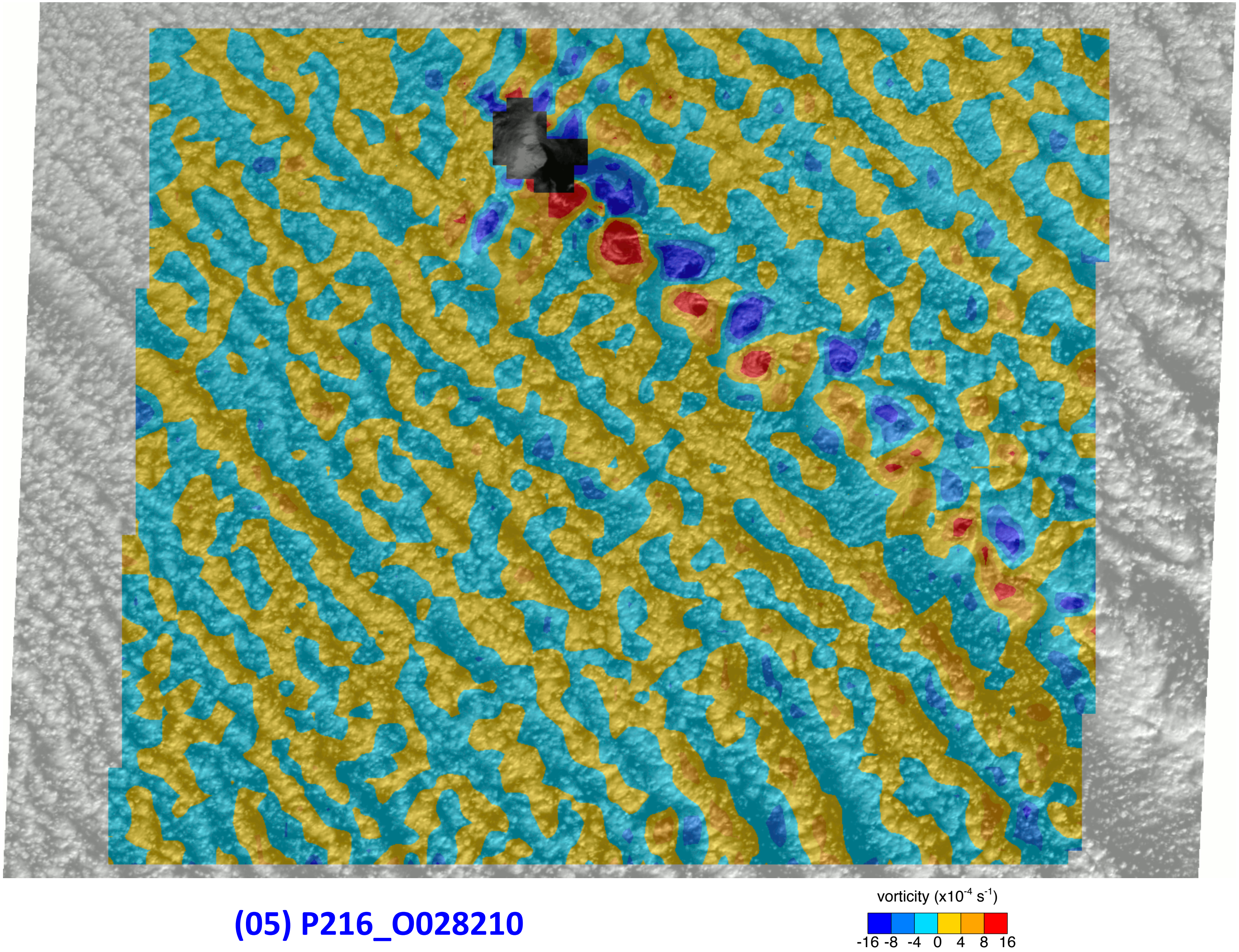


Wind Speed



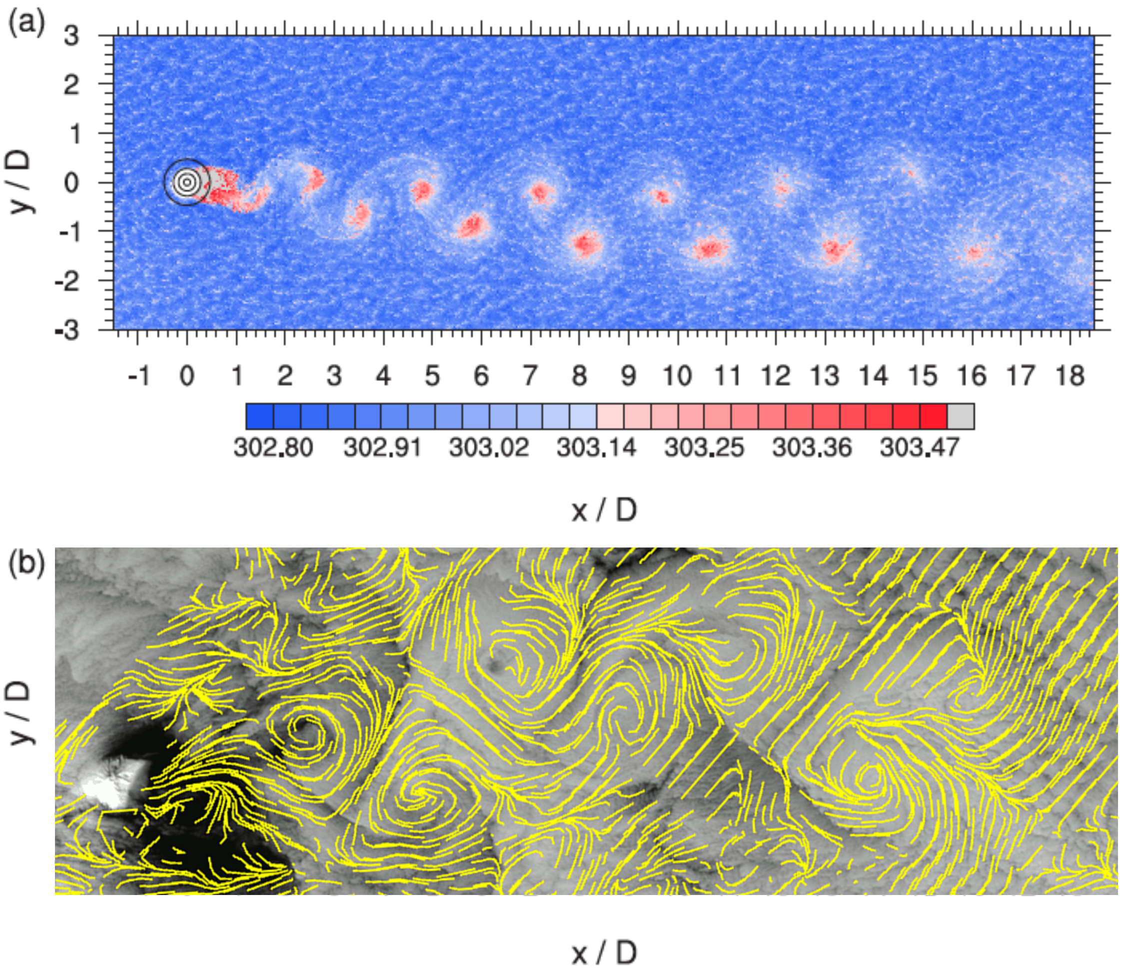
(05) P216_O028210

Vorticity Field



(05) P216_O028210

Idealized Large Eddy Simulation

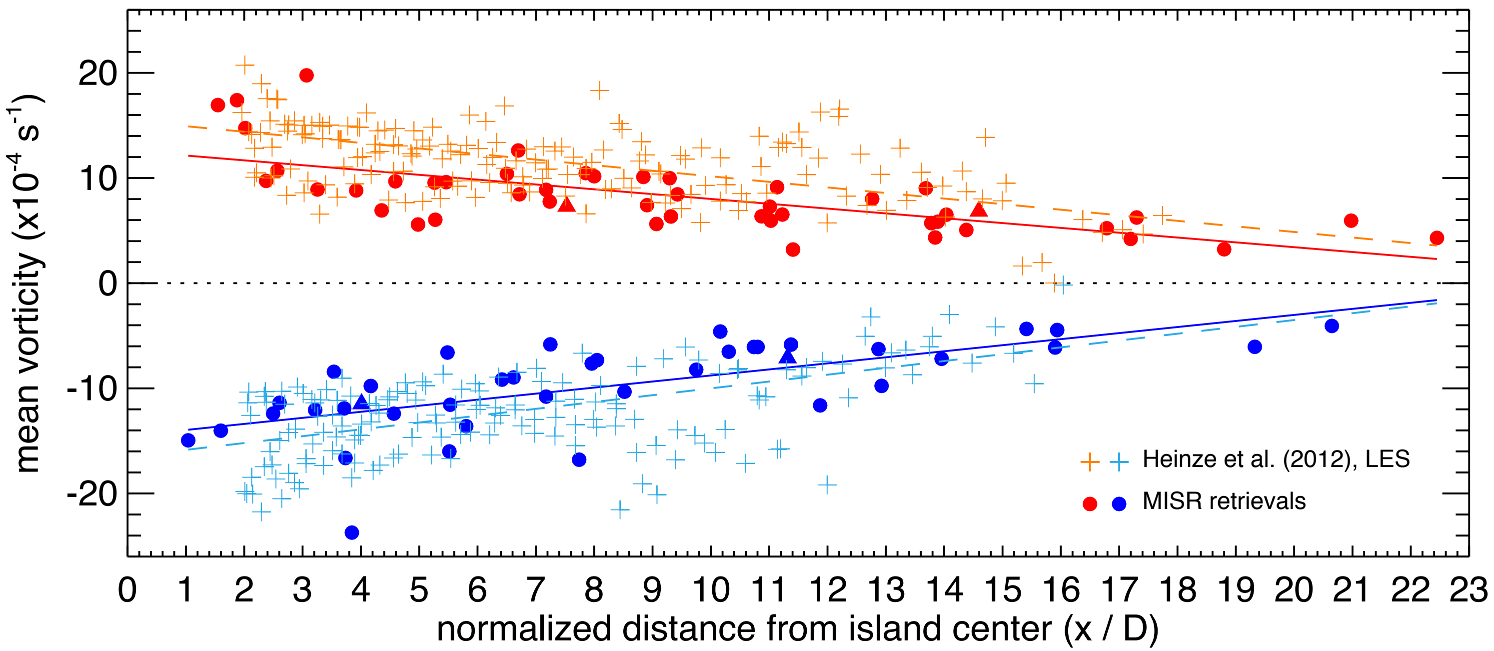


potential temperature

streamlines
/mean wind subtracted/

Heinze et al. [2012], Meteorol. Z.

Mean Vorticity vs. Distance From Island

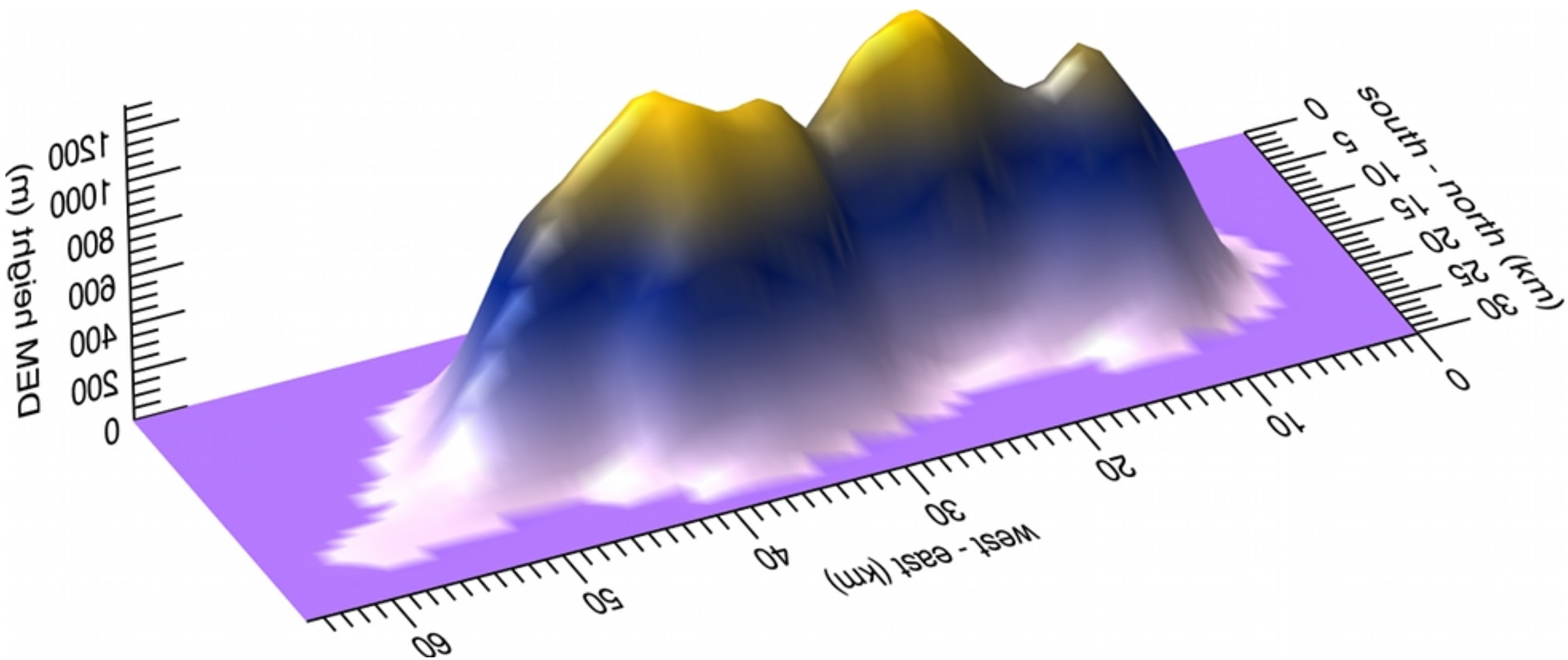


Sample number: MISR = 88, LES = 333

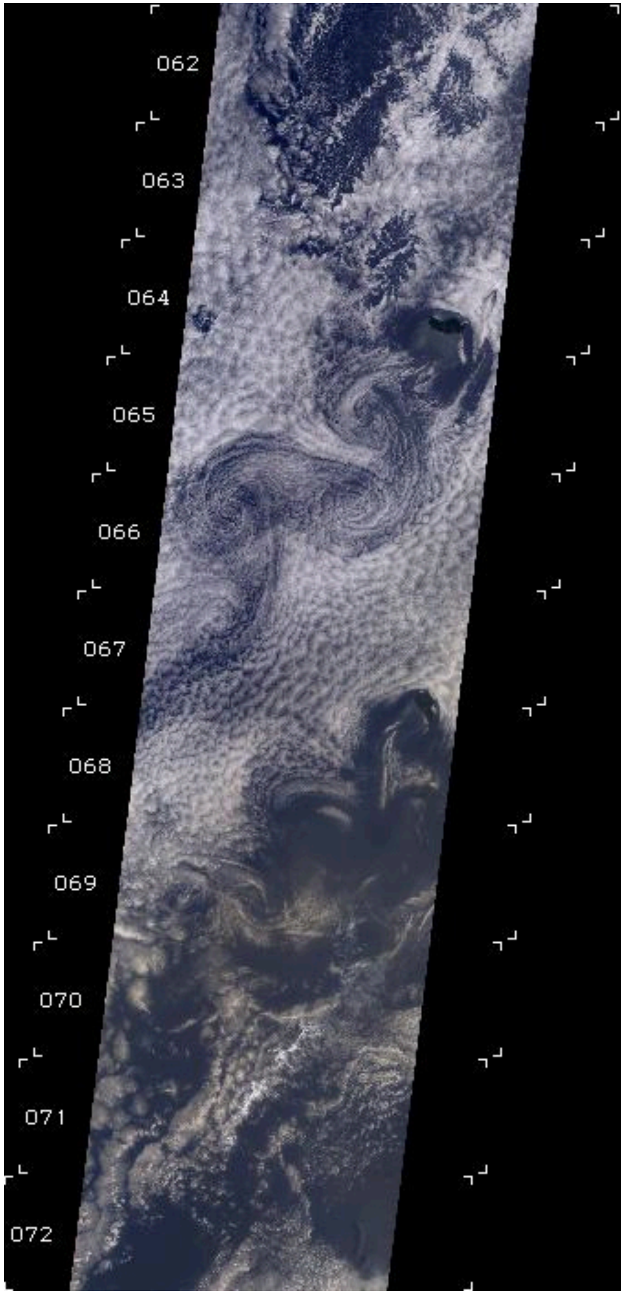
WRF Simulation of Madeira, 9 July 2010

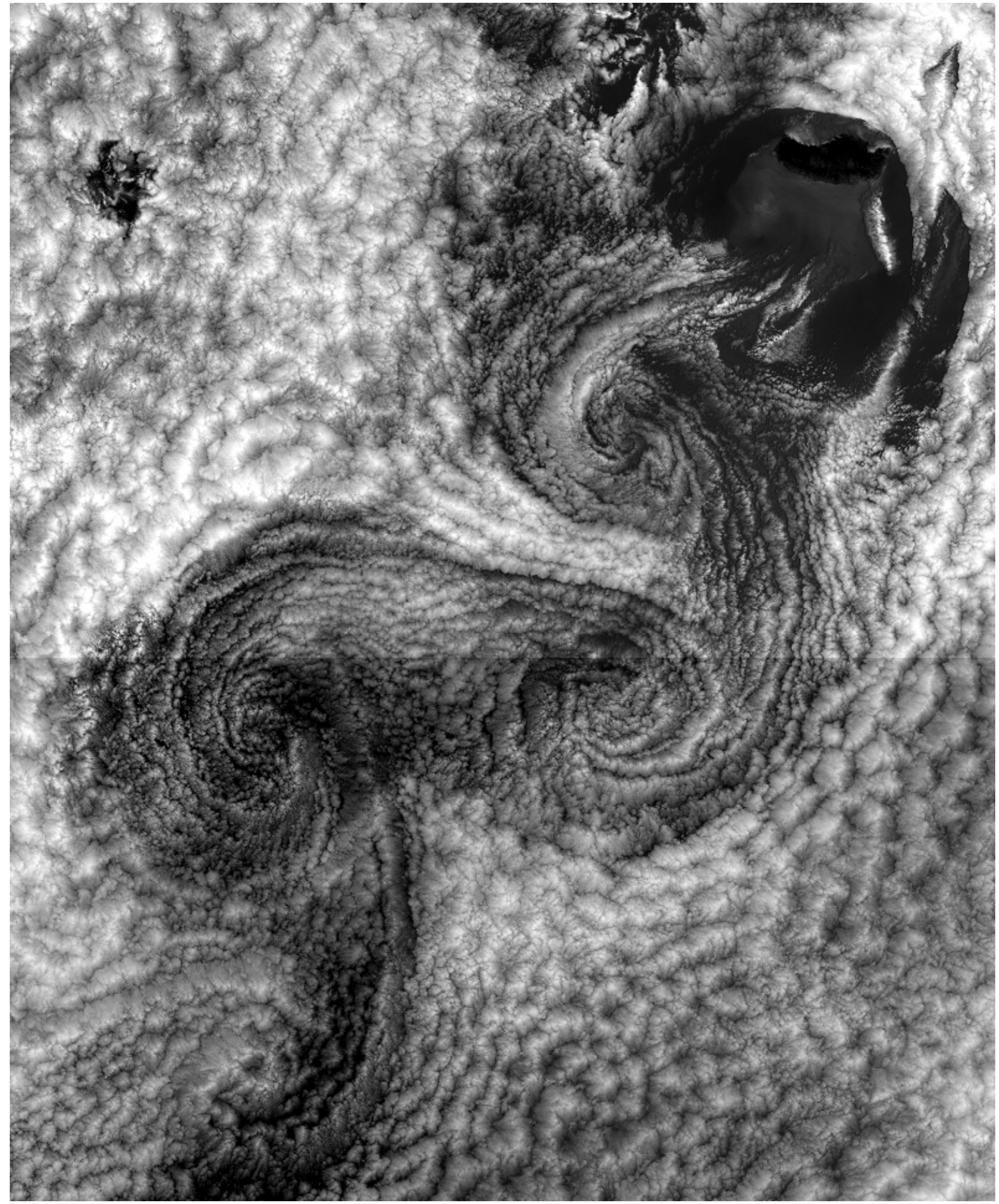
- **Initial/Boundary Conditions**
  - ERA-Interim Reanalysis
- **3-D Domain**
  - 1 km x 1 km horizontal resolution
  - 50 vertical grid points
- **30-hour simulation (Δt = 10 min)**
  - 8 July 18:00 to 9 July 24:00 (MISR at 10:30, 9 July)
- **Default Physics Schemes**

WRF DEM Peak Elevation = 1318 m

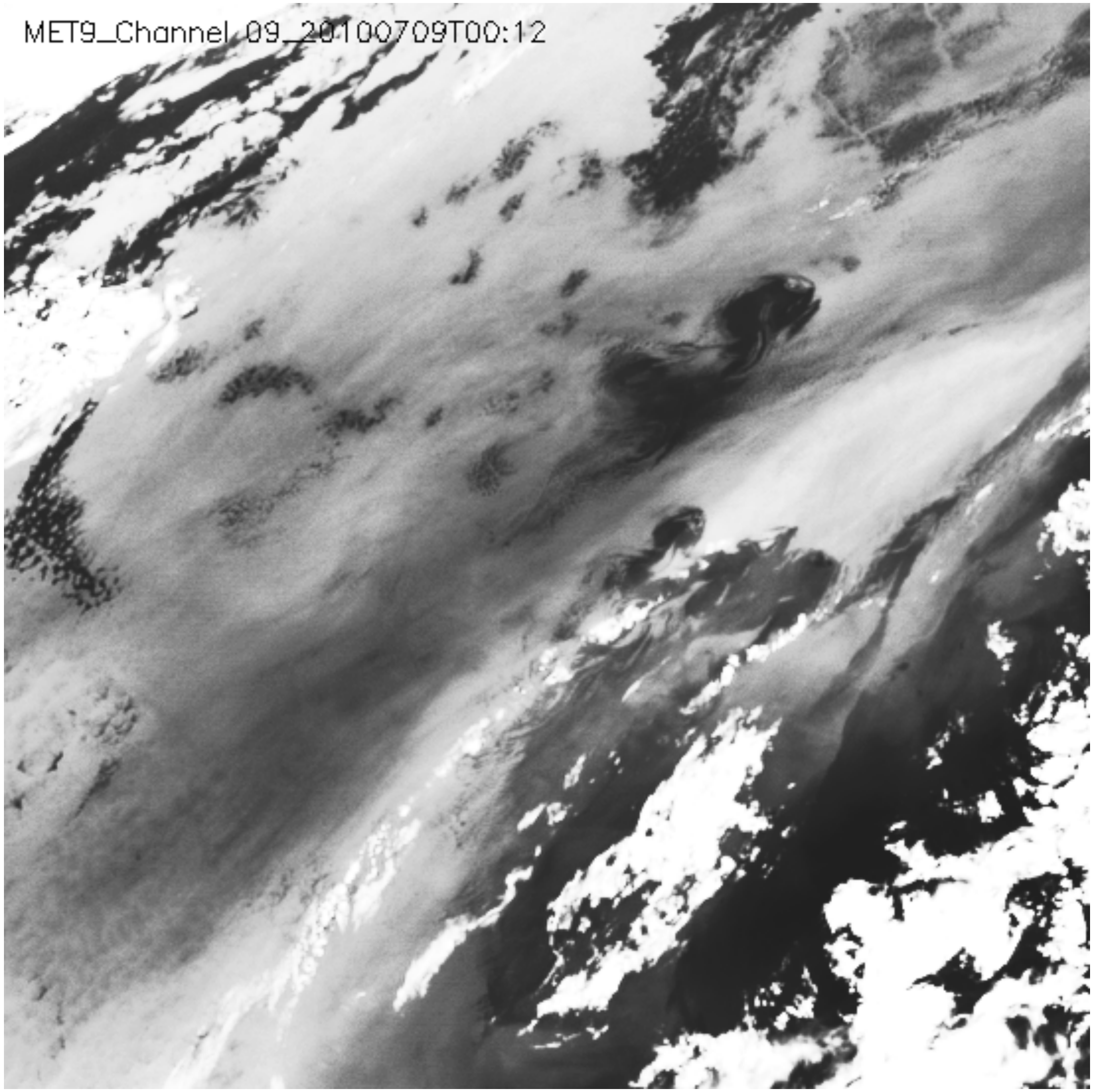


Madeira, 9 July 2010: MISR P209_O056155





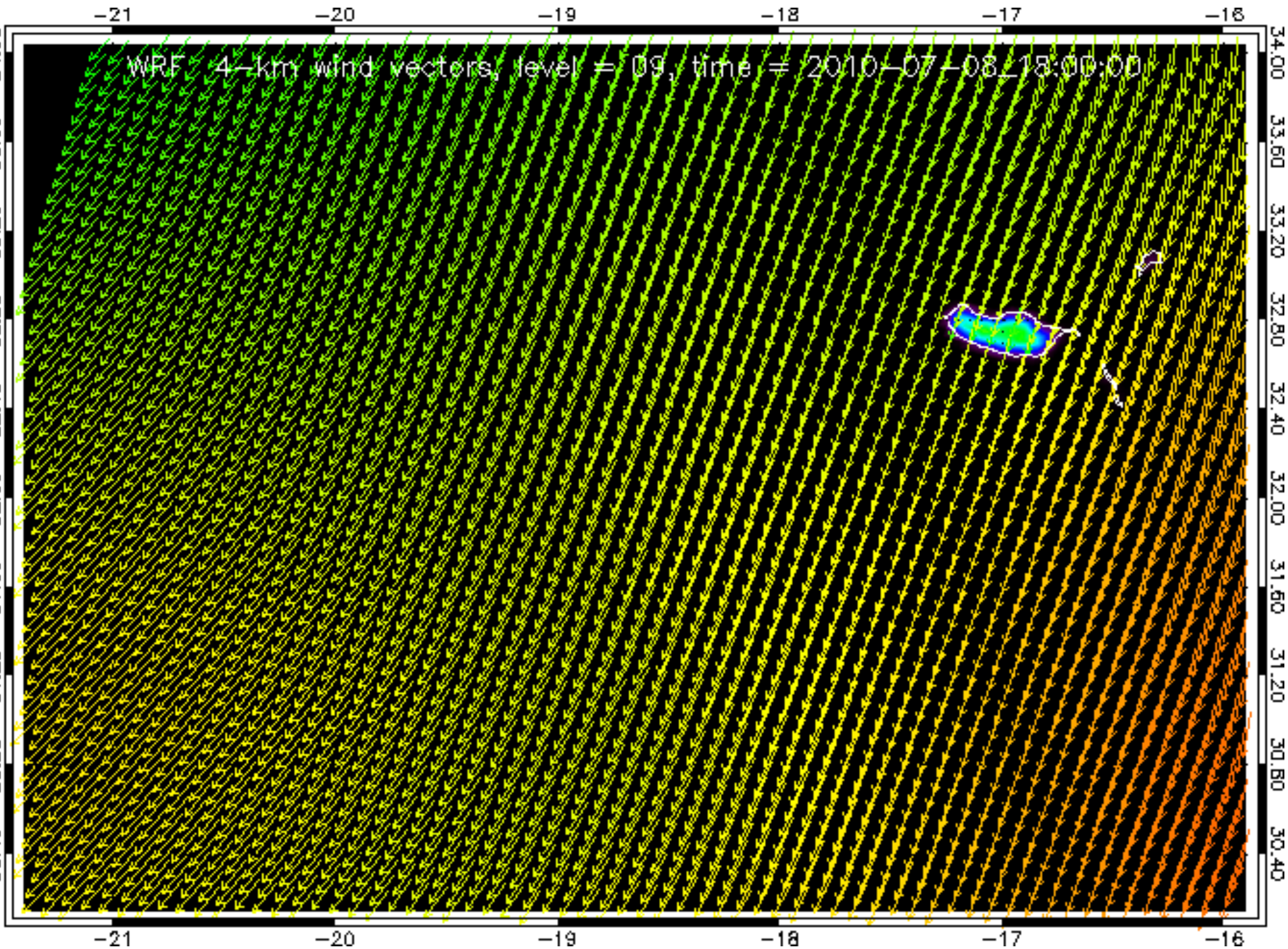
Madeira, 9 July 2010: Meteosat-9 IR



Madeira, 9 July 2010: Meteosat-9 VIS

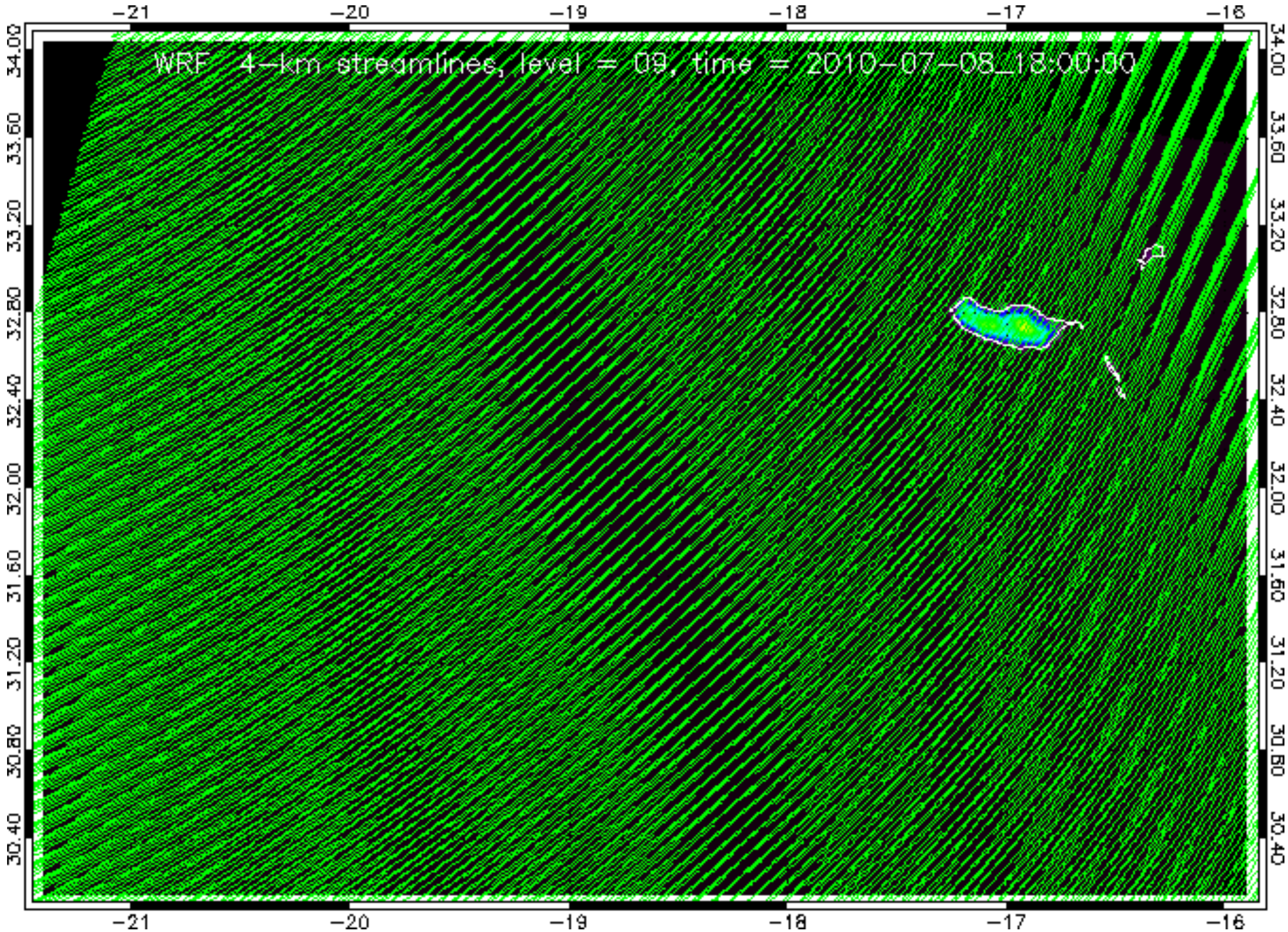
Vortex shedding frequency 4-5 hours

Madeira, 9 July 2010: WRF simulation



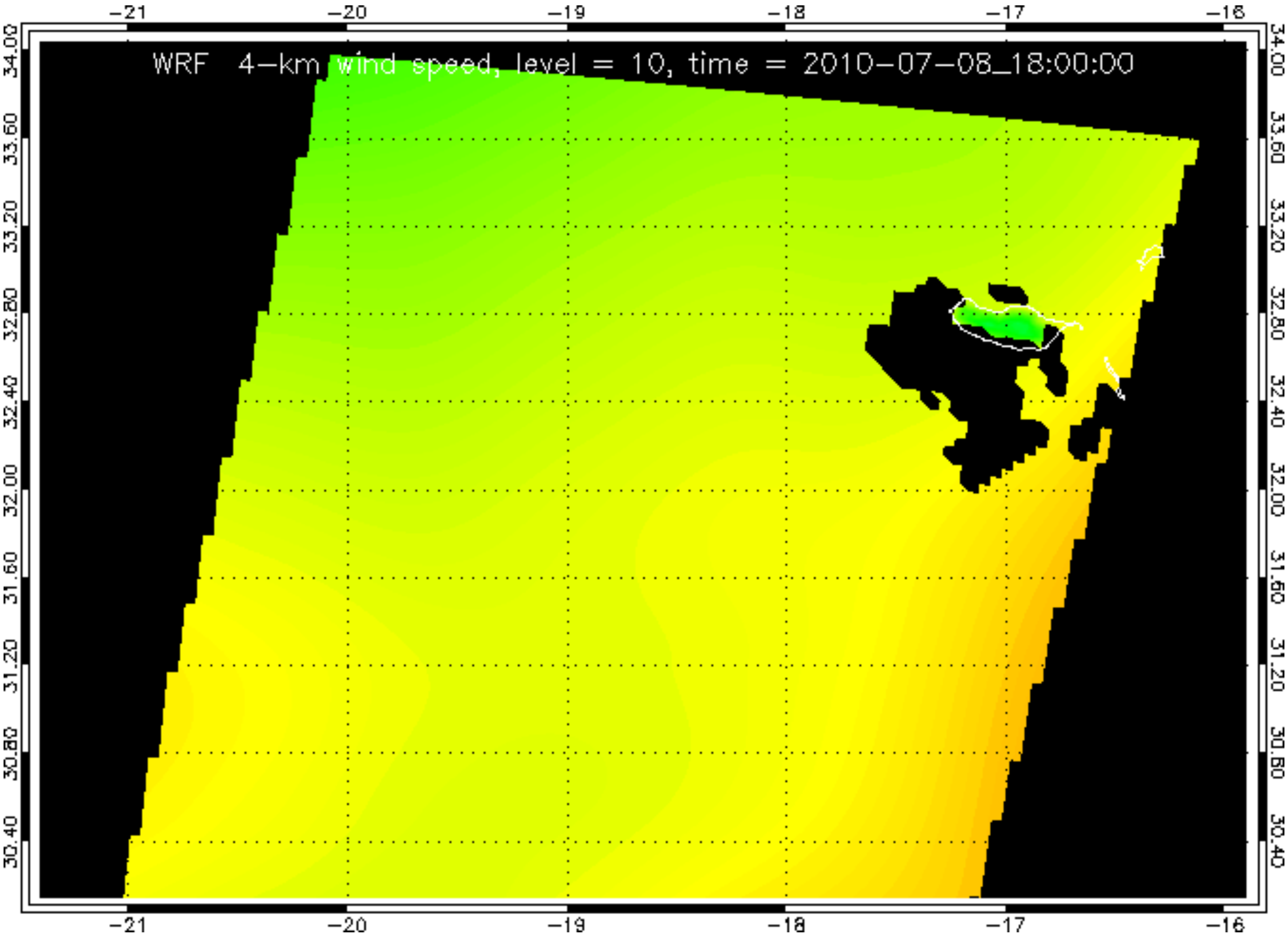
Wind vectors at level 10 (~400 m)

Madeira, 9 July 2010: WRF simulation



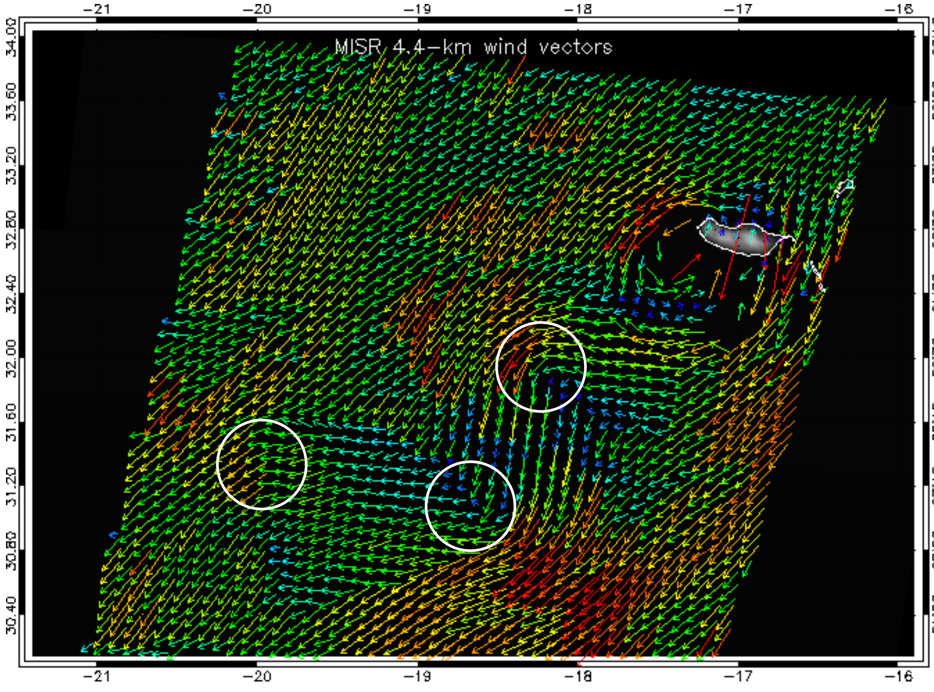
Streamlines at level 10 (~400 m)

Madeira, 9 July 2010: WRF simulation

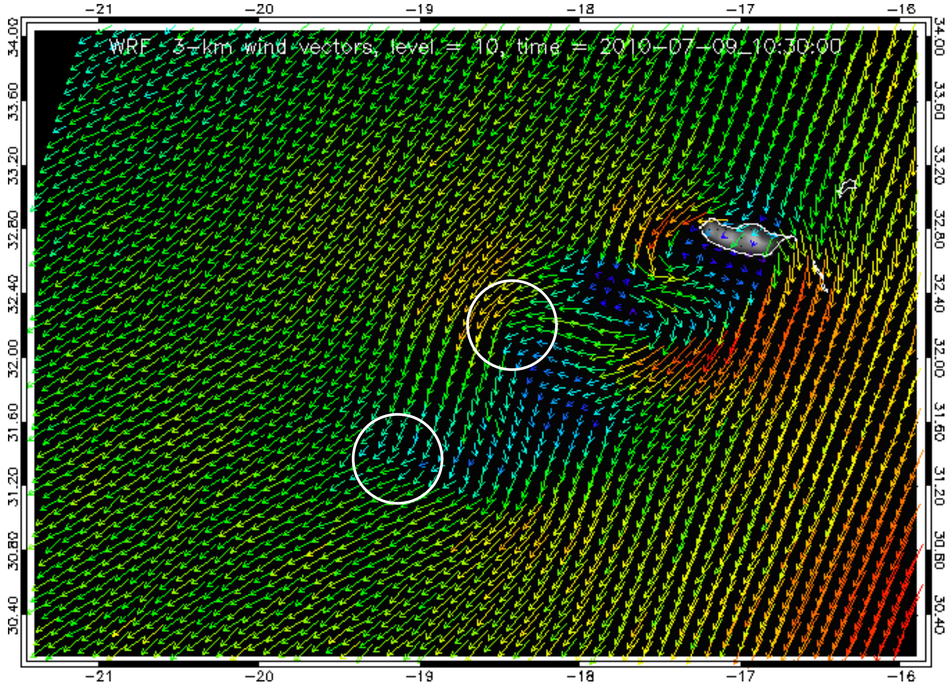


Wind speed at level 10 (~400 m)

Madeira, P209_O056155: wind vector comparison level = 10

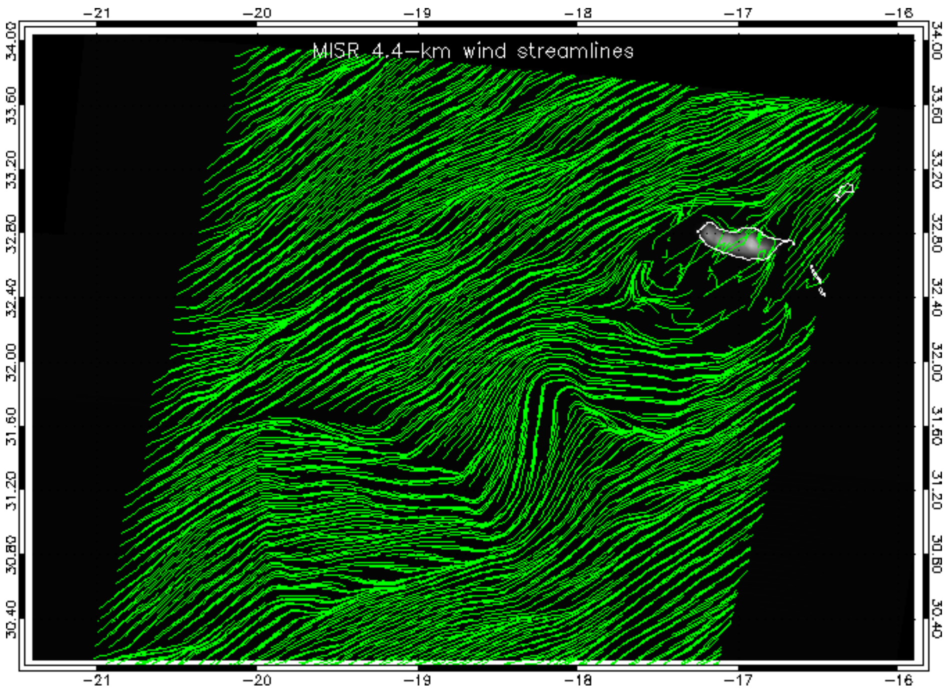


MISR

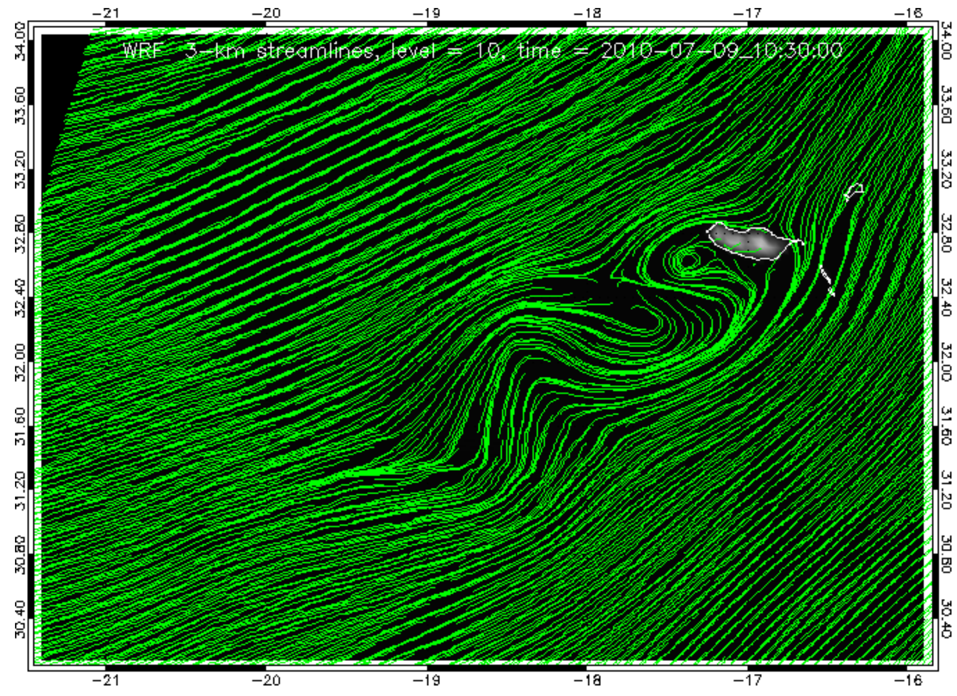


WRF

Madeira, P209_O056155: streamlines comparison level = 10

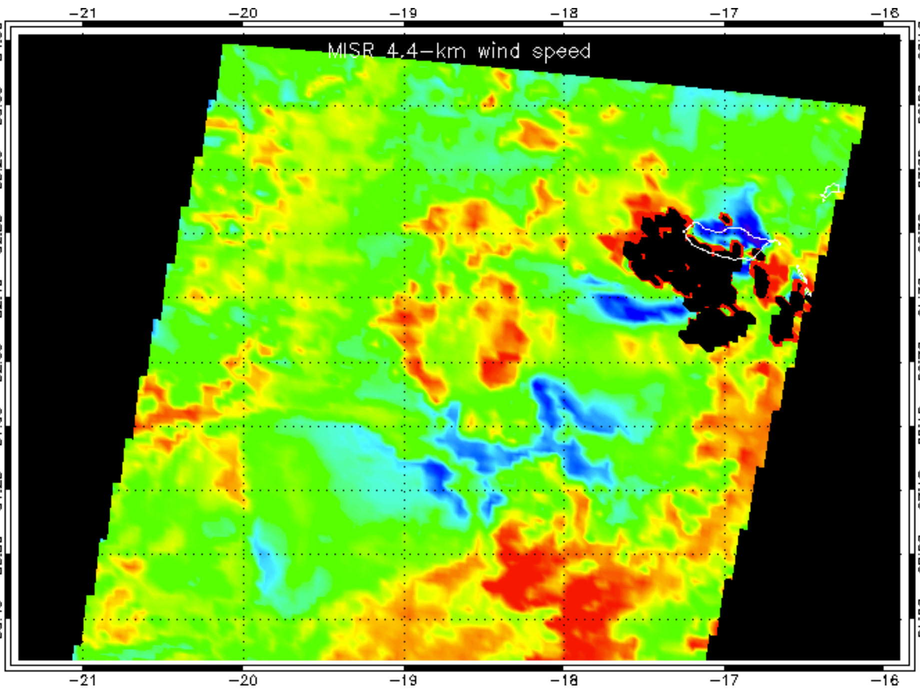


MISR

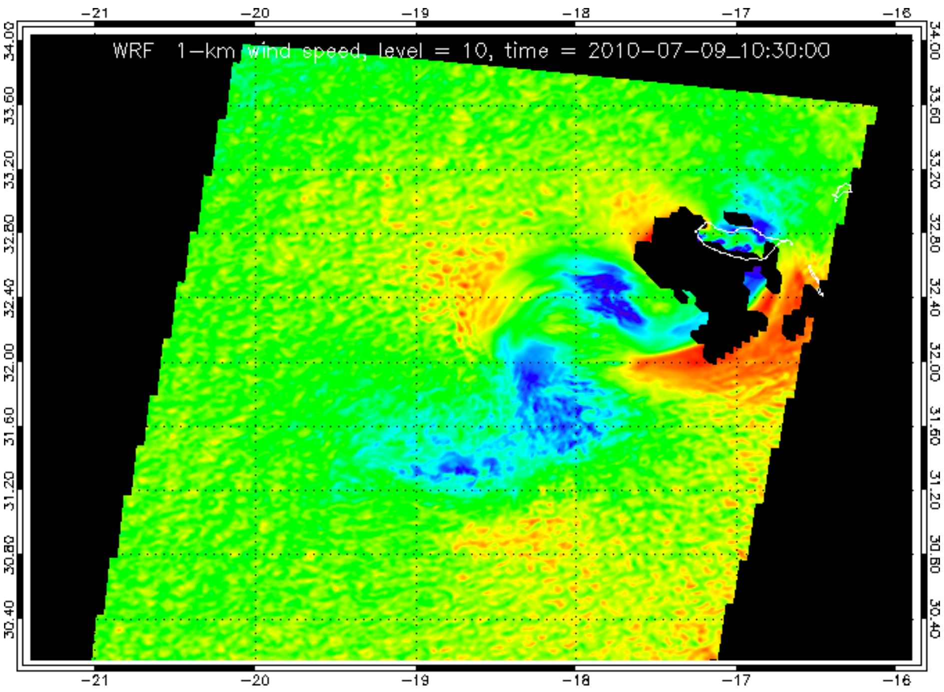


WRF

Madeira, P209_O056155: wind speed comparison level = 10

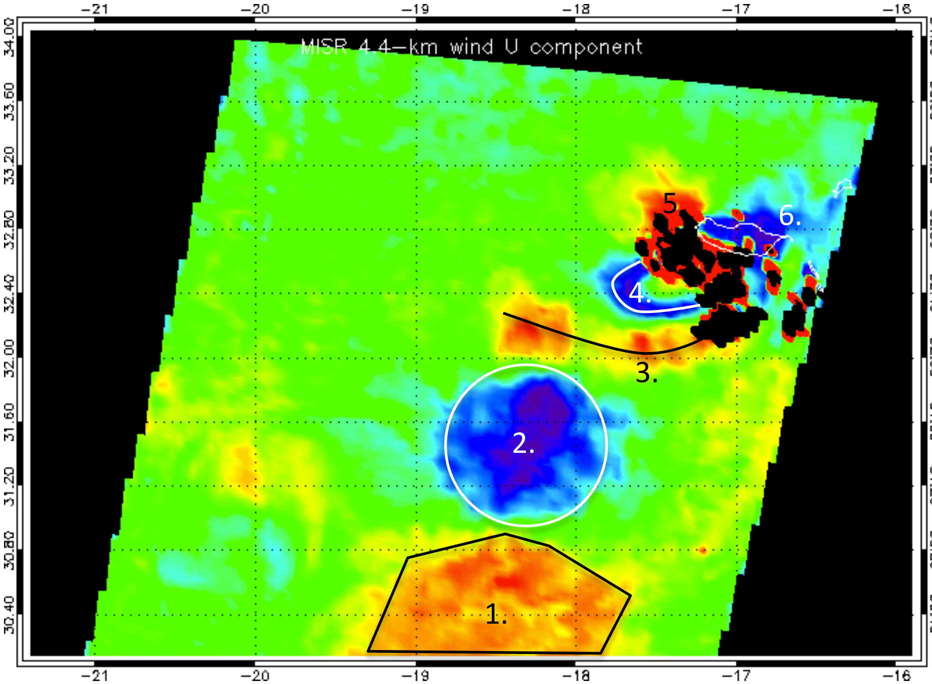


MISR

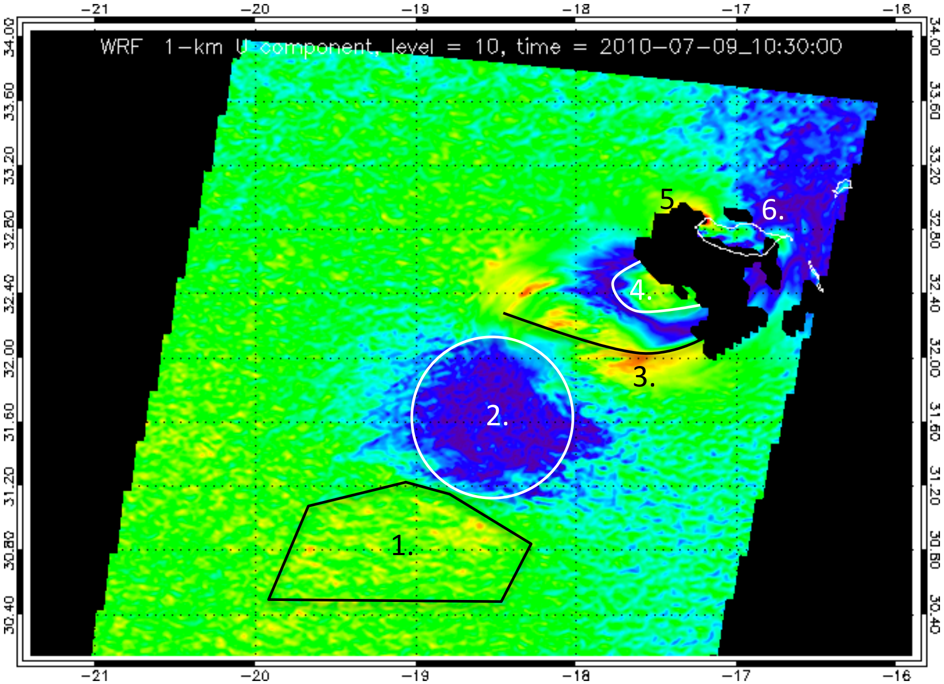


WRF

Madeira, P209_O056155: U component comparison level = 10

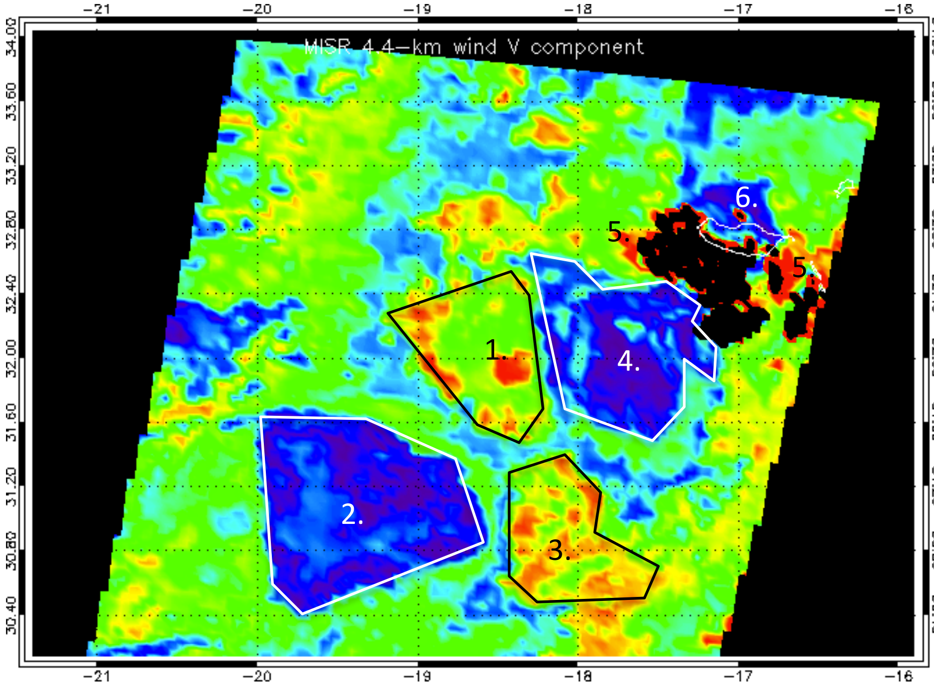


MISR

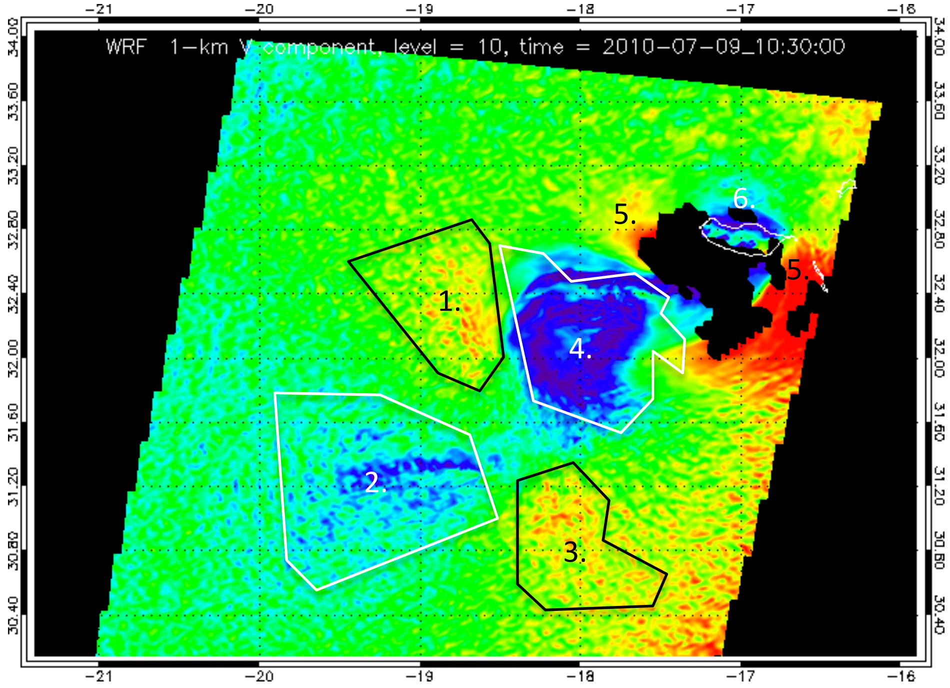


WRF

Madeira, P209_O056155: V component comparison level = 10

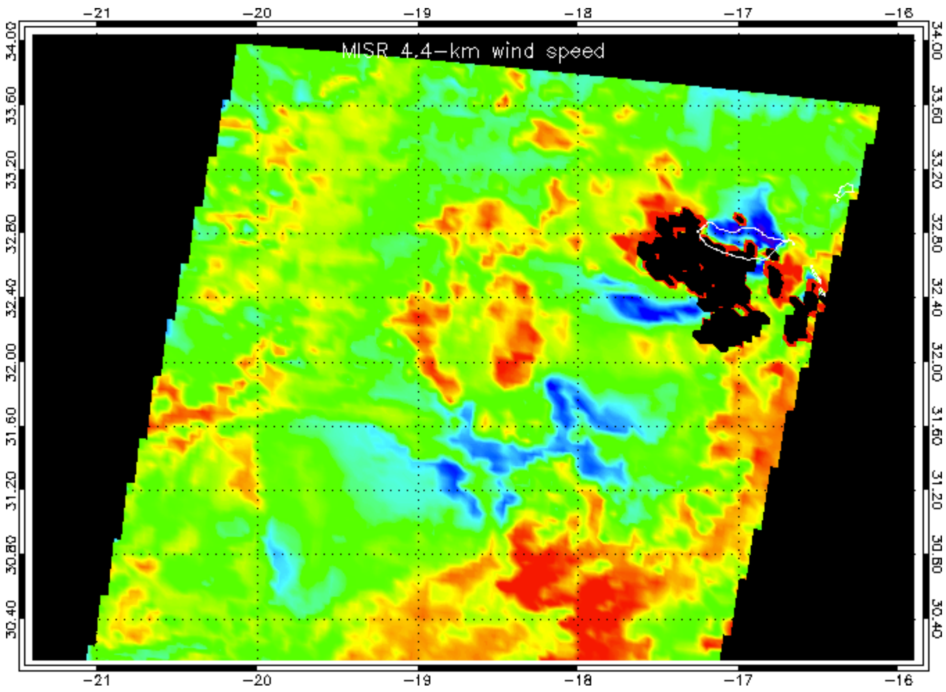


MISR

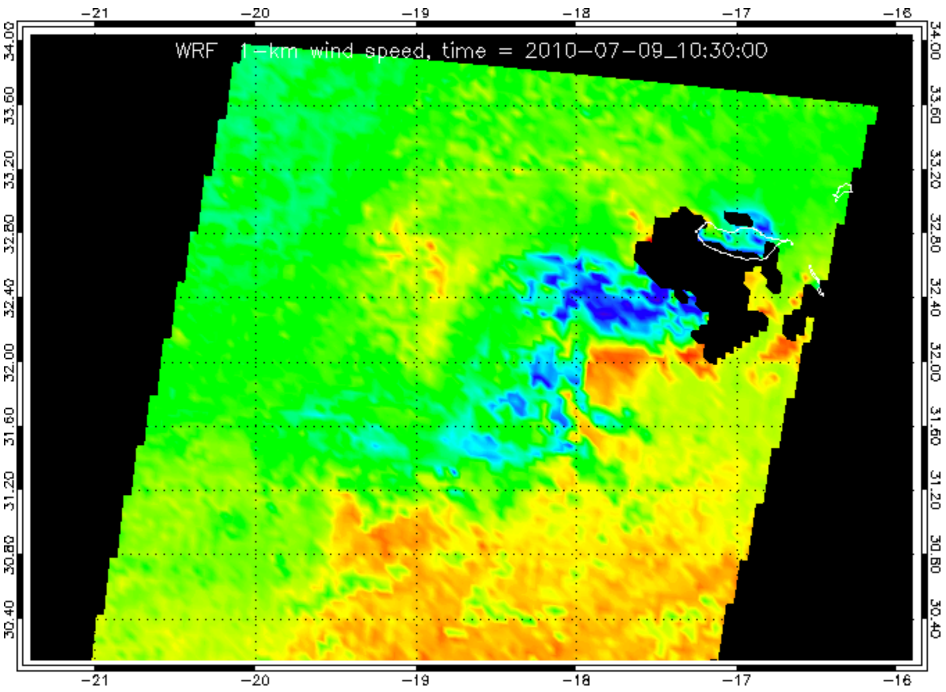


WRF

Madeira, P209_O056155: wind speed comparison using MISR absolute heights

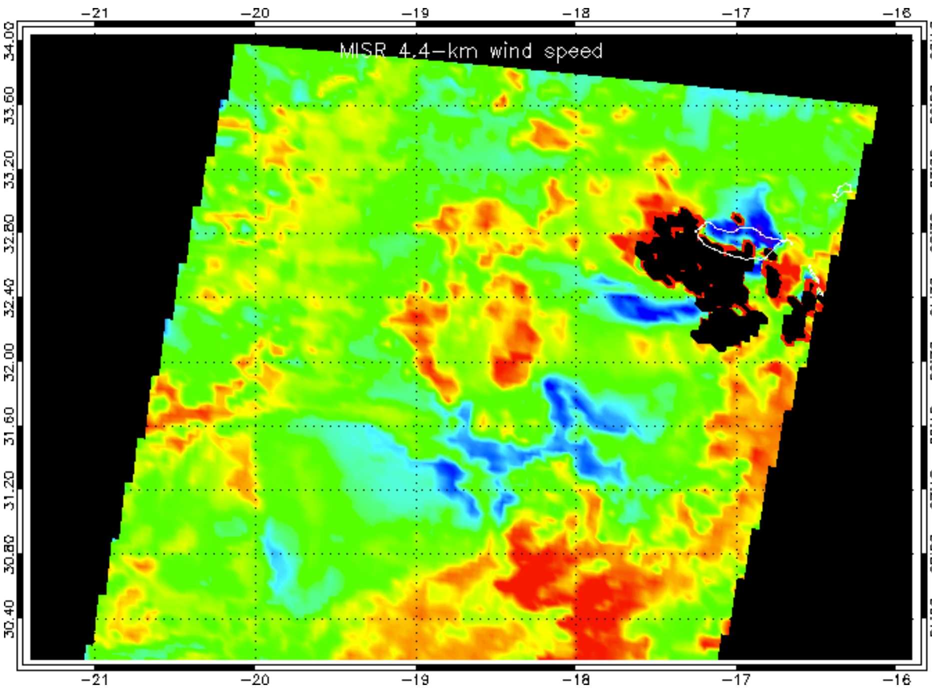


MISR

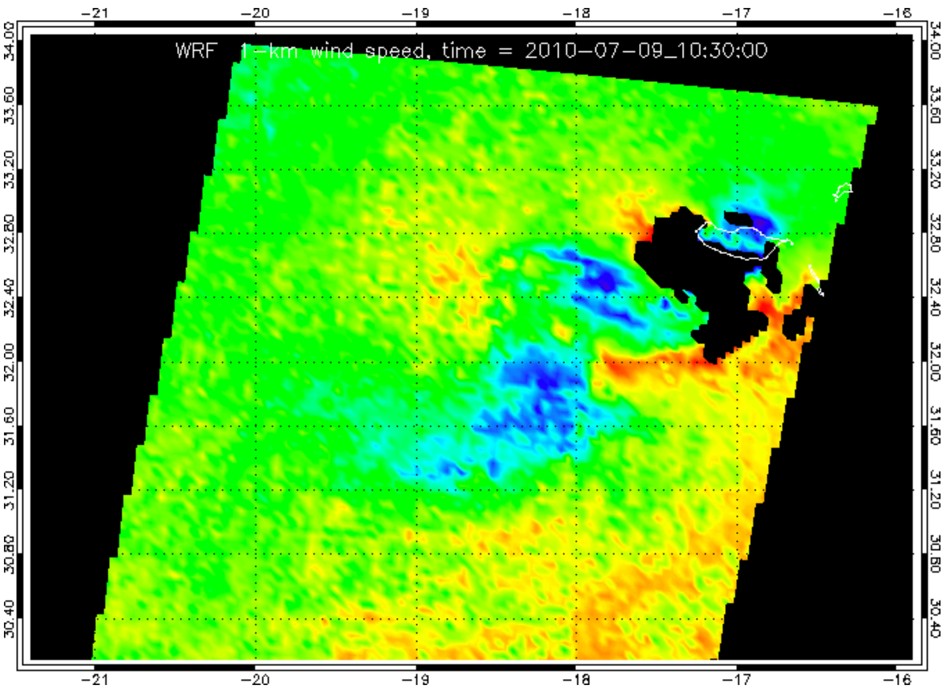


WRF

Madeira, P209_O056155: wind speed comparison using MISR relative heights

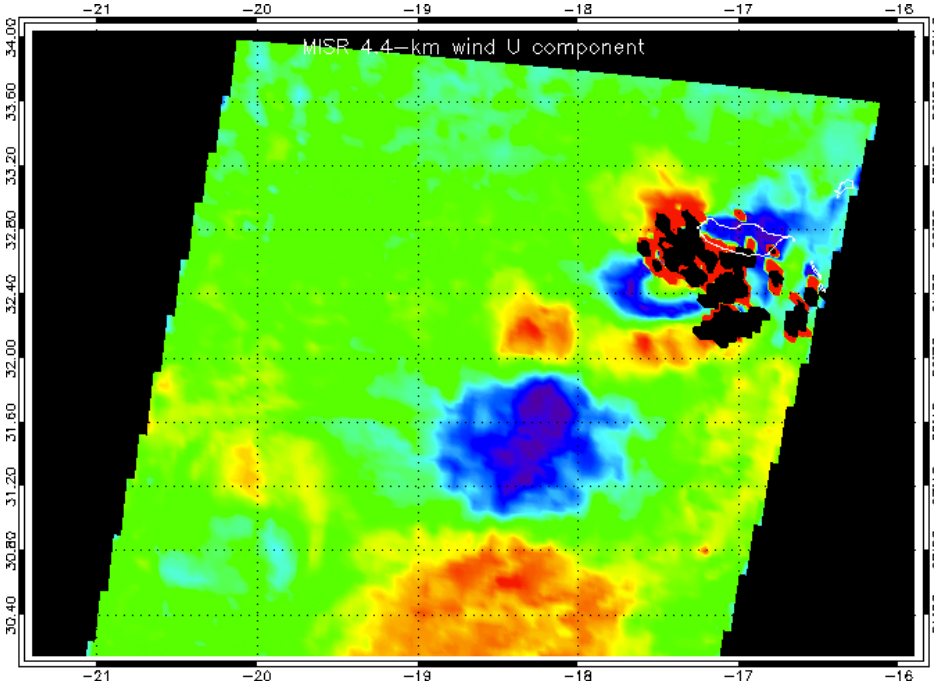


MISR

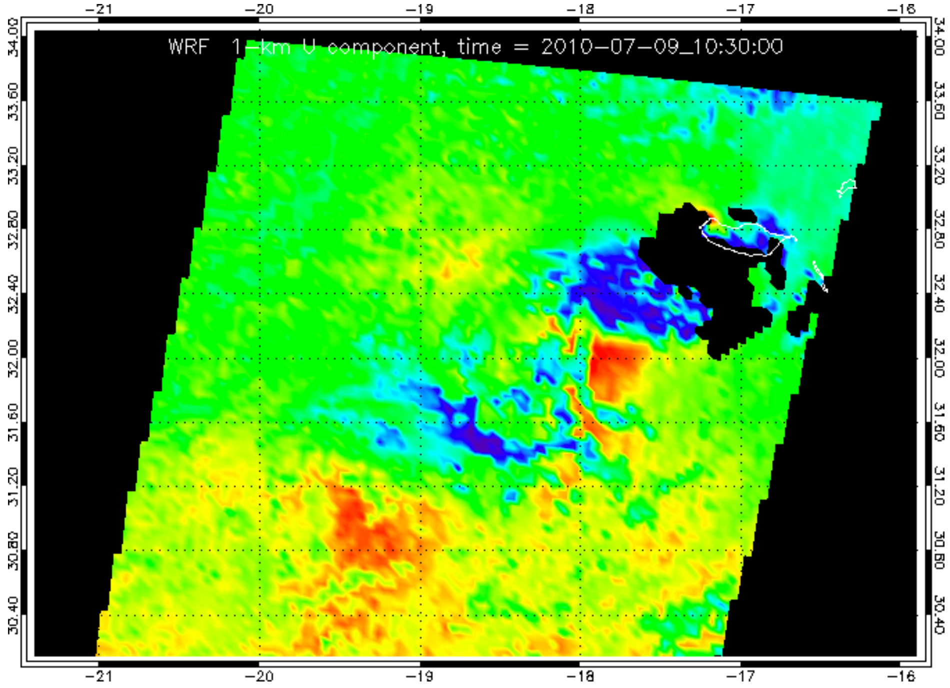


WRF

Madeira, P209_O056155: U component comparison using MISR absolute heights

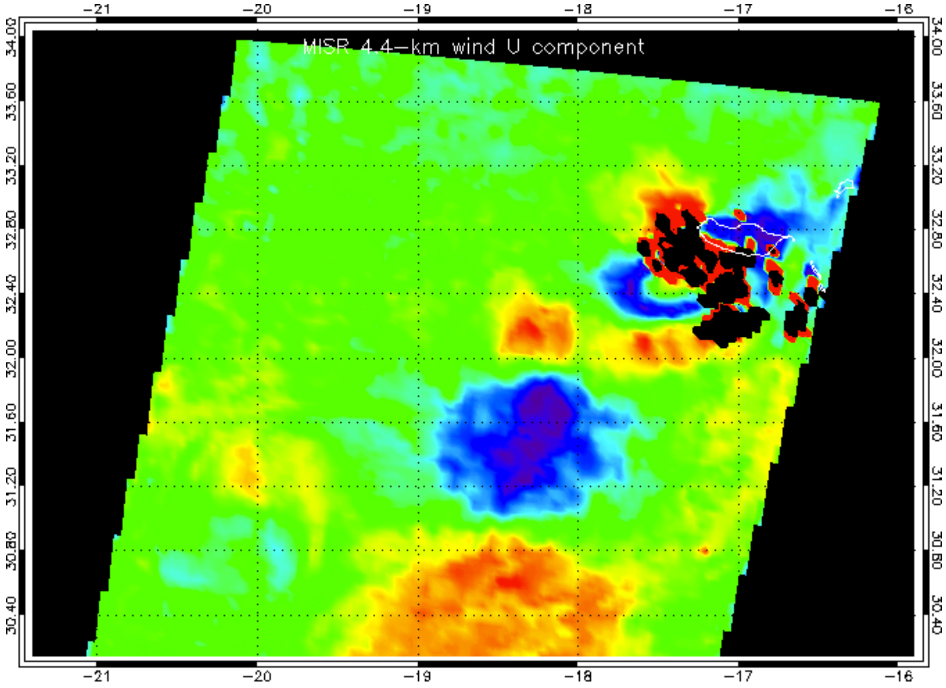


MISR

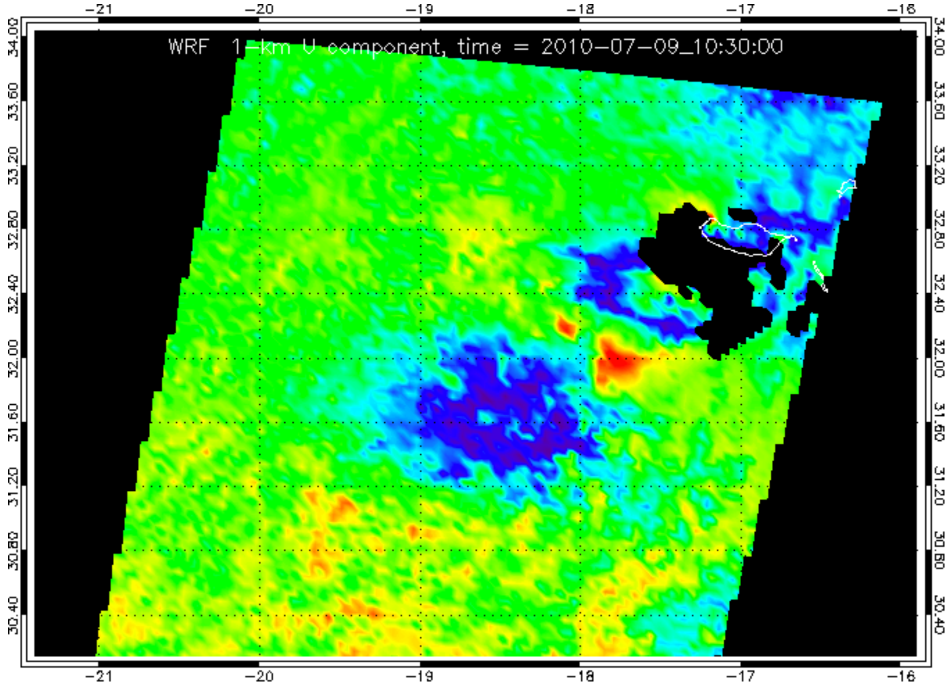


WRF

Madeira, P209_O056155: U component comparison using MISR relative heights

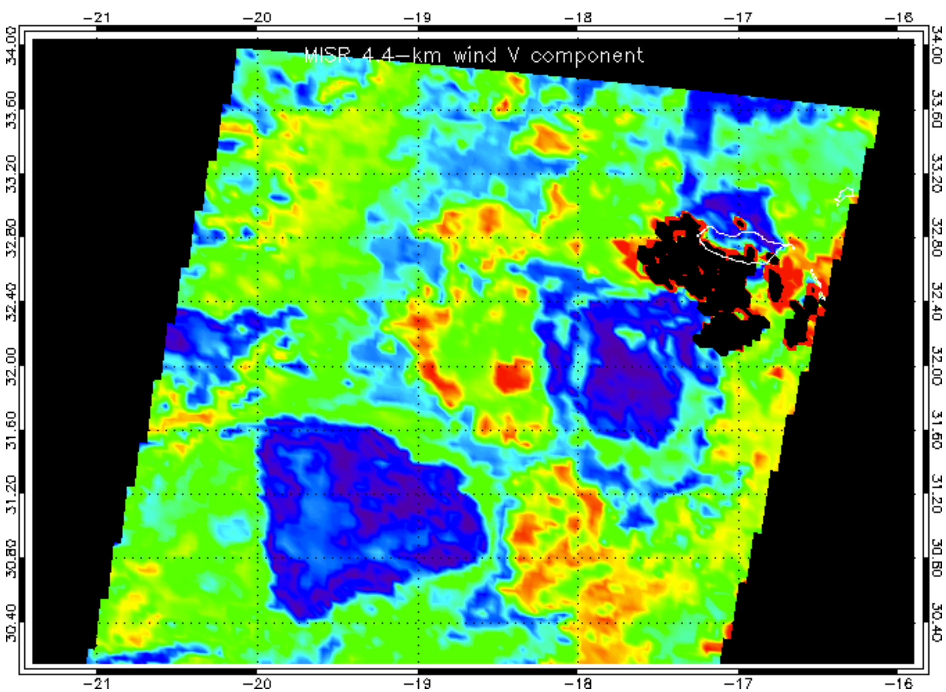


MISR

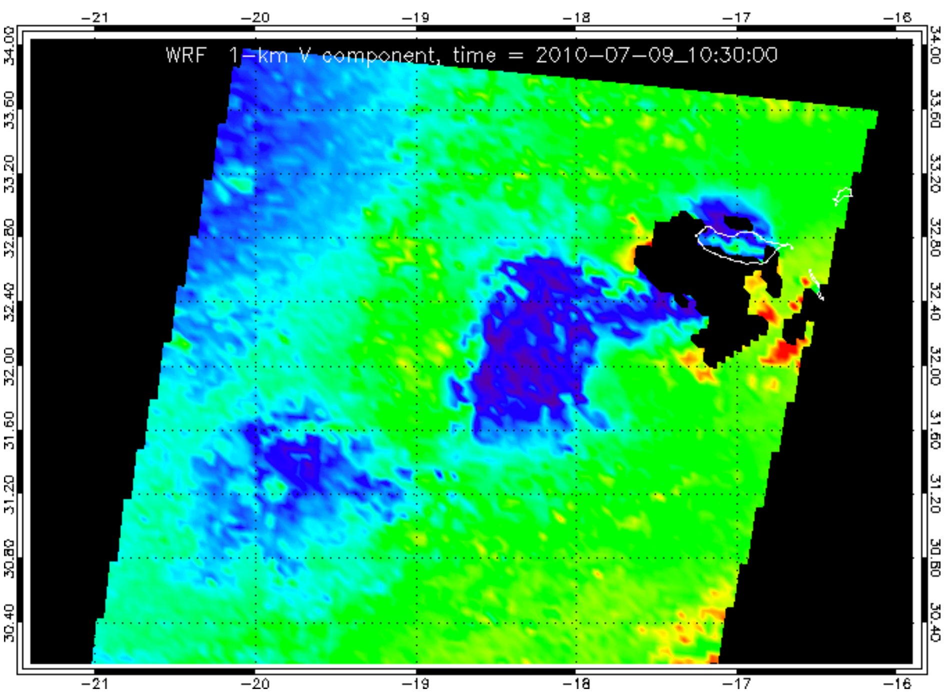


WRF

Madeira, P209_O056155: V component comparison using MISR absolute heights

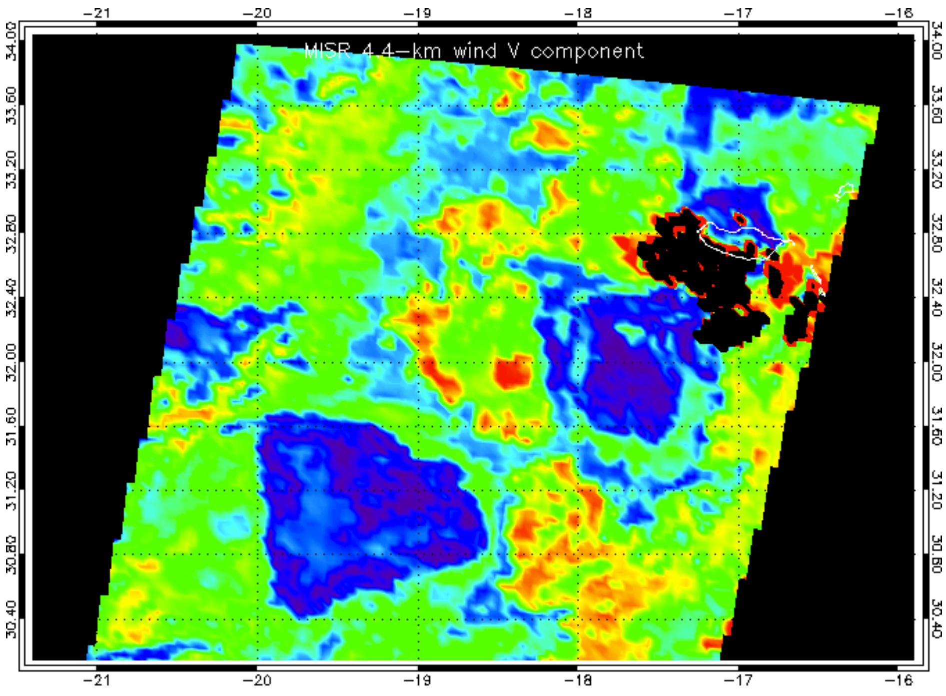


MISR

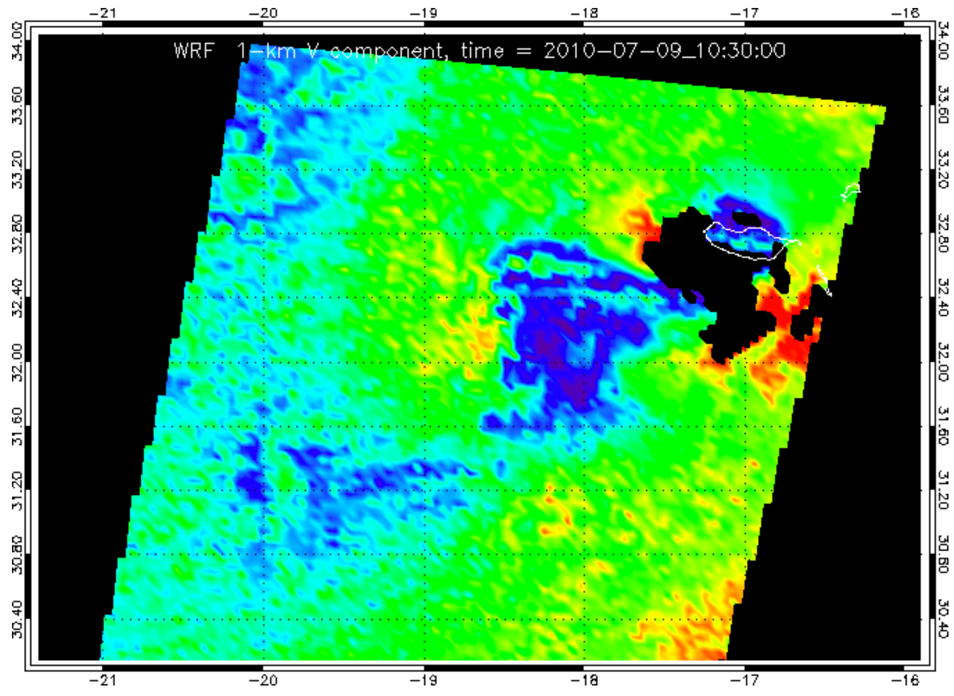


WRF

Madeira, P209_O056155: V component comparison using MISR relative heights



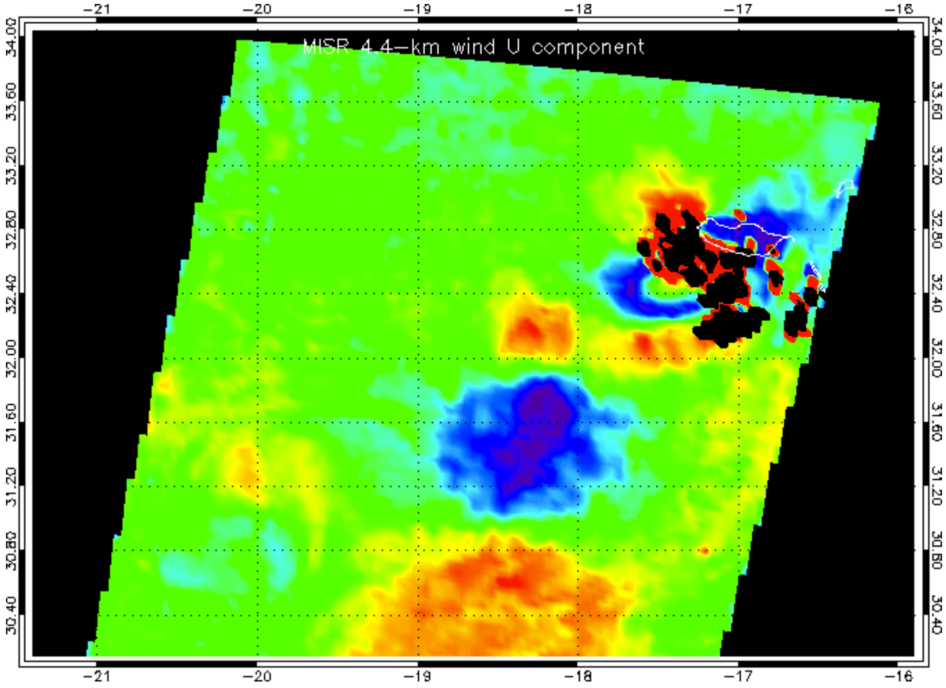
MISR



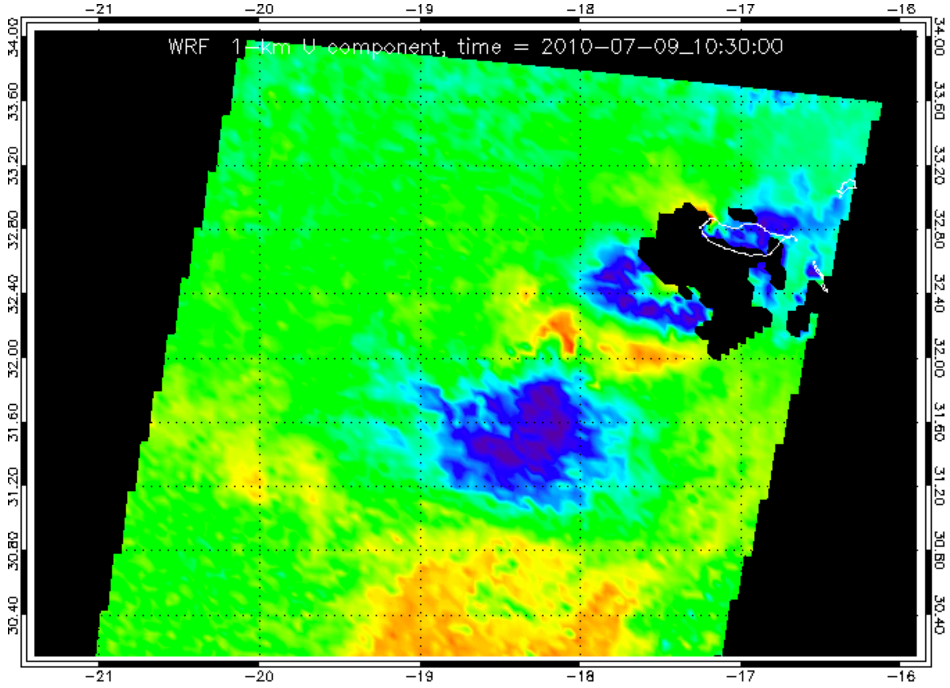
WRF

Madeira, P209_O056155: U component comparison

using MISR relative heights ±1 WRF levels



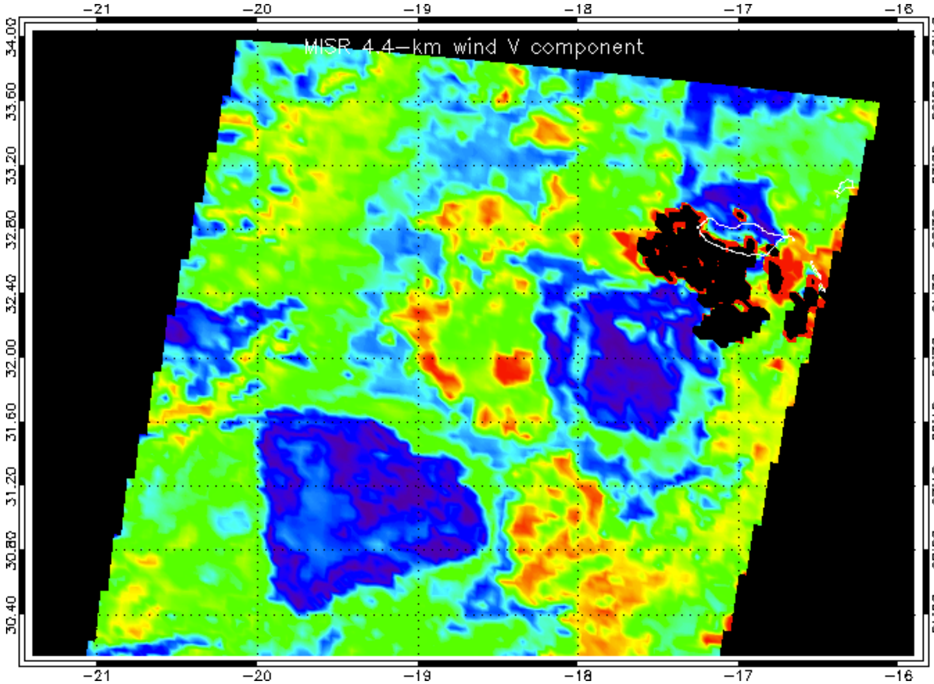
MISR



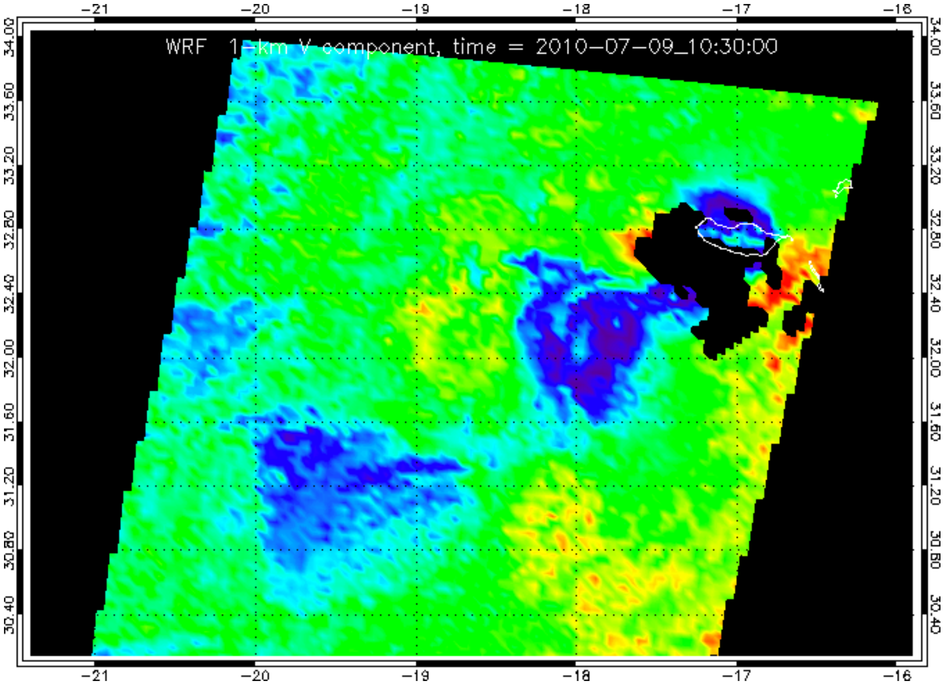
WRF

Madeira, P209_O056155: V component comparison

using MISR relative heights ±1 WRF levels



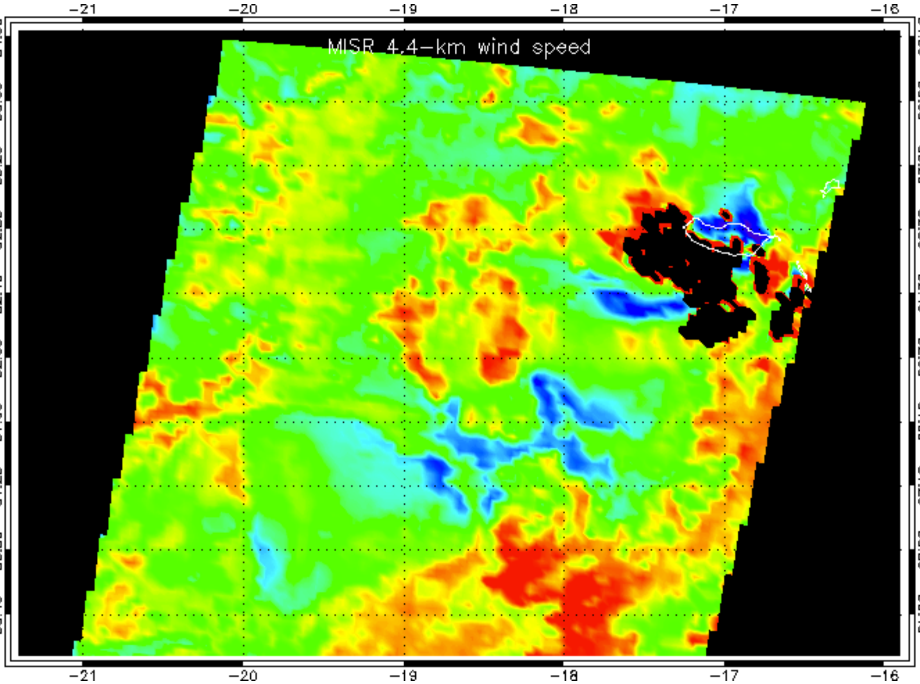
MISR



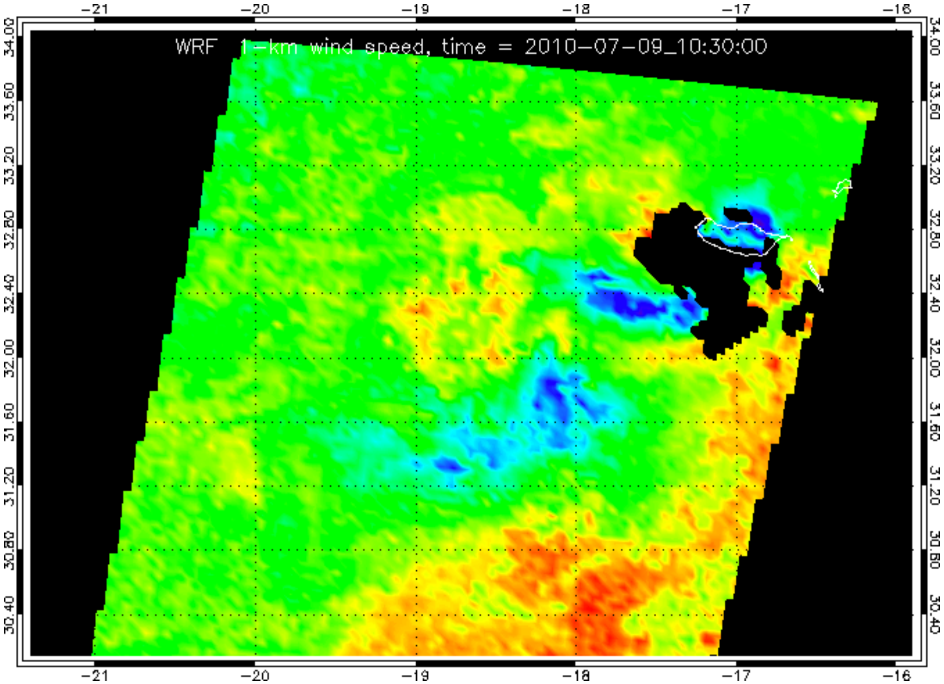
WRF

Madeira, P209_O056155: wind speed comparison

using MISR relative heights ±1 WRF levels



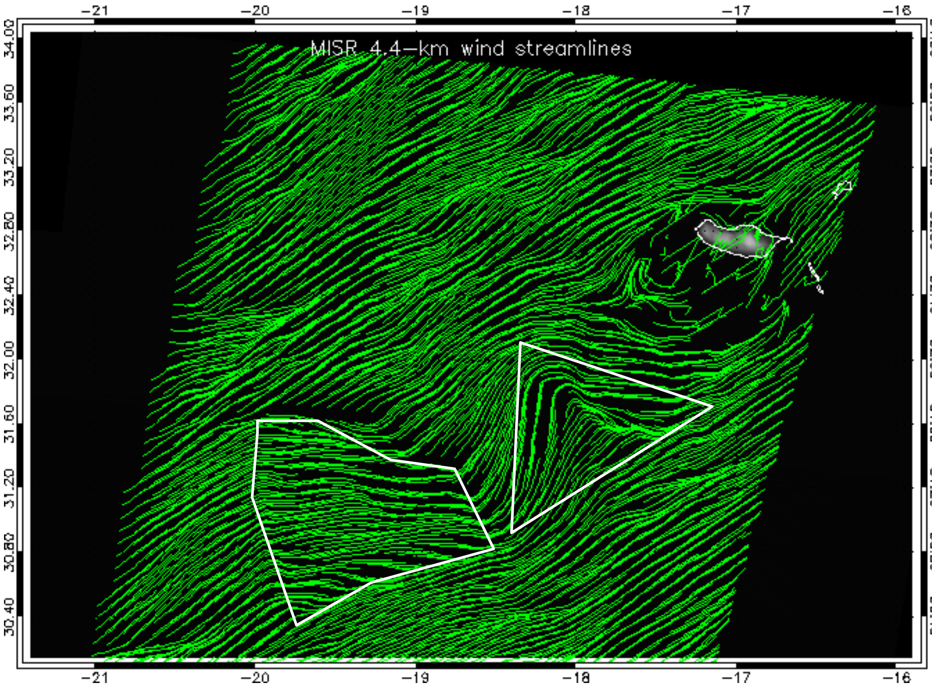
MISR



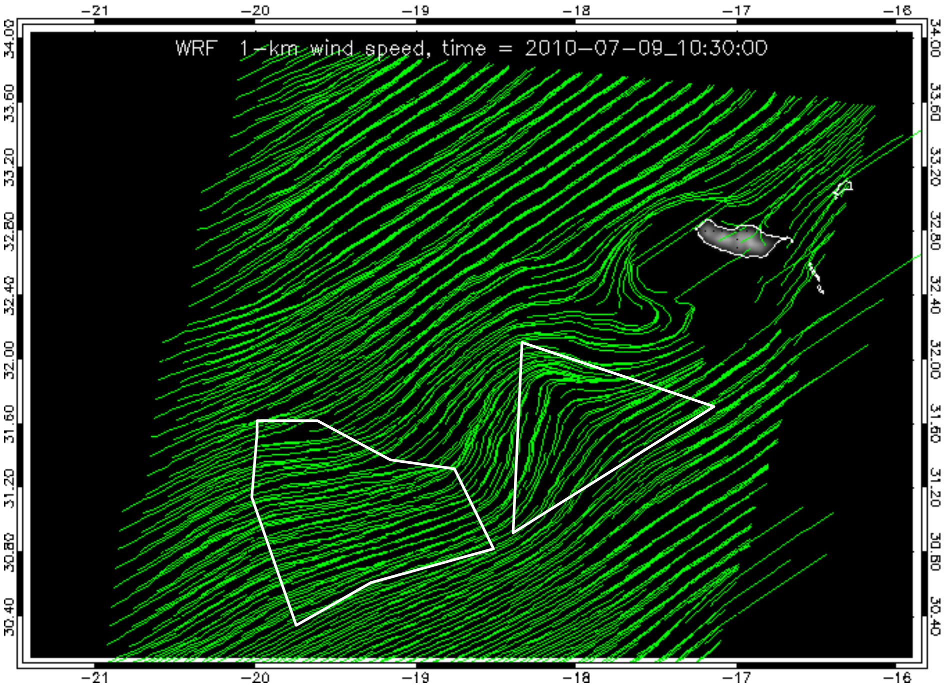
WRF

Madeira, P209_O056155: streamlines comparison using MISR relative heights ±3 WRF levels

level = 10



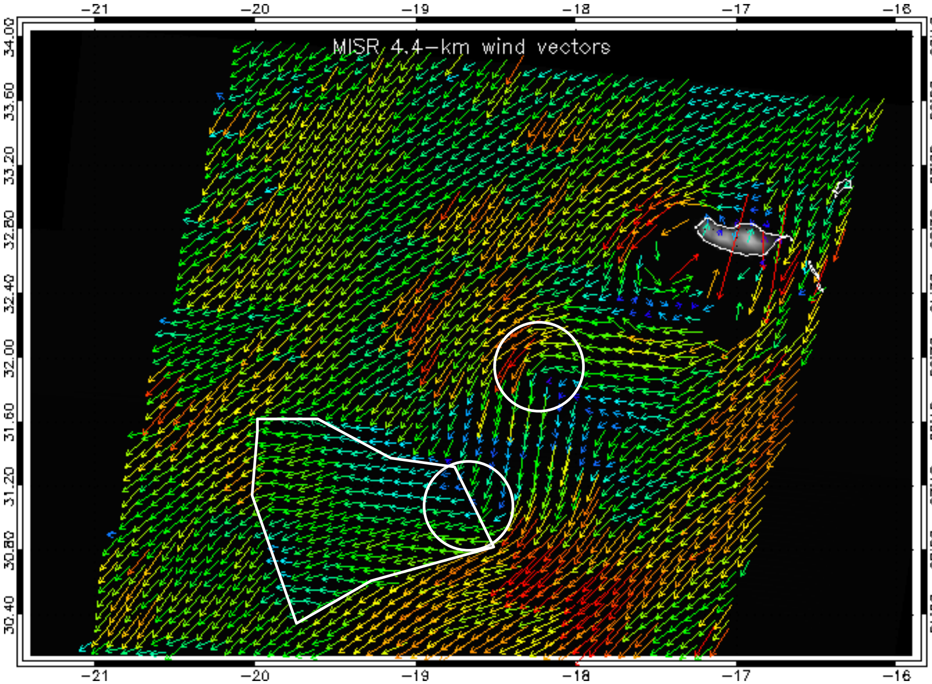
MISR



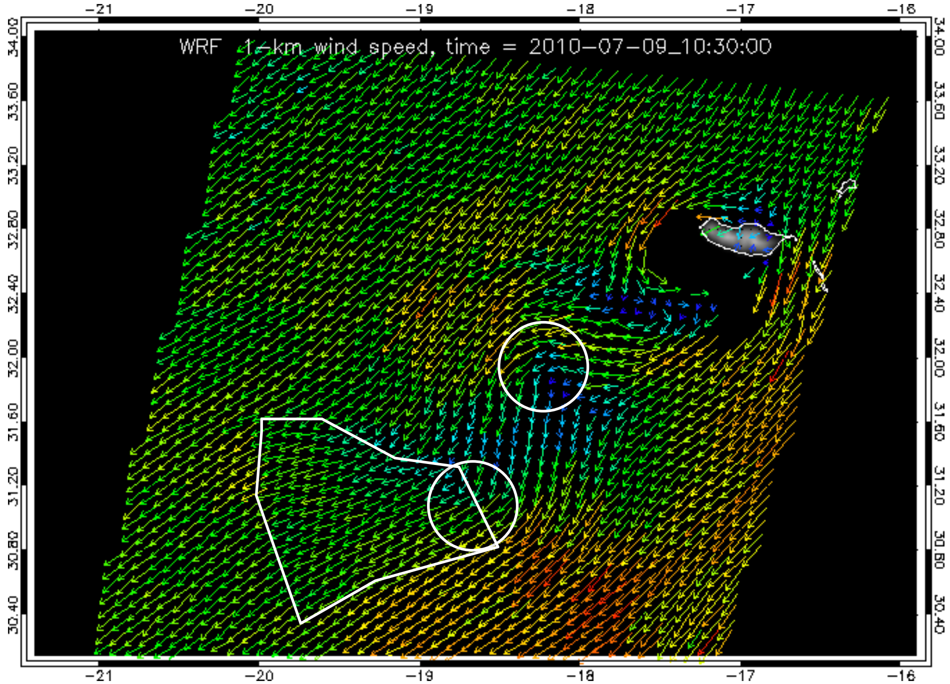
WRF

Madeira, P209_O056155: wind vector comparison using MISR relative heights ±3 WRF levels

level = 10

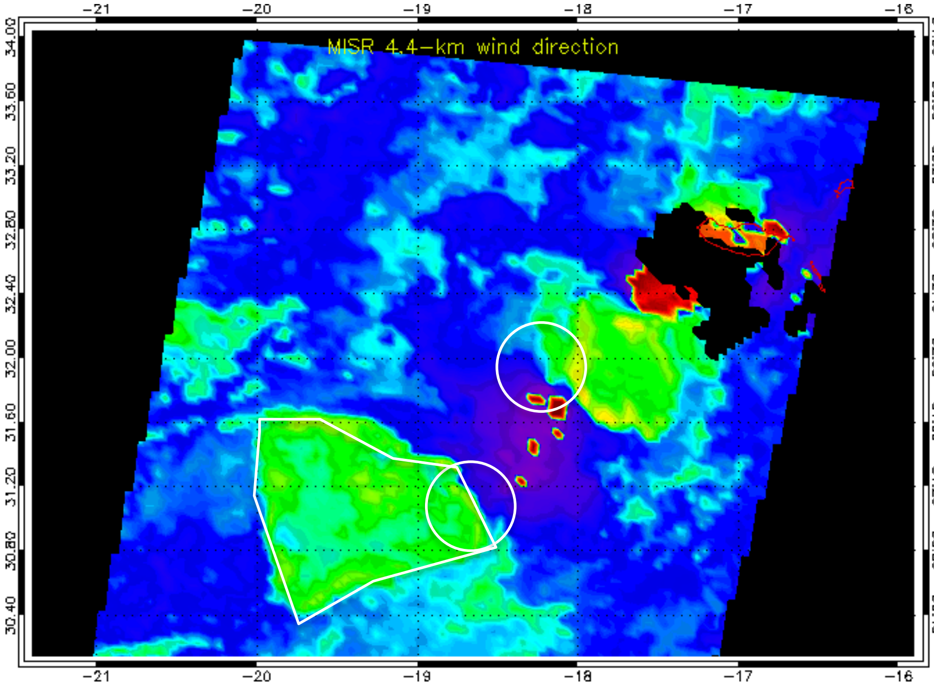


MISR

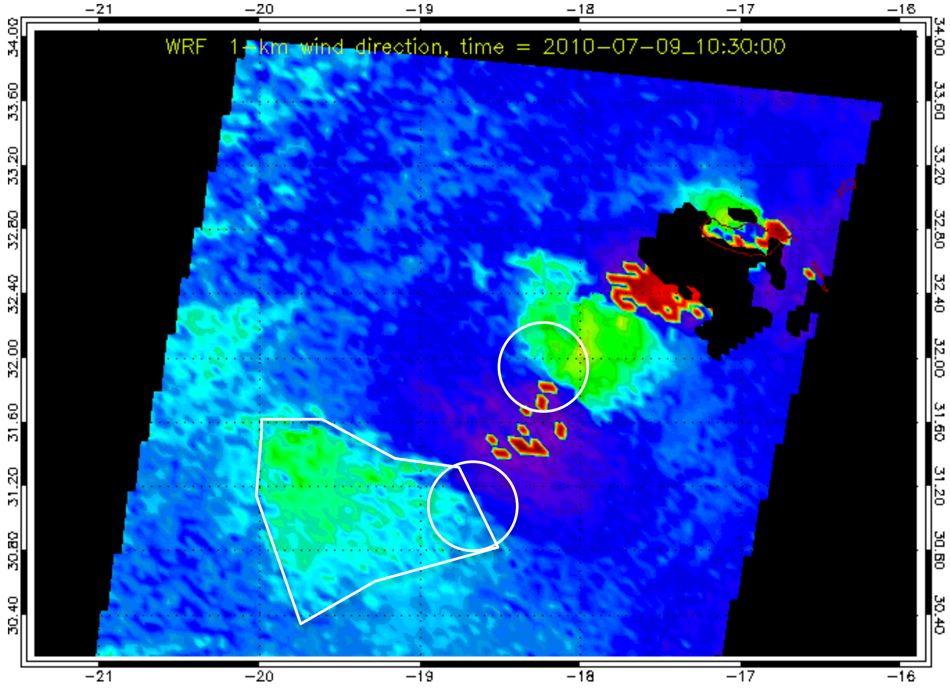


WRF

Madeira, P209_O056155: wind direction comparison using MISR relative heights ±3 WRF levels

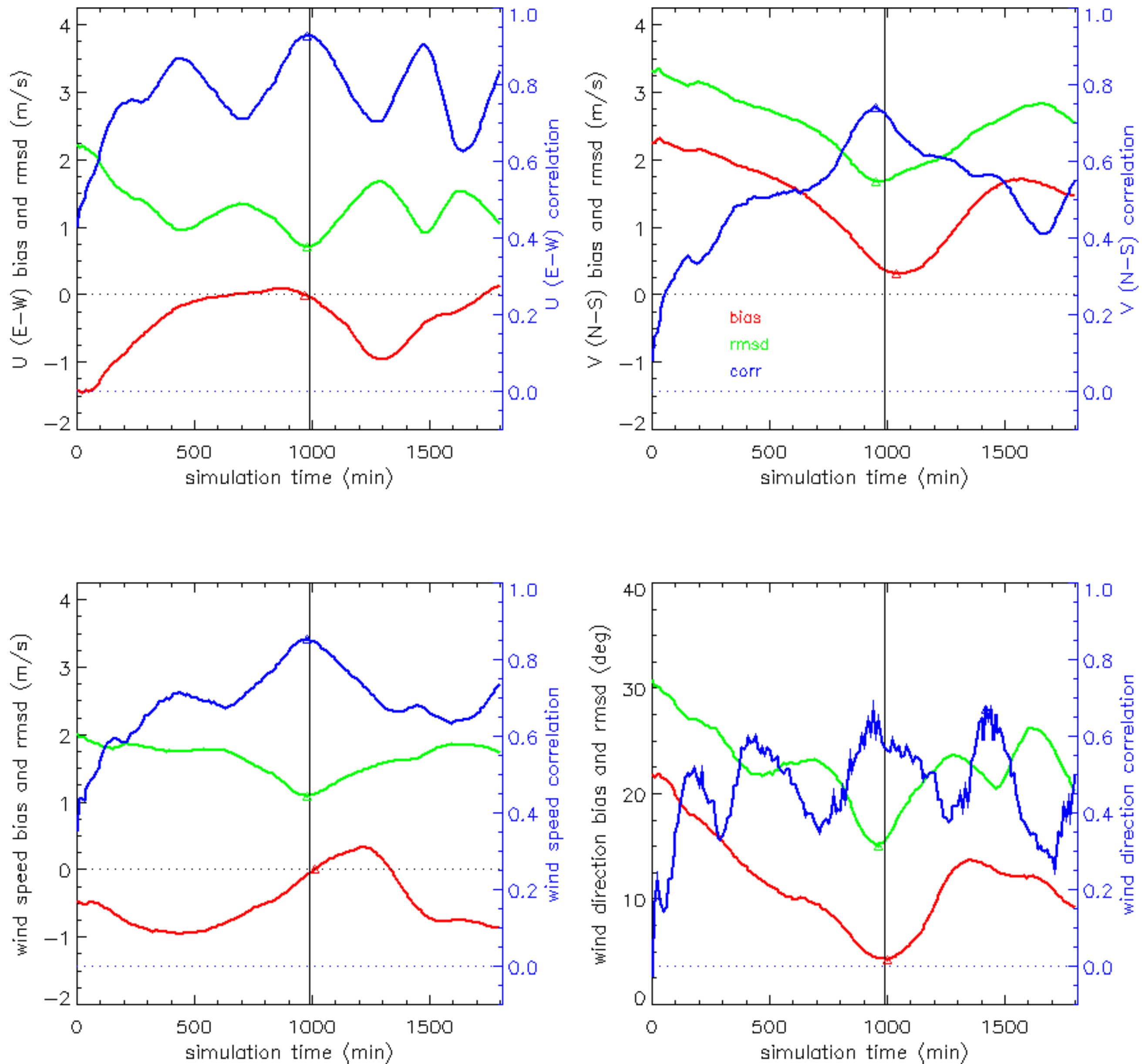


MISR

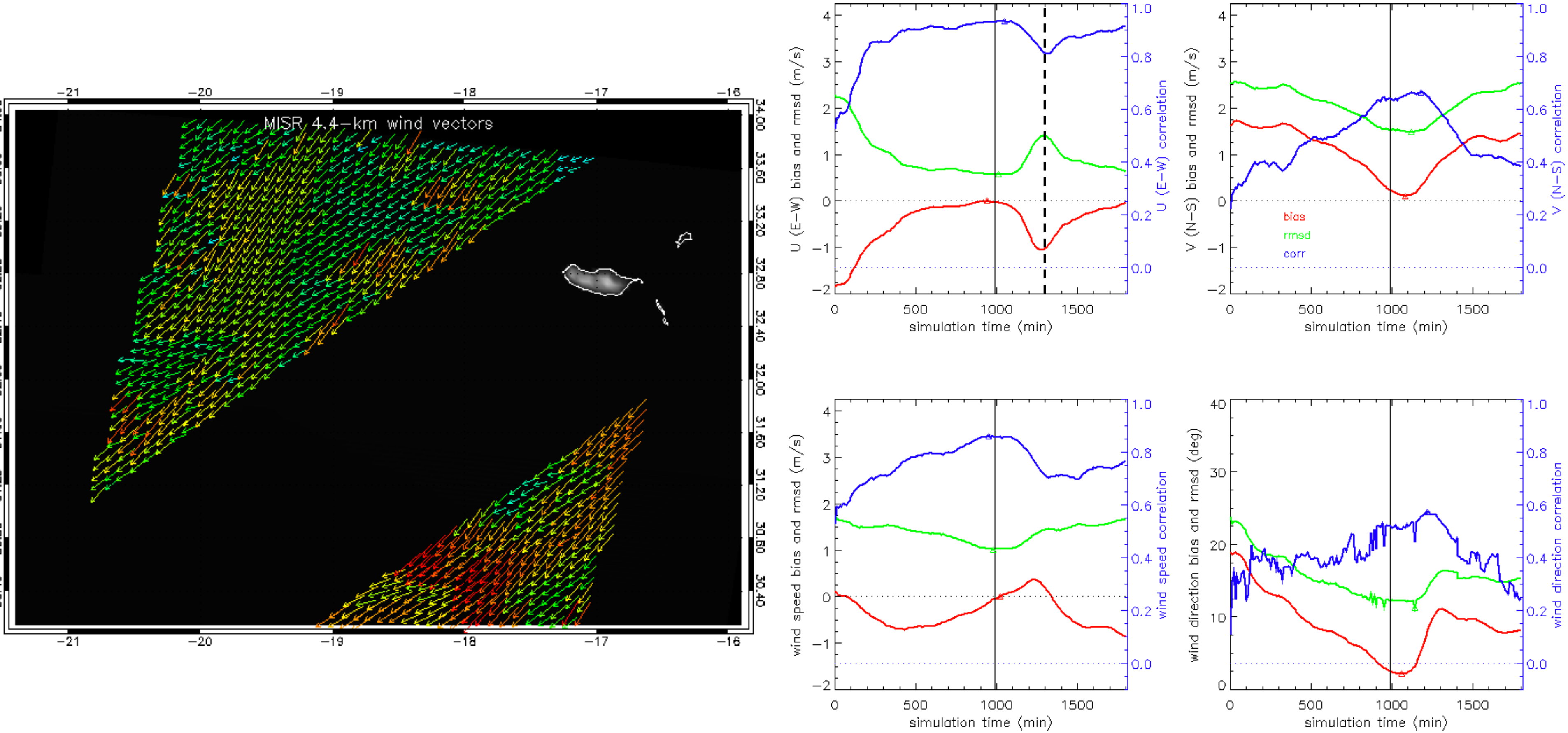


WRF

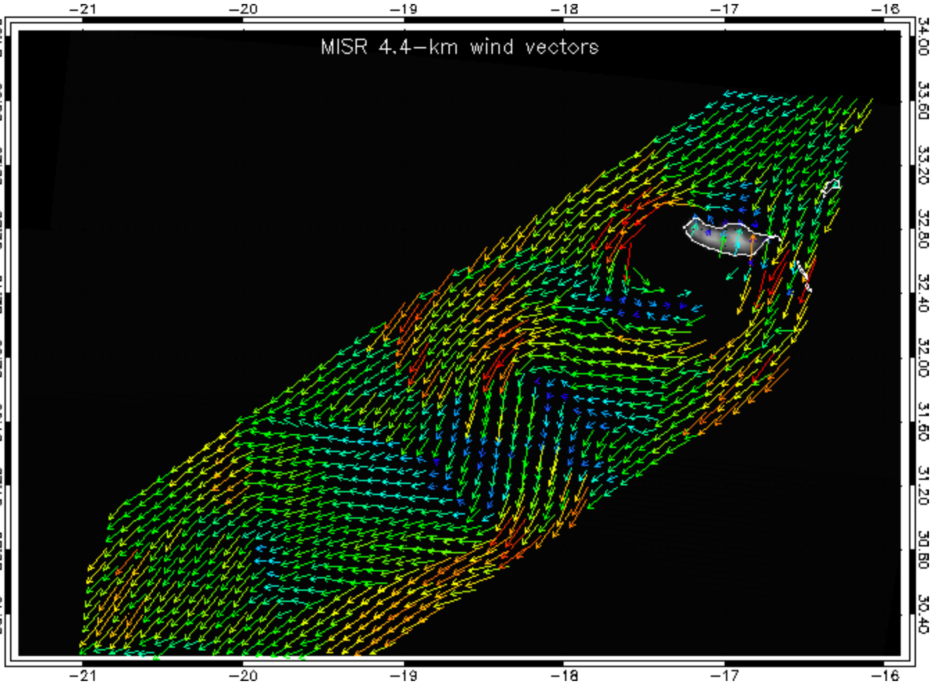
Madeira, P209_O056155: wind field comparison statistics using MISR relative heights ±3 WRF levels

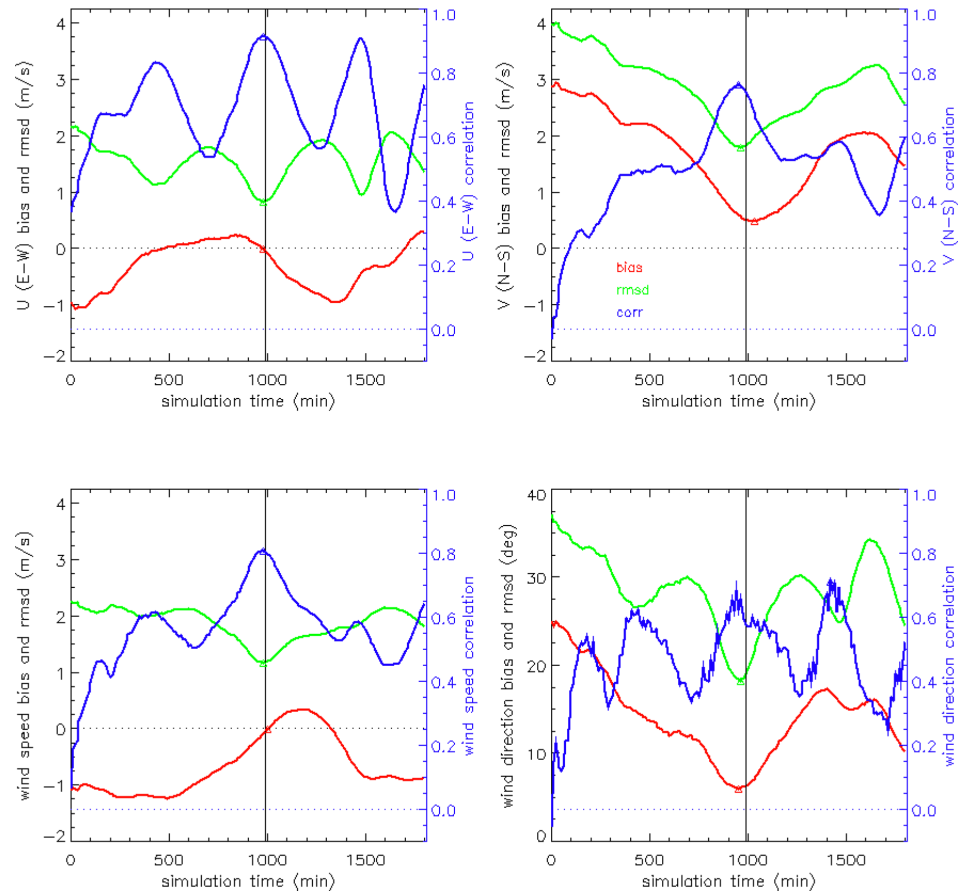


Madeira, P209_O056155: wind field comparison statistics using MISR relative heights at WRF levels, outside wake



Madeira, P209_O056155: wind field comparison statistics using MISR relative heights ±3 WRF levels, inside 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

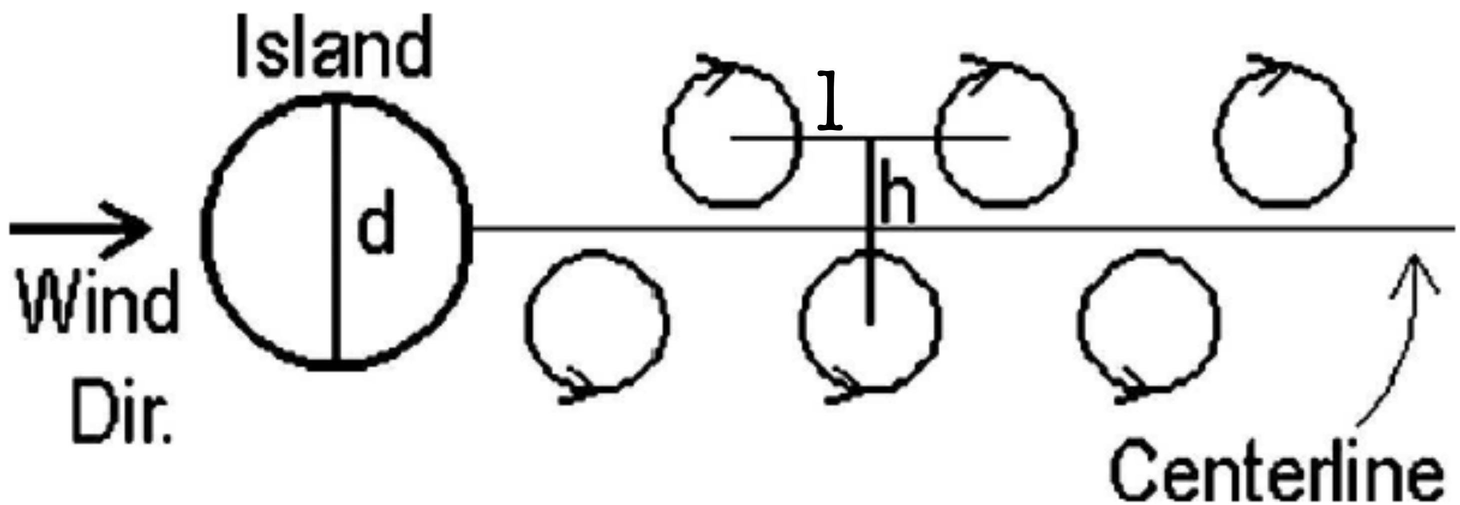
- Using relative (to the mountain peak) heights and accounting for uncertainty in MISR height retrievals yields decent agreement between measured and modeled wind fields

- 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

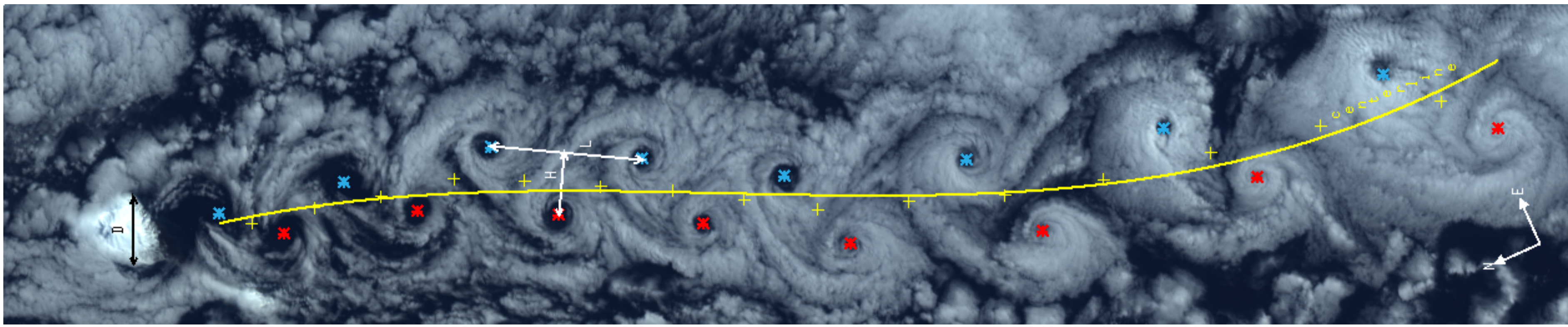
Classic von Kármán Vortex Street



aspect ratio: **h / l = 0.28** (*Kármán and Rubach* [1912])

dimensionless width: **h / d = 1.20** (*Tyler* [1930])

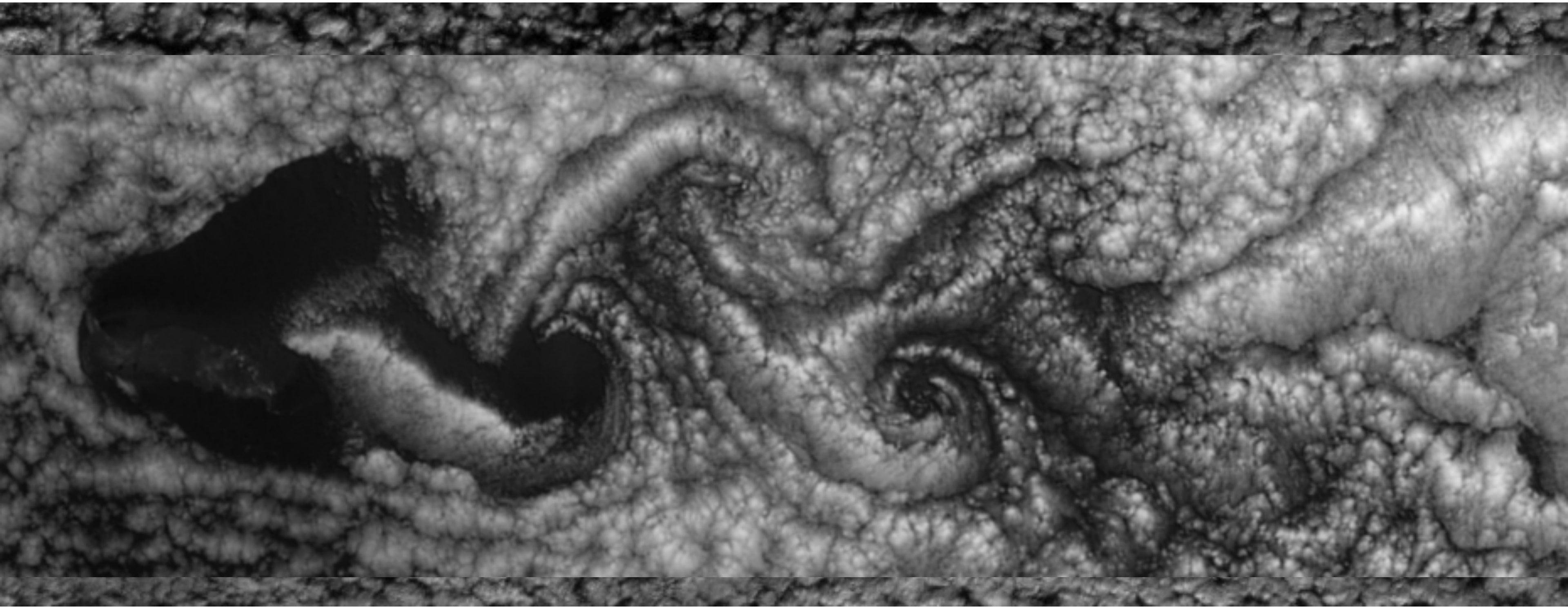
Vortex Geometry Analysis



* *	vortex centers
+	intervortex midpoints
—	3rd order polynomial centerline
H,L,D	calculate ratios H / L and H / D

(02) P217_O007808

Analyzed Cases



(0[illegible]) P[illegible]_O0[illegible]

[illegible]/[illegible]/200[illegible]

(Guadalupe Island)

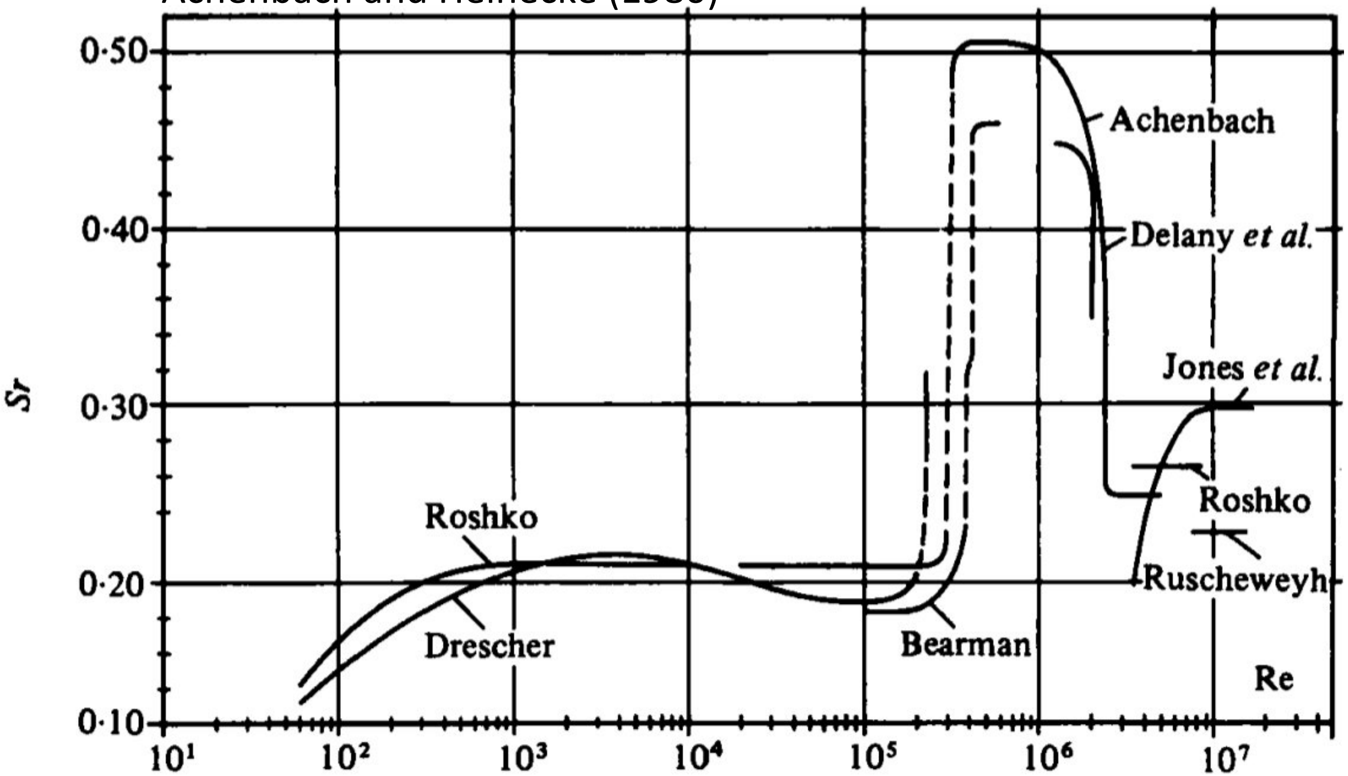
Measured Vortex Geometry

Path_Orbit	H / L (aspect ratio)	H / D (dimensionless width)
(01) P215_O006672	0.47	1.54
(02) P217_O007808*	0.36	0.94
(03) P214_O023812*	0.38	1.60
(04) P213_O024875	0.32	1.29
(05) P216_O028210	0.30	0.62
(06) P217_O028778*	0.37	0.91
(07) P218_O033540*	0.39	1.11
(08) P213_O051903*	0.37	1.56
(09) P218_O051947	0.12	0.46
(10) P213_O065417	0.46	1.38
Kármán and Rubach [1912]	0.28	
Tyler [1930]		1.20
Young and Zawislak [2006] (MODIS, 30 cases)	straight centerline: 0.36 - 0.47 curved centerline: 0.30 - 0.43	straight centerline: 1.23 - 2.00 curved centerline: 1.40 - 2.25

*well-developed vortices, extensive cloud sheets, clear centers

Sr-Re Similarity Theory

Achenbach and Heinecke (1980)



Strouhal Number (Sr):

$$Sr \equiv \frac{NL}{U_o}$$

Reynolds Number (Re):

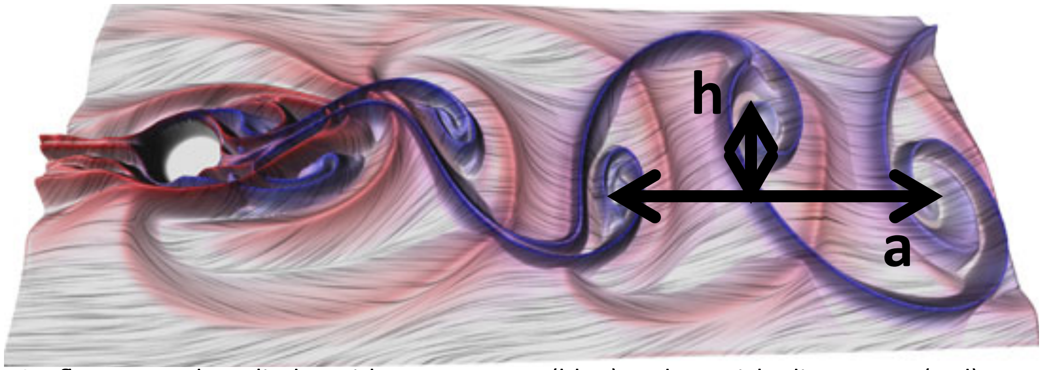
$$Re \equiv \frac{U_o L}{\nu}$$

U_o = freestream flowspeed
L = length scale
N = vortex shedding frequency
ν = kinematic viscosity

- 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

- *From von Kármán's 1912 Theory:*

  $\frac{h}{a}$ *~ 0.28 (aka aspect ratio)*

  for mechanically stable VKVSs

- *In the atmosphere, aspect ratio has been observed climatologically to be around .42 (Young and Zawislak 2006)*

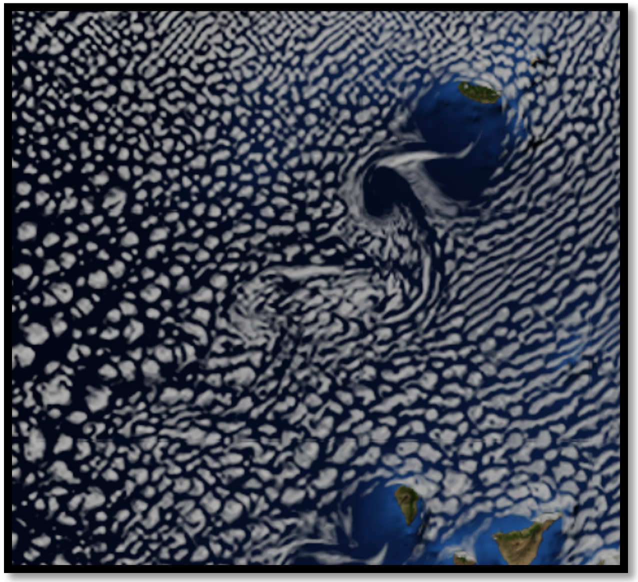
- *a is dictated by shedding frequency 'N' (i.e.* $a = \frac{Speed\ of\ Vortices}{N}$*)*

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

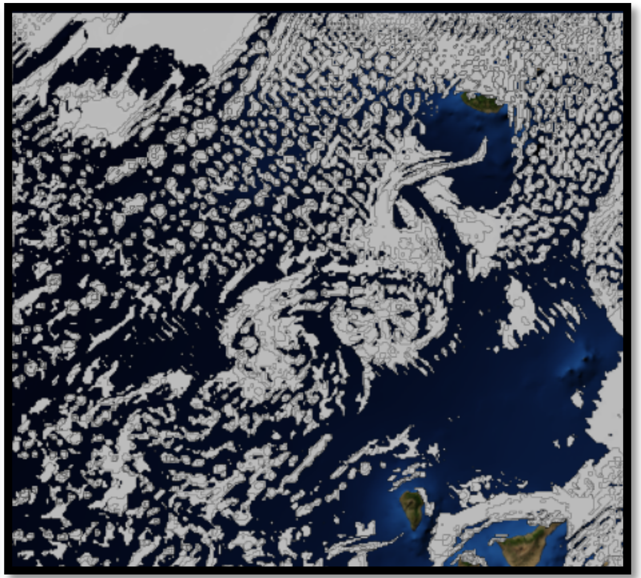
However, laboratory studies have proved similarity relationships between Reynolds number and dimensionless shedding frequency (Sr)…

PBL-Parameterization Sensitivity: cloud cover

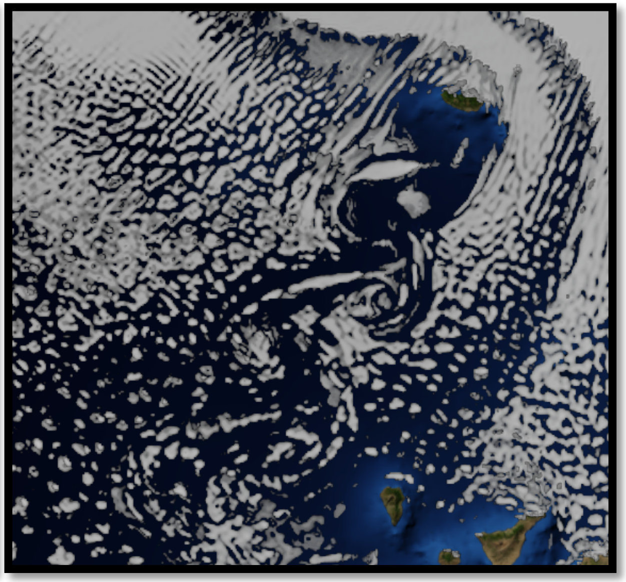
MYJ-scheme

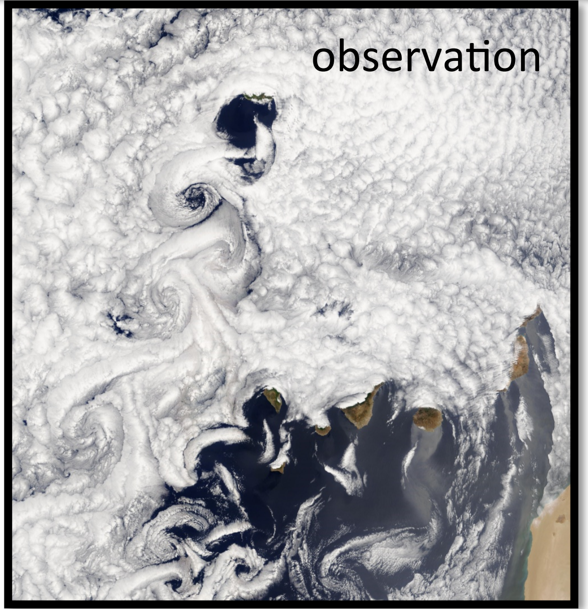


QNSE-scheme

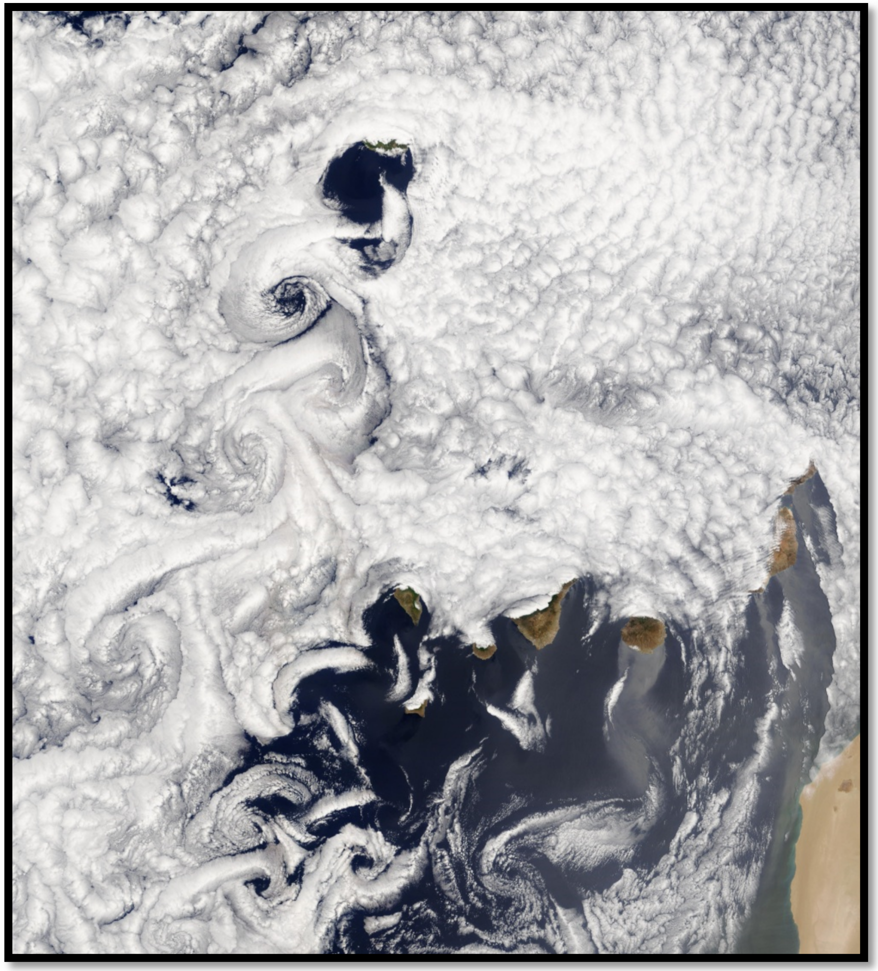


ACM2-scheme

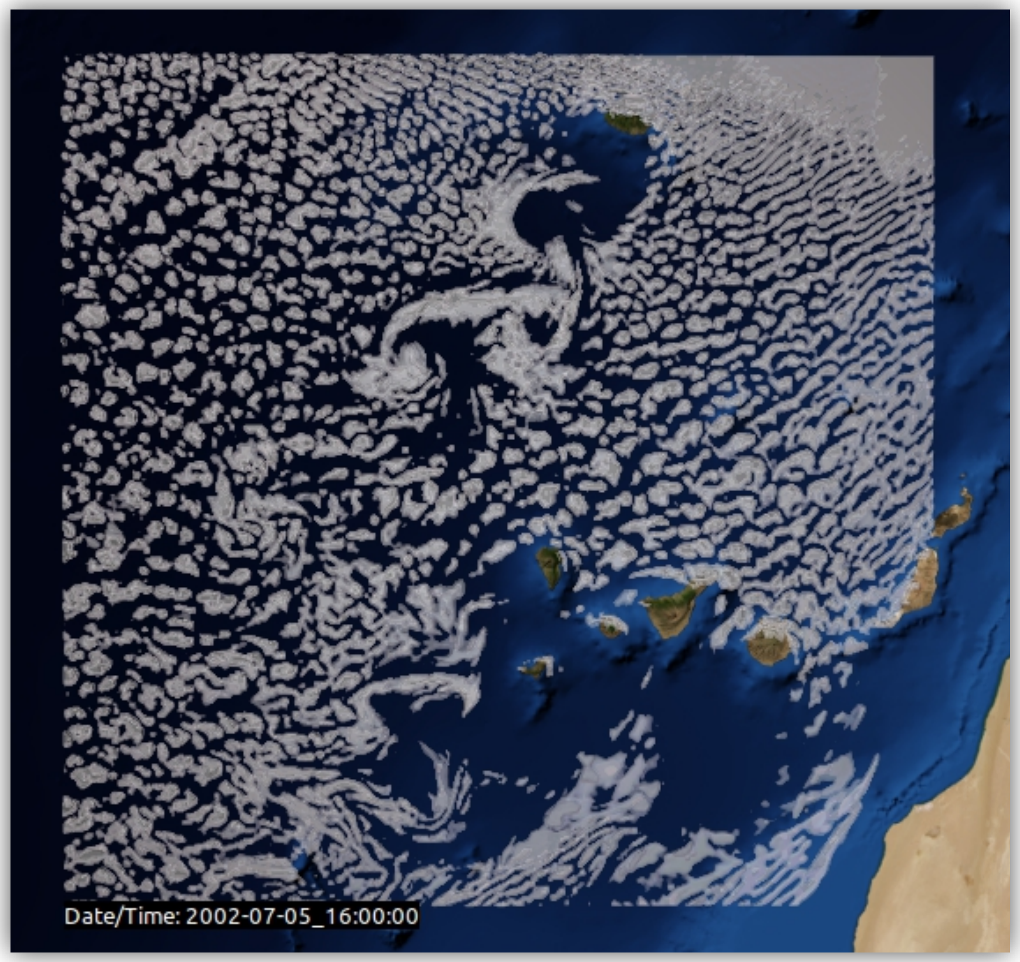




Real Case Study: Madeira and the Canary Islands



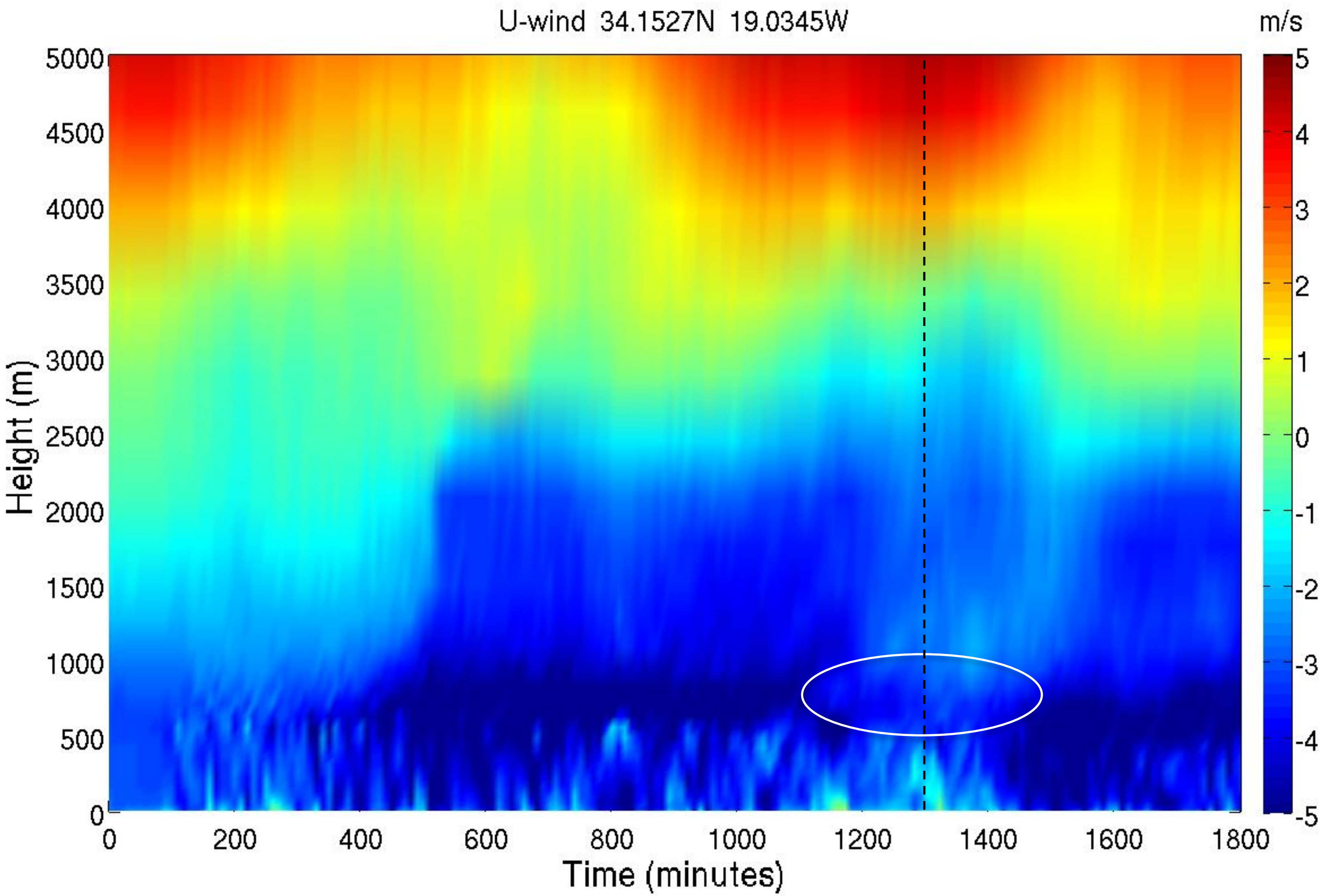
MODIS



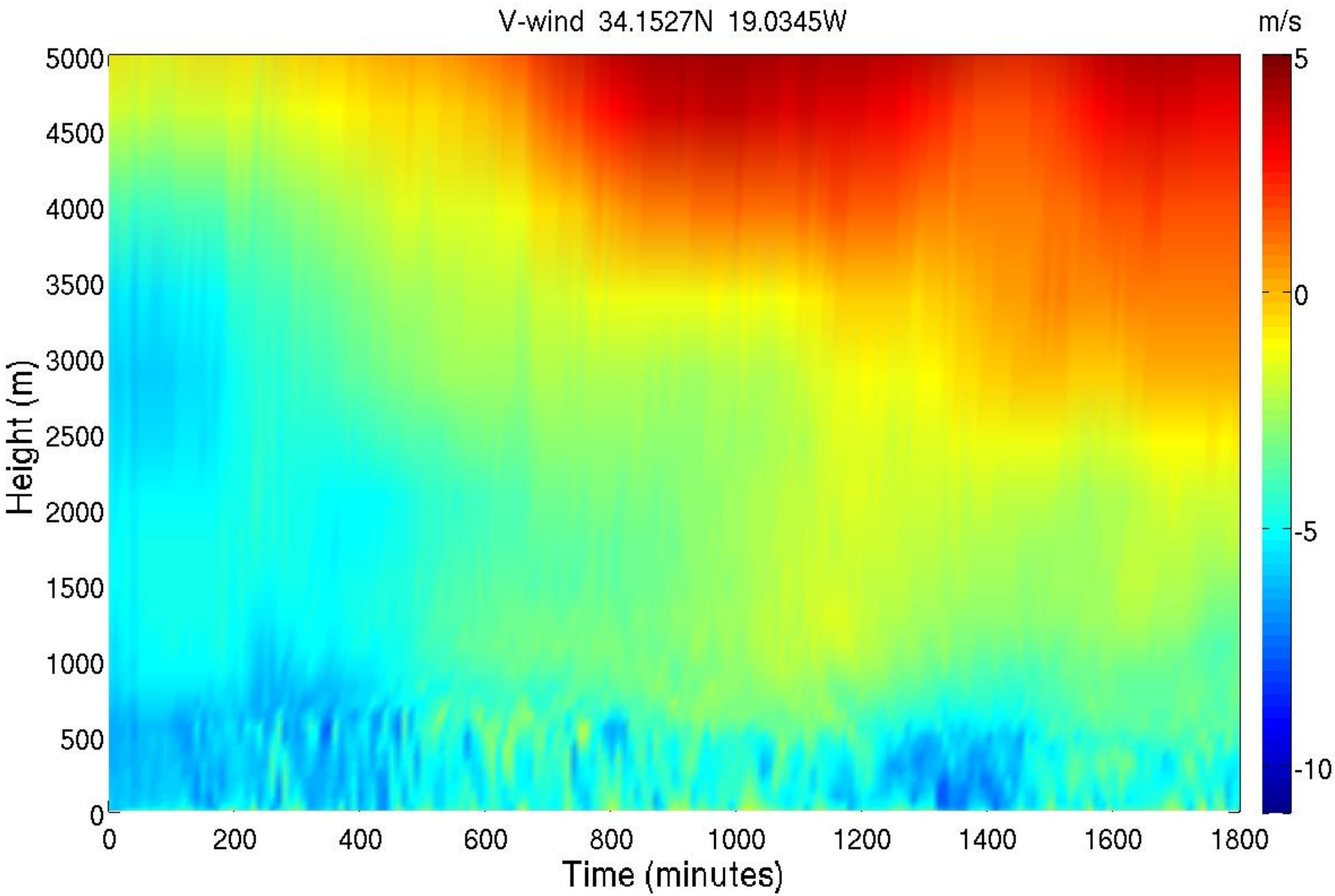
WRF Simulated Clouds

Shedding frequency ~5.5 hours

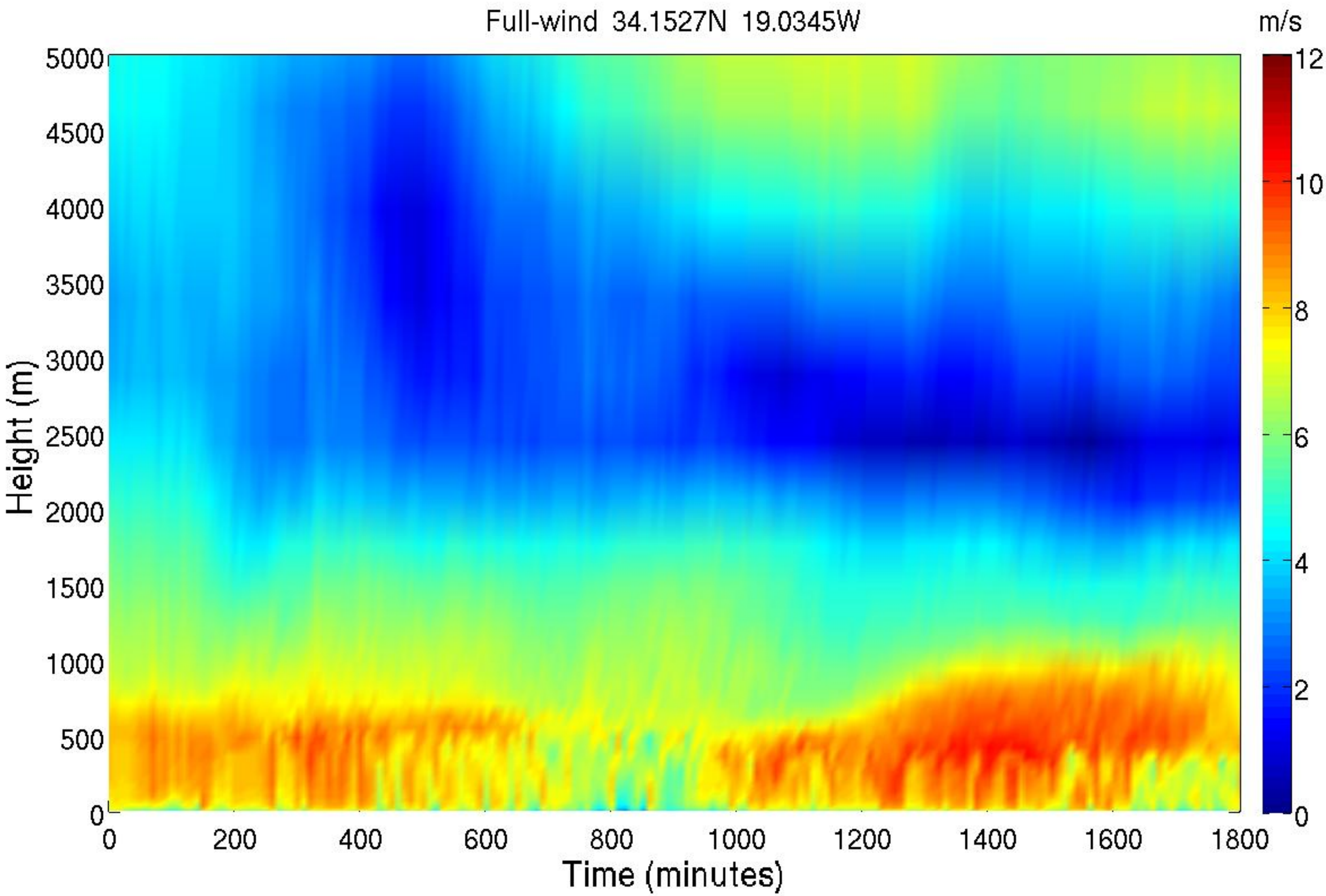
Madeira, P209_O056155: WRF U-wind time-height plot



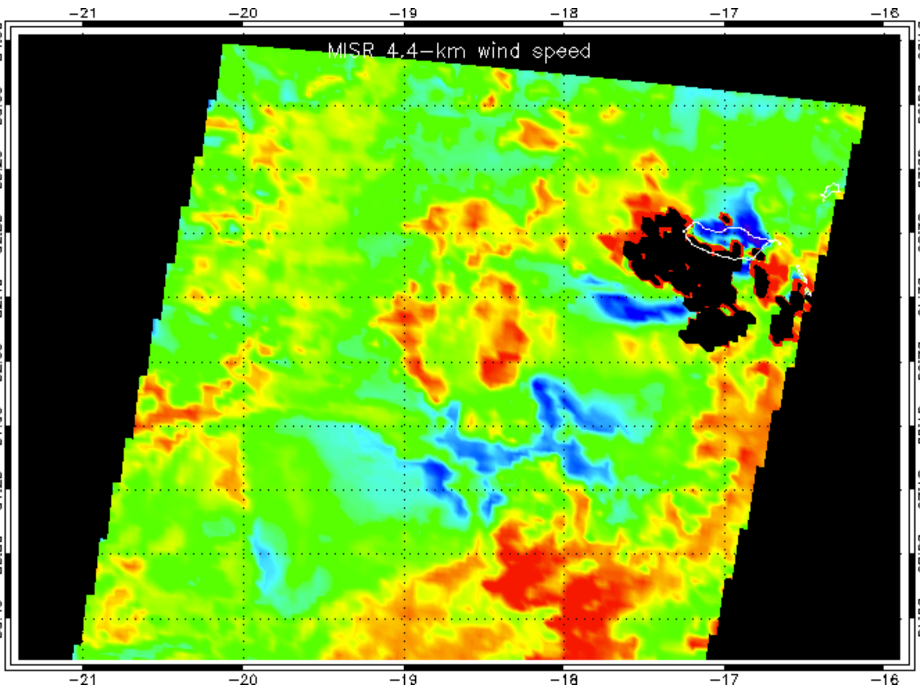
Madeira, P209_O056155: WRF V-wind time-height plot



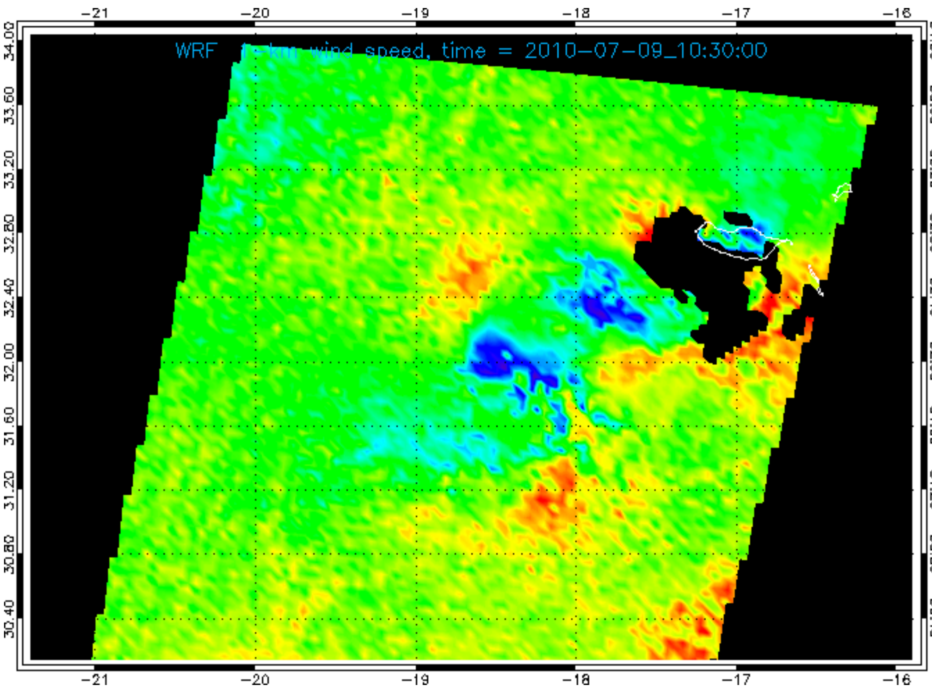
Madeira, P209_O056155: WRF full wind time-height plot



Madeira, P209_O056155: wind speed comparison using MISR relative heights +3/-9 WRF levels



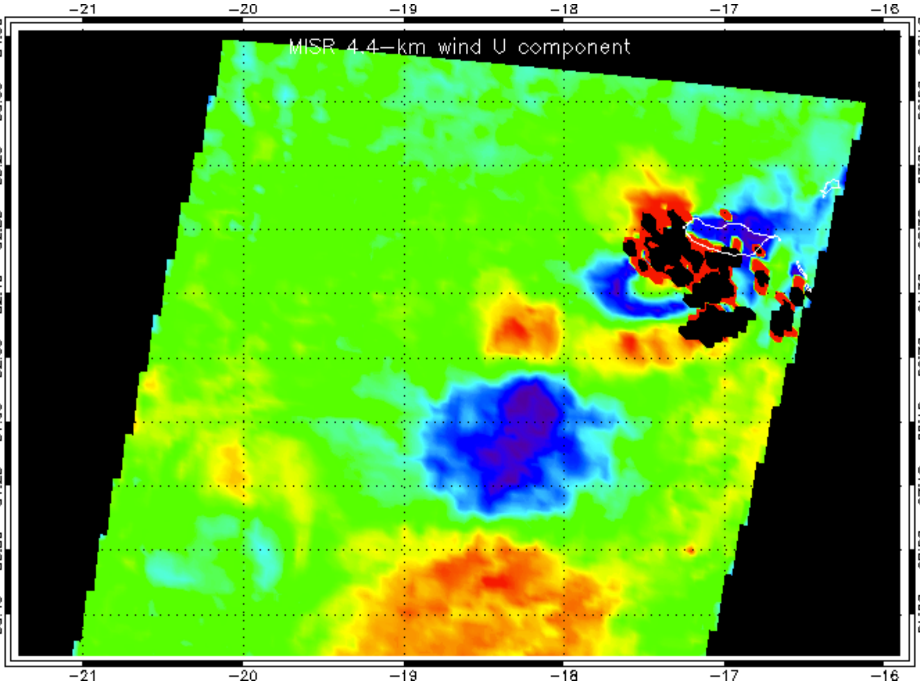
MISR



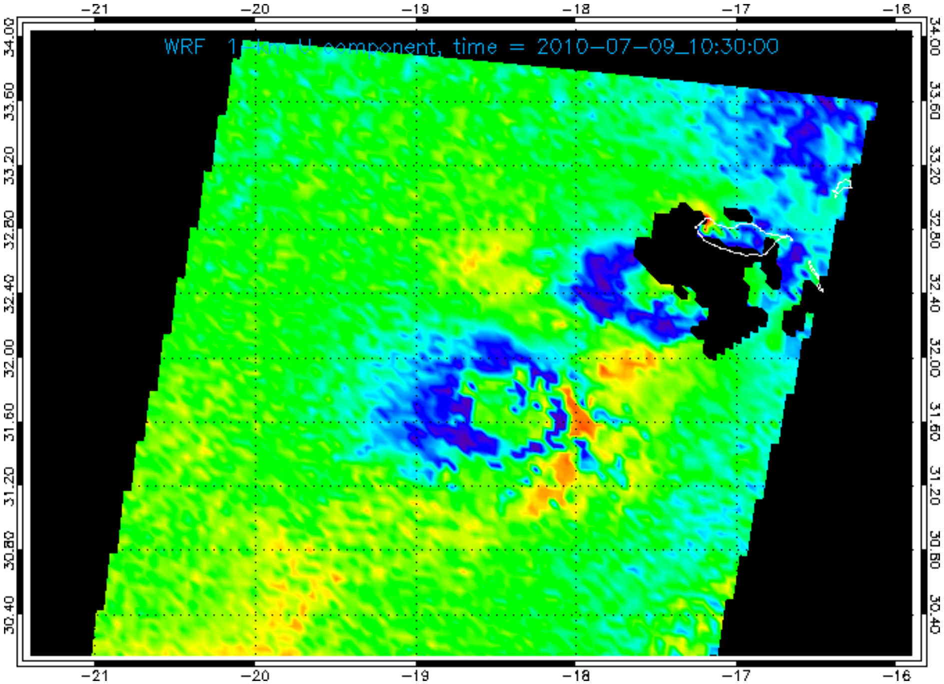
WRF

Madeira, P209_O056155: U component comparison using MISR relative heights + 3/3 WRF levels

using MISR relative heights + 1/3-9 WRF levels

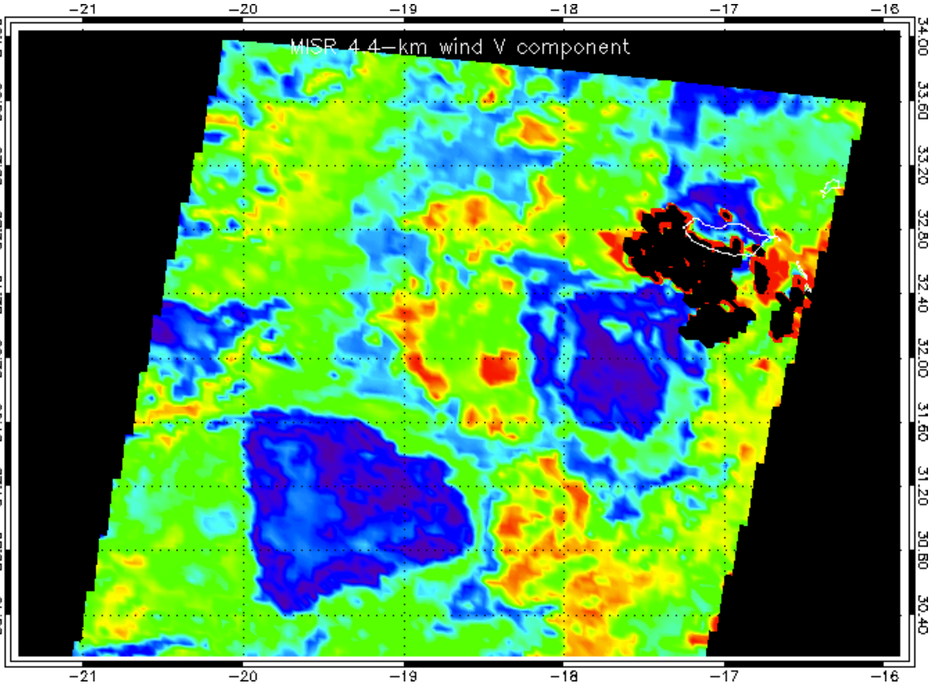


MISR

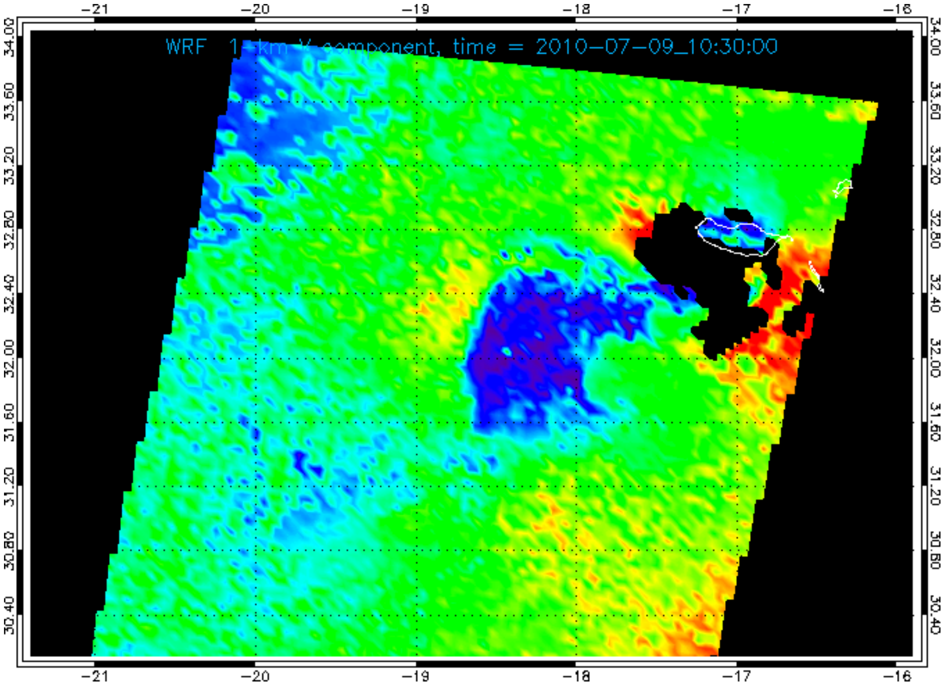


WRF

Madeira, P209_O056155: V component comparison using MISR relative heights + 1/3-9 WRF levels



MISR



WRF

Madeira, P209_O056155: wind field comparison statistics using MISR relative heights + 3/9 WRF levels