Dynamical Aspects of the Atmospheric Wake of Madeira Island

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Madeira: Location and Topography

Island Facts:
Location: 32.7°N 17.0°W
Length: 57km
Width: 22km

Highest Peak: Pico Ruivo (1862m)
Capital: Funchal
Political: Portugal

[Source: http://www.worldmap.org]
[Data Source: http://www.viewfinderpanoramas.org/dem3.html]
Inversion Height

Trade wind inversion height in 2010

In 2010:
117 days with an inversion of $d\theta/dz > 0.03 \, K/m$
underneath 4000 m

[Data Source: University of Wyoming http://weather.uwyo.edu/upperair/sounding.html]
Flow Regimes in Madeira

The formation of a wake leeward of Madeira is quite likely.
The I-Wake Campaign

Dates: 26 Aug – 5 Sep 2010

Field campaign designed to study air-sea coupled system and to obtain first in situ airborne measurements of Madeira’s wake

Observational Platforms
1) Research vessel (SST and vertical profiles)
2) Research aircraft:
   ATR-42 (Météo France) operated by SAFIRE

Case Study
Research flight with the highest spatial coverage and the most optimal atmospheric conditions
2 September 2010

Parameters used for further analysis
- Potential temperature
- Wind direction
- Wind speed
- Sea surface temperature (SST)
Numerical Model Setup

Used Model: **WRF ARW V3.3** (Weather Research and Forecasting Model)

<table>
<thead>
<tr>
<th>Single Domain</th>
<th>Initial Boundary Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions: 500 km x 500km x 58 vertical levels</td>
<td>ECMWF operational analysis</td>
</tr>
<tr>
<td>Hor. grid spacing: 1 km</td>
<td>Hor. resolution: 0.25°</td>
</tr>
<tr>
<td>Vert. spacing: Variable, higher level density at the inversion height</td>
<td>Number vert. levels: 92</td>
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</tbody>
</table>
On 2 Sep 2010 two research flights were flown:

**Morning:** Verification of the forecast from the day before  
**Afternoon:** Measurements along 10 flight legs + 1 sounding downstream
2 Sep 2010: Observed Wake

Research Flight
13:30 – 18:00 UTC
100 m ASL

Observed wind vectors

SST anomaly & Wind speed
Vertical Profile on 2 Sep 2010

09:15 UTC - morning

Model run: SST +1K
Comparison between Simulation and Measurements

Comparison of zonal wind speed along the 10 flight legs

1. Measurements
2. WRF-ARW

U Component [m/s]

Longitude [°E]
Vorticity Budget

**Lagrangian approach:**
Vorticity budget analysis along trajectory
⇒ Successful for highly idealized conditions

\[
\frac{\partial \zeta}{\partial t} = -u \frac{\partial \zeta}{\partial x} - v \frac{\partial (\zeta + f)}{\partial y} - w \frac{\partial \zeta}{\partial z} - (\zeta + f) \cdot \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)
\]

- Advection term
- Divergence term

\[
- \left( \frac{\partial w}{\partial x} \frac{\partial v}{\partial z} - \frac{\partial w}{\partial y} \frac{\partial u}{\partial z} \right) + \frac{1}{\rho^2} \left( \frac{\partial \rho}{\partial x} \frac{\partial p}{\partial y} - \frac{\partial \rho}{\partial y} \frac{\partial p}{\partial x} \right) + \left( \frac{\partial F_x}{\partial x} - \frac{\partial F_y}{\partial y} \right)
\]

- Tilting term
- Baroclinic term
- Friction term

\[
\zeta = \frac{\partial^2 \psi}{\partial z \partial t} + \frac{\partial u}{\partial x} \frac{\partial \psi}{\partial y} - \frac{\partial v}{\partial y} \frac{\partial \psi}{\partial x}
\]

\[
\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x} \left( \frac{\partial \phi}{\partial x} \right) - \frac{\partial}{\partial y} \left( \frac{\partial \phi}{\partial y} \right) - \frac{\partial}{\partial z} \left( \frac{\partial \phi}{\partial z} \right)
\]

- Advection term
- Divergence term

- SOLAR DIFFUSIVITY
- THERMAL DIFFUSIVITY
- TURBULENT DIFFUSIVITY

- SOLAR RADIATION
- THERMAL RADIATION
- TURBULENT RADIATION

**Diagram:**

- **A:** 3D representation of relative vorticity (\(\zeta\))
- **B:** Latitude vs. Relative Vorticity (\(\zeta\)) with tilting and divergence
- **C:** Latitude vs. Relative Vorticity (\(\zeta\))
- **D:** Latitude vs. Altitude

**Color Coding:**
- Blue: Rel. Vorticity from Budget
- Red: Rel. Vorticity diagnosed

**Equation:**

\[
\frac{\partial \zeta}{\partial t} = -u \frac{\partial \zeta}{\partial x} - v \frac{\partial (\zeta + f)}{\partial y} - w \frac{\partial \zeta}{\partial z} - (\zeta + f) \cdot \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)
\]
Sensitivity test on surface friction

Even if the surface drag coefficient $C_D = 0$, large values of PV are produced in the model. $\Rightarrow$ Friction at the steep coasts plays a minor role in the vorticity budget

$\Rightarrow$ The potential vorticity must arise from dissipation in the interior of the fluid
Wave Breaking

Critical level at 5000 m a.s.l. where \( \Omega = \omega - \bar{u}k = 0 \)

The upward propagating mountain wave breaks underneath the critical level

Kinetic energy dissipates in the WB region and a PV dipole is generated

This is consistent with idealized studies

* Cross section parallel
Summary

• Wake formation in summer likely due to strong inversion and steady trade winds

• 2 Sept 2010 Madeira’s wake was strong and unsteady with a vortex street

• WRF reproduced the observations quite well

• The potential vorticity in the wake arises from dissipation in the interior of the fluid

• A decoupled second wake in the mid-troposphere is present simultaneously to the one trapped in the MBL
Thank You!

- Madeira
- Canary islands
Climatology of Wake Events

In average 115 wakes per year from 2003 – 2010 evident in satellite images

- Again increasing strength towards summer months
- Again decreasing jump from Aug to Sep
- During summer mainly southwesterly wakes

[Source of both plots: Brigitta Goger, Bachelor thesis 2011, University of Vienna]
Sounding upstream: extracted from 4 WRF simulations with identical setup but different SST

SST Sensitivity

2 Sep 2010
09:15 UTC
SST Sensitivity Test

Simulations vs. Observations:
RMSE of ten flight legs for different SST offset experiments

Potential Temperature

U - Component

V - Component

Simulation scoring best in the RMSE ensemble mean:
+1 K SST offset => Control Run
The Wake Event on 2 Sep 2010

Due to the Azores High:

• Sustained winds from NE hitting the island perpendicularly
• Strong trade wind inversion at 1000 m a.s.l.

ECWMF MSLP on 2 Sep 2010 at 12:00 UTC
[Source: European Center for Medium Range Forecast]

VIS Satellite image on 2 Sep 2010 at 12:00 UTC
[Source: http://www.sat24.com]
2 Sep 2010:

Satellite measurements confirm the SST anomaly in the in situ measurements of the aircraft and agree with the ECMWF SST’s.

[MODIS data source: http://coastwatch.noaa.gov/]

Satellite Measurements
Eddy Shedding Period

Based on RMSE:
- different time shifts between simulation and observations

Based on power spectrum of time series

model 3.5 h earlier than observations

model 3.5 h later than observations

model time = observation time
Air-Sea Interaction in the Wake Region

Strong dependence of SST in the wake region on the wind speed

Data: ATR-42 aircraft observations at 100 m ASL
Due to the strong correlation of wind speed and SST:
The variable **SST anomaly** of the wake **can be computed** in a model from the 10 m wind speed

⇒ Variable SST fields can be used instead of static ones

**Benefits**
- Surface fluxes can be modeled more accurately
- Forecast skills in coastal regions can improve

**Application**
- This functionality can be easily added to the surface layer scheme in WRF with an updated SST field at every time step
- First successful tests were made with an adapted Mellor Yamada Janjić surface layer scheme