Mediterranean Lee Cyclogensis

The influence of the Alps on the development of a symmetric, warm-core subsynoptic cyclone during MAP D-PHASE (15-16 November 2007)

Ron McTaggart-Cowan¹ and Tom Galarneau Jr.²

¹ Environment Canada
² University at Albany
Outline

• Review of lee cyclogenesis mechanisms:
  – Barotropic vortex shedding
  – PV streamer generation
  – Normal mode baroclinic growth

• Analysis of 15 November 2007 lee cyclone

• Forecast model (CMCGEML/CMCGEMH) development of lee cyclone

• Attribution integrations with modified orography

• Discussion
Review of Lee Cyclogenesis

• Lee Cyclones:
  - Flow splitting around terrain induces vortex shedding (Krishnamurti 1968)
  - Cross-barrier pressure/temperature perturbation creates a surface PV anomaly as front “hangs up” on the Alpine block (Bleck and Mattocks 1984)
  - Mesoscale concentration of vorticity in PV banners (Aebischer and Schar 1998)
  - Normal mode baroclinic growth (Buzzi and Speranza 1986)

• Mediterranean “Hurricanes”:
  - Axisymmetric structure with convectively-generated warm core and WISHE-triggering winds
Rapid Subsynoptic Cyclogenesis

- Strong northerly flow across the Alps on 15 November during trough / front passage and cutoff

GFS Analysis valid 0000 UTC 16 11 2007

Streamfunction and nondivergent wind at 500 hPa computed from the 0.5° GFS final analysis. Extent of snow cover is shown by grey shading. Short, long and pennant wind barbs represent wind speeds of 2.5, 5 and 25 ms⁻¹, respectively.
Rapid Subsynoptic Cyclogenesis

- Orographic blocking of cold air leads to a large cross-Alpine pressure gradient

Analysis of surface observational data for 1200 UTC 15 November. Isobars at 2 hPa intervals are plotted with solid blue lines, and surface potential temperatures at 2 K intervals are plotted with dashed red lines.
Rapid Subsynoptic Cyclogenesis

- Vortex develops on cyclonic shear side of Mistrals in strong confluent frontogenesis

Analysis of surface observational data for 1200 UTC 15 November. Isobars at 2 hPa intervals are plotted with solid blue lines, and surface potential temperatures at 2 K intervals are plotted with dashed red lines.

Analysis Valid 1200 UTC 15 November 2007

Case Study 15-16 November
Rapid Subsynoptic Cyclogenesis

Meteosat visible satellite image for 0800 UTC 16 November 2007.

- Cyclone develops an axisymmetric warm core structure as the remnant front progresses eastward.

- Cyclone sustains hurricane-force surface winds of $(30 \text{ ms}^{-1})$ by 0000 UTC 16 November.

QuickScat retrieved wind speed (colour bar) and vectors (black arrows) for morning 16 November.
Model Description

- CMCGEML/CMCGEMH (15 / 2.5 km) driven by GEM global (35 km) ICs/BCs for 18h forecasts
- Inner grid shifted slightly southward to better position the cyclone of interest
- Microphysical parameterization updated to correct problems noted during D-PHASE
- Orography growth (as implemented in MC2 following original MAP campaign) over 6-h in CMCGEML and 4-h in CMCGEMH
Evaluation of Control Forecast

- Coherent tropopause disturbance (CTD) at the base of the trough moves across the Alps
- Lower level vorticity is generated by Alps and horizontal shear zone
- CTD is fragmented as convection is triggered over the warm Mediterranean waters
- Resulting cyclone has spiral vorticity structure

Dynamic Tropopause (DT) potential temperature (as indicated on the greyscale) and winds (knots), and 925-850 hPa layer-average relative vorticity (magenta contours > $2 \times 10^{-4}$ s$^{-1}$ at $4 \times 10^{-4}$ s$^{-1}$ intervals) from the control forecast.
Attribution Test: Alpine Removal

- Alpine orography is relaxed to a regional average during spin-up to avoid initial shock
- Cyclone develops over Corsica (east of position in the control forecast)
- Intensity and final cyclone location are similar in control forecast and “Alps” attribution test

Curvature component of vorticity ($10^4 \text{ s}^{-1}$) for the control forecast and attribution tests as indicated in the legend.
Attribution Test: Alpine Removal

- Trough and CTD remain essentially unaffected by the removal of the Alpine barrier over this short time scale.
- Despite the dramatic nature of the modifications, a subsynoptic cyclone develops in the Gulf of Genoa.

DT potential temperature and winds, and 925-850 hPa relative vorticity, as in previous figures.
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“Lee” cyclogenesis proceeds without the Alps, suggesting that the atmosphere was already primed for subsynoptic cyclogenesis before 0000 UTC 15 November.

Did the Alps contribute to this preconditioning?
Attribution Test: $T_{0-12h}$ Control

- Control forecast system is rerun from analyses 12h earlier (1200 UTC 14 November 2007)
- Trough progresses southward more rapidly and triggers development before the CTD reaches the Mediterranean
- Cyclone develops further east, but near the observed time

DT potential temperature and winds, and 925-850 hPa relative vorticity, as in previous figures.
Attribution Test: T_{o-12h} Alpine Removal

- Large-scale upper level structure is not notably modified from T_{o-12h} control
- The CTD is unable to couple with a lower-level PV perturbation for development and begins to decay
- No cyclone forms in the Gulf of Genoa

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Alpine modification to the local flow was crucial to establishing a favourable environment between 1200 UTC 14 and 0000 UTC 15 November

What mountain-induced element was the key to preconditioning?
Alpine Influence on Development

- Comparison of the 12h forecast from the $T_{o-12h}$ Alpine Removal and the control initialization shows a large thickness difference.
- Alpine blocking holds back the cold front and creates a relative warm area in the lee.
- Warm pool is a surface potential temperature anomaly ($\theta'_{sfc}$).

Thickness (1000-500 hPa) difference between the 12h forecast of the $T_{o-12h}$ Alpine Removal and the initializing data for the control forecast (warm colours indicate areas where the control data is warmer). Control forecast thicknesses are plotted at 6 dam intervals with magenta contours. Anomaly inversion area is indicated by the blue box.
Attribution Test: $T_{o-12h}$ Warm Pool

- PV inversion uses $\theta'_sfc$ as a lower boundary constraint
- The balanced flow associated with $\theta'_sfc$ in the northern Gulf is inserted into the 12h forecast from the $T_{o-12h}$ Alpine Removal
- This attribution test isolates this single effect of the Alps

Inverted $\theta'_sfc$ (Kelvin, 0>K as indicated on the colour bar) and winds (yellow barbs in knots) at 1000 hPa, and zonal cross-section of potential temperature (1 K intervals as indicated on the greyscale) and meridional winds (blue contours in 1 kt intervals) as indicated on the plan view.
Attribution Test: $T_{o-12h}$ Alpine Warm

- CTD moves further around the base of the trough and eastward before triggering convection
- Cyclone develops further east, between Cypress and Italy
- PV coupling occurs further east as a result of the displacement of the upper and lower level features

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Cyclone tracks beginning at first identifiable time, and ending at 0000 UTC 16 November 2007.

Curvature component of vorticity ($x10^4$ s$^{-1}$) for the control forecast and attribution tests as indicated in the legend.
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Alpine blocking of the cross-barrier flow developed a warm anomaly in the lee that acted as a lower-level PV feature capable of coupling with the upper-level CTD

This effect is reproduced by inserting a similar anomaly in the absence of the Alps themselves
Discussion

• An intense, warm-core subsynoptic cyclone developed over the Gulf of Genoa during the MAP D-PHASE project

• Attribution tests involving Alpine removal show that the effects of the Alps during development were restricted to structural changes in the cyclone rather than intensity

• The lee-side warm anomaly generated by blocking was synthesized and shown to be sufficient to promote development
Alpine vortex shedding, normal mode growth and banner generation did not play a leading role in this case of lee cyclogenesis; however,

The Alps preconditioned the atmosphere for subsynoptic cyclogenesis by blocking the flow during frontal passage, creating a surface $\theta$ anomaly that coupled with an upper-level CTD to promote rapid development.
The END

What are you doing, Dave?

That was the END Dave ... why don't you take a chill pill?
Orographic Modifications

Model orography and cyclone tracks (9-18h range, circle for genesis) for attribution tests
Despite differing genesis locations and tracks, all test cases develop cyclones of varying strengths.

Removal of local orography and Apennines enhances vortex strength beyond the control.
Cyclone Energetics (Eddy APE)

- Elimination of cold air damming allows for greater cold outflow over the western Mediterranean:
  - Enhanced conversion of APE to eddy APE (left)
  - Reduced stability in the cold northerly flow limits convective eddy APE generation (right)

Proportional to mean $V'T'$

Proportional to mean $Q'T'$

**Figure:**
- Eddy Available Potential Energy Generation (Conversion from basic state APE to eddy APE)
- Eddy Available Potential Energy Generation (Diabatic generation of eddy APE)
Cyclone Energetics (Eddy APE)

Elimination of cold air damming allows for greater cold outflow over the western Mediterranean:

- Enhanced conversion of APE to eddy APE
- Reduced stability in the cold northerly flow limits convective eddy APE generation (right)

1000-500 hPa thickness from attribution tests (colour shading as indicated on the colour bar) and 700 hPa winds as on previous figures.
Cyclone Energetics (Eddy APE)

Air/sea temperature difference (K, as indicated on the colour bar) after 12 h of integration.

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Cyclone Energetics (EKE)

- Elimination of perturbing near-vortex orography allows for effective coupling (active PV “hook”), enhancing barotropic KE – EKE conversion (left)

- A strong thermally direct circulation in the Dry run effectively converts eddy APE to EKE (right)
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DT potential temperature from tests as indicated (colour shading as indicated on the colour bar) and DT winds as on previous figures.
Summary
• Lee cyclone (Uberstromungs-type) forms along a confluence line at intersection of PV banners
• Orographic attribution study suggests that orography is not a necessary component:
  − Control: mountain triggering of diabatically developed “Mediterranean hurricane” type
  − Alps: rapid baroclinic development with strong air-sea temperature differences (polar low)
  − Full removal: combined baroclinic and barotropic forcing with diabatic assistance to generate the strongest cyclone in the tests (polar low)

Integrated suspended hydrometeor after 18 h of integration.
Conclusion

The mountains are not a necessary condition...

Alpine (and surrounding) orography modifies the morphology of the "lee cyclone" in this case by modifying the regional flow, but does so in the context of an atmosphere already pre-disposed to rapid sub-synoptic cyclogenesis.
Evaluation of Control Forecast

- Orographic blocking is well represented in the control.
- Core structure is warm and axisymmetric.
- Cyclone is isolated from thermal ridge (black dashed line).

1000-500 hPa thickness (values as indicated on the colour bar) and near-surface winds (barbs as in previous figures).
Rapid Subsynoptic Cyclogenesis

- Strong northerly flow across the Alps on 15 November during trough / front passage and cutoff

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Review of Mesoscale Cyclogenesis

- Strong cross-barrier flow, orographic cold frontal blocking and airstream split around the obstacle
- Warm air left in the lee acts as a boundary PV anomaly: cyclonic flow and pressure perturbation
- Mesoscale mechanisms concentrate PV:
  - GW or friction-induced PV banners
  - Convective redistribution of PV
- Convective coupling may enhance interaction with upper trough during baroclinic development
Review of Mesoscale Cyclogenesis

- Form in regions of strong surface baroclinicity, weak convective stability and strong surface fluxes in the presence of an upper-level trigger.
- Moist processes are crucial for coupling small-scale upper disturbances with the surface vortex.
- Growth rates larger than baroclinic.
- Warm core forms by seclusional process.
- Structure modified by environmental shear.

Total condensed water results from idealized IC modelling tests by Yanase and Niino (2007).
Review of Mesoscale Cyclogenesis

• Subsynoptic cyclones that are morphologically similar to Atlantic hurricanes:
  - Axisymmetric structure (implies little baroclinicity)
  - Initiated by baroclinic or orographic mechanism (TT)
  - Intensity maintained by WISHE process (>10ms⁻¹)

• Warm core and eye form following traditional tropical pathway as RMW contracts during intense convection