Development and Tropical Transition of an Alpine Lee Cyclone.  
Part II: Orographic Influence on the Development Pathway

RON MCTAGGART-COWAN  
Numerical Weather Prediction Research Section, Meteorological Service of Canada, Dorval, Québec, Canada

THOMAS J. GALARNEAU JR. AND LANCE F. BOSART  
Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, Albany, New York

JASON A. MILBRANDT  
Numerical Weather Prediction Research Section, Meteorological Service of Canada, Dorval, Québec, Canada

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ABSTRACT

The development and subsequent tropical transition of a subsynoptic-scale cyclone over the Gulf of Genoa (GoG) on 15 November 2007 led to the rapid onset of tropical storm-force winds near the islands of Corsica and Sardinia. This study evaluates the influence of two key ingredients on the cyclogenesis event: a near-surface warm potential temperature perturbation in the lee of the Alps and a mountain-scale potential vorticity (PV) banner. A high-resolution modeling system is used to perform a set of attribution tests in which modifications to the Alpine orography control the presence of the cyclogenetic ingredients. When either feature exists in the initial state, a GoG cyclone develops even when the Alpine barrier is removed; however, when neither the warm perturbation nor the PV banner is present, there is insufficient lower-level PV to couple with the upper-level trough to promote cyclogenesis. A conceptual model involving the complimentary interaction of the two PV features is presented that accurately describes the development location of the cyclone beneath a midlevel vorticity maximum.

Despite development in most of the attribution tests, the energy sources for the cyclones vary widely and represent a spectrum of cyclogenetic pathways from baroclinically to convectively dominant. Removal of the Alpine barrier allows for a stronger thermal wave and a baroclinic mode of development, rather than the diabatically generated hurricane-like vortex seen in the control and available observations. Similarly, insufficient flow interaction with the low-resolution representation of the Alps in the global-driving model is shown to favor a baroclinic mode of cyclogenesis in that integration. Adequate resolution of both the Alpine terrain and the incipient cyclone itself are shown to be important to correctly predict the evolution of the system from both structural and energetic perspectives.

1. Introduction

The development of an intense subsynoptic cyclone over the Gulf of Genoa (GoG; Fig. 1) on 15 November 2007 was shown by McTaggart-Cowan et al. (2010, hereafter referred to as Part I) to arise from the passage of an upper-level trough and embedded coherent tropopause disturbance (CTD) across the Alps. Two diabatically generated lower-level potential vorticity (PV) anomalies—a leeside warm anomaly and a mountain-scale PV banner—were hypothesized to have influenced the development of the system by providing a lower-level vorticity source for a cyclogenetic event that relied heavily on moist convection for its rapid evolution. In this study, the influence of the Alpine barrier on the presence and nature of GoG cyclogenesis in this case is investigated using one of the numerical modeling systems that was employed during the Mesoscale Alpine Project (MAP) demonstration of...
probabilistic hydrological and atmospheric simulation of flood events in the Alpine region project (D-PHASE; Rotach et al. 2009).

The extent that the Alps modulate GoG cyclogenesis has been studied by terrain modifications in numerical models (Dell’Osso and Tibaldi 1982; Dell’Osso 1984; McGinley and Goerss 1986; Tafferner and Egger 1990; Aebischer and Schär 1998). McGinley and Goerss (1986) find that 12-h forecasts without the Alps for an April 1982 GoG cyclone generate a subsynoptic feature that compares well with the observed low; however, cyclogenesis did not occur in a similar experiment run for a case that occurred a month earlier. The ambiguity of this finding is echoed by Tafferner and Egger (1990), who show that a “lee cyclone” forms in their 24-h no-mountain integration of a different March 1982 system, although the surface vortex is displaced eastward compared to their control forecast. This is consistent with the results of a similar study by Dell’Osso and Tibaldi (1982).

Whether the initiation of such cyclones is strongly influenced by upstream orography, these subsynoptic-scale systems can follow numerous development pathways, each of which relies on specific sources of storm-scale energy. Bresch et al. (1997) find that a polar low (Businger and Reed 1989) over the Bering Sea is morphologically similar to an oceanic baroclinic cyclone, whereas Businger and Baik (1991) come to the conclusion that the same case constitutes an Arctic hurricane. Yanase and Niino (2007) use an idealized model to study the progression of

energy sources for a subsynoptic-scale cyclone from convective under weak shear conditions to baroclinic in a strongly sheared environment.

The present study investigates the influence of the Alps on the development and tropical transition (TT; Davis and Bosart 2004; Moscatello et al. 2008; Hulme and Martin 2009) of an intense subsynoptic-scale GoG cyclone using a combination of diagnostics and numerical modeling. Section 2 describes the datasets and methodologies used during the investigation. A brief description of the 15–16 November 2007 GoG cyclogenesis event follows in section 3. A set of attribution tests, which quantify the influence of two lower-level cyclonic PV features on the system’s development, are presented in section 4. Section 5 focuses on the energy sources for the development of the storm, whereas section 6 addresses issues related to the resolution of the Alps and the developing vortex in the model. The study concludes with a discussion of the findings in section 7.

2. Model, data, and diagnostics methodology

The Global Environmental Multiscale (GEM) model and analyses from the Canadian Meteorological Centre (CMC) are used throughout this study and are described in detail in Part I. The model is run in three configurations, with a series of attribution tests undertaken on the high resolution (CMCGEMH/S) domain, as indicated in Table 1. Some of these tests involve the relaxation of the Alpine orography to representative values for the surrounding region (Fig. 2) over the first 6 h of integration. This approach avoids the initial shocks and errors in boundary layer structure that result from the immediate elimination of orography and the introduction of extrapolated subterranean profiles into the free atmosphere at the cost of introducing near-surface vertical motions over the adjustment period. The 6-h relaxation period is chosen to minimize these vertical velocities while ensuring that orographic adjustment is complete before the high-resolution domain is initialized.
The evolution of the power spectrum of kinetic energy in the Global and CMCGEML integrations initialized at 0000 UTC 15 November (Fig. 3) highlights the ability of the orographic relaxation technique to limit the shock generation of spurious finescale structures during the period of orographic adjustment. The development of small-scale temporal and spatial variability in the vertical motion field in the CMCGEML integration (Fig. 4) provides additional information about the filling of the short wavelength end of the power spectrum. In this example, the Alps are removed either progressively (as in the remainder of this study) or immediately at initialization (a common practice for orographic sensitivity tests). These techniques are identified as GROW and SHOCK in Figs. 3 and 4 (Table 1). The initial spectrum of GROW follows that of the initializing Global analysis closely, as expected for an unperturbed state. The SHOCK spectrum, however, contains much more energy at small wavelengths (Figs. 3a and 4). This energy, introduced by the violation of dynamic balance and the extrapolation of profiles below the analyzed terrain during initialization, is entirely spurious because the analysis does not contain information at small length scales. The magnitude of each of these noise sources is evaluated at 0000 UTC 15 November in Fig. 4, where it is clear that the imbalances that result from the resolution increase during nesting are roughly half as large as those generated by orographic effects. The rapid decay
in oscillatory perturbations (Fig. 4a) suggests that 2 h of integration is sufficient to damp these instantaneously generated waves. The 6-h orographic relaxation window is chosen to coincide with the growth of finescale spatial structures shown in Fig. 4b, wherein the flattening of the curves at later times demonstrates that the complete development of the finest-scale motions in the model requires this initialization period. Although the energy at these scales saturates more quickly in SHOCK (Figs. 3b,c), the artificial nature of the structures has the potential to irreversibly damage the simulation, especially if these perturbations project onto growing error modes in the meso- and synoptic scales. This analysis suggests that orographic relaxation should be used whenever a terrain adjustment sensitivity test is undertaken. The extent to which this technique is necessary during standard nesting with changed resolution will be evaluated in an upcoming study.

The eddy energetic diagnostics presented in sections 5 and 6 are based on the wave energy equations developed by Lorenz (1955) and subsequently used by Muench...
TABLE 2. Description of eddy and basic-state energy symbols used throughout the text. Energy measures are shown in the top rows, with conversion and generation terms in the bottom rows.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\overline{A}$</td>
<td>Available potential energy</td>
<td>Lorenz (1955)</td>
</tr>
<tr>
<td>$A_E$</td>
<td>Eddy available potential energy</td>
<td>Eq. (1)</td>
</tr>
<tr>
<td>$K_E$</td>
<td>Eddy kinetic energy</td>
<td>Section 2</td>
</tr>
<tr>
<td>$C_A$</td>
<td>Conversion of basic state $\overline{A}$ to $A_E$</td>
<td>Eq. (3)</td>
</tr>
<tr>
<td>$C_E$</td>
<td>Conversion of $A_E$ to $K_E$</td>
<td>Eq. (4)</td>
</tr>
<tr>
<td>$G_E$</td>
<td>Diabatic generation of $A_E$</td>
<td>Eq. (5)</td>
</tr>
<tr>
<td>$R$</td>
<td>Residual of $A_E$ budget</td>
<td>Eq. (2)</td>
</tr>
<tr>
<td>$Q$</td>
<td>Eddy available potential energy Eq. (1)</td>
<td></td>
</tr>
<tr>
<td>$\rho_b g \overline{T}$</td>
<td>Conversion of $A_E$ to $K_E$</td>
<td>Section 2</td>
</tr>
<tr>
<td>$\int_{p_b}^{p} \left[ \frac{\omega'}{\sigma} \right] d\rho$</td>
<td>Diabatic generation of $A_E$</td>
<td>Eq. (5)</td>
</tr>
<tr>
<td>$\int_{p_b}^{p} \frac{Q'}{c_p \sigma} d\rho$</td>
<td>Residual of $A_E$ budget</td>
<td>Eq. (2)</td>
</tr>
</tbody>
</table>

(1965), Norquist et al. (1977), Parker and Thorpe (1995), and others. For reference, Table 2 presents a summary of the quantities defined here. Here, eddy available potential energy $A_E$ is defined as

$$A_E = \int_{p_b}^{p} \left[ \frac{\omega'}{\sigma} \right] d\rho.$$  \hspace{1cm} (1)

All symbols have their usual meteorological meanings, where $p_b = 85$ hPa and $p_0 = 250$ hPa represent the lower and upper limits of integration and $\overline{T} = g((\overline{T}) - \rho/\rho_b))$ is the area-averaged static stability. The integration limits of 850 hPa and 250 hPa have been chosen to approximate the depth of the free troposphere during the development of the GoG cyclone. All pressure-based diagnostics are masked to avoid the use of extrapolated values below terrain. Square brackets $[()]$ indicate quantities that are zonally averaged and overbars $\overline{[\cdot]}$ denote area averages. Perturbations from these values are indicated using primes ($\cdot'$) for departures from the zonal mean and asterisks $\ast$ for departures of the zonal mean from the area average (Norquist et al. 1977).

The conversion terms that influence the time tendency of $A_E$ are

$$\frac{\partial A_E}{\partial t} = C_A - C_E + G_E + R,$$ \hspace{1cm} (2)

where $C_A$ is the conversion of basic-state available potential energy $\overline{A}$ to $A_E$, $C_E$ is the conversion of $\overline{A}$ to eddy kinetic energy $K_E = \frac{1}{g} \int_{p_b}^{p} \left[ \frac{u'^2 + v'^2}{2} \right] d\rho$, $G_E$ is the diabatic generation of $A_E$, and $R$ is a residual term that includes the effects of boundary fluxes into the computational domain (a storm following $8^\circ \times 8^\circ$ latitude box) and discretization errors. Additional components of the residual term arise from the movement of the grid, but it will be shown in section 5 that $R$ is small compared to the physical $C_A$, $C_E$, and $G_E$ sources that are the focus of this study. The leading terms are defined as

$$C_A = -\int_{p_b}^{p} \frac{\rho}{\rho_b} \left[ \frac{\omega'}{\sigma} \right] \frac{\partial \overline{T}}{\partial y} d\rho - \int_{p_b}^{p} \frac{\rho}{\rho_b} \left[ \frac{\omega'}{\sigma} \right] \frac{\partial \overline{T}}{\partial \rho} d\rho,$$ \hspace{1cm} (3)

$$C_E = -\int_{p_b}^{p} \frac{1}{R} \frac{\rho}{\rho_b} \left[ \frac{\omega'}{\sigma} \right] \frac{\partial \overline{T}}{\partial \rho} d\rho,$$ \hspace{1cm} (4)

$$G_E = \int_{p_b}^{p} \frac{Q'}{c_p \sigma} d\rho,$$ \hspace{1cm} (5)

where $Q$ is the diabatic heating rate, which in the case studied here is primarily due to moist convection.

Studies by Parker and Thorpe (1995), Moore and Montgomery (2004, 2005), and Conzemius et al. (2007) use the ratio of diabatic $A_E$ generation to $A_E$ increases through conversion from $\overline{A}$.

$$R = \frac{G_E}{C_A}.$$ \hspace{1cm} (6)

to identify the dominant mode of energy conversion within a circulation. Near-zero values of $R$ are expected for a system that undergoes primarily baroclinic growth, whereas a value approaching or exceeding unity is indicative of a structure whose evolution is dominated by diabatic processes.

3. Case description

A detailed description of the 15–16 November 2007 GoG cyclone forms the basis of Part I of this investigation; a brief summary of the event is presented here for reference. Geographical locations referenced throughout this study are plotted in Fig. 1, along with the track of the GoG cyclone from 1200 UTC 15 November to 1500 UTC 16 November.

A positively tilted upper-level trough, with an embedded CTD in its base, moves across the Alps on 15 November. The associated surface front slows as it crosses the barrier (O’Handley and Bosart 1996) and triggers a transition from “flow over” to “flow around” the Alpine block. Prior to this transition, heavy precipitation occurs on the Alpine northside and downsloping in the lee leads to the generation of a warm-surface potential temperature $\theta$ anomaly downstream. Following the flow transition, vertical vorticity is generated by tilting and stretching in the strong northerly flow at the southwestern corner of the Alps, leading to the development of a primary PV banner over the western GoG due to the finite viscosity of the flow (Rotunno et al. 1999). A series of idealized simulations presented in Part I demonstrate that the presence of a hydraulic jump, shown by Epifanio and Durran (2002) to be potentially necessary for PV enhancement in the wake,
is not crucial for the formation of the Alpine banner in this case. Diabatically enhanced coupling between the upper- and lower-level PV features promotes the development and TT of a subsynoptic-scale cyclone with tropical storm-force surface winds and a tropical cyclone-like structure by 0000 UTC 16 November.

4. Attribution study of PV features

This section describes the results of a set of sensitivity tests undertaken to diagnose the relative contributions of two identifiable PV features to the development of the GoG cyclone: the lower-level $\theta$ anomaly and the primary PV banner. The PV maximum associated with either of these elements could serve as a source of lower-level PV for the developing system. The lower-level warm $\theta$ anomaly is generated by a combination of diabatic processes on the windward slopes and orographic frontal retardation and is a key component of models for lee cyclogenesis proposed by Radinović (1965) and Egger (1972). The primary PV banner forms as a result of dissipative processes acting on enhanced vertical vorticity generated by tilting and stretching as the flow is accelerated around the southwestern tip of the Alps (Rotunno et al. 1999). Such banner features have been hypothesized by Aebischer and Schär (1998) to constitute an important lower-level PV source for incipient vortices forming in the Alpine wake.

A pair of initialization times is used to test the sensitivity of this case of GoG cyclogenesis to these PV features. The “early” set of simulations begins at 1200 UTC 14 November, before strong blocking is established across the Alpine barrier (Part I, Fig. 5) and the transition of the flow to around the mountain chain (Part I, Fig. 13a). Simulations described as “late” are initialized at 0000 UTC 15 November, following the flow transition and the development of a strong easterly wind component on the Alpine southside (Part I, Fig. 13d). The early control simulations were evaluated in Part I of this study and demonstrate the ability of the high-resolution model to depict the development and TT of the GoG cyclone at a lead time of 24 h. Table 3 identifies the initialization time for each of the attribution tests described in this section.

This section begins with a review of the control forecast (CTL); thereafter, an integration that involves the removal of the Alpine orography (ALPS) is described, in which a cyclone still forms in the GoG. To determine what aspect of the initial state is responsible for this development, a similar pair of control–sensitivity tests is performed with an initial time 12-h earlier (CTL-12 and ALPS-12)—no GoG development occurs in ALPS-12. The surface $\theta$ anomaly is shown to be the primary difference between the ALPS and ALPS-12 simulations at 0000 UTC 15 November, leading to a final pair of sensitivity tests, WARM and COLD. In WARM, a warm anomaly is inserted into ALPS-12 at this time, whereas in COLD the same anomaly is removed from CTL (Table 3). The tracks and central pressures for each of the control and attribution tests are presented in Fig. 5.

a. Late control forecast (CTL)

The development of the GoG cyclone in CTL closely follows the evolution of the early control simulation described in detail in Part I. The 0000 UTC 16 November position of the GoG cyclone in the integration is 80 km southeast of the system’s analyzed position, with a simulated intensity very close to that diagnosed from
the analysis (Fig. 5) and near-surface winds exceeding 23 m s\(^{-1}\) (Table 4). The structure of the resulting cyclone is shown in Fig. 6. The central pressure of the simulated storm is 997 hPa, with an isolated warm core present in the 1000–500-hPa thickness field (Fig. 6a). A strong lower-level cyclonic circulation leads to a symmetric vorticity structure near the center, with a separate zonal band of enhanced vorticity to the north of the GoG cyclone associated with warm advection ahead of the downshear remnant thermal ridge. The CTD is represented by a region of \(\theta_{DT}\) < 300 K above and to the west of the low center, although regions of heavy precipitation have eroded the feature over a broad area. At this time, areas of active deep convection result in localized regions of elevated \(\theta_{DT}\) values (\(\theta_{DT} > 320\) K) in this and similar figures.

b. Late Alpine removal (ALPS)

Despite the dramatic nature of the modification to local forcings implied by the removal of the Alpine terrain in this integration, the leeside warm \(\theta\) anomaly is present in the initial state (Table 3) and a well-defined incipient vortex forms 70 km to the east–northeast of the analyzed GoG cyclone position at 1200 UTC 15 November (Fig. 5a). Without the Alps to channel the postfrontal northerly flow into the western Mediterranean, the mistral winds extend further eastward and a northerly steering flow guides the developing cyclone due southward. These results are consistent with the findings of Dell’Osso and Tibaldi (1982) and Tafferner and Egger (1990).

The ALPS forecast for 0000 UTC 16 November shows the low center on the northwest Sardinian coast, with a warm-core structure separated from the enhanced downshear baroclinic wave by less than 50 km (Fig. 7a). The broadened area of strong northerly winds—a direct result of the absence of frontal retardation by the Alps—allows the CTD to penetrate further toward the developing lower-level vortex in this integration relative to the control (cf. Figs. 6b and 7b). The increased near-storm baroclinicity results in an occluded structure in the lower-level vorticity field (Fig. 7b) in this integration.

c. Early control forecast (CTL-12)

The development of the cyclone in ALPS suggests that the necessary conditions for subsynoptic cyclogenesis were present in the 0000 UTC 15 November initial state and that Alpine flow modification was not uniquely responsible for the development of the GoG cyclone after this time. As a first step toward investigating the role that the Alps played in the establishment of this initial state, CTL-12 is run from initial conditions 12-h prior to those used for CTL (Table 3). Differences between the CTL and CTL-12 results (Figs. 6 and 8) are therefore indicative of the predictability of GoG development with this longer lead time.

The development of the GoG cyclone in CTL-12 is described in detail in Part I. As in CTL, the center tracks southwestward until making a cyclonic turn under the influence of the mistral winds. Although lower \(\theta_{DT}\) are present to the southwest of the cyclone in this simulation, the similarity of the lower-level thermal and vorticity structures (cf. Figs. 6 and 8) suggests that both integrations reliably simulate the cyclogenesis event.

d. Early Alpine removal (ALPS-12)

The removal of the Alpine terrain before the 15 November flow transition implies that neither the surface \(\theta\) anomaly nor the PV banner is present in this integration (Table 3). No notable cyclogenesis occurs in this sensitivity test, as shown in Fig. 9. The early removal of the

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**Table 3.** Summary of control experiments and sensitivity tests described in the text. The terrain used for each simulation is defined in the fourth column as either full or Alpine removed (AR), corresponding to the orographic fields shown in Figs. 2a,b, respectively.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Description</th>
<th>Initializing analysis</th>
<th>Orography</th>
<th>PV features Surface (\theta) PV banner</th>
<th>First trackable time</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>Late control simulation</td>
<td>0000 UTC 15</td>
<td>Full</td>
<td>Yes Yes</td>
<td>0800 UTC 15</td>
</tr>
<tr>
<td>ALPS</td>
<td>Late Alpine removal</td>
<td>0000 UTC 15</td>
<td>AR</td>
<td>Yes No</td>
<td>1200 UTC 15</td>
</tr>
<tr>
<td>CTL-12</td>
<td>Early control simulation</td>
<td>1200 UTC 14</td>
<td>Full</td>
<td>Yes Yes</td>
<td>1200 UTC 15</td>
</tr>
<tr>
<td>ALPS-12</td>
<td>Early Alpine removal</td>
<td>1200 UTC 14</td>
<td>AR</td>
<td>No No</td>
<td>Not applicable</td>
</tr>
<tr>
<td>WARM</td>
<td>Surface PV anomaly insertion</td>
<td>1200 UTC 14</td>
<td>AR</td>
<td>Yes No</td>
<td>0600 UTC 15</td>
</tr>
<tr>
<td>COLD</td>
<td>Surface PV anomaly removal</td>
<td>0000 UTC 15</td>
<td>Full</td>
<td>No Yes</td>
<td>0900 UTC 15</td>
</tr>
</tbody>
</table>

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**Table 4.** Intensity measures (max wind speed and min MSL pressure) of simulated GoG cyclones in control and sensitivity test forecasts valid at 0000 UTC 16 Nov.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Max near-surface winds (m s(^{-1}))</th>
<th>Min MSLP (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>23</td>
<td>997</td>
</tr>
<tr>
<td>ALPS</td>
<td>24</td>
<td>998</td>
</tr>
<tr>
<td>CTL-12</td>
<td>22</td>
<td>1000</td>
</tr>
<tr>
<td>ALPS-12</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td>WARM</td>
<td>20</td>
<td>1000</td>
</tr>
<tr>
<td>COLD</td>
<td>21</td>
<td>1001</td>
</tr>
</tbody>
</table>
Alpine barrier leads to the rapid progression of the cold front across the GoG and western Mediterranean, resulting in reduced thicknesses across the domain and a broad cyclonic flow beneath the upper-level trough (Fig. 9). Although local vorticity maxima are generated by stretching in isolated precipitation cells, no organization is evident in the 30-h forecast valid at 0000 UTC 16 November (Fig. 9b).

**e. Warm anomaly insertion—Alpine removal (WARM)**

A comparison of the 12-h forecast from ALPS-12 and the ALPS initializing analysis supports the hypothesis that the primary modification to the flow by the Alps prior to the 15 November flow transition is the generation of the warm $\theta$ anomaly in the lee. This positive lower-boundary PV perturbation is inverted using the piecewise technique developed by Davis (1992), yielding the balanced flow shown in Fig. 10. The resulting structure (valid at 0000 UTC 15 November) is inserted into ALPS-12 after 12 h of integration to construct the WARM sensitivity test. The development of a cyclone in this simulation suggests that the PV associated with the leeside warm anomaly (Bleck and Mattocks 1984; Tafferner 1990) is an important component of cyclogenesis in this case.

The cyclone in WARM develops east of Corsica (Fig. 5a) as a result of the southward advection of the warm surface $\theta$ anomaly. The intensification of the system occurs earlier than in the control runs, and it ends as the center makes landfall in western Italy at 2100 UTC 15 November. Although the low continues curving cyclonically and away from the coast, its circulation is smaller than that of the CTL-12 system at 0000 UTC 16 November (Fig. 11a). As for ALPS-12, the CTD is able to wrap further around the base of the trough, resulting in reduced $\theta_{DT}$ over the compact lower-level vorticity structure at this time (Fig. 11b).
f. Warm anomaly removal—Full orography (COLD)

The development of a subsynoptic cyclone in WARM suggests that the surface \( \theta \) anomaly is a key ingredient for cyclogenesis; however, PV banners have been hypothesized by Aebischer and Schär (1998) to be important for cyclogenesis in the GoG. To determine whether development would have proceeded without the warm anomaly, but with the PV banner, the warm perturbation structure (Fig. 10) is removed from the CTL initialization (COLD, Table 3). The development of a cyclone in this simulation suggests that, in addition to the warm anomaly, the primary Alpine PV banner is an important factor in GoG cyclogenesis in this case.

Instead of developing in the GoG, the cyclone in COLD is initiated near the French coast (Fig. 5) on the cyclonic shear side of the PV banner described in Part I. The vortex develops rapidly until 1800 UTC 15 November; however, its final intensity and location are similar to those of the CTL cyclone (Table 4). The crest of the downstream thermal wave (Fig. 12a) reaches north of the storm at 0000 UTC 16 November, implying greater local baroclinicity than in the CTL simulation (c.f. Figs. 6a and 12a). The CTD successfully couples with the developing lower-level feature early in COLD, leading to a region of depressed \( \theta_D \) near the highly asymmetric center at 0000 UTC 16 November (Fig. 12b).

g. Discussion of attribution tests

The local environment of the GoG cyclone is dominated by a pair of diabatically-generated PV anomalies: the leeside warm \( \theta \) perturbation and the primary Alpine banner. However, development does not occur as a direct result of either except in ALPS, WARM, and COLD (Table 3). Instead, the combined influence of the two PV features appears to control the development location, as shown in Fig. 13. The PV associated with each anomaly is isolated and inverted (Davis 1992), yielding a balanced estimate of the flow associated with each element in isolation. The superposition of these piecewise flow component results in a midlevel vorticity maximum northwest of Corsica, near the position of the GoG cyclone in the analysis and control simulations at 1200 UTC.
15 November. Situated above the individual PV anomalies themselves, this vorticity maximum exerts quasigeostrophic ascent forcing through upward-increasing cyclonic vorticity advection. The feature is well positioned to couple with the resulting convectively induced lower-level vorticity center to form the GoG cyclone.

A conceptual model of the key components involved in this case of GoG cyclogenesis is shown in Fig. 14. The generation of the leeside warm $\theta$ anomaly by moist processes and frontal retardation shown in Fig. 14a is followed by the flow transition and development of a primary PV banner at the southwestern tip of the Alps (Fig. 14b). The GoG cyclone develops between the two features, where the flow induced by the PV anomalies leads to lower- and midlevel circulations favorable for cyclogenesis.

5. Energetics of the GoG cyclone

The sources of energy for the development of the tropical storm–force winds around the GoG cyclone are investigated in this section. The methodology employed here follows the work of Lorenz (1955), Muench (1965), and Norquist et al. (1977), as applied recently by Moore and Montgomery (2005). As described in section 2, this approach involves the evaluation of a budget equation for $A_E$ [Eq. (1)]. The evolution of the individual physical source terms ($C_A$, $C_E$, and $G_E$ as described in Table 2) provides information about the origins of the local thermal structures and flows that serve as the sources of energy for the GoG cyclone’s development and intensification.

In this section, the influence of the Alpine barrier on the eddy energy balance of the GoG cyclone is diagnosed using a subset of the integrations discussed in section 4: CTL, CTL-12, ALPS, and ALPS-12. The primary $A_E$ source for the cyclone is shown to shift from diabatic to baroclinic when the mountains are not present in the simulation. This demonstrates the importance of the Alpine barrier in enhancing the moist convective nature of the GoG cyclogenesis, thereby promoting its TT and evolution along the Mediterranean hurricane development pathway.

The control simulations (CTL and CTL-12) show similar evolutions of $A_E$ in Fig. 15a, with a slow increase in intensity throughout the integration. The strongest baroclinic development based on regional $A_E$ is diagnosed for ALPS. A near-steady climb between 1200 UTC 15 November and 0000 UTC 16 November results in maximum

![Figure 10](image-url)
$A_E$ values in ALPS that are 30% larger than those in CTL. The increase of $A_E$ in ALPS-12 is similar in magnitude to that of ALPS, but its initial value is lower because of the absence of the leeside warm anomaly in the former integration. These results suggest that the Alps—while creating the PV anomalies necessary for initiating GoG cyclogenesis—limit the ability of the developing vortex to concentrate energy in this case by reducing baroclinicity near the developing center.

The components of the $A_E$ balance equation [Eq. (2)] are shown for CTL from 1200 UTC 15 November to 0000 UTC 16 November in Fig. 16. The magnitude of each of the physical source terms is larger than that of the residual $R$ over the area of interest at all times in the integration. This demonstrates that the changes in $A_E$ over this period are dominated by the underlying dynamics rather than by sources that constitute artifacts of the $A_E$ budget calculation. Analysis of the other attribution test results presented in this study leads to a similar conclusion in all cases. This allows us to focus on the physical source terms as the dominant drivers for changes in $A_E$ associated with the GoG cyclone.

A comparison of the physical sources of $A_E$ highlights differences between the representations of the GoG cyclone in the two sets of integrations. Both ALPS and, to a lesser extent, ALPS-12 effectively convert $A$ to $A_E$ throughout the simulation [Eq. (3) and Fig. 15b]. Uninhibited cold advection into the base of the trough is responsible for this source of $A_E$. Although a similar process occurs as a result of the mistral winds in the controls, its efficiency is limited because of the restricted zonal extent of the cold northerly flow (Table 5).

Strengthening local baroclinicity due to cold advection beneath the trough enhances the magnitude of $T'$; however, the developing cyclone in the warm air ahead of the trough in ALPS is required to convert the resulting $A_E$ into $K_E$ through a thermally direct circulation [Eq. (4)]. The lack of cyclonic development in ALPS-12 severely limits the efficiency $C_E$ by failing to provide sufficient flow perturbation to tap into the $A_E$ source. Therefore, despite the favorable local baroclinic environment, there is no lower-level PV feature capable of coupling with the CTD to promote a baroclinic mode of development in the ALPS-12 case (Hoskins et al. 1985).
The diabatic generation of $A_E$ by moist processes [Eq. (5)] is most effective in CTL and CTL-12 as the GoG cyclone undergoes TT (Fig. 15d). Despite the initial strength of the diabatic source in ALPS, widespread convection in the cold air over the western Mediterranean after 1800 UTC 15 November leads to a suppression of this $A_E$ source. In ALPS-12, the lack of organizing cyclogenesis restricts the $G_E$ source term to near-zero values.

The dramatic differences in $R$ Eq. (6) shown in Fig. 17 suggest that the energy source for the GoG cyclone is strongly influenced by the Alpine orography. Through cold-frontal retardation and associated blocking of the cold northerly flow, the Alps promote the development of a hurricane-like vortex dominated by latent heat release, particularly during the pulse of convection associated with the onset of TT prior to 1800 UTC 15 November. Conversely, as evidenced by values of $R$ that remain below 0.5 throughout most of ALPS, the removal of the Alpine barrier allows for a strengthened zonal thermal gradient across the western Mediterranean and for the development of a cyclone whose energy source is rooted in local baroclinicity.

6. Effects of model resolution on cyclogenesis

The Alpine barrier plays an important role in the evolution of the GoG cyclone by limiting baroclinic development and initiating a diabatically driven cyclone that undergoes TT to follow the Mediterranean hurricane development pathway. Using the eddy energetics introduced earlier, the ability of the 0000 UTC 15 November Global, CMCGEML, and CMCGEMH/S late model integrations to depict accurately the evolution of the orographically influenced flow and its effect on GoG cyclogenesis is evaluated in this section (Fig. 18, note that the CMCGEMH/S integration here is the same as CTL discussed in sections 4 and 5, as indicated in Table 1). The $A_E$ time series for the three integrations are shown in Fig. 19. The storm-centered values of $A_E$ vary between...
the runs, with the poorly resolved vortex in the Global configuration possessing the lowest values of $A_E$ (Fig. 19a). Despite this offset, the similar rate of increase in $A_E$ between the Global and CMCGEMH/S integrations suggests that the GoG cyclone in these runs develops to a similar intensity with the effects of model resolution taken into account. Overdevelopment of $A_E$ in CMCGEML is evidenced by the sharp rise early in the time series and will be discussed in section 6.2.

### a. Development in the global integration

The evolution of $A_E$ over the course of the Global integration is shown in Fig. 19a. Although scale sensitivity exists in the $A_E$ time series, $C_A$ is essentially unaffected by changes in model resolution (Fig. 19b). The reduction in the Global run’s $C_E$ (Fig. 19c) compared to the other integrations is a direct result of $A_E$ values that remain

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Mean wind speed (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>13</td>
</tr>
<tr>
<td>ALPS</td>
<td>18</td>
</tr>
<tr>
<td>CTL-12</td>
<td>13</td>
</tr>
<tr>
<td>ALPS-12</td>
<td>16</td>
</tr>
</tbody>
</table>
30%–50% lower—reduced $A_E$ means that less potential energy is available for conversion to kinetic energy.

The most striking difference between the Global and higher-resolution integrations is the reduced magnitude of diabatic generation of $A_E$ shown in Fig. 19d. Combined with $C_A$ values that remain essentially unchanged in the three integrations (Fig. 19b), this leads to an $R$ value that remains near 0.5 throughout the course of the integration (Fig. 20), indicating that the GoG cyclone in the Global run is primarily a baroclinically driven feature unlike its higher-resolution counterparts.

The difference in the development pathway of the GoG cyclone in the three integrations is highlighted by the storm structures shown in Fig. 21. The cyclone in the Global integration (Fig. 21a) is undergoing a seclusional process (Keyser and Shapiro 1986), with a triple point over Corsica and a coherent region of upward motion associated with strong frontogenesis along the bent-back warm front to the north and west of the cyclone center. Posselt and Martin (2004) found that this structure leads to the erosion of the PV anomaly aloft and the development of a PV hook (treble clef feature) such as that shown in Fig. 23a of Part I. This upper-level PV structure is sensitive to moist processes and model physics and can be associated with large errors in short-range guidance as shown by Bosart (1999) and Dickinson et al. (1997). A recent study by Hulme and Martin (2009) further linked this stage of development with the TT of initially baroclinic vortices; however, the minimal latent heat release in the Global run (Fig. 19d) suggests that moist processes were insufficient to promote a transition to a diabatically sustained system in this integration.

The baroclinic nature of the GoG cyclone in the Global run is consistent with the analysis of the depressed diabatic ratios for ALPS and ALPS-12 (Fig. 17). This suggests that the development pathway of the storm in simulations with insufficient resolution of the Alpine barrier is generally similar to that of the high-resolution integration with the Alpine orography eliminated. Therefore, by the criterion of a similar development pathway—in terms of eddy energetics, $R$, and storm structure—the Global configuration does not possess sufficient resolution to accurately simulate the development of the GoG cyclone in this case.

b. Development in the CMCGEML integration

The overdevelopment of the GoG cyclone in the CMCGEML integration, discussed briefly in Part I, is evident from both the central pressure and $A_E$ time series (Figs. 18b and 19a). Rapid conversion from $A_E$ to $P_E$ ($C_E$, Fig. 4) appears to be responsible for a rapid increase in
vortex strength between 1200 and 1800 UTC 15 November in this integration. The origin of this additional $A_E$ source is the enhanced $G_E$ values shown in Fig. 19d and discussed further at the end of this section.

The similarity of the $A_E$ time series between the CMCGEML and CMCGEMH/S integrations suggests that the evolution of the regional flow is well depicted in the former (Fig. 19a). Although reduced $C_A$ values between 1700 and 2200 UTC combine with the large diabatic heating rates described earlier to produce an $R$ that is much greater than unity in the CMCGEML run (Fig. 20), the GoG cyclone’s near-core thermal structure approaches that of the CMCGEMH/S integration at 0000 UTC 16 November (cf. Figs. 21b,c). While a band of frontogenesis and vertical motion persists along a remnant warm front northwest of the center, an area of diabatically enhanced vertical motion and warming exists near the core. The latter is largely isolated from the warm region east of 10°E and cold air nearly surrounds the center. These results suggest that, although the CMCGEML configuration adequately resolves the influence of the Alpine barrier on the flow, it is barely sufficient to depict the development pathway of the GoG cyclone.

Insufficient activity of parameterized convection—used in the CMCGEML integration but not the CMCGEMH/S run—is responsible for the large magnitude of $G_E$ as demonstrated by sensitivity tests involving modified convective-triggering parameters (not shown). Over much of the GoG, convective instability is not released in the CMCGEML integration until gridscale saturation is achieved; thus, it allows the explicit microphysics scheme to

![Fig. 19. As in Fig. 15, but for the late Global, CMCGEML, and CMCGEMH/S (CTL) integrations as indicated in the legend on each panel.](image1)

![Fig. 20. As in Fig. 17, but for the late Global, CMCGEML, and CMCGEMH/S (CTL) integrations as indicated in the legend; however, the ordinate has been extended to ratio values above 2 to display the results from the CMCGEML run.](image2)
generate overdeveloped cells northwest of Corsica, co-
incident with $T^* > 0$ K. The moistening and decreased
convective stability of the mean CMCGEML column over
the GoG region is shown in Fig. 22. This instability leads to
a 15% increase in domain-averaged precipitation com-
pared to the CMCGEMH/S integration described below.
In future studies, $G_E$ could be used during domain con-
figuration to optimize factors in the convective parameter-
ization scheme to limit the overdevelopment of $A_E$, and
its subsequent transfer to the GoG cyclone’s intensity.

c. Development in the CMCGEHM/S (CTL) integration

The primary difference in the evolution of storm-
centered eddy energetics between the CMCGEML and
CMCGEMH/S integrations—aside from overintensi-
fication in the former as described earlier—lies in the $C_E$
conversion (Fig. 19c). The elimination of spurious con-
vection in CMCGEMH/S is a direct result of the use of
a convection-permitting resolution (Bryan et al. 2003).
This allows the model atmosphere to maintain cooler
temperatures behind the cold front, thereby supporting
larger values of $C_A$. Despite the fact that this term is of
a similar magnitude to that of the Global integration,
enhanced $G_E$ (Fig. 19d) leads to $R$ values that peak well
above unity at the onset of TT and remain above 0.6
throughout the integration (Fig. 20).
The symmetric, diabatically enhanced nature of the
GoG cyclone in the CMCGEMH/S integration is evident
in Figs. 20 and 21c. Convective bands and isolated cells are
responsible for ascent around the center, and frontogen-
esis is associated with circulations induced by the indi-
vidual cores rather than being related to the structure of
the synoptic-scale flow (Fig. 21). The structure of the GoG
cyclone in this run was shown in Part I to correspond with
available satellite and in situ observations. This leads to
the conclusion that the resolution of the CMCGEMH/S
integration is sufficient to accurately represent not only
the interaction of the flow with the Alpine barrier but also
the nature of the GoG cyclogenesis event itself.

7. Discussion

The development of a GoG cyclone on 15 November
2007—during the MAP D-PHASE project—has been
analyzed through a set of diagnoses and model simula-
tions. In Part I, it was shown that cyclogenesis in this case
is related to the passage of an upper-level positive PV
disturbance across the Alps and the retardation of
the associated surface front by the barrier. A transition from
flow over to flow around the block occurs as the cross-
barrier winds weaken behind the synoptic-scale trough
and the frontal inversion reaches the Alpine crest. Prior
to the flow transition, heavy precipitation falls on the Alpine northside and adiabatic descent in the lee leads to the formation of a near-surface warm $\theta$ perturbation (positive PV anomaly). Following the flow transition, dissipative processes acting on vertical vorticity generated by tilting and stretching at the southwestern tip of the Alps generate a primary PV banner that extends over the western GoG. These two orographically generated PV features are shown here to be important for the initiation of the GoG cyclone in this case.

A set of control and attribution tests have been undertaken to quantify the effects of the Alpine orography on the GoG cyclone. Removal of the barrier in integrations initialized at 0000 UTC 15 November does not prevent the development of the GoG cyclone (Fig. 7, consistent with the results of Dell’Osso and Tibaldi 1982; McGinley and Goerss 1986; Tafferner and Egger 1990); however, a similar removal in a simulation initialized 120-h earlier results in no cyclogenesis (Fig. 9, consistent with the results of McGinley and Goerss 1986). The primary difference between the 12-h forecast of this ALPS-12 sensitivity test and the initializing ALPS analysis is the diabatically generated warm-surface $\theta$ perturbation in the lee of the Alps (Fig. 10). Insertion of this anomaly into the WARM integration (Fig. 11) results in cyclogenesis, although the cyclone is displaced eastward of its analyzed position. This result suggests that the orographic modifications in the studies noted earlier may have been ineffective at modulating GoG cyclogenesis because the barrier had already preconditioned the local environment through the generation of the warm perturbation. Removal of this anomaly from the CTL initial state constitutes the COLD sensitivity test (Fig. 12) in which a system develops on the cyclonic shear side of the PV banner, 150 km west of the analyzed GoG cyclone.

The superposition of the flows induced by the key lower-level PV ingredients results in a midlevel vorticity maximum that is capable of inducing and focusing moist ascent in the developing circulation (Fig. 13). A conceptual model demonstrating the interaction between the key PV ingredients for cyclogenesis (Fig. 14) is the main result from this portion of the study. An analysis of the $A_E$ associated with the GoG cyclone shows that despite development in most of the attribution tests (all except ALPS-12 generated a GoG cyclone), the cyclogenetic pathway differs greatly between the simulations (Fig. 15).
Larger baroclinicity generated by the uninhibited cold northerly flow following the removal of the Alpine barrier causes rapid $A_E$ increases in ALPS. This important structural difference leads to the development of a GoG cyclone in ALPS, whose primary energy source is baroclinic in nature; conversely, cyclogenesis in CTL and CTL-12 is strongly controlled by diabatic energy generation, primarily due to moist convection as the system undergoes TT (Fig. 17). The Alps are therefore capable of controlling not only the cyclogenetic process (no cyclone forms in ALPS-12) but also the dominant developmental pathway: baroclinic (ALPS) or diabatic (CTL, CTL-12).

The ability of the simulations used in this study to resolve the Alpine orography is highly variable, with the Global integration only capable of roughly resolving the barrier while the CMCGEMH/S runs are influenced by individual elements in the terrain. The Global integration generates a baroclinic cyclone with a warm core created by a frontal seclusion process (Fig. 21a). This developmental pathway is similar to that taken by the GoG cyclone in ALPS, suggesting that the interaction of the flow with the poorly resolved Alpine orography in the Global integration is too weak to induce the observed diabatic mode of cyclogenesis—the right answer (presence of a GoG cyclone) but for the wrong reason. Despite overdevelopment of the GoG cyclone in the CMCGEMH/S integration, the cyclone forms in an environment similar to that of the CMCGEMH/S run and it undergoes TT (Fig. 19). The CMCGEM/S integration is capable of accurately depicting the influence of the Alps on the flow, but its resolution is barely sufficient to reliably simulate the nature of the cyclogenesis event (Fig. 21). In contrast, the CMCGEMH/S integration generates a symmetric, warm-core circulation following TT, with intensity close to that of the observed storm as demonstrated in Part I. Its high resolution is therefore found to be necessary for accurately simulating both the influence of the Alpine terrain on the flow and the evolution of the GoG cyclone in this case.

The effects of model resolution and orographic modification on the mode of development may explain, at least in part, the ambiguity of the Alpine modification findings presented by Dell’Osso and Tibaldi (1982), McGinley and Goerss (1986), Tafferner and Egger (1990), and others. Because all of these studies used modeling systems with grid spacings coarser than the Global integration presented here, the Alpine influence on the flow may have been insufficient to induce a diabatically dominated mode of cyclogenesis in cases in which it should have in fact occurred. It is unlikely that a simulated GoG cyclone that follows the incorrect developmental pathway will demonstrate a realistic sensitivity to modifications of Alpine orography; however, further study is required to evaluate this hypothesis.

The diagnosis of the influence of individual PV elements on GoG cyclogenesis presented here not only highlights the rich spectrum of features that are involved in such an event, but also demonstrates a range of developmental pathways that can be followed by storms generated in the region. The large potential impact of these rapidly intensifying storms on local inhabitants and infrastructure makes continued investigation of their development a valuable problem for further study.

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