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REVIEW ARTICLE

Cyclogenesis in the lee of the Alps: a review of theories

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Abstract
Although the phenomenon has been known, and investigated, as early as the nineteenth century, the interest in understanding Alpine lee cyclogenesis (often called Genoa cyclogenesis) has grown since the middle twentieth century, when it was realized that the largest fraction of cyclones affecting the central-eastern Mediterranean and later Eastern Europe originated in the area south of the Alps, more often in the Gulf of Genoa. Forecasting this type of cyclogenesis remained a challenging task until at least the mid-late 1980s, even after the development of the earlier NWP models, which failed in predicting this phenomenon, lacking the ability to adequately represent the orographic forcing. Monitoring and understanding of cyclogenesis in the lee of the Alps was the main objective of field projects, the most important being GARP-ALPEX in 1982. The following years were full of ideas and theories about this phenomenon, which is representative of orographic cyclogenesis in other regions of the world. The main steps in understanding the complex phenomenon of lee cyclogenesis, with particular reference to the Alps, are outlined here, focusing on theoretical explanations.

Keywords Cyclogenesis · Cyclones · Orography · Lee cyclogenesis · Genoa cyclogenesis · Theory of cyclogenesis

1 Introduction

1.1 Preface

A "theory" in dynamic meteorology is something quite different from a theory as is intended in other areas of physics, where theories can be verified (or falsified) with measurements and experiments of extreme accuracy. In meteorology, a theory involves, at best, the formulation of a simplified (hopefully not over-simplified) model for which analytical or semi-analytical

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solutions of the governing equations can be found. These analytical solutions, which are, with very few exceptions, approximated and linear, aim at "explaining" some class of meteorological phenomena, taken in isolation. Due to the application of drastic conceptual simplifications, there is little hope to verify quantitatively such theories in the real atmosphere or in the laboratory. Only with the aid of numerical experiments those solutions can be reproduced to some extent, evaluating their limitations by varying external parameters. Numerical models can serve also to test the validity limits of linear theories in non-linear extensions and/or in cases in which the basic flow configuration is too complex to be amenable to analytical treatment. In this kind of experiments, sensitive dependence on initial conditions must be kept in mind when non-linear systems are integrated forward in time from similar, but not identical, initial conditions. Moreover, care is needed when interpreting forward model results starting from arbitrary initial conditions that may be far away from any realistic condition of the atmosphere.

In order to be accepted by the scientific community, theories in meteorology must be able to quantitatively describe at least the correct spatial and temporal scales, the approximate spatial organization and structure, and the correct energetics of the phenomena considered. For example, the classical theory of baroclinic instability (Charney 1947; Eady 1949), although limited to linearity, in its original formulation, satisfactorily describes the basic properties of mid-latitude mobile cyclones and anticyclones.

Due to the above problems and limitations of analytical theories, in meteorology often "theories" and "conceptual models" are not very distinct and partly overlap in terminology. Conceptual models denote qualitative or only partly quantitative explanations of observed phenomena based on skilful combinations of analysis of observational data (case studies, statistics), of numerical model outputs, normally in the absence of full solutions of the equations. Early forecasting practice, before the advent of numerical models, was based on conceptual models of the genesis and evolution of meteorological phenomena. Conceptual models are also subject to verification, but this again is possible only in a qualitative way, often obtaining a barely sufficient consensus of the meteorological community. This implies that conflicts may arise between different theories and conceptual models, and it is difficult to reconcile them in the absence of rigorous verification/falsification methods.

In this paper, we shall mainly deal with theories of Alpine lee cyclogenesis in the meaning of analytical or semi-analytical solutions, but paying attention also to the conceptual models that were proposed to explain the nature of this very complex phenomenon. After completing the Introduction with a historical overview of the problem, we devote Section 2 to the description of the (partly competing) theories of orographic cyclogenesis that were proposed by the mid-1980s and subsequently refined. Section 3 describes the criticisms and limitations of the theories exposed in Section 2, and the attempts of their validation/falsification. In Section 3, the conceptual models proposed as alternatives or extensions of the analytical theories, in parallel with new theoretical advances, are examined. Section 4 considers the still open challenges, addressing the problem of understanding the direct and indirect aspects related to the orographic modification of the upper potential vorticity (PV) evolution. Since this work originated from a presentation at the symposium honouring Richard Rotunno held in Riva del Garda—September 2019, we have devoted the entire Section 5 to outlining his contribution to the understanding of basic dynamical properties of flow over orography, baroclinic instability, and cyclones, all aspects that are of crucial importance for the subject of this review. Finally, conclusions are presented in Section 6.

1.2 A glance at synoptic and climatological investigations

The oldest synoptic chart we know depicting a well-developed cyclone in the lee of the Alps is shown in Fig. 1 (De Marchi 1900), with a rather typical double minimum, one over the Gulf of Genoa, and the other over northern Adriatic. Another distinct feature is the packing of the isobars across the Alps.

Another example of an historical map (Bergeron 1928) is given in Fig. 2. In this case, the depression in the lee of the Alps is weak, but this well-known chart emphasizes the strong deformation of the surface cold front due to the blocking exerted by the Alps, while the frontal movement is accelerated on both sides of the massif. Bergeron noted that Mediterranean cyclones present features distinct from those of Atlantic cyclones.

In the 1950s, there was an important rise of interest on Alpine cyclogenesis, at that time generally called “Genoa cyclogenesis” because the pressure minimum is most often observed to appear first in the Gulf of Genoa, and on Mediterranean cyclogenesis in general. Studies of synoptic climatology, based mainly on hand-drawn charts of surface pressure, focused on statistics of cyclogenesis and cyclone paths over the Mediterranean. A famous picture in Petterssen’s book (1956) indicated the western-central Mediterranean as the most active cyclogenetic area in the northern hemisphere in winter.

Other investigations (Pisarski 1955; UK Meteorological Office 1962; Radinović 1965b) spotted cyclogenetic areas in the Mediterranean with higher spatial resolution and also traced the trajectories preferentially followed by developed cyclones. While cyclogenesis was confirmed to occur most frequently in the Gulf of Genoa, other cyclogenetic areas were identified:

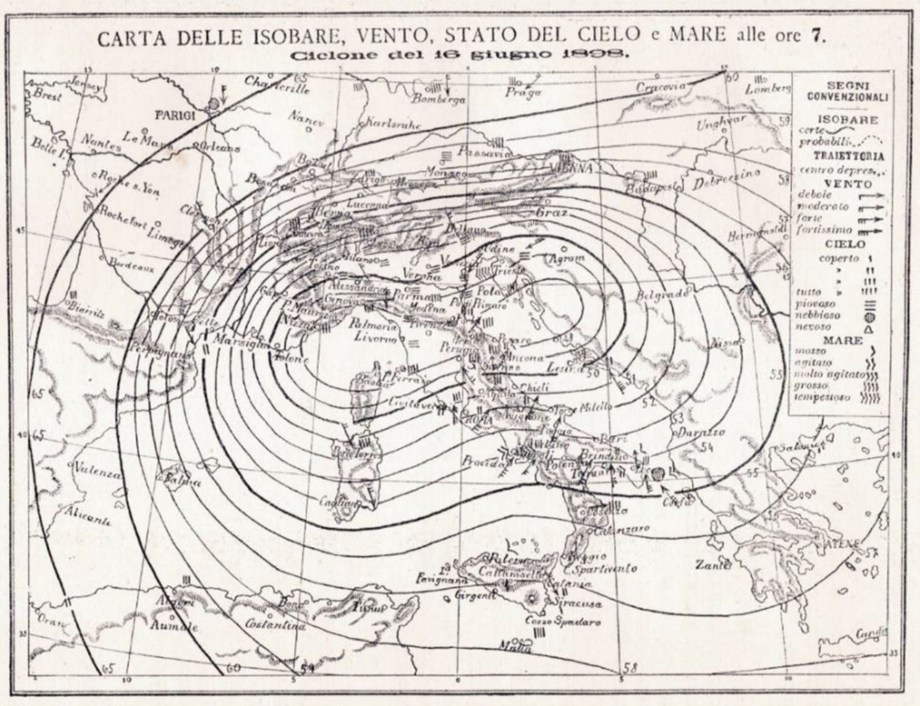


Fig. 1 Synoptic chart of the cyclone of June 16, 1898. Isobars are drawn every 1 mmHg (after De Marchi 1900)

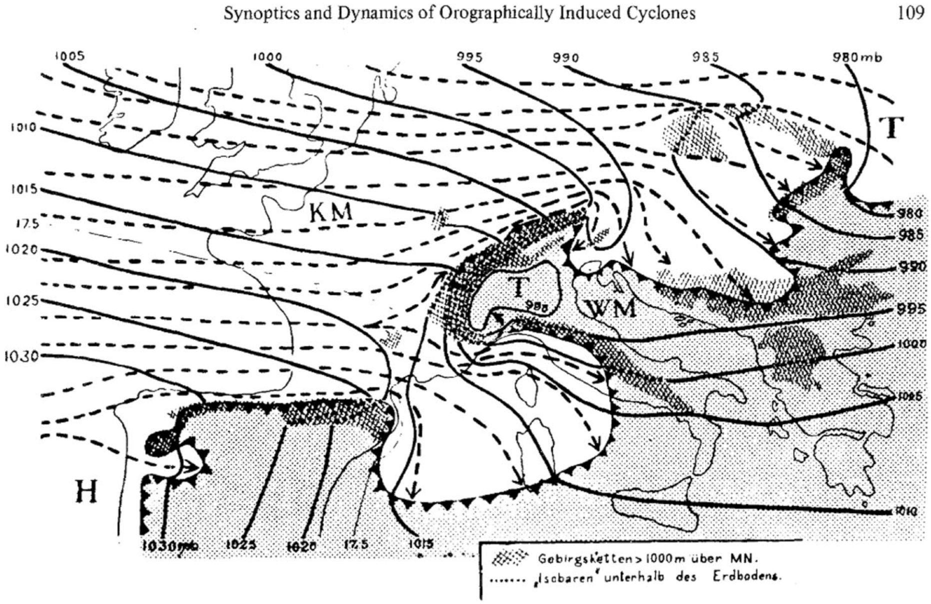


Fig. 2 Orographic disturbances of the velocity and pressure fields and of a cold front over Central Europe (after Bergeron 1928)

north-west of the Balearic islands (in the lee of the Pyrenees), over the northern Adriatic (south-east of the Alps), over the southern Adriatic and Ionian Sea (south-west of the Dinaric mountains), over the Cyprus area (south of the Anatolian mountains), and also in the lee (to the south) of the Atlas mountains in north-western Africa (see also Fig. 3 described below). All the above areas are located in the vicinity of mountain chains, which, if considered from a large-scale point of view (that is the scales of cyclones, of the order of 1000–4000 km), form a long orographic complex aligned mainly along the zonal direction at mid-latitudes. This represents a rather peculiar topographic characteristic of the Mediterranean region.

Regarding cyclone trajectories, they are generally directed from the Mediterranean towards the north-east, the east, or the south-east, so that cyclones originated in the Mediterranean can affect the weather in an area extending from Russia to all Eastern Europe and the Middle East. This explains why the interest in these types of cyclones was not limited to meteorologists of countries facing the Mediterranean. More refined and recent investigations of statistical-dynamical properties of Mediterranean cyclones continued in the following decades, also exploiting the potentialities of model-based reanalyses (see, among others, Trigo et al. 2002; Homar et al. 2006; Horvath et al. 2006; Horvath et al. 2008; Bartholy et al. 2009; Flaounas et al. 2018). Figure 3 shows the Homar et al. (2006) climatology of intense (mature) Mediterranean cyclones, computed over the 45 years of ERA-40 reanalysis. The cyclogenetic areas connected with Mediterranean mountains, as mentioned in the previous paragraph, can be identified as the areas from which most of the strong cyclones represented in Fig. 3 originated. For example, in Fig. 3, the maximum over the Tyrrhenian Sea is related mainly, though not exclusively, to cyclones initially formed over the Gulf of Genoa.

The pioneering hemispheric-wide analysis of Petterssen (1956) was generalized by Hoskins and Hodges (2002), who considered 3-D atmospheric fields and showed that the maximum

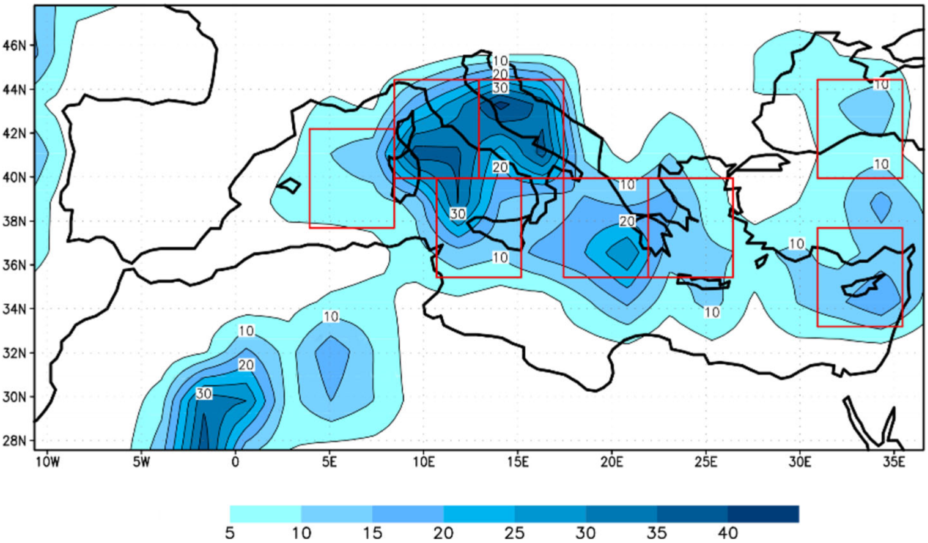


Fig. 3 Number of intense cyclones over the 45 years ERA-40 period at mature stage per squares of 2.25° × 2.25° (after Homar et al. 2006)

frequency of cyclogenesis in the Western Mediterranean is associated with a distinct spot of positive vorticity genesis at 850 hPa.

In the 1950s and 1960s, national and international efforts were made to improve the observations and forecasting of lee cyclones in the Mediterranean (Speranza 1975). A Summer School held in Venice in 1973, organized by the National Research Council of Italy (CNR), was devoted to study Alpine lee cyclones, since they were considered to be frequently associated with the occurrence of storm surges in Venice. But it was only with the planning and implementation of the ALPEX project in 1982 (the last project of the GARP series: Kuettner 1982) that the interest on this phenomenon, that had escaped reliable short-range forecasting even with the most sophisticated models available at that time, became worldwide, in part because cyclones in the lee of the Alps were considered prototypes of similar phenomena occurring in other parts of the Earth.

1.3 Early numerical model-based studies

Research in the 1970s (neglecting here earlier conceptual models, e.g. von Ficker 1920; Radinović 1965a) started with the application of numerical models to study lee cyclogenesis as it was simulated in idealized conditions. Egger (1972) obtained a secondary cyclone in the lee of a box-type mountain in a primitive equation model, initialized with a finite-amplitude vortex superimposed on a baroclinic zonal flow, in a periodic channel. Although the grid spacing was very coarse (350 km), the mountain geometry, an “L-box” shape having high vertical walls, allowed efficient blocking of the flow. The basic ingredients were already there: a primary disturbance in baroclinically unstable flow interacting with a steep mountain. Trevisan (1976) adopted a similar approach (baroclinic basic state in zonal channel), using an isentropic-coordinate model, with a west-to-east smooth ridge in the middle with a gap (to represent the gap between the Pyrenees and the Alps). The baroclinic growth, initiated with a small amplitude, exhibited the basic features of a lee cyclone south of the ridge, distinct but phase-locked with the primary cyclone growing on the northern half of the channel.

In the following years, preceding or immediately following the ALPEX field experiment, various numerical models developed in the meantime were applied to study the phenomenon of lee cyclogenesis, attempting, for the first time, the simulation of real cases. Bleck (1977), implementing a realistic orography in his isentropic model with nested grids (the inner one with 85 km mesh), was able to "hindcast" realistic, though somehow under-represented, Alpine lee cyclones. Mesinger and Strickler (1982), applying the HIBU model (originally formulated at the Federal Hydrometeorological Institute and Belgrade University—see Janjić 1977, and Mesinger 1981—with GFDL further contributions) at about 80 km grid resolution, investigated the effects of changing the orography on 4 events of cyclogenesis and pointed out that the role played by the mountains varies from case to case. Tibaldi and Buzzi (1983) and Dell'Osso (1984) used some of the earliest versions of the ECMWF model. The former authors explored the European-scale impact of Alpine cyclones, evidencing the dipolar nature of the mountain-induced perturbation on the geopotential fields (see Fig. 4), while the latter author, using a limited area version of the ECMWF model, showed that a high-resolution

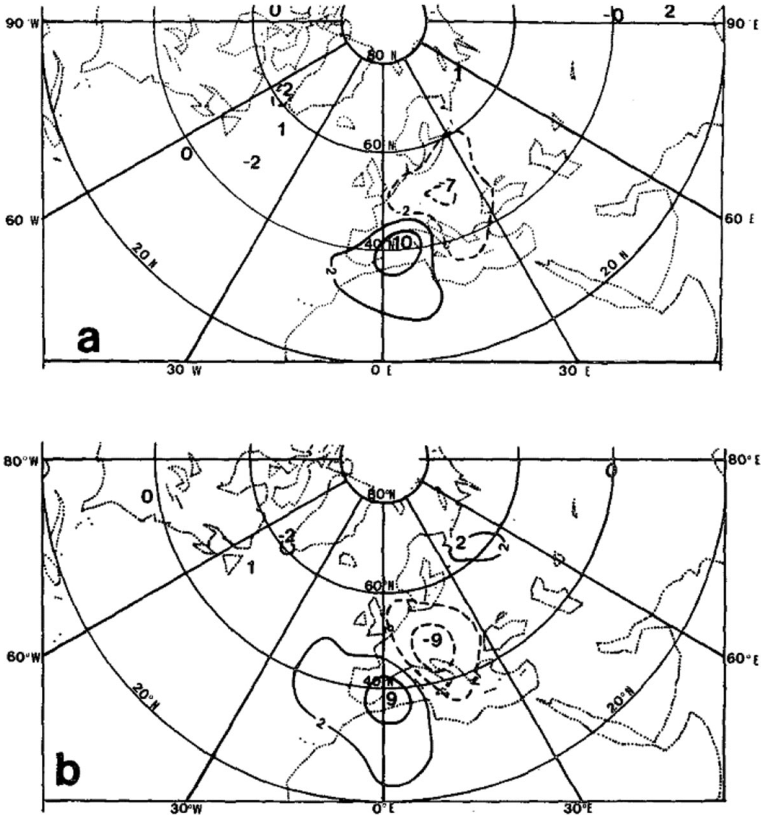


Fig. 4 Geopotential differences (dam) at (a) 1000 hPa and (b) 500 hPa, after 48 h integration, between a control experiment with smooth orography and an experiment with enhanced Alps (after Tibaldi and Buzzi 1983, and Speranza et al. 1985)

(namely a grid distance of a few tens of km) is needed for a satisfactory forecasting of Alpine cyclogenesis.

The idealized numerical approach of the earlier investigators was adopted by Tibaldi et al. (1980), who performed an analysis of the energetics confirming the baroclinic conversion associated with lee cyclone growth, using a channel version of the HIBU model. By means of the same model, Tosi et al. (1983) studied the effects of changing basic flow parameters on energy conversions as modified by the orographic forcing and on the genesis and subsequent development of the orographic cyclone. Working on a hypothesis formulated earlier by Illari et al. (1981), Tosi et al. tried to relate the occurrence of deep, local, development, as opposed to a rapid eastward displacement, to the strength of the mean wind and the amplitude of the primary wave impinging on the idealized Alps. The theoretical concept of absolute as opposed to convective instability (with a different meaning from that commonly used in meteorology) is reviewed in Huerre and Monkewitz (1990). Its application in this instance was strictly numerical since no analytic “dispersion relation” is available for this problem. Further, by slowly removing the mountain after the inception of the orographic cyclone, they showed that the continued presence of the mountain is needed for the deep local development and therefore that the mountain had, in the cases examined, a role as a “catalyst” of energy conversions, rather than as a mere “trigger”.

1.4 Diagnostics of real case studies

While understanding the phenomenon under question was advancing with the aid of numerical models, mostly at their infancy, more traditional analyses of the observations were conducted in parallel. We refer to Speranza (1975) for a thorough review of research on Alpine lee cyclogenesis (case studies, sub-synoptic aspects, climatology, simulations) until the mid-1970s. Speranza, in addition to presenting partial theoretical explanations based on the characteristics of flow around obstacles, pointed out that real lee cyclones, exhibiting a deep vertical extension, should not be confused with weak and shallow depressions confined near the surface, mainly of thermal origin.

Among the relevant papers of the subsequent period based on analyses of case studies, we mention Buzzi and Tibaldi (1978) and McGinley (1982). The former authors, relying upon the synoptic analysis of a single case of rapid and deep cyclogenesis in the lee of the Alps, noted that two phases of cyclone growth can be distinguished (see Fig. 5). The first phase, characterized by a rapid growth, is associated with the 3-D deformation of the cold front impinging on the Alps. In the second phase, more typical of baroclinic instability, the cyclone acquired a consistent deep structure, including self-organized frontal and precipitations systems. Buzzi and Tibaldi (1978) computed isentropic trajectories and showed that most intense precipitation was associated with rising motion in an occluded front that formed south of the Alps, in the region of confluence between cold air turning sharply clockwise around the eastern tip of the Alps and warm air advected from the south by the newly formed lee cyclone circulation.

McGinley (1982) applied a variational objective analysis scheme to two Genoa cyclone events. He based his detailed analysis on the Q-vector diagnosis of the secondary circulation and computed the energy budget for the two case studies. He confirmed the multistage nature of the cyclogenesis, providing a better quantification of the processes associated with the frontal passage over the Alps, which produces rising motions in the mid troposphere in the lee region, and of the baroclinic energy conversion in the later stage.

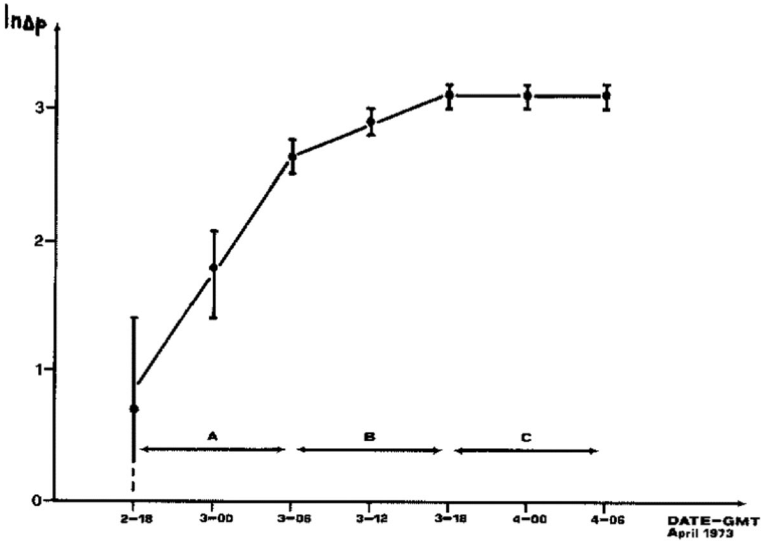


Fig. 5 Growth in the intensity of the lee cyclone, plotted as the evolution in time of the natural logarithm of the difference between the ideal "undisturbed" (no mountain effect) reconstructed pressure and the actual pressure in the centre of the cyclone (after Buzzi and Tibaldi 1978). Two phases (segments A and B) of the lee cyclone growth are identified

2 Theories

Most of the early attempts to represent analytically the basic features of lee cyclogenesis were based on the lee wave model that is considering an incoming rectilinear flow impinging perpendicularly on a ridge or an isolated mountain. A main change in this approach, which led to the formulation of a more suitable flow-obstacle model, came when it was realized that (a) a baroclinic sheared basic flow, with rotation, was a necessary ingredient and (b) the main process to be taken into account was the interaction between the baroclinic waves themselves and the topography and not between the basic flow and the topography. Since the flow associated with unstable baroclinic waves has a large component perpendicular to the mean flow and along the basic thermal gradient, the relevant topographic slopes are those parallel to the basic thermal gradient, which deflect the horizontal wind and, in doing so, modify the baroclinic energy conversion cycle. In this way, the vertical motion forced at the lower boundary modifies the primary baroclinic wave.

The prototypical theoretical model that analyses the flow-mountain geometry described above was presented by Blumsack and Gierash (1972), who considered the effect of an inclined bottom surface, sloping perpendicularly to the basic state, at the lower boundary of Eady's (1949) model of baroclinic instability. This paper was intended to address an aspect of the atmospheric circulation of the planet Mars, but its results were illuminating for more "earthly" studies (see below). They showed that a moderate positive slope (i.e. terrain elevation growing in the direction of colder air) increases the growth rate of the unstable modes, while a negative slope stabilizes the waves and reduces the most unstable wavelength (Fig. 6). They noted that a positive (negative) slope forces low-level vertical velocities that have the same (opposite) sign of the mid-level vertical velocities of the waves, hence enhancing (hindering) the energy conversion from available potential energy of the basic state into wave energy. Equivalently, the result can be appreciated in terms of stretching/shrinking of vortex tubes.

It is only in the mid-1980s, following the involvement of the international meteorological community in ALPEX, that more complex "competing" theories begin to appear in the literature. Speranza et al. (1985, hereafter SBTM) proposed a theory of orographic cyclogenesis that generalizes the Blumsack and Gierasch problem to a more recognizable "mountain" (infinite ridge or 3-D elliptical), with solutions found either in a two-layer model including the beta-effect or in an Eady environment, i.e. vertically continuous, quasi-geostrophic, *f*-plane model. The orography was assumed perturbative and modified the baroclinic wave properties, which were investigated in detail and compared analytically with the same properties without orography. Regarding the growth rate of the unstable modes, SBTM show that the orography tends to decrease it globally (as was earlier found numerically by Mesinger and Strickler 1982). The shape of the "mountain-induced perturbation" is a dipole across the orography zonal axis (Fig. 7 a and c). When superposed to the primary baroclinic wave this implies a larger wave amplitude on the warmer (south in the Northern Hemisphere) side of the mountain than on the colder (north) side, and also a phase shift that advances the wave front on the north side and retards it on the south side (Fig. 7 b and d).

These results for a finite-width ridge are consistent with Blumsack and Gierasch findings (baroclinic waves are stabilized/destabilized on a negative/positive slope) since disturbance amplitudes are weaker (stronger) to the north (south) of a ridge, where the orographic slope is negative (positive). The dipolar structure of the mountain-induced perturbation, revealed by previous numerical simulations, and the properties of the perturbation thermal field, including frontogenetical/frontolytical effects (in the linear limit), were shown by SBTM to be fairly consistent with the observations.

Pierrehumbert (1985) presented a somehow similar theory, still based on a quasi-geostrophic westerly baroclinically unstable flow. Its main difference from SBTM consisted in the topography representation, namely, a "knife-edge" semi-infinite ridge, parallel to the basic flow and completely blocking the lower layer of a two-layer channel model. Some lee cyclone features were identified by the author in the pressure pattern immediately downstream and to the south of the obstacle edge (Fig. 8). However, the total blocking of the meridional

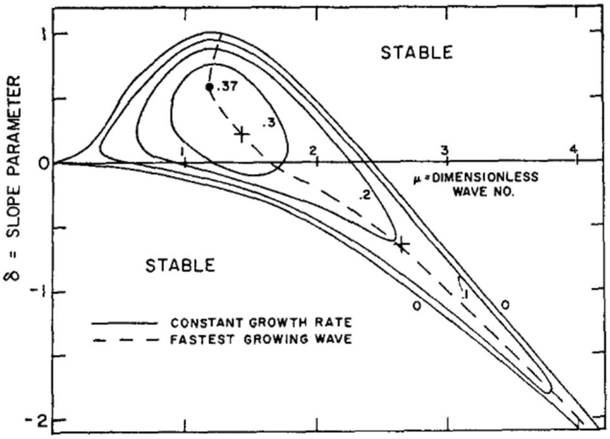


Fig. 6 Lines of constant (dimensionless) growth rate for the two-dimensional model (after Blumsack and Gierash 1972)

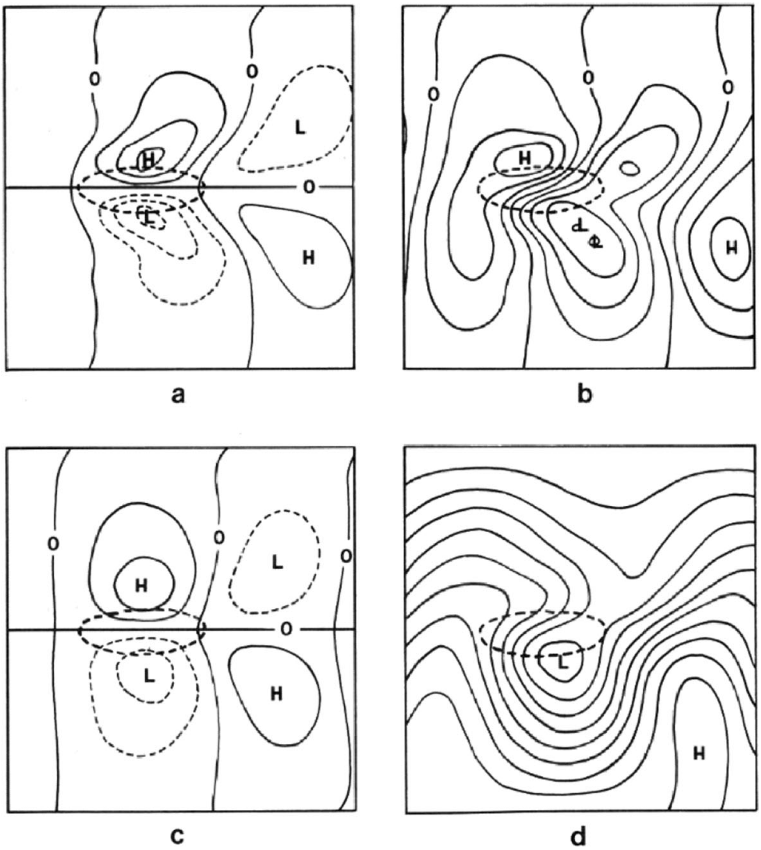


Fig. 7 Solution for a baroclinic wave in the continuous Eady model in a long periodic channel with isolated topography. Dashed lines mark topographic contour (e^{-1} max. height). (a) Streamfunction of orographic perturbation only at $z = 0$; (b) total streamfunction of modified baroclinic wave at $z = 0$; (c) and (d) as in (a) and (b), respectively, but at $z = 0.5$. The basic zonal wind is added in (d) (after Speranza et al. 1985)

flow component in the entire lower layer exerted by the vertical wall and the lack of finite-volume effects of the obstacle limited the realism of this model, at least if it is intended to be applied to the Alpine area.

Smith (1984, 1986) adopted a different approach to develop another theory of Alpine cyclogenesis. Similarly to the theories mentioned above, he considered a baroclinic basic state, but his model belongs to the family of "lee wave" theories, since the flow impinging on the mountain is assumed rectilinear, no primary wave being present upstream of the obstacle. Smith (1984) discovered, with a sophisticated analytical approach, that a baroclinic depression develops and, in the range of certain flow parameters (a wind reversal with height, i.e. the existence of a critical level, is a necessary condition), becomes standing in the lee of a 3-D mountain (Fig. 9). This low, coexisting with warmer air partly advected from the warm side of the basic flow and partly due to orographic descent, does not exceed a few hPa, but can trigger subsequent baroclinic instability in the lee (Smith 1986) that grows in the absence of a primary disturbance.

All the mid-1980s theories mentioned above, including Smith (1986) extension, invoke baroclinic instability to account for the formation of a lee cyclone, addressing therefore the

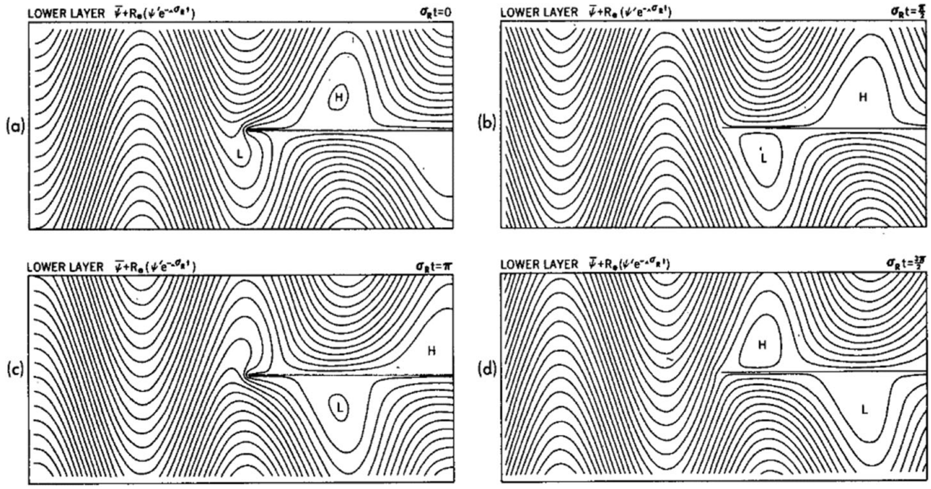


Fig. 8 Streamfunction of mean flow plus perturbation in the lower layer at different times, from $t = 0$ in (**a**) to $t = 3\pi/(2\sigma)$ in (**d**), where σ is the non-dimensional phase speed (after Pierrehumbert 1985)

second phase of cyclogenesis as identified by Buzzi and Tibaldi (1978), while Smith's (1984) analytical time-dependent model appears to be more suitable to explain the first phase of growth. However, in the latter case, the requirement of a critical level in a horizontally uniform and rectilinear basic flow does not seem to be a commonly observed feature. Moreover, a rectilinear flow impinging on the mountain does not account for the typical nature of lee cyclogenesis, which normally occurs as secondary cyclogenesis, in response to the arrival of a "primary wave".

The three theories share the application of the quasi-geostrophic approximation, which is a limitation in consideration of the relatively small scales of the Alps (but the SBTM theory was extended to primitive equations, as detailed in the next section). They are quite different for what concerns the representation of the mountain and the geometry of flow-mountain interaction. The Pierrehumbert and SBTM points of view are somehow complementary: the former includes flow blocking exerted by a very high and steep obstacle, but not vertical velocities forced at the lower boundary, while the latter, in its first formulation, includes only lower boundary forcing due to mountain slopes. The SBTM setup is the closest to the numerical experiments in a channel model described in the subsection "Early numerical model-based studies" above.

3 Criticism of the theories and further progresses

The above theories were criticized for their limiting assumptions and inadequacy to fit observed events. In particular, Egger (1988) and Egger and Tafferner (1990), using numerical simulation experiments based on real events of Alpine cyclogenesis, concluded that none of the theories presented in the previous section could be quantitatively verified. Clearly, their failure to verify any "theory" has to do with a methodology that does not take into account the aspects outlined in the Preface: real events evolve along a non-linear "trajectory" of the atmospheric system that cannot be followed exactly by linear models, and the essential purpose of idealized models is to extract general common features and not to reproduce

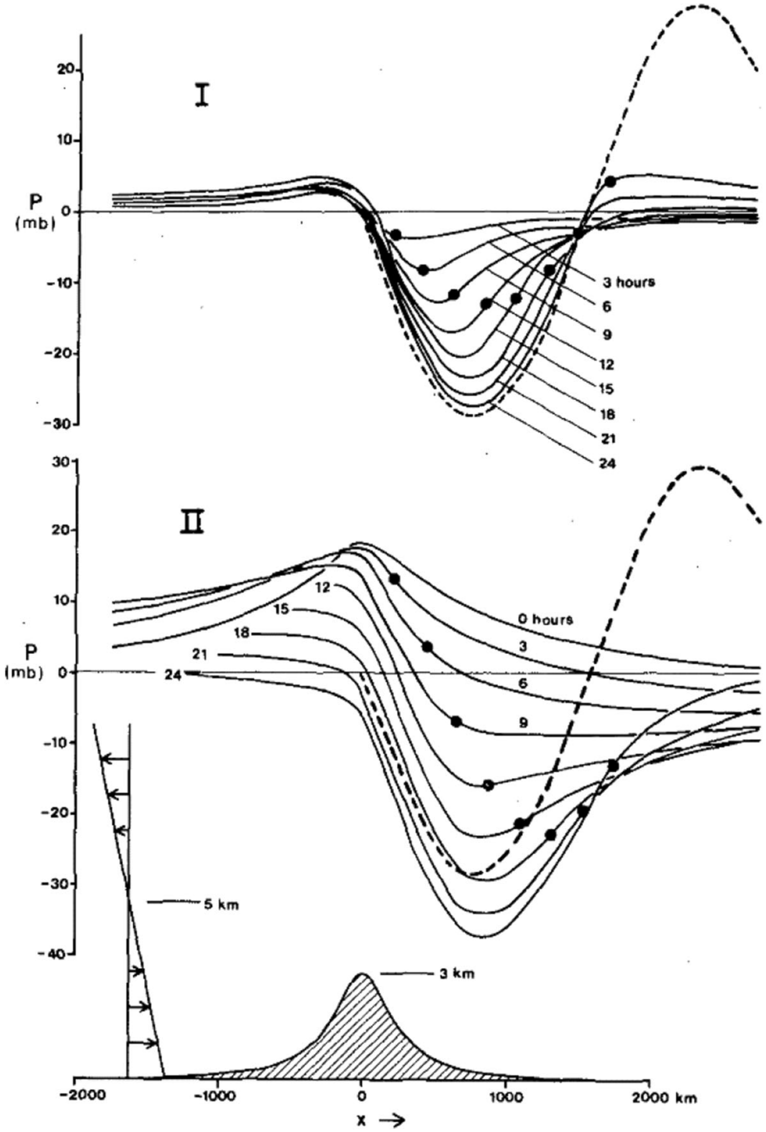


Fig. 9 Time development of surface pressure (hPa) near a 3-km ridge in a sheared background flow according to quasi-geostrophic linearized theory. The fluid is trying to form the first trough of a standing baroclinic lee wave (dashed). The distance covered by the group velocity ($C_g = U_0 = 20$ m s^{-1}) is indicated by the dot on each curve. Initial condition I (undisturbed flow) produces the simple pattern of a wave growing away from its source, while condition II exhibits a rapid decay of the initial mountain anticyclone and a bit of overshoot in the lee trough amplitude (after Smith 1984)

details. Although rather unfair, these criticisms stimulated, on one side, the extension of theories to more realistic and complex situations and, on the other side, the elaboration of more refined conceptual models.

The SBTM theory, in his first formulation, had a number of limitations which were addressed in subsequent papers by those authors and colleagues of the same research group operating in Bologna. The computations of the unstable normal modes were extended first to finite-amplitude mountains, still in the quasi-geostrophic case (Buzzi and Speranza 1986), and then to primitive equations (Malguzzi et al. 1987), dealing with realistically high and steep orography. The most unstable normal modes with primitive equations present important differences in the vicinity of the mountain, where non-geostrophic effects are expected, and, in some cases, less unstable modes exhibit different symmetry properties developing alternatively on either side of the ridge (Fig. 10).

Buzzi et al. (1987) showed that at least some other types of orographic cyclogenesis in the world share basic properties with Alpine cyclogenesis and that they can be also interpreted with the aid of the theory of baroclinic waves modified by orography of different shapes.

The sensitivity to basic flow parameters and the relationship between the properties of the most unstable normal mode and the corresponding initial value problem in the presence of a zonal ridge were examined in detail by Trevisan and Giostra (1990). Analytical, linear, and finite-amplitude solutions of the initial value problem in the case of a 3-D mountain were computed by Malguzzi and Trevisan (1991), who concluded that “the topographic modifications proper of normal modes are robust features which emerged from the integration of the initial value problem” (Fig. 11).

The above papers, especially the latter one, were stimulated by the discussion arising in dynamic meteorology about the problem of the correct interpretation of cyclone development in terms of “global unstable normal modes” versus “local” growth. The debate was not new, going back at least to Petterssen and Smebye (1971) classification of type A cyclogenesis as opposed to type B, the latter being associated with rapid and intense isolated cyclones, and revived by Farrell’s (Farrel 1982; Farrell 1984) rediscovery of Orr’s (Orr 1907) continuous spectrum solutions. The Hoskins et al. (1985) paper that introduced the “Isentropic Potential Vorticity (IPV) thinking” offered an attractive paradigm associating type B cyclogenesis with phase locking between an upper PV anomaly and a lower thermal (or PV) anomaly. This induced some meteorologists to apply the same conceptual explanation to Alpine cyclogenesis, assuming that the role of the mountains is important in the initial stage, when the orographic blocking/retardation of the arriving cold front produces the required warm anomaly in the lee.

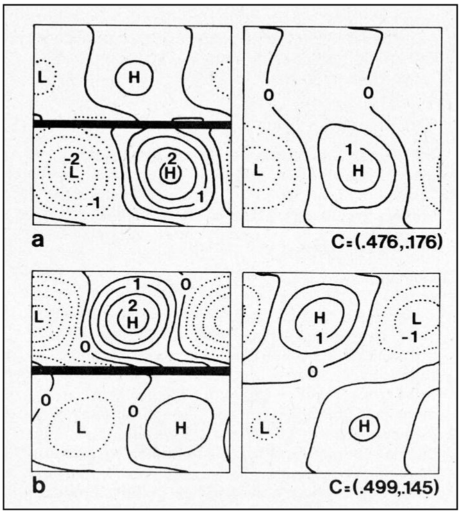
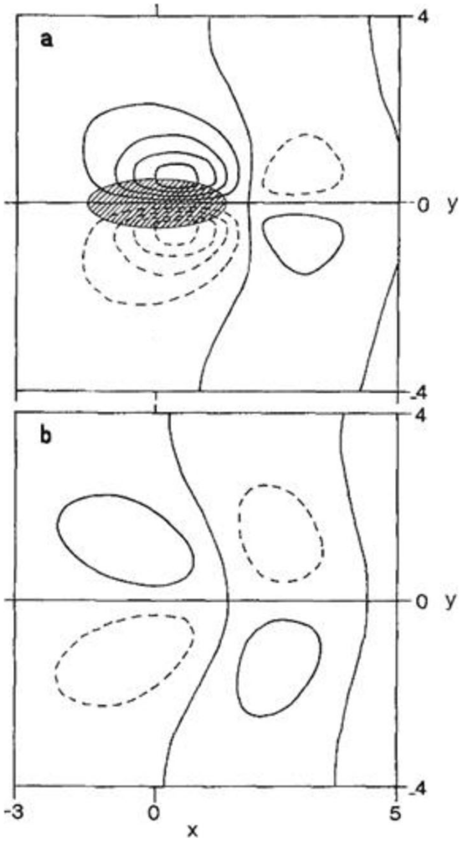


Fig. 10 (a) Geopotential at $z = 0.1$ and $z = 0.5$ for the most unstable eigenmode in a channel, in a primitive equation model. The intersection with the ridge is shaded black. (b) As in (a) but for the second most unstable eigenmode (after Malguzzi et al. 1987)

Fig. 11 Orographic modification computed at the lower level (a) and at the upper level (b) (after Malguzzi and Trevisan 1991)



This conceptual model, not entirely new (the prototypal formulation can be attributed to von Ficker 1920), was refined through several papers (Mattocks and Bleck 1986; Pichler and Steinacker 1987; Tafferner 1990; Egger 1995), based on real case studies and numerical simulations. In the meantime, Aebischer and Schär (1998) noted that positive low-level PV anomalies, deriving from the wrapping up of “PV banners” forming in the Mistral area, can appear in cases of lee cyclogenesis, reinforcing the cyclonic circulation in the Gulf of Genoa.

In parallel with the improvements of the conceptual models, new theoretical studies explored additional aspects of baroclinic normal modes modified by orography. Orlanski and Gross (1994) examined the intensity of vorticity growth south of a zonal ridge, noted the similarity between linear and non-linear modes, and contrasted the warm advection in the lee cyclone to the south of the mountain with the cold advection in the anticyclone to the north of it (see Fig. 12). Davis and Stoelinga (1999) evaluated the non-linear effects on the baroclinic waves with topography by computing first- and second-order perturbations. Fantini and Davolio (2001) examined again how the concept of absolute versus convective instability (see also subsection “Early numerical model-based studies”) can be applied to orographic cyclones: they first obtained unstable perturbations on an Eady wave of arbitrary amplitude; then they showed that, in the interaction with localized topography, packets of such perturbations are generated which show “absolute” behaviour (i.e. deep local development) if the amplitude of the primary wave is large enough.

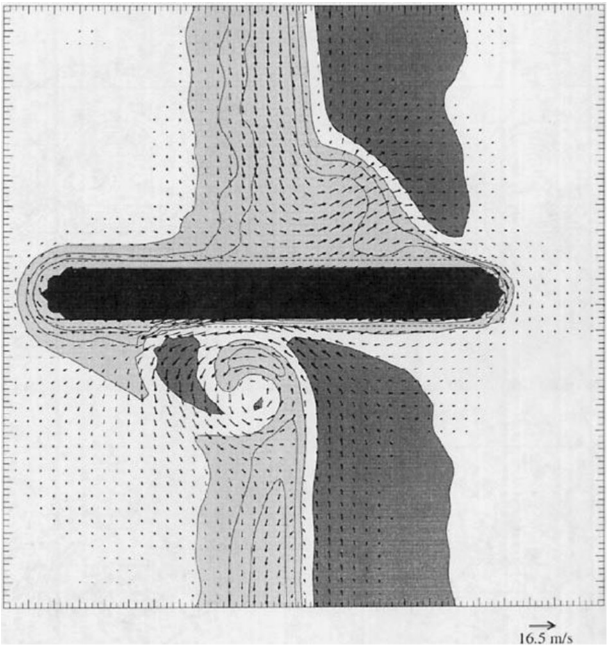


Fig. 12 Potential temperature and horizontal velocity at $z = 1000$ m for the baroclinic simulations. The temperature bands correspond to $\theta < 3$ K (light grey), < 3 K $\leq \theta < 4$ K (white), and $\theta \geq 4$ K (dark grey). The topographic cross section at this height is shaded black. The longest vector corresponds to a speed of 16.5 m s^{-1}. Tick marks are placed every 60 km (after Orlanski and Gross 1994)

Finally, a few papers were devoted to compare observations and theories from a climatological point of view, starting from the search of typical "signatures" of lee cyclogenesis that can be identified in statistical indicators, rather than focusing on individual case studies. The main questions are the following: (a) which elements better characterize the "signature" of transient eddies modified by orography in the Alpine region (besides the high frequency of cyclogenesis); (b) are there statistical properties that can be directly compared with theoretical expectations? In trying to answer these questions, Buzzi and Tosi (1989) and Buzzi (2012) compared the storm track properties in the European-Mediterranean area (as derived from high-pass filtered standard deviation of geopotential height, using ECMWF analyses/reanalyses data sets) with the variability predicted by analytical and numerical models of baroclinic eddies in the presence of orography.

One of the most significant attributes of the mountain-induced perturbation on the transient disturbances, strictly related to the dipolar structure mentioned in Section 2, was identified with the vertical correlation of geopotential variability that is a direct manifestation of the vertical tilt of the west-to-east travelling perturbations, reflecting the phase lag of the wave propagation on either sides of the mountain (Buzzi 2012; Fig. 13).

The arrows show the shift that would give maximum correlation of the upper and lower features, namely the shift that would bring them in vertical coherence with each other. This lag in the low-level pressure tendency, which emerges from the observations as well as from the theory and simulation of unstable eddies in the presence of a west-to-east elongated mountain, was first noted by von Ficker (1920), after examining transects of barometric records across the Alps. The climatological analysis of high-frequency eddies (in the cold semester) shows

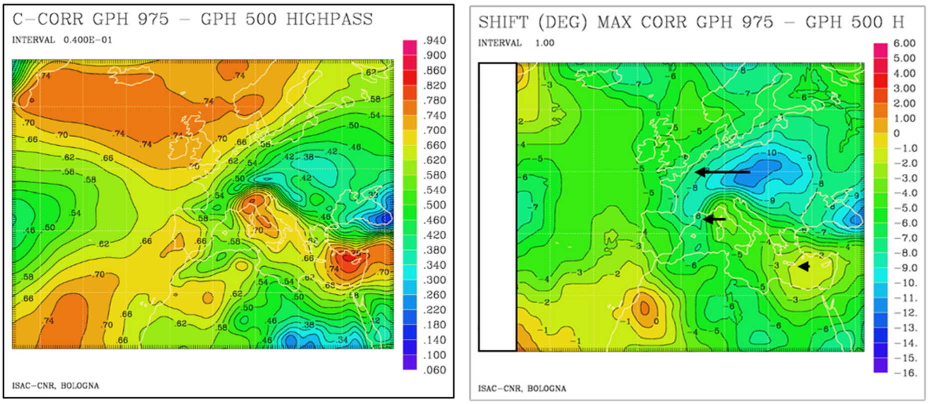


Fig. 13 Left: cross-correlation between the high-pass filtered 975 and 500 hPa geopotential height, in westerly flow regime. Right: E-W shift (lag in degrees longitude, indicated by black arrows) giving maximum correlation between the same geopotential height fields (see also Buzzi 2012)

that (a) a Mediterranean secondary storm track, initiating in the lee of the Alps, is identified in the lower troposphere, while in the upper troposphere it appears as a bifurcation of the Atlantic storm track; (b) spatial correlation maps reveal the mean eddy structure, having the maximum amplitude in the lee of the Alps; and (c) the vertical tilt of eddies south of the Alps is distinctly smaller (more vertical) than that on the north side of the Alps, while the typical tilt of growing baroclinic eddy over flat terrain (e.g. over the Atlantic) is in between the above values. In synthesis, these analyses show increased amplitude of the westerly baroclinic disturbances over the Mediterranean south of the Alps, associated with a retarded movement, while the opposite occurs north of the Alps.

The observed dynamical features described above were compared with those predicted by the theory of baroclinic eddies modified by orography by Buzzi et al. (1990). Using a two-layer numerical model, they evaluated the statistical properties of small and finite-amplitude baroclinic eddies developing in a channel with isolated topography. Although the fully turbulent non-linear properties exhibit quantitative differences from those of normal modes, the similarities in storm-track splitting, eddy shape, and eddy vertical tilt are evident.

The above statistical properties may not be representative of the properties of individual strong events of cyclogenesis, but reflect the peculiar properties of mobile cyclones (and anticyclones) in the southern Europe-Mediterranean area.

4 Progresses in observational/numerical studies and open problems

Following the time of the “competing theories”, for approximately the next 25 years, a considerable number of papers have appeared in the literature investigating sub-synoptic and mesoscale aspects and properties of cyclones forming in the lee of the Alps and of other mountain ranges of the Earth. These papers were mainly based on analyses and numerical simulations of real case studies. Many aspects were identified as important in determining the characteristics of the entire life cycle of cyclones generated in the lee of the Alps, from the initial growth to the decay stage: different types of lee cyclones, the dynamics of interaction of fronts with the orography, the orographic winds like Mistral and Bora, the energy budget, the generation of precipitation and the role of latent heat release, the surface heat and moisture fluxes, the characteristics of upper and lower PV, the gravity waves and mountain drag, and so on. However, since the scope of this review is restricted mainly to theories and interpretation, we mention here only a few of these papers.

Pichler and Steinacker (1987) distinguished between different orientations of the synoptic-scale flow, leading to different types of Alpine cyclogenesis. Michaelides (1987) presented the energy budget of a case of Genoa cyclone. Mesinger et al. (1988) showed the good performance of their step-mountain model in simulating different cases of lee cyclogenesis. Zupanski and McGinley (1989) presented model diagnostics of the effects of jets, fronts, and mountains on Alpine lee cyclogenesis. Gross (1994) examined the interaction of a front with an isolated mountain, using a primitive-equation model in idealized conditions. Alpert et al. (1996) studied the relative combined roles played by different processes (orographic forcing, convection, heat fluxes), applying the factor separation technique, during different stages of evolution of a lee cyclone monitored during the ALPEX experiment. Kljun et al. (2001) characterized in detail, using trajectory analysis, several mesoscale processes occurring during another ALPEX case of cyclogenesis. Buzzi et al. (2003) modelled a case of rapid Alpine cyclogenesis occurred during the MAP field phase, showing the effects of different mountain representations on geopotential and precipitation forecast errors. Hoinka and Davies (2007) considered the evolution of upper PV streamers in the proximity of the Alps during MAP. McTaggart-Cowan et al. (2010a, b) studied a case of Alpine cyclogenesis, diagnosing its evolution and transition to a tropical-like cyclone, with the aid of detailed simulations. The above papers conveyed very valuable new information about the physical properties of lee cyclones and their modelling, adding evidence to the awareness that theories in meteorology can only cover a few aspects of very complex phenomena.

As exposed above, a number of papers applied the “PV-thinking” framework to lee cyclogenesis as a conceptual model that aims at explaining more realistic aspects than analytical theories. In this view, deep lee cyclones form when high PV anomalies/streamers approach the Alps from the N-W quadrant, while low-level pressure compensation due to convergence/cold advection is blocked by the massif, causing a preferential pressure drop in the lee (south) and dynamical coupling between the upper PV maximum and the lower positive thermal anomaly. This process concerns mainly the initial growing stage, basically assuming that the upper PV anomaly is not affected by the presence of the orography. However, an important question, which addresses a still open problem, is how the mature cyclone evolution feeds back to the structure of the PV anomaly itself. In other words, how does the upper PV evolution depend on the presence of the orography? The numerous numerical experiments, presented in the literature quoted in the previous sections (see e.g. Buzzi et al. 2003), that compare model evolutions with and without (or with reduced) orography indicate that even in cases characterized by strong “upper level forcing”, in which cyclogenesis would occur somewhere in the area even in the absence of the mountains, orographically modified cyclones develop in a different position, i.e. some hundred kilometers more to the west or south-west than in the flat terrain case, while the formation of an upper-level cut-off low is enhanced. Some time (12–24 h) after the inception stage, the model evolution of the upper PV anomaly is different in the mountain and flat cases. Therefore, although the orographic perturbation decreases with height, evidence of a mutual interaction between the lee cyclone circulation and upper PV dynamics emerges in the presence of topography, which is not the same as in the absence of topography. This is consistent with the notion that the upper PV dynamics is not independent from the dynamics in the lower troposphere that are directly modified by the presence of orography.

A contribution in clarifying the above aspect came from Tsidulko and Alpert (2001), who investigated the “synergistic” role of PV advection and orography, applying the factor separation technique to simulations of the ALPEX case of 5 March, 1982. Summarizing from their conclusions, (a) the pure (no mountain) contribution of PV advection is generally cyclogenetic; (b) the pure topographic contribution (PV removed) produces a dipolar structure, but the pressure drop is relatively small; (c) the synergistic PV-topography contribution is strong; and (d) slight modifications in either the direction or the intensity of the PV advection may lead to a cyclone formation at some different location or no cyclone at all. Point (c) is particularly relevant in this discussion.

The Tsidulko and Alpert (2001) results indicate that the presence of a PV anomaly, which is associated with the primary cyclone and upper trough, is necessary for the formation of a fully developed intense lee cyclone, but they also stress the importance of the combined presence of PV and topography. This means that the topography definitely enhances the local cyclogenetic effect of the upper PV anomaly.

In the following, we present further evidence of the above problems as derived from parallel simulations, made with realistic orography and an orography in which the Alps have been reduced by a factor of 10, using a 2-D Gaussian tapering function. The simulations were made with the BOLAM NWP model (Buzzi et al. 1994; Malguzzi et al. 2006; Buzzi et al. 2014), starting 00 UTC of May 4, 2019, using ECMWF operational analysis/forecasts as initial/boundary conditions. An Alpine lee cyclone formed between 4 and 5 May.

Figure 14 shows the mean sea level pressure difference and the 300-hPa geopotential height difference between the control (realistic Alps) and reduced-Alps experiments. The well-known low-level dipolar structure, SW-NE oriented, becomes at upper levels (right panel of Fig. 14) a “tripole”, as noted already by Buzzi et al. (2003), that is a large positive anomaly over the Alps surrounded by two negative anomalies along a SW-NE axis. This configuration reflects the fact that the upper level trough is weaker over the Alps and shifted westward due to the presence of the mountain chain (by comparing experiments where all diabatic processes are suppressed, it emerges that a large part of the upper level positive difference is due to latent heat release and convection, which contribute to warm up the upper troposphere).

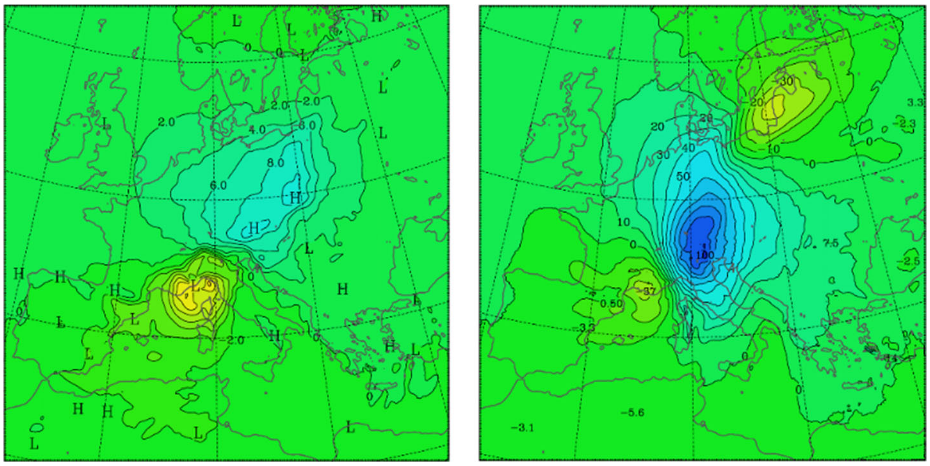


Fig. 14 Left: mean sea level pressure difference between a reference experiment with full orography and an experiment with Alps removed, after 30 h of integration, verifying May 5, 2019, 06 UTC (interval: 2 hPa). Right: as left but for the 300-hPa geopotential height (interval: 10 dam)

In any case, the mountain-induced anticyclonic circulation near the tropopause acts to rotate clockwise the PV streamer (see Fig. 15), in such a way that near the Alps, it is located to the west and over central Europe to the east, with respect to the position it would assume without the Alps.

The above considerations indicate that non-linear processes (self-advection) are already acting even after less than 24 h of development. This corroborates the concept that the evolution of the upper level PV cannot be considered only as an independent upper level forcing, since it depends also on the presence of the mountains (as hypothesized also by Buzzi et al. 2003, Hoinka et al. 2003, and Hoinka and Davies 2007). Diabatic processes (especially latent heating and convection) strongly influence the non-linear stage, especially at upper levels. This is consistent with important results of Rotunno's and co-authors' on cyclone dynamics and predictability, which strongly depend on diabatic processes and convection (see e.g. Zhang et al. 2007) and that we discuss in the next section.

5 Richard Rotunno's contributions to the understanding of basic dynamical aspects

From the above discussion, a number of fundamental problems in the interpretation of the complex phenomenon of lee cyclogenesis emerge. On one side, the flow modifications induced by steep orographic massifs like the Alps raise the problem of the adequacy of the approximations made in the set of equations (e.g. the quasi-geostrophic approximation adopted in many theoretical investigations), and of the representation of the orography itself in analytical and numerical models. On another side, the problem of assessing the adequacy of the classical baroclinic instability theory in explaining cyclogenesis in general applies also to the problem of orographic cyclogenesis.

Although Rotunno did not publish papers addressing specifically the phenomenon of lee cyclogenesis, his contributions to the dynamics of flow over mountains and cyclogenesis in general are relevant for the theoretical developments that are the subject of this review. In addition, he authored or co-authored papers that investigate mesoscale aspects of dry as well as

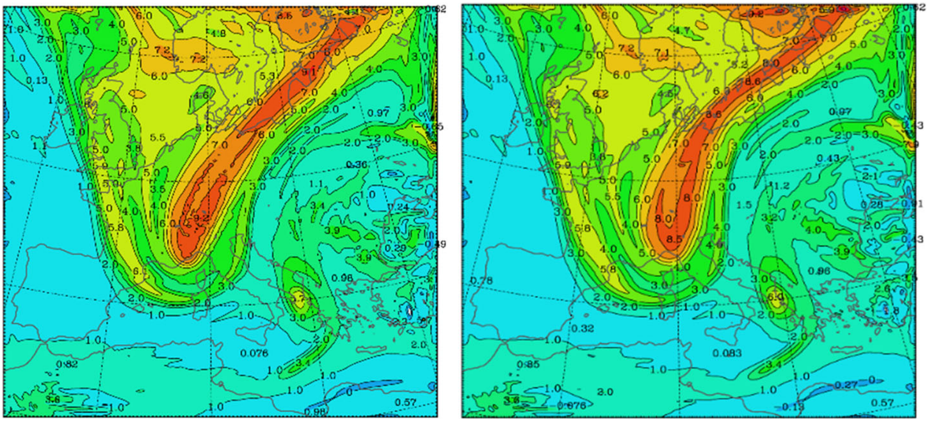


Fig. 15 Potential vorticity on the isentropic surface $\theta = 325$ K. Left: reference experiment with full orography, after 30 h of integration, verifying May 5, 2019, 06 UTC. Right: as left, but for an experiment with Alps removed

moist flows over topography, contrasting dry and moist dynamics, and that deal with some meteorological phenomena typical of the Alpine area, as detailed below.

Smolarkiewicz and Rotunno (1989) and Rotunno et al. (1999) considered low Froude number flow past three-dimensional mesoscale obstacles and studied the mechanisms of generation of baroclinic vortices in the lee. Although this type of baroclinicity does not derive from that of the upstream flow but from the tilting of the isentropic surfaces over orography, this mechanism may also be relevant for lee cyclogenesis, in particular for the evolution of vorticity and potential vorticity in the mountain wake.

We should also mention here studies on cyclogenesis in general, and therefore relevant to lee cyclogenesis as well. Rotunno and Fantini (1989) and Rotunno and Bao (1996) showed that type B cyclogenesis (Petterssen and Smebye 1971) can be described with a superposition of normal modes, until then considered only relevant to type A cyclones, without resorting to the more exotic continuous spectrum.

In Rotunno and Ferretti (2001), a mechanism of intense Alpine rainfall was proposed to explain the heavy precipitation often occurring south of the Alps, namely, the coexistence of saturated and sub-saturated flow branches, having different effective stratification, impinging on the mountain chain from the south and leading to enhanced convergence and lifting. Although the types of cyclones conducive to this specific flow pattern cannot be classified as the result of cyclogenesis in the lee of the Alps, this mechanism is strictly related to how mountains perturb the atmosphere in dry and moist conditions, in the presence of a large variability in static stability of the upstream flow. This basic problem, and also the dependency of stratified flow past mountains on the horizontal scales of the obstacle, is schematically represented in a regime diagram appearing in the same paper and reported here in Fig. 16.

According to the diagram of Fig. 16, we should classify lee cyclogenesis among the phenomena characterized by a Rossby number of the order of 1 or less, for what concerns the scales of the cyclone, but larger than 1 for what concerns the mesoscale motions induced by the orography, which mediate the interaction of the Alps with the synoptic scale flow ("far field" and "near field", respectively, as described in SBTM and, more appropriately, in Malguzzi et al. 1987). The mountain-induced perturbation has to be considered non-linear in the same diagram, since the Alps have an effective height of about 2 km which, combined with typical values of stratification N (about 10^{-2} s^{-1}) and horizontal velocity V (about 10 m/s), gives an inverse orographic Froude number HN/U of about 2.

Miglietta and Rotunno (2006) and Rotunno and Houze (2007) present, respectively, studies of moist, nearly neutral flow over a ridge, and the progresses made in understanding orographic precipitation in the Mesoscale Alpine Programme (MAP). The latter field experiment (Bougeault et al. 2001) was devoted to investigating mesoscale dynamical and microphysical phenomena in the Alpine region, including heavy precipitation, but not specifically lee cyclogenesis. However, the occurrence of one strong example of lee cyclogenesis during MAP provided the opportunity for some investigations mentioned in Section 4 above.

6 Conclusions

As we stated at the outset, we cannot expect, in dealing with a complex system as the Earth's atmosphere, to formulate "theories" that can be "verified" quantitatively to many decimal places. The most we can accomplish is to extract from observations and numerical experiments a general view of the process, and of the relative importance of the dynamical mechanisms

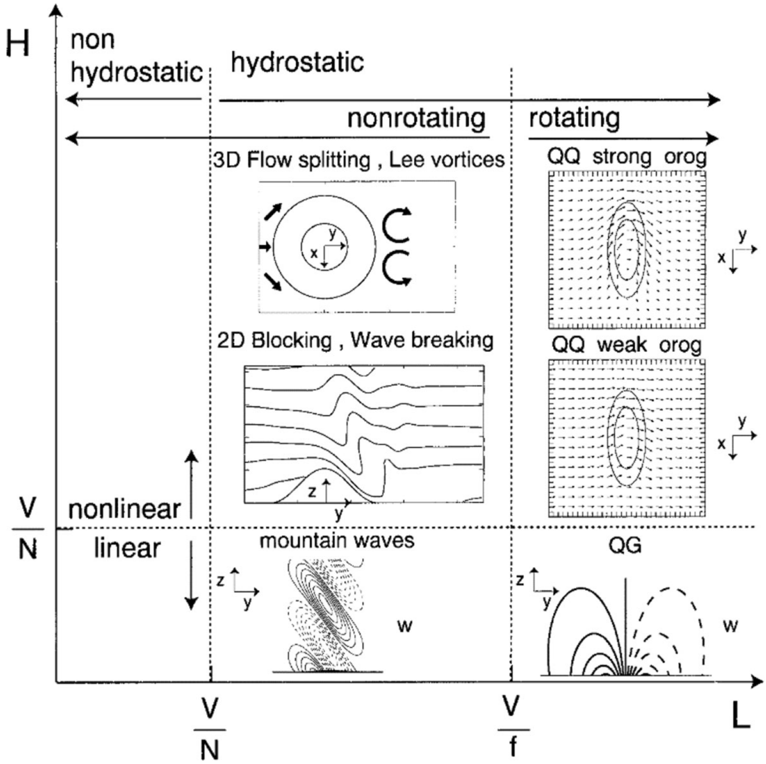


Fig. 16 Regime diagram for dry-adiabatic, constant flow (*V*) of a uniformly stratified (*N* = *constant*) fluid on an *f* plane past an obstacle of height *H* and breadth *L*. The diagram assumes typical Northern Hemisphere mid-latitude values for *N* and *f* such that $N >> f > 0$ (after Rotunno and Ferretti 2001)

involved. Based on our survey of the literature and direct experience in research, we consider the mechanism as analytically identified by SBTM, with the subsequent extensions and generalizations, the most relevant for the preferential development of cyclones in the lee of the Alps. However, baroclinic instability modified by topography is the basic subject of most of the theories expressed on the phenomenon. All theoreticians agree about the importance of a baroclinic atmosphere: even Smith's (1984, 1986) theory, although not considering a primary disturbance in the oncoming flow, requires the presence of a strong vertical shear implying intense baroclinicity. All theories indicate that the presence of an obstacle inducing vertical and horizontal deviations of the flow has important consequences on the spatial characteristics and rate of growth of the cyclonic disturbances.

Theories, however, are very limited in application and cannot cope with large uncertainties as to specific forecast of individual cases and weather features. Moreover, the intricacies of multiscale phenomena induced by orography like the Alps cannot be treated by the filtered set of equations that have been used in most cases. Therefore, theories are to be complemented by conceptual models, like those based on the PV point of view, which appear to be more helpful than the normal modes in interpreting isolated and intense cyclogenesis. In fact, despite their satisfactory spatial structure and conceptual relevance, global normal modes of an idealized mean state, that are linear, and may take a long time to appear out of the background flow, may not be too appealing for those who are interested in interpreting synoptic meteorology and weather forecasting. Although in principle an initial value problem can be described with a superposition of normal modes, we cannot be certain, in a complex, time evolving, real atmosphere situation, that the linearity, completeness, and time-scale separation properties are satisfied. And this even if we do not take into account the fact that non-adiabatic processes may even negate the superposition property of the modes. For all these reasons, the search for a more compact representation of the process, of which the PV description is an instance, represents a valuable approach for further progress.

As can be noted from the near absence of references in the last 10 years, the interest for this topic seems to be waning. Certainly, this is partly due to the fact that nowadays NWP models, with grid distances of about 10 km or less, are basically capable of predicting Alpine lee cyclones, although small-scale features, like orographic winds and precipitating system, and boundary layer-surface processes are still poorly predicted and modelled over and near complex orography. Therefore, the attention in recent coordinated international efforts such as the Hydrological Cycle in the Mediterranean Experiment (HyMeX, see Drobinski et al. 2014) and the multiscale transport and exchange processes in the atmosphere over mountains programme (TeamX; see Serafin et al. 2020) has been focused mainly on small-scale phenomena (e.g. strong winds and heavy precipitation) and processes (boundary layer effects, surface exchanges) often associated with cyclones (Flaounas et al. 2016, among others), which are still poorly understood and predicted over and near complex orography.

However, if the diminished interest in lee cyclogenesis comes from considering the problem solved, the summary presented here should dispel this notion. If instead this is due to the meteorological community being too focused on other, perhaps more subtle problems, we hope that this review has highlighted the challenging aspects of the phenomenon, and will stimulate a renewed effort toward solving it in a manner satisfactory to everybody. In any case, meteorology of the Mediterranean and of other regions characterized by important orography cannot leave aside the phenomena and their interpretations reviewed in this paper, which represent a solid basis for the investigation of Mediterranean cyclones foreseen in the recently approved COST Actions CA19109 “European network for Mediterranean cyclones in weather and climate” (https://www.cost.eu/actions/CA19109).

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References

Aebischer U, Schär C (1998) Low-level potential vorticity and cyclogenesis to the lee of the Alps. J Atmos Sci 55:186–207

Alpert P, Tsidulko M, Krichak S, Stein U (1996) A multi-stage evolution of an ALPEX cyclone. Tellus 48(A): 209–220

Bartholy J, Pongracz R, Pattantyus-Abraham M (2009) Analyzing the genesis, intensity, and tracks of western Mediterranean cyclones. Theor Appl Climatol 96:133–144

Bergeron T (1928) Ueber die dreidimensional verknuepfende Wetteranalyse. Geof Publ 5:99 pp

Bleck R (1977) Numerical simulation of lee cyclogenesis in the Gulf of Genoa. Mon Weather Rev 105:428–445

Blumsack SL, Gierash PJ (1972) Mars: the effects of topography on baroclinic instability. J Atmos Sci 29:1081–1089

Bougeault P, Binder P, Buzzi A, Dirks R, Kuettner J, Houze R, Smith RB, Steinacker R, Volkert H (2001) The MAP special observing period. Bull Am Meteorol Soc 82:433–462

Buzzi A (2012) Synoptic-scale variability in the Mediterranean. Predictability in the European and Atlantic regions from days to years. *ECMWF Seminar Proceedings*. Reading (UK), 15-29

Buzzi A, Speranza A (1986) A theory of deep cyclogenesis in the lee of the Alps. Part II: effects of finite topographic slope and height. J Atmos Sci 43(2826):2837

Buzzi A, Tibaldi S (1978) Cyclogenesis in the lee of the Alps: a case study. Q J Roy Meteor Soc 104:271–287

Buzzi A, Tosi E (1989) Statistical behaviour of transient eddies near mountains and implications for theories of lee cyclogenesis. J Atmos Sci 46(1233):1249

Buzzi A, Speranza A, Tibaldi S, Tosi E (1987) A unified theory of orographic influences upon cyclogenesis. Meteorol Atmos Phys 36:91–107

Buzzi A, Malguzzi P, Trevisan A (1990) The statistical properties of the interaction of high frequency eddies with mountains in a two layer model. Tellus 42 A:28–40

Buzzi A, Fantini M, Malguzzi P, Nerozzi F (1994) Validation of a limited area model in cases of Mediterranean cyclogenesis: surface fields and precipitation scores. Meteorol Atmos Phys 53:137–153

Buzzi A, D'Isidoro M, Davolio S (2003) A case study of an orographic cyclone south of the Alps during the MAP SOP. Q J Roy Meteor Soc 129:1795–1818

Buzzi A, Davolio S, Malguzzi P, Drofa O, Mastrangelo D (2014) Heavy rainfall episodes over Liguria in autumn 2011: numerical forecasting experiments. Nat Hazards Earth Syst Sci 14:1325–1340. https://doi.org/10.5194/nhess-14-1325-2014

Charney JG (1947) The dynamics of long waves in a baroclinic westerly current. J Meteorol 4:136–162

Davis CA, Stoelinga MT (1999) The transition to topographic normal modes. J Atmos Sci 56:3321–3330

De Marchi L (1900) Il Secolo XIX nella vita e nella cultura dei popoli – *La Fisica Terrestre*. F. Vallardi Ed., 227-257

Dell'Osso L (1984) High-resolution experiments with the ECMWF model: a case study. Mon Weather Rev 112: 1853–1883

Drobinski P, Ducrocq V, Alpert P, Anagnostou E, Béranger K, Borga M, Braud I, Chanzy A, Davolio S, Delrieu G, Estournel C, Filali Boubrahmi N, Font J, Grubišić V, Gualdi S, Homar V, Ivančan-Picek B, Kottmeier C, Kotroni V, Lagouvardos K, Lionello P, Llasat MC, Ludwig W, Lutoff C, Mariotti A, Richard E, Romero R, Rotunno R, Roussot O, Ruin I, Somot S, Taupier-Letage I, Tintore J, Uijlenhoet R, Wernli H (2014) HyMeX, a 10-year multidisciplinary program on the Mediterranean water cycle. Bull Am Meteorol Soc 95: 1063–1082

Eady ET (1949) Long waves and cyclone waves. Tellus 1:33–52

Egger J (1972) Numerical experiments on the cyclogenesis in the Gulf of Genoa. Beitr Phys Atmos 45:320–346

Egger J (1988) Alpine lee cyclogenesis: verification of theories. J Atmos Sci 45:2187–2203

Egger J (1995) Interaction of cold-air blocking and upper-level potential vorticity anomalies during lee cyclogenesis. Tellus 47(A):597–604

Egger J, Tafferner A (1990) Test of theories of lee cyclogenesis: ALPEX cases. J Atmos Sci 47:2417–2428

Fantini M, Davolio S (2001) Instability of neutral Eady waves and orography. J Atmos Sci 58:1146–1154

Farrel BF (1982) The initial growth of disturbances in a baroclinic flow. J Atmos Sci 39:1663–1686

Farrell BF (1984) Modal and nonmodal baroclinic waves. J Atmos Sci 41:668–673

Flaounas E, Lagouvardos K, Kotroni V, Claud C, Delanoë J, Flamant C, Madonna E, Wernli H (2016) Processes leading to heavy precipitation associated with two Mediterranean cyclones observed during the HyMeX SOP1. Q J Roy Meteor Soc 142:275–286

Flaounas E, Kelemen FD, Wernli H, Gaertner MA, Reale M, Sanchez-Gomez E, Lionello P, Calmanti S, Podrascanin Z, Somot S, Akhtar N, Romera R, Conte D (2018) Assessment of an ensemble of ocean–atmosphere coupled and uncoupled regional climate models to reproduce the climatology of Mediterranean cyclones. Clim Dyn 51:1023–1040

Gross BD (1994) Frontal interaction with isolated orography. J Atmos Sci 51:1480–1496

Hoinka KP, Davies HC (2007) Upper-tropospheric flow features and the Alps: an overview. Q J Roy Meteor Soc 133:847–865

Hoinka KP, Richard E, Poberaj G, Busen R, Caccia J-L, Fix A, Mannstein H (2003) Analysis of a potential vorticity streamer crossing the Alps during MAP IOP-15 on 6 Nov. 1999. Q J Roy Meteor Soc 129:609–632

Homar V, Jansà A, Campins J, Ramis C (2006) Towards a climatology of sensitivities of Mediterranean high impact weather – first approach. Adv Geosci 7:259–267

Horvath K, Fita LL, Romero R, Ivančan-Picek B (2006) A numerical study of the first phase of a deep Mediterranean cyclone: cyclogenesis in the lee of Atlas Mountains. Meteorol Z 15:133–146

Horvath K, Lin Y, Ivančan-Picek B (2008) Classification of cyclone tracks over the Apennines and the Adriatic Sea. Mon Weather Rev 136:2210–2227

Hoskins BJ, Hodges KI (2002) New perspectives on the Northern Hemisphere winter storm tracks. J Atmos Sci 59:1041–1061

Hoskins BJ, McIntire ME, Robertson AW (1985) On the use and significance of isentropic potential vorticity maps. Q J Roy Meteor Soc 111:877–946

Huerre P, Monkewitz PA (1990) Local and global instabilities in spatially developing flows. Annu Rev Fluid Mech 22:473–537

Illari L, Malguzzi P, Speranza A (1981) On the breakdown of the westerlies. Geophys Astrophys Fluid Dyn 17: 27–49

Janjić ZI (1977) Pressure gradient force and advection scheme used for forecasting with steep and small scale topography. Contrib Atmos Phys 50:186–199

Kljun N, Sprenger M, Schär C (2001) Frontal modification and lee cyclogenesis in the Alps: a case study using the ALPEX reanalysis data set. Meteorol Atmos Phys 78:89–105

Kuettner J (1982) ALPEX experiment design. GARP-ALPEX no. 1. WMO, Geneva, 99 p

Malguzzi P, Trevisan A (1991) Normal mode theory of lee cyclogenesis and the initial value problem. Meteorol Atmos Phys 46:115–122

Malguzzi P, Trevisan A, Speranza A (1987) Effects of finite height topography on nongeostrophic baroclinic instability: implications to theories of lee cyclogenesis. J Atmos Sci 44:1475–1482

Malguzzi P, Grossi G, Buzzi A, Ranzi R, Buizza R (2006) The 1966 ‘century’ flood in Italy: a meteorological and hydrological revisitation. J Geophys Res 111:D24106

Mattocks C, Bleck R (1986) Jet streak dynamics and geostrophic adjustment processes during the initial stages of lee cyclogenesis. Mon Weather Rev 114:2033–2056

McGinley J (1982) A diagnosis of Alpine lee cyclogenesis. Mon Weather Rev 110:1271–1287

McTaggart-Cowan R, Galarneau TJ, Bosart LF, Milbrandt JA (2010a) Development and tropical transition of an Alpine lee cyclone. Part I: case analysis and evaluation of numerical guidance. Mon Wea Rev 138:2281–2307

McTaggart-Cowan R, Galarneau TJ, Bosart LF, Milbrandt JA (2010b) Development and tropical transition of an Alpine lee cyclone. Part II: orographic influence on the development pathway. Mon Wea Rev 138:2308–2326

Mesinger F (1981) Horizontal advection schemes of a staggered grid—an enstrophy and energy-conserving model. Mon Weather Rev 109:467–478

Mesinger F, Strickler RF (1982) Effects of mountains on Genoa cyclogenesis. J Meteorol Soc Japan 60:326–337

Mesinger F, Ianjić ZI, Ničković S, Gavrilov D, Deaven DG (1988) The step-mountain coordinate: model description and performance for cases of Alpine lee cyclogenesis and for a case of an Appalachian redevelopment. Mon Weather Rev 116:1493–1518

Michaelides SC (1987) Limited area energetics of Genoa cyclogenesis. Mon Weather Rev 115:13–26

Miglietta MM, Rotunno R (2006) Further results on moist neutral flow over a ridge. J Atmos Sci 63:2881–2897

Orlanski I, Gross BD (1994) Orographic modification of cyclone development. J Atmos Sci 51:589–611

Orr WMF (1907) Stability or instability of the steady motions of a perfect liquid. Proc Roy Irish Acad 27:9–69

Petterssen S (1956) Weather analysis and forecasting, vol 1. McGraw-Hill, New York

Petterssen S, Smebye SJ (1971) On the development of extratropical cyclones. Q J Roy Meteor Soc 97:457–482

Pichler H, Steinacker R (1987) On the synoptics and dynamics of orographically induced cyclones in the Mediterranean. Meteorol Atmos Phys 36:108–117

Pierrehumbert RT (1985) A theoretical model of orographically modified cyclogenesis. J Atmos Sci 42:1244–1258

Pisarski A (1955) The Mediterranean cyclones and their influence on the weather in Bulgaria. Hydrol Meteorol 6: 3–15

Radinović D (1965b) Cyclonic activity in Yugoslavia and surrounding areas. Arch Meteor Geophys Bioklim A14:391–408

Radinović D (1965a) On forecasting of cyclogenesis in the West Mediterranean and other areas bounded by mountain ranges by baroclinic model. Arch Meteor Geophys Bioklim A14:279–299

Rotunno R, Bao J-W (1996) A case study of cyclogenesis using a model hierarchy. Mon Weather Rev 124: 1051–1066

Rotunno R, Fantini M (1989) Petterssen’s “Type B” cyclogenesis in terms of discrete, neutral Eady modes. J Atmos Sci 46:3599–3604

Rotunno R, Ferretti R (2001) Mechanisms of intense Alpine rainfall. J Atmos Sci 58:1732–1749

Rotunno R, Houze RA (2007) Lessons on orographic precipitation from the Mesoscale Alpine Programme. Q J Roy Meteor Soc 133:811–830

Rotunno R, Grubišić V, Smolarkiewicz PK (1999) Vorticity and potential vorticity in mountain wakes. J Atmos Sci 56:2796–2810

Serafin S, Rotach MW, Arpagaus M, Colfescu I, Cuxart J, De Wekker SFJ, Evans M, Grubišić V, Kalthoff N, Karl T, Kirshbaum DJ, Lehner M, Mobbs S, Paci A, Palazzi E, Raudzens Bailey A, Schmidli J, Wohlfahrt

G, Zardi D (2020) Multi-scale transport and exchange processes in the atmosphere over mountains - programme and experiment. Innsbruck University Press 42 pp
Smith RB (1984) A theory of lee cyclogenesis. J Atmos Sci 41:1159–1168
Smith RB (1986) Further development of a theory of lee cyclogenesis. J Atmos Sci 43:1582–1602
Smolarkiewicz PK, Rotunno R (1989) Low Froude number flow past three-dimensional obstacles. Part I: baroclinically generated lee vortices. J Atmos Sci 46:1154–1164
Speranza A (1975) The formation of baric depressions near the Alps. Ann Geofis 28:177–217
Speranza A, Buzzi A, Trevisan A, Malguzzi P (1985) A theory of deep cyclogenesis in the lee of the Alps. Part I: modifications of baroclinic instability by localized topography. J Atmos Sci 42(1521):1535
Tafferner A (1990) Lee cyclogenesis resulting from the combined outbreak of cold air and potential vorticity against the Alps. Meteorol Atmos Phys 43:31–47
Tibaldi S, Buzzi A (1983) Effects of orography on Mediterranean lee cyclogenesis and its relationship to European blocking. Tellus 35(A):269–286
Tibaldi S, Buzzi A, Malguzzi P (1980) Orographically induced cyclogenesis: analysis of numerical experiments. Mon Weather Rev 108:1302–1314
Tosi E, Fantini M, Trevisan A (1983) Numerical experiments of orographic cyclogenesis: relationship between the development of the lee cyclone and the basic flow characteristics. Mon Weather Rev 111:799–814
Trevisan A (1976) Numerical experiments on the influence of orography on cyclone formation with an isentropic primitive equation model. J Atmos Sci 33:768–780
Trevisan A, Giostra U (1990) Dynamical criteria determining lee cyclogenesis. J Atmos Sci 47:2400–2408
Trigo IF, Bigg GR, Davies TD (2002) Climatology of cyclogenesis mechanisms in the Mediterranean. Mon Weather Rev 130:549–649
Tsidulko M, Alpert P (2001) Synergism of upper level potential vorticity and mountains in Genoa lee cyclogenesis – a numerical study. Meteorol Atmos Phys 78:261–285
UK Meteorological Office (1962) Weather in the Mediterranean I. MO 391, HMSO, London, 362 pp
von Ficker H (1920) Der Einfluß der Alpen auf Fallgebiete des Luftdruckes und die Entstehung von Depressionen über dem Mittelmeer. Meteor Z 37:350–363
Zhang F, Bei N, Rotunno R, Snyder C, Epifanio CC (2007) Mesoscale predictability of moist baroclinic waves: convection-permitting experiments and multistage error growth dynamics. J Atmos Sci 64:3579–3594
Zupanski M, McGinley J (1989) Numerical analysis of the influence of jets, fronts and mountains on Alpine lee cyclogenesis. Mon Weather Rev 117:154–176