environmental sciences proceedings

MDPI

Proceeding Paper

Diagnostics of Mediterranean Explosive Cyclogenesis Using the Pressure Tendency Equation †

John Kouroutzoglou [1,2,*], Christos Lamaris [3], Helena A. Flocas [2,*], Maria Hatzaki [4], Georgios Kafkoulas [3] and Platon Patlakas [2]

1 Hellenic National Meteorological Service, Hellinikon, 16777 Athens, Greece
2 Sector of Environmental Physics—Meteorology, Department of Physics, National and Kapodistrian University of Athens, University Campus, 15784 Athens, Greece; platon@mg.uoa.gr
3 Regional Meteorological Centre, Hellenic Tactical Air Force, 41001 Larisa, Greece; christos.lamaris@hnms.gr (C.L.); georgios.kafkoulas@hnms.gr (G.K.)
4 Sector of Geography and Climatology, Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, University Campus, 15784 Athens, Greece; marhat@geol.uoa.gr
* Correspondence: ioankour@phys.uoa.gr (J.K.); efloca@phys.uoa.gr (H.A.F.)
† Presented at the 16th International Conference on Meteorology, Climatology and Atmospheric Physics—COMECAP 2023, Athens, Greece, 25–29 September 2023.

Abstract: The objective of this study is the evaluation of the physical processes responsible for the genesis and evolution of an explosive cyclone in the central Mediterranean with the aid of the surface pressure tendency equation. For this reason, the equation is solved numerically, providing the opportunity to quantitatively specify the relative significance of the diabatic processes in Mediterranean explosive cyclogenesis, contrary to the qualitative approach of previous studies. Our approach allows for the first time a direct comparison of the physical mechanisms between the cyclogenesis over the northern and the southern part of the central Mediterranean. The results demonstrate that the interaction between the upper level baroclinic and low-level diabatic processes triggered the development of the explosive cyclone, but low-level baroclinicity and diabatic processes prevailed during the cyclone evolution.

Keywords: surface pressure tendency equation; Mediterranean explosive cyclones; diabatic and baroclinic processes

Citation: Kouroutzoglou, J.; Lamaris, C.; Flocas, H.A.; Hatzaki, M.; Kafkoulas, G.; Patlakas, P. Diagnostics of Mediterranean Explosive Cyclogenesis Using the Pressure Tendency Equation. *Environ. Sci. Proc.* **2023**, *26*, 140. https://doi.org/10.3390/environsciproc2023026140

Academic Editors: Konstantinos Moustris and Panagiotis Nastos

Published: 31 August 2023

1. Introduction

Mediterranean explosive cyclogenesis has been systematically studied during the last decades, regarding both its climatological characteristics and the dynamic processes evolved [1–6]. In the above studies, both the baroclinic and diabatic processes and their relevant importance on cyclones' rapid deepening were examined, but the approach was in all cases from the qualitative point of view.

In this study, the modified version of the pressure tendency equation (hereafter, PTE) is employed based on the study of [7] and applied to the ERA-5 1hr reanalysis dataset in order to quantitatively assess the contribution of the diabatic processes to the deepening of a case of explosive cyclogenesis over the central Mediterranean, during the period 12–16 November 2017, and more specifically during the first hours of the 15 November 2017, where the western parts of Athens were affected by strong flash floods which led to 21 human life losses [8,9].

2. Materials and Methods

The new ECMWF/ERA5 dataset [10] is employed, while the atmospheric fields used at surface and on pressure levels are on an hourly time step and on 0.25° × 0.25° regular latitude-longitude grid. The diagnostic approach is based on the surface PTE [7] which considers an air column from the surface up to an upper boundary with pressure equal to p_2 following the equation:

$$\underbrace{\frac{\partial p_{sfc}}{\partial t}}_{Dp} = \underbrace{\rho_{sfc}\frac{\partial \varphi_{p2}}{\partial t}}_{D\varphi} + \underbrace{\rho_{sfc} R_d \int_{sfc}^{p_2} \frac{\partial T_v}{\partial t} d\ln p}_{ITT} + \underbrace{g(E-P)}_{EP} + RES_{PTE} \quad (1)$$

where p_{sfc} is the surface pressure, ρ_{sfc} is the respective air density at surface, φ_{p2} is the geopotential height at the pressure level equal to p_2, R_d is the gas constant for dry air, T_v is the virtual temperature, and g is the gravitational acceleration. The terms of the above equation from the left to the right denote the rate of surface pressure tendency (Dp), the rate of geopotential change at the upper boundary of the air column (Dφ), the vertically integrated virtual temperature tendency (ITT), the mass loss (increase) by surface precipitation P (evaporation E) (EP), and a residuum due to discretization (RES_{PTE}).

The ITT term of Equation (1) was further analyzed as follows [7]:

$$ITT = \underbrace{+\rho_{sfc} R_d \int_{sfc}^{p_2} -\overline{v}\overline{\nabla}_p T_v d\ln p}_{TADV} + \underbrace{\rho_{sfc} R_d \int_{sfc}^{p_2} \left(\frac{R_d T_v}{c_p p} - \frac{\partial T_v}{\partial p}\right)\omega d\ln p}_{VMT} + \underbrace{\rho_{sfc} R_d \int_{sfc}^{p_2} \frac{T_v \dot{Q}}{c_p T} d\ln p}_{DIAB} + RES_{ITT} \quad (2)$$

where T is temperature, v and ω the horizontal and vertical wind components, respectively, c_p the specific heat capacity at constant pressure, and Q the diabatic heating rate. The first and second terms on the right-hand side describe the effect of horizontal temperature advection (TADV) and vertical motions (VMT) on the column-integrated temperature tendency. DIAB contains the influence of diabatic processes such as radiative warming/cooling, latent heat release due to phase changes of water, diffusion, and dissipation. The term RES_{ITT} represents errors due to discretization in time and space. The ITT term also includes a small term arising from changes in the humidity content in the column, which is neglected for reasons explained in [7].

The surface PTE is evaluated over a $3° \times 3°$ latitude-longitude box extending from the surface to 100 hPa centered on the position of the cyclone, as derived following the minimum mean sea level pressure (MSLP) from the ECMWF/ERA5 dataset. DIAB had to be calculated as the residuum of the equation determining the ITT and is therefore termed $DIAB_{RES}$, which almost coincides to the DIAB term [7]. Finally, the relative contribution of $DIAB_{RES}$ to the total pressure tendency, $DIAB_{ptend}$, is defined by $DIAB_{ptend}$ equation of [7] (Equation (3) of Fink et al. 2012 [7]).

3. Results

3.1. Application of the PTE for the First Phase of the Case of Explosive Cyclogenesis in the Gulf of Genoa

The explosive cyclone phase includes the time period between 12/00 UTC and 13/11 UTC (Figure 1a), namely the period where the upper-level cyclonic circulation in NW Europe begun to develop until the formation of surface explosive cyclogenesis in the Gulf of Genoa [11]. However, surface MSLP analysis shows one cyclone center is formed in the Ligurian Sea, while a secondary center is located over northern Italy, both with a pressure of about 990 hPa (Figure 1b). Since the calculation of the physical parameters considers an area (box), both the implication of the ''reference" cyclone center in the Ligurian Sea and of the secondary cyclone over northern Italy is included.

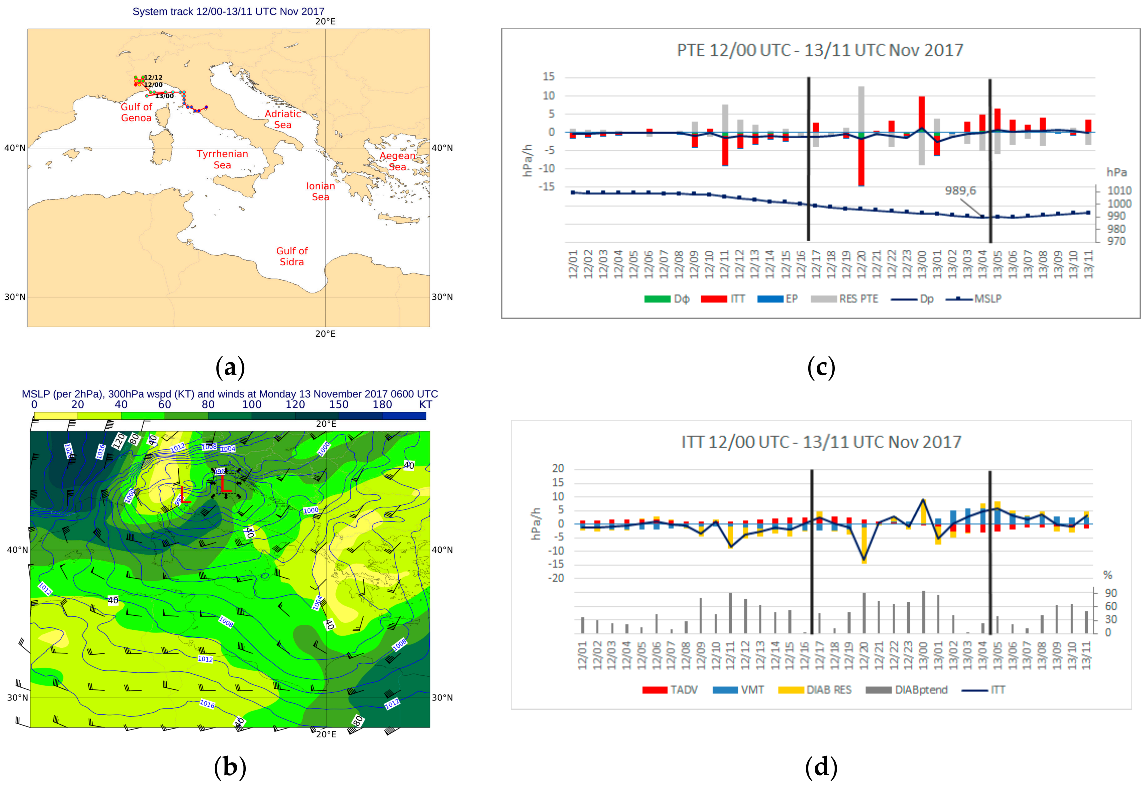


Figure 1. (**a**) Track of the explosive cyclone during the first phase (12/00 UTC-13/11 UTC) following the minimum MSLP, (**b**) MSLP (continuous lines; per 2 hPa), 300 hPa windspeed (shading; K), and winds at 13/06 UTC, (**c**) the results of the PTE. At the bottom is depicted the temporal evolution of the MSLP (in hPa) of the explosive cyclone, and (**d**) the respective numerical results of the ITT term. Gray bars (in %) at the bottom depict the $DIAB_{ptend}$ term. The vertical bold lines delineate the interval of explosive deepening.

The numerical simulation of the PTE has a theoretical basis only if the Dφ term is significantly smaller than the respective ITT term [7]. Indeed, according to Figure 1c, the Dφ values are significantly smaller than the ITT values. RES_{PTE} is almost negligible during the incipient stage, although it strengthens during the rapid deepening stage, strongly implying that even with the advanced ERA5 dataset, deficiencies arise when the quantitative precipitation simulation is performed on an hourly time step, in accordance with the results of [7]. The Dφ term is negative almost throughout the cyclone evolution until the explosive cyclogenesis, which denotes a positive effect on the pressure tendency, considering that the 100 hPa isobaric level descends towards lower isentropic surfaces, which implies upward motions in the lower troposphere [12]. The respective ITT term (Figure 1c) presents negative values and differential warming during the greatest part of the cyclone evolution, which proves that the variations in the upper-level dynamics result in the rapid deepening of the surface cyclone. According to [7], such an interaction between the Dφ and ITT terms can be observed in cases where the explosive deepening occurred within the left exit region of the polar front jet streak (Figure 1b) [13].

Figure 1d shows that the ITT term significantly contributes to the surface deepening. Although at isolated hourly time steps the ITT term contributes to the surface rise, the RES_{PTE} term is also enhanced, which is probably related to the discretization of the precipitation simulation [7]. Moreover, negative VMT values were calculated during the time period between 12/00 -13/01 UTC. It should be noted that if downward motions are strong in the upper and the middle troposphere due to positive potential vorticity anomalies (not shown), they can balance the effect of low-level unstable conditions [14]. Also, one of the primary characteristics which was also observed by [7] is that the TADV term presents an opposite sign from the respective VMT term, with similar absolute values. Actually, this cancellation results from the upward motions of the air over the isentropic surfaces to the east (downstream) of a mid-latitude frontal depression [15], where low-level warm air advection dominates. Moreover, the positive values of TADV imply that the differential temperature advection in the middle and upper level surpasses the surface and low-level warm air advection. The $DIAB_{RES}$ term presents small values, although larger during the period of the explosive cyclogenesis, denoting the effect of diabatic heating during the rapid deepening. It should be also noted that the DIAB term is closely related to the VMT term, considering the latent heat release due to condensation.

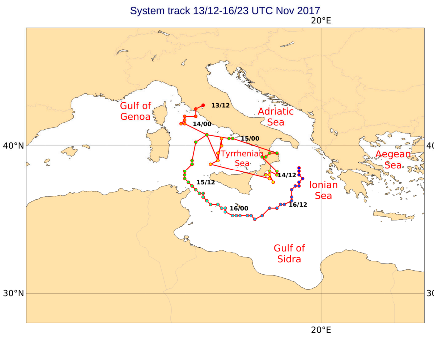
After all the above, Figure 1d shows that during almost all the time period, the $DIAB_{RES}$ term is negative and thus the $DIAB_{ptend}$ term simulates the quantitative effect of the diabatic processes in the surface cyclone deepening. Thus, during the initiation of the surface cyclogenesis where the cyclone was located to the lee of the Alps, the effect of the diabatic processes was relatively small with a contribution between 10 and 30% of the total surface pressure fall, while the frontal depression begun its rapid deepening, the degree of influence of the diabatic processes enhanced, and $DIAB_{ptend}$ presented values between 60 and 90%, demonstrating that diabatic processes dominated over the baroclinic ones.

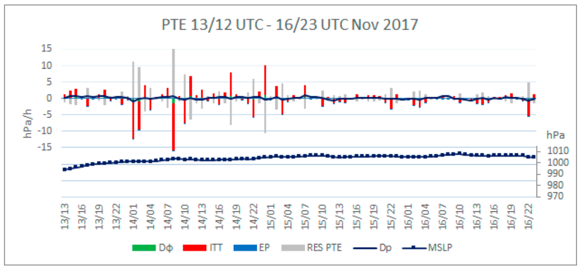
3.2. Application of the PTE for the Second Phase of the Case of Explosive Cyclone Evolution

The analysis of the PTE and ITT equations for the period between 13/12 UTC and 16/23 UTC is presented in Figure 2c,d, while Figure 2a shows the respective cyclone track. Figure 2b presents the formation of a secondary surface cyclogenesis in the Gulf of Syrte with a pressure of about 1008 hPa, which is distinct from the explosive depression. The specific surface cyclone propagated E-NE towards the southern Ionian Sea without tendency of further deepening.

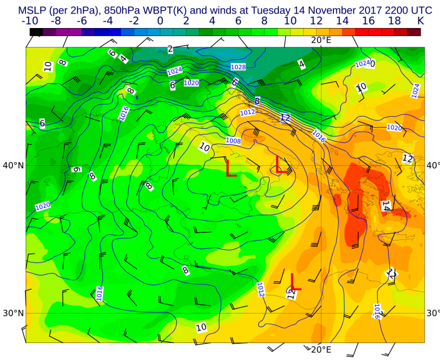
Figure 2c shows that Dφ values are significantly smaller than the respective ITT values. It should be noted that the Dp curve includes the influence of the cyclogenetic activity over the southern central Mediterranean parts. The ITT term is dominant during the largest part of the explosive cyclone phase. The RES_{PTE} term presents relatively large values in those stages where ITT values are also enhanced and is always with an opposite sign compared to the ITT, in accordance with [7]. Dφ is also negative throughout the cyclone evolution, which implies the positive response in the surface cyclone deepening and the fact that the upper-level dynamics continued to contribute. The ITT term presents positive values over the longest time period, indicating a differential cooling in the atmospheric layer. Nevertheless, the above synoptic behavior would not be so important if the cyclogenetic activity in the Gulf of Syrte would not have been triggered. The low-level warm air advection above the extended area of the Gulf of Syrte reaching the southern Ionian Sea, combined with the cold air advection from the N-NW parts of the area, enhanced the low-level baroclinicity and the tendency for surface frontogenesis over the southern parts of the central Mediterranean area (Figure 2b).

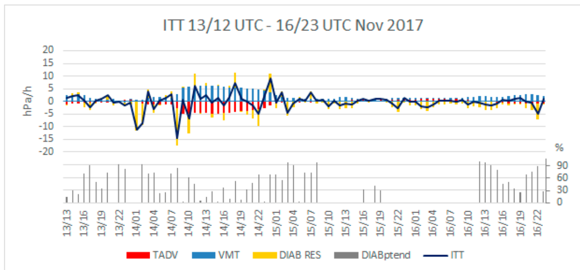
The behavior of the ITT term in Figure 2d strongly demonstrates that during the time period between 13/13 UTC and 15/04 UTC, including thus the time period where the strong phenomena occurred over the western parts of Athens, the ITT term contributes to the ascending motions and the surface deepening of the explosive cyclone. Nevertheless, considering the integration procedure performed for the calculations, the above temporal variations are affected from the contribution of the successive surface cyclogenetic events over the southern parts of the central Mediterranean. Although during the onset of the explosive cyclogenesis the middle and upper air descending motions managed to dominate over the low-level ascending motions, considering the positive VMT values during the next stage, the low-level environment with the occurrence of pre-existed warm and moist air (Figure 2b) enhanced the ascending motions, although the upper-level dynamics were reduced. The TADV term presents an opposite sign to the VMT term with similar absolute values. Actually, these two terms tend to cancel the effect due to the ascending motions downstream of a surface depression, namely in areas where a typical mid-latitude frontal depression or a surface of low-level temperature discontinuities with orientation of the isotherms from S-SW to N-NE and warm air advection, prevail over these areas [16]. The $DIAB_{RES}$ term presented small values in general, but it is stronger during the initiation of surface successive secondary cyclogenesis in the Gulf of Syrte implying the effect of the diabatic processes in the area between S. Italy, Sicily, the Tyrrhenian Sea, the South Adriatic Sea, and the Gulf of Syrte.





(**a**) (**c**)





(**b**) (**d**)

Figure 2. (**a**) Track of the explosive cyclone during the second phase (13/12 UTC-16/23 UTC) following the minimum MSLP, (**b**) MSLP (continuous lines; per 2 hPa), 850 hPa wet-bulb potential temperature (shading; K), and winds at 14/22 UTC, (**c**) the results of the PTE. At the bottom is depicted the temporal evolution of the MSLP (in hPa) of the explosive cyclone and (**d**) the respective numerical results of the ITT term. Gray bars (in %) at the bottom depict the $DIAB_{ptend}$ term.

Finally, the quantitative evaluation of both the baroclinic and diabatic processes is presented in the gray bars of Figure 2d. During almost all of the period except the time between 15/10 and 16/10 UTC, the $DIAB_{ptend}$ term presents significant values and seems to be dominant, with values between 70 and 90%. Considering that the $DIAB_{RES}$ term is negative, the $DIAB_{ptend}$ term imprints the quantitative effect of the diabatic processes in the sustainment of the ascending motions at the surface and the lower troposphere. On the contrary, the minima of $DIAB_{ptend}$ during the time period between 15/10 and 16/10 UTC implies that about 70–90% of the surface pressure deepening is the result of the TADV term, since this time period coincides to the formation of a new upper-level cyclonic disturbance from the west parts of the almost stationary closed cyclonic circulation (not shown) [17].

4. Conclusions

In this study, a case of explosive cyclogenesis in the central Mediterranean was examined, accompanied by severe weather over the central and southern parts of the Greek area including the western parts of Athens. The new dimension presented in this work is the numerical solution of the PTE, which provided the opportunity to quantitatively specify the relative significance of the diabatic processes.

All the analyses in this work showed that although surface cyclogenesis over the southern parts of the central Mediterranean basin might not be as strong as the respective of the northern central Mediterranean parts [18,19], in fact the low-level baroclinic and diabatic processes over the warm Mediterranean Sea can be connected to severe weather.

Author Contributions: Conceptualization, J.K. and H.A.F.; Data curation and Investigation, J.K. and C.L.; Methodology, J.K. and H.A.F.; Resources and Software, C.L. and G.K.; Supervision, H.A.F.; Visualization, C.L. and G.K.; Writing—original draft, J.K., H.A.F., and M.H.; Writing—review and editing, J.K., H.A.F., M.H. and P.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The ERA-5 Reanalysis are openly available via Copernicus (www.copernicus.eu), accessed on 12 September 2022.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Capaldo, M.; Conte, M.; Finizio, C.; Todisco, G. A detailed analysis of a severe storm in the central Mediterranean—The case of the Trapani flood. *Riv. Di Meteorol. Aeronaut.* **1980**, *40*, 183–199.
2. Karacostas, T.; Flocas, A. The development of the "Bomb" over the Mediterranean area. *La Meteorol.* **1983**, *34*, 351–358.
3. Conte, M.; Piervitali, E.; Colacino, M. The meteorological "bomb" in the Mediterranean. In *INM/WMO International Symposium on Cyclones and Hazardous Weather in the Mediterranean*; MMA/UIB: Palma de Mallorca, Spain, 1997; pp. 283–287.
4. Lagouvardos, K.; Kotroni, V.; Defer, E. The 21–22 January 2004 explosive cyclogenesis over the Aegean Sea: Observations and model analysis. *Q. J. R. Meteorol. Soc.* **2007**, *133*, 1519–1531. [CrossRef]
5. Flaounas, E.; Raveh-Rubin, S.; Wernli, H.; Drobinski, P.; Bastin, S. The dynamical structure of intense Mediterranean cyclones. *Clim. Dyn.* **2015**, *44*, 2411–2427. [CrossRef]
6. Kouroutzoglou, J.; Avgoustoglou, E.N.; Flocas, H.A.; Hatzaki, M.; Skrimizeas, P.; Keay, K. Assessment of the role of sea surface fluxes on eastern Mediterranean explosive cyclogenesis with the aid of the limited-area model COSMO.GR. *Atmos. Res.* **2018**, *208*, 132–147. [CrossRef]
7. Fink, A.H.; Pohle, S.; Pinto, J.G.; Knippertz, P. Diagnosing the influence of diabatic processes on the explosive deepening of extratropical cyclones. *Geophys. Res. Lett.* **2012**, *39*, L07803. [CrossRef]
8. Varlas, G.; Anagnostou, M.N.; Spyrou, C.; Papadopoulos, A.; Kalogiros, J.; Mentzafou, A.; Michaelides, S.; Baltas, E.; Karymbalis, E.; Katsafados, P. A multi-platform hydrometeorological analysis of the flash flood event of 15 November 2017 in Attica, Greece. *Remote Sens.* **2018**, *11*, 45. [CrossRef]
9. Spyrou, C.; Varlas, G.; Pappa, A.; Mentzafou, A.; Katsafados, P.; Papadopoulos, A.; Anagnostou, M.; Kalogiros, J. Implementation of a nowcasting hydrometeorological system for studying flash flood events: The Case of Mandra, Greece. *Remote Sens.* **2020**, *12*, 2784. [CrossRef]
10. Hoffmann, L.; Günther, G.; Li, D.; Stein, O.; Wu, X.; Griessbach, S.; Heng, Y.; Konopka, P.; Müller, R.; Vogel, B.; et al. From ERA-Interim to ERA5: The considerable impact of ECMWF's next-generation reanalysis on Lagrangian transport simulations. *Atmos. Chem. Phys.* **2019**, *19*, 3097–3124. [CrossRef]
11. Buzzi, A.; Davolio, S.; Fantini, M. Cyclogenesis in the lee of the Alps: A review of theories. *Bull. Atmos. Sci. Technol.* **2020**, *1*, 433–457. [CrossRef]
12. Kurz, M. *Training Guidelines of the German Meteor. Service*; German Meteorological Service: Offenbach am Main, Germany, 1998.
13. Keyser, D.; Carlson, T.N. Transverse ageostrophic circulations associated with elevated mixed layers. *Mon. Weather Rev.* **1984**, *112*, 2465–2478. [CrossRef]
14. Hoskins, B.; McIntyre, M.; Robertson, A. On the use and significance of isentropic potential vorticity maps. *Q.J.R.* **1985**, *111*, 877–947. [CrossRef]
15. Carlson, T.N. Airflow through midlatitude cyclones and the comma cloud pattern. *Mon. Weather. Rev.* **1980**, *108*, 1498–1509. [CrossRef]
16. Bader, M.J.; Forbes, G.S.; Grant, J.R.; Lilley, R.B.E.; Waters, A. *Images in Weather Forecasting. A Practical Guide for Interpreting Satellite and Radar Imagery*; Cambridge University Press: Cambridge, UK, 1995.
17. Prezerakos, N.; Flocas, H.; Michaelides, S. Absolute vorticity advection and potential vorticity of the free troposphere as synthetic tools for the diagnosis and forecasting of cyclogenesis. *Atmos.-Ocean.* **1997**, *35*, 65–91. [CrossRef]

18. Trigo, I.F.; Davies, T.D.; Bigg, G.R. Objective climatology of cyclones in the Mediterranean region. *J. Clim.* **1999**, *12*, 1685–1696. [CrossRef]
19. Kouroutzoglou, J.; Flocas, H.A.; Keay, K.; Simmonds, I.; Hatzaki, M. Climatological aspects of explosive cyclones in the Mediterranean. *Int. J. Climatol.* **2011**, *31*, 1785–1802. [CrossRef]