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Diagnosis of the atmospheric circulation systems associated with an episode of extensive floods over Greece

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Summary. An attempt is made to study the basic characteristics of the atmospheric circulation which caused the mixed-type (large-scale and convective-scale) elongated heavy rainfalls in the Greek area from 21 to 23 October 1994 leading to extensive floods in Attica, Karditsa-Trikala and Kassos island territories and the loss of eleven human lives. The analysis showed that during this time period a blocking-type anticyclone dominated the mid-tropospheric circulation of central and eastern Europe. Greece was situated at the south flank of the large surface anticyclone which was blocking the north-eastern progression of a synoptic-scale frontal depression coming from western Mediterranean and rejuvenating over Sicily area by dynamical factors. Along with the blocking anticyclone a quasi-stationary surface front crossing the northern coasts of Turkey and through Greek mainland and the eastern coast of the Adriatic Sea reached the Eastern Alps. This synoptic situation was associated with the advection of warm and moist unstable air masses along the height of the whole troposphere towards Greece coming from south over the Mediterranean, whereas in the lower part of the planetary boundary layer cold and moist masses coming from north-east were passing over the Black and the Aegean Seas being warmed from below, interleaving the warm moist air over Greece which resulted in an unstable saturated mixing layer. Strong low tropospheric convergence and positive advection of absolute vorticity at 500 hPa were bringing the saturated mixing layer up to the level of free convection releasing the real latent instability. So in the continuous upslide rain many thunderstorms occurred. Their intensity depends partly on local factors. The combination of the elongated and of large-scale and convective-scale heavy precipitation along with local factors resulted in the extensive floods over Greece. These rainfalls according to other Greek authors who studied their main parameters statistically can be classified in the category of 'natural disasters'.

Analyse der atmosphärischen Zirkulationssysteme, die zu ausgedehnten Überflutungen in Griechenland führten

Zusammenfassung. Es wird versucht, die wesentlichen Muster der atmosphärischen Zirkulation zu untersuchen, die langanhaltende schwere Regenfälle (groß-skalige und konvektive) vom 21. bis 23. Oktober 1994 in Griechenland in Attika, Karditsa-Trikala und auf der Insel Kasos verursachten, und die 11 Menschenleben forderten. Zu diesem Zeitpunkt dominierte ein blockierendes Hoch die Zirkulation über dem mittleren und östlichen Europa. Griechenland befand sich an der Südflanke dieses Hochs, das eine Nordostwärts-Verlagerung einer Tiefdruckstörung aus dem westlichen Mittelmeer verhinderte. Diese Störung verstärkte sich über Sizilien. Es bildete sich eine quasi-stationäre Bodenfront, die sich von der Nordküste der Türkei über Griechenland bis zu den östlichen Alpen erstreckte. Dabei wurde warme und feucht-labil geschichtete Luft von Süden über das Mittelmeer nach Griechenland geführt. Dagegen wurden im unteren Teil der Grenzschicht kalte und feuchte Luftmassen über das Schwarze Meer und die Ägäis herangeführt und von unten erwärmt. Die Überlappung beider Luftmassen über Griechenland führte zu einer instabilen, gesättigten Mischungsschicht. Starke niedertroposphärische Konvergenz und positive Advektion von absoluter Vorticity in 500 hPa hoben diese Luftmasse und lösten Konvektion aus. Daher traten in dem durch Aufgleiten verursachten Regen viele Gewitter auf. Ihre Intensität erklärt sich teilweise durch lokale Faktoren. Die Kombination von Aufgleiten, Konvektion und von lokalen Faktoren führte zu ausgedehnten Überschwemmungen, die auch von anderen Autoren als Naturkatastrophe bezeichnet wurden.

1. Introduction

Heavy elongated rainfalls occurred over the Greek area in the period 21–23 October 1994 that caused floods in Attica, Thessaly and especially in the village of Metamorfosi and the islands of the south-eastern Aegean Sea, especially in Kasos (Fig. 1a). The damages are thoroughly reported in the Greek press of this period, in DALEZIOS et al. (1995), ICONOMOU et al. (1995) and LAGOUVARDOS et al. (1996). Eleven human lives were lost, nine of them in Attica, while the agricultural harvest of a major area of Thessaly was totally destroyed. The area of the extensive damages has been estimated to be 26000 hectares over Thessaly by means of satellite data of METEOSAT (PDUS) and NOAA/AVHRR (DALEZIOS et al. 1995).

The damages were mainly caused by the rainfalls which occurred in the afternoon of 21st until the noon of 22nd October 1994. During this period an atmospheric disturbance which passed over Greece was the trigger effect for the occurrence of intense storms leading to an asymmetrical distribution of the intensity of total amount of rainfall forming the local character of the phenomenon.

The distribution of the rainfall height every 12 h between 1800 UTC/20, 0600 UTC/21, 1800 UTC/21, 0600 UTC/22, 1800 UTC/22 and 0600 UTC/23 October is presented in Fig. 1a, 1b, 1c, 1d and 1e, respectively. The examination of the automatic raingage graphs of the meteorological stations

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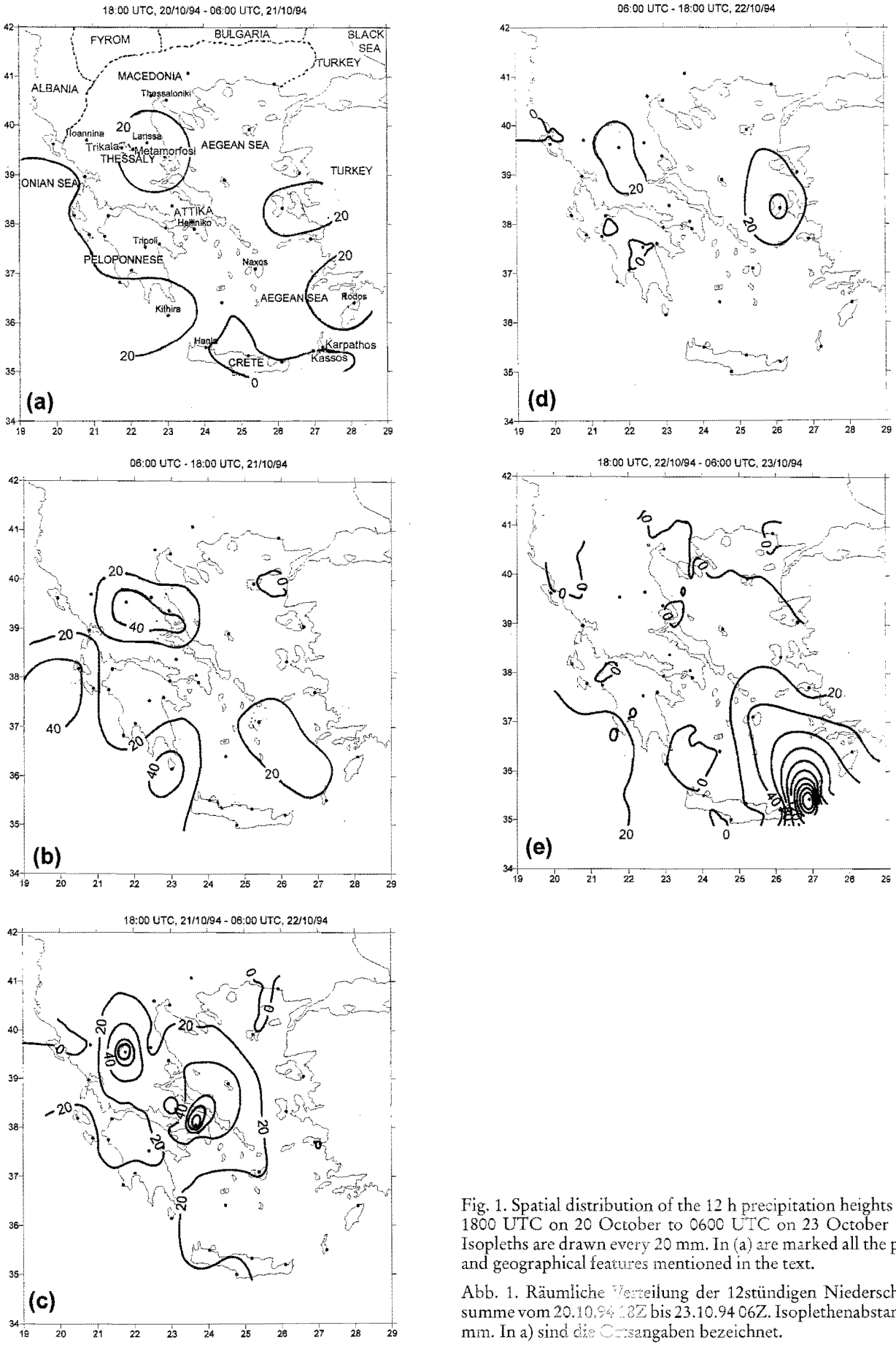

Fig. 1. Spatial distribution of the 12 h precipitation heights from 1800 UTC on 20 October to 0600 UTC on 23 October 1994. Isopleths are drawn every 20 mm. In (a) are marked all the places and geographical features mentioned in the text.

Abb. 1. Räumliche Verteilung der 12stündigen Niederschlagssumme vom 20.10.94 18Z bis 23.10.94 06Z. Isoplethenabstand: 20 mm. In a) sind die Ortsangaben bezeichnet.

of the Hellenic National Meteorological Service revealed that the hourly rainfall heights are more important than the 12 h total heights providing a clearer picture of the stormy and local character of the rainfalls. Utilizing these hourly precipitation heights recorded in some meteorological stations in Attica along with satellite imageries and tephigrams, an attempt will be made later to discuss the severity of the storm and to determine its trajectory through Attica, where Athens belongs to.

As LAGOUVARDOS et al. (1996) have already reported on the simulations of the storm occurred, conducted by two numerical models: the Colorado State University – Regional Atmospheric Modelling System (CSU – RAMS) and the USA National Meteorological Centre ETA (from the Greek letter η which denotes a vertical co-ordinate system generalizing the σ-co-ordinates) model confining their investigation to test the ability of these two models to predict the distribution of the large-scale and convective precipitation in time and space. As many differences appeared between the models results and the observed data available, a need was derived to see what really happened.

Thus the objective of this study is to investigate in a diagnostic manner the dynamical and physical mechanisms that played an important role in the occurrence of this episode, taking into account all the data and information available in the Hellenic National Meteorological Service and the European Centre for Medium Range Forecast (ECMWF). Special emphasis has been given on the quantitative comparison of the various meteorological parameters in order to identify their contribution to the intensity and extension of the rainfalls.

2. Data and methodology

The data used in this study are obtained from the ECMWF archived operational objective analyses with resolution 1.5°: components of the horizontal wind (u, v), temperature, humidity, height of the isobaric surfaces 1000, 850, 700, 500, 300, 250, 200 hPa, the mean sea level pressure analysis, large-scale vertical velocities at 850, 700 and 500 hPa. The fields of convergence-divergence, vorticity, absolute vorticity advection, thermal advection at certain isobaric surfaces and cross sections of potential temperature and potential vorticity (PV) were computed in the ECMWF. The positioning of the fronts was determined with the aid of the isothermal analysis at 850 hPa and the EUMETSAT satellite images. Radiosonde data and EUMETSAT satellite images were also obtained from the Hellenic National Meteorological Service.

3. Analysis of the meteorological data discussion

The large-scale circulation over the Mediterranean and central Europe associated with intense rainfalls over Greece established a few days before. From 14 until 19 October the air mass in the lower troposphere and more precisely in the Mediterranean boundary layer, in the south of Italy and western Greece, became potentially unstable and moist in great depth. The boundary layer over Greece became also potentially unstable mainly due to evaporation of surface waters and moist ground resulting from previous rainfalls. On 18 October a synoptic-scale through at 500 hPa being accompanied by a cold surface front passed over Greece causing significant rainfall. The front was positioned along northern Turkey, central Greece, the northern coast of the Adriatic Sea and remained quasi-stationary. In the free troposphere an omega-type blocking system developed, in a way that the axis of the ridge stretches from the western Scandinavian coast south-eastwards to Egypt on 20 October (Fig. 2a). Also, a low system at 500 hPa appeared in western Europe centered south-west of Ireland (Fig. 2a). In its western flank, the flow is very intense from north-west and strengthens the regional vorticity of a diffluent through over Spain. The synoptic-scale circulation over the western Mediterranean and north-western Africa is cyclonic. Small-scale disturbances are embedded over this flow. Fig. 2b depicts a quasi-stationary front over Greece, the western coast of Adriatic Sea and Northern Italy and a cold front over the eastern Spanish coast that extends to the east becoming occluded over southern France. The wind blows from south directions from the surface up to 500 hPa veering with height. Thus warm advection occurs over the whole Mediterranean, especially in the lower atmospheric layers. So, in the regions of convergence of the lower troposphere, the air masses are lifted up to LCL (Lifting Condensation Level) and the LFC (Level of Free Convection). This occurs along the quasi-stationary front over the Greek area, as shown in the 850 hPa isothermal analysis (Fig. 2b) and the thermal advection analysis (not shown) since the front is positioned where the warm advection from the south approaches the cold advection from the north-east revealing that its part over Turkey is becoming warm while its part over Greece is becoming cold. It should be noted that a mixing of the cold and relatively dry air mass from the north-east (although the Black Sea and the northern Aegean Sea have enriched it with moisture) with the warm and moist air mass from the south occurs in the planetary boundary layer along the quasi-stationary front. This results in the creation of saturated air which can very easily ascend due to the stationary front convergence, the orography or friction (sea-land contrast) and precipitate. The surface chart of the European Bulletin and the surface plotted charts of Hellenic National Meteorological Service (not shown) report intense persistent rainfall in north-western Greece, past rainfall in Crete and thunderstorms in the region of Sicily. This is consistent with the EUMETSAT image at 0030 UTC on 20 October (not shown). Furthermore, according to the EUMETSAT image the clouds form zones directed along the winds: the lower clouds with south and south-east direction while the higher clouds with south-west or west direction. The Cb clouds are clearly evident as white bright circle dots with various sizes within intense white regions giving to the precipitation the character of mixed type (JANSA 1992).

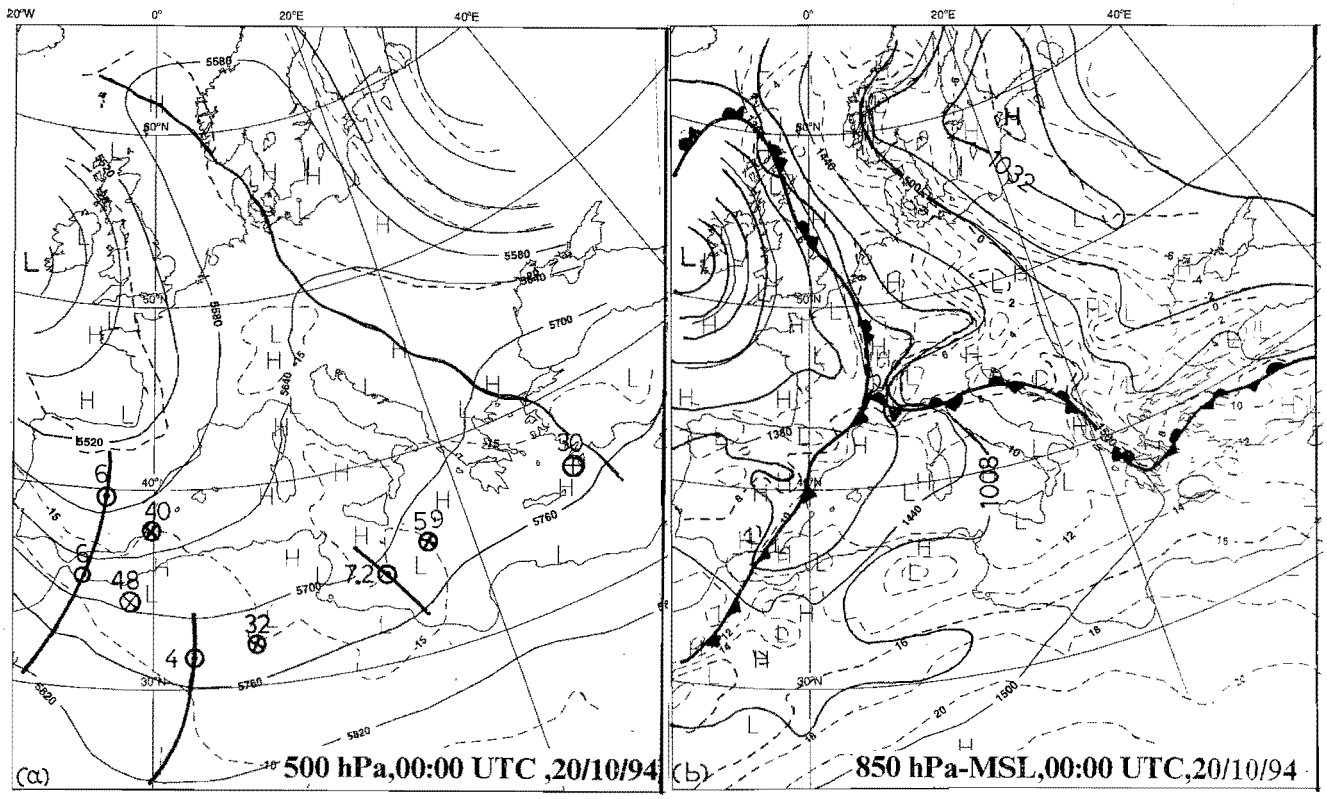

Fig. 2. a) 500 hPa objective analysis for 0000 UTC on 20 October 1994; continuous lines are contours drawn every 60 gpm and dashed lines are isotherms drawn every 5 °C. The thick continuous line segments are the trough axes. Circled dots are the positions of relative vorticity maxima while circled crosses are the positions of absolute vorticity advection maxima with their values nearby ($\times 10^{-5}s^{-2}$ for the relative vorticity and $\times 10^{-10}s^{-2}$ for the absolute vorticity advection). b) 850 hPa and surface analyses; thin continuous lines are contours drawn every 60 gpm, dashed lines are isotherms drawn every 2 °C and thick continuous lines are isobars drawn every 4 hPa when they are less or equal to 1008 hPa and greater or equal to 1024 hPa. The surface fronts are denoted by the conventional international symbols.

Abb. 2. a) Objektive Analyse der 500 hPa-Fläche für den 20.10.94 00Z. Dicke ausgezogene Linien sind Trogachsen. Kreise mit Punkten zeigen die Positionen von Maxima der relativen vorticity, während Kreise mit Kreuzen Maxima der Advektion von absoluter vorticity mit den zugehörigen Werten daneben kennzeichnen. b) Analyse der 850 hPa-Fläche der Bodendruckverteilung und der Bodenfronten. Bodenisobaren (alle 4 hPa) sind nur für weniger als 1008 hPa oder für mehr als 1024 hPa gezeichnet.

In the next 24 h the warm advection, the mixing of different air masses and the convergence in the boundary layer over Greece became stronger. The diffluent trough continued intensifying in the western Mediterranean while, at the same time, vorticity maxima at 500 hPa were moving towards Greece. At 1200 UTC, 20 October a combination of warm advection in the lower troposphere (at 850 hPa the maximum value is 9.2 °C/12 h positioned south-west of Peloponnese) with positive advection of absolute vorticity (at 500 hPa the maximum value is 52×10^{-10} s^{-2} positioned over Peloponnese) results in strong vertical velocities over the Ionian Sea and south-western Greece valued -20.9×10^{-1} $Pa \cdot s^{-1}$ (Fig. 3) corresponding to extensive cloudiness situated between Sicily and Greece. This disturbance as passed over Greece produced significant amounts of rainfall as shown in Fig. 1a. Due to the same physical mechanism (Fig. 3) the amount of rain in Rhodes Island region was produced, where vertical velocity value exceeds 18×10^{-1} $Pa \cdot s^{-1}$ absolutely. The intensification of the diffluent trough con-

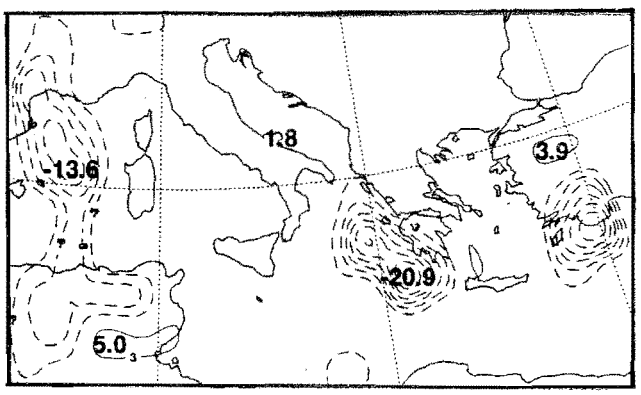

Fig. 3. 500 hPa vertical velocities at 1200 UTC on 20 October 1994; Isopleths drawn every 3×10^{-1} $Pa \cdot s^{-1}$. Dashed lines: negative (upward), continuous lines: positive (downward).

Abb. 3. Vertikalgeschwindigkeit in 500 hPa am 20.10.94 12Z. Gestrichelt: negative (aufwärts) Geschwindigkeit, Isolinienabstand: 3×10^{-1} $Pa \cdot s^{-1}$.

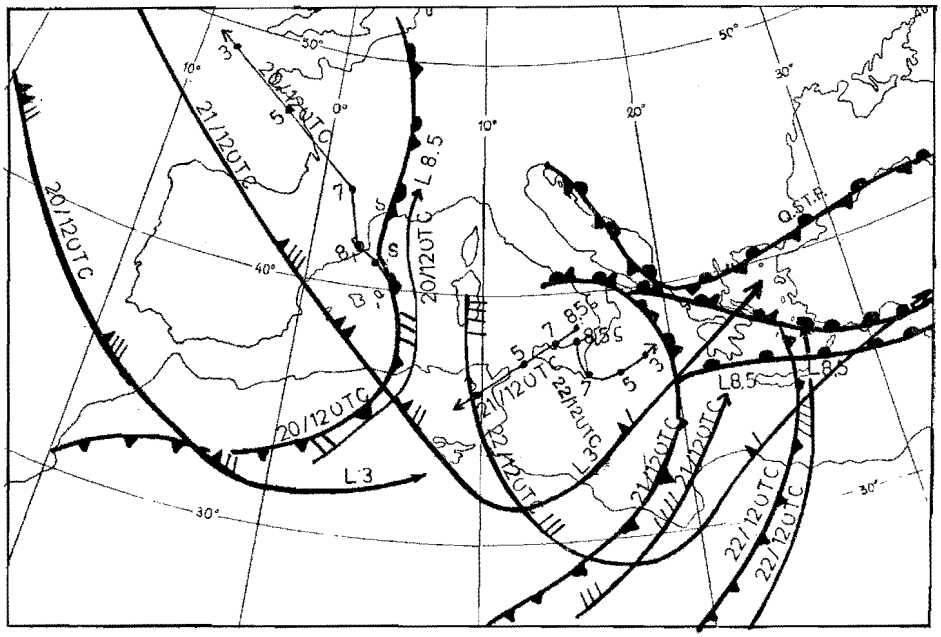

Fig. 5. 24 h continuity chart for the positions of the fronts, polar front jet stream axes and the centres of the atmospheric circulation system at the mandatory levels from 1200 UTC on 20 October 1994 to 1200 UTC on 22 October 1994. Thick arrows: 300 hPa jet stream axes. Thin arrows: 850 hPa jet stream axes. The dots denoted s (surface), 8.5 (850 hPa), 7 (700 hPa), 5 (500 hPa) and 3 (300 hPa) being on thin arrows represent the centres of the atmospheric circulation system at these isobaric surfaces. The fronts and the wind are denoted with the conventional international symbols and Q.ST.F. means quasi-stationary front.

Abb. 5. Lage der Fronten, der Polarfront-Jetachse und der Tiefdruckzentren auf den Hauptdruckflächen vom 20.10.94 12Z bis zum 22.10.94 12Z. Dicke Pfeile: Jetachse in 300 hPa, dünne Pfeile: Jetachse in 850 hPa. Die Punkte sind mit s (Boden), 8.5 (850 hPa), 7 (700 hPa), 5 (500 hPa) und 3 (300 hPa) bezeichnet. Q.S.T.F. markiert die quasi-stationäre Front.

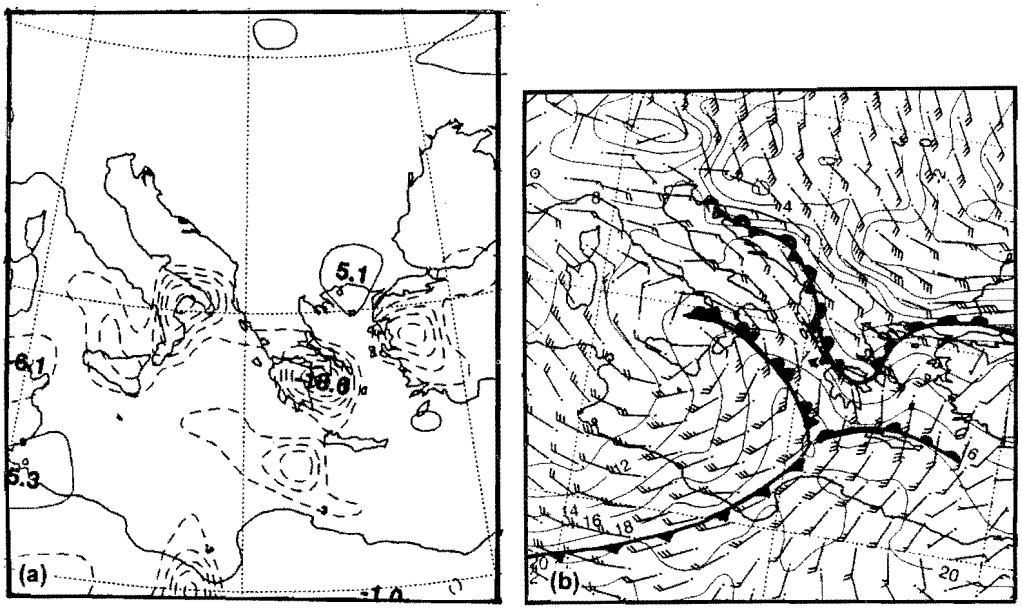

Fig. 6. a) As Fig. 3, but for 21 October. b) 850 hPa objective analysis for 1200 UTC on 21 October 1994, isotherms every 2 °C and wind, 1 barb = 5 m·s^{-1}. The front is the surface one of the same time.

Abb. 6. a) Wie Abb. 3, aber für den 21.10.94. b) Objektive Analyse der 850 hPa-Fläche Isothermen im Abstand von 2 °C. Ein ganzer Strich an den Windfähnchen bezeichnet 5 m·s^{-1}. Zusätzlich sind die Bodenfronten eingezeichnet.

ing area. The centre of the surface cyclone is positioned where the 1000–500 hPa thickness is minimal. This process involves a lowering of the centre of gravity of the system and a decrease in its potential energy being converted to kinetic energy. When the surface cyclone is at the stage of the cessation of the advection of vorticity and temperature and at the same time an interleaving of moist and dry air streams occurs, the occlusion process has been completed. In the case under consideration during the period 0000–1200 UTC, 21 October the cyclogenesis in the area just north of Sicily is very rapid as the synoptic wave in the free troposphere disrupts and a closed low forms at all the isobaric surfaces. The position of the low pressure centres at the surface (s), 850 (8.5), 700 (7), 500 (5) and 300 (3) hPa are shown in Fig. 5. At 1200 UTC, 21 October the centres are aligned with an orientation from north-east to south-west and from the surface to 300 hPa. Over Sicily, south-eastern mainland of Italy and the sea between them there is ascending motion of warm air (12–14 °C) as shown in Fig. 6a and 6b. This ascending motion over southern Italian

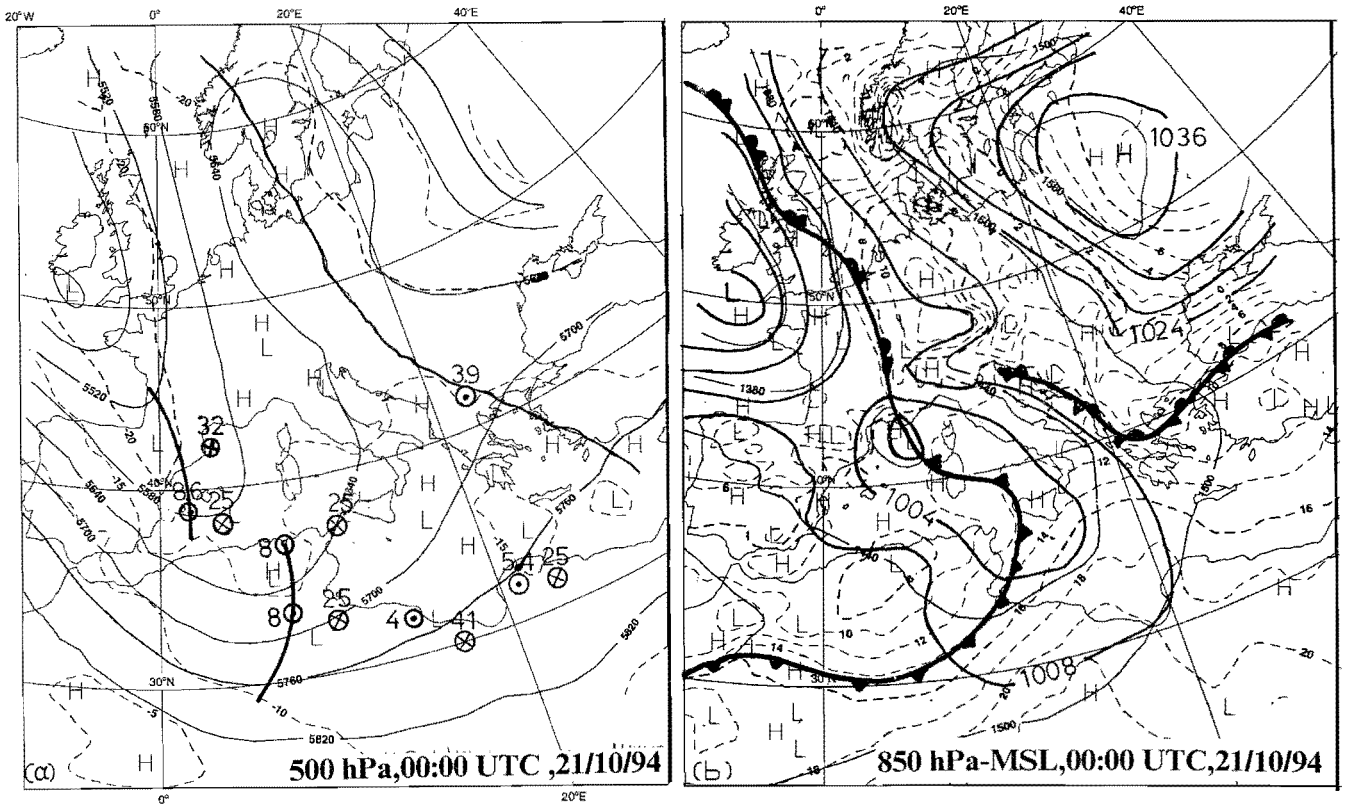

Fig. 4. As Fig. 2, but for 21 October 1994.

Abb. 4. Wie Abb. 2., aber für den 21.10.94.

tinued until 0000 UTC, 21 October favouring rapid and substantial development. Indeed, a vorticity maximum produced strong positive advection of absolute vorticity (25×10^{-10} s^{-2}) in the area of Sicily (Fig. 4a) where a warm air mass (13 °C) (Fig. 4b) at 850 hPa is shown. In addition, the temperature gradient is directed across the latitude circles increasing the eddy available potential energy. The warm advection at 850 hPa extends over almost all Greece. Strong gradient of warm advection is observed over Peloponnese. These are advocated by the EUMETSAT satellite image at 0000 UTC, 21 October. In this image, the warm conveyor belt as described by BROWNING (1990) is not evident, rather than well-formed cloud zones still existing due to the southerly winds that prevail over the Mediterranean. These zones are similar to those of the warm sector ones described by HOUSE et al. (1976) although their scale is larger. To the significant rainfall amounts (more than 30 mm) that have fallen over Greece (see Fig. 1) in the 12 h period between 1800 UTC, 20 October and 0600 UTC, 21 October apart from other reasons mentioned above the potential instability of the air mass especially over the Ionian and the Aegean Seas contributed greatly. The 0000 UTC tephigram of the upper-air station of Hellinikon on 21 October shows that the lower part of the boundary layer and the layer 830–700 hPa are potentially unstable. The winds are north-easterlies up to 950 hPa while they are veering with height upwards from this level confirming the advection of warm and potentially unstable air from the south over a relatively colder mass from the north-east that has warmed and moistened from below as crossing the Black Sea and the Aegean Sea.

The atmospheric pressure decreased by 6 hPa over the area of Sicily during the period 1200 UTC, 20 October and 0000 UTC, 21 October implying that the cyclogenetic process has initiated over this area. In the following 12 h, a further pressure fall of another 8 hPa is observed and therefore a deep depression with a warm occlusion has formed over the region of Sicily at 1200 UTC on 21 October (Fig. 5, 6). The 12 h period is considered rather short for the formation of such an occlusion. Nevertheless, according to CARLSON (1991) occlusion is not so much an overrunning of retreating cold air by advancing cold air but the result of an evolution which forces the occluding cyclone to move into the cold air to the west of the polar front jet stream, which gives the impression of a roll-up of the warm front. This movement is a result of increasing ascent north and west of the cyclone responding to increased vorticity and temperature advection in that region. This increasing ascending motion in the north (and north-east) of the depression is due to the strong warm air advection, while that in the west is due to the strong positive advection of absolute vorticity occurring mainly in the cold air. Where cold air advection is combined with ascending motion (adiabatic cooling), thickness decreases as compared to the neighbour-

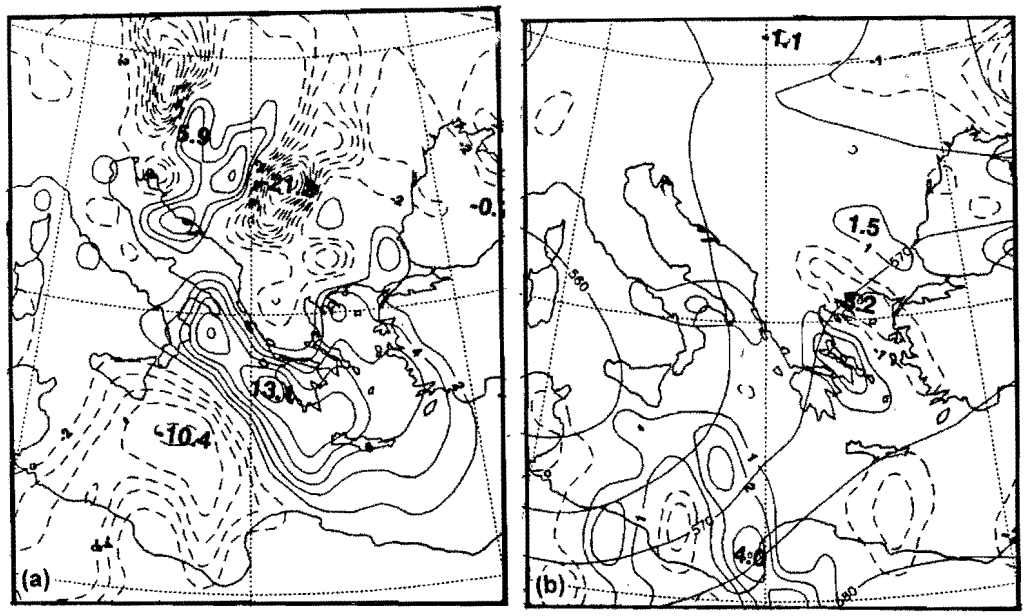

Fig. 7. a) 850 hPa thermal advection at 1200 UTC, 21 October 1994; isopleths drawn every 2 °C (12 h)$^{-1}$, continuous: positive (warm), dashed: negative (cold). b) 500 hPa absolute vorticity advection; isopleth drawn every 1×10^{-9} s^{-2}, continuous: positive, dashed: negative. 500 hPa geopotential heights; contours are drawn every 50 gpm.

Abb. 7. a) Temperaturadvektion in 850 hPa am 21.10.94 12Z. Isoplethen im Abstand 2 °C (12 h)$^{-1}$. Ausgezogen: Warmluftadvektion. b) Advektion von absoluter Vorticity in 500 hPa, Isoplethen im Abstand $1\cdot10^{-9}$ s^{-2}, ausgezogen: positiv. Zusätzlich ist das Geopotential in 500 hPa eingezeichnet, Abstand 50 gpm.

mainland is due mainly to the lower tropospheric warm advection (Fig. 7a) in association with positive advection of absolute vorticity exceeding 20×10^{-10} s^{-2} as Fig. 7b shows. Over Sicily, where cold advection occurs (Fig. 7a) and just north of it where there is no thermal advection at all the depicting ascending motion (Fig. 6a) and the pressure falling mentioned above must exclusively be due to the positioning of the free troposphere developing low over this region and the release of static instability since absolute vorticity advection is completely absent (Fig. 7b). This is where the vertical cross section along 37° N crosses the front at 1200 UTC, 21 October (approximately 20° E), the isotherms of potential temperature form a trough supporting the idea of occlusion (Fig. 8a). The PV cross section along the same latitude presents a tendency for downward extension of the PV anomaly and cutting-off above 15° N where the region of the surface pressure falling is (Fig. 8b). Another maximum of positive absolute vorticity advection at 500 hPa is located just south-west of the point where the polar front axis crosses the surface front (Fig. 5 and 7b) tending to superimpose the 850 hPa area of strong warm advection (Fig. 7a) where a surface secondary low develops coinciding with the triple point of connection of the occluded, warm and cold front. However what usually occurs in the central Mediterranean cyclogenesis (KAREIN 1979, GEORGIEV 1992, PREZERAKOS and FLOCAS 1996) is firstly the formation of this surface low, which in this case is called secondary low. The appearance of the surface low beneath the midtropospheric cold pool follows, just west of the advancing surface low. The combination of the cloud systems of these two surface lows provides a picture similar to that of a mature occluded depression. The METEOSAT imagery

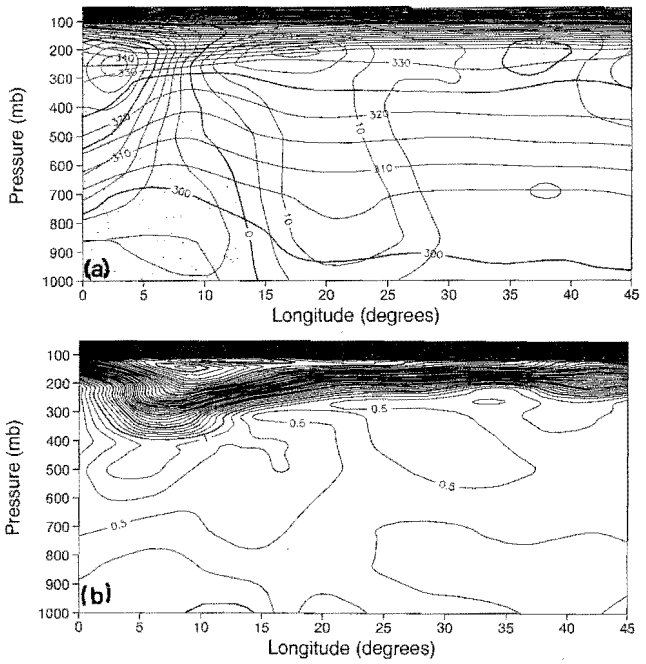

Fig. 8. Cross sections along parallel 37 °N at 1200 UTC, 21 October 1994. a) Potential temperature and wind perpendicular to the cross-section. Isopleths are drawn every 5 K for potential temperature and 5 m/s for the wind. The stippled area denotes northerlies. b) Potential vorticity, isopleths are drawn every 0.25 PVU.

Abb. 8. Breitenkreis-Höhen-Schnitte entlang 37 °N für den 21.10.94 12Z. a) Potentielle Temperatur und Wind senkrecht zur Schnittebene. Isolinienabstand 5 K und 5 m·s^{-1}. Gepunktete Fläche: Nördliche Winde. b) Potentielle vorticity, Isolinienabstand: 0,25 PVU.

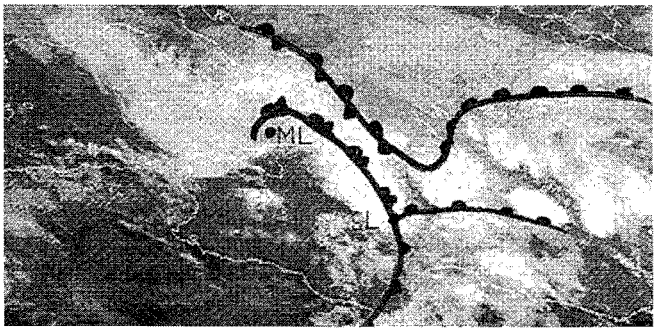

Fig. 9. Infra-red imagery from EUMETSAT received at 1200 UTC on 21 October 1994. The front is the same one as in Fig. 6b and is denoted with the conventional international symbols. ML: Main Low, SL: Secondary Low.

Abb. 9. EUMETSAT-Bild im Infraroten, aufgenommen am 21.10.94 12Z. Die Frontlage ist aus Abb. 6b übernommen. ML: Haupttief, SL: Randtief.

taken at 1200 UTC on 21 October 1994 (Fig. 9) verifies this argument showing clearly the position of the main low centered just north of Sicily and the secondary low centered west of Crete.

The distribution of the low pressure centres at the various isobaric levels (Fig. 5) results in a statically unstable atmospheric environment contributing to the development of stormy clouds over the whole region. The jet at 850 hPa is almost parallel with the polar front jet at 300 hPa (Fig. 5) implying that there is no intensification of the frontal surface. However, the system as moving eastwards being blocked merely by the anticyclone positioned north of Greece, approaches the quasi-stationary front. This synoptic stuation is accompanied by strong ascending motions at all levels up to 500 hPa over south and central Greek mainland (Fig. 6a) being due mainly to the strong warm advection (Fig. 7a) and secondarily to the positive vorticity advection at 500 hPa plus orography. Yet, the 1200 UTC, 21 October skew-T log p diagram at Helliniko (WMO 16716) (Fig. 10) provides that the air mass over Greece, apart from a near-saturated state, presents significant conditional instability (latent instability) with a LCL at 960 hPa (approximately 400 m) and a LFC at 920 hPa (approximately 720 m). Since the synoptic-scale ascending motion is $-1\ Pa \cdot s^{-1}$ (at 850 hPa and the mean convergence within 1000–850 hPa layer is $-((5+4)/2) \times 10^{-5} = -4.5 \times 10^{-5} s^{-1}$ (Fig. 11) the vertical motion in the lower boundary layer is upward, weaker than $-1\ Pa \cdot s^{-1}$). So, in the lower troposphere, the surface air mass requires few hours to reach the LFC. This time period reduces significantly because the whole mixing layer ascends with increasing speed whose scale is less than the synoptic one. Therefore, the storms initiated at Helliniko 8 h after 1200 UTC, 21 October with the maximum of their activity at 0000 UTC, 22 October.

At 0000 UTC, 22 October the triple point, the accompanying 500 hPa vorticity maximum with its corresponding advection maximum and the occluded front (Fig. 12a and 13) moved north-eastwards in a rather slow speed obstacled

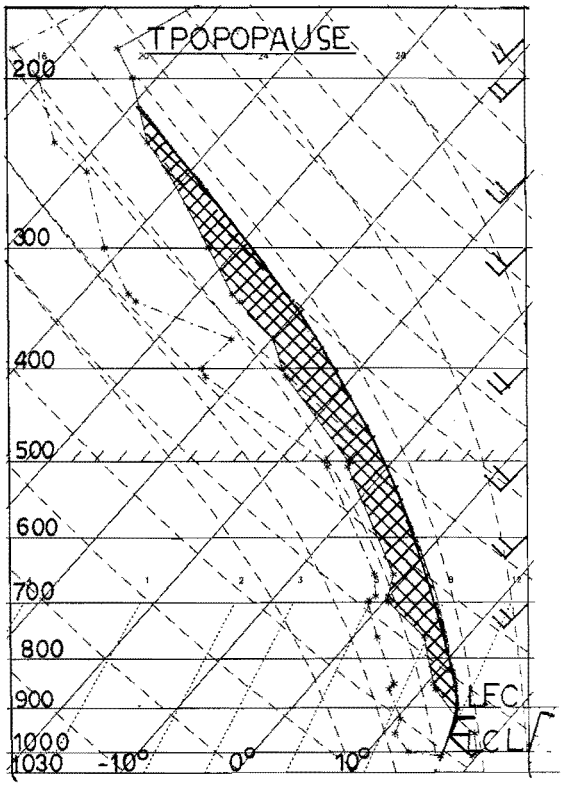

Fig. 10. Skew-T Log p diagram for Helliniko upper air station at 1200 UTC on 21 October 1994. Dashed line with asterisks: dew point ascent, solid line with asterisks: temperature ascent, LCL: Lifting Condensation Level, LFC: Level of Free Convection. Isobaric surface wind in degrees/kn (1 kn ≈ 0.5 $m \cdot s^{-1}$) one barb is equal to 5 $m \cdot s^{-1}$. The stippled area shows the energy of the real conditional instability.

Abb. 10. Skew T-log p-Diagramm mit den Daten der Radiosonde von Helliniko am 21.10.94 12Z (Temperatur, Taupunkt und Winde). Die markierte Fläche ist proportional zur Energie der bedingten Instabilität.

by the quasi-stationary front and the high pressures extended over Greece. The depression, however, remains stationary in the area of Sicily, implying the disruption of the occluded front at a later stage. The main core of the occluded front approaches slowly the quasi-stationary front that moves northwards becoming a warm front. The advection of the cold and moist air in the lower half of the planetary boundary layer of northern and central Greece and the advection of warm, unstable moist air in the rest of the troposphere all over Greece (Fig. 12b) in association with the convergence in the lower troposphere by (a) dynamical factors (positive absolute vorticity advection) (b) friction (land sea contrast) (c) complex terrain (convergence and upslide $\vec{V} \cdot Vz$, where z is the mountain height), cause ascent of the mixing layer over Greece to the free convection level. This procedure continues for hours causing persistent rainfalls. The rainfall was very heavy in Attica, Thessaly and eastern Aegean Sea because the intensity of the thunderstorms depends mainly on smaller-scale local factors.

Trying to investigate the rainstorm with only the synop-

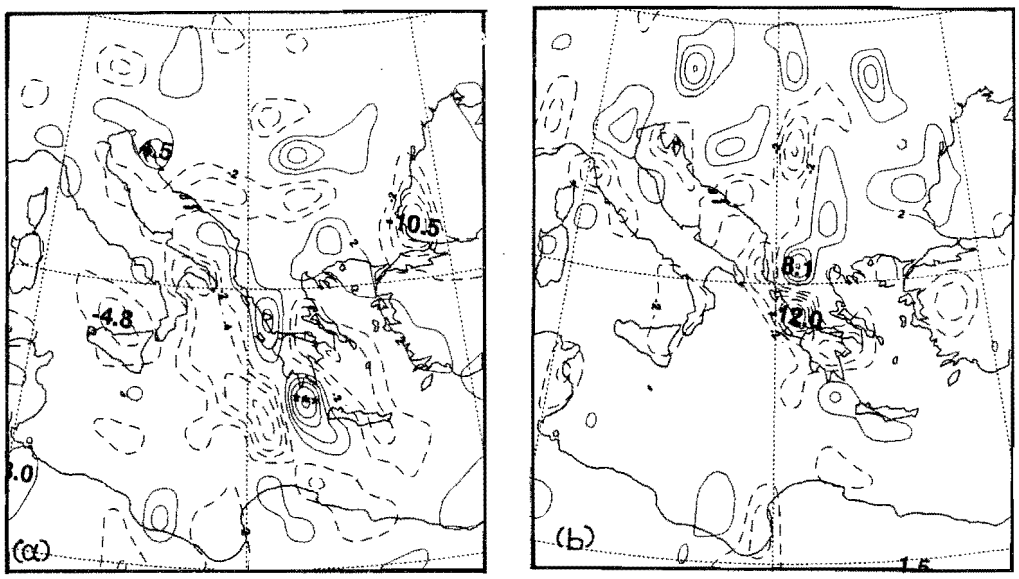

Fig. 11. Divergence field analyses at a) 1000 hPa and b) 850 hPa at 1200 UTC on 21 October 1994. Isopleths drawn every 2×10^{-5} s^{-1}. Continuous lines positive (divergence), dashed lines negative (convergence). The area with asterisks in a) is below the earth surface.

Abb. 11. Divergenz des Windfeldes in a) 1000 hPa und in b) 850 hPa am 21.10.94 12Z. Isolinienabstand: $2\cdot10^{-5}$ s^{-1}. Ausgezogen: Divergenz, gestrichelt: Konvergenz.

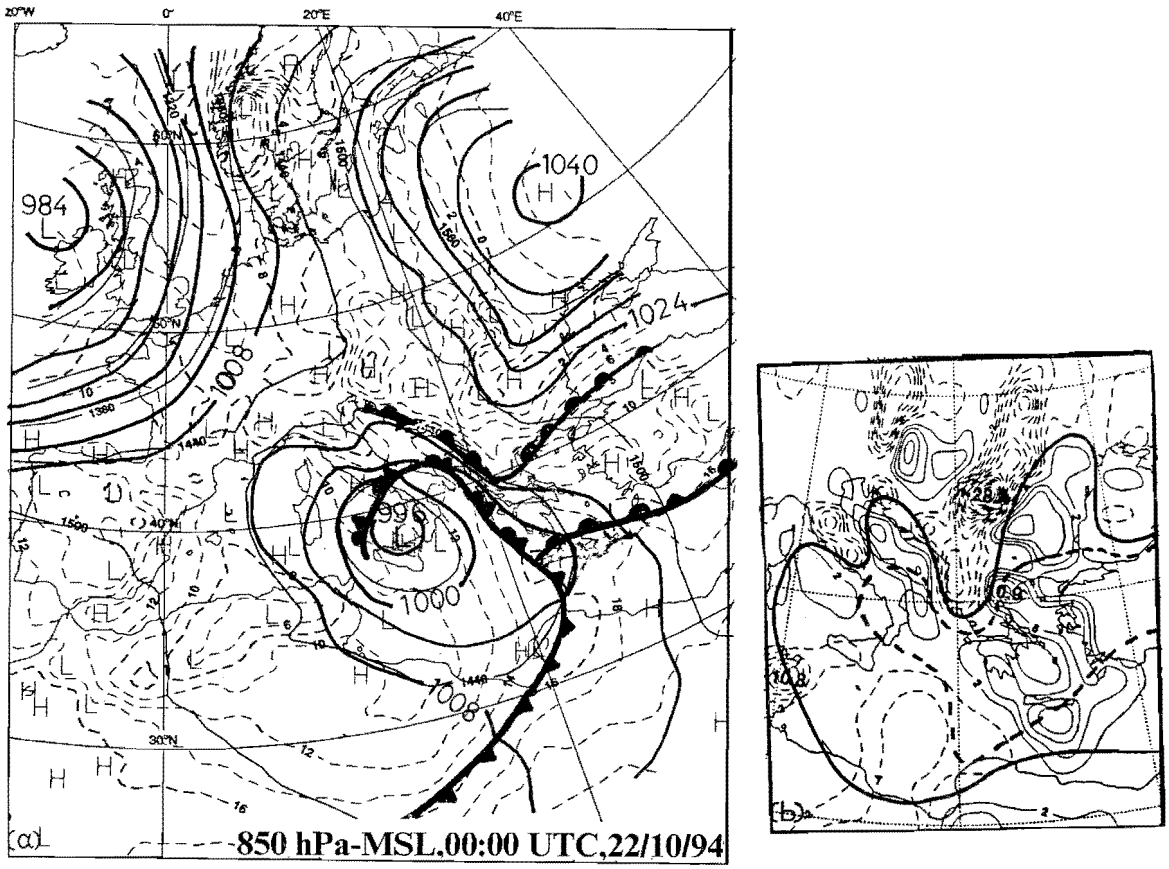

Fig. 12. a) As Fig. 2b, but for 0000 UTC on 22 October 1994. b) As Fig. 7a, but for 0000 UTC on 22 October 1994. The continuous thick line is the boundary of the region with relative humidity greater than 70 % at 700 hPa (dew-point depression less than 5 K) and dashed thick line the boundary of the region with relative humidity greater than 90 % (dew-point depression less than 2 K).

Abb. 12. a) Wie Abb. 2b, aber für den 22.10.94 00Z. b) Wie Abb. 7a, aber für den 22.10.94 00Z. Innerhalb der dick gestrichelten Linie ist die relative Feuchte in 700 hPa über 90 % (Taupunktsdifferenz kleiner als 2 K), innerhalb der dicken Linie ist die relative Feuchte in 700 hPa über 70 % (Taupunktsdifferenz kleiner als 5 K).

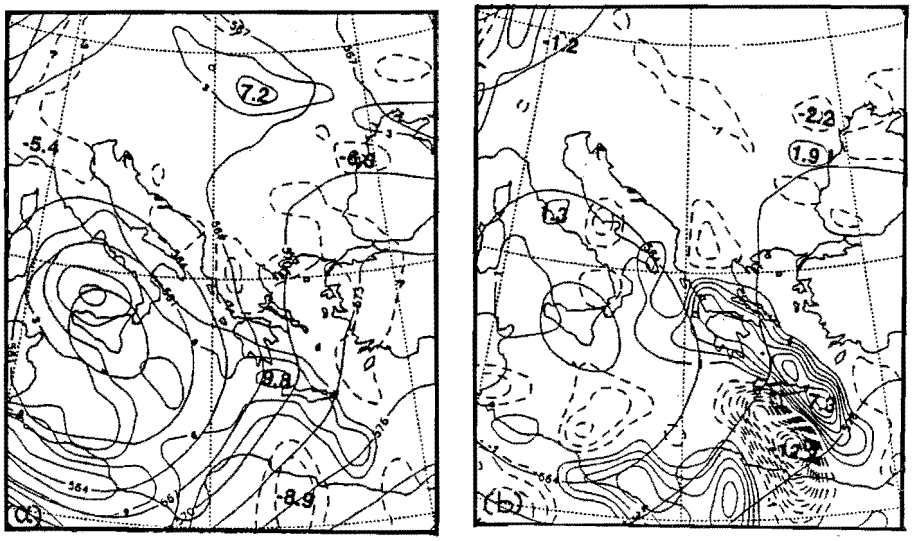

Fig. 13. a) 500 hPa heights and relative vorticity at 0000 UTC, 22 October 1994. Height contours drawn every 30 gpm; vorticity isopleth are drawn every 3×10^{-5} s^{-1}, continuous: positive, dashed: negative. b) As Fig. 7b, but for 0000 UTC on 22 October. Height contours are drawn every 60 gpm.

Abb. 13. a) Geopotentiale und relative vorticity in 500 hPa am 12.10.94 00Z. Isolinienabstand: 30 gpm und $3 \cdot 10^{-5}$ s^{-1}. Ausgezogen: positive relative vorticity. b) Wie Abb. 7b, aber für den 22.10.94 00Z und Höhenlinienabstand 60 gpm.

tic observations indicates that these observations are unsatisfactory for the study of the meso-scale character of the storm. Thus it is necessary to have available precise observations on a smaller space-scale and time scale than the usual synoptic observations. Such observations, however, are still lacking in Greece, in an routine operational base.

In order to overcome this obstacle, in a somewhat manner, records from autographic raingages, satellite imageries and radiosonde ascents can be considered, in a broad sense, as belonging to a smaller scale than the synoptic one capable to track the storm through the major region of Attica, where Athens belongs to and the damages were pronounced. Thus Fig. 14 shows that the synoptic disturbance provoked rain in Attica as three meteorological stations evenly distributed indicate (Fig. 15) in the time period between 0900 LTC (0700 UTC) on 21 to 1400 LTC (1200 UTC) on 22 October 1994, while the storm (built up cumulonimbus) with thunders and showers occurred in the time interval 1800 LTC on 21 to 0500 LTC on 22 October 1994 ahead of the approaching occluded front as schematically illustrated in Fig. 17. The approaching occluded front was one of the factors mentioned just above, which caused ascent of near-saturated mixing layer (Fig. 16) up to LFC being low at about 900 hPa level. As the wind direction in the boundary layer is SE about 10 ms^{-1} feeding Attica with the warm and moist air of the Aegean Sea and at 750 hPa SSW with the same force the sequence of the times of the maxima of hourly precipitation occurring at these three stations coinciding with the time of the mature stages of the cumulonimbus being over indicating a trajectory of this cumulonimbus cells to be contrary with the low tropospheric flow. This means that most of the cumulonimbus cells developed locally triggered additionally by local factors. E.g. Spata (WMO No. 16741) is at the windward side of the mount Hymettus and New Philadelphia (WMO No. 16701) has an elevation about 138 m, whereas Hellinikon (WMO No. 16716) and Spata have 15 m and 67 m respectively. Thus at the station of New Philadelphia the maximum hourly rainfall amounts equal to 42.7 mm reported at around 1700 UTC/21 October while at the station of Hellinikon the respective maximum height was 20.0 mm on 0000 UTC/22 October and in Spata, where the new Athens airport is being constructed, was 48.9 mm on about 0100 UTC/22 October. It should be noted that it was the second

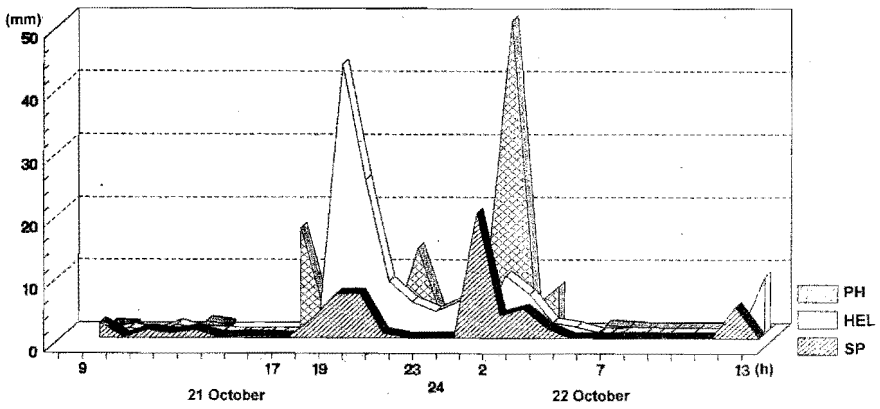

Fig. 14. Temporal variation of hourly precipitation heights in three meteorological stations in Attica, Spata (SP), New Philadelphia (PH) and Hellinikon (HEL) during the storm event on 21–22 October 1994. Time is the local one.

Abb. 14. Zeitlicher Verlauf der stündlichen Niederschlagsmengen an den drei Stationen Attika, Spata (SP), Neu-Philadelphia (PH) und Hellinikon (HEL) am 21. und 22.10.94 (lokale Zeit).

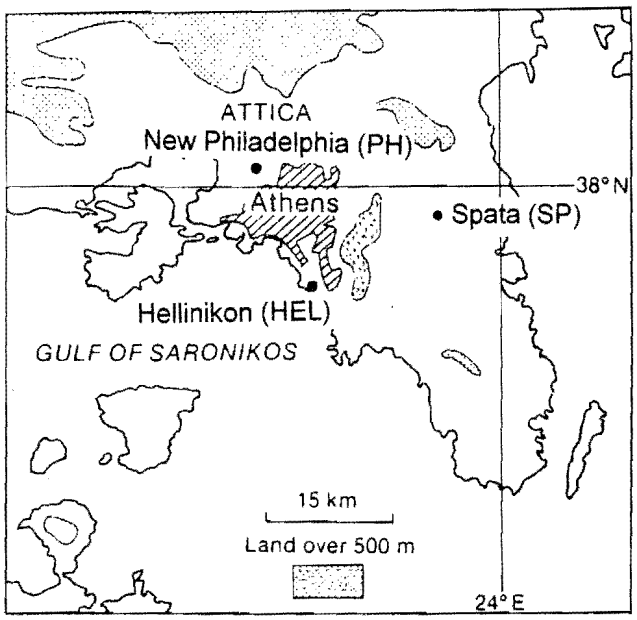

Fig. 15. Map of Attica showing the sites of three meteorological stations mentioned in the text. The elevated ground between Athens and Spata is mount Hymettus with a maximum height of 1026 m.

Abb. 15. Lage der drei im Text erwähnten meteorologischen Stationen in Attika. Die angedeutete Erhebung ist der zwischen Athen und Spata gelegene Berg Hymettus mit einer Gipfelhöhe von 1026 m.

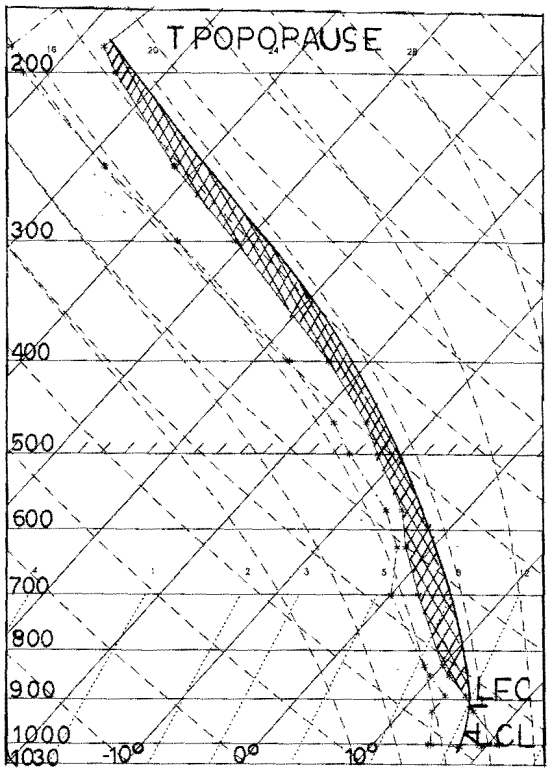

Fig. 16. As Fig. 10, but for 0000 UTC, 22 October 1994.

Abb. 16. Wie Abb. 10, aber für den 22.10.94 00Z.

time after 1955 that such a maximum value was reported in New Philadelphia. In Thessaly a similar intense and extensive rainfall also occurred within the period 14–15 September 1978 when the total rainfall amount was 201.4 mm in less than 24 h in Larissa (WMO No. 16648) and the maximum hourly height equal to 33.4 mm (KARACOSTAS and FLOCAS 1983).

The total precipitation occurred in the time period between 1600 UTC on 21 October and 0400 UTC 22 October 1994 was 108.6 mm for New Philadelphia, 45.8 mm for Hellinikon and 114.4 mm for Spata. The hourly maximum height of precipitation in New Philadelphia is more than twice of that in Hellinikon but less than the respective one in Spata. However, the damages caused by the large run-off were more significant in New Philadelphia, where the 10 minute maximum height was 26.0 mm, much higher than that of Spata which was 19.6 mm. The fact that New Philadelphia is an urban area, while Spata is a rather rural one contributed crucially to the space distribution of the floods and damages, the maximum of which appeared in New Philadelphia. A forecaster associates the occurrence of thunderstorms in a region with (a) the degree of instability, (b) the amount of moisture available, and (c) the presence of a trigger to release the instability. Considering the data available we can see that the storm of 21–22 October 1994 in Attica includes all the above meteorological parameters but the pronounced ones are the moisture available which extends through the whole troposphere and the real conditional instability of the warm air masses coming from the sea which forces cummulonimbus to break tropopause and enter stratosphere as Fig. 16 shows. The sequence of the plotted surface charts issued in the Greek National Meteorological Centre every three hours with atmospheric pressure analysed every 2 hPa show the exact positions of the thunderstorms in the time interval between 1500 UTC on 21 October to 0600 UTC on 22 October 1994 verifying Fig. 17 showing the thick cloud system over the Greek mainland. The form of the cloud system associated with the

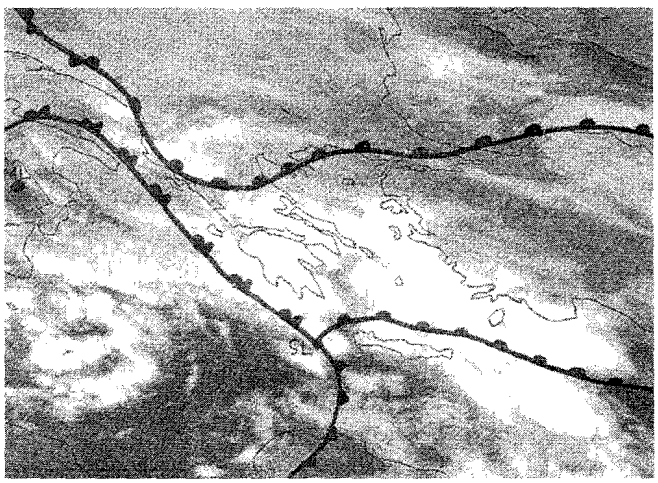

Fig. 17. As Fig. 9, but for 0000 UTC, 22 October 1994.

Abb. 17. Wie Abb. 9, aber für den 22.10.94 00Z.

fronts does not resemble that described by BROWING and ROBERTS (1994), since the cold advection at the cold front region was weakened significantly with the subsequent weakening of the front. Instead of the presence of the warm conveyor zone ahead of the cold front only a region with scattered convective clouds appears and a cloud zone along the warm front and the occluded one east resembling rather to the well-known classical picture of the cloud distribution of the warm front with many thunderstorms embedded. The satellite imagery is consistent with the pronounced advection of the warm and very moist unstable air masses dominating the atmospheric circulation in the Greek region and especially the southern one (Fig. 17). Another Greek territory hit by the rainstorm was, as mentioned above, Thessaly and especially the Metamorfosi village located between Larissa and Trikalla (Fig. 1a). Unfortunately there is no meteorological station at Metamorfosi and so Trikala (WMO No. 16645) and Larissa (WMO No. 16648) are used. The temporal distribution of the hourly precipitation heights at these two stations shows that the rainstorm passed through Larissa in the time interval between 1900 UTC on 21 October to 0100 UTC 22 October with a maximum hourly height of precipitation of 3.7 mm occurred at 2200 UTC on 21 October. The maximum height of precipitation at Trikala was 12.2 mm occurred at 0200 UTC on 22 October. Of course, the rate of precipitation at Metamorfosi, where the core of the thunderstorms occured and the agricultural harvest was completely destroyed, must be much greater. Further the stormy character of the episode, the total amounts of precipitation accumulated in Thessaly were due to the quasi-stationary front which crosses the territory from 19 to 22 October 1994 causing frontal continuous rain (Fig. 2, 4, 5, 12).

The occlusion is positioned over central Greece very close to quasi-stationary front (see Fig. 5) at 1200 UTC, 22 October and the secondary low pressure centre over Aegean Sea at the point 37.0° N, 25.5° E. The polar front jet has weakened and remains parallel to the jet stream at 850 hPa. The comparison of the maximum wind of the two jets suggests that the system is no longer baroclinic and weakens. Nevertheless, the thunderstorms persist for a long time because of the unstable atmospheric environment, especially over the Aegean Sea and west and south-west of Crete, where the area with the convective cloud in the rear of the weakening cold front shows a tendency to approach Crete. An indication that the cold front has already weakened significantly is the entire absence of cold advection over the eastern Mediterranean and only strong warm advection dominates from Libya to Bulgaria showing furthermore the modification of the frontal system to a warm front (Fig. 18a). Although the centre of the main surface low remains almost stationary at the northern coast of Sicily, another surface low appears to develop exactly below the centre of the 600 hPa low where the maximum of the static instability exists.

In the following 24 hours, on 23 October, the main system has moved to Turkey and affected the eastern Aegean Sea (especially the island of Kassos) before noon. The EUMETSAT image at 0000 UTC, 23 October (Fig. 19) presents a cloud system over the area of Eastern Aegean Sea extending to Turkey. A convective activity appears at the region between Rhodos and Crete, where the islands of Karpathos and Kassos are. This activity is due to the convective clouds appeared in the rear of the weakening cold front mentioned above. This convective activity depicted clearly in Fig. 19 provoked significant amounts of rain in the islands of Crete (eastern part), Karpathos (89.0 mm) and Kassos (more than 160.0 mm) during the 5 h interval spanned from 0000 UTC to 0500 UTC on 23 October 1994 as shown in Fig. 1e. Also the distribution of the warm advection depicted in Fig. 18 is consistent with the frontal analysis in Fig. 19 showing a warm occlusion over the eastern coasts of the Aegean Sea and a warm front south of the warm advection maximum shown in Fig. 18b. It should be noted that at 0000 UTC, 23 October a meso-scale shallow surface low appeared at Crete. This low having a diameter as long as half of Crete tracked a trajectory depicted in Fig. 19 ending over Turkey during the night to

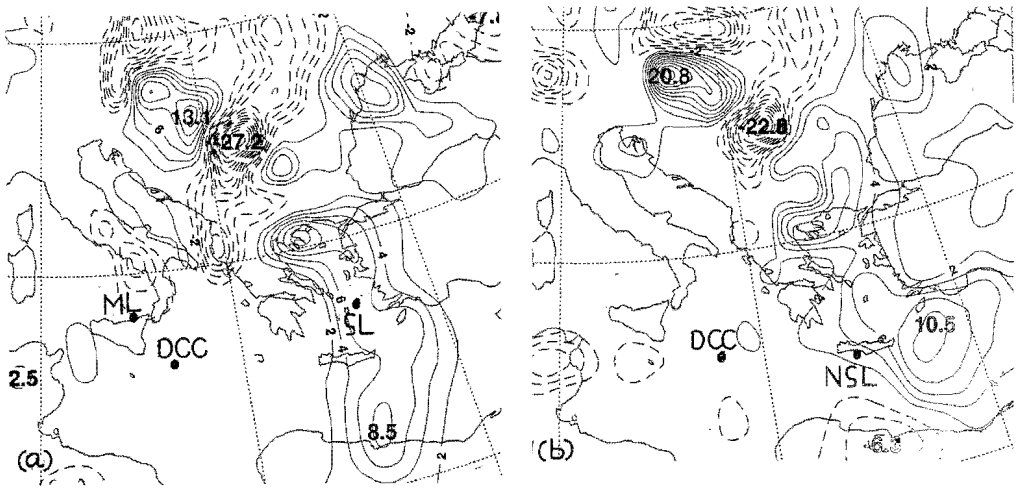

Fig. 18. As Fig. 7a, but for a) 1200 UTC, 22 October and b) 0000 UTC, 23 October 1994. Acronyms ML and SL as Fig. 9, DCC: Developing Convective Cyclone, NSL: New Shallow Low.

Abb. 18. Wie Abb. 7a, aber für a) 22.10.94 12Z und für b) 23.10.94 00Z. Die Abkürzungen ML und SL haben dieselbe Bedeutung wie in Abb. 9. DCC: sich entwickelndes konvektives Tief, NSL: neues flaches Tief.

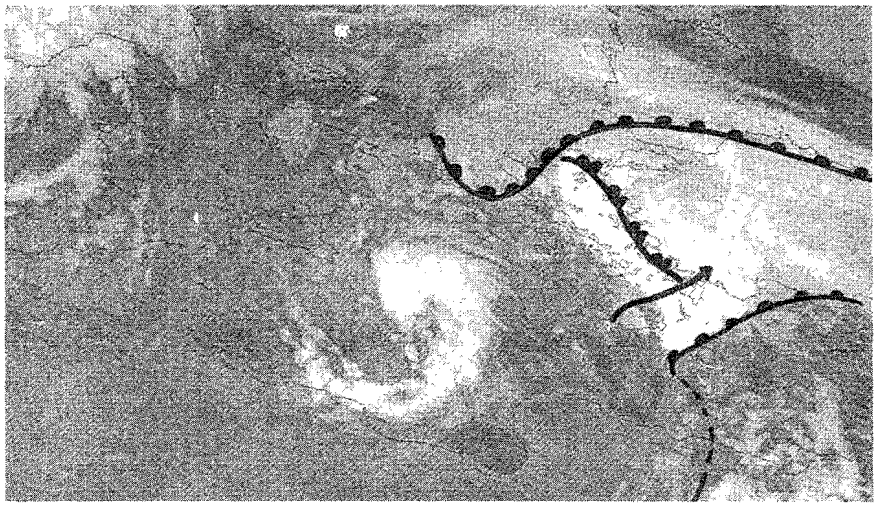

Fig. 19. As Fig. 9, but for 0000 UTC, 23 October 1994. Thick curved arrow denotes the track of the New Shallow Low (NSL). The starting position is at 0000 UTC and the final position is at 2400 UTC on 23 October 1994.

Abb. 19. Wie Abb. 9, aber für den 23.10.94 00Z. Der dicke gebogene Pfeil bezeichnet die Zugbahn des „Neuen flachen Tiefs" (NSL). Der Anfangspunkt ist um 00Z, der Endpunkt um 24Z des 23.10.94.

24 October. The physical mechanism to which the formation of the meso-scale low is attributed could be, according tothe Bjerknes pressure tendency equation (CARLSON 1991), the strong warm advection and the subsequent vertical motion at Crete as Fig. 18 shows. The primary main depression that developed over Sicily has jumped to the central Mediterranean between Sicily and Crete where a vortex has formed resembling a secondary polar low (BADER et al. 1995). The primary system has become barotropic as the low pressure centres at the various isobaric surfaces coincide in the vertical. The lower tropospheric layer is warm and especially moist (with surface temperature ranging between 20 and 22 °C and 850 hPa temperature 12 and 14 °C with T–Td = 2 °C). On the contrary, the air mass is substantially cold at 500 and 300 hPa with temperature –16 and –40 °C, respectively. Therefore, the static instability favours the development of the polar low. The vortex moved south-eastwards (Fig. 20) over the sea and therefore the associated weather conditions were not known. However they should have been very intense (RASMUSSEN and ZICK 1987, JANSA 1992). The development and evolution of this type of short life vortex (decayed in the night to 24 October) appears to be a subject of special future research.

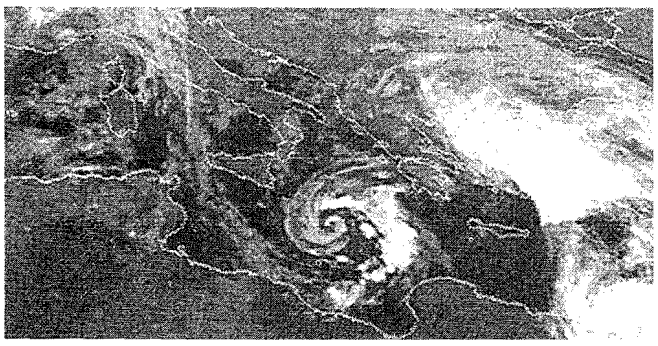

Fig. 20. As Fig. 9, but for 0530 UTC, 23 October 1994.

Abb. 20. Wie Abb. 9, aber für den 23.10.94 05.30Z.

4. Concluding remarks

The analysis of the available meteorological data showed that the intense, elongated and extensive rainfalls which fell over Greece from 21 to 23 October 1994 were the result of the interaction of: (a) a relatively shallow quasi-stationary front along northern Greece, (b) a warm occlusion that passed over Greece in 22 October, (c) a secondary vorticity maximum accompanying the southern edge of the occlusion. It should be noted that the occlusion resulted from the dynamical process that maintained the depression in the west (Sicily) and the interleaving of dry and moist air streams (CARSON 1991). The physical mechanism associated with the interaction of these meteorological parameters is the intense advection of warm and moist unstable air within the troposphere towards Greece, while in the lower half of the planetary boundary layer over northern and central Greece (at least up to Athens according to its upper-air station) the advection of cold and less moist air from the north-east dominates. Due to mixing, an almost saturated air mass formed, that rose up to the LFC, due to the convergence associated with dynamic and topographic factors thus providing the triggering effect for the release of the latent instability and the occurrence of thunderstorms. The intensity of the thunderstorms depended on local factors as well. Maxima of vorticity at 500 hPa that passed over central and southern Greece played an important role in the episode. The most important maximum was the one that has passed in the early morning in 22 October. This is consistent with LALIOTIS (1977) who showed that the most significant rainfalls occur over Greece when the vorticity maxima at 500 hPa approach Greece from the south-southwest. This investigation furthermore implies that the rainfalls become heavy and elongated when a large-scale blocking anticyclone covers the major Greek area preventing the lower tropospheric flow of warm and very moist air to the north.

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