III. ΚΛΙΜΑ

SYNOPTIC AND GEOGRAPHICAL CONCIDERATION OF THE SEVERE HEAT-WAVE OVER GREECE IN JULY 1987

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INTRODUCTION

Air temperatures that exceed 40°C or even 45°C do not constitute an unusual fact for Greece. If we run trough the archives of the Hellenic National Meteorological Service, we can find many cases with such high temperatures, which nevertheless did not last for many days. One characteristic such case occured on the 10th of July 1977 where the temperatures in the county of Attica and especially at Elefsina meteorological station (WMO (WMO N°16718) and Tatoi (WMO N°16715) rose to a maximum of 48°C, while the maximum temperature on those same stations on the 9th and 11th of July was approximately 12°C. less.

In contrast to the above, the time period from 19 to 27 July 1987, portrayed high temperatures which were less than those of older cases, but their duration in days and the duration in the same day as well were unusual. For 9 successive days spanning from 19 to 27 July the maximum temperature in many stations spread around Greece, rose over the 38°C. The minimum temperatures were also relatively high, and the diurnal temperature range was small. Another characteristic was the fact that the values of the maximum temperatures were kept overall near the values of the maximum temperatures for many hours during the day so that the discomfort conditions for the people, animals, and even plants were elongated for many hours every day with tragic results.

ΣΥΝΟΠΤΙΚΗ ΚΑΙ ΓΕΩΓΡΑΦΙΚΗ ΘΕΩΡΗΣΗ ΤΟΥ ΙΣΧΥΡΟΥ ΚΑΥΣΩΝΑ ΣΤΗΝ ΕΛΛΑΔΑ ΤΟΝ ΙΟΥΛΙΟ ΤΟΥ 1987.

ΝΙΚΟΣ Γ. ΠΡΕΖΕΡΑΚΟΣ, ΠΡΟΪΣΤΑΜΕΝΟΣ ΤΜΗΜΑΤΟΣ ΕΡΕΥΝΩΝ-ΜΕΛΕΤΩΝ ΤΗΣ ΕΘΝΙΚΗΣ ΜΕΤΕΩΡΟΛΟΓΙΚΗΣ ΥΠΗΡΕΣΙΑΣ, Τ.Θ. 73502, ΤΤ 16603 ΕΛΛΗΝΙΚΟ, ΑΘΗΝΑ.

We state below some selected reports of the newspapers which presented the heatwave and its unpleasant results in their own manner.

Since the phenomenon, as we will see below, belongs to the atmospher's synoptic scale circulation, Hellenic National Meteorological Service based upon the data received by ECMWF, was able to predict the phenomenon two days in advance (that is from 17 July 1987) thus issuing a special warning. Unfortunately noone seemed to realize, the scale of the weather variations that were about to happen. On sunday 19th of July, which was the first day of the heatwave, the temperature rose to or even surpassed the 38°C. The newspapers named for the possibility of incoming disastrous effects, with large frontpage titles, like "killer heatwave". On Monday the 20th of July the maximum temperature in Athens rose to the 41°C while the Hellenic National Metevrological Service was assuring that the heatwave would continue. At the same time, the first victims of the heatwave had already started arriving at the hospitals, while it was evident that the general public was suffering, with the weaker individuals being at a more disadvantageous position. On Tuesday the 21st of July the public information media announced the first casualties, while the temperature in the county of Larissa rose to the 41°C, and increased air pollution were detected in Attica. On Wednesday the 22nd of July the casualties rose to 20, while the heatwave was continuing and the demand for all sorts of airconditioning devices had reached its peak. To top the above, water scarcity was reported in certain suburbs of Athens. On Thursday the 23rd of July the lifes lost were 150, while water scarcity was becoming, a severe problem. On Friday the 24th of July the country was declared in a state of emergency. The casualties were 1000 already, and severe space problems were being created at the morques and cemeteries. The people started flocking towards the beaches, to relieve some of the extreme discomforts caused by the temperature, but even that did not prove to be useful as the temperature of sea water at the shores was also showing unusual high temperatures. People had to stay continuously in it to relieve the effect of the heatwave only in a small degree. The heat continued at the same rate all through the 27th of July bringing the total number of casualties to over 1500.

In this paper an effort is being made to analyse the circulation of the atmosphere, and the values of the meteorological data for the time period ranging from the 19th throught the 27th of July of 1987. A study of the circulation of the atmosphere 2 days in advance of the above mentioned event is being made, in order to determine possible centres of action or to detect the meteorological factors which led to this situation. Furthermore a calculation of Thom's discomfort index is being done from the above data for many cities in Greece, to prove the extremely discomfortable weather conditions to which people, animals and plants were subjected. Finally an effort is being made to ascertain whether the phenomenon was the first of its kind in harshness and duration for the Greek territory.

THE CONCEPT OF THE HEATWAVE

In the above discussion, we used the term "heatwave" when we were refering to the very high maximum temperatures that were recorded in Greece in the time period from 19 to 27 July 1987. A strict definition of the term "heatwave" has not been precicely given in the literature. Many research meteorologists have given loose definitions for the word "heatwave", (also mentioned as warm invasion), but those definitions are always given with respect to their own perception, having as a result a big variation on the nature of the defined phenomena. In Greece, there are a few scientists (Mariolopoulos and Carapiperis 1956, Flocas 1970, Repapis 1975, Metaxas and Repapis 1978) having dealt with warm invasions or large warm advections, terms which, sometimes, can easily replace the word "heatwave".

A distinction has been done by Metaxas and Kallos (1980) between the consepts of warm invasion or large warm advection and heatwaves giving, in the same time, the criteria to define a heatwave day in Greece. These criteria are:

a. The maximum temperature in Athens Observatory must be at least 37°C.

b. The average daily temperature must be at least 31°C, at the same station.

c. The maximum temperature at Larissa meteorological station (WMO N°16648) must be at least 38°C in this day.

These two meteorological stations were used because it is commonly beleived that they are representative of the Greek region for the Athens Observatory being located in the main residential area and near the sea and Larissa is a purely continental station, where the heat wave phenomenon is strong and apparent.

From the above discussion it can easily be seen that the definition of a warm invasion, or even that of a large warm advection is not completely coincident with the definition of a heatwave. A heatwave is a series of successive days during which the recorded temperatures, especially the maximum ones, are so high, that multiple kinds of problems are created, the most important being healthhazards to men and animals. The heatwave bears a relationship to the seasons. A warm invasion, that will increase the temperature by 10°C within 24 hours, can happen during the January when the average maximum temperature in Athens for example, is 15°C, and can be considered as a pleasant spring day, or can happen in July when the average maximum temperature in 32°C, and be considered as a heatwave. These last constitute the reason why the crucial value of the daily maximum temperature, which varies from place to place, governs the fact whether a temperature increase can be labelled as a heatwave or not.

In Greece experience has shown that during the summer season a day can be characterized as a heatwave day if its maximum temperature surpasses the 38°C. In the United States those limits differ from state to state, so the term heatwave is used only for the summer, while a sudden increase in temperature during any other season of the year is characterized as a warm invasion or a large warm advection.

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DATA AND METHOD USED

To study the synoptic evolution of the atmospheric circulation, which resulted in the heatwave over south Italy and the Balkans, we used the synoptic surface and upper air observations of the eastern Atlantic, Europe, north Africa and west Asia areas.

These observations have been selected regularly via the Global Telecommunication System (GTS). Special emphasis was given to the analyses of surface and 500 hPa synoptic charts which constitute the main tools for weather analysis and forecasting in the Greek National Meteorological Centre. Some of them are presented further on. Also the relative wind vorticity at 500 hPa and the thermal advection at 850 hPa with the associated mean wind fields were calculated from the ECMWF unitialized data. Moreover vertical velocity at 700 and 500 hPa were calculated from ECMWF's initialized data as well, to show the possible large scale subsindence. To find out the particular characteristics of the heatwave and its effect on the weather of Greece, all the observations from the Greek meteorological stations, especialy those of temperature, humidity and wind, were carefully collected from 15 up to 28 July 1987. Imageries of the Meteorological satellites NOAA 9 and METEOSAT were also analysed.

For a better study of the synoptic structure and evolution of the atmospheric circulation and its possible centres of action, which caused the heatwave, a mean chart of 500 hPa height was prepared for the 9 day period, that is from 19 to 27 July 1987, and for both the 0000 GMT and 1200 GMT synoptic observations. Also the height anomaly field, i.e. its departude from 1949-1973 July's average (published by Deutscher Wetterdienst), and the t (student) test for 0.01 and 0.05 statistical level, have been calculated (Brooks and Carruthers, 1953). The mean field and its anomaly have been analysed manually.

Since, as known (Reiter 1975), the subtropical jet stream is the principal atmospheric circulation feature over the region under consideration during summer, its positions for both the 0000 and 1200 GMT synoptic observations were drawn, whenever, of course, this was possible.

Also, the mean positions of the polar jet stream for the period from 19 to 24 July and from 25 to 27 July 1988 were drawn in order to determine the possible interaction, (Reiter 1975) between these two main atmospheric jet streams.

Finally by calculations Thom's discomfort index $I_d = 0.4\ (T + T_w) + 4.8$ (T:dry-bulb temperature and T_w: wet bulb temperature in °C) for all synoptic observations during the whole period of duration of the heat-wave, it has been possible to establish, the number of hours during which the highest discomfort conditions occurred within each day.

SYNOPTIC CONSIDERATION OF THE HEATWAVE

On 15 July 1987, a long wave dominates the atmospheric circulation over Europe and northeast Atlantic, on the 500 hPa chart (Fig.1). This long wave looks like a meridional blocking, showing a tendency to move slowly eastwards. A ridge line almost coincides with the12.5° meridian. This ridge line is located more towards east, over north Italy's region. West and east of this ridge low systems appear centred on about 58°N. A synoptic-scale ridge covers the region of the northwest coasts of Africa.

At the surface (Fig. 1) an almost stationary warm low lying on northwest Africa causes the warm advection from the southeast regions towards the northwest ones, whereas at the middle east, the indian summer monsoon low, is being extended towards Cyprus, advecting thus very warm air masses to the eastern Mediterranean and the south Balkans.

On 16 July the ridge over Europe has advanced slowly eastwards, whereas the lows' centres lying west and east of the ridge are moving towards south, especialy the western one, thus strengthening the westerlies in northwest Africa.

At the surface, the synoptic situation looks as if it is unchanged with one thermal low transfering warm air masses into northwest Africa from the southeast and the.

other one from the east-southeast towards the south Balkans.

On 17 July 1987 the aforementioned ridge is lying on central Europe, with the main portion of the ridge line coinciding with the meridian at 20°E, whereas its northermost part is coinciding with the meridian 12.5°E thus showing an inclination from northwest to southeast (Fig.2). In Greece, the 5820 gpm contour on the 500 hPa chart shows that a somewhat cyclonic atmospheric circulation exists. In northwest Africa the warm advection is being maintained almost unchanged, whereas the extension of the summer monsoon low towards the south Balkans has ceased, since it has already transferred a great deal of comparatively warm air masses, stagnating now over the south Balkans, but mainly over Greece and western Turkey (Fig. 3). We also can see in Figure 3, that the western Mediterranean has become a region of warm advection, coming from northwest Africa and marching northeasterwards. In North Spain and south France an intense thermal gradient is observed, (Fig. 3) which is associated with strong northwesterlies resulting thus in a remarkable cold advection towards southeast Spain. On 500 hPa (Fig.2) the cold advection towards Spain results in the formation of a cut off low, which makes the circulation aquire a SW - NE direction and to intensify in the same time over the western Mediterranean and northwest Africa on 19 July 1987, as it is shown in figure 4. The aforementioned cold advection seems to be caused by the field of strong NW winds between the low being over British Isles, and the large scale warm ridge in the northeast Atlantic advacing slowly eastwards while being strengthened, and while shifting its ridge line, adopting a direction from SW to NE (Figs. 2,4). Moreover the ridge over central Europe has been displaced over Russia, the Black Sea, and the central Mediterranean where it is being terminated in a warm high.

The sort of atmospheric circulation, which the western cut off low of the long wave has set up, results in an intense negative advection of relative vorticity, and warm advection in the middle troposphere towards Italy. This area of negative advection of relative vorticity shows a tendency to be extended to include the south Balkans.

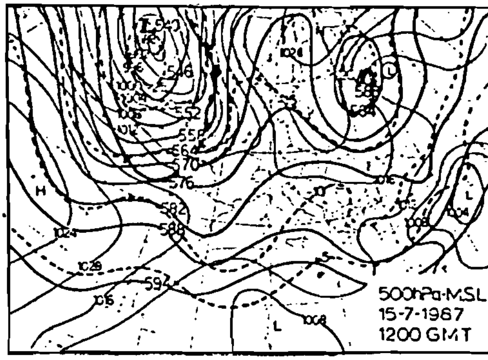

Fig.1. Subjective analysis of 500 hPa height and temperature fields and also surface pressure field for 15 July 1987/1200 GMT. Thick continuous lines are contours in a 6 gpdam interval, thick dashed lines are isothemrs in a 5°C interval and thin continuous lines are isobars in a 4 hPa interval. Presentation of surface fronts accordingly to WMO's guide on the global data processing system (WMO publication No.305).

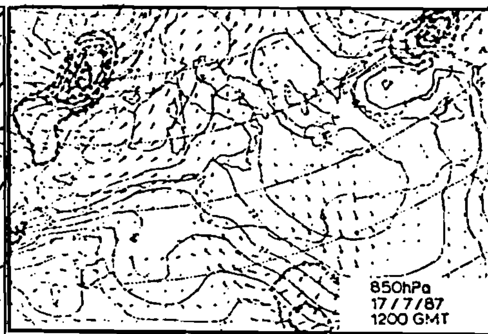

Fig.3. Objective analysis of 850 hPa temperature and thermal advection fields for 17 July 87. Continuous lines are isotherms in a 2°C interval, dotted continuous lines are thermal advection iseopleths in a 50 X 10^{-6}°C sec^{-1} interval,drawn only when the thermal advection values are absolutely greater than 100 X 10^{-6}°Csec^{-1}. Arrows represent 850 hPa mean wind field. The lenght of the arrows is proportional to the wind speed. Calculations are based on ECMWF's initialized data.

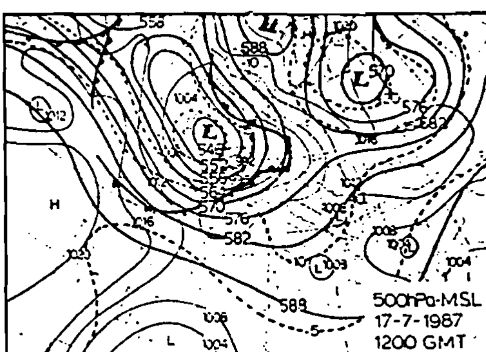

Fig.2. Same as Fig.1, but for 17 July 1987.

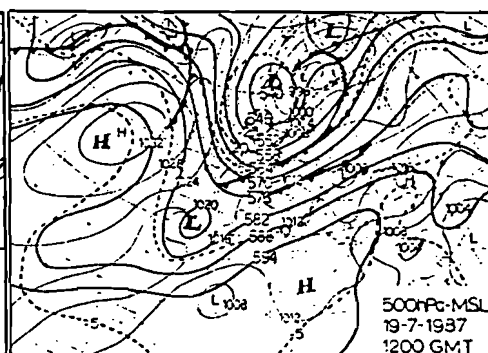

Fig.4. Same as Fig.1, but for 19 July 1987.

On 850 hPa (Fig.5) the air flow, shown over northwest Africa and the western Mediterranean, coming from southwest, transfers very warm and dry air masses of Sahara origin (Tc) northeastwards. So the region southwest of Rome aquires the greatest values of the warm advection, that is more than 200 X 10^{-6}°C/sec. The isotherm labelled 26°C reaches Sicily. This day, 19 July 1988, can be characterized as a heatwave day in Greece, because the Metaxas and Kallos (1980) criteria are fulfillied, and the maximum temperature overshoots the value of 38°C in many Greek cities simoultaneously.

On the next days, the high's northernmost portion is weakening gradually, being displaced slowly eastwards, whereas the southern portion is rather strengthening due to the western low,which has moved very slowly southeastwards, being cut off (Fig.6), maintaining a southwest direction for the tropospheric circulation over northwest Africa and the western Mediterranean and also extending it over south Italy and the south Balkans. In the same time the warm advection over the Balkans made the 26°C isotherm on the 850 hPa chart (Fig.7) to be over Bulgaria on 22 July.

Apart from the horizontal intense warm advection the large scale subsidence associated mostly with the negative advection of relative vorticity (the circulation is more anticyclonic on 23 July), appearing over Greece on 500 hPa (Fig. 8) must contribute to this intensive temperature rise (Lyall 1971, 1979). Over the sea, large scale downward vertical velocities dominate at all levels whereas over land, being mostly mountainuous, overheated by the seasonal prolonged solar radiation the vertical velocities appear to be slightly (1-3 hPa/h) upward up to 700 hPa associated with absolute instability in the most of the boundary layer (Fig.9). Thus the right hand terms of the thermodynamic equation (Wiin Nielsen, 1973).

$$\left(\frac{\partial T}{\partial t}\right)_p = -\vec{V}\cdot\nabla_p T + \omega(\Gamma_\alpha - \Gamma) + \frac{1}{c_p}\frac{\delta q}{dt} \qquad (1)$$

(T : temperature, $\vec{V}$: wind, t : time, $\omega = \frac{dp}{dt}$: vertical velocity, Γ_α = [illegible]/∂p : adiabatic lapse rate moist or dry

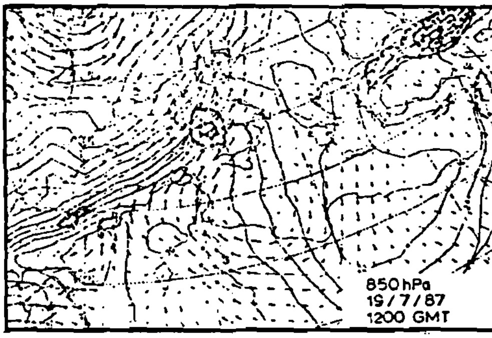

Fig.5. Same as Fig.3, but for 19 July 1987.

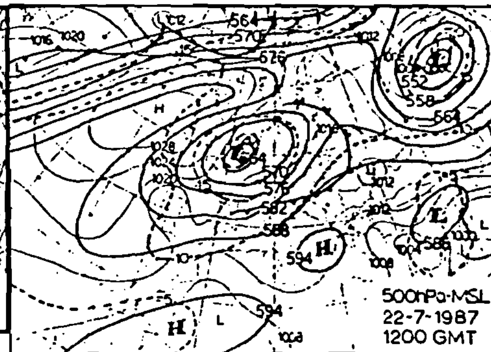

Fig.6. Same as Fig.1, but for 22 July 1987.

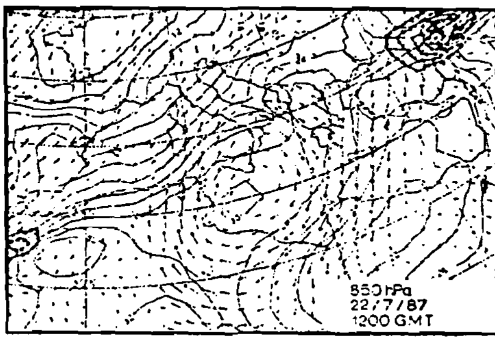

Fig.7. Same as Fig.3, but for 22 July 1987

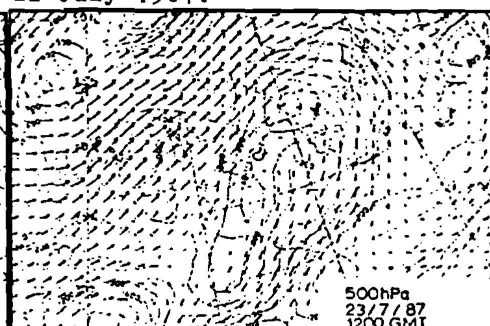

Fig.8. Objective analysis of 500 hPa relative vorticity for 23 July 1987/1200 GMT. Relative vorticity isopleths are drawn in a 100 X $10^{-7}sec^{-1}$ interval. Arrows represent the mean wind field. Calculations based on ECMWF's initialized wind data.

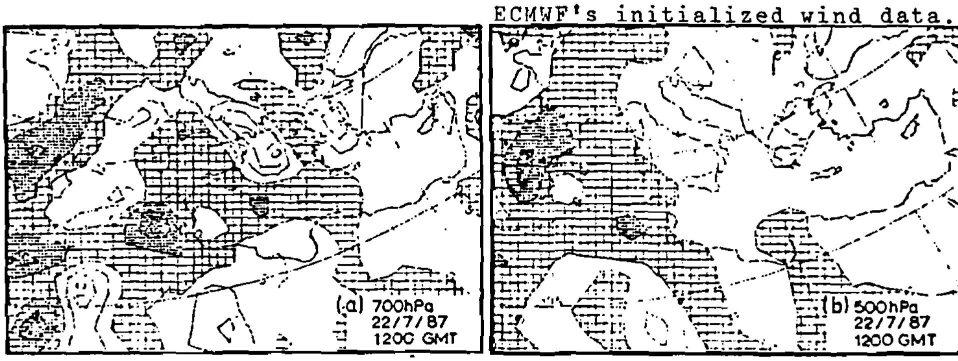

Fig.9. Objective analysis of vertical velocities (a) at 700 hPa (b) at 500 hPa for 22 July 1987/1200 GMT. Isopleths are drawn in a 5 hPa h^{-1} interval. Shaded areas include upward vertical velocities.

depending upon whether the air is saturated, $\Gamma = \frac{\vartheta T}{\vartheta p}$: actual lapse rate, c_p : specific heat of moist air at constant pressure, $\frac{\delta q}{dt}$: heat-energy change per unit mass caused by processes other than condensation, ∇_p : horizontal gradient on an isobaric suface) favor the local increase of the temperature at all levels of the lower troposphere. During the night, large scale downward vertical velocities occur at all levels from surface up to 500 hPa (not shown) over Greece, and the neighbouring countries. As a result, even the second of the right hand terms of the equation (1) contributes fully to the temperature's increasing, counterbalancing thus the losses by radiation.

These synoptic conditions were kept unchanged from 19 to 22 July 1987, resulting in the creating of two warm pools on the 850 hPa chart (Fig.7). One of them centred on 35°N, 12°E and labelled 30°C and the other one centred over Greece with a value greater than 28°C.

After the 23rd of July the 500 hPa low, having become a cut off low, being thus not yet fed with cold air, is being degenerated, while moving in the same time slowly northeastwards from the area being northwest of Italy. South Italy and the southern and eastern Balkans have been covered by tropical continental air masses, as the values of their tropopause height (about 100 hPa) and temperature (about -70°C) indicate (see table I).

On 25 July the synoptic situation in Greece remains almost unchanged (Fig.10). So the temperature increases even more, making this day be the warmest day of the heatwave period for many Greek cities. But just before 25th of July the ridge over the north east Atlantic has moved even further eastwards and has strengthened once more, while its line still had a SW - NE direction. The build-up of excessive anticyclonic curvature on the ridge is a consequence, of the wind speed increase at the western flank of the ridge, causing the warm advection which, in turn, causes the strengthening of the ridge.

The expected increase of the wind at the eastern flank of the ridge, advecting polar maritime air and kinetic energy from the north east Atlantic towards the western Europe, resulted in the rejuvenation of the low with a new centre lying over England on 25 July (Fig.10). This low is a vigorous synoptic pattern which, in turn, dominates the atmospheric circulation. This low, moved northeastwards, but a major trough of it with the associated cold front moving southeastwards, caused the severe weather which appeared over Yugoslavia. Furthermore the anticyclonic circulation continues to cause the large scale subsidence with a somewhat temporary increase, especially over eastern Greece (not shown). The warm pool over Greece also continues to exist, being shown on the 850 hPa chart (Fig. 11), while maintaining the surface temperature values at high levels.

On 27th of July the atmospheric circulation became cyclonic at least over north Greece (Fig.12) with the corresponding cold advection. The value of this cold advection is greater than 250×10^{-6} °C/sec. (Fig. 13). In southern and eastern Greece, as a consequence of this synoptic situation, the wind shear on 500 hPa chart is intensively anticyclonic, resulting in maintaining the large scale subsidence of the tropospheric air over this regions (Fig. 14). As a result the maximum temperature in the cities of the eastern Greek mainland adopted their greatest values. These values were predicted successfully by the D+3 forecast of the ECMWF model. The election of the Athens meteorological station (Helliniko, WMO N°16716) for the verification of this forecast (Rubli 1987) is not suggested, because Helliniko's temperature depends on the sea-breeze mesoscale circulation showing, thus, a great bias from the predicted temperatures (Helliniko is a coastal station). The 27th of July was the last day of the heatwave period for eastern continental Greece, because on that day maximum temperatures had already been reduced remarkably in northern Greece.

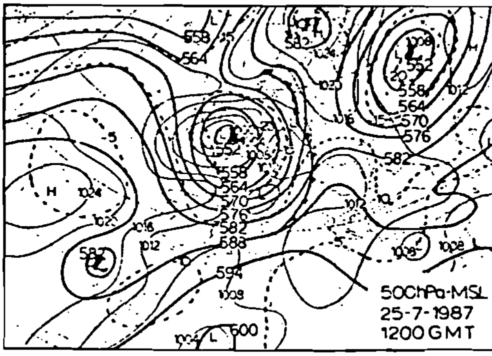

Fig. 10. Same as Fig.1, but for 25 July 1987.

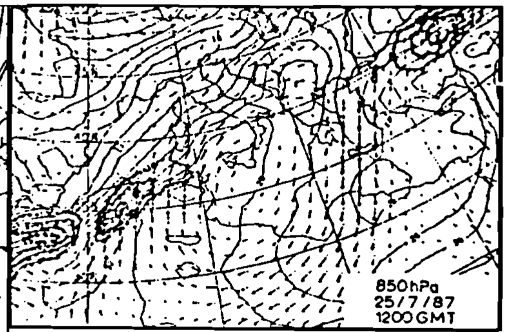

Fig.11. Same as Fig.3, but for 25 July 1987.

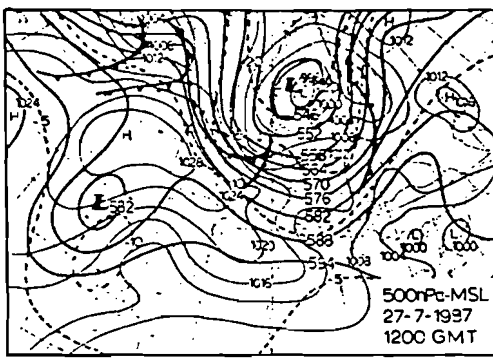

Fig.12. Same as Fig.1, but for 27 July 1987.

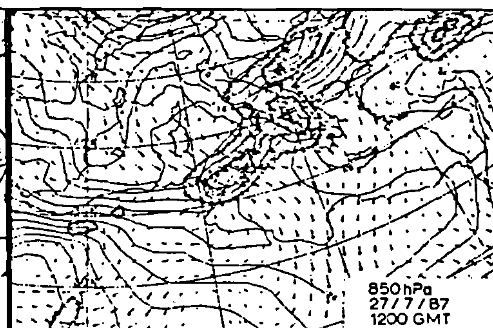

Fig.13. Same as Fig.3, but for 27 July 1987.

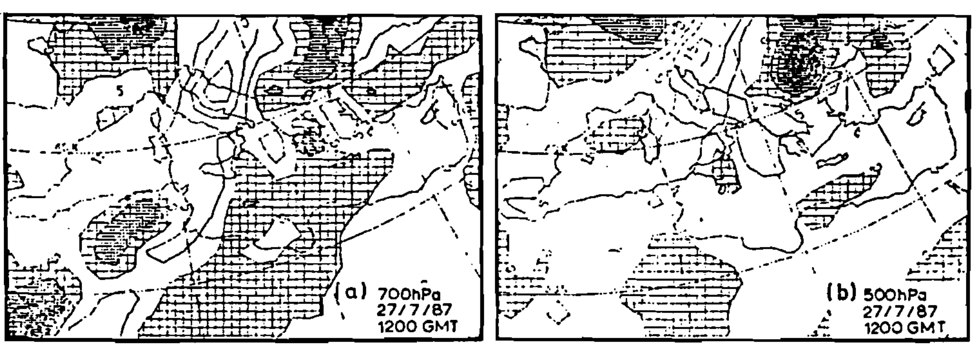

Fig.14. Same as Fig.9, but for 27 July 1987.

MEAN ATMOSPHERIC CIRCULATION DURING THE TIME PERIOD THAT THE HEATWAVE AFFECTED GREECE.

Figure 15 shows the mean atmospheric circulation from 19 to 27 July 1987 as it is illustrated by the mean chart of the 500 hPa height. This mean chart indicates that a long wave with ridges over central Europe and the north Atlantic and a low between these two ridges dominates the atmospheric circulation.

The question which is now arising is whether a feature of the three comprising the long wave appearing on the 500 hPa chart plays the most important role in the creation of the heatwave. To decide this we examined closely the 500 hPa height's anomaly field that is the differences of the July's long-term average 500 hPa height values from the mean 500 hPa height values of the time period from 19 to 27 July 1987 and for both 0000 and 1200 GMT observations. For the study of such meteorological and climatological topics the anomaly field plays the most important role (Stringer 1972). This anomaly field shows that Azores anticyclone has experienced an intesive strengthening and displacement towards the north. Anomaly values in north Atlantic's region overshoot the 210 gpm being mostly statistically significant at the 0,01 level of significance, fact which indicates that these high values of the anomaly field are due to the steady residence of the same ridge over the region. This centre of action must play the most important role in the creation of the cold advection towards northwest Europe. This cold advection is performed by the strong north-northeasterlies (as the strong anomaly gradient shows at the east part of the system) depicted in Figure 16 by the earlier mean position (from 19 to 24 July 1987)of the polar jet stream. The extension of the western ridge northeastwards adopting the shape of a meridional blocking results in the setting up of an intense cyclonic circulation of the eastern flank of this ridge (Bjerknes, 1951). Successive maxima of vorticity are created moving south-southwestwarfds and at the same time cold air masses are advected maintaining the low system in a very active condition being characterized thus as the key system and also generating a strong horizontal temperature gradient. This temperature gradient adopts a NW - SE direction making the thermal wind increase in the lower half of the troposphere resulting in the strengthening of the southwesterly winds in the whole troposphere.

Thus south Italy and the south and eastern Balkans are covered by Tc air masses of a northwest African origin. This,besides the tropopause height and temperature values shown in table 1, is also concluded by the high values of the anomaly field (Fig.15) that they are greater than 120 gpm in the Bulgarian region. These balues are mostly significant at the 0,01 level of significance. This means that the anomaly values have a likelihood less than 1 per cent to be random (Brooks and Carruthers 1953). It also means a continuous increasing of the 500 hPa height in the area from the beginning of the heatwave's appearance as far as its peak owing to the same steadily operating meteorological factors or circulation patterns.

One more indication, which advocates for the air masses being over Greece and the neighbouring coutries have a Saharan origin, is the subtropical jet stream's positions as they are shown in Figure 16. It is worth mentioning that before the 25th of July 1987 there didn't exist any indication either on maximum wind chart or in satellite imageries to help us to indetify the subtropical jet stream's position. It seens that the warm air masses that had occupied the south Balkans due to the likely extension westwards of the summer Indian monsoon low, mentioned above, diminished the thermal contrast at jet stream's level, nothing thus left to witnesses its presence. Even the characteristics bands or cirrus clouds accompaning the subtropical jet stream (Reiter, 1975) are completely absent from the satellite imageries. The subtropical jet stream makes sense of his presence on 25th of July interacting with the polar jet stream over north Italy and north Yugoslavia causing the extremely severe weather occured there on 25th and 26th of July. On next days the subtropical jet stream retrogrates southwards getting gradually away from the polar jet stream and adopting its usual summer position, that is between south Greek mainland and Crete (Prezerakos 1978, 1985).

Table 1. Mean and maximum values of height and temperature at tropopause, 500 and 850 hPa at Helliniko upper air station from 19 to 27 July 1987.

Meteorological Parameters / Levels	Tropopause	500 hPa	850 hPa
Height mean	107 (hPa)	5926(gpm)	1558(gpm)
Height maximum	100 (hPa)	5970(gpm)	1590(gpm)
Mean Temperature	-68°C	-7,12°C	24,17°C
Absolute maximum temperature	-70°C	-6°C	28°C

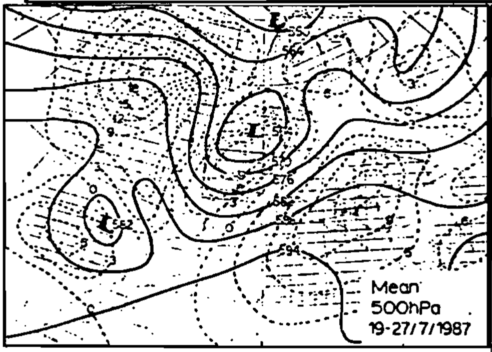

Fig.15. Mean 500 hPa heights for the time period from 19 to 27 July 1987 and for both 0000 and 1200 GMT,and their anomalies, e.g. the departures of the 1950-1973's average from this mean. Thick lines are contours drawn in a 6 gpdam interval, dashed lines are anomaly isopleths in a 3 gpdam interval. Horizontaly hatched areas include anomaly values significant at 0.05 level of significance and crossed hatched areas include anomaly values significant at 0.01 level of significance.

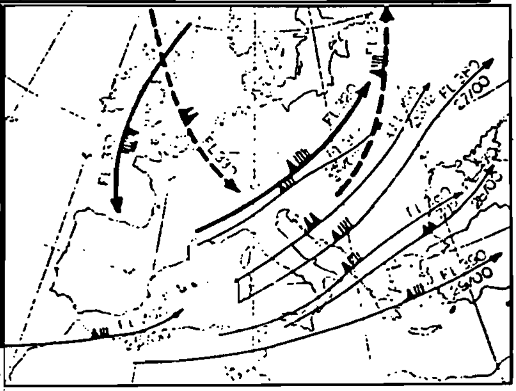

Fig.16. Positions of main jet streams during the heatwave time period. The thick continuous line is the mean position of the polar jet stream for the time period from 19 to 24 July and the thick dashed line in the mean position of the polar jet stream for the time period from 25 to 27 July 1987. Thin continuous lines represent the positions of the subtropical jet stream from 25 to 29 July 1987. Maximum winds are plotted as on the upper air synoptic charts. FL and the following number denote the level of the maximum wind in hundreds of feets, whereas the numbers below them denote day and time.

From the above discussion anyone can conclude that the very warm weather in Greece occurs when the subtropical jet stream lies north of Greece or has become a very weak circulation feature being further north or having diminished there.

THE EFFECTS OF THE HEATWAVE ON THE WEATHER CONDITIONS OF GREECE IN ASSOCIATION WITH THE GEOGRAPHICAL CHARACTERISTICS.

The synoptic discussion and the study of the mean atmospheric circulation during the heatwave's occurrence, pointed out clearly that this meteorological phenomenon belongs to the synoptic and larger scale atmospheric circulation. For that reason, the ECMWF model's three day forecast was proved quite successful, and subsequently the Hellenic National Meteorological Centre was able to warn the general public two days in advance.

Let us see now in detail the direct effect of this synoptic scale atmospheric circulation on local Greek weather conditions, which caused the loss of more than 1500 lives.

We can easily see from table 2, that the maximum temperature values, rounded off, at certain meteorological stations located in urban or rural areas of relatively large Greek cities overshot the value of 37°C during most of the time period ranging from 19 to 27 July 1987. These cities, have been selected so as to represent all kinds of Greek local climates. Some of these stations are purely continental e.g. Larissa, Aliartos, some of these partly continental e.g. Nea Philadelphia being in Athens' region about 20 km from the sea, some of these are coastal stations of the Greek mainland e.g. Helliniko, Elefsina, Kalamata and Athens Observatory. The last one lies about 5 km from the sea. Finally, there are coastal stations on the Aegean sea islands as Kos, Naxos or on the Ionian sea islands as Corfu and Zakynthos. Heraklio is a coastal meteorological station lying at northern coasts of Crete and Tybaki at southern coasts of the same island. However many differences referred to the maximum temperature values, appear between these cities of different local climates or geographical characteristics.

In general we can easily realize that Metaxas and Kallos' (1980) criteria for defining a heatwave day are fulfilled for almost all days in the time period from 19 to 27 July 1987 except for the first one namely 19 July 1987.

However the maximum temperatures reached the value of 38°C at the purely continental meteorological stations, and even more in Nea Philadelphia and Tybaki on 19 July 1988. On the same day many purely continental Greek meteorological stations not included in table 2 appeared to record maximum temperatures having just exceeded the value of 37°C.

It is noteworthing, that some of the meteorological stations of table 2 show a fluctuation of their maximum temperature values during the time period considered. This fluctuation appears only in the coastal stations which are located either in the Greek mainland or in the islands. Some meteorological stations lying on the Aegean sea islands, maintained the air temperature values in low levels far from heatwave's levels. One of these stations, namely Naxos, is the most representative of this category. Naxos recorded maximum temperature's values below 33°C during all the heatwave's period and so we can say that it was not affected at all by the heatwave. Something similar happened to almost all meteorological stations lying on the northern coasts of the Aegean sea islands. The reasons must be attributed to the composite phenomenon of the sea-breeze blowing from the same direction with the etesians, which are the prevailing northerly or northeasterly winds mainly over Aegean sea (but frequently extending westwards) during the whole of the summer (Karapiperis, 1951). Etesians are due to the synoptic scale pressure gradient and oppose sea breeze at the stations lying on the southern coasts of the Greek Islands or the Greek mainland.

To explain the fluctuation of maximum temperature values which are shown in table 2, we have once more to recourse to the local sea-breeze circulation, which did not appear on some days of the period under consideration.

Table 2. Maximum and minimum temperatures recorded from 19 to 27 July 1987 at some Greek meteorological stations.

Meteorological Stations	NO WMO		Days of July 1987									$\bar{T}$max / $\bar{T}$min
			19	20	21	22	23	24	25	26	27	
Athens Observatory	714	Tmax	36	38	41	42	43	41	41	41	41	32.2
		Tmin	24	25	27	28	28	29	28	27	28	22.9
		D.T.R.	12	13	14	14	15	12	13	14	13	9.3
Nea Philadelfia	701	Tmax	38	41	42	43	42	42	41	43	44	33.2
		Tmin	22	23	26	28	28	28	27	27	26	20.5
		D.T.R.	16	18	16	15	14	14	14	16	18	12.7
Helliniko	716	Tmax	33	37	36	40	42	38	36	37	36	31.6
		Tmin	23	23	25	25	26	26	28	25	25	22.7
		D.T.R.	10	14	11	15	16	12	18	12	11	8.9
Elefsina	718	Tmax	36	41	41	42	43	41	42	41	45	32.7
		Tmin	25	26	26	28	30	25	29	27	29	22.1
		D.T.R.	11	15	15	14	13	16	13	14	16	10.6
Aliartos	674	Tmax	38	39	40	40	40	39	40	42	44	32.0
		Tmin	20	21	21	25	22	23	22	23	25	17.6
		D.T.R.	18	18	19	15	18	16	28	19	19	14.4
Larissa	648	Tmax	38	40	41	40	41	39	42	43	43	33.1
		Tmin	19	20	21	21	21	23	21	22	22	17.5
		D.T.R.	19	20	20	19	20	16	21	21	21	15.6
Kos	740	Tman	31	36	38	38	38	37	37	38	38	28.7
		Tmin	21	23	27	28	29	25	28	28	27	21.2
		D.T.R.	10	13	11	10	9	12	9	10	11	7.5
Naxos	732	Tmax	30	30	31	32	32	31	31	33	33	26.7
		Tmin	22	23	26	28	28	26	26	26	25	21.6
		D.T.R.	8	7	5	4	4	5	5	7	8	5.1
Heraklion	754	Tmax	30	32	32	31	32	32	33	32	36	28.7
		Tmin	20	22	23	24	23	25	27	25	24	21.4
		D.T.R.	10	10	9	7	9	7	6	7	12	7.3
Tybaki	759	Tmax	38	39	40	39	41	41	40	40	44	31.5
		Tmin	19	23	23	25	26	26	25	25	21	20.3
		D.T.R.	19	16	17	14	15	15	15	15	23	11.2
Kalamata	726	Tmax	33	34	34	34	43	37	39	41	41	31.1
		Tmin	18	21	20	20	22	22	20	19	22	18.1
		D.T.R.	15	13	14	14	21	15	19	22	19	13.0
Corfu	641	Tmax	35	35	39	40	41	41	39	41	34	30.6
		Tmin	18	20	20	22	23	22	22	21	22	18.0
		D.T.R.	17	15	19	18	18	19	17	20	12	12.6
Zakynthos	719	Tmax	34	36	39	40	42	41	41	42	36	30.3
		Tmin	18	18	22	23	24	23	23	22	20	21.0
		D.T.R.	16	18	17	17	18	18	18	29	16	9.3

Explanation of symbols :

Tmax = Maximum Temperature, Tmin = Minimum Temperature,

D.T.R. = Diurnal Temperature Range.

$\bar{T}$max = July long-term-average maximum temperature, $\bar{T}$min = July long-term avera minimum tempterature.

On these days the large scale thermal advection and the air subsidence which were the main factors mostly controlling the air temperature variation over the whole of the Greek region did not allow adequate horizontal temperature gradients to develope between the air over the sea and land to produce sea breeze or particularly sea breeze strong enough to predominate the light etesians blowing from the opposite direction. This was the reason why the Helliniko meteorological station (WMO N°16716) which is a coastal station in Attica, the major region to which Athens belongs, the sea breeze did not appear to blow at all on 22, 23 and 24 July, whereas a weak sea breeze circulation occurred on 19, 20, 25 and 27 July 1988. The latter fact affects the registration of the temperature (Fig. 17a), which shows peaks on the days when the sea breeze circulation did not occur, whereas it shows a fluctuation around the maximum temperature on the days when the sea breeze appeared. Something similar the registration of the relative humidity shows (Fig. 17b). On these latter days, the maximum temperature values were kept below the value of 37°C at the Helliniko meteorological station. We have to mention that on 27th of July 1987, a day which was for many cities of the eastern Greek mainland the peak of the heatwave period, the maximum temperature at the Helliniko meteorological station, just reached the value of 36°C, due to the sea breeze blowing, an event which did not occur at the Elefsina meteorological station, although the latter is also a coastal station at a distance of a few kilometers from Helliniko. As a result of this last fact, the maximum temperature reached the value of 45°C at the Elefsina meteorological station on 27th of July 1987. This maximum temperature value was the greatest during the heatwave's period not only for the Elefsina station, but for the whole of Greece as well. The fact that sea breezes do not occur simultaneously at all of Athens region's coastal meteorological stations, is a problem which is attributed to the interaction between mesoscale and synoptic scale circulations and it has not yet been fully investigated (Prezerakos, 1985). Moreover the sea breeze, wherever it occured, was bery weak and restricted at the coasts. This can be concluded from the fact that the Athens Observatory and Nea Philadelphia meteorological stations being relatively close to the coasts of Attica, did not provide any evidence of sea -breeze circulation during the whole of the heatwave's time period for Nea Philadelphia. This is evident from the registrations of the temperature and relative humidity (Fig. 17).

Considering the maximum remperature values, which were recorded during the heatwave's period, as a series of observations belonging to an extended period of unusually hot weather, it would be reasonable to decide whether a temperature break, that is a sudden change in the temperature, occured or not. Using Oerlemans' (1979) approach we found that a break did not occur in the beginning of the heatwave period, whereas a remarkable break occurred at the end, that is on 27th of July, for some meteorological stations of northwestern Greece, and on 28th of July for some other stations of eastern Greece. Calculations were made for the maximum temperature values of a few stations, where the speed of the change equals 2, that is $\beta = 2$ (Oerlemans 1979). This break analysis, showed that the heatwave arrived into Greece smoothly and gradually, whereas it left Greece very suddenly.

We can also realize from table 2, that the minimum temperature values were high during most of the heatwave time period. This fact reduced the daily temperature range elongating thus the duration of the discomfort conditions, which were making people suffer ceasellessly even during the night.

There was also a remarkable contribution, to the heatwave because of the fact that many hours during each day the temperature reading was close to its daily maximum value. This was derived by examining the thermographs of many meteorological stations distributed over Greece. Some typical of them are shown in Fig. 17a.

In order to accurately determine the discomfortability and length of the weather conditions over Greece during the time period under consideration Thom's discomfort index (I_d) was calculated from a selection of Greek meteorological

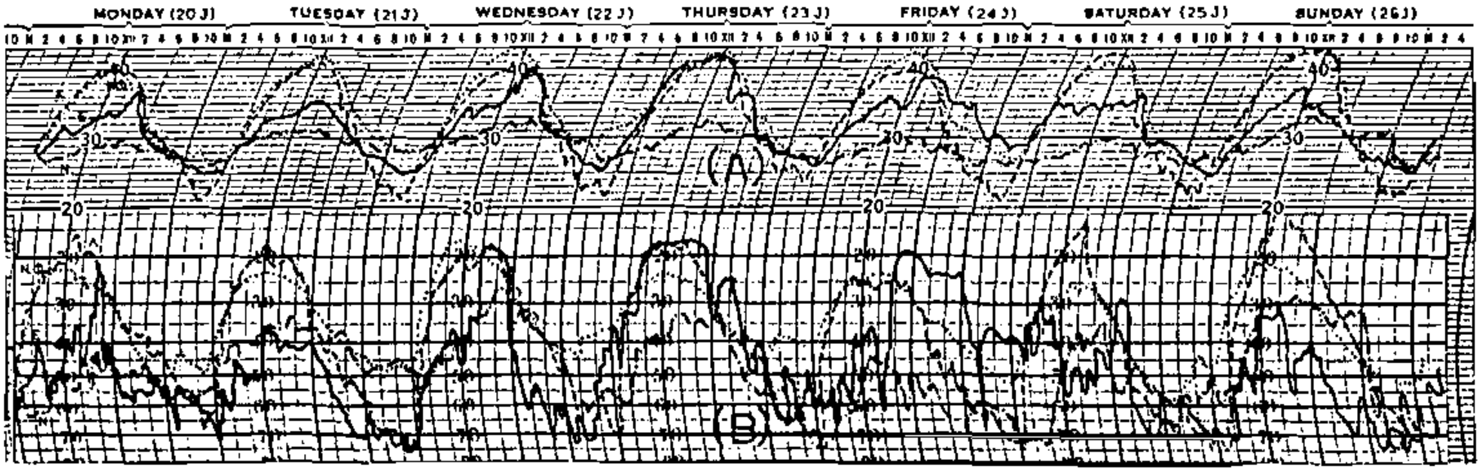

Fig.17. Some typical registrations of (a) temperature and (b) relative humidity from Monday 20 July to Sunday 26 July 1987. Continuous line : Helliniko meteorological station, dashed line : Larissa, dotted line : New Philadelphia and dashed-dotted line : Naxos.

stations. This index is a suitable one for closed spaces e.g. offices or rooms but we think that in such windless or with very light winds weather conditions it works satisfactorily even outdoors (Thom 1959). Table 4 shows that the daily maximum, and even the daily minimum values of Thom's discomfort index, were very high during the whole of the heatwave's time period thus maintaining very discomfortable weather conditions for many hours each day, a fact which was the main reason for the loss of so many lives. The index's values ranged high for a rather long time period during each day, having as a result the cancelling of all the civil services, a step usually taken in USA, when Thom's index adopts values 30 or greater. It is well known (Thom 1959) that when $24 \leq I_d < 26$ then the 50% of the total population feels discomfort, when $I_d \geq 26$ then the entire population feels discomfrt and when $I_d > 26.7$ the discomfort feeling is very strong and dangerous. It is noteworthy to mention that Thom's index values should be much higher if the warm air masses which had settled over Greece were not of a Saharan origin, that is Tropical continental (TC). In some coastal cities where the humidity was also high the weather conditions were really intolerable.

The last question which remains to be answered is whether the heatwave phenomenon under consideration was really an unprecedented one. In order for this question to be answered accurately, it should constitute the subject of a specific investigation, which should include the analysis of the data of many Greek meteorological stations setting up this way, adequate criteria. However a heiristic answer could be given by saying that maximum temperature values greater than those of the 19 to 27 July 1987 period have been recorded in the past, e.g. on 10th of July 1977, when the maximum temperature adopted the value of 48°C at Elefsina and Tatoi meteorological stations as we have already mentioned in the introduction. Also maximum temperature values greater than 38°C were recorded at most of the Greek meteorological stations.

Table 3. Daily maximum and minimum values of Thom's discomfort index and their times of occurrence from 19 to 17 July 1987 at some Greek meteorological stations.

Meteorological Stations	WMO N°		DAYS OF JULY 1987								
			19	20	21	22	23	24	25	26	27
HELLINIKO	716	Id max	26,6	28,8	29,1	29,7	30,8	30,1	29,7	29,6	29,4
		Oc time LCT	1500	1800	1800	1800	1500	1500	1800	1500	1500
		Id min	22,1	22,4	22,9	23,7	25,3	24,9	26,2	24,2	24,2
		Oc time LCT	0600	0300	0300	0600	0300	0300	0300	0600	0600
N.PHILADELFIA	701	Id max	29,8	30,7	31,3	32,2	31,4	31,4	31,2	31,5	31,8
		Oc time LCT	1500	1500	1500	1500	1500	1500	1500	1500	1500
		Id min	24,2	24,9	25,9	26,5	27,7	26,3	25,8	26,2	26,1
		Oc time LCT	0900	0900	0900	0900	0900	0900	0900	0900	0900
THESSALONIKI	622	Id max	27,5	27,4	27,7	28,8	29,0	28,4	28,8	29,1	28,7
		Oc time LCT	1800	1500	1500	1500	1500	1500	1500	1500	1500
		Id min	20,9	21,3	22,0	22,6	22,1	23,2	22,4	23,2	21,5
		Oc time LCT	0900	0300	0300	0300	0300	0300	0300	0300	0600
LARISSA	648	Id max	29,2	26,1	29,6	29,7	29,6	29,5	28,7	29,7	30,5
		Oc time LCT	1500	1500	1500	1500	1500	1500	1500	1500	1500
		Id min	19,8	21,5	21,8	22,8	22,1	22,5	22,0	22,5	19,2
		Oc time LCT	0600	0300	0300	0300	0300	0300	0300	0300	0600
KALAMATA	726	Id max	26,7	27,2	27,6	28,4	30,4	29,2	28,0	28,8	30,4
		Oc time LCT	1800	1500	1500	1500	1500	1500	1500	1500	1500
		Id min	19,0	21,6	21,6	22,1	22,3	22,1	21,6	22,0	20,9
		Oc time LCT	0300	0300	0300	0300	0300	0300	0300	0200	0600

Explanation of symbols : Id = [illegible], T_d = dry bulb temperature and T_w = wet bulb temperature max = maximum, min = minimum Oc.time = occurrence time, LCT = Local Civil Time

Such maxima have been reported many times in the past during similar yearly periods. The Metaxas Kallos' (1980) investigation about heatwaves in Greece was based upon that material.

Finally, runing through the archives of the Hellenic National Meteorological Service, which are stored in magnetic tapes and which have 1953 as a starting year with the exception of the Athens Observatory stored data, which have 1896 as a starting year, we can conclude that cases of 9 successive days with maximum temperature values more than or equal to 37.5°C, have not been recorded at any Greek meteorological station with the exception of Larissa, where it occured once. Moreover, the case of 8 successive days during which the maximum recorded temperature was grater or equal to 41°C been reported at most of the purely continental meteorological stations of eastern Greece from 20 to 27 July 1987 is really an unprecedented phenomenon concerning observations since 1953 and since 1896 for the Athens region individually. Unfortunately, there is not sufficient data to accurately answer whether the duration of very discomfortable weather conditions is an unprecedeted phenomenon. There exists strong evidence however, verifying that the loss of 1500 lives is indeed an uprecedented phenomenon locally, as something similar has been reported never before.

CONCLUDING REMARKS

From the study of the synoptic atmospheric circulation in the time period from 15 to 28 July 1987 we were able to conclude that the heatwave phenomenon having appeared over south Italy and the Balkans belongs to the synoptic scale and larger atmospheric circulation and the meteorological factors which are responsible for its generation are :

a. The very intensive thermal advection in the whole of the free troposphere transfering very hot and dry air from north Africa towards the south Italy and the Balkans. These tropical continental air masses came over the already warm air masses stagnating over the Balkans having arrived there by the extension of the Indian summer monsoon.

b. The atmospheric circulation, in the western Mediterranean and the Balkans appeared to be extremely anticyclonic, with direct consequence the negative advection of relative vorticity and the large scale subsidence in the area from Libya to the Balkans.

c. An intense diabatic warming due to persisting sunshine on a very mountainous region as the Balkans is.

The main centre of action was detected because of the study of the mean atmospheric circulation based upon the mean 500 hPa height and its anomaly fields. This centre of action was a meridional blocking high meandering over northeast Atlantic, which was controlling the circulation, making a deep low, situated at the eastern flank of the ridge to be maintained active and persist over northwest Europe for many days, thus becoming the key system. This key system caused the intensive warm advection, mentioned above, towards south Italy and the Balkans, whereas the subtropical jet stream was located on a position being to the north of the Balkans during the heatwave period.

Also the heatwave time period portrayed high temperatures, which surpassed the value of 38°C at most of the Greek meteorological stations for many days, thus producing extremely discomfortable weather conditions, which caused the loss of more than 1500 lives.

The fact that 9 successive days appeared having maximum temperature values greater or equal to 30°C during the heatwave, was not unprecedented for all of the Greek meteorological stations. 8 successive days with maximum temperatures greater or equal to 41°C have never been seen since 1953 at Nea Philadelfia and since 1096 at the Athens Observatory meteorological stations.

The fact that the values of the temperatures were overall kept near the values of the maximum temperatures for many hours during the day, were unique for the majority of the Greek meteorological stations.

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ΠΕΡΙΛΗΨΗ

Στην εργασία αυτή γίνεται προσπάθεια να προσδιοριστούν και μελετηθούν τα χαρακτηριστικά της συνοπτικής κλίμακας κυκλοφορίας της ατμόσφαιρας, η οποία προκάλεσε τις εξαιρετικά υψηλές και παρατεταμένες θερμοκρασίες στην Ελλάδα του Ιούλιο του 1987. Ακόμη διερευνάται ο ρόλος των φυσικογεωγραφικών χαρακτηριστικών των διαφόρων περιοχών της Ελλάδας που συνέβαλαν στη διαμόρφωση της κατανομής των θερμοκρασιών αυτών στη χώρα μας.

Η μελέτη έδειξε ότι το κέντρο δράσεως ήταν ένας μεγάλης κλίμακας αντικυκλώνας τύπου μεσημβρινού εμποδισμού στη μέση τρόπόσφαιρα. Το σύστημα αυτό κείτονταν στην περιοχή του βορειοανατολικού Ατλαντικού ελέγχοντας την ατμοσφαιρική κυκλοφορία. Η ισχυρή κυκλοφορία στα ανατολικά κράσπεδα του μεγάλης κλίμακας αντικυκλώνα προκάλεσε τη δημιουργία ενός βαθέος χαμηλού στην περιοχή της βορειοδυτικής Ευρώπης.

Το χαμηλό παρέμεινε εξαιρετικά ενεργό επί πολλές ημέρες κι έγινε έτσι το σύστημα κλειδί. Το σύστημα αυτό κλειδί προκάλεσε την παρατεταμένη και ισχυρή νοτιοδυτική κυκλοφορία πάνω από τη βορειοδυτική Αφρική, τη δυτική Μεσόγειο και τα Βαλκάνια με συνέπεια τη μεταφορά τροπικών ηπειρωτικών αερίων μαζών στη νότια Ιταλία και τα Βαλκάνια σε συνθήκες μεγάλης κλίμακας ατμοσφαιρικής κατολίσθησης. Η κατολίσθηση αυτή σε συνδυασμό με την έντονη ηλιακή ακτινοβολία πάνω στην επιφάνεια της Ελληνικής γής που κατά το πλείστον είναι ορεινή συνετέλεσε στην περαιτέρω αύξηση της θερμοκρασίας στο ύψος του κλωβού.

Ακόμη με βάση ορισμένες θερμοκρασιακές παραμέτρους και το δείκτη δυσφορίας του Thom έγινε δυνατός ο χαρακτηρισμός των καιρικών συνθηκών που επικρατούσαν στην Ελλάδα από 19 μέχρι 27 Ιουλίου 1987 ως εξαιρετικά επικίνδυνων για τους ανθρώπους τα ζώα και ακόμη για τα φυτά επί πολλές ώρες κάθε ημέρα με συνέπεια το θάνατο πάνω από 1500 ατόμων.

Τέλος έγινε μια προσπάθεια να βρεθεί αν το φαινόμενο αυτό του καύσωνα ήταν πρωτοφανές σε ένταση και διάρκεια στην Ελλάδα.