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SUMMARY - This is a study of the synoptic structure and evolution which causes heat waves in July and August in Greece. At first, based upon some temperature parameters in Athens and Larissa, we define the heat wave cases, each consisting of several days, in the period 1951-1972. In each case, *D day* is the day when temperature in Athens showed a maximum. Before entering the main subject, i.e. the synoptic structure, we used the well known superposed epoch analysis, monthly, for some temperature parameters, the relative humidity and the wind, for a period of 9 days, i.e. four days before and four days after *D day*. It came out among others that the mean duration of a heat wave is about four days. The maximum temperature appears in Larissa about one day before the one in Athens. Also, etesian winds start about one or two days after *D day*.

The synoptic study is based upon mean charts for surface, 500 mbar and 1 000-500 mbar thickness charts, separately for July and August and for D−4, D−2, D−1, D, D+1 and D+2 days. The charts contain the mean isobars (for the surface chart) and the mean contours, their anomalies from normal with their statistical significance using the t-test. It is found that the key system is a highly significant deep low, being at D−4 over W or NW Europe, and moving to NE, deepening up to E Scandinavia at D+2 day. For several days it causes warm air flow S-SW over Greece, as is shown in the thickness charts. A cold front, associated with the above low, invades Greece about two days after *D day* with another etesian period.

Vagues de chaleur au point de vue synoptique

RÉSUMÉ - On étudie les configurations synoptiques et les relatives évolutions des vagues de chaleur qui intéressent la Grèce aux mois de Juillet et Août.

Au préalable, sur la base de quelques paramètres de température concernant Athènes et Larissa, on définie les vagues de chaleur — chacune de la durée de plusieurs jours — qui ont en lieu dans la période 1951-1972. Au cours de chacune de ces vagues, le jour où l'on enregistre la température la plus élevée à Athènes est dit *D day*. Avant d'aborder le sujet principal, c'est-adire la configuration synoptique, on a appliqué pendant des mois la très connue analyse de périodes superposées à qualques paramètres de température, tandis qu'à l'humidité relative et au vent la susdite analyse a été appliquée pour une période de neuf jours, précisément quatre jours avant et quatre jours après le *D day*. On a trouvé, entre autres, que la durée moyenne d'une vague de chaleur est d'environ quatre jours et que la température maximale est atteinte à Larissa un jour avant qu'à Athènes. L'étude synoptique se base sur les cartes moyennes relatives à la surface, au niveau de 500 mbar et à la couche 1 000-500 mbar, séparément pour Juillet et Août et pour les jours D−4, D−2, D−1, D, D+1, D+2.

Onde di calore da un punto di vista sinottico

RIASSUNTO - Vengono studiate le configurazioni sinottiche e le relative evoluzioni delle onde di calore che interessano la Grecia nei mesi di luglio ed agosto. Preliminarmente, sulla base di alcuni parametri di temperatura riferiti ad Atene e Larissa, vengono definiti gli eventi di onde di calore — ciascuno della durata di diversi giorni — verificatosi nel periodo 1951-1972. Nel corso di ciascun evento viene detto *D day* il giorno in cui si registra la temperatura più alta in Atene. Prima di affrontare l'argomento principale, cioè la configurazione sinottica, è stata applicata la ben nota analisi di periodi sovrapposti, per mesi, relativamente ad alcuni parametri di temperatura, all'umidità relativa e al vento, per un periodo di nove giorni, precisamente quattro giorni prima e quattro giorni dopo il *D day*. Ne è risultato, tra l'altro, che la durata media di un'onda di calore è di circa quattro giorni e che la punta massima di temperatura viene raggiunta a Larissa un giorno prima che ad Atene.

Lo studio sinottico si basa su carte medie relative alla superficie, al livello di 500 mbar e allo strato 1 000-500 mbar, separatamente per luglio ed agosto e per i giorni D−4, D−2, D−1, D, D+1, D+2.

1. Introduction

Heat waves over an area are a very important phenomenon from both a practical and a theoretical point of view. On the practical side, apart of their effect on human comfort, they affect most of the human activities. From a theoretical point of view, they concern the synoptic and other processess which lead to an excess rise of air temperature in an area.

It is well known that the basic cause of a heat wave is a synoptic process, a warm air invasion. Experience shows that during the winter time, this invasion is in fact a warm front passage. Metaxas and Repapis (1, 2, 3) showed that this passage is not accompanied normally by important rainfall amounts, mainly due to the fact that, other thermal cyclogenetic factors, as static stability and diabatic cooling, counterbalance the warm advection effect. They also described the synoptic processes leading to a warm advection in different seasons. But they (1, 2, 3) aimed at the study of the synoptic condition, Lyall (4, 5) showed that an intensive not to a *summer heat wave*, which is the subject of the present study.

Apart of the horizontal warm air advection, Lyall (4, 5) showed that an intensive temperature rise might be caused also by large scale subsidence warming in a downward vertical velocity field, along with, perhaps, diabatic warming due to persisting sunshine. The same factors are emphasized by Popov (6) for the USSR. In the Greek mainland during the summer, common experience shows that very warm and dry air can be produced when already warm air masses are further warmed diabatically in the highlands during noontime and then, under a favourable wind field, they are even more warmed adiabatically by descending eastwards into the plains (*livas*). This phenomenon causes severe agricultural damage when it takes place early in the summer.

In the present work, we intend to study mainly the general synoptic conditions leading to a summer heat wave. We believe that the factors underlined by Lyall could be also decisive. But this is not the object of the present study.

2. Data processing and method of analysis

Karapiperis and Mariolopoulos (7), defined a *heat wave case* as a series of consecutive days, forming a half wave, with the mean air temperature for at least one day ⩾ 5 °C above the normal air temperature of the corresponding date.

From 1861 till 1978, 176 days in July and 163 days in August were observed (table I), with a maximum temperature recorded at the National Observatory of Athens higher than 37 °C. It is worth mentioning that for the last eight years ,in 1971-1978, not a single such day is found during August. In table I, one can also distinguish the well known climatic fluctuation in this period.

The criteria that we used in this study to define a heat wave day are the following:

a) the maximum temperature in Athens (Observatory) must be at least 37°C;

b) the average daily temperature must be at least 31°C, in the same station;

c) the maximum temperature at the me-

TABLE I

Period / Month	1861 to 1870	1871 to 1880	1881 to 1890	1891 to 1900	1901 to 1910	1911 to 1920	1921 to 1930	1931 to 1940	1941 to 1950	1951 to 1960	1961 to 1970	1971 to 1978	Total interval 1861-1978
July	24	8	18	3	6	10	12	29	24	13	10	13	176
August	10	7	10	11	6	4	28	17	25	24	19	2	163

teorological station of Larissa (16648) must be at least 38°C on this day.

We believe that these two stations are representative of the Greek region, because the Athens Observatory is 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.

For the period 1950-1972, 12 cases for July and 15 for August were found fulfilling the above criteria. In the period 1969 to 1972, there were no such days found. The day in a heat wave period, with the maximum temperature in Athens, is called *D day*.

Based upon grid point values for surface pressure, 500 mbar and 1000/500 mbar trickness, kindly provided by the English Meteorological Office, mean values and their anomalies for these levels were plotted and analysed, for each of the days D — 4, D — 2, D — 1, D, D+1, D+2. The grid points values were available for every 5° latitude and 10° longitude, covering the Northern Hemisphere. The normal values for each grid point were calculated using the daily values of the period 1949-1972. Making use of a computer, at each grid point, for the above six days and for surface pressure, 500 mbar and 1000/500 mbar thickness, the mean height values of the above-mentioned selected cases and their anomalies from the normal were calculated along with the t-value, to evaluate the significance of the anomalies. The isoanomalies are shown as thick lines, continuous when the anomaly is statistically significant to at least the 95% level, otherwise as dashed lines. An area with a strong mean anomaly center (max. or min.) could be approximated to a mean relative vorticity center, mainly where no permanent seasonal centers exist, as it is the case on the surface (see e.g. 8).

3. Superposed epoch analysis

a. *Temperature and humidity*

By examining the change with time of some weather parameters, as temperature and humidity, we believe that we can draw certain useful conclusions from our study. Using the method of superposed epoch analysis, we studied the evolution for our selected cases, for July and August and for four days before and four days after the D-day (fig. 1) of the following quantitives: *a*) maximum temperature in Athens (Observatory) and Larissa (fig. 1 a); *b*) the average daily temperature in Athens (fig. 1 b); *c*) the relative humidity in Athens and Larissa (fig. 1 c) and *d*) the mean daily relative humidity in Athens (fig. 1 d). The resulting mean values with a statiscally significant differences from the normal (period 1951-1972), at least at the 95% significance level, are shown for Athens by open circles over crosses -◇- and for Larissa by extended triangles ⅄ . In addition, consecutive values with statistical significant differences, at the same significance level, are shown with continuous lines, otherwise with dashed lines. The appropriate t-test has used for the above significance estimation.

Looking at fig. 1, we observe that the maximum temperature starts increasing about two days before D-day, reaching a maximum value, for both months, on D — 1 day in Larissa and on D day in Athens. The average temperature in Athens follows a similar course. On the other hand, the relative humidity and the average relative humidity start decreasing about two days before D day. Their minimum values in both stations and for both months, occur on D day. We conclude also that the mean duration of heat waves over the Greek mainland for both, July and August, is about four days.

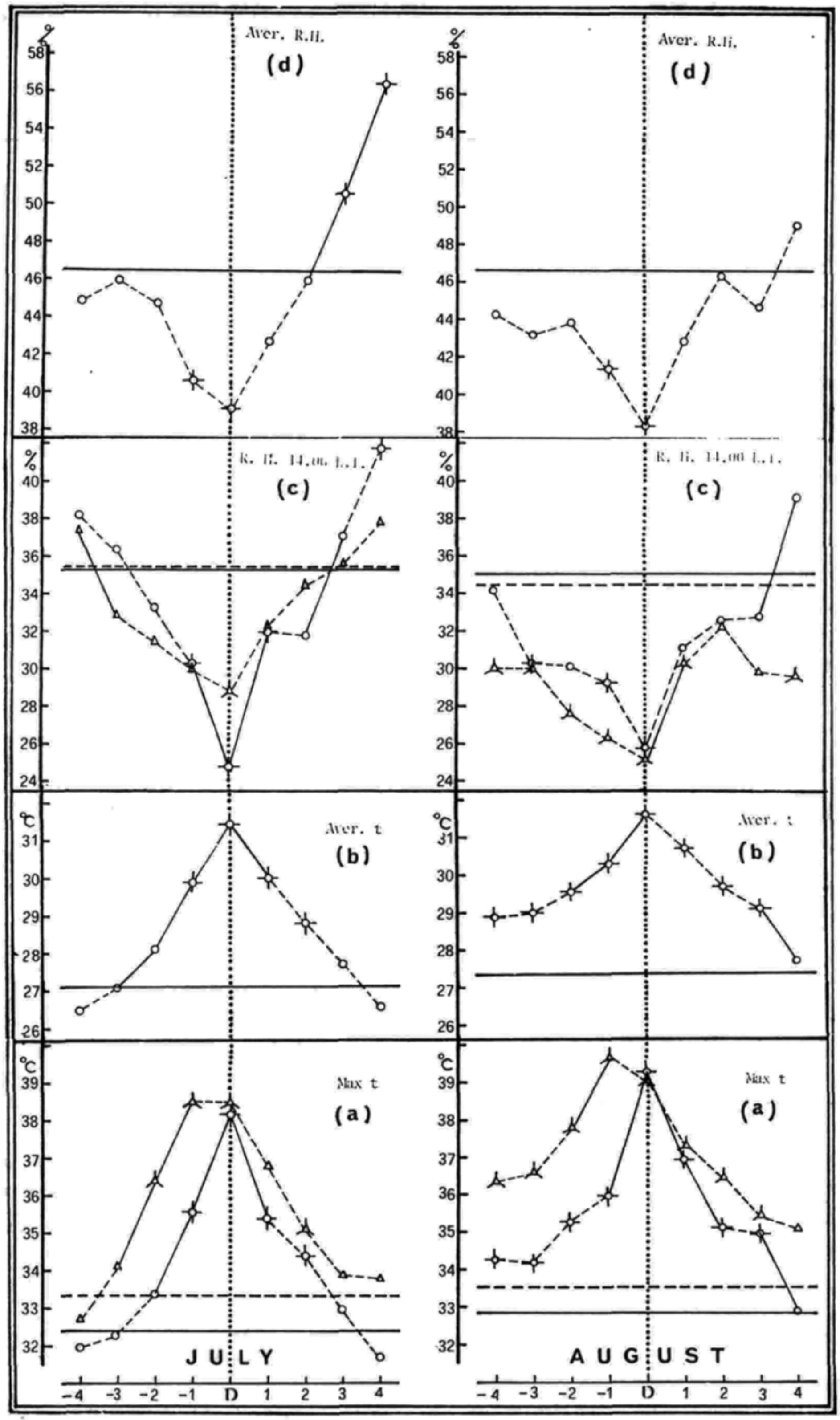

Fig. 1 - *Superposed epoch analysis of temperature and relative humidity parameters in Observatory of Athens* (○) *and in Larissa* (▵) *for:* (a) *max. temperature* (°C); (b) *aver. temperature* (°C); (c) *rel. humidity* (%) *at 14 00 hrs local time;* (d) *aver. rel Hum.* (%) (24 hrs). Horizontal continuous lines: *normal corresponding values, 1951-1972 in Athens* Obs. Horizontal broken lines: *normal corresponding values 1951-1972 in Athens Obs.* Horizontal broken lines: *normal corresponding values 1951-1972 in Larissa. Open circles over cross* -ɸ- *and extended triangle* ⅄ *for values with statistically significant departure from normal. Consecutive values with statistically significant are joined by a continuous line* (95% leval at least)

b. *Wind analysis*

In order to examine the role of the wind during the heat waves we looked at the wind conditions in Athens and Larissa at the times 08 00, 14 00 and 20 00 L.T. (diagrams of fig. 2). One can see that, during July, in Athens in the morning there were northerly winds with relatively high constancy during all days. During noon the wind velocity decreased and there was no constant direction. In the evening the wind became stronger but it still did not have constant direction. In Larissa in July there was no wind blowing during morning; at noon there were easterly winds with moderate strength and constancy, while in the evening the wind was about as at noon. In general there was a decrease of the NE winds, the *etesians* (which blow during this season over Eastern Greece and the Aegean Sea), observed during the days before the peak of the heat wave. The same conditions occured during August.

This wind speed decrease for both months during the heat wave should be attributed to the fact that during the days of the heat wave, the warming of the air masses above the earth's surface leads to an intensification the sea breeze pressure gradient. KARAPIPERIS (9) reported that the sea breeze in Athens opposes the etesian. Because the sea gradient is stronger during noon and blows from SW, the NE wind (the etesian) shows a decrease. In Larissa on the other hand, there were mainly eastward winds during noon, which show no significant decrease on the days of the heat wave. There was, though, a velocity increase observed after the morning hours due to the morphology of the area (a plane surrounded by mountains with an opening to the sea to the east). These phenomena occur in Larissa because the sea breeze does not oppose the entrance of the etesian.

4. SYNOPTIC CONDITIONS

We now examine the synoptic conditions, in the upper atmosphere and on the surface, during the formation of a heat wave. We discuss the mean atmospheric circulation as it appears on the mean maps for 500 mbar, 1 000/500 mbar thickness and surface pressure maps. (These maps are found in the Appendix). In the description, only the significant anomaly centers will be mentioned

1. July

D−4 day. On this day there are two cold air masses accompanied by troughs or lows at 500 mbar; one over Asia Minor and the other over the NE Atlantic, separated by a warm air mass over northern Italy, and by a ridge at 500 mbar (not highly significant). On the surface, the pattern of the isobars shows winds (etesian) over the Aegean and Greece.

D−2 day. The above-mentioned significant warm air mass by now extendeds over a larger area and has moved over the Balkans. The cold air mass of the NE Atlantic moved NE ward and the same movement is observed in the accompanying upper vorticity maximum. At the same time, this low extends towards the South. This movement and extension of the cold air mass cause the transportation of warm air mass from around NW Africa to Greece.

D−1 day. During this day the warm air mass covers the Balkan area, southern Italy and Asia Minor. The cold air and the upper vorticity maximum over England moved both to the northeast. On the surface there are two main systems: the Azores anticyclone and the thermal low over Iraq. Over West Africa relatively high pressures persist.

D day. The warm air mass now moved slightly eastwards though the cold air mass with the accompanying upper low are stationary. No significant differences are observed on the surface.

D+1 day. On this day the warm air mass starts moving to the southeast. The cold air mass and the upper low moved northeast.

D+2 day. The warm air mass moved more to the east, the main cold air moved over Scandinavia, but its southern parts cover the north half of Italy. One could guess that there is a cold front associated which should affect Greece on the following day.

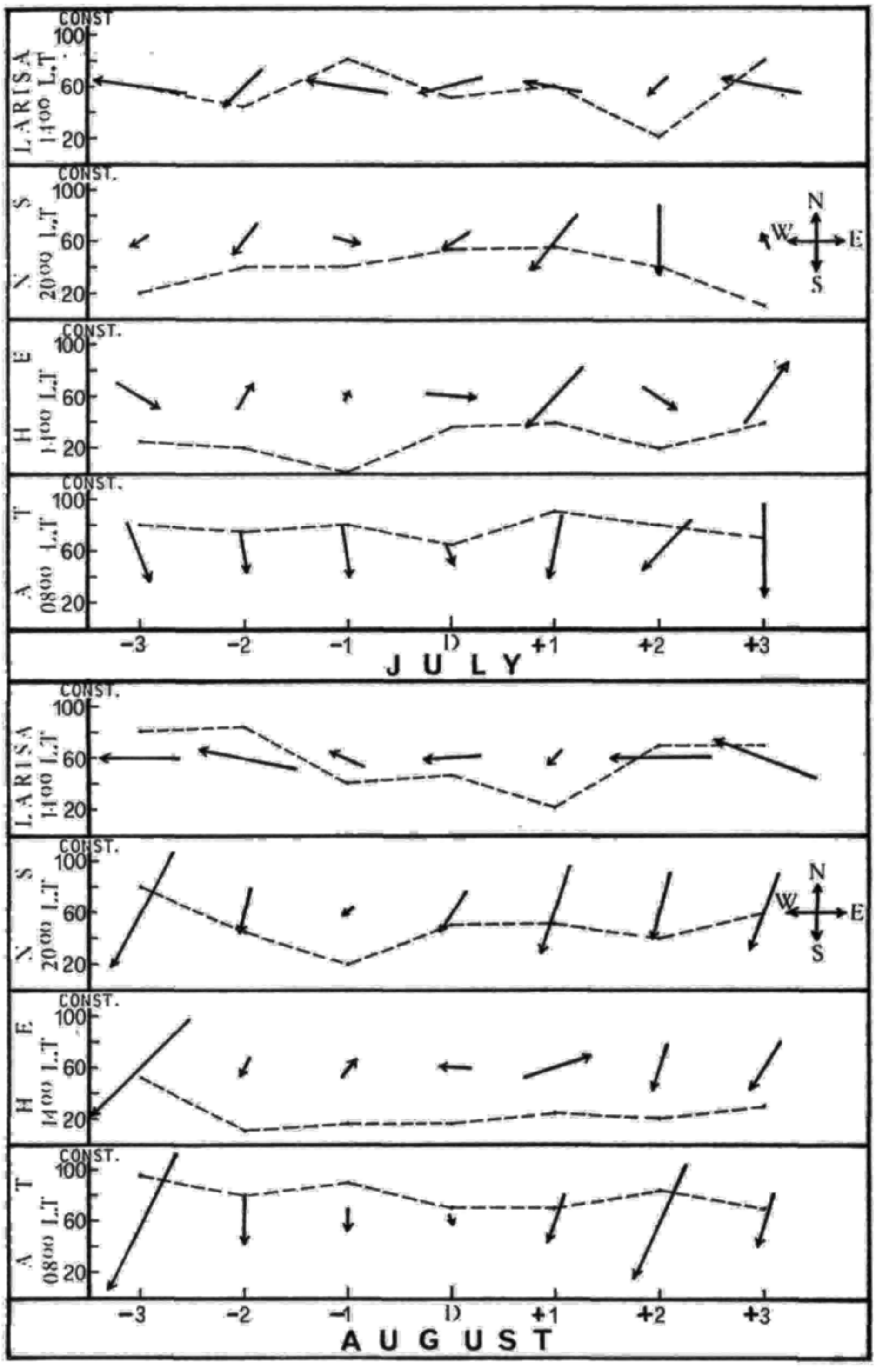

Fig. 2 - *The arrows indicate the velocity and direction of the mean resultant mind (——per 1m/sec). The broken lines show the constancy % of the wind*

2. August

D−4 day. On this day a warm air mass covers the W Mediterranean. A cold air mass (not significant) and the associated upper vorticity maximum lie over the NE Atlantic. The surface low is west of Britain.

D−2 day. The warm air mass now moves east and covers a larger area, of the Central Mediterranean and Southern Europe. The cold air mass along with the upper vorticity maximum moved southeastward, becoming stronger. This system causes strong and prolonged winds and advects warm African air masses over the Balkans.

D−1 day. The warm air mass moved slightly further to southeast. The cold air mass and the upper and surface low moved northeastwards.

D day. A further slight eastward movement of the warm air mass is observed. The cold air and the low moved faster to northeast over northern Europe.

D+1 day. The warm air mass seems to remain stationary with its core over the Aegean. The cold air and the low are over England.

D+2 day. No significant change is detectable in the warm air as far it concerns Greece. But the cold air moved more to the SE. A thermal gradient is created or intensified over Italy as in July, with a cold front, which should pass through Greece in one or two days, establishing a period of etesian winds.

5. Conclusions

From the above analysis we can see that the deep low that persist over the North-eastern Atlantic four days before D day is the key system. It gradually moved eastwards or northeastwards over Western Europe. Ahead of it an upper high or a ridge consists of a warm air mass, as the surface systems are weak. The effect of the above mentioned key system causes a prolonged transportation of a warmer air masses (tropical continental African air masses) over Southern Europe. Two days before D day the warm air mass is over Greece. Downward vertical velocity fields must persist during the large warm advection in the Greek area. These air masses may be diabatically heated, even more at noon, as they pass over the Greek highland and are almost stationary over the Greek area for about 4-5 days.

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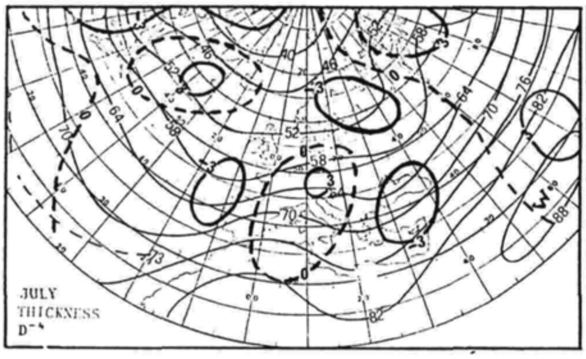
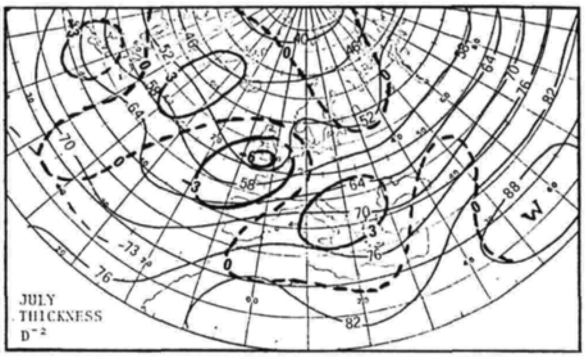
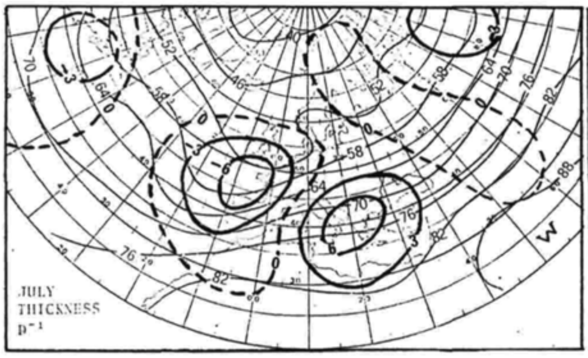
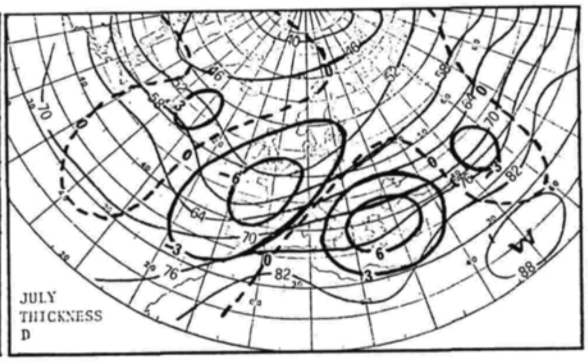
APPENDIX

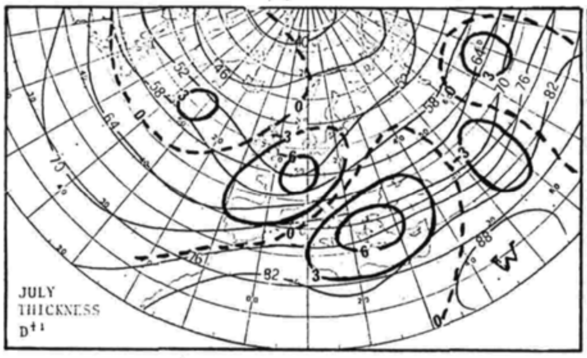
The maps on the following pages are mean maps for the heat-wave cases and for the 1 000/500 mbar thickness, 500 mbar levels and surface pressures, for July and August, and for the days: D−4, D−2, D−1, D, D+1 and D+2. The thick lines (continuous or dashed) show the anomalies from the normal (continuous when the anomalies are significant at least at 95%). Thin lines are mean isobars and contours.

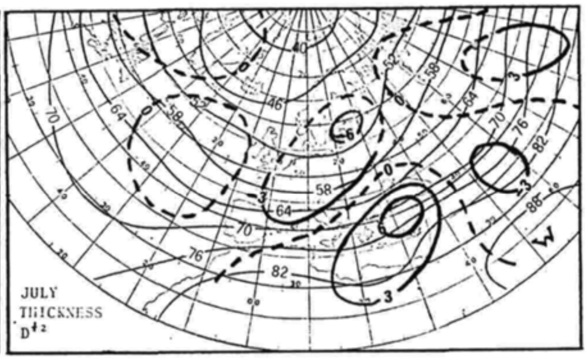


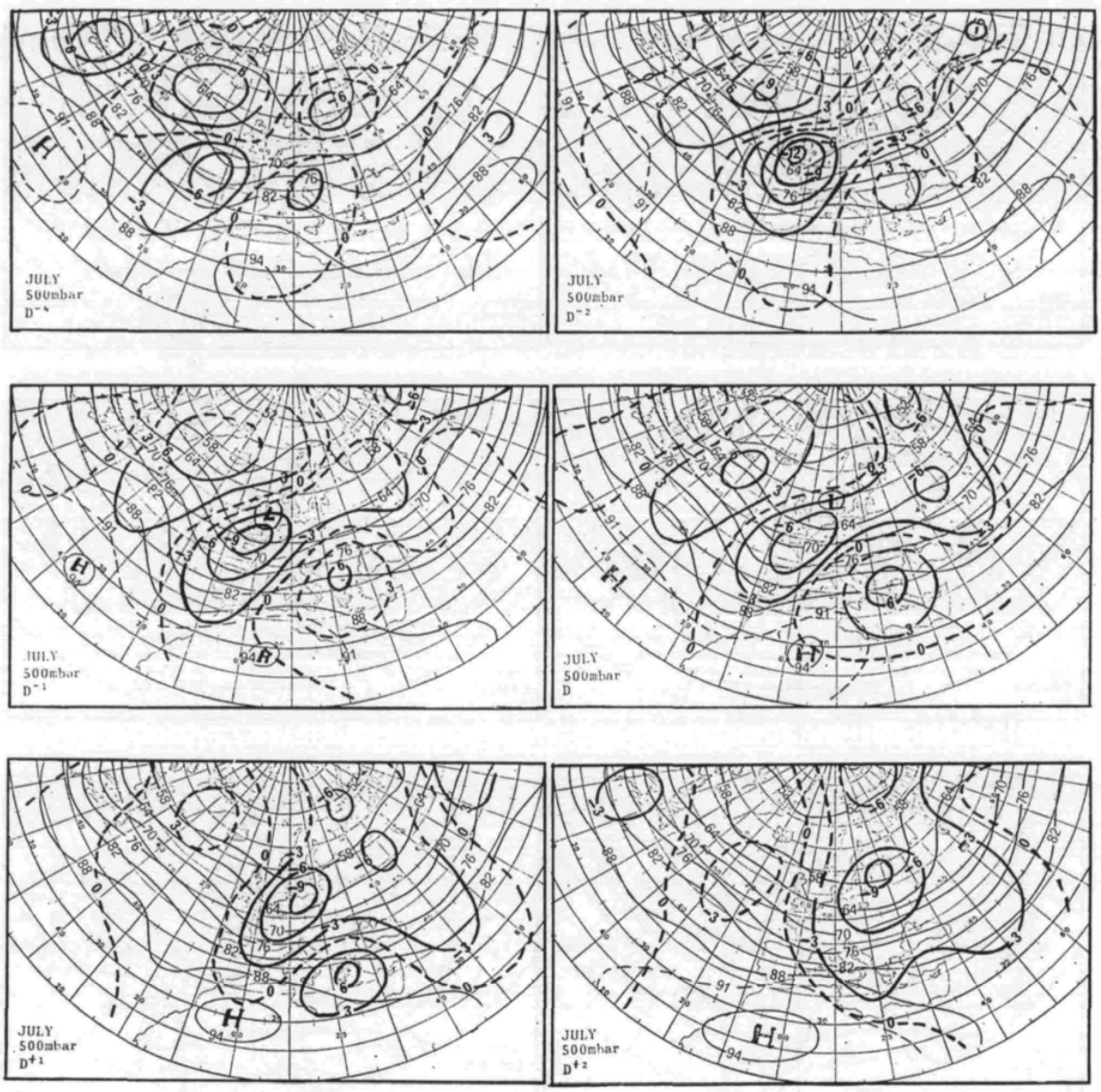








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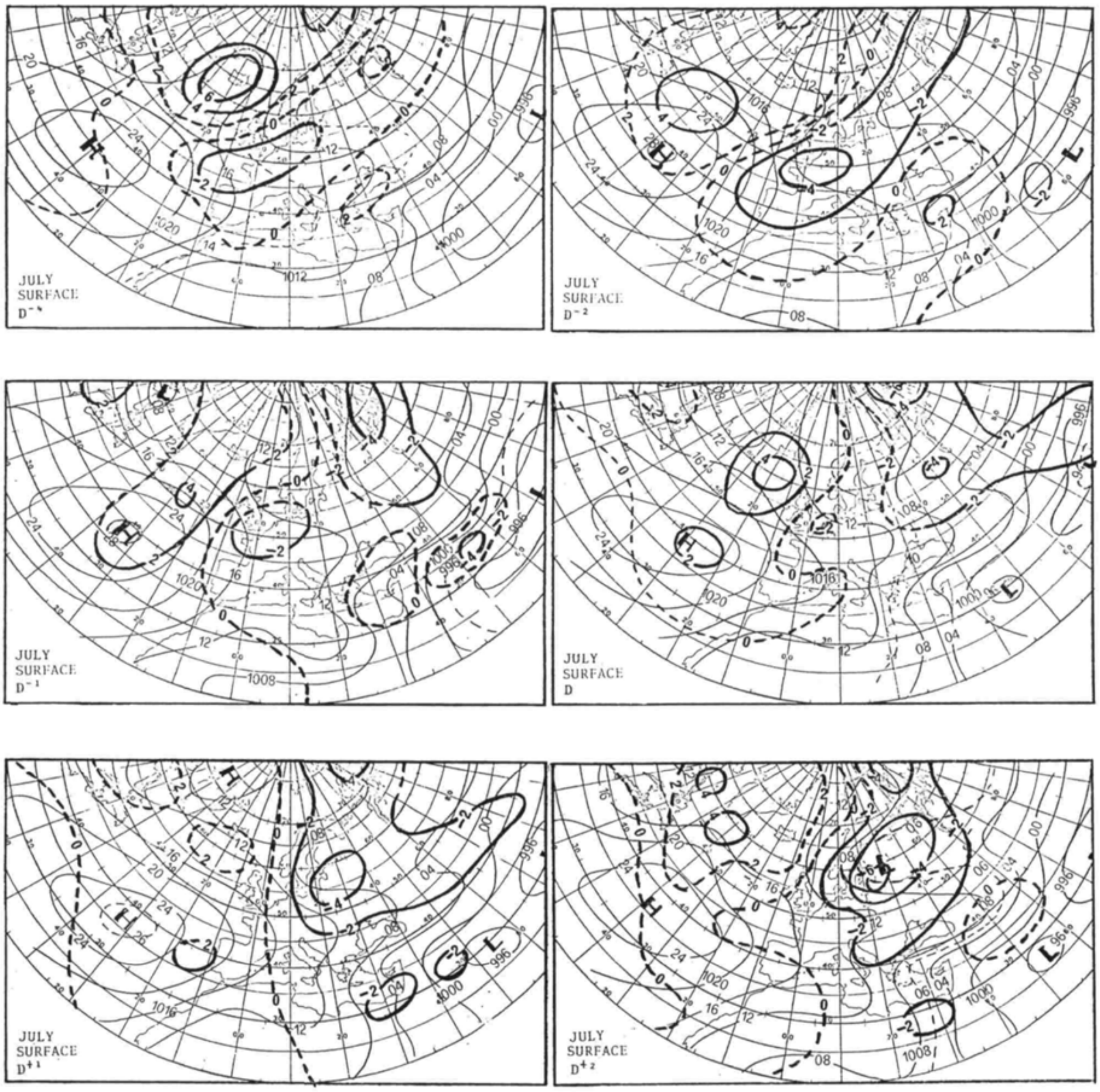
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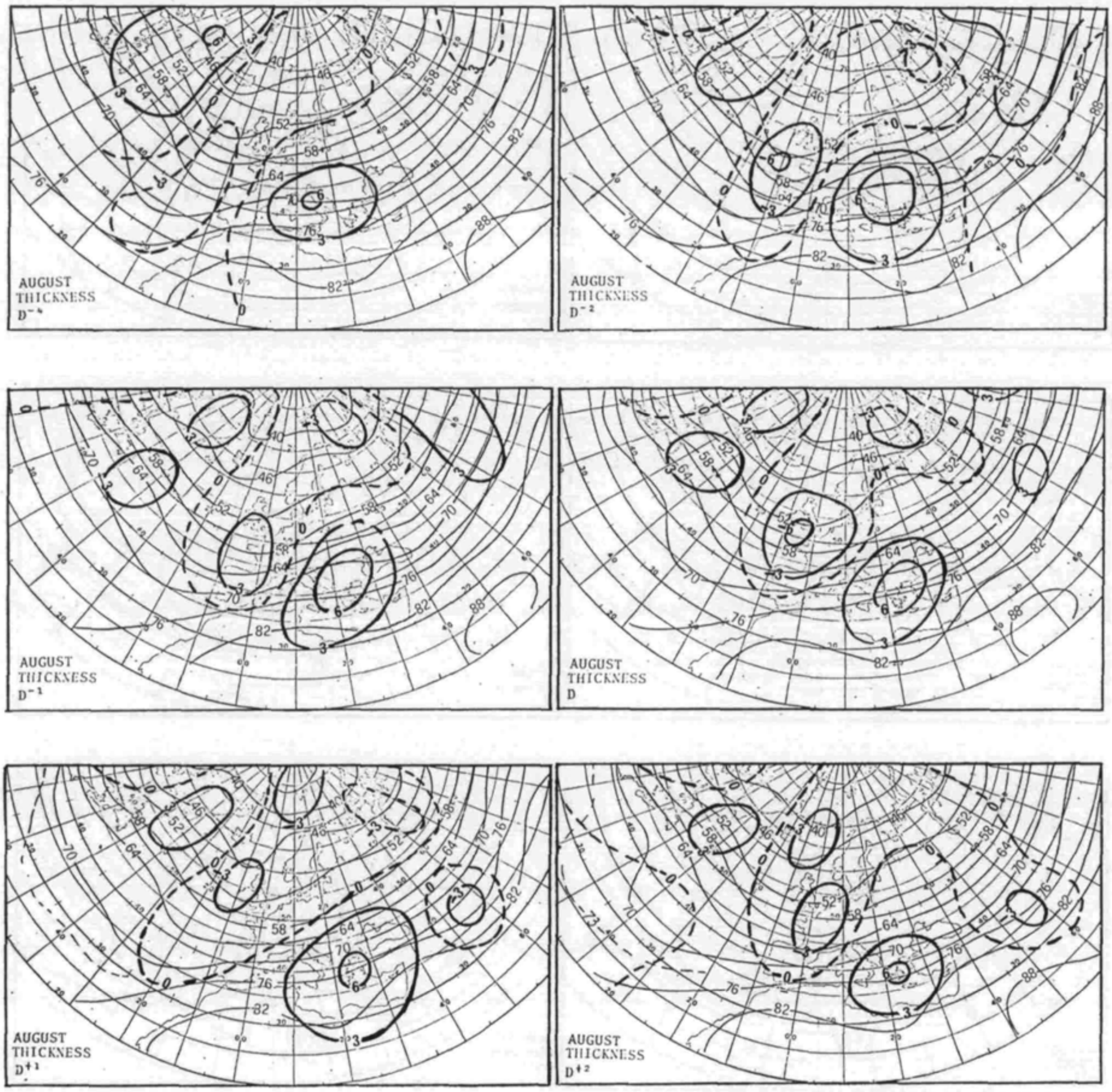
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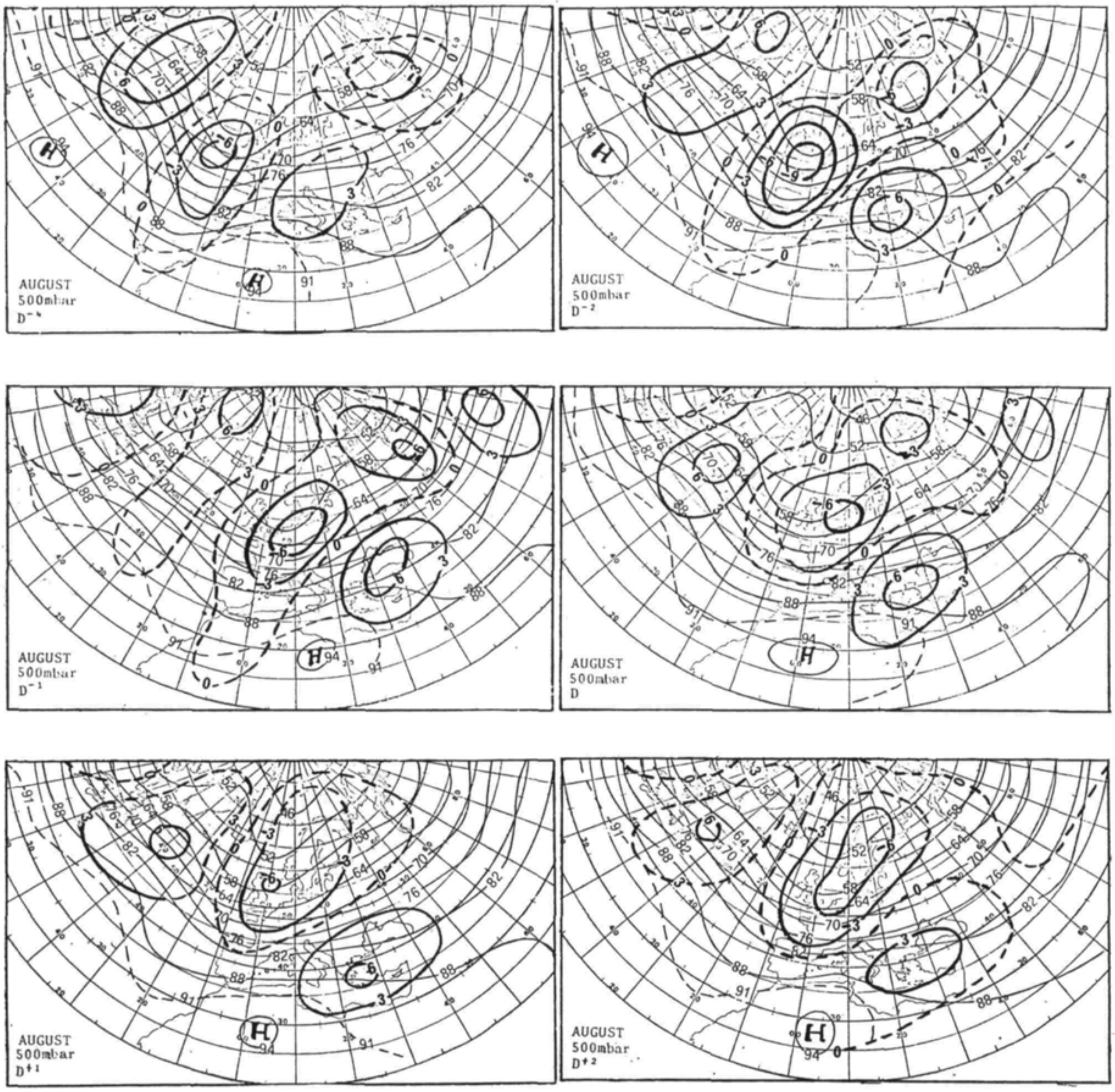
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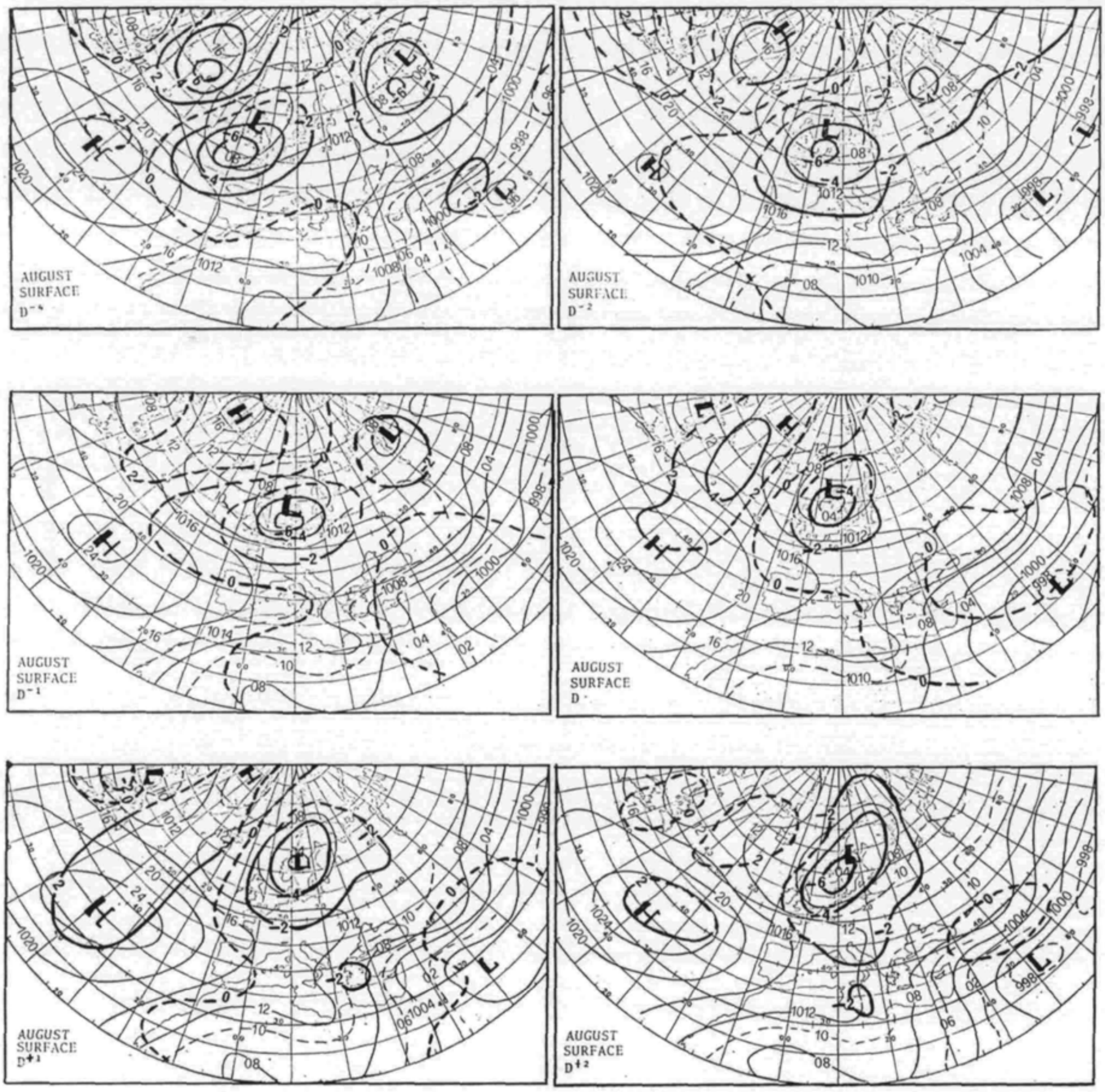
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