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A Contribution to the Study of the Vardaris Wind Regime of the Last 60 Years †

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Abstract: Episodes of NNW-erly windstorms, known in the area of Balkan Peninsula as Vardaris, were identified, with the aid of wind archive data, from the Regional Meteorological Centre of Makedonia of the Hellenic National Meteorological Service of Greece. The study of the seasonal, interannual, and diurnal variations of the occurrence of Vardaris windstorms, as well as their intensity, shows that it is a severe, long-lasting, and mainly winter-time feature, usually commencing in the morning hours. Preliminary results of the study of dynamic features accompanying Vardaris have shown that these windstorms are almost totally associated with cold fronts coming from northern sectors. The presence of a northerly jet or a tropopause fold aloft contributes to increases in the intensity or duration of the windstorms. The connection of Vardaris with these dynamical features implies that the observed negative (positive) trends of the occurrence frequency/duration (intensity) of Vardaris windstorms is in accord with the scenario of climate change.

Keywords: windstorm; seasonal–interannual variation; tropopause fold; climate change

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1. Introduction

One of the strongest, coldest, and most persistent winds in N. Greece blows through the Moravia gap towards the Valley of Axios or Vardaris River, and, with a somewhat reduced speed, over the whole region of Central Makedonia. Due to the orientation of the above valley, the basic direction of the so-called Vardaris wind is 340–350° [1]. It is essentially a local wind with katabatic characteristics, and tends to dry out the lower troposphere and reduce cloudiness and rainfall. The airport of Thessaloniki, Makedonia, due to its geographical position, is one of the most representative sites of the intensity of Vardaris. Due to the high wind speeds, as well as the long duration, Vardaris windstorms often cause disruption in aviation and navigation, and even potential accidents. The subject of this paper is Vardaris windstorms. Its aim is firstly to provide statistics regarding the 60-year climatology of the regional features of Vardaris windstorms, and, moreover, to study the synoptic-scale dynamic features of these windstorms.

The study period comprises 1961–2019. A Vardaris windstorm is here defined as an episode of NNW-erly ($340 \pm 30°$) wind which is equal or stronger to 15 Kts and lasts for at least 12 h, according to the SYNOP observations and messages of the competent meteorological station of Regional Meteorological Centre of Makedonia based at Thessaloniki's airport. Only one 3 h disruption is allowed in this 12 h period.

Emphasis will be placed on main climatology statistics, such as the interannual and seasonal variations of the occurrence frequency of Vardaris windstorms, and, moreover, the total duration and the maximum intensity of the windstorms.

As far as synoptic scale dynamics are concerned, an isentropic coordinate framework was adopted in order to better approximate the movement of air masses. The results, however, are presented on the more conventional isobaric charts. Due to data availability, space, and time limitations, the study period for significant episodes (wind speed gusts $\geq$ 35 Kts are required) was limited to 2007–2019.After applying the above criteria to the wind observations database, forty-four (44) cases emerged. Emphasis will be placed on the atmospheric processes responsible for the onset and maintenance of the windstorms.

2. Climatological Statistics

Vardaris windstorms are quite severe (Figure 1a), as their dominant (42% probability) maximum intensity lies in the range of 35–45 Kts, and the maximum observed gust has reached 80 Kts. Vardaris windstorms also tend to be quite persistent, as the distribution of their occurrence frequency is rather heavy-tailed at the right end, exceeding three days, as can be seen in Figure 1b.

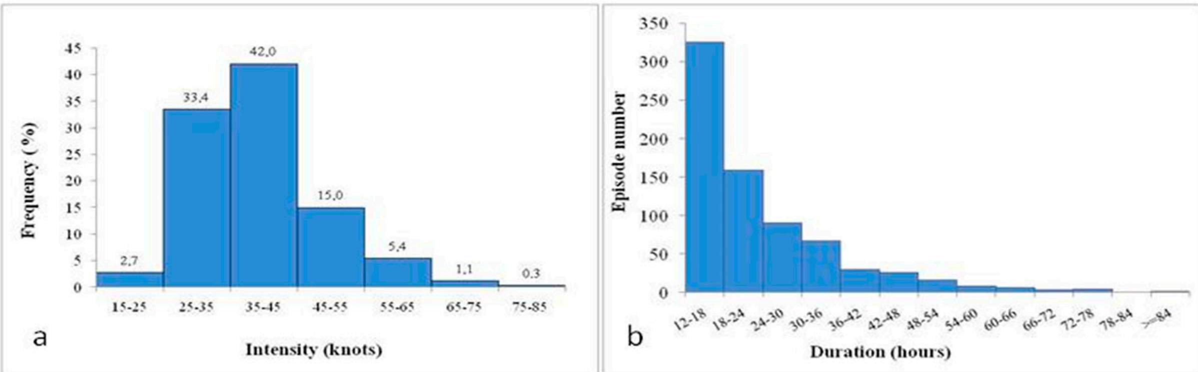

Figure 1. Histogram of Vardaris windstorm episodes distribution according to (**a**) maximum wind speed (1970–2019) and (**b**) duration (1960–2019).

The annual number of episodes of Vardaris windstorms throughout the period of 1961–2019 is shown in the graph in Figure 2a. In 95% of the years, long-lasting episodes ($\geq$24 h) occurred nearly half as often as the shorter ones (<24 h), as an average number of ~8 (4) episodes lasting less (more) than 24 h occur per year. Only in the years 1967, 1974, and 2008 did the long-lasting storms exceed the shorter ones.

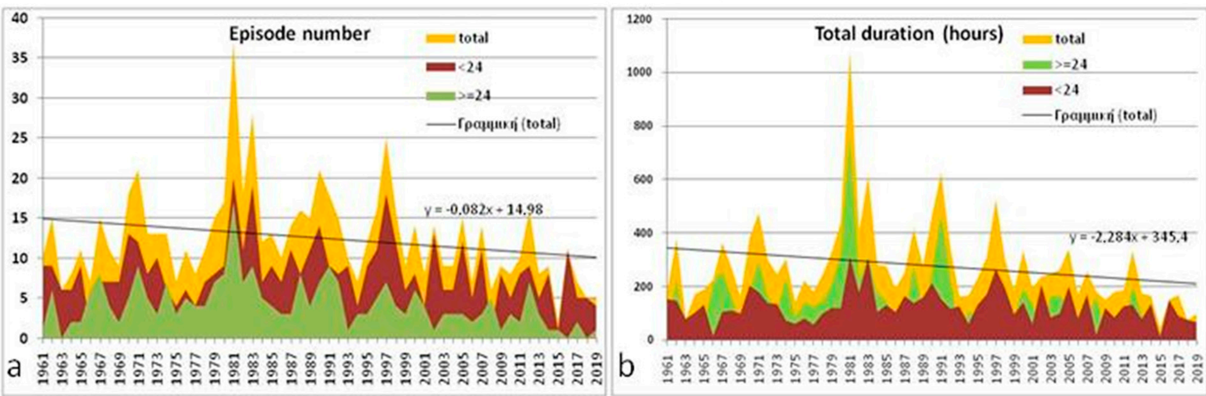

Figure 2. (**a**) Annual number of Vardaris windstorms according to duration. Red: <24 h. Green: $\geq$24 h. Yellow: total. (**b**) As in a, but for the total annual duration (hours) of Vardaris windstorms.

A general negative trend was observed, as the total occurrence number reduced from 15 to 10 episodes yearly, on average, over the study period. The total annual duration of Vardaris episodes exhibited similar variations and trends throughout the study period, as can be seen in Figure 2b. The seasonal cycle of Vardaris windstorms can be observed in Figure 3. As seen from the monthly occurrence of Vardaris windstorms, as well as their total durations, we determined that most of the activity occurs during the winter. The maximum occurs in January, with 110 windstorms (Figure 3a) and 2700 h (Figure 3b), reflecting the effect of the increased cold frontal activity at this time of the year. A rapid reduction occurs towards spring, with the minimum occurring in May, with 25 windstorms (Figure 3a) and 603 h (Figure 3b). Quite interestingly, a secondary maximum occurs in July, reflecting the response of the lower troposphere (Etesians) to the intense heating, both due to diabatic and adiabatic processes. From Figure 3b, it may further be gathered that the number of windstorms in the cold half of the year (October–March) is twice that in the warm half of the year. Finally, the study of the diurnal cycle of Vardaris revealed that the windstorms tend to begin in the morning hours (figure not shown). The seasonal (interannual) intensity variations of Vardaris windstorms are shown in Figure 4a,b. The highest wind speeds were observed in the winter (approx. 40 Kts on average), being reduced by 3–4 Kts during spring, summer, and early autumn, with an exception in July (38.7 Kts). Interannually, most of the highest wind speeds were observed in the early 1980s. Some other years with high Vardaris wind speeds were 1972, 2007–2008, 2017, and 2019. A positive trend was observed, especially in the last 20 years.

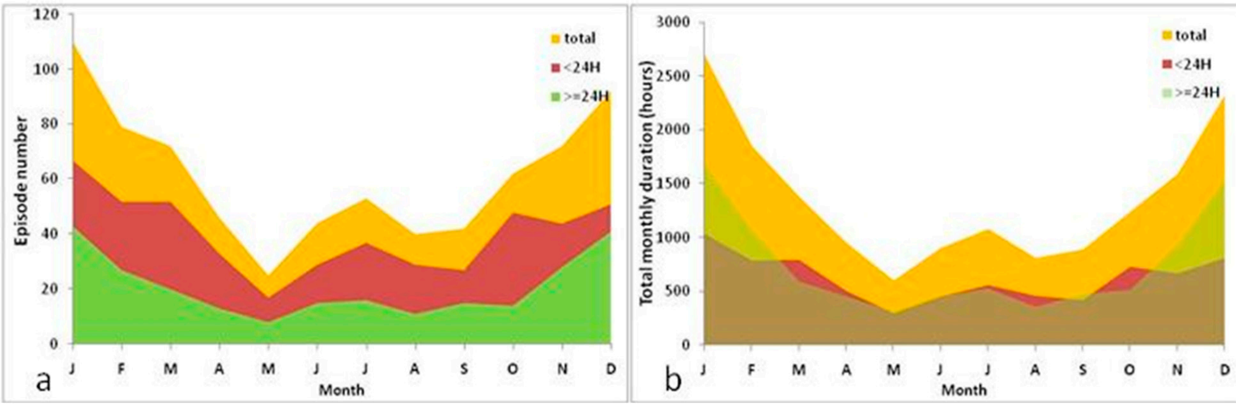

Figure 3. As in Figure 2, but for the monthly average values of occurrences (**a**) and duration (**b**) of Vardaris windstorms.

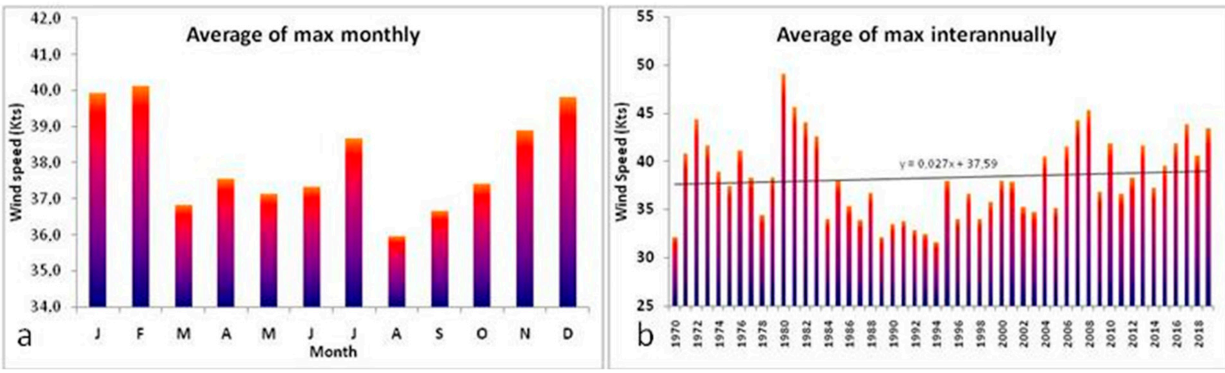

Figure 4. Seasonal (**a**) and interannual (**b**) variations of average value of the Vardaris episodes' maximum wind speeds.

3. Dynamical Study of Two Contrasting Cases: 10 November 2007 and 28 January 2008

According to preliminary results of the synoptic-scale study on physical/dynamical processes, associated with the 44 cases of Vardaris windstorms, nearly all windstorms were associated with a cold front moving in the region of central Makedonia from the northern sector. The windstorm begins with the arrival of the front. The Sawyer–Eliassen (S-E)-type cross-front circulation alone may well be associated with Vardaris gusts up to 35–50 Kts. The presence of upper-level northerly jets contributes to the maintenance of

Vardaris windstorms, or a temporal reinforcement of their intensity up to 60 Kts. Last but not least, stratospheric/dry air intrusions from the NNW sector also contribute significantly to increasing wind speeds, even to above 60 Kts. Variations in the relative importance of the above three processes are reflected by quite different synoptic-scale air flow configurations during a Vardaris windstorm. In order to provide an example of this, two contrasting cases are presented: the case of 10 November 2007 and the case of 28 January 2008. The synoptic situation for these two cases is described below with the aid of 500/850 hPa and SFC charts, as well as meridional and zonal cross-sections of the atmosphere. On the 10th of November 2007, a fast-moving cold front affected Greece from the northwest (Figure 5a,b). A combination of upper-level cold air and cyclonic vorticity advection, locally reaching 40 °C/day and 4×10^{-8} s^{-2}, respectively, promoted vigorous cyclogenesis in the Northeast Aegean Sea, which increased the isallobaric component of the wind. At 12 UTC, the front had just passed to the southeast of Thessaloniki, the location of which is shown by the vertical dotted lines in the sections of Figure 5c,d. The 285 K isentrope (12 °C at 1000 hPa) may have served to delineate the leading edge of the cold air mass in these vertical sections. The cross-front S-E vertical circulation is evident in the meridional cross-section of Figure 5c as a nearly vertical couplet of northerlies/southerlies of respective intensities of 22/37 m/s, located at ~41 oN/45 oN and 850/400 hPa in the vertical. The windstorm was associated with the lower, northerly branch of this S-E circulation. Despite of the absence of any northerly jet above the windstorm, further west (Figure 5d), there was a northwesterly jet, acting to transfer northwesterly momentum to the Vardaris windstorm under study. Combining the information from the 500 hPa chart (Figure 5b) and the cross sections (Figure 5c,d), it emerged that a dry/stratospheric air intrusion was under way along the cyclonic flank of the northwesterly jet over the Adriatic Sea. The significant subsidence and the increased westerly component of the flow (see Figure 5d), which prevailed in the area between the NW-erly jet and the Vardaris windstorm site, transferred NW-erly momentum to the area of the windstorm, the intensity of which reached 65 Kts at 12 UTC. It is quite interesting that this windstorm, despite its record-breaking intensity, developed in an environment of a southerly (see Figure 5c) upper-level flow. This was associated with increased baroclinicity at all tropospheric levels, as the trough axis was still upstream of the windstorm.

In contrast to the above case, two-and-a-half months later, a Vardaris case occurred on 28 January 2008, which was more uniform in terms of height flow. As can be seen in all panels of Figure 6, northerlies prevailed nearly everywhere. Essentially, this case is associated with a strong northerly jet dominating most of the European continent, with a core of nearly 70 m/s at 350 hPa. Greece is located under the exit of the jet. Because of the presence of the cold front directly under the jet exit, northerly momentum is advected downwards, which appears to be one of the main causes of the Vardaris windstorm (nearly 60 Kts between 06 and 12 UTC). Almost all cases studied here are classified to either the type of the former, termed here as the "active front" type, or the latter case described above, termed here as the "jet" type. The differences between these two types are as follows. In the active front (jet) type, the windstorm develops ahead (behind) of the axis of the upper trough. This is associated with the upper flow having a uniform northerly direction at all levels for the jet type, whereas, in the active front type, there is southerly flow at the mid-upper levels. The reversal of the sign of the flow direction with height is associated with a frontogenetically active front, which is, most of the time, accompanied by clouds and even rainfall. In both types, but most severely in the active front type, stratospheric air with NW-erly momentum may subside towards the site of the Vardaris windstorm, promoting cyclogenesis in its eastern vicinity, which increases the isallobaric component of the windstorm.

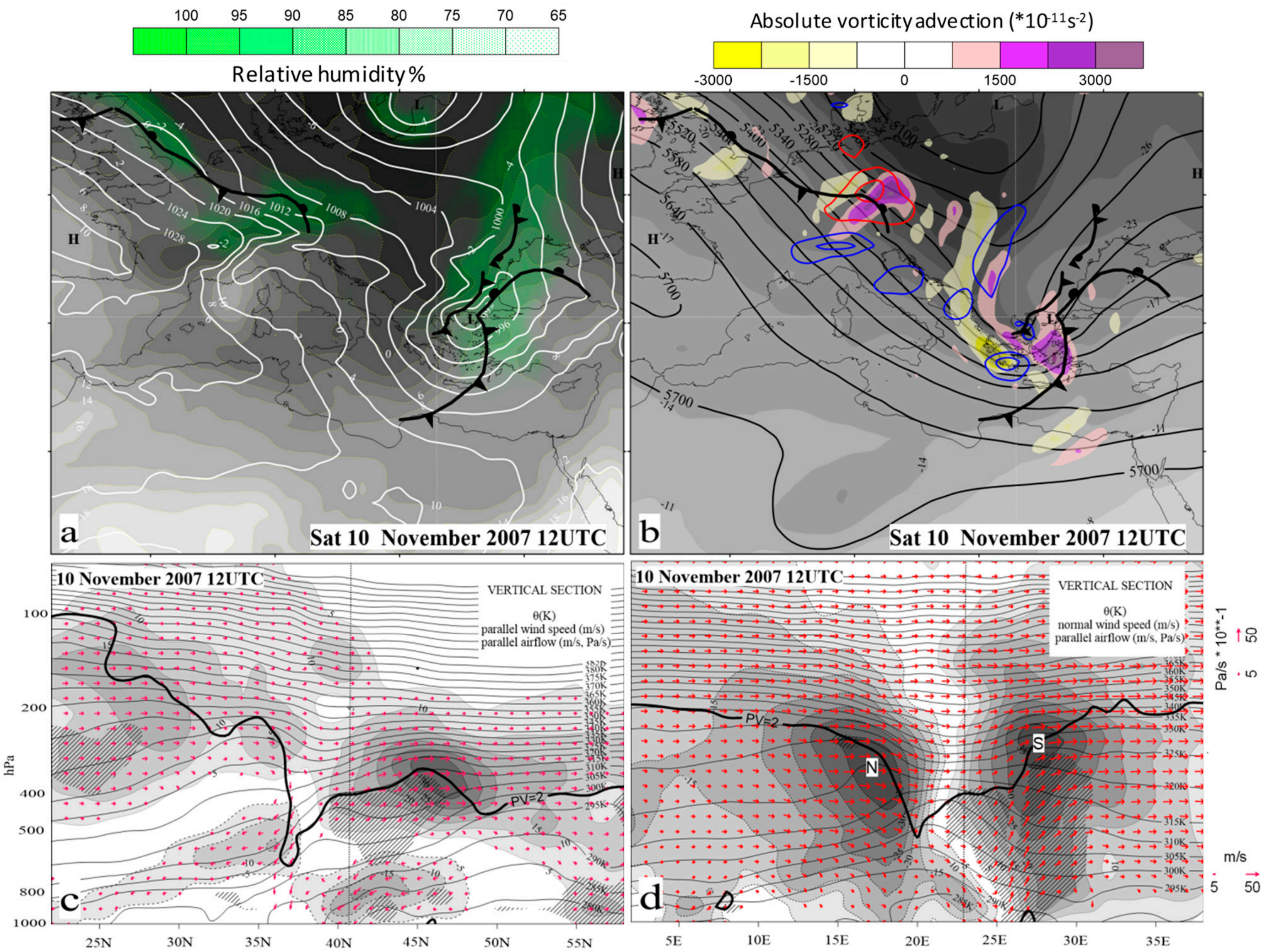

Figure 5. 10 November 2007 12 UTC. (**a**) Mean sea level pressure (white lines per 4 hPa), 850 hPa temperature (decreasingly shaded per 2 °C) and 700 hPa relative humidity > 65%, increasingly (shaded as shown in the color bar above the chart). (**b**) 500 hPa geopotential height (black lines, per 60 gpm), temperature (decreasingly shaded per 3 °C), absolute vorticity advection > ±750 × 10^{-11} s^{-2} (shaded as shown in the color bar above the chart) and thermal advection > ±20 °C/day, with red (blue) contours enclosing areas of warm (cold) air advection, per 20 °C/day. (**c**) Meridional vertical cross section of the atmosphere along the white line shown in charts (**a**,**b**). Thin black lines: potential temperature per 5 K. Shading: meridional wind component > ±10 m/s. Dotted (continuous) contours enclose areas where the meridional wind component is northerly (southerly). Arrows: vertical circulation along section. Hatching: relative humidity > 80%. Thick black line: PV = 2 PV units (dynamic tropopause). (**d**) As in panel (**c**), but for a zonal section. Vertical dotted line shows the location of Makedonia airport in both sections (**c**,**d**).

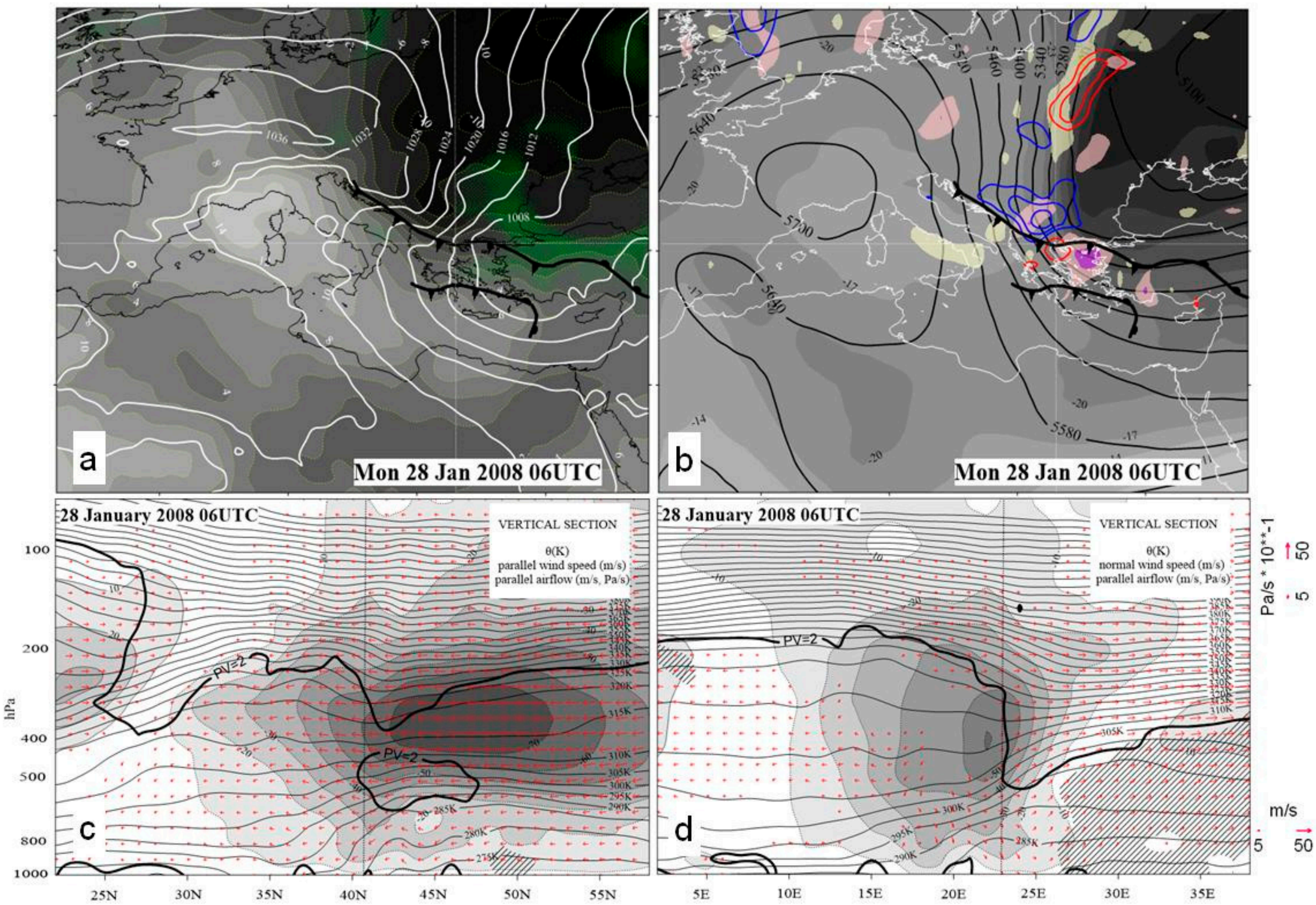

Figure 6. 28 January 2008 06 UTC. (**a**) Mean sea level pressure (white lines per 4 hPa), 850 hPa temperature (decreasingly shaded per 2 °C) and 700 hPa relative humidity > 65%, increasingly (shaded as shown in the color bar above the chart). (**b**) 500 hPa geopotential height (black lines, per 60 gpm), temperature (decreasingly shaded per 3 °C), absolute vorticity advection > $\pm 750 \times 10^{-11}$ s^{-2} (shaded as shown in the color bar above the chart) and thermal advection > ±20 °C/day, with red (blue) contours enclosing areas of warm (cold) air advection, per 20 °C/day. (**c**) Meridional vertical cross section of the atmosphere along the white line shown in charts a, b. Thin black lines: potential temperature per 5 K. Shading: meridional wind component > ±10 m/s. Dotted (continuous) contours enclose areas where the meridional wind component is northerly (southerly). Arrows: vertical circulation along section. Hatching: relative humidity > 80%. Thick black line: PV = 2 PV units (dynamic tropopause). (**d**) As in panel (**c**), but for a zonal section. Vertical dotted line shows the location of Makedonia airport in both sections (**c**,**d**).

4. Conclusions

A 60-year-long wind database was analyzed, and evidence has been provided that Vardaris windstorms are quite vigorous phenomena, with dominant wind speeds of 35–45 Kts and maximum observed gusts up to 80 Kts. The duration of the windstorms is up to three days, which is quite long compared with observed windstorms in the literature (see [2] and references therein). They are more frequent during the winter, especially the longest ones, but there also is a secondary maximum of their occurrence frequency in mid-summer. Maximum wind speeds are also highest in the winter, with a secondary maximum occurring in mid-summer.

Almost all Vardaris windstorms are associated with a cold front moving in the area of Central Makedonia from the north sector. A northerly upper-level jet, accompanied by subsidence, acts by transferring northerly momentum to a Vardaris windstorm, increasing its duration, or even—temporally—its intensity. Tropopause folds/stratospheric air intrusions also act to strengthen Vardaris windstorms, either directly, by northwesterly momentum transfer downwards, or indirectly, via the isallobaric component of the wind, which blows towards areas of ensuing cyclogenesis to the east. Especially during the summer, Vardaris windstorms may be enhanced by the Etesians mechanism, which reflects the response of the atmosphere to the intense diabatic and, especially, adiabatic heating that takes place in the Eastern Mediterranean region [3].

The negative (positive) trends of the occurrence frequency and the total duration (maximum intensity) of Vardaris windstorms are in agreement with the climate change scenario. Regardless of the physical mechanisms that lie behind them and how these may vary due to climate fluctuations, the fact is that Vardaris windstorm are violent and occur every three weeks in the cold half of the year, lasting for about one-and-a-half days. This does not take into account Vardaris cases that last less than 12 h. From this point of view, the present study provides evidence that Vardaris windstorms actually define the climate of the region of Central Makedonia.

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