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The Impact of Atmospheric Temperature Variations on Glycaemic Patterns in Children and Young Adults with Type 1 Diabetes

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Abstract: Seasonal variations in glycaemic patterns in children and young adults affected by type 1 diabetes are currently poorly studied. However, the spread of Flash Glucose Monitoring (FGM) and continuous glucose monitoring (CGM) systems and of dedicated platforms for the synchronization and conservation of CGM reports allows an efficient approach to the comprehension of these phenomena. Moreover, the impact that environmental parameters may have on glycaemic control takes on clinical relevance, implying a need to properly educate patients and their families. In this context, it can be investigated how blood glucose patterns in diabetic patients may have a link to outdoor temperatures. Therefore, in this study, the relationship between outdoor temperatures and glucose levels in diabetic patients, aged between 4 and 21 years old, has been analysed. For a one-year period (Autumn 2022–Summer 2023), seasonal variations in their CGM metrics (i.e., time in range (TIR), Time Above Range (TAR), Time Below Range (TBR), and coefficient of variation (CV)) were analysed with respect to atmospheric temperature. The results highlight a negative correlation between glucose in diabetic patients and temperature patterns (R value computed considering data for the entire year; Ry = −0.49) , behaviour which is strongly confirmed by the analysis focused on the July 2023 heatwave (R = −0.67), which shows that during heatwave events, the anticorrelation is accentuated. The diurnal analysis shows how glucose levels fluctuate throughout the day, potentially correlating with atmospheric diurnal temperature changes in addition to the standard trend. Data captured during the July 2023 heatwave (17–21 July 2023) highlight pronounced deviations from the long-term average, signalling the rapid effects of extreme temperatures on glucose regulation. Our findings underscore the need to integrate meteorological parameters into diabetes management and clinical trial designs. These results suggest that structured diabetes self-management education of patients and their families should include adequate warnings about the effects of atmospheric temperature variations on the risk of hypoglycaemia and about the negative effects of excessive therapeutic inertia in the adjustment of insulin doses.

Keywords: temperature; type 1 diabetes; climate change; atmosphere; glucose pattern

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Citation: Chiacchiaretta, P.; Tumini, S.; Mascitelli, A.; Sacrini, L.; Saltarelli, M.A.; Carabotta, M.; Osmelli, J.; Di Carlo, P.; Aruffo, E. The Impact of Atmospheric Temperature Variations on Glycaemic Patterns in Children and Young Adults with Type 1 Diabetes. *Climate* **2024**, *12*, 121. https://doi.org/10.3390/cli12080121

Academic Editors: Diogo Guedes Vidal and Hélder Silva Lopes

Received: 26 June 2024
Revised: 7 August 2024
Accepted: 8 August 2024
Published: 12 August 2024

1. Introduction

Type 1 diabetes is one of the most frequent chronic diseases in paediatric age [1,2]. From pre-adolescence to emerging adulthood, metabolic control undergoes significant deterioration, and in general, a minority of patients achieve the recommended glycaemic targets [3,4] despite the introduction of new insulins and the diffusion of technologies such as CGM systems and, more recently, of smart pens and Advanced Hybrid Closed-Loop (AHCL) system insulin pumps. Many of these devices are often underutilised due to both economic limitations in some countries and a lack of professional resources to provide effective training. Data are often not provided correctly to diabetes care treatment teams by patients/family members, resulting in a lack of adjustment of nutritional and insulin therapy aimed at improving metabolic control. On the other hand, the spread of devices for continuous glucose monitoring and the possibility of sharing reports in real time with health professionals has provided such an enormous amount of data that the introduction of new metrics for assessing metabolic control has become necessary [5]. Usually, short periods (2 weeks) are considered enough for judgments referring to the last three months if CGM has been active for more than 70% of the 14 days analysed, and similar considerations have been made for the use of CGM in clinical trials. The influence of seasonality and vacations has rarely been evaluated as a function of metabolic control and the prevalence of hypoglycaemia, especially in paediatric age, nor have studies considered the effects of acute variations in atmospheric temperature on metabolic control. It has been shown that atmospheric temperature variations correlate with increased morbidity and cardiovascular risk [5–9]. In individuals with type 2 diabetes, extreme atmospheric temperatures correlate with adverse effects such as increased severe hypoglycaemic risk, ketoacidosis (DKA), and major cardiovascular events [10]. In adults with type 1 and type 2 diabetes, air temperature has been observed to correlate with hospitalisations for acute complications [9,11–13]. Specifically, severe hypoglycaemia was found to be more frequent in summer in adults with type 1 diabetes [14] It has been estimated that a 5 °C increase in the average daily temperature on the same day is associated with an 8% increase in hospitalisation due to complications of type 1 diabetes [12]. Regarding paediatric age, there are not many studies on this in the literature [12,15,16]. It is also useful to point out that the mechanisms underlying the increased occurrence of hypoglycaemia and DKA under high temperatures include changes in glucose metabolism and increased insulin uptake [17,18]. However, there are not many studies in the literature with regard to this in paediatric age [12,15,16]. It should also be considered that children have lower thermoregulatory abilities and often spend a longer time outdoors compared with adults [19,20]. Therefore, for a one-year period (Autumn 2022–Summer 2023), seasonal glycaemic trends and the prevalence of hypoglycaemia were analysed in 138 young people with type 1 diabetes treated with multiple daily injection (MDI) who used FGM or CGM consistently. A discussion of the possible causes of hypoglycaemia and clinical implications for the management of diabetes is provided. The results of this study could offer advice to clinicians on intervening more effectively and with less latency during periods of metabolic deterioration related to seasonal and/or temperature variations; at the same time, knowledge of periods of increased hypoglycaemic risk could allow for better prevention.

2. Materials and Methods

2.1. Research Design

A cluster of 138 subjects with type 1 diabetes, aged between 4 and 21 (12.01 ± 4.48 yrs) and followed at the UOSD Regional Service of Paediatric Diabetology Hospital Polyclinic "SS. Annunziata", was included in the study. All patients used the Freestyle 2-3® system and had high adherence to continuous glycaemic monitoring (>70%). Data for all patients were synchronised on a cloud-based management system (Freestyle® LibreView system) and shared with the diabetes care team. The inclusion criteria were an age between 4 and 21 years; a diagnosis of T1D confirmed by the positivity of at least one antibody against islet cells (ICA), insulin (IAA), glutamate dehydroxilase (GADA), islet antigen 2 (IA2A), or zinc-transporter protein 8 (ZnT8A) [21]; and following multiple daily injection (MDI) therapy as an insulin regimen. The exclusion criteria were children with more than one episode of DKA in the last year, uncontrolled coeliac disease or hypothyroidism, oncohaematologic diseases, severe psychiatric disorders, or therapy with systemic steroids during the study year. Chronic conditions, such as hypothyroidism and coeliac disease, were clinically well controlled by periodically monitoring the affected patients. Their glycaemic profiles were evaluated in relation to atmospheric temperature patterns related to the patients' area of residence. Temperature data were obtained from the Regional Hydrographic Office. To relate the described parameters, a statistical analysis was conducted on the one-year-period data (Autumn 2022–Summer 2023) using seasonal variations in the CGM metrics, means, STD, Singular Spectrum Analysis (SSA), scatter plots, and correlation coefficients.

2.2. Medical Data

The data were accessed for the first time for research purposes on 31 January 2024 in a pseudonymised format that did not allow the authors (with the exception of the hospital doctors involved in the study who treated the patients) to access information that could identify individual participants during or after the data collection. The data considered cover a period from 20 September 2022 to 21 September 2023. Quality-checking of the data on glucose daily and hourly mean involved investigating the actual number of patients in the sample with data available for each day and hour. The analysis showed a consistent and mostly complete dataset (>70% for all the time spans considered). The demographic and clinical characteristics of the patients included in the studied cluster are shown in Table 1. This table summarises the key demographic and clinical characteristics of the study participants, providing an overview of the patient population's age distribution, gender, associated illnesses, duration of diabetes, average HbA1c levels, and insulin usage patterns. Such comprehensive data are crucial for analysing the impact of various factors on glycaemic control and diabetes management in young patients. Only three cases of severe hypoglycaemia associated with convulsions, loss of consciousness, and glucagon use were recorded in the cluster studied and during the period under analysis.

Table 1. Demographic and clinical participant characteristics.

Number of Patients	138
Gender (M/F)	
Males	47%
Females	53%
Age	
0–6 years	3%
7–8 years	7%
9–11 years	11%
12–17	53%
18–21	26%
Concomitant illness	
Celiac disease	11%
Hypothyroidism	9%
Diabetes duration (years)	1–8
Mean HbA1c % (mmol/mol)	7.08 ± 1.2 (54 ± 13)
% of patients characterised by HbA1c target [22]	
HbA1c < 7.5% (<58 mmol/mol)	63%
HbA1c ≥ 7.5% (≥58 mmol/mol)	37%
Type of insulin	
Pre-prandial insulin/kg (mean value)	0.47 IU/kg
Basal insulin/kg (mean value)	0.38 IU/kg

2.3. Meteorological Data

Regarding the meteorological data, we accessed raw instrumental temperature data spanning from 1 January 2022 to 31 December 2023 for all available stations provided by the Regional Hydrographic Office. This dataset, which includes date, solar time, and 15 min averaged measured temperatures, was sourced directly from the data acquisition systems of the 102 monitoring stations used in this study. In our research, a quality check process was also applied to the temperature dataset. We carefully evaluated any potential anomalies such as missing data or spikes to enhance the reliability of the dataset. In this study, data related to all available stations and referring to the period from 20 September 2022 to 21 September 2023 were employed.

3. Results

3.1. Annual Analysis

An evaluation of the annual trends in mean glucose and atmospheric temperature was performed. For this purpose, the mean of the daily glucose averages of the 138 patients was calculated for each day during the period from 20 September 2022 to 21 September 2023. The resulting glucose pattern was compared to the temperature trend in the same period (Figure 1), highlighting the contrast in phase of the two curves, which was confirmed by the correlation analysis, showing a moderately negative correlation coefficient between the two parameters.

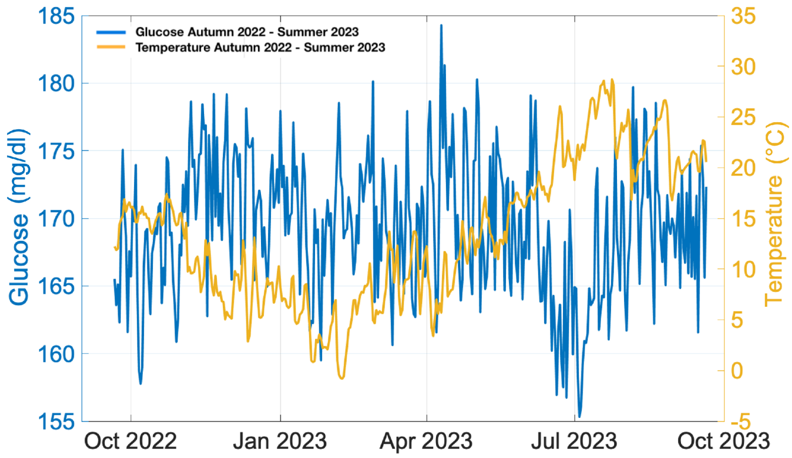

Figure 1. Daily mean glucose levels and atmospheric temperature variations observed from Autumn 2022 to Summer 2023.

To investigate this relationship in more detail, a comparative analysis of the temperature and glucose values, based on daily cycles, was carried out for both diabetic and healthy patients (in this case, we referred to the pattern described in the literature [23]). The outputs show a negative correlation between the blood glucose trends in the diabetic patients and the temperature values; regardless, Lanzinger et al. (2023) show that the diurnal blood glucose trends in healthy people follow a similar behaviour to that seen in the diabetic patients, suggesting a positive correlation between blood glucose and atmospheric temperature [15]. As a consequence, the link between atmospheric temperature values, i.e., seasonality, and changes in insulin doses has also been investigated. These parameters are susceptible to variations depending on temperatures and seasonality (also related to greater physical activity, holidays, etc.) and are adjusted according to individualised algorithms which are adapted to each patient. To this end, an analysis of the differences in glycaemic trends and the frequency of hypoglycaemic episodes in the patient sample considered was performed.

The International Consensus [24] defined, through the work of an international group of experienced clinicians and researchers, key metrics for the evaluation of CGM data [5]:

- Number of days for which the sensor was worn (recommended ≥ 14 days)
- CGM utilisation rate (recommended >70%)
- Average blood glucose
- Estimated glycated haemoglobin
- Glycaemic variability (target CV ≤ 36%)
- TAR (>250 mg/dL) [Level 2]: <5%
- TAR (181–250 mg/dL) [Level 1]: <25%
- TIR (70–180 mg/dL): >70%
- TBR (54–69 mg/dL) [Level 1]: <4%
- TBR (<54 mg/dL) [Level 2]: <1%

Considering these indications, after performing an initial filtering based on the first two items, adherence to these conditions was observed in the entire pool of patients analysed (138 patients), as shown in Table 1. For each season, the glycaemic variability was evaluated; a second filtering was performed based on this basis, removing all patients characterised by a CV > 36% (Table 2); this affected the sample's numerosity (shown in Table 2 for different seasons) but allowed for the removal of possible outliers. Seasonal differences in glycaemic trends and the frequency of hypoglycaemic and hyperglycaemic episodes were analysed using the standard metrics (TIR, TAR level 1 and level 2, and TBR level 1 and level 2) (Table 3) according to their definitions given above. In Table 3, the percentages in the second column refer to the recommended values for the percentage of time in the reference interval (first column), while those in the header refer to the number of patients who met these values. The TIR and TBR results showed percentages of time spent within the target that were lower in summer than in the other seasons, which led us to consider there to be a higher frequency of hypoglycaemic events in this season. Conversely, the TAR results, both at the first and second levels, highlighted a percentage of time within the target lower in winter than in the other seasons, which led us to deduct a higher frequency of hyperglycaemic events in this season. This behaviour is coherent with the yearly pattern analysis (Figure 1).

Table 2. Glycaemic variability was computed, and on this basis, a second filtering was performed, removing all patients characterised by a CV > 36%. % of patients characterised by CV target in table.

Season-Year	% of Patients
Autumn-2022	33%
Winter-2022	30%
Spring-2023	30%
Summer-2023	31%

Table 3. Seasonal differences in glycaemic trends and frequency of hypoglycaemic and hyperglycaemic episodes. Variations in the CGM metrics in table.

Parameter	Recommended Value	% of Patients Autumn 2022	% of Patients Winter 2022	% of Patients Spring 2023	% of Patients Summer 2023
TAR (>250 mg/dL)	<5%	60%	55%	63%	60%
TAR (181–250 mg/dL)	<25%	78%	71%	73%	79%
TIR (70–180 mg/dL)	>70%	27%	26%	27%	21%
TBR (54–69 mg/dL)	<4%	100%	98%	98%	93%
TBR (<54 mg/dL)	<1%	100%	100%	100%	100%

3.2. Heatwave Analysis

During July 2023, southern Europe experienced a heatwave [25–27]. Starting in the first decade of July 2023, there was a definite expansion toward the Mediterranean of a promontory of a subtropical desert matrix, which extended from North Africa into Italy. This anticyclone, well structured at altitude, was associated with the transport of very warm air with isotherms of up to 24–26 °C at 850 hPa. From the mid-month onward, further strengthening was seen. Over the Mediterranean area, high-altitude temperatures at 850 hPa were between 24 and 30 °C, values usually found over the Sahara Desert during the same period. A warm air mass at high altitudes with such characteristics promotes rising temperatures even in the lower layers, such that significantly high values were reached in parts of central and southern Italy [28]. In this context, we focused on the relation between atmospheric temperature and glucose trends for the 17–21 July 2023 period, both in terms of time series (Figure 2) and daily patterns. In this period, the averaged difference between the hourly values of temperature and the monthly mean was +3 °C. These results highlight the negative correlation between these two parameters (Figures 3 and 4). Moreover, the estimated slope between temperature and glucose during the heatwave (−0.84 °C/mg/dL) was higher than that estimated during the whole period studied (−0.22 °C/mg/dL); this behaviour confirms that glucose tends to decrease faster in the occurrence of heatwave events.

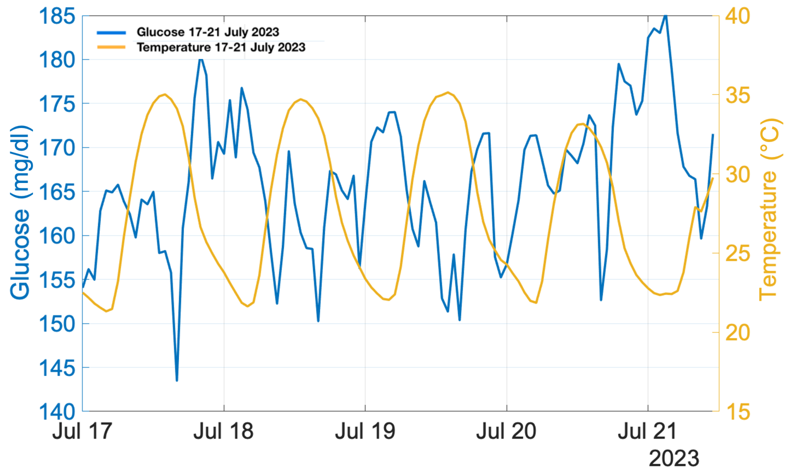

Figure 2. Glucose levels and atmospheric temperature variations from 17 July to 21 July 2023.

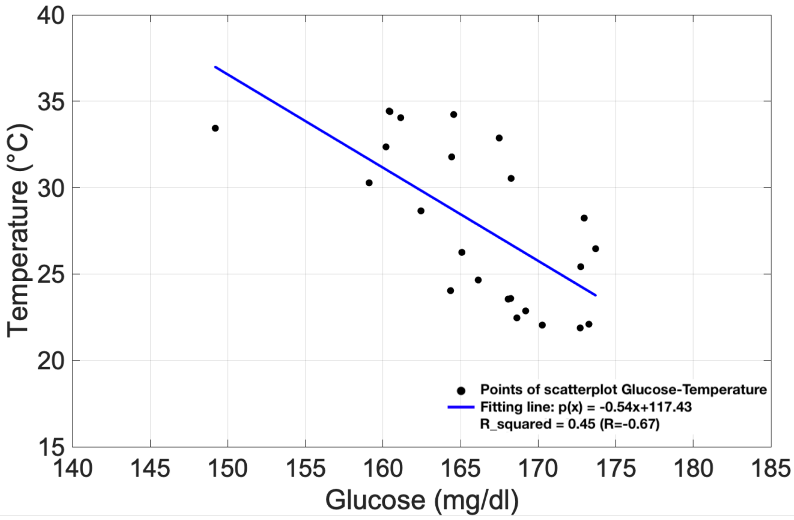

Figure 3. Relationship between glucose levels (mg/dL) and atmospheric temperature (°C) from 17 July to 21 July 2023.

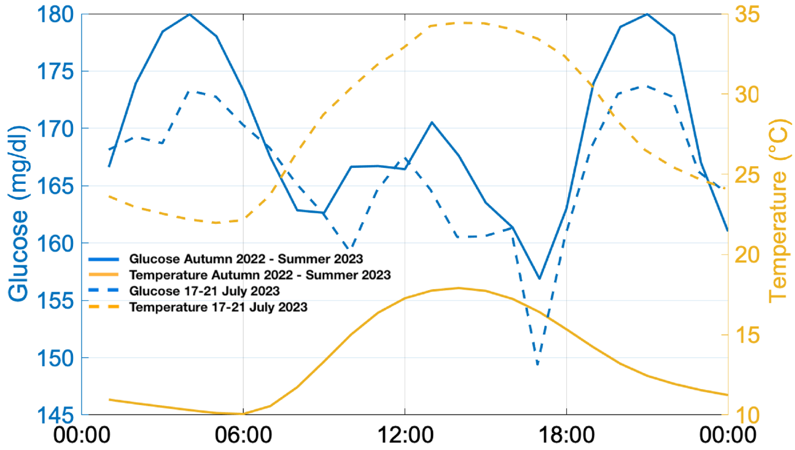

Figure 4. Diurnal patterns of glucose levels and atmospheric temperature during the 17–21 July 2023 heatwave compared to data from the Autumn 2022–Summer 2023 period.

3.3. Overall Results Analysis

Before the extensive use of CGM, seasonal variations in glycated haemoglobin were reported (HbA1c) in both adults and children with type 1 diabetes, with the lowest values during summer and the highest levels during winter [6–9,17,29,30]. Studies evaluating glycaemic trends in a population exclusively composed of children and young adults with type 1 diabetes are very rare [15] and have shown that for every 1 degree increase in atmospheric temperature, there is an acute decrease in cases of TAR level 2 (>250 mg/dL) [15]. Information collected with wearable devices through automatic storage and synchronisation systems allows us to assess glycaemic patterns and therefore to study the distribution of hypoglycaemia episodes. Hyperglycaemia and hypoglycaemia were correlated with environmental temperature. Previously, self-monitored blood glucose (SMBG) technologies offered a discontinuous and often biased view of glucose changes. Furthermore, hypoglycaemic episodes were only valued in patient history if symptomatic and associated with neurological impairments, glucagon administration, and/or emergency service intervention. The availability of these data also offers us the possibility to assess the variations in glycaemic levels in relation to correct patient/family behaviours, such as timely increases in insulin doses during periods of hyperglycaemia or conversely their reduction after prolonged periods of low glycaemic values. This also allows clinicians to focus on individual problems through educational reinforcement or psychological/behavioural support, either in the case of excessive fear of hypoglycaemia or conversely in the case of failure to perceive the risks posed by hypoglycaemia. The deployment of CGM systems has revolutionised our understanding of glycaemic patterns in relation to environmental factors. Historically, the literature highlighted seasonal variations in HbA1c levels in type 1 diabetic individuals, indicating lower values during warmer months and elevated levels in colder periods [1,3,5,6,8,18,23]. The phenomenon of seasonal variations in HbA1c levels has been found to be clinically relevant in school-age children with type 1 diabetes and is a significant phenomenon that should be addressed in patient or family education on diabetes management [30]. Moreover, this should be considered in the design of clinical trials, as it can significantly influence the results when these variations include HbA1c levels and blood glucose levels. Our analysis, enhanced by granular data from wearable CGM devices, reaffirms these seasonal trends and extends our understanding of atmospheric temperature's acute impact on glycaemic excursions. With our dataset, indeed, we observed some key topics. The first one is seasonality, for which, confirming the previous findings, we noticed distinct seasonal patterns, with glucose levels being more stable during the summer months, as depicted in Figure 1. Another key output is atmospheric temperature's anticorrelation with glucose patterns, as illustrated in the scatter plot in Figure 3 (each point represents a simultaneous measurement of glucose and regional mean temperature, with the fitted curve indicating the overall trend of a decreasing temperature as glucose levels increase; R = −0.67), where we found an anticorrelation between temperature increases and glycaemic levels, providing further evidence of the relationship already known in literature [15] between the two parameters. As for the diurnal analysis results, our detailed hourly analysis from Figure 2 demonstrates how glucose levels fluctuate throughout the day, potentially correlating with atmospheric diurnal temperature changes in addition to the standard trend related to dietary habits. Additional focus was centred on the impact of the heatwave. The data captured during the July 2023 heatwave (17–21 July 2023), shown in Figure 4, highlight pronounced deviations from the long-term average, signalling the immediate effects of extreme temperatures on glucose regulation. The scatter plot data from the heatwave periods, aligned with our linear fit analysis, suggest a quantifiable impact of temperature on glucose levels. These findings are pivotal when placed alongside the literature, showcasing both parallels and novelties in our results. As we navigate through a landscape of increasing temperature fluctuations, our findings underscore the need to integrate meteorological parameters into diabetes management and clinical trial designs. They also underscore the necessity of enhancing patient and family education to address the metabolic control challenges presented by seasonal and short-term atmospheric temperature changes. In the context of seasonality, other aspects cannot be neglected. For instance, physical activity probably plays an important role because many individuals, including children, increase their physical activity from winter to spring or summer. Therefore, body fat commonly increases during winter, with worsening lipid profile, blood pressure, and thrombophilia indices as well [31]. Moreover, these changes tend to recur following winter and are generally not compensated for in summer. The health consequences of seasonal changes in physical activity, especially for those who engage in little physical activity, include increased cardiovascular risk and increased fat mass, with a cumulative effect year after year [31]. These phenomena could be related to the worsening of metabolic control during autumn and winter. Changes in dietary patterns could also contribute to weight gain and the deterioration of metabolic control, as demonstrated in obese adults, especially during winter vacations, where total energy expenditure does not decrease due to rest but total caloric intake increases [32]. Severe hypoglycaemia in patients with type 1 diabetes occurs more frequently in summer than in winter, and the incidence of severe hypoglycaemia in these patients may fluctuate with changes in atmospheric temperature [14]. As for the risk of severe hypoglycaemia, environmental factors (temperature) seem to affect subjects with type 1 diabetes more than patients with type 2 diabetes. From the bibliography, in fact, in adult type 2 diabetes, the incidence of hypoglycaemia is higher during the winter period (December to March) than during the summer. The peak period of hypoglycaemia always occurs in the winter months (January and February) [33]. Recently, it was shown that for every 1 degree increase in average daily temperature, there is a short-term increase in the risk of hypoglycaemia [15]. Results from the DPV registry showed small but significant changes in TBR and TAR in association with increased short-term temperature. Higher blood flow and faster insulin uptake could be possible mechanisms behind this [15]. Global warming and more frequent periods of atmospheric temperature fluctuations, with meteorological impacts on time in range, could become even more relevant [15,16]. In summary, our results echo the documented influence of environmental factors on glucose levels while providing fresh insights into the acute effects of atmospheric temperature variance. This information is crucial for optimising diabetes management in facing global climate trends. Anomalies in cutaneous blood flow, together with increases in physical activity, especially during transition periods from cold to hot temperatures, could contribute to a reduction in blood glucose levels and an increase in the frequency of hypoglycaemia due to greater physical activity as well, especially in childhood, where this is often unpredictable and unplanned [12,18,34]. On the other hand, especially in patients and families who use fixed schedules for insulin doses and do not promptly adjust insulin doses due to an insufficient capacity or fear of hypoglycaemia, in the transition from hot to cold months, there may be an increase in average blood sugar levels, with worsening metabolic control [15,35].

4. Conclusions

The use of CGM systems has led to changes in the study and comprehension of glycaemic patterns, and it will become increasingly capable of supporting research on analysing the trends in clinical parameters in diabetic patients in relation to environmental factors. The conducted study involved an analysis of the glycaemic patterns and associated metrics in a group of 138 patients, aged 0 to 21 years old, monitored over a one-year period (Autumn 2022–Summer 2023). In line with the scientific literature, the research outputs show a negative correlation between blood glucose trends in diabetic patients and atmospheric temperature values (R value computed considering data for the entire year; $Ry = -0.49$), behaviour strongly confirmed by the glucose pattern during the July 2023 heatwave (correlation coefficient between glucose and temperature: $R = -0.67$), which shows that during heatwave events, the anticorrelation is accentuated. The results emphasise the need for an integrated approach in which weather parameters are considered in the management of diabetes and, more specifically, in clinical trial designs. These findings, indeed, have important clinical implications. To prevent hypoglycaemia, the alert level must be highest during periods of increased risk, also depending on external temperatures. The ability to adjust insulin doses in patients on MDI therapy with flexible algorithms must be implemented promptly and effectively during periods in which their average glucose levels tend to increase. Future studies, on which we are already working, will be aimed at highlighting the impact of using advanced algorithms on glycaemic fluctuations related to atmospheric temperature trends. Further research is needed to understand how the results of studies using advanced technologies for diabetes relate to or translate to patients who use them and to the broader population of people with diabetes who do not have access to advanced technologies such as CGM systems, such as people on low incomes and/or racial minorities.

Author Contributions: Conceptualisation, P.C., S.T. and A.M.; methodology, P.C., S.T., E.A., P.D.C. and A.M.; formal analysis, P.C. and A.M.; data curation, P.C., A.M., L.S., M.A.S., M.C. and J.O.; writing—original draft preparation, P.C., S.T., E.A., P.D.C. and A.M.; writing—review and editing, P.C., S.T., E.A., P.D.C. and A.M.; supervision, P.D.C., S.T. and E.A.; funding acquisition, P.D.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union, NextGenerationEU, under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 (M4C2), Investment 1.5 Call for tender No. 3277 of 30 December 2021, Italian Ministry of University, Award Number ECS00000041, Project Title "Innovation, digitalization, and sustainability for the diffused economy in Central Italy", Concession Degree No. 1057 of 23 June 2022 adopted by the Italian Ministry of University. CUP: D73C22000840006.

Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Biomedical Research Ethics Committee of "C.Et.R.A.—Comitato Etico Regione Abruzzo" (protocol code 1782 of 8 May 2023).

Informed Consent Statement: Patient consent was waived due to the study being retrospective and not requiring it, as reported in the protocol (code 1782 of 8 May 2023, p. 13).

Data Availability Statement: The medical data are unavailable due to privacy and ethical restrictions. The meteorological data belong to the "Centro Funzionale e Ufficio Idrologia, Idrografico, Mareografico-Agenzia di Protezione Civile della Regione Abruzzo".

Acknowledgments: Alessandra Mascitelli, Piero Chiacchiaretta, Eleonora Aruffo, and Piero Di Carlo acknowledge the financial support of the European Union, NextGenerationEU, under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 (M4C2), Investment 1.5 Call for tender No. 3277 of 30 December 2021, Italian Ministry of University, Award Number ECS00000041, Project Title "Innovation, digitalization, and sustainability for the diffused economy in Central Italy", Concession Degree No. 1057 of 23 June 2022 adopted by the Italian Ministry of University. CUP: D73C22000840006. The authors acknowledge the "Centro Funzionale e Ufficio Idrologia, Idrografico, Mareografico-Agenzia di Protezione Civile della Regione Abruzzo" for providing the meteorological data. The authors thank the local association of families and children with diabetes "ABCDEF aps" (Associazione Bambini Con Diabete e Famiglie).

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

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