A Study

The Tower as an Instrument

Meteorological and Geophysical Research on the Eiffel Tower

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Fig. 1. *The Eiffel Tower seen from the Trocadéro gardens, early twentieth century.*

Abstract

The Eiffel Tower is usually described as an engineering symbol of Paris and of the 1889 World's Fair; no less important, however, was its role as a vertical scientific station. From the very beginning Gustave Eiffel defended the structure not only as an architectural emblem of the centenary of the French Revolution, but as an instrument for meteorology, atmospheric physics, aerodynamics, radio communication and metrology. This essay examines the circumstances of the Tower's construction, the dispute over its temporary or permanent existence, the transformation of its upper platform into a meteorological laboratory, the part played by Éleuthère Mascart, Alfred Angot, Gustave Eiffel, Theodor Wulf, military radio engineers and other researchers, and the instruments and methods used at a height of about 300 m. Particular attention is paid to why this tower in particular became such a fortunate experimental site: it offered a vertical cross-section of the atmosphere rare over a lowland city, it allowed self-recording instruments to be installed, upper sensors to be linked to ground-level registration, and the data to be compared with the network of the Central Meteorological Bureau of France.

Introduction: an Exhibition Monument and a Scientific Instrument

The history of the Eiffel Tower begins as the history of a temporary exhibition structure. The Paris World's Fair of 1889 was meant to display the industrial, engineering and cultural power of France a hundred years after 1789. The competition for the principal vertical landmark of the Champ-de-Mars was won by the design for a three-hundred-metre iron tower, prepared in Gustave Eiffel's bureau by the engineers Maurice Koechlin and Émile Nouguier and then architecturally reworked by Stephen Sauvestre [2, 11, 12]. Already in this initial situation the Tower was a double object: on the one hand a spectacle of the fair, on the other an extreme engineering experiment with wind, metal, assembly, lifts, pressure and observation.

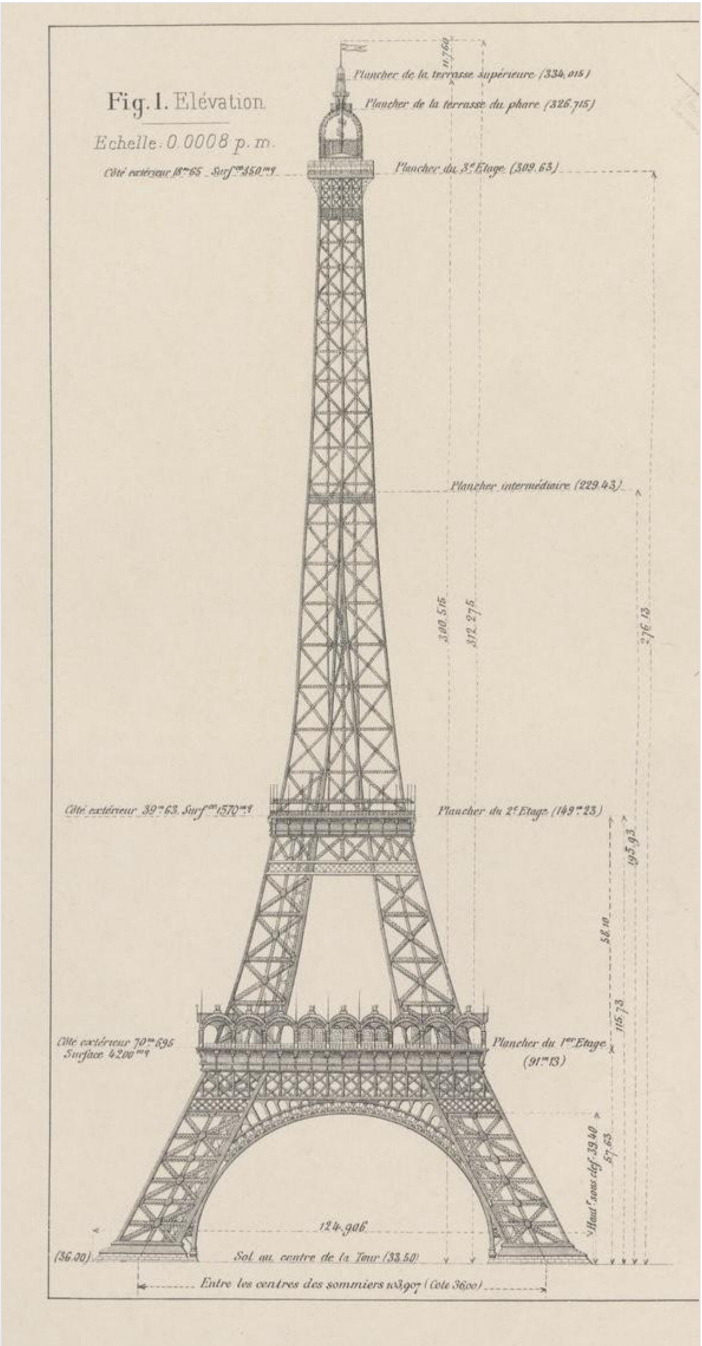

Fig. 2. *Elevation of the Tower, with the heights of its platforms and terraces.* After G. Eiffel, La Tour de trois cents mètres (1900).

The Tower was built not as a traditional stone monument but as a spatial lattice structure of puddled iron. Its form was governed by the calculation of wind loads: the curvature of the legs had to carry the wind's thrust into the foundations without destructive bending moments. The meteorological theme was therefore not a late decorative addition; it was inscribed in the very logic of the structure. To build the tallest artificial object in the world one had to understand the wind, and once built the Tower itself became a means for studying it [2, 10].

At the turn of the nineteenth and twentieth centuries meteorology was rapidly turning from a descriptive science into a measuring discipline. National services were collecting regular observations of temperature, pressure, humidity, precipitation and wind; recording instruments were developing; interest in the vertical structure of the atmosphere was growing. Before the widespread use of sounding balloons, aeroplanes and radiosondes, stable high-altitude platforms were a rarity. Towers, mountain stations, lighthouses and bell-towers offered only partial possibilities. The Eiffel Tower became a unique urban “mast” 300 m high, accessible every day and connected to laboratories, electricity and municipal institutions. Its use as a meteorological laboratory was therefore no accident but a consequence of the coincidence of engineering height, exhibition publicity and a scientific programme.

The Construction of the Tower and the Argument of Science

The contract for the Tower assumed its operation for a limited term: the structure was to pay for itself through the fair's visitors and then, once the concession expired, might be dismantled. This temporary status gave rise to the well-known conflict between the champions of engineering progress and the critics who regarded the Tower as a disfigurement of Paris. In reply, Eiffel insisted that the structure had practical and scientific value. In public statements and technical descriptions he listed its possible uses: meteorological and astronomical observations, physics experiments, the study of air resistance, optical telegraphy, military observation, electric lighting, the calibration of instruments and, later, wireless telegraphy [2, 15].

Fig. 3. *Building the great piers on the Champ-de-Mars.* From H. Rivière, *Les trente-six vues de la Tour Eiffel* (1902).

It was the scientific argument that helped the Tower escape the fate of a temporary attraction. Eiffel wanted to show that a three-hundred-metre structure was not an empty demonstration of height. On the frieze of the first storey he inscribed the names of seventy-two French scientists, engineers and mathematicians. The gesture was symbolic: the Tower placed itself, as it were, under the patronage of science. But the symbol was followed by practice. Soon after the opening a meteorological station was set up on the upper level, and in the following years the Tower served for measurements of atmospheric electricity, of vertical gradients of temperature and humidity, of wind speed and pressure, for aerodynamic experiments with falling bodies, and later for radio-meteorological and military applications [2, 5, 6].

Fig. 4. *Riveters at work high on the rising Tower. From H. Rivière, Les trente-six vues de la Tour Eiffel (1902).*

Work began on 28 January 1887, the main metal parts were assembled by March 1889, and the ceremonial opening took place on 31 March 1889. A height of 300 m was unprecedented for a permanent structure. This had a direct meteorological meaning: the observer obtained not merely a high point but an almost laboratory cross-section of the surface layer of the atmosphere above a great city. In the Paris of the late nineteenth century, with its stove heating, industrial smoke and dense building, such a measurement made it possible to separate local street conditions from the freer air flow above the city.

The chief reason for Gustave Eiffel's interest in meteorology was the wind. In designing metal bridges and the Eiffel Tower he was continually confronted with wind loads and called the wind his “chief enemy”. Eiffel regarded meteorology as an applied science that ought to bring immediate benefit to people; in his view the results of observation should be easy to understand and fit for practical use by aviators, sailors and farmers. In the list of uses he proclaimed for the Tower — “meteorological and astronomical observations, physics experiments, a strategic observation post, an optical-telegraph station, an electric lighthouse and the study of the wind” — meteorology stood first, and it remained the field in which the Tower worked most continuously. In 1906 Eiffel published his own *Atlas météorologique*, containing daily, monthly, seasonal and annual graphs of observations for twenty-four districts of France and Algeria — one of the first attempts at a systematic publication of regional climatic data in convenient graphical form. Eiffel actively supported the development of scientific meteorology, cooperated with French meteorologists and took part in the work of the French Meteorological Society [8].

The Mascart–Angot Meteorological Station (1889–1894)

The observation service arose together with the structure itself. From the very start of construction, in 1889, under the care and direction of Éleuthère Mascart (1837–1908) — physicist, member of the Institute and director of the Central Meteorological Bureau of France (the Bureau Central Météorologique, which he had founded in 1878, the direct predecessor of Météo-France) — an “extremely important” meteorological service, in Eiffel's own words, was established on the Tower. Eiffel himself called the Tower “an incomparable meteorological observatory”, stressing that its value lay not in its absolute altitude (only about 334 m above sea level) but in the height above the ground of the air layer under study, freed from the disturbances of the immediate vicinity of the soil [1].

The measuring instruments stood on the small platform, 1.60 m across, that crowns the Tower 300 m above the ground; by means of a cable they transmitted their readings electrically to self-recording instruments installed on the ground floor of the neighbouring building of the Central Bureau. All observations were taken hour by hour — wind speed and direction, temperature, atmospheric pressure, humidity and so on; they were entered in the Bureau's registers, and their summary appeared in the daily Bulletin [1].

The observations were centralized by Alfred Angot (1848–1924), doctor of science and permanent meteorologist of the Central Bureau, who analysed them in comparison with the observations made in the Bureau's own premises and set them out in learned memoirs printed in the *Annales du Bureau*. The first memoir concerned the results of 1889; five more covered the years 1890, 1891, 1892, 1893 and 1894; a general memoir summed up these five years, except for the wind, to which a separate work was devoted, carried down to 1895; a second summary memoir, reaching to 1899, was in preparation. This body of work Eiffel justly called “a veritable scientific monument” [1, 6]. It is significant that the corresponding chapters of Eiffel's book are verbatim extracts from Angot's memoirs, with the mathematical parts omitted — so that we have here a primary source almost at first hand.

Fig. 5. *Alfred Angot (1848–1924), permanent meteorologist of the Central Bureau, who centralized and analysed the Tower's observations.*

The observations were compared, on the one hand, with the readings of the Central Bureau itself (its courtyard, at a height of about 33 m) and, on the other, with the observatory of Saint-Maur near Paris, which gave normal values for the Parisian climate free of the disturbing influence of the city. Angot justified the choice of a suburban station rather than a point in Paris itself in sharp terms: "the temperature of Paris, properly speaking, does not exist; it is entirely artificial and may vary by several degrees according to the placing of the instruments, the state of the sky, the direction of the wind, and so on" [1]. Besides the summit, registration was carried out at intermediate levels of the Tower — the second platform (about 123 m) and the intermediate platform (about 197 m) — which turned the structure into a vertical cross-section of the atmosphere.

Eiffel extended the Tower's experience to a network of his own: four stations on his estates — at Beaulieu-sur-Mer (1901), near Bordeaux on the land of his son Édouard (1902), and in the Breton village of Ploumanac'h, in the house of his son Albert, tellingly named "Ker Awell", the "house of the wind" (1905). He summed up the decade in a book issued at his own expense, *Dix années d'observations météorologiques* (1901). For Eiffel the wind remained a quantity above all of engineering: “Le vent, mon ennemi” — “The wind, my enemy”, he said, meaning the chief design factor of his metal structures.

Instruments, the Cross-Section of the Atmosphere, and Data Transmission

All the station's instrumentation — from barographs to anemometers and the system of electrical transmission — was conceived and built by the house of the Richard brothers (Richard frères). As early as 1888, with Mascart's support, the firm obtained Eiffel's agreement to equip the summit of the still-rising Tower with a full meteorological station; this installation, together with its display in Class 15 (“Precision Instruments”), won the Richard brothers the Grand Prix of the 1889 fair [8]. The instruments are described below by meteorological element, in the way Eiffel himself sets them out [1].

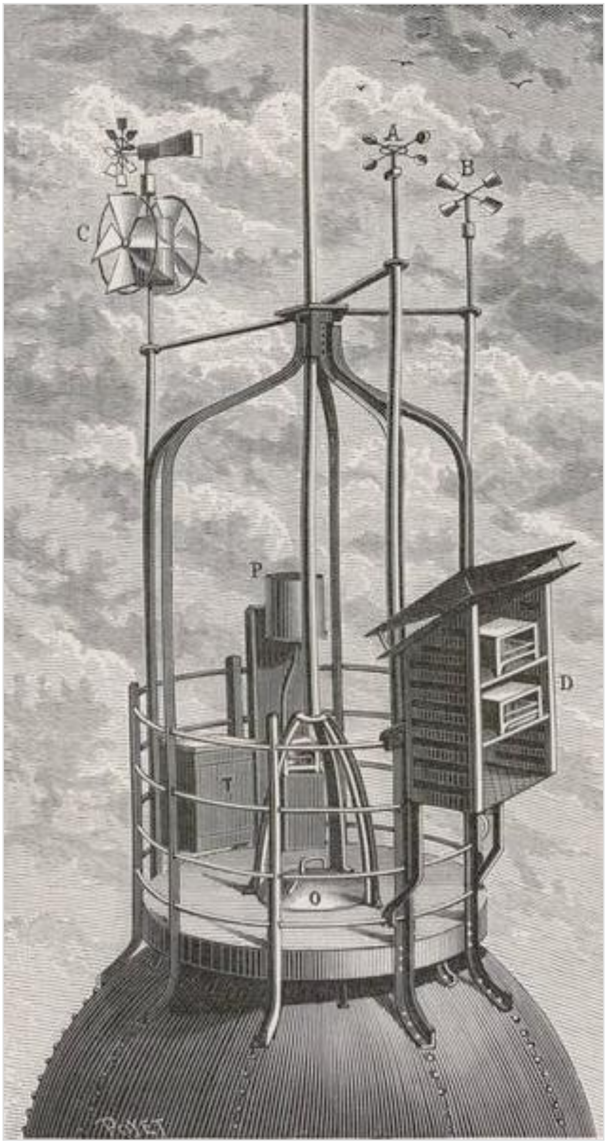

Fig. 6. *The meteorological installation at the summit: the louvered double-roofed thermometer shelter (D) and the wind instruments — the speed anemometer and vanes (A, B, C). From G. Eiffel, Travaux scientifiques (1900).*

Atmospheric pressure was recorded by Richard self-recording mercury barometers, which doubled the amplitude of the variations they traced; one stood at the Bureau at a height of 33.40 m, the other on the Tower, in a room above the third platform, at 312.90 m. The difference in level was 279.5 m, with a horizontal separation of about 480 m. The recorders were checked against direct readings of two wide-cup mercury barometers compared with each other — three times a day at the Bureau, four or five times a week (and more often in summer) at the Tower. All readings were reduced to zero, corrected for instrumental error, brought to sea level and to normal gravity (latitude 45°). The chief result was unexpected: the pressure at the summit came out systematically, in every month, too low relative to the Bureau — and this was a real fact, not an instrumental error. Angot explained it thus: because of the great wind speeds at 300 m, a kind of "cushion of air" (*matelas d'air*) forms near the ground, held by friction and compressed between the soil and the more mobile layers above. At the same time the accidental fluctuations of the barometer at the summit and below ran almost identically — reduced to a common level, they differed only by tenths of a millimetre, at most by one millimetre in extreme cases, as in the storm of late November 1889, when a cyclone centred to the south-west of Norway (735 mm) drove the Paris barometer down to 752.8 mm [1, 6].

Temperature was measured under louvered, double-roofed shelters — at the Bureau at a height of 31.6 m (1.60 m above the ground), and on the Tower at 335.3 m above sea level and 301.8 m above the ground, in a shelter hung on the north side beyond the balustrade of the lightning-rod platform. The strong wind at this height reduced the shelter's errors to negligible amounts, so that the conditions of observation were reckoned excellent. Under the shelter stood a whole set of instruments: a psychrometer, a maximum thermometer, a minimum thermometer, a Richard self-recording thermometer and hygrometer, and an electric transmitting thermometer invented by the Richard brothers, which gave the Central Bureau the continuous course of the temperature at the summit. Beyond these, two further series of direct-reading and self-recording thermometers were installed on the Tower — on the intermediate levels — making it possible to follow the temperature profile within a single structure [1].

Atmospheric humidity was recorded from 10 July 1889 by a hair hygrometer (*hygromètre à cheveu*) of the Richard brothers, set beside the thermometers at 301.8 m above the ground and checked by direct psychrometer readings [1]. The same hair-hygrometer principle would find its way, nineteen years later, into a children's cut-out (see below) — a rare case in which a laboratory instrument and a folk toy use one and the same physics.

With precipitation the Tower suffered a telling failure. Eiffel plainly declined to give its figures, "because they have no real significance": the wind here is so strong that in most cases the raindrops move almost horizontally and do not fall into the rain gauge. It frequently happened that during heavy downpours the gauge showed nothing, the floor of the upper platform was barely wetted, receiving only a few drops, while vertical objects streamed with water. To obtain meaningful numbers one would have had to change the ordinary mode of observation entirely — to collect the rain in a gauge whose funnel, instead of remaining horizontal, could be tilted and set at right angles to the wind [1].

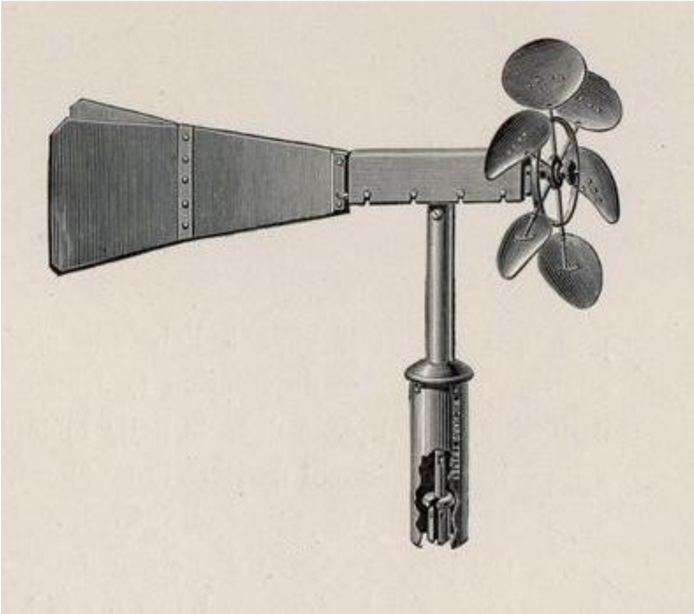

Fig. 7. *The Richard brothers' vane anemometer: six aluminium blades and an orienting tail, one turn per metre of wind.* From G. Eiffel, *Travaux scientifiques* (1900).

Wind speed was measured by Richard anemometers, identical at the Bureau and on the Tower. Each consisted of a wheel of six aluminium blades set at 45° and riveted to very light steel arms; the dimensions were chosen so that the wheel made exactly one turn per metre of wind travelled, and its rate was verified on a whirling-arm stand (*manège*), with a table of corrections drawn up where necessary. The complete wheel weighed only 150 g, presented about 6 square decimetres to the wind, and had a self-lubricating axle. Its sensitivity was remarkable — the instrument caught speeds of as little as 0.1–0.2 m/s, began to turn the instant the wind rose and stopped as soon as it fell; in this it compared favourably with the Robinson cup anemometer, which because of its greater mass is slow to accelerate and goes on turning long after the wind has ceased.

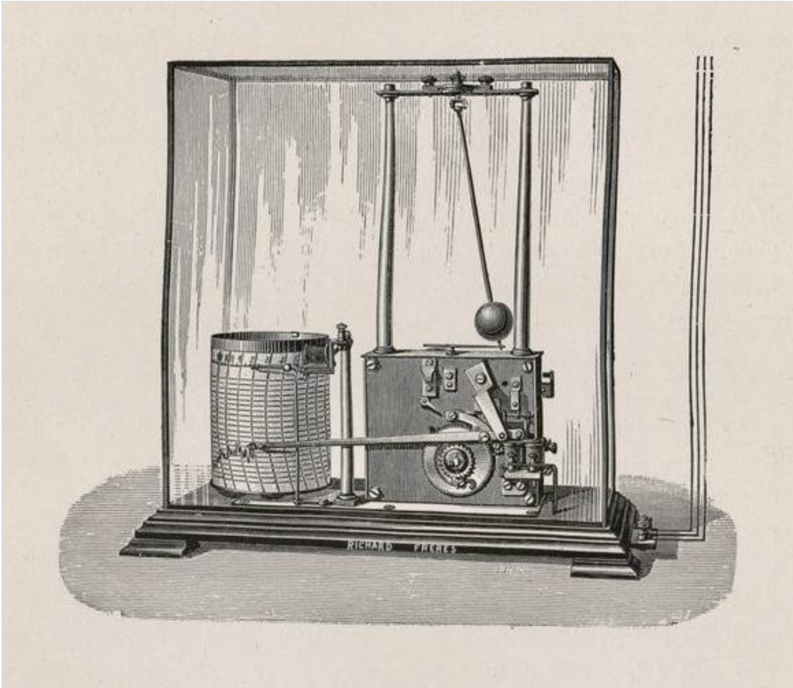

Fig. 8. *The receiving anemo-cinémographe of Richard frères, which stood in their display case at the 1889 Exhibition before being moved into the Tower.* From G. Eiffel, *Travaux scientifiques* (1900).

The wheels transmitted their readings to Richard *cinémographes*, which recorded at once both the instantaneous speed in metres per second and the time taken by the wind to travel a distance of 5 km; the recording cylinder made one revolution a day (an hour corresponding to 15.15 mm of trace). The Tower's anemometer stood at 338.5 m above sea level and 305 m above the ground, above the vane C. During the fair the receiving recorder stood in the Richard brothers' display case in the Palais des Arts Libéraux; in November 1889 it was moved to the machine hall of the Tower at the base of the South pier. Observations began on 16 June 1889; they were interrupted only twice — for two days in November (during the move of the recorder from the fair) and for six days in December (13–19), when a thick coating of frost completely immobilized the wheel.

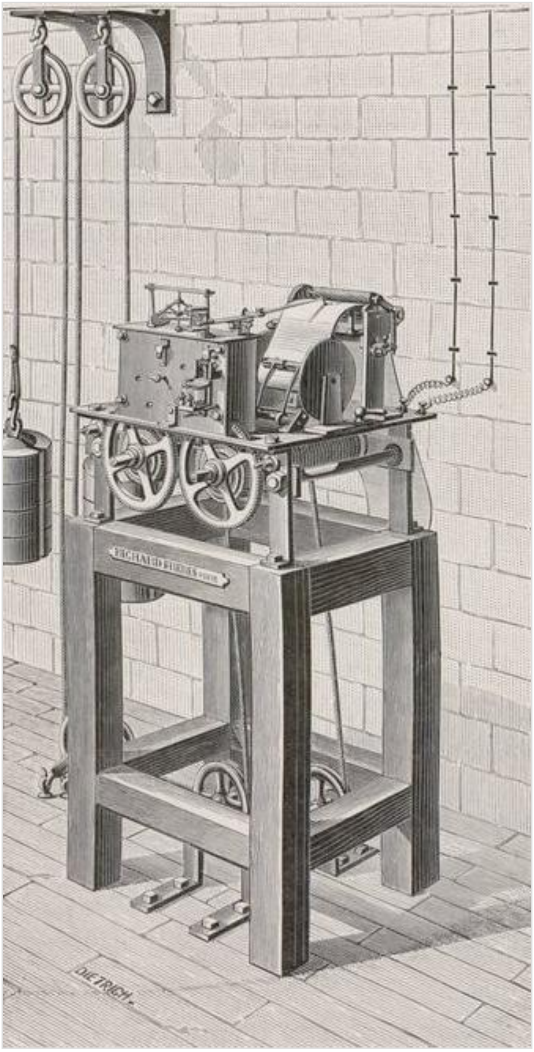

Fig. 9. *The instantaneous-reading cinémographe that Eiffel added in October 1890 and presented to the Central Bureau.* From G. Eiffel, *Travaux scientifiques* (1900).

In October 1890 an instantaneous-reading *cinémographe* was added, which Eiffel presented to the Central Bureau [1]. All this registration rested on an extended communication line. A twenty-wire electric cable, running from the Tower through the sewers of the Champ-de-Mars and the rue de l'Université, ended in a communications box F, from which the wires fanned out to all the receiving instruments gathered in a single room of the Bureau; all of them, as has been said, were built by the Richard brothers. Angot described this arrangement in an article in the journal *La Nature* of 9 May 1891 [1]. It is precisely this detail that turns the Tower from a “place of observation” into a measuring system: the sensors above, the recorders below, and between them a cable running through the city's sewers.

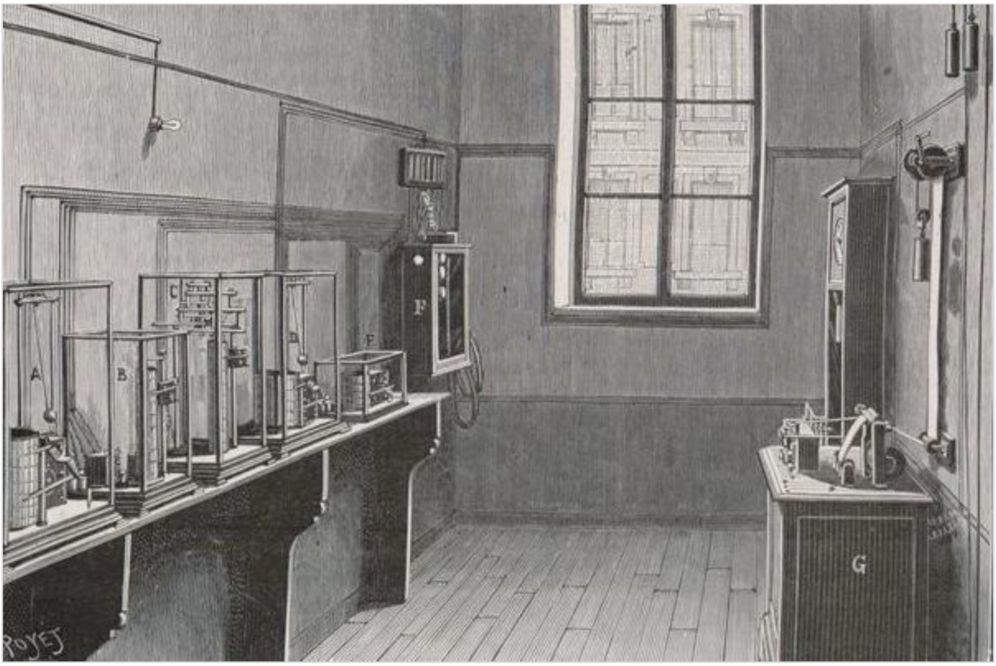

Fig. 10. *The room at the Central Bureau where all the Tower's recorders were gathered; on the wall, the communications box F in which the twenty-wire cable terminated.* From G. Eiffel, *Travaux scientifiques* (1900).

Wind direction was registered differently above and below. At the Bureau an ordinary two-vaned weathercock served, its axis turning a vertical paper cylinder directly; a pen driven by clockwork descended one centimetre an hour (a full rotation of the wind corresponding to 157 mm on the paper). On the Tower the vane C consisted of two wheels on a common horizontal axis, self-orienting to the wind; a special electric transmission requiring only three wires, devised by the Richard brothers, reproduced every movement of the vane at a distance on a cylinder identical to that of the Bureau. The contacts were arranged so that transmission proceeded in portions of 1/128 of the circumference: it sufficed for the wind direction to change by 2°48′45″ for the distant receiving cylinder to turn by the same amount; the interval is so small that the curve exactly repeated the record of direct mechanical transmission. During the fair the receiver stood beside those of the anemometers, then in the machine hall, and from October 1890 it was installed definitively in the Bureau itself. Direction was read off on a scale from 0 to 32 (0 for north, 8 for east, 16 for south, 24 for west). The first summaries already showed that calm days were far more numerous at the base of the Tower than at the summit (15 per cent against 2 per cent), and that winds of the northern and southern sectors were markedly more frequent at the summit [1].

Finally, in July 1889 a wheel for studying the vertical component of the wind (marked B) was installed at the summit — four flat blades at 45° on a vertical axis. By its very construction it remained motionless in a horizontal current, turning one way when the wind had an ascending component and the other when it had a descending one. Observation, however, proved extremely difficult: the wheel could turn even in a perfectly horizontal current if the wind speed was not strictly the same at both ends of its diameter, and the smallest obstacle sufficed for this. The very first observations of 1889 revealed just such a systematic error, caused by the presence of the central rod carrying the lightning conductor [1].

Free Air above Paris: the Principal Observations

Angot summed up the first years' results in an article in *La Nature* of 25 January 1890, and they are worth giving without wearisome tables [1]. The first thing that struck the observers was the wholly unforeseen force of the wind already at 300 metres. Over the first one hundred and one days of observation (from mid-June to 1 October, in fine weather) the mean speed was 7.05 m/s — more than 25 km/h — whereas an identical instrument on the Bureau's turret, 21 metres above the ground and about 500 metres from the Tower, showed only 2.24 m/s, that is, less than a third. That wind speed increases with height had been known before; but so rapid a law of increase had not been supposed. For the future of aerial navigation this mattered directly: at 300 m the wind held above 8 m/s for 59 per cent of the time and above 10 m/s for 21 per cent [1].

Still more unexpected was the daily rhythm. Below, as at all low-lying stations, the speed is least around sunrise and greatest at midday; on the Tower it is the reverse — the least speed (about 5.4 m/s) falls between 9 and 10 in the morning, and the greatest (8.8 m/s) in the middle of the night, towards 11 p.m. This is almost exactly what happens on mountain summits — the Puy-de-Dôme, the Pic-du-Midi — where the course of wind speed is the inverse of the lowland one. The ratio of the speeds, Tower to Bureau, reached 5 between 2 and 4 in the morning and fell to 2 in the daytime hours. As Angot noted, such an inversion had been observed for the first time at so low a height in the atmosphere [1].

The temperature régime confirmed the same picture of “free air”. With the usual gradient (1° per 180 m) the summit ought to have been constantly 1.6° colder than the open country. In fact, by day, at the moment of the maximum, the summit turned out colder than the foot even more than in theory — days aloft are relatively cool; but the nights are very warm: the difference not only failed to reach 1.6°, but the summit proved the warmest in absolute value. On calm clear nights it was 5–6° warmer aloft than below. The amplitude of the daily march of temperature on the Tower (336 m) was nearly equal to, and sometimes less than, that at the summit of the Puy-de-Dôme (1470 m) — precisely because the Tower stands in genuinely free air, whereas near a mountain the mass of the massif still makes itself felt. The cause, Angot held, was the weak absorptive and emissive power of the air, which by day heats little directly and by night cools little [1].

Especially striking was the way the weather ran ahead at height. At a change of régime the shift often showed itself at 300 metres several hours, even days, before it did at the ground. November 1889 gave a vivid example: while below, from the 10th to the 24th, a region of high pressure lay with weak easterly winds, clear sky and cold, on the Tower the wind already, on the evening of the 21st, suddenly freshened and turned to the south-south-west, and the temperature, instead of falling, rose by more than 8° by two in the morning. From that moment until the morning of the 24th it was steadily much warmer aloft than at the ground — that is, the change of régime declared itself at 300 metres more than two days before it was felt below. Most remarkable of all, nothing below foretold it: the sky was cloudlessly clear and a complete calm reigned, while at the summit a warm south-south-west wind blew at 6–8 m/s. Hence Angot's conclusion: despite its modest height, the station on the Tower is “the first that really gives us observations made in free air, outside the influence of the ground”, and it “surely holds in reserve for meteorologists more than one surprise and more than one lesson” [1].

Finally, the Tower left a vivid chronicle of storms — and here Angot's meteorology meets Eiffel's engineering anxiety. In one of the most violent Parisian storms, that of 12 November 1894, the wind twice reached a mean speed of 42 m/s on the Tower, against only 13.7 on the Bureau's terrace. On 18 June 1897 a tornado devastated the northern suburbs of Paris: on the Tower the mean speed reached 28 m/s and the peak 34 m/s, while a few kilometres away the wind was tearing down houses and uprooting twenty-metre poplars. On 6 September 1899 a squall raised the speed in an instant from 4 to 42 m/s and held it for two or three minutes, preceded by frequent and vivid lightning. These records led to a subtle observation that Eiffel reports after S. P. Langley: ordinary chronographic recording “smooths” an instantaneous stopping of the wind into a mere slackening, and so a contact was arranged for every half-revolution of the wheel, giving several records a second. It is precisely the pulsations of the wind — with an interval of about ten seconds between maximum and minimum and swings of some 4.5 m/s — that are, in Eiffel's words, “of capital importance” from the point of view of the engineer and the stability of structures, whereas the averaged speeds of ordinary instruments are of “very slight interest” to him [1]. From this thought there runs a direct road to Eiffel's aerodynamic experiments.

The Three-Hundred-Metre Mercury Manometer

The height of the Tower made it possible to house an instrument for which there was no room anywhere else — an open mercury manometer running the whole vertical of the structure, about 300 m. A column of such length made it possible to measure high pressures accurately and served as a standard for calibrating the industrial metal and gas manometers used in industry. The experiment lies on the border between meteorology and metrology, but it belongs to the same logic: to use the vertical scale of the Tower as a physical instrument.

Atmospheric Electricity and Lightning (1889–1920s)

The Tower's meteorological laboratory was not confined to weather in the narrow sense. Being the first metal structure in the world of such considerable height, the Tower proved a natural target and a natural laboratory of atmospheric electricity. In the late nineteenth century measurements of the electric potential of the air were regarded as an important way of studying the state of the atmosphere, fog, smoke and ionization. The data of the potential gradient collected on the Eiffel Tower were later used by historians of science and physicists of the atmosphere to reconstruct the air pollution of nineteenth-century Paris [9].

Already in August 1889 the squadron commander of artillery A. Terquem carried out precise measurements of the Tower's own electrical conductivity and of its earth connections; the results were set out in a note presented to the Academy of Sciences on 2 December 1889 [21]. The question was put in strict engineering terms: does the riveted iron frame, assembled with countless hot-set rivets, conduct current as a single whole? The summit was protected by nine lightning conductors joined directly to the frame.

Direct lightning strikes were recorded from the first months. One of the early observations was left by the head of the Tower's electrical service, Foussat: on the evening of 19 August 1889, in a strong north-west wind and light rain, with no visible signs of a storm, lightning struck the Tower. Systematic measurements of the electric potential gradient began at the summit at the end of 1893. A thread electrometer was used; to stay within measurable potentials, the length of the instrument's outlet tube had to be cut down to 40 cm — at such a height the equipotential surfaces around the Tower are extremely crowded. Observations at the summit were carried on in summer and autumn, in parallel with the ground measurements of the Central Bureau. All these works on the atmospheric electricity of Paris were summed up by B. Chauveau in a fundamental review of 1925 [22].

The later fate of these data is telling. In the twenty-first century Chauveau's series of the potential gradient at the summit was reworked to reconstruct the air pollution of nineteenth-century Paris: an aero-electrical parameter measured for its own sake turned out to be an indirect indicator of the aerosol state of the city's atmosphere a century ago [9].

Cosmic Rays: Theodor Wulf's Experiment (Easter 1910)

The most significant physical episode in the Tower's history is bound up with the riddle of the "penetrating radiation" that ionized the air in closed vessels and found no explanation. Theodor Wulf (1868–1946), a German physicist and Jesuit priest who taught at the Jesuit college of Valkenburg (the Netherlands) and had studied under Walther Nernst at Göttingen, built in 1909 a two-thread (bifilar) electrometer of his own. Unlike the fragile gold-leaf electroscopes, in Wulf's instrument two fine metallized glass threads were fastened at their lower ends to an insulator by quartz strings; the cylindrical zinc body was 17 cm in diameter and 13 cm deep, with a sensitivity of about 1 volt. The instrument was not only more precise but — decisively — more portable than its predecessors.

Wulf's hypothesis was simple: if the ionizing radiation comes from the radioactive substances of the earth's crust, it should fall off rapidly with height. He decided to test it on the Tower, thereby removing a hindrance of the earlier balloon experiments — the influence of the balloon's motion. Having obtained the permission and help of his French colleagues Jules Violle and Paul Langevin, Wulf spent four days of Easter week 1910 (March–April) taking measurements at the summit of the Tower, framing them with readings at its foot and at home in Valkenburg [17].

The result contradicted expectation. The intensity of the ionization fell from about 6 ions·cm^{-3} at the ground to about 3.5 ions·cm^{-3} at the summit (about 300 m). Yet if the source were the γ-radiation of the earth's surface, the intensity should have halved within 80 metres of air. The weakening observed was too slight: part of the radiation, therefore, came from above, from outside. Wulf published his results in the *Physikalische Zeitschrift* on 15 September 1910 [18, 19, 20].

The conclusion was not accepted by his contemporaries at once; Wulf himself framed it cautiously, the more so as the iron of the Tower had a radioactivity of its own that acted as an additional disturbing factor. Nevertheless the experiment of 1910 preceded Victor Hess's famous balloon flights (1912), which earned the Nobel Prize of 1936, and together with Domenico

Pacini's underwater measurements in the bay of Livorno it stands at the origins of the physics of cosmic rays. In this line the Eiffel Tower is one of the first sites at which the extraterrestrial origin of penetrating radiation was noticed [17, 18, 19, 20].

Gustave Eiffel as Organizer of Observations

Fig. 11. *Gustave Eiffel (1832–1923), engineer, contractor and organizer of the Tower's scientific work.*

Gustave Eiffel was not only a contractor and engineer but an active organizer of scientific work. After the completion of his great construction projects, and especially after the crisis connected with the Panama Canal, he devoted himself increasingly to research in meteorology and aerodynamics. In his published work *La Tour de trois cents mètres* he set out in detail not only the history of the construction but the scientific uses of the Tower, including the meteorological observations [2]. This book, together with the separate compendium *Travaux scientifiques exécutés à la tour de 300 mètres* (1900), is important as a primary source: Eiffel deliberately presented the Tower as a laboratory and not merely a monument [1].

His part took several forms. First, he provided the space, the technical infrastructure and the means. Second, he cooperated with professional meteorologists, above all with the Central Bureau. Third, he published the results, understanding that a long series of observations is valuable only when it is available to the scientific community. Fourth, he linked meteorology with aerodynamics: wind, air resistance and the stability of the structure were treated as parts of one physical problem.

Eiffel also used the upper rooms for experiments of his own. In the late nineteenth and early twentieth centuries he conducted experiments on the fall of bodies along a vertical path and on air resistance. Later these researches led him to create aerodynamic laboratories and wind tunnels — first on the Champ-de-Mars, then at Auteuil. His works on air resistance became a significant contribution to early aviation science [3, 4]. The meteorological Tower thus became a bridge between classical observational meteorology and experimental aerodynamics.

Methods: from Single Readings to Continuous Series

The development of methods on the Tower can be described as a passage from demonstration measurement to systematic registration. In the first months after the opening it was important to prove that instruments could work at all at such a height: that they could be serviced, protected from rain and icing, joined by electric lines to recorders, and compared with ground stations. Then began the stage of regular series, in which the chief value lay in duration and comparability.

The meteorological meaning of long series is especially great for temperature and wind. A single day may be accidental, but months and years reveal stable regularities: the mean vertical gradient, the frequency of inversions, seasonal differences, the connection of gusts with cyclones, the peculiarities of fog and haze over the city. The Tower made it possible to observe the urban atmosphere as a dynamic system. Later, such approaches became the basis of urban climatology and of studies of the atmospheric boundary layer.

Methodological refinement also concerned the placing of the instruments. Measuring the wind on a metal tower is difficult: the structure itself distorts the flow, while the heating of the metal by the sun and its cooling at night complicate thermometry — hence the double louvered shelters, the projection of the sensors beyond the balustrade, and the comparison of several points by height. These difficulties did not diminish the Tower's value; on the contrary, they spurred the development of an instrumental culture.

The Tower, Balloons, and the Rise of High-Altitude Meteorology

To grasp the singularity of the Eiffel Tower it is worth comparing it with the other ways of studying the upper layers of the air at the end of the nineteenth century. Before the coming of the radiosonde, scientists used balloons, kites, mountain stations, lighthouses and tall buildings. A balloon gave great height, but the observation was brief, dependent on the wind and requiring a dangerous ascent. Kites could lift thermometers and anemometers, but they were limited by the weather and gave no permanent platform for complex instruments. Mountain observatories, for example on the Puy-de-Dôme or Mont Blanc, were important, but they stood in a different orographic environment: there one measured the atmosphere of the mountain, not that of a lowland metropolis.

The Eiffel Tower took an intermediate place between the ground station and free flight. Its height was modest compared with a balloon, but enormous by the measure of a permanent urban station. It made possible what was hard to do from a balloon: to repeat a measurement at the same hour of the day, to return to an instrument, to repair it, to change a screen, to compare methods, to keep a parallel series at the ground and aloft. In the science of weather it is precisely repeatability that is often more important than extreme height. The Tower made it possible to study not “the atmosphere in general” but the behaviour of the lowest few hundred metres of air, where fog, haze, urban heat exchange and dangerous gusts are formed.

In this sense the Tower was a forerunner of the high-altitude meteorological masts of the twentieth century. A modern mast usually has sensors at several levels, cable transmission of data, protection against the interference of the structure, and regular servicing. Almost all these principles were present in embryo on the Tower: levels, remote registration, comparison with ground observations, the struggle with the heating of metal and with the distortion of the air flow. Its significance is therefore not exhausted by particular figures of temperature or wind. It demonstrated the very type of the experiment: a permanent vertical infrastructure can reveal the structure of the surface layer of the atmosphere.

Radio-Meteorology: from Spark Telegraphy to the First Radio Forecast (1898–1929)

In the end the structure was saved not by meteorology but by radio; yet the weather report was among the first substantial cargoes sent from the Tower into the ether.

The first public demonstration of wireless communication was given by Eugène Ducretet: on 5 November 1898 he transmitted a signal in Morse between the Tower and the Panthéon (about 4 km). In 1903 Eiffel offered the Tower as an antenna support to Captain (later General) Gustave Ferrié, who was engaged in the military applications of wireless telegraphy; six antenna wires were stretched from the summit. In 1905 the naval lieutenant Tissot proposed sending regular time signals from the Tower for ships; the project was approved by the Bureau des Longitudes. An underground military radiotelegraph station came into service in August 1909, and by the beginning of 1910 it had become the most advanced in Europe.

From 1910 the station transmitted time signals twice a day (at 00:00 and 10:00), to which Ferrié logically added the meteorological data of the Central Bureau: thus a regular link was set up between the Bureau and the station on the Champ-de-Mars. The regular daily transmission of weather bulletins by French wireless began on 1 September 1913 (the Marconi company had been making similar transmissions in Morse for transatlantic ships since 1902). A year later the war began, and meteorological information was classified; in 1914 Ferrié's interceptions helped the success of the French counter-attack on the Marne [13, 15].

After the war Ferrié arranged the transmission of the observations of fifteen French stations three times a day. The Copenhagen meteorological conference of 1929 established a world plan of meteorological radiograms, and the Tower was charged with broadcasting, three times a day, the observations of 350 stations distributed from Iceland to the Cape Verde Islands. Finally the civil station Radio Tour Eiffel — the first regular radio station of France, officially opened on 6 February 1922 — from its first broadcasts read the bulletins of the

National Meteorological Service, intended above all for sailors and farmers. It was from here that the first weather forecast in France transmitted by the human voice was heard.

Radio and meteorology were closely linked: aviation, artillery, navigation and military planning all required information about wind, pressure, cloud and the electrical state of the atmosphere. The Tower, where a culture of measurement already existed, became part of a broader system of scientific and technical observation. Thus a temporary exhibition object was turned into a permanent infrastructure of the city.

The Urban Climate of Paris as an Object of Measurement

Another important direction is bound up with the fact that the Tower stood neither in a desert nor on a mountain but in Paris. The late nineteenth century was an age of coal heating, industrial emissions, smoke, condensation fogs and heated sanitary debates about the air of great cities. The Tower's meteorological observations were therefore at the same time observations of the urban climate. The difference between the Tower's platforms and street level made it possible to judge how greatly the city's surface alters temperature, humidity, visibility and the electrical state of the air. It was no accident that Angot refused to speak of “the temperature of Paris” as of anything definite, taking suburban Saint-Maur for comparison.

Fig. 12. *Paris under smoke and morning mist, the Tower on the horizon — the “breathing of the city” the station was built to read.* *From H. Rivière, Les trente-six vues de la Tour Eiffel* (1902).

The Parisian townscape created a complex lower layer: the roadways heated by day and gave off heat by night; the Seine influenced humidity and fogs; the gardens of the Champ-de-Mars differed from the stone quarters; smoke and soot altered the transparency of the air. At street level a meteorological instrument recorded the sum of these influences. On the upper platform part of the local effects weakened, and the observer was able to compare the “breathing of the city” with a freer flow. Later such differences came to be described through the notions of the urban heat island, the roughness of the underlying surface, and turbulent exchange. The Tower did not give the whole of the modern theory, but it provided the material without which that theory would have developed more slowly.

The data of atmospheric electricity are especially instructive. Smoke and aerosols altered the conductivity of the air and the electric potential. The old curves taken on the Tower therefore proved useful already in the twenty-first century for reconstructing the pollution of Paris [9]. This is a rare example of historical meteorological measurements gaining a second life: at first they served the physics of the atmosphere, and afterwards became a testimony to the ecological history of the city.

The Tower as Instrument in the Popular Imagination: the Épinal Hair Hygrometer (1908)

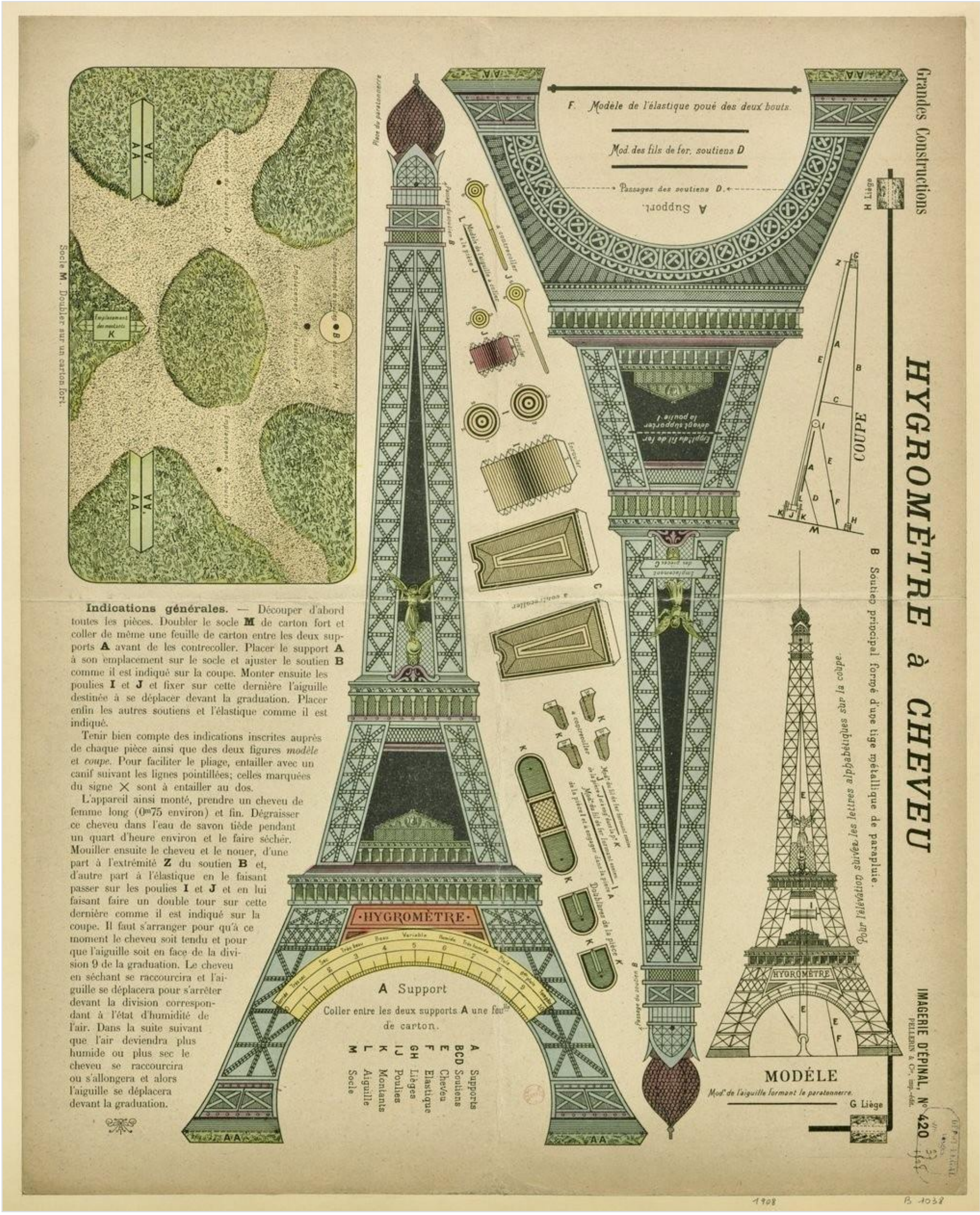

Fig. 13. *"Hygromètre à cheveu" — the cut-out Eiffel Tower assembled as a working hair hygrometer.*
Imagerie d'Épinal, Grandes Constructions no. 420, 1908. Bibliothèque nationale de France, Gallica.

The thesis of the Tower as a measuring instrument found an unexpected and literal confirmation — not in the academic *Annales*, but in the products of popular printing. In 1908 the celebrated factory of folk pictures Imagerie d'Épinal (Pellerin & Cie) issued, in the series "Grandes Constructions", sheet no. 420 — a paper cut-out from which a child, cutting the parts out with a knife along the dotted lines, folding and gluing them, assembled a three-dimensional model of the Eiffel Tower. But this model was no mere souvenir: the large heading of the sheet proclaimed it a working instrument — HYGROMÈTRE À CHEVEU, a “hair hygrometer”.

The principle at the base of the toy was quite scientific and by then already more than a century old. As early as 1783 Horace Bénédict de Saussure had shown that a degreased human hair lengthens as the humidity of the air rises and shortens as it falls; fixed at one end and passed over a system of pulleys, it can turn a needle along a scale. It was just this mechanism that the Épinal sheet wittily fitted into the silhouette of the Tower. On the diagram all the parts of a real hygrometer are marked: the pulleys (*poulies*) I and J, the main tensioning support B, the elastic band F that keeps up a constant tension, and the curved graduation scale at the base — with divisions from “très sec” to “très humide” (“very dry” to “very damp”). The instructions bade one take a fine woman's hair about 0.75 m long, degrease it in warm soapy water, stretch it over the pulleys and set the needle at the ninth division of the scale; thereafter the instrument worked of itself, responding to the humidity of the air in the room [27].

The sheet was accompanied, besides the assembled “model” (MODÈLE), by a section (COUPE) with letter designations of the parts — that is, by a language borrowed directly from the technical drawing. Even a small detail betrays this intention: the needle crowning the Tower is labelled as “forming the lightning rod” (*aiguille formant le paratonnerre*), which refers at once to atmospheric electricity and to the Tower's real lightning conductors. The folk picture thus reproduced exactly the duality that had been built into the structure itself: the Tower as spectacle and the Tower as instrument in one object. And the very hair hygrometer of the Richard brothers that had honestly worked at the summit since July 1889 turned here into a cheap toy for the parlour.

The value of this testimony lies not in the toy hygrometer's giving accurate readings, but in its documenting the depth to which the Tower's scientific reputation had penetrated everyday culture. A mere nineteen years after the opening, both the meteorological programme of Mascart and Angot and the general image of the Tower as a measuring device had entered the mind so firmly that “the tower that measures the air” had become the natural subject of a cheap children's sheet. If Eiffel's scientific memoirs defended the structure from above, appealing to the Academy, the Épinal cut-out fixed the same idea from below — turning the abstract thesis “a monument can be an instrument” into an object that thousands of families held in their hands and hung on the wall. A rare case in which the central idea of an object's scientific history is imprinted also in its folklore.

The Modern Monitoring of Greenhouse Gases (1992 to the Present)

The Tower's meteorological function did not cease. Observations of carbon-dioxide concentration in the Île-de-France go back to 1992 (the Saint-Jacques tower); afterwards occasional measurements were made on the Eiffel Tower, until at the beginning of 2015 a permanent measuring station opened there.

The systematic use of the summit had resumed earlier, within the project CO_2-MegaParis (2009–2012). In the summer of 2010 three new stations for the continuous measurement of CO_2 were deployed within the infrastructure of the AIRPARIF agency: on the summit of the Eiffel Tower (designation EIF, 317 m above the ground), at Gonesse (GON) and at Montgé-en-

Goële (MON). The processing was carried out by the Laboratory of Climate and Environmental Sciences (LSCE, CEA–CNRS–UVSQ). On the basis of these and of the network's reference stations (Traînou, Gif-sur-Yvette) a Bayesian inversion of the emissions of the Paris agglomeration was built, with a spatial resolution of 2 km (F.-M. Bréon and co-authors, 2015). The instruments are cavity-ring-down spectrometers (CRDS, Picarro), calibrated to the scale of the World Meteorological Organization [23, 24].

The instrument's high position gives rise to a characteristic daily signal: every morning the sensor at the summit records a sharp peak of CO_2 concentration at the very moment when the growing atmospheric boundary layer reaches the height of measurement and carries up the carbon dioxide accumulated overnight in the surface layer. This is the same nocturnal stability of the lower layers of the atmosphere that Angot in the 1890s discovered with a thermometer as a temperature inversion, now read off through the concentration of carbon. The Parisian network developed since 2015 (seven stations, continued by the ICOS Cities project under the direction of Michel Ramonet, LSCE) records a steady rise in background concentrations — of the order of +2.34 ppm CO_2 and +11.1 ppb CH_4 a year over 2015–2022 — in agreement with the data of remote observatories such as the Jungfraujoch [25, 26].

Thus a circle almost a century and a half long is closed: the vertical scale of the Tower, with which Mascart and Angot measured the inversion of temperature and the daily march of pressure, today serves the same atmosphere — but now for the accounting of its carbon balance.

Why the Tower Was an Especially Fortunate Site

The success of the Eiffel Tower as a meteorological laboratory is explained by several circumstances. The first is height. Three hundred metres above lowland Paris gave an almost unique opportunity to observe a layer of the atmosphere ordinarily inaccessible without a balloon. Mountain stations stood higher, but they studied the mountain atmosphere, not the urban one. The Tower, by contrast, made it possible to study vertical differences directly above the metropolis.

The second is stability and accessibility. A balloon gave great height but was dependent on the weather and short-lived. The Tower was permanent; it had stairs, lifts, rooms, electric lines and staff. An instrument could be left for weeks and months, serviced, compared with other instruments, and made to yield continuous records.

The third is the engineering openness of the structure. The lattice form reduced windage and let the air pass through the structure. The Tower did, of course, distort the flow, but far less than a massive stone tower of the same height would have. This was important for wind measurements. Moreover, the various platforms offered a choice of places for installation.

The fourth is the nearness of scientific institutions. Paris was a centre of academies, engineering schools, the meteorological service, instrument-making and printed publication. The data could quickly be brought into scientific circulation. The Tower stood not in a remote expedition but at the centre of a communication network.

The fifth is Eiffel's personal strategy. He understood that scientific usefulness protects a structure from demolition. He therefore did not merely permit experiments but actively created a scientific image around the Tower. Meteorology became part of the politics of preserving the monument. In this sense the laboratory was at once a research space and an argument in a public dispute.

Conclusion

The Eiffel Tower became a meteorological laboratory because its existence required scientific justification and its physical properties gave real research value. Built for the World's Fair of 1889, it soon passed beyond the exhibition spectacle. On its upper levels worked instruments for temperature, pressure, humidity, precipitation, wind and atmospheric electricity; the data were processed by the Central Meteorological Bureau; Gustave Eiffel published the results and developed from them a programme of aerodynamic research; Theodor Wulf used the Tower for an experiment bound up with the future discovery of cosmic rays; military radio engineers turned it into a strategic antenna.

The chief conclusions drawn thanks to the Tower may be divided into the meteorological, the methodological and the engineering. Meteorologically, it was shown that in the lowest few hundred metres of the atmosphere above a city stable vertical differences exist. The wind strengthens and grows more regular with height, and its daily course is reversed, as on a mountain; the daily variations of temperature and humidity are smoothed with height, and on calm clear nights the summit proves warmer than the foot; ground conditions depend more strongly on the urban surface. These data helped to refine ideas of the surface and urban layer of the atmosphere.

Methodologically, the Tower proved the value of continuous high-altitude observation. It was a forerunner of meteorological masts, high-altitude observatories and automatic stations. The electrical transmission of readings along a twenty-wire cable, the self-recording instruments of the Richard brothers, the comparison of levels and the long series became important elements of modern observational practice.

In engineering, the Tower became a test of wind-load calculations and a source of data for aerodynamics. Observations of the unforeseen force of the wind at height and of the significance of its instantaneous pulsations led Eiffel from the building of bridges and towers to the experimental science of air resistance. This line led on to works important for aviation, which was just then, at the beginning of the twentieth century, becoming a new field of technology.

Finally, the scientific-cultural significance of the Tower lay in its changing the very notion of a monument. A monument could be not only a sign of memory or power but a working instrument. The Eiffel Tower was a visible emblem of progress and at the same time produced data. Its history therefore shows how, in the industrial age, architecture, a state exhibition, a patent, a laboratory and a national meteorological service could be joined in a single object.

It was precisely the combination of permanent height, an urban setting, accessibility, electrical infrastructure and scientific ambition that made the Tower a fortunate site for experiments. It was a laboratory not because it had walls and tables, but because it turned the space above Paris into a measurable object. In this lies its special place in the history of meteorology: the Eiffel Tower showed that the atmosphere of a city has a vertical structure, and that an engineering monument can become an instrument of science.

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