

# EARLY OBSERVATIONS OF ROTOR CLOUDS BY ANDRIJA MOHOROVIČIĆ

BY VANDA GRUBIŠIĆ AND MIRKO ORLIĆ

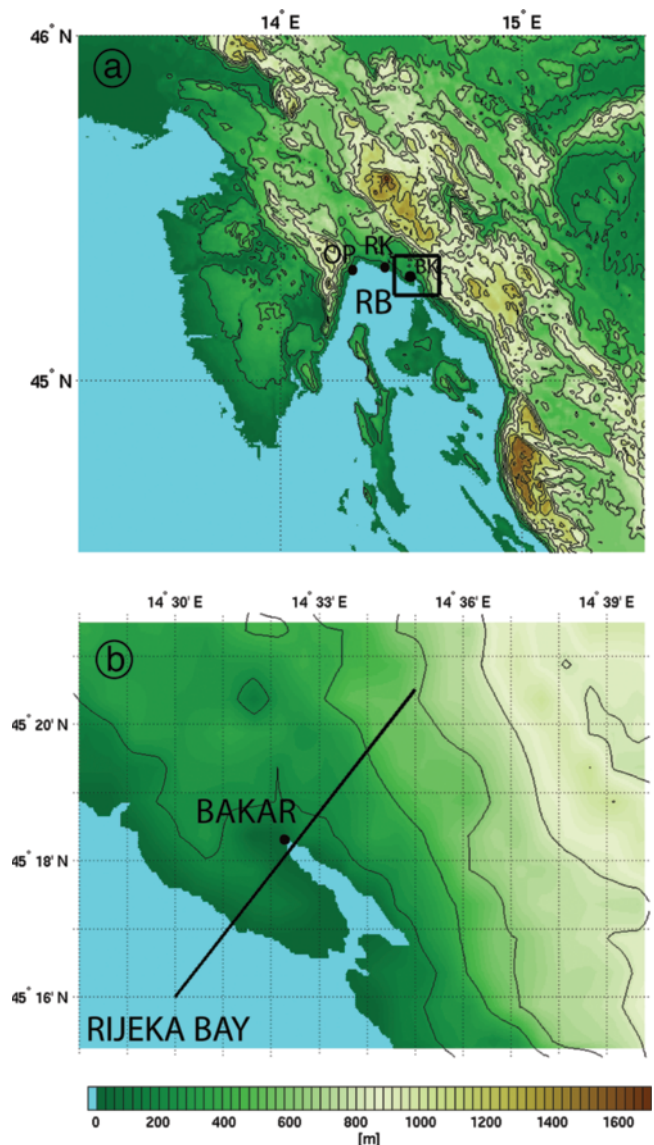
Well known for his discovery of discontinuity between Earth's crust and mantle, this all-around geophysicist also made pioneering observations of rotor-type circulation in bora.

**A**ndrija Mohorovičić initiated his cloud observations on 1 May 1888 while a professor at the Royal Nautical School in Bakar, Croatia. Located in the Kvarner region of the northern Adriatic at the foot of steep coastal mountains, Bakar (45°18'N, 14°32'E) lies at the north end of Bakar Bay in the east part of the larger Rijeka Bay on the northern Adriatic coast of Croatia (Fig. 1). The Royal Nautical School there was established in 1849,<sup>1</sup> and Mohorovičić joined its faculty in late 1882 as a lecturer, shortly after completing his studies of physics and mathematics at the University of Prague (Skoko and Mokrović 1982).

Mohorovičić's interest in clouds was motivated by the desire to contribute to the general theoretical understanding of the dynamics of upper-air currents and their relation to air movements near the ground. Living at the base of the coastal mountains in the northern Adriatic, where the famous bora wind frequently makes

<sup>1</sup> The Nautical School at Bakar was closed in 1856, but reopened in 1871, and it has been in continuous operation since that time under various names.

**FIG. 1. Diagrams of (a) the northern Croatian coast and (b) the Bakar Bay area. Topography contours are shown every 200 m. The solid rectangle marks the inset shown in panel (b). In (a) are marked the following toponyms: OP (Opatija), RK (Rijeka), BK (Bakar), and RB (Rijeka Bay). The solid line in (b) represents the baseline of the vertical section shown in Fig. 2.**



its appearance, he also drew his motivation from the desire to explain the dynamics of bora, recognizing the need to predict the onset of this severe gusty wind for the benefit of many communities on the shore and for nautical operations at sea.

Most of the late-nineteenth-century contemporaneous work on cloud observations, including their physical measurements and classification, had been done in northern Europe. As noted by Mohorovičić (1891), there was an absence of similar work in southern Europe, and he set out to change that. In his pursuit of cloud observations, he followed in the footsteps of his Scandinavian colleagues who made extensive use of a nephoscope for measurements of cloud movements (Ekholm and Hagström 1887).

In the course of this painstaking observational work on clouds, and with his general interest in the bora dynamics, Mohorovičić made observations of a special type of stationary cumulus clouds that formed occasionally during bora events over Bakar Bay, appearing to reside on top of a horizontal vortex downwind of the coastal mountain range (Mohorovičić 1889a). In view of the renewed interest in the study of atmospheric rotors, leading to the recently completed Terrain-Induced Rotor Experiment (T-REX; Grubišić et al. 2004), our goal is to bring Mohorovičić's early observations of atmospheric rotors into focus and set them in a wider historical context.

Section 2 contains a summary of Mohorovičić's observations of this special type of orographic clouds in Bakar, including a reproduction of the original diagram by Mohorovičić, which appears to be the first published illustration of the entire closed horizontal circulation of an atmospheric rotor, including the reversed surface flow branch. In section 3, we provide a contemporary setting of Mohorovičić's note on rotor cloud observations, and emphasize the role of the nineteenth-century journal editor in fostering the exchange of scientific ideas. A biographical note

on Mohorovičić and his scientific legacy is presented in section 4. Section 5 concludes the paper.

## MOHOROVIČIĆ'S OBSERVATIONS OF ROTOR CLOUDS.

From the outset of his cloud studies, and in addition to the regular hourly observations of cloud cover and cloud type carried out in collaboration with his colleague A. M. Zuvičić from the Royal Nautical School from 0700 to 2100 LT daily, Mohorovičić had conducted measurements of the direction and speed of cloud movement. These measurements were carried out 4 times daily at 0700 (0800 in winter), 1000, 1400, and 1600 LT, and whenever a new cloud appeared in the sky, which was sufficiently often for Mohorovičić (1891) to state<sup>2</sup>

Clouds are strange fellows, and you must catch them when they appear, and not when you would like to. Their directions and speeds also vary a great deal.

The measurements were made with a nephoscope that he constructed adapting the school-owned camera obscura (Mohorovičić 1888). Mohorovičić carried out the measurements of cloudiness, cloud types, and their movements for 2 yr, from 1 May 1888 to 30 April 1890. Employing elaborate trigonometric considerations, he had also developed a method for quantitative determination of the vertical velocity component using his measurements of the direction and speed of cloud movement (Mohorovičić 1889b,c). The analysis and summary of the cloud observations in the Bakar area represent the subject of Mohorovičić's doctoral thesis, which he successfully defended at the University of Zagreb in 1893.

During this 2-yr period of observation, he noted a special type of stationary cumulus cloud that occasionally formed during bora events over Bakar Bay. A particularly striking example of this type of cloud, which formed on 18 October 1888, prompted Mohorovičić to submit a short note to the *Meteorologische Zeitschrift* (Mohorovičić 1889a).<sup>3</sup> In this note he delivers a detailed description of orographic clouds and other meteorological conditions observed, together with a tabular summary of 4-times-daily measurements of pressure, temperature, vapor pressure, relative humidity, wind, cloudiness, and

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<sup>2</sup> The English translation of this paragraph comes from Skoko and Mokrović (1982).

<sup>3</sup> The author of this note is presented as Professor H. Mohorovičić. Because Mohorovičić had only one name—Andrija—this leads us to conclude that initial H. is the result of a typographical error.

cloud movements during a 3-day period surrounding this bora event.<sup>4</sup>

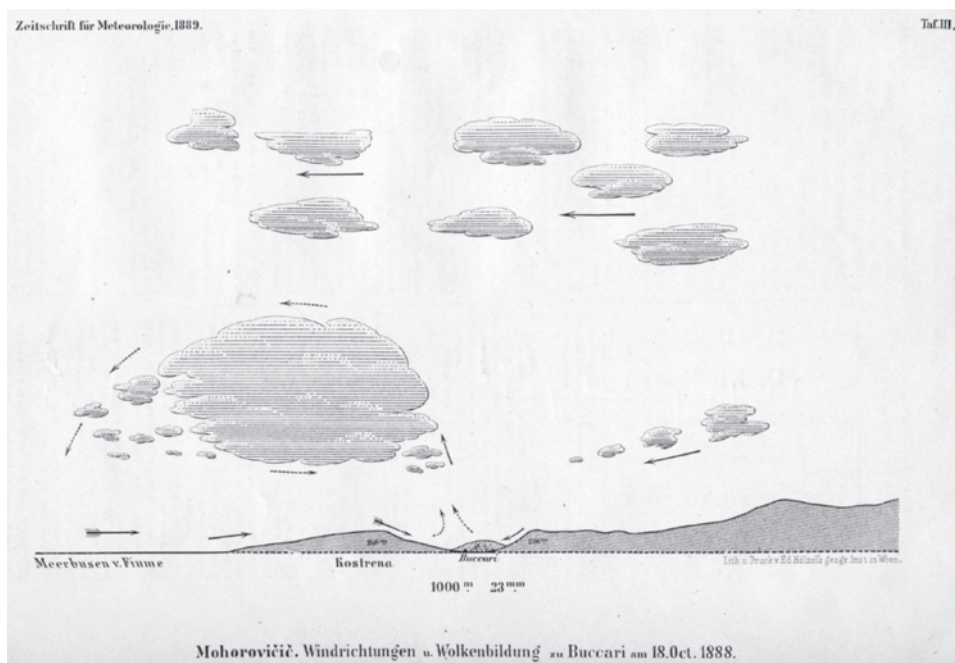
The key signature of this short note, in addition to a keen set of observations delivered in Mohorovičić's succinct writing style, is a diagram of the observed clouds and the attendant circulation in a vertical cross section over Bakar Bay parallel to the bora flow (Fig. 2). The diagram shows the following three major groups of clouds:<sup>5</sup> i) a stationary cumulus cloud with the leading edge over Bakar Bay, ii) fragmented stratocumulus clouds farther aloft moving steadily in a strong northeast flow, and iii) some smaller fragments of disappearing cumulus coming down the mountain slope. The large stationary cumulus cloud formed a line parallel to the coastal mountains, and "it extended as far as could be seen [in the northwest-southeast direction]."<sup>6</sup> A thick cumulus cloud bank, a bora-cap cloud, was present over the coastal mountains as well [not part of the diagram in Fig. 2, but shown in Mohorovičić (1891)], with some clear skies and cirrus seen in between the two cloud lines through

the stratocumulus aloft. From the torn peaks and edges of the mountain-cap cloud, smaller fragments of cloud broke off and gradually disappeared in the strongly marked descending motion down the mountain slope. Over Bakar, near the leading edge of the stationary cumulus cloud, smaller cumulus clouds that formed at lower altitudes moved swiftly (at the estimated  $15\text{--}16\text{ m s}^{-1}$ ) before reaching and merging into the large stationary cumulus. Mohorovičić interpreted the continuous formation of new clouds at the leading edge of the stationary cumulus mass as an indication of a sustained updraft at that location. The downwind edge of the stationary cumulus was also fringing, and the small cloud fragments that were torn from it were observed to disappear rapidly—a solid indication to Mohorovičić of a strong downwelling current at that end. The available surface observations from Rijeka Bay, where a strong west-northwest wind was reported (among other sources by a local steamer); from Bakar, where weak and variable winds were observed; and from the Kostrena side of Bakar Bay,

<sup>4</sup> It was a common practice at that time to provide tabulated observational surface data as core scientific material.

<sup>5</sup> The general cloud classification system Mohorovičić used was developed by Luke Howard.

<sup>6</sup> Bracketed information within quotes is provided by the authors.



**FIG. 2.** Clouds and winds observed from Bakar (Buccari in Italian) on 18 Oct 1888 as reported by Mohorovičić (1889a). The sea (Meerbusen v. Fiume, i.e., Rijeka Bay) is on the left, the mountains on the right. Full arrows mark the observed winds, dashed arrows are the winds deduced on dynamical grounds. The name of the journal in which this figure was published in 1889 was *Meteorologische Zeitschrift*. The reason why the older abbreviated name appears in this figure remains unclear.

showing winds similar to those over the Rijeka Bay, allowed Mohorovičić to close his diagram of attendant circulation, revealing a large horizontally oriented vortex. This cloud configuration persisted from the morning hours through the late afternoon (~1700 LT), with only a short break around local noon, leading Mohorovičić (1889a) to conclude<sup>7</sup>

It is impossible to imagine the existence of such a permanent mass of cumulus unless on the assumption of a rotary motion about a horizontal axis.

Mohorovičić speculated that the vortex formation was probably due to the particular geometry of the lee-slope terrain, which descends to the sea surface in a series of terraces.

While likely unaware of the precedent he was setting by providing a diagram of the circulation in what appears to be an atmospheric rotor, Mohorovičić was clearly aware that a large vortex with a horizontal axis is a rather unusual atmospheric phenomenon, opening his note by stating

We do not often read of a whirlwind with its axis horizontal, and I have not been able to find any notice of such a phenomenon in the *Meteorologische Zeitschrift*. I think, therefore, that what I say may be of interest.

Indeed, this short note by Mohorovičić was of great interest to the journal editor Julius von Hann, who appended it with his commentary on observations of stationary orographic clouds associated with horizontal circulations in the lee of complex terrain in various locations worldwide.

**CONTEMPORANEOUS OBSERVATIONS OF STATIONARY OROGRAPHIC CLOUDS: ROLE OF THE NINETEENTH-CENTURY JOURNAL EDITOR.** Mohorovičić's note on stationary orographic clouds in bora was published in *Meteorologische Zeitschrift*,<sup>8</sup> which at that time was the leading meteorological journal in continental Europe. In its stature and rating this journal was

only equaled by the *Quarterly Journal of the Royal Meteorological Society (RMS)* published in the United Kingdom. Julius von Hann, the director of the Zentral Anstalt für Meteorologie und Geodynamik (ZAMG) in Vienna, Austria, served as the editor of the *Meteorologische Zeitschrift* for more than 50 yr (1866–1920). At the time when the peer review process was not yet known,<sup>9</sup> the journal editor played a pivotal role in determining the profile of a journal by personally selecting the material for publication. In the *Meteorologische Zeitschrift*, research articles were mixed with short contributions, often dealing with interesting observations, as was the case with Mohorovičić's note. Described as a “living encyclopedia of his chosen [meteorological] science” (Ward 1922), Hann himself used to provide commentary and notes to accompany journal contributions in which he brought related material to the reader's attention. In the commentary following Mohorovičić's note, Hann lists observations of similar features observed in South Africa, Greenland, and north of the United Kingdom.

Perhaps the most interesting of these locations is that of Cross Fell in Cumberland in the north of England. The local wind there, known as helm,<sup>10</sup> has a long history of documentation [Brunskill (1884) contains appended earlier observations dating back to 1777]. Similar to bora, this gusty, violent, easterly cold wind is associated most often with bad weather as illustrated by a common saying from Penrith, a town located some 10 km west of Cross Fell (RMS Committee 1885): “The Helm is on, we shall have no good weather till the Helm is gone.” Characteristic cloud formations associated with the helm wind consist of a helm(et) cloud over the high peaks, a horizontal slim bar of a cloud (helm bar) that forms several miles to the west of and parallel to the mountains (with sometimes four or five of these bars being present downwind of Cross Fell), and a gap with clear skies in between (Fig. 3). The diagram in Fig. 3 was published in Marriott (1889), which is the full report to the RMS “Helm Wind Inquiry,” which contains the translation to English of all of Mohorovičić's (1889a) *Meteorologische Zeitschrift* note.<sup>11</sup>

<sup>7</sup> The English translation comes from Marriott (1889).

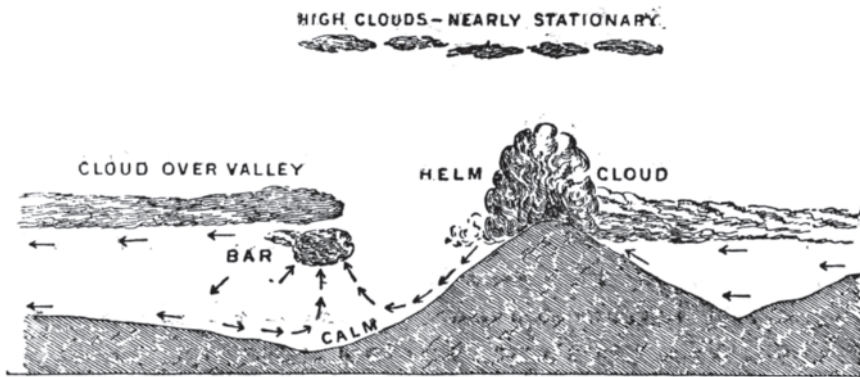
<sup>8</sup> Up to volume 18 (1883), the name of this journal was *Zeitschrift der Österreichischen Gesellschaft für Meteorologie* or abbreviated *Zeitschrift für Meteorologie*. In subsequent volumes, the journal was renamed the *Meteorologische Zeitschrift*, with the change of name coinciding with the Deutsche Meteorologische Gesellschaft joining the effort of journal publication.

<sup>9</sup> This touchstone of modern scientific method has been in place only since the middle of the twentieth century.

<sup>10</sup> The name “helm wind” most likely derives from the helmet-looking cloud that forms over Cross Fell during these events.

<sup>11</sup> An earlier version of this diagram, which is almost identical to the one in Fig. 3, except for the reversed-flow branch underneath the bar opposing the helm wind, was published in Marriott (1886).





**FIG. 3. Airflow and clouds in helm wind of Cross Fell (England). (From Marriott 1889.)**

That Hann was not just familiar with unusual cloud formations associated with the helm wind but also quite intrigued by them is clear from his note in the discussion section of Brunskill (1884). There, as in the commentary to Mohorovičić's note, Hann (an honorable member of the Royal Meteorological Society) points to a similarity between the helm cloud formations and those in the flow past Table Mountain in South Africa (Herschel 1862) and over the center of the Ivigtut Fjord in southwest Greenland (Fritz 1883). He also offers a possible explanation for the helm cloud and helm bar as being part of a sinusoidal airflow response to an isolated mountain, and suggests that, perhaps, in the case of helm wind there are vortices with horizontal axes. "A sketch, no matter how rough," summarizing all the essential elements of this phenomenon with respect to the local terrain, "would be of great use," states Hann. Given his statement of need for the diagram that shows all aspects of airflow and clouds in relation to the local terrain and his hypothesis about vortices with horizontal axes, we can only imagine his delight in seeing such a diagram and reading the conjectures in Mohorovičić's (1889a) note, prompting him to publish these observations and his commentary in the *Meteorologische Zeitschrift*.

## MOHOROVIČIĆ— AN ALL-AROUND GEOPHYSICIST.

*Who was Andrija Mohorovičić? Andrija Mohorovičić was born on 23 January 1857 in Volosko near Opatija, a coastal resort town in Croatia, then part of the Austrian (Habsburg) Empire (Skoko and Mokrović 1982). After graduating from the high school (gymna-*

*sium) in Rijeka in 1875, Mohorovičić enrolled in the study of physics and mathematics at the University of Prague. There he attended classes offered by Ernst Mach, the famous physicist and philosopher who subjected classical mechanics to thorough criticism, and Heinrich Durège, a well-known mathematician with a particular interest in complex analysis and elliptical functions. Following graduation from the University of Prague, Mohorovičić returned to Croatia and taught at high schools in Zagreb and Osijek, but finally settled in 1882 as a lecturer of mathematics, physics, and meteorology at the Royal Nautical School in Bakar, in close proximity to his birthplace. As already mentioned, in Bakar he started the research on clouds and related air motion, which led to his first scientific publications (Mohorovičić 1888, 1889a,b,c, 1891)<sup>12</sup> and, eventually, to the doctoral thesis defended at the University of Zagreb in 1893.*

*In 1892 Mohorovičić succeeded Ivan Stožir as the head of the Meteorological Observatory in Zagreb (Fig. 4) and remained there until his retirement 30 yr later. During this period he expanded work at the observatory and gradually added to it new components—seismology, geomagnetism, and time keeping<sup>13</sup>—so that the observatory was renamed the Geophysical Institute in 1921.<sup>14</sup> Moreover, he introduced geophysical courses at the University of*

<sup>12</sup>As the capital of the Austro-Hungarian Empire, as well as of its predecessor the Austrian Empire, Vienna was the most important center of politics and science in Central Europe at that time. It is not surprising then to find Mohorovičić, an ambitious scientist from Croatia who was educated in Bohemia (Prague), both of which were parts of the Austro-Hungarian Empire, to seek recognition by publishing in the most prominent journal in his field in continental Europe, published in Vienna.

<sup>13</sup>Mohorovičić had introduced observations of star passage through the meridian using a passage instrument and, later, had initiated synchronization of the observatory clocks utilizing the time coincidence signal received from an astronomical observatory. The clocks he maintained were used to time stamp the data collected at the observatory, but also to provide information on accurate time to the public.

<sup>14</sup>Today, the Geophysical Institute in Zagreb, which carries his name, continues the tradition of geophysical research in a broader sense, including the solid earth, oceans, and atmosphere, within the Department of Geophysics at the University of Zagreb.



**FIG. 4. Hitherto unpublished picture showing (from right to left) Andrija Mohorovičić, Spas Vatzov (1856–1928, founder of the Bulgarian Meteorological Service), and Ivan Stožir (1834–1908, founder of the Zagreb Meteorological Observatory and Mohorovičić’s predecessor at the observatory). The picture was taken in Zagreb in the 1890s, a few years after Mohorovičić had performed observations at Bakar.**

Zagreb in the 1894/95 academic year and taught them by himself for over more than two decades. After arriving at the observatory, Mohorovičić continued with meteorological research. His published papers from that period cover such diverse topics as a whirlwind (tornado) observed in the continental part of Croatia, the climate of Zagreb, and the decrease of air temperature with height. Around the turn of the century, however, he switched from meteorology to seismology and soon arrived at his most important discovery.

While analyzing seismograms of the earthquake near Zagreb that occurred on 8 October 1909, Mohorovičić noticed that at epicenter distances ranging from 300 to 720 km two longitudinal and two transverse waves were recorded, and that at other locations only one longitudinal and one transverse wave were observed. With the flash of a genius he concluded that, in addition to a continuous increase in the speed of seismic waves with depth, the interpretation these observations demanded is that of the existence of a discontinuity where the waves are reflected and refracted. By applying a simple model he determined the depth of the discontinuity as well as the speed of the seismic waves above and below it. The existence of the surface that separates the Earth’s crust from

the mantle was thus demonstrated for the first time (Mohorovičić 1910). After publishing the seminal finding, Mohorovičić continued to do important work in seismology by proposing construction of a new seismograph, developing an original method for the location of epicenters, constructing reliable travel-time tables for distant earthquakes, and studying the response of buildings to earthquakes. Mohorovičić’s work in seismology established him as one of the leading Earth scientists of all times. He died on 18 December 1936 in Zagreb. Today, the discontinuity he discovered is named after him (the Mohorovičić discontinuity or MOHO), as is a crater on the moon and asteroid 8422.

*Mohorovičić’s scientific legacy.* Obviously, Mohorovičić was scientifically active in two fields of geoscience research: in meteorology until his 40s and in seismology subsequently, with almost no overlap of the two

sets of activities. Many of his biographers assumed implicitly, and some stated explicitly (e.g., Maksić 1960), that while both lines of research were stimulated by regional phenomena, they differed in their impact; whereas the seismological work influenced the development of Earth science worldwide, the meteorological work was only relevant regionally. The truth, however, is more complex.

As we have seen, the note in which he describes rotary motion of the air about a horizontal axis (Mohorovičić 1889a) was translated into English and published in the same year in the *Quarterly Journal of the Royal Meteorological Society* (Marriott 1889). The note was subsequently cited in some of the most influential meteorological textbooks of the time, for example, in those published by Hann (1901; and later editions) and Wegener (1911; and a later edition). This note is also cited in seminal papers on aerial observations of mountain lee waves (Küttner 1938, 1939). In his review of early observations of stationary clouds and circulations on the lee side of mountains, Kuettner<sup>15</sup> cites Mohorovičić (1889a) and

<sup>15</sup>Joachim Küttner changed the spelling of his last name to Kuettner after emigrating to the United States after World War II.

his diagram of a “Bora Roller,”<sup>16</sup> stating a similarity with circulations and stationary clouds observed in the lee of Cross Fell, Greenland, and later observational accounts in the lee of Riesengebirge.<sup>17</sup>

After this time, Mohorovičić’s note disappears from international literature; for example, Mohorovičić was neither cited in Queney et al. (1960) in their overview of studies addressing airflow over mountains, nor by Yoshino (1976) in the only monograph published to date on the bora wind. Thus, by the time Mohorovičić became subject of biographical research, he was no longer cited in widespread meteorological publications,<sup>18</sup> although his work was by then firmly incorporated into the existing knowledge on atmospheric rotors.

While Mohorovičić was clearly a pioneer of atmospheric rotor research, this field of research was slow in developing and his direct contribution gradually faded away. Instead, much later observational work by Kuettner from the 1930s in the lee of the Riesengebirge is remembered today—the work that had directly motivated and led to subsequent research on mountain waves and rotors,<sup>19</sup> including both theoretical and further observational studies (Grubišić and Lewis 2004). On the other hand, Mohorovičić’s pioneering work in seismology had a strong, immediate impact, and his contribution to this field is regarded as seminal. Although in both cases he showed an ability to do first-class research, it was only in seismology that his skill in combining empirical and theoretical approaches would be fully employed. His scientific approach, however, makes it clear that objective, reasoned thinking in the presence of careful observations remains the hallmark of discovery in science.

**OUTLOOK.** From the time of Mohorovičić to today, illustrations of atmospheric rotors remain dominated

by two-dimensional diagrams indicating the presence of anticyclonic rotary motion underneath the crests of mountain lee waves in a stable airstream over a mountain ridge (Doyle and Durran 2004). Paralleling the advancements in understanding of the rotor phenomenon, these diagrams have morphed from early attempts to grasp an unusual atmospheric behavior using sharp observations and thoughtful deductions to schematic diagrams representing conceptual models of time-averaged behavior of turbulent rotors. Very detailed observations by a multitude of sophisticated airborne and ground-based, in situ, and remote sensors deployed in the recently completed Terrain-Induced Rotor Experiment (T-REX; Grubišić et al. 2004), combined with the power of high-resolution numerical simulations, offer a unique and an unprecedented opportunity to obtain a more realistic depiction of the spatially and temporally varying terrain-induced rotors.

From those early days of Mohorovičić’s keen deductions on rotary motion about a horizontal axis, unraveling the mysteries of atmospheric rotors continues to the present day. Continued also is the effort to understand the complex mesoscale structure of the bora flow. Significant progress has been achieved with aerial observations of bora in the Alpine Experiment (ALPEX; Smith 1987) and the Mesoscale Alpine Programme (MAP; Grubišić 2004), which have, respectively, offered a two-dimensional view of bora as the hydraulically controlled severe downslope wind<sup>20</sup> and revealed its three-dimensional variation along the coastal mountain range with a number of individual bora jets and wakes within the Dinaric Alps wake. Today, availability of high temporal and spatial resolution observations and high-resolution numerical simulations offers new possibilities for investigating small-

<sup>16</sup>This was called the “Bora Walze” in the original German publication (Küttner 1938).

<sup>17</sup>One of those observations that has made a particularly strong impression on Kuettner is that of H. Koschmieder, the well-known dynamicist, who had photographed some rotor clouds and had subsequently carried out a thorough analysis of these cloud observations, similar to what Mohorovičić undertook decades earlier with a different set of observations on clouds, to obtain an estimate of a  $10 \text{ m s}^{-1}$  updraft at the leading edge of the rotor (Koschmieder 1920).

<sup>18</sup>Even in Croatia, where Mohorovičić’s note has been regularly cited from at least the 1930s, his diagram of a bora-related rotor seemingly fell into oblivion, probably because it was not published along with the text, but in an appendix to the 1889 issue of the *Meteorologische Zeitschrift*. The diagram was rediscovered in 2005, which prompted the present study of Mohorovičić’s early contributions to meteorology.

<sup>19</sup>Subsequent observational documentation of atmospheric rotors is closely tied to observations of mountain waves. This is not surprising given that the earliest aerial documentation of mountain lee waves was done with gliders, which had to pass through turbulent rotors on their way to smooth wave updrafts (Kuettner and Hertenstein 2002; Grubišić and Lewis 2004).

<sup>20</sup>Incidentally, elongated cumulus cloud lines downwind of and parallel to the coastal mountain range are shown in Smith (1987), who refers to them as “turbulent lee clouds” or “lee-side ‘jump’ or ‘rotor’ clouds.” In T-REX terminology, this likely represents a reference to the hypothesized type II or a hydraulic jump rotor (Grubišić et al. 2004).

scale structures within the bora flow. And, thus, it is not surprising to see studies of bora rotors emerge again (Gohm and Mayr 2005), nearly 120 years after Mohorovičić discovered them.

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