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SUTCLIFFE, REGINALD COCKCROFT

(*b.* Cleckheaton, Yorkshire, 16 November 1904, *d.* Cadmore End, Buckinghamshire, 28 May 1991),*synoptic and dynamic meteorology, numerical weather forecasting, weather forecasting, aerology, wartime meteorology.*

Sutcliffe was the first meteorologist who, after World War II, brought mathematically-based scientific principles and methods into daily, operational weather forecasting. This paved the way for the application of computers into meteorology.

Reginald Cockcroft Sutcliffe was born in Yorkshire in northeastern England to Ormerod Greenwood Sutcliffe and Jessie Sutcliffe (née Cockcroft). There were four sons in the marriage, of which Reginald was the third. The oldest died at five of diphtheria; the remaining three brothers were Robert, Reginald, and Alfred. When Reginald died in 1991, he was survived by his wife Evelyn and two daughters.

Early Career. It was not because of any deeper interest in meteorology or even in weather that R. C. Sutcliffe in summer 1927, at the age of twenty-three, joined the United Kingdom Meteorological Office(UKMO). He had just gained his PhD in statistics at the universities of Leeds and Wales after leaving school in his home county Yorkshire. But the times were bad and it was difficult even for a newly promoted PhD to get a job. Luckily the UKMO needed a statistician for climatological work for proposed air routes across the Mediterranean to Africa and India.

When Sutcliffe entered meteorology there was a wide gulf between the weather forecasters and the few meteorological scientists. Forecasting was a matter of intuition and experience based on rather elementary theory. There was practically no formal meteorological training available in Britain. The idea was, he remembered later, to pick up information "by a process of osmosis"(Burton, 1990, p.3).

After some months at the forecast bench he was posted to Malta from 1928 to 1931 to get firsthand experience of Mediterranean weather patterns by making forecasts for the Royal Navy. During his first winter he was fortunate to be joined by the renowned Swedish colleague Tor Bergeron, who had been contracted to study the Mediterranean weather in the light of the new meteorological theories of the Bergen School where low-pressure cyclones were seen as developing in the border zones ("fronts") between air masses of different densities. Bergeron imbued in Sutcliffe a belief in the importance of combining fundamental physical and mathematical approaches with the study of observational data.

Back in the United Kingdom in 1932 Sutcliffe was posted to the Felixstowe flying boat base and in 1935 at the UKMO headquarters at the Air Ministry in Kingsway. In 1937, while stationed at Thorney Island aviation base near Portsmouth, responsible for educating and examining pilots, he got six-month paid leave to write an elementary textbook in meteorology, *Meteorology for Aviators* (Sutcliffe, 1938a). He had now acquired a deeper interest in dynamical meteorology and the three-dimensional nature of the atmospheric circulation, and became involved in research into the formation of cyclones together with an older colleague, Charles Sumner Durst.

The Problem of Wind and Low and High Pressure Systems In the nineteenth century there were two prevailing theories to account for mid-latitude low pressure cyclones. The *dynamic theory* argued that they were created by opposing air currents of different density. The *thermal theory* held that they developed by rising warm and often moist air. There was no satisfactory hypothesis about the formation of their counterpart: high pressure anticyclones.

At the beginning of the twentieth century meteorologists began to realize that the formations of low pressure cyclones and high pressure anticyclones involved both dynamic and thermal processes. They were two aspects of the same problem, represented by conversion between kinetic and potential energy, the mutual relation between motion (wind) and mass (the pressure field).

In 1860 the American W. Ferrel had mathematically defined an idealized "geostrophic wind" blowing parallel to the isobars, its strength inversely proportional to the distance between the isobars (the pressure gradient force) and the sine of latitude (the Coriolis force). Gradually meteorologists realized that this geostrophic wind was not only a good approximation of the real wind, but provided a clue to an understanding of atmospheric motion. The acceleration and deceleration of the wind was caused by the imbalance between the two forces involved, the pressure gradient force and the Coriolis force. The motions of converging or diverging air masses, the real "going on" in the atmosphere, were a reflection of the fact that the geostrophic approximation was never exact.

In this precomputer era it was not feasible to mathematically calculate atmospheric motions from such basic physical principles. Instead meteorologists tried to find and explore simple relations between the wind and the pressure field. Beside the *geostrophic wind balance* there was the *gradient wind balance*, which expanded the geostrophic wind to include the effect of the curvature of the motion. Another was the *thermal wind balance*, the strong tendency of vertical changes in horizontal wind to be parallel and proportional to the mean temperature contrast.

Work with C. S. Durst. In 1933 C. S. Durst had successfully applied these relations to explain the maintenance of stable high-pressure systems. In a joint paper, Durst and Sutcliffe (1938b) used the same approach to explain the deepening of tropical cyclones. Downward motion in anticyclones and upward motion in tropical storms would make the wind deviate toward higher pressure and in the case of the high-pressure anticyclone "squeeze" it, in the case of the tropical cyclone deepen and intensify it.

But when they tried to extend their theories to extratropical systems, they ran into contradictions. While stable high-pressure systems and tropical storms are warm-core systems, mid-latitude cyclones, and some continental highs, are cold-core systems. The vertical motion would in these cases make the displaced horizontal wind deviate toward lower pressure, tend to equalize the horizontal pressure contrasts, and thus weaken the systems.

To solve the problem Sutcliffe and Durst (1938) introduced the concept of *quasi geostrophy*, which they defined as a departure from the geostrophic velocities which were generally small compared with the actually observed wind, but still of dynamical significance. Although mathematically inconsistent from a rigorous point of view, it turned out to be a fruitful approach. it provided meteorologists with a mathematical formalism where the departures from geostrophic balance could partially be taken into account and enable approximate, but quantitative, calculations. This would ultimately open up the gates for use of computer-based weather forecasting.

The 1939 Development Equation. In those days atmospheric "development" was simply identified with pressure changes, the change of the accumulated weight in a column of air due to horizontal mass in- and outflow. The problem was that the pressure change was a very small residual of two large changes of opposite signs, located one above another in the vertical. One would represent convergence (inflow) and the other divergence (outflow); each of these could only be estimated approximately.

The breakthrough came in 1939, when Sutcliffe recognized that there was no real need to compute the divergence and convergence separately. Drawing on an idea by the British meteorologist William Henry Dines, Sutcliffe realized that just because the divergence and convergence of the horizontal mass flux took opposite signs their differences, more than their absolute values, would identify regions of cyclonic and anticyclonic development.

Sutcliffe now approximated "development" by the acceleration of the wind and introduced the thermal wind, $V_T = V - V_0$, as the link between two levels with winds V and V_0. After some manipulations he arrived at an equation in Cartesian coordinates, expressing the acceleration of an individual air parcel

$$\frac{dV}{dt} \approx (V_T \cdot \nabla)\, V_0 + \frac{dV_T}{dt},$$

where the first term on the right side described the effect of the flow difference between upper and lower atmospheric levels, and the second term the time evolution of the thermal pattern. There was no need to know the upper winds, just the vertical wind change, given by the thermal field. The further interaction between the two levels leads to promote either cyclonic or anticyclonic development. The latter aspect was perhaps the most innovative part of his theory because it presented for the first time a quantitative way to forecast changes also of a high-pressure system.

The War Years. In October 1939 "Cyclonic and Anticyclonic Development" was published in the *Quarterly Journal.* By then the war had started and Sutcliffe was transferred to the Royal Air Force headquarters in France, where he served as a squadron leader with a mobile meteorological unit supporting the British Expeditionary Force.

In May 1940 Sutcliffe was evacuated from Boulogne to south of Paris just before the collapse of the British forces in the area. When France capitulated he was in Marseilles and arrived in Britain after a dangerous sea journey via Gibraltar. He was then posted as Senior Meteorological Officer at the headquarters of No. 3 Bomber Group of the RAF near Newmarket. His main task was to prepare weather forecasts for bombing operations over Germany, mostly nighttime raids. The problem was to estimate the upper wind without much more information than scant aircraft reports and radio sonces (balloon-carried instruments transmitted to the ground by radio).

The years he had invested in thinking about the three-dimensional structure of the troposphere, the mechanisms of pressure changes, and the cause of cyclone developments were now rewarded. Where his colleagues only used extrapolation techniques mixed with some empiricism, Sutcliffe was able to see much deeper and make more elaborate deductions. This is evident in a wartime memorandum (Sutcliffe, 1941) about a case he had experienced of a rapid development when mild and moist maritime tropical air and cold air from the Arctic moved toward each other, a scenario that was illustrated by the second term in his 1939 equation. With the Belgian mathematician Odon Godart, who also served as a weather forecaster, Sutcliffe suggested the use of pressure instead of height as vertical coordinate (Sutcliffe and Godart, 1942). This simplified the mathematics and proved to be another innovative contribution paving the way for numerical forecasting by computers.

Sutcliffe was not directly involved in the D-day weather forecast in June 1944, but took part on a telephone line in the daily weather discussions between the three main forecast teams, one American, one British and one mixed English-Scandinavian. He tended to align himself with the outlook, mainly promoted by American forecasters, which correctly foresaw that the flow pattern over the North Atlantic would change from westerly to northerly, but tended to be overly optimistic about the actual weather at the landing beaches, where the judgments of the non-American teams proved to be more realistic.

The 1947 Development Equation. After Germany's capitulation Sutcliffe was put in charge of reorganizing the weather service in Hamburg and screening the German meteorologists, many of whom were prisoners of war. In 1946 he was back in Britain awaiting the postwar reorganization of the UKMO, during which time he started to rewrite his 1939 paper. Again linking "development" with the difference between upper and lower in- and outflow, Sutcliffe derived a new version of his 1939 equation, with three terms in pressure coordinates. Probably influenced by Carl-Gustaf Rossby's Chicago school, Sutcliffe chose to formulate his equation in terms of the horizontal wind shears instead of wind components (Sutcliffe, 1947).

Scientifically and practically this equation was less elegant then its 1939 predecessor and with its three terms too laborious for operational use. Only after he had dropped two of the terms and kept one "development term,"

$$-V_T \frac{\delta \zeta_T}{\delta s},$$

the advection of the thermal vorticity ζ_T by the thermal wind itself V_T, did his formula become a tool for operational forecasting although it never made any deeper theoretical impact on the meteorological science

The Advent of the Computer. After the war Sutcliffe played a leading role in the establishment of a strong research center at the UKMO, culminating in his appointment as director of research in 1957. The introduction of Sutcliffe's development equation coincided with the advent of the computer and encouraged the start of numerical weather prediction (NWP) in Britain. Like many others of his generation he had mixed feelings about the advent of the computer. He felt it had come "too early," when the full potential of the human forecaster, armed with Sutcliffe's rules and experience, had not yet been exhausted.

On the other hand he welcomed the opportunity to test his ideas about the motion of the atmosphere determined by thermal contrasts. His belief was shaken twice: first when the Americans and Scandinavians managed to make realistic forecasts of the large-scale motions by neglecting any thermal contrasts; secondly when Sutcliffe's scientists found that taking the thermal contrasts into account for NWP turned out to be much more complicated than envisaged. Sutcliffe chose to stand aside with a rather laid-back, skeptical attitude. This eventually led him to doubt any radical advance in weather forecasting, in particular the possibility of NWP (Persson, 2005).

The same could not be said about the 1939 version, although the influence was secondhand. A copy of Sutcliffe's 1941 memo reached the meteorological department at University of Chicago, probably during an unofficial visit by Sutcliffe in autumn 1944. the wartime discussion of a real-case weather situation in the light of the 1939 paper came to have profound influence on the explorations of jet-stream dynamics by leading American meteorologists and later it influenced studies of cross-frontal circulations (Hoskins, 1994).

In 1965 Sutcliffe welcomed the invitation, on approaching retirement from the UKMO, to establish a new department of meteorology in the University of Reading. He was its head until his final retirement in 1970. During this time he turned increasingly to problems related to the global water balance, climate, and climate change.

Sutcliffe was honored by an OBE in 1942, a CBE in 1961. He was editor at the Royal Meteorological Society (1947–1949) and (1970–1973), and its president from 1955 to 1957. Sutcliffe's scientific achievements were recognized by election to the Royal Society in 1957, the award of the Symons Gold Medal of the Royal Meteorological Society in 1955, the Charles Chree Medal of the Physical Society in 1959, and the International Meteorological Organization (IMO) Prize in 1963. From 1975 he was an honorary member of the American Meteorological Society, from 1976 of the Royal Meteorological Society.

Personality and Legacy. Sutcliffe contributed with pleasure to scientific discussions. They were always directed at any scientific weak points but always with a uniquely elegant wit. He would not allow loose scientific thinking to go unchallenged, but did so in a kind and uniquely witty manner. In 1957 he revived the Meteorological Dining Club originally founded in 1909. It continues to serve as the informal get-together for influential decision-makers from different sectors of British meteorology. Younger colleagues who had high regard for his intellectual ability, insight, and understanding of atmospheric behavior were nevertheless disappointed that he did not make even greater contributions to science than he actually did. They felt he seemed to lack the personal ambition or the deep conviction for the future progress the subject required, nor to drive himself and others to great achievements. This might be true of the Sutcliffe that rose to fame after the war, but does not seem to apply to the very ambitious and energetic Sutcliffe of prewar days.

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Anders Persson

TEISSERENC DE BORT, LÉON PHILIPPE

(*b.* Paris, France, 6 November 1855; *d.* Cannes, France, 8 January 1913), *meteorology, aerology.*

Teisserenc de Bort is famous in meteorology for his discovery of the stratosphere, "the most surprising discovery in the whole history of meteorology" (Shaw, p. 225), but also for his works on dynamic meteorology (the science that attempts to explain atmospheric motions), on the classification of clouds, and on the general circulation of the atmosphere.

He was born to a prominent and wealthy family, never got married, and devoted his fortune to atmospheric research. Suffering from poor health, he was taught at home by a private tutor who gave him his taste for sciences. For the same reason he made several long stays in Grasse, in the hinterland of Cannes, France, where he started meteorological observations that were sent for publication to the Société météorologique de France