6

Observations and initial fields

> *'. . . the icy layers of the upper atmosphere contain conundrums enough to be worthy of humanity's greatest efforts . . . ' . (Hergesell, 1905)*

We have seen in the last chapter how Richardson constructed a complete algorithm for integrating the equations of motion and, in the following one, we will study the application of his method to an actual weather situation. To do that, initial conditions are required, and we describe in this chapter the means of obtaining them. We outline the emergence of aerology, the study of the upper atmosphere. We describe an ingenious instrument for making aerological observations Then we consider some results of Bjerknes' 'diagnostic programme'. Finally, we discuss the preparation of the initial fields for the numerical forecast.

6.1 Aerological observations

During the 19th century, measurements of atmospheric conditions at the Earth's surface were made on a regular basis, and daily surface weather maps were issued by several meteorological institutes. Observations at elevated locations were much more difficult to obtain. A number of mountain stations were established towards the end of the century: Mt. Washington in 1870, Pike's Peak in 1873, Pic du Midi in 1886, Fujiyama in 1898 and Zugspitze in 1900 (Khrgian, 1959). However, climatological conditions at mountain stations have particular characteristics. What was desirable was an investigation of conditions in the free atmosphere. Several intrepid balloonists ascended with instruments to measure the vertical structure of the atmosphere. James Glaisher, of the Royal Observatory in Greenwich, made numerous ascents in the 1860's to measure the variations of temperature and humidity with height. Such explorations were both expensive and dangerous; indeed, there were a number of fatalities. The credit for initiating systematic observations of the upper air goes to Lawrence Rotch of Blue Hill Observatory, Boston, who around 1895, started the method of attaching self-recording instruments to kites. Kites and tethered balloons had a limited vertical range, and the steel piano-wire used to control them occasionally snapped, with serious consequences.[1]

Sounding balloons, which carried self-registering instruments aloft as they rose by natural buoyancy, were proposed by George Besançon and Gustave Hermite (a nephew of the renowned mathematician, Charles Hermite) as a powerful, practical technique for exploring the higher reaches of the atmosphere. These balloons were tracked by two theodolites, separated by a baseline of 1 km or more. Balloons launched at night were equipped with a small light to render them visible. The wind speed and direction at each level could be deduced from the azimuth and elevation bearings of the theodolites. A large specially-designed slide-rule was used for the calculations, and the winds were available in near ‘real-time’. Pilot balloons were small balloons without any instruments attached. They were named for the aviators who launched them prior to take-off to see how the winds aloft were blowing. For the temperature and humidity, the recording instrument had to be recovered. This normally took at least several days. Such data were clearly of no relevance for operational weather prediction, but would prove hugely beneficial to researchers.

In addition to the government-funded activities, several aerological observatories were established by enthusiasts. Thus, the observatories at Blue Hill, Boston and at Trappes, Paris were run by Lawrence Rotch and Teisserenc de Bort respectively, using their own financial resources. Aeronautical pioneers also contributed to the advancement of this emerging science.[2] The first instrumented balloon ascent was carried out by Gustave Hermite on September, 17th, 1892, using a waxed paper balloon. Constant volume balloons halt their ascent when they reach their level of neutral buoyancy. Around 1900, Richard Assmann, Director of the Royal Prussian Observatory in Berlin, revolutionised the sounding technique when he introduced rubber balloons. These expand with height, maintaining an approximately constant rate of ascent. Assuming this rate to be known, the position can be determined by means of a single theodolite. These expanding balloons never reach a position of equilibrium, but continue to rise until they burst. They enable measurements to be made at heights up to 15 or 20 km. They are reliable and relatively inexpensive and are still in use today. The method of upper air observation using sounding balloons came into widespread use from this time. It was now possible

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[1] In one notorious incident an array of kites, launched by Teisserenc de Bort, broke loose and drifted across Paris trailing 7 km of wire. They stopped a steamer and a train and disrupted telegraphic communications with Rennes on the day when the results of the Dreyfus court-martial in that city were anxiously awaited (Ohring, 1964).

[2] Bjerknes (1910) summarized the symbiosis between aviation and aerology: ‘The development of aeronautics will make these [aerological] observations not only possible, but also necessary.’

Fig. 6.1. International Meteorological Conference, Paris, 1896 (from Shaw, 1932).

to launch balloons simultaneously from several locations, raising the possibility of synoptic aerology (Nebeker, 1995).

At the Conference of the International Meteorological Organization in Paris in 1896 (see Fig. 6.1), a Commission for Scientific Aeronautics (ICSA) was established. Hugo Hergesell, Director of the Meteorological Institute of Strasbourg, was appointed President of the Commission. Hergesell was actively involved in upper air observations. He was also a consummate diplomat, and succeeded in overcoming the rivalry between the French and German scientists and establishing excellent international collaboration. The tasks of the Commission were to co-ordinate and regulate upper air research in Europe, to establish standards and to organize simultaneous observations of the free atmosphere on 'International Aerological Days'. Hergesell published a series of reports of the ICSA Conferences. He also published, between 1901 and 1912, some 22 volumes of data acquired during the Aerological Days. The first such experiment was on 13/14 November, 1896, with remarkable results, which Shaw would, much later, refer to as 'the most surprising discovery in the whole history of meteorology' (Shaw, 1932, p. 225). The sonde launched from Paris showed an isothermal layer above 12 km. This was the first indication of the stratosphere, but the measurements were discounted as erroneous and it took several years before the existence of the tropopause and stratosphere were firmly established, independently by Teisserenc de Bort and Richard Assmann. For an interesting account of the events surrounding the discovery of the tropopause, see Hoinka, 1997.

Upper air observations were made only intermittently, typically for one or a few days each month, as agreed by the countries participating in the work of the ICSA. European aerological stations active at this time included Aachen, Bath, Berlin, Copenhagen, De Bilt, Guadalajara, Hamburg, Kontcheiv, Lindenberg, Milan, Munich, Pavia, Pavlovsk, Strasbourg, Trappes, Uccle, Vienna and Zurich. The International Aerological Days, or 'Balloon Days', were normally on the first Thursday of each month. In three months of each year the adjacent Wednesday and Friday were added, giving three consecutive days and, once a year, six consecutive days, the 'international week'. The co-operation came to a sudden end with the First World War. Although the radiosonde was invented in 1927, it was not until after the Second World War that a real synoptic upper air network was established in Europe.

6.2 Dines' meteorograph

William Henry Dines (Fig. 6.2) was a master in the design and construction of meteorological instruments. He was active on the Wind-Force Committee that was set up following the Tay Bridge disaster. A train fell into the river when the bridge was blown down in a storm in December, 1879, with the loss of over one hundred lives. This provided a strong incentive for the development of instruments capable of measuring the wind accurately. One result was Dines' pressure-tube anemometer, an ingenious construction that gives a continuous record of the wind speed and direction, with detailed reading of gusts and lulls. Dines also expended considerable energy investigating solar and terrestrial radiation, and undertook some more general studies of atmospheric structure. However, his main contributions were to the study of the upper atmosphere. Although it was not until 1908 that regular aerological observations began in England, Dines began his investigatons of observing techniques some years earlier. Shortly after Sir Napier Shaw took charge of the Met Office in 1900, he encouraged Dines to undertake observational studies of the upper air. Dines had exceptional flair in designing meteorological instruments, and his meteorograph, which we will describe now, was a masterpiece of economy and efficiency (Dines 1909).

Registering balloons measured pressure, temperature and humidity during their ascent and recorded the values by means of an instrument called a meteorograph. Analysis of the values was dependent upon this instrument being found after its de-

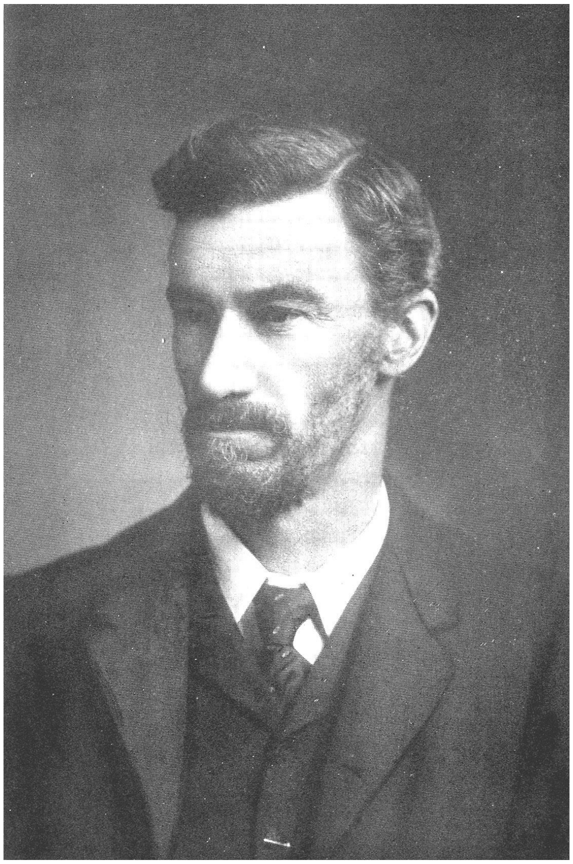
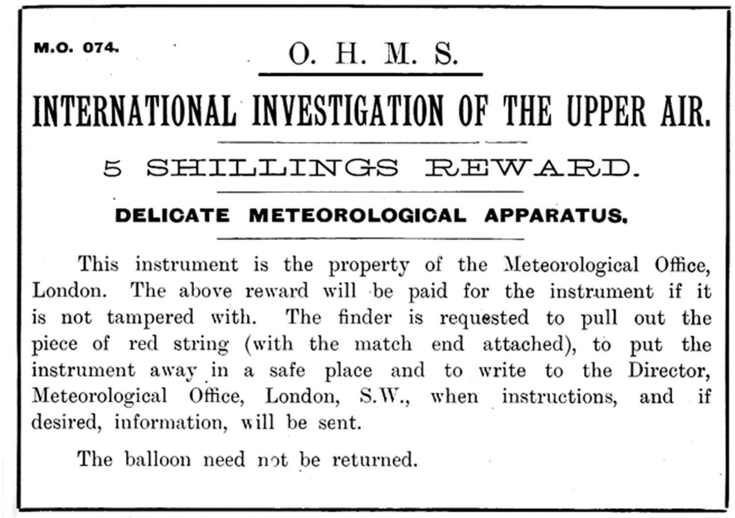


Fig. 6.2. W. H. Dines (1855–1927). From *Collected Scientific Papers of William Henry Dines*, Royal Meteorological Society, 1931.

scent by parachute. To encourage finders to return the device, a notice was attached to the instrument, offering a reward (see Fig. 6.3). According to Dines (1919) 'it is astonishing how many are returned; the [European] continental stations do not lose more than one out of ten, but in England many fall in the sea and the loss reaches 30 or 40 per cent.'

Wind speeds and directions at various heights were deduced by following the course of the ascending balloon. Obviously this became impossible once the balloon entered cloud. But these observations were available promptly, whereas the pressure and temperature data were obtained only when the instrument was found and returned after its descent. As Dines wrote (1919), 'The mere sending up of a registering instrument attached to a balloon does not necessarily mean a good observation. The instrument may never be found, the clock may stop, the pen may



M.O. 074.

O. H. M. S.

INTERNATIONAL INVESTIGATION OF THE UPPER AIR.

5 SHILLINGS REWARD.

DELICATE METEOROLOGICAL APPARATUS.

This instrument is the property of the Meteorological Office, London. The above reward will be paid for the instrument if it is not tampered with. The finder is requested to pull out the piece of red string (with the match end attached), to put the instrument away in a safe place and to write to the Director, Meteorological Office, London, S.W., when instructions, and if desired, information, will be sent.

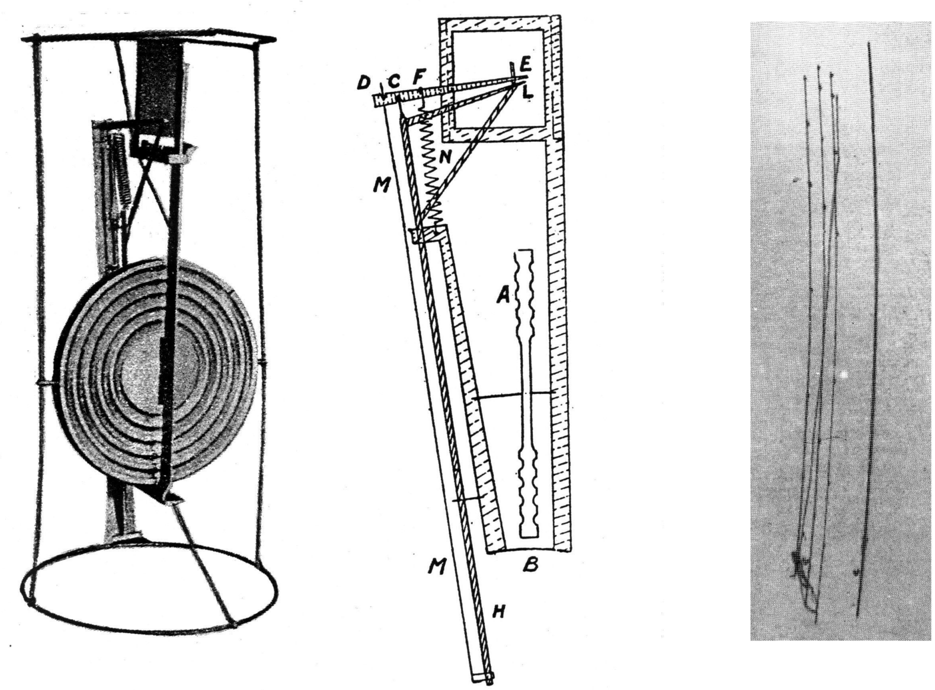
The balloon need not be returned.

Fig. 6.3. Label attached to meteorographs of the Met Office, offering a five shilling reward for return of the instrument (from Dines, 1912).

not write, the finder may efface the record; there are many possibilities of failure.' On 20 May 1910, for example, the observation for Vienna comprised only winds; no pressures or temperatures were available, the registering balloon being recorded as *bis heute noch nicht gefunden* (Hergesell, 1913). It is unlikely to be found now.

The instruments were not standardised, different systems being used in different countries. In the French and German instruments, records were made on smoked paper secured to a drum which was turned by a clock. The instruments weighed about 1 kg and required a ballon of diameter 2 m to carry them. The meteorograph designed by Dines was of elegant simplicity, inexpensive to make and weighing about an ounce (30 g). Its cost was only £1, in comparison to £15 or £20 for instruments used in other countries. It carried no clock but recorded temperature as a function of pressure. In favourable circumstances the instrument could be carried by a small balloon to a height of 20 km.

A diagram of Dines' meteorograph is presented in Figure 6.4. The frame is cut from a single piece of metal, the end B being turned down at right angles to allow it to open and close like a pair of scissors as the aneroid box A expands or contracts with changing pressure. One side of the frame carries two steel points (pens) E and L and on the other there is a small square metal plate the size of a postage stamp on which they etch marks as they move. Pen L, attached to bar H records the pressure. The lever DCF carrying pen E is free to pivot about C; as the temperature falls, the strip M of German silver contracts, so point D moves



(A) (B) (C)

Fig. 6.4. Dines meteorograph for upper air soundings. (A) Photograph of instrument showing the aneroid box. (B) Schematic diagram indicating the operating principle. (C) Meteorogram, showing scratches on a small metal plate. [Dines, 1909, 1912].

downward and pen E upward. With uniform temperature, a decrease of pressure causes two parallel scratches on the plate, whereas a change of temperature causes a change in the distance between the scratches. After retrieval, the small plate is removed from the instrument and examined under a microscope. The distance between the marks indicates the temperature as a function of the pressure. A third element to measure humidity can easily be added. It is similar to the temperature element but the expanding metal strip is replaced by strands of hair, the length of which is sensitive to the relative humidity of the air. The right-hand panel in Fig. 6.4 is a meteorogram produced by Dines' instrument.

The height may be obtained by means of the hydrostatic relationship so that, for a column between pressures p_1 and p_2, the thickness is

$$\Delta z = z_2 - z_1 = \frac{\Re \bar{T}}{g} (\log p_1 - \log p_2)$$

where $\bar{T}$ is the mean temperature of the column. This can easily be evaluated using special graph-paper. A detailed example was given in Dines (1909). He also gave an estimate of the accuracy of his meteorograph: the error in temperature is generally less than 3°C; the pressure error less than 10 mm Hg (about 13 hPa). This means that at 10 km the height error may be up to 400 m, and at 20 km up to about 1500 m. These are quite large errors and cause considerable uncertainty, particularly for the analysis at higher levels.

6.3 The Leipzig charts

The forecast made by Richardson was based on ‘one of the most complete sets of observations on record’ (WPNP, p. 181). At the time he made this forecast (between 1916 and 1918) a comprehensive set of analyses of atmospheric conditions had become available. The two volumes of ‘Dynamic Meteorology and Hydrography’, by Vilhelm Bjerknes and various collaborators, had appeared in 1910 and 1911. The second volume was accompanied by a large atlas in which the first isobaric analyses were published. These maps were the first attempt to analyse synoptic conditions in the upper atmosphere. On becoming Director of the new Geophysical Institute in Leipzig, Bjerknes began a consolidated and systematic diagnostic analysis of the aerological data. The first of the series of ‘Synoptische Darstellungen atmosphärischer Zustände’ (the synoptic representation of the atmospheric conditions) was published in 1913. This related to January 6, 1910. Further analyses, also relating to the year 1910, appeared over the following two years. The issue of primary interest to us is Bjerknes, 1914b.

Bjerknes’ analyses consisted of sets of charts of atmospheric conditions at ten standard pressure levels from 100 hPa to 1000 hPa. These charts were produced to high-quality, in large format (64×40 cm), covering Europe at a scale of 1:10,000,000. There were normally fourteen charts for each observation time (see Table 6.1). The compilation of the charts was performed for the most part by Bjerknes’ assistant, Robert Wenger. They were the first comprehensive aerological analyses ever published. They enabled Bjerknes to study the three-dimensional evolution of atmospheric conditions, and to test his prognostic methods that were based on graphical techniques (Bjerknes, *et al.*, 1910, 1911). He was convinced that, ultimately, charts such as these would be the basis for a rational forecasting scheme. In this he was correct, although perhaps not in the manner he envisaged:

Table 6.1. *Analysed charts in* Synoptische Darstellungen atmosphärischer Zustände. *Jahrgang 1910, Heft 3 (Bjerknes, et al, 1914b). The Roman numerals in column 2 are the level indicators used by Bjerknes. For 0700, 20 May, 1910 the 100 mb analysis is missing, due to lack of sufficient observational data at this level.*

Chart	**Level**	**Content**
1		Sea Level Pressure (mm Hg) and Temperature (°C)
2		Surface streamlines and isotachs (m/s)
3		Cloud cover and precipitation
4	X	1000mb Height and 1000-900 Relative Topography
5	IX	900mb Height and 900-800 Relative Topography
6	VIII	800mb Height and 800-700 Relative Topography
7	VII	700mb Height and 700-600 Relative Topography
8	VI	600mb Height and 600-500 Relative Topography
9	V	500mb Height and 500-400 Relative Topography
10	IV	400mb Height and 400-300 Relative Topography
11	III	300mb Height and 300-200 Relative Topography
12	II	200mb Height and 200-100 Relative Topography
13	I	100mb Height
14		Tropopause Height

the charts provided Richardson with the data required for his arithmetical forecasting procedure.

The 'international days' were normally on the first Thursday of each month. In normal circumstances, there would have been a balloon day on Thursday, 5th May, 1910. It is interesting that the observational period for May 1910 was postponed to coincide with the passage of Halley's comet. There was some speculation that the comet might cause a detectable response in the atmospheric conditions, and what would now be called an 'intensive observing period' was undertaken. For example, on 19 May, a series of hourly ascents over a period of twenty-four hours was carried out at Manchester to ascertain the diurnal variation of temperature. The comet passed between the Earth and the Sun on 18th May; as the tail curved slightly backwards, the passage of the Earth through it occurred a little later, on the 20th, the day chosed by Richardson (Lancaster-Browne, 1985). Comets are popularly thought to portend dramatic events; one may say that on this occasion a

Table 6.2. *Upper Air Observations from registering balloons, pilot balloons and kites for 0700 UTC, 20 May, 1910. For the full reports, see Hergesell, 1913.*

Location of Launch	**Minimum Pressure (mm Hg)**	**Maximum Height (metres)**	**Temperature (°C)**	**Instrument**
Aachen	360	6,000	-15.3	Registering Balloon
Bergen		9,600		Pilot Balloon
Christiania		8,100		Pilot Balloon
Copenhagen		12,020		Pilot Balloon
Friedrichshaven	460	4,110	-3.9	Kite Balloon
Hamburg	195	10,410	-50.1	Registering Balloon
Lindenberg	299	7,420	-25.9	Registering Balloon
Munich	186	10,600	-55.6	Registering Balloon
Nizhni-Olchedaev	632	1,580	5.9	Captive Balloon/Kite
Pavia	108	13,850	-63.7	Registering Balloon
Pavlovsk	132	12,560	-46.5	Registering Balloon
Pyrton Hill	69	17,600	-45.5	Registering Balloon
Strasbourg	85	15,530	-54.2	Registering Balloon
Tenerife		4,710		Pilot Balloon
Uccle	91	14,980	-57.8	Registering Balloon
Vienna		19,700		Reg. Balloon (lost)
Zurich	118	13,450	-47.7	Registering Balloon

comet was associated with an event of great significance for meteorology, though not due to its having any direct influence on the atmosphere.

The date and time chosen by Richardson for his initial data was 20 May, 1910, 0700 UTC. During the three day observing period there ascended altogether 73 registering balloons (33 of which included wind observations), 35 kite and captive balloons, 81 pilot balloons and four manned balloons. Aerological observations were reported for the following locations: Aachen, Bergen, Christiania, Copenhagen, De Bilt, Ekaterinburg, Friedrichshafen, Hamburg, HMS Dinara (near Pola), Lindenberg, Manchester, Munich, Nizhni-Olchedaev, Omsk, Pavia, Pavlovsk, Petersfield, Puy de Dome, Pyrton Hill, Strasbourg, Stuttgart, Tenerife, Trappes, Uccle, Vienna, Vigne di Valle, Zurich and, from outside Europe, Apia, Blue Hill and Mt. Weather. The stations of most relevance for Richardson's forecast are indicated in Fig. 6.9 on page 109 below. The soundings and reports of upper level winds over western Europe for 0700 on 20th May, 1910 are given in Table 6.2. The full compi-

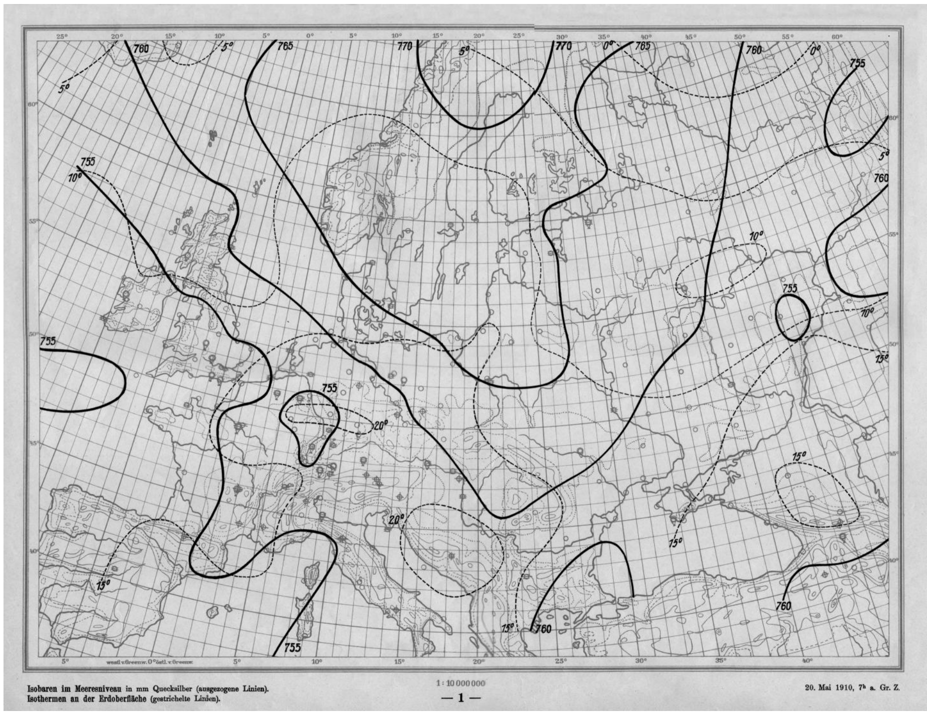


Fig. 6.5. Bjerknes' analysis of sea level pressure (solid lines, mm Hg) and surface temperature (dashed lines, °C) for 0700 UTC on May 20, 1910.

lation of observations occupies more than one hundred pages in Hergesell (1913). The observations are tabulated in a compressed form in Bjerknes, 1914b.

The weather conditions during the period 18–20 May, 1910 were summarized in Hergesell's publication:

> The distribution of atmospheric pressure was very irregular on the days of the ascents and, consequently, there were frequent thunderstorms, especially in western and central Europe. A cyclone moved northwards from the Bay of Biscay while a weak minimum drifted westwards from the Adriatic, gradually intensifying and an anti-cyclone over Scandanavia gradually increased in strength (Hergesell, 1913).

The Leipzig publication contains 13 charts for the time in question: sea-level pressure and surface temperature, surface streamlines and isotachs, cloud and precipitation, geopotential heights and thicknesses for nine standard levels at 100 hPa intervals from 1000 hPa to 200 hPa, and tropopause height (see Table 6.1). The

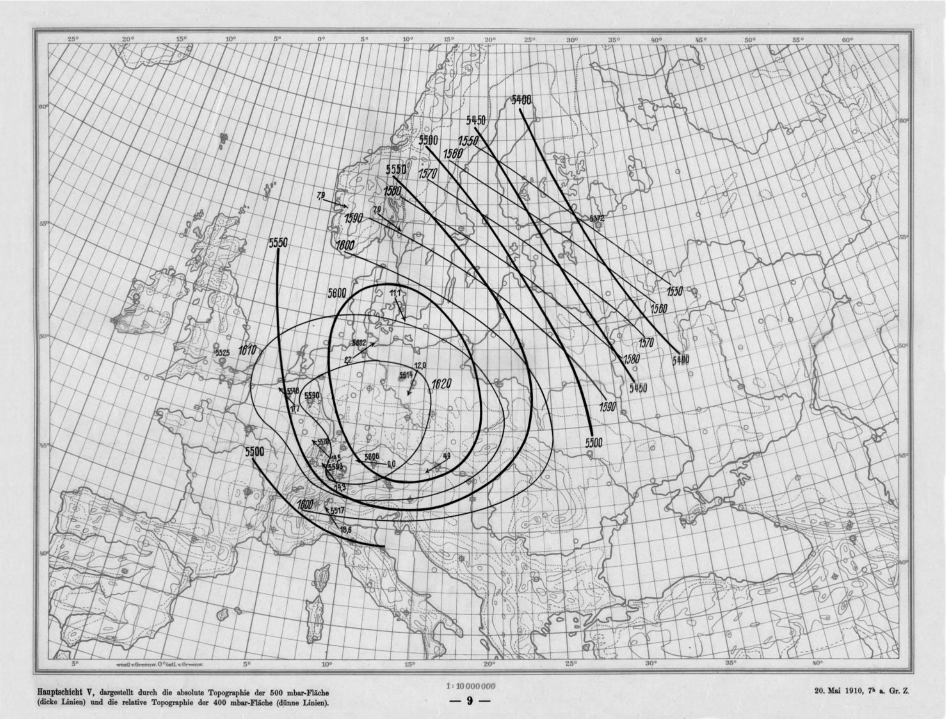


Fig. 6.6. Bjerknes' analysis of 500 hPa height (heavy lines, dam) and 500–400 hPa relative topography (light lines, dam) for 0700 UTC on May 20, 1910.

sea-level pressure and surface temperature chart is reproduced in Fig. 6.5 and the 500 hPa height in Fig. 6.6.[3]

Data coverage was reasonable at the surface; for the upper levels, the number of observations is seriously limited, leaving great uncertainty over much of the area of interest. In a commentary on the analysis, Wenger wrote that there was no cause to doubt the reliability of any of the ascents. He further commented that 'the good agreement of the wind vectors with the topography of the main isobaric levels' was a ground for confidence in the pressure analysis. Thus, he explicitly recognized that the flow in the free atmosphere should be close to geostrophic balance.

Conditions at the surface are also shown in the analysis of the Met Office (Fig. 6.7). The left panel shows the sea level pressure at 0700 UTC. It is in general agreement with Bjerknes' analysis (Fig. 6.5). There is high pressure over Scandanavia and low pressure over Biscay, associated with a generally south-easterly drift over Germany and France. The right panel of Fig. 6.7 shows the sea-level pressure at 1800 UTC on the same day. There is little change in the overall pattern

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[3] The full series of charts is available online at http://maths.ucd.ie/∼plynch/Dream/Leipzig-Charts.html.

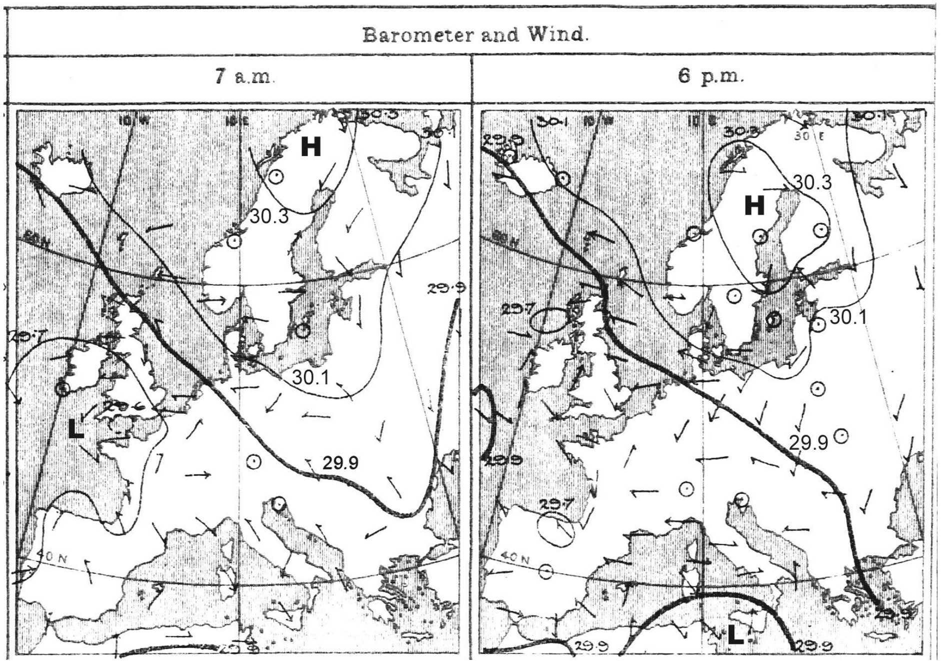
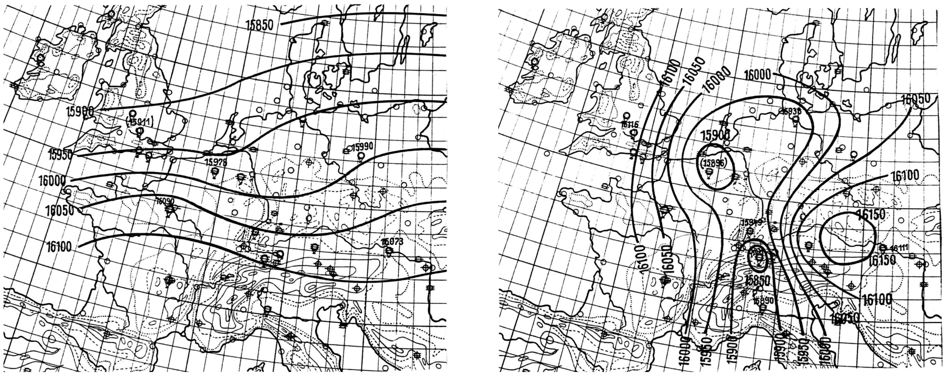


Fig. 6.7. Surface analysis over Europe for Friday, 20th May, 1910. Left: Sea-level pressure and surface wind at 0700 UTC. Right: Sea-level pressure and surface wind at 1800 UTC. Pressures are in inches of mercury. [From UKMO *Daily Weather Report.* Some contour labels and H and L marks have been added].

and the pressure over Bavaria remains essentially unchanged. Winds were generally light although a number of thunderstorms were reported. It might reasonably be expected that a pressure forecast for this region would be consistent with the steady barometer. As we will see, this was not true of Richardson's forecast.

The Leipzig publication did not include a chart of 100 hPa height for the time in question. Only one registering balloon, that launched from Pyrton Hill in England, reached a height sufficient to record the 100 hPa value (see Table 6.2; note that 100 hPa $\approx$ 75 mm Hg). The problem of accurate analysis at this level, with so few observations, is vividly illustrated by Bjerknes' 100 hPa analyses for the previous day: the charts for 0200 UTC and 0700 are shown in Fig. 6.8; they show dramatically different flow patterns, and cannot be reconciled with each other considering that their 'valid times' are only five hours apart. The observational errors may have been due to the 'radiation effect', heating of the thermometer by direct or reflected sunlight. This was one of the most serious defects of early meteorographic equipment.



(a) Valid time 0200 UTC

(b) Valid time 0700 UTC

Fig. 6.8. Bjerknes' height analyses at 100 hPa at two times on 19 May, 1910. (a) Analysis at 0200 UTC. (b) Analysis at 0700 UTC. Note that only five hours separate the two analysis times.

6.4 Preparation of the initial fields

6.4.1 Richardson's analysis

Using the most complete set of observations available to him, Richardson derived the values of the prognostic parameters at a small number of grid points in central Europe. The values he obtained were presented in his 'Table of Initial Distribution' (WPNP, p. 185). Richardson chose to divide the atmosphere into five layers, centered approximately at pressures 900, 700, 500, 300 and 100 hPa (see Fig 5.1 on page 89). He divided each layer into boxes and assumed that the value of a variable in each box could be represented by its value at the central point. The boxes were separated by $\Delta\lambda = 3.0^\circ$ in longitude and $\Delta\phi = 1.8^\circ$ in latitude. Richardson tabulated his initial values for a selection of points over central Europe. The area is shown on a map on page 184 of WPNP (reproduced as Fig. 6.9).

In §9/1 of WPNP, Richardson describes the various steps he took in preparing his initial data. He prepared the mass and wind analyses independently (today, this is called univariate analysis). The data were obtained from the compilations of Hergesell and the aerological charts of Bjerknes. The pressure values were computed from heights read directly from Bjerknes' charts. The momentum values were computed using the observations tabulated by Hergesell, followed by visual interpolation or extrapolation to the grid points. Richardson recognized the uncertainty of this procedure: 'It makes one wish that pilot balloon stations could be arranged in rectangular order, alternating with stations for registering balloons

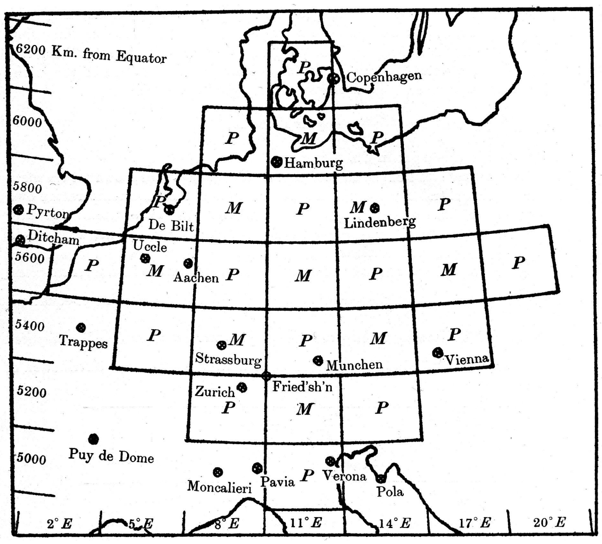


Fig. 6.9. Grid used by Richardson for his forecast. The pressure was specified at points denoted P, and the momentum at points denoted M. The prediction was confined to the calculation of the initial tendencies at the P-point near Munich (München) and the M-point directly to the north.

…', as depicted on the frontispiece of WPNP (see Fig. 1.6 on page 21). In his Preface, Richardson acknowledges the substantial assistance of his wife Dorothy in processing the observational data.

The values given by Richardson in his 'Table of Initial Distribution' are reproduced in Table 6.4 on page 115 (the values are converted to modern units). For the white cells, the pressure (in hPa) at the base of each layer is given. For the black cells, the eastward and northward components of momentum for each of the five layers are tabulated (units $10^2 \times \mathrm{kg\,m^{-1}s^{-1}}$). The surface elevation in metres is also given (the bottom number in each cell). The latitude is indicated on the left-hand side and the longitude in the top row. We will compare Richardson's values to the reanalysed values after the method of obtaining the latter is discussed.

6.4.2 Reanalysis of the data

The initial fields used in the present study were obtained from the same data sources as those used by Richardson, but we did not follow his method precisely; the procedure adopted for the re-analysis is outlined below. The geographical coverage used in repeating Richardson's forecast is shown in Fig 6.10. P-points are indicated by solid circles and M-points by crosses. The region was chosen to best fulfil con-

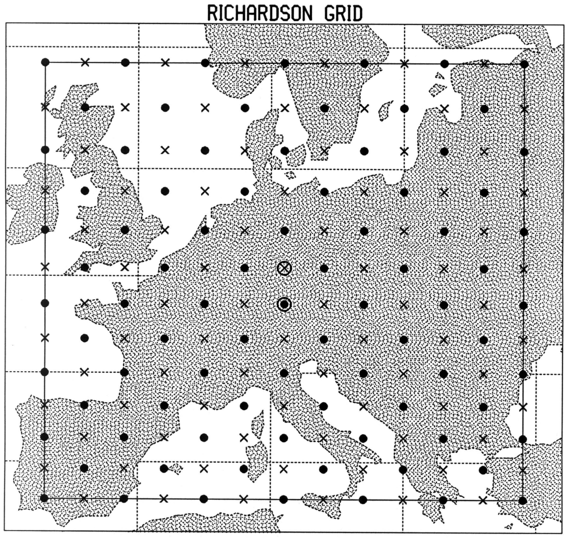


Fig. 6.10. The geographical coverage used in repeating and extending Richardson's forecast. P-points are indicated by spots and M-points by crosses. The P-point and M-point for which Richardson calculated his tendencies are shown by encircled marks.

flicting requirements: That it be as large as possible; that data coverage over the area be adequate; and that the points used by Richardson be located centrally in the region. The absence of observations precluded the extension of the region beyond that shown. The P-point and M-point for which Richardson calculated his tendencies are shown by encircled marks. In order that the geostrophic relationship should not be allowed to dominate the choice of values, the pressure and velocity analyses were performed separately (and by two different people).

The mass field

The initial pressure fields at level interfaces were derived from Bjerknes' charts of geopotential height at 200, 400, 600 and 800 hPa (his charts 6, 8, 10 and 12). A transparent sheet marked with the grid-points was super-imposed on each chart and the height at each point read off. Each level p_k corresponds to a standard height z_k with temperature T_k. Conversion from height z to pressure p was made using the simple formula

$$p = p_k \left(1 - \frac{z - z_k}{H_k} \right)$$

where $H_k = \Re T_k/g$. The geodynamic heights z_k of the standard levels were 1.959, 4.113, 7.048 and 11.543 km (see WPNP, p. 181). The standard temperatures T_k at the surface and interfaces were $+15^\circ\mathrm{C}, +2^\circ\mathrm{C}, -12^\circ\mathrm{C}, -32^\circ\mathrm{C}$ and $-50^\circ\mathrm{C}$.

Sea-level pressure values were extracted in the same way as heights, from Bjerknes' Chart #1 (Fig. 6.5). His values, in mm Hg, were converted to hectopascals by multiplication by 4/3. Then the surface pressure p_{S} was calculated from

$$p_{\mathrm{S}} = p_{\mathrm{SEA}}\left(1 - \frac{\gamma h}{T_0}\right)^{g/\gamma\Re}$$

where h is orographic height at the point in question, p_{SEA} is the sea-level pressure and standard values $T_0 = 288\,\mathrm{K}$ and $\gamma = 0.0065\,\mathrm{K\,m}^{-1}$ were used for the surface temperature and vertical lapse-rate.

In the absence of a 100 hPa chart in the Leipzig collection for the time in question, the 100 hPa topography and 200-100 hPa thickness were analysed using the few available observations and a generous allowance of imagination. The thickness values $\Delta z = z_{100} - z_{200}$ were then used to calculate the stratospheric temperature,

$$T_1 = \left(\frac{g\bar{p}}{\Re\Delta p}\right)\Delta z,$$

where $\bar{p} = 150\,\mathrm{hPa}$ and $\Delta p = 100\,\mathrm{hPa}$ are the mean pressure and pressure thickness of the layer. Considering the uncertainties, the values were surprisingly close to those obtained by Richardson (see below).

The momentum field

The initial values of momenta for each of the five layers are required. These were derived from the wind velocities at the intermediate levels 100, 300, 500, 700 and 900 hPa. The observed wind speeds and directions for each level, as compiled by Hergesell and also tabulated in Bjerknes' publication, were plotted on charts upon which isotachs and isogons (lines of constant wind speed and direction) were then drawn by hand. The grid-point values of speed and direction were then read off. It was necessary to exercise a degree of imagination as the observational coverage was so limited, particularly over the Iberian peninsula. The wind values were converted to components u and v and the layer momenta U and V were defined by

$$U = Ru = \frac{\Delta p}{g}v\,, \qquad V = Rv = \frac{\Delta p}{g}v \tag{6.1}$$

where Δp is the pressure across the layer (obtained in the pressure analysis).

Orography

The atlas included with Part II of *Dynamic Meteorology and Hydrography* (Bjerknes, *et al.*, 1911) contains two charts of orographic height, one 'moderately ideal-

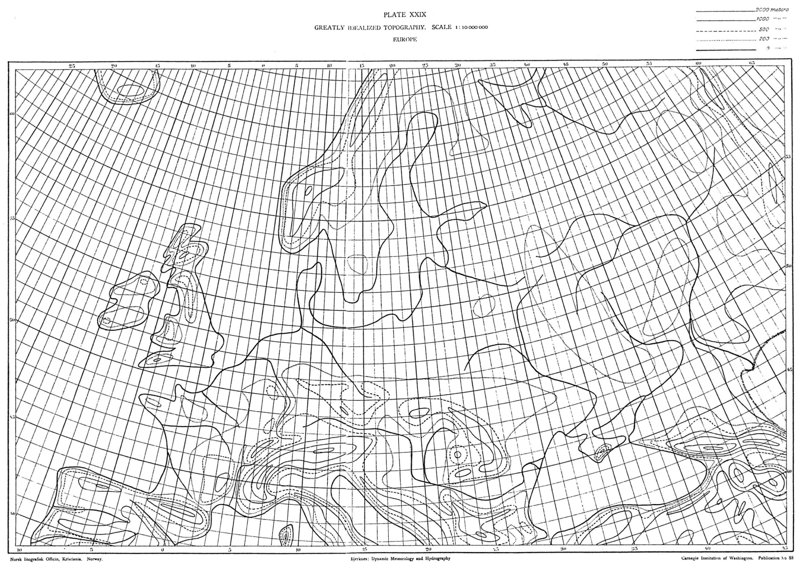


Fig. 6.11. Bjerknes' chart of 'greatly idealized' orography. Contours are at 200 m (dotted), 500 m (dashed), 1000 m (solid) and 2000 m (solid). (Plate XXIX in Bjerknes, *et al.*, 1911).

ized' and one 'greatly idealized'. Values of surface height at each grid-point were read off from the latter chart (Bjerknes, *et al.*, 1911, Plate XXIX), which is reproduced in Fig. 6.11. As Richardson remarks, 'At some points there is a large uncertainty as to the appropriate value of h; for example in Switzerland the uncertainty amounts to several hundred metres.'

6.4.3 *Tables of initial data*

The pressure, temperature and momentum values, at a selection of points in the centre of the domain, resulting from the reanalysis, are given in Table 6.3. The corresponding values obtained and used by Richardson, extracted from his 'Table of Initial Distribution'(WPNP, p. 185), are reproduced in Table 6.4. The orographic heights are also indicated (bottom number in each block). To facilitate comparison, the orography values used by Richardson were also used in the reanalysis.

There is reasonable agreement between the pressure and stratospheric temperature values in the two tables. In general, pressure differences are within one or two hectopascals. There is a notable exception at the point $(48.6^\circ\,\mathrm{N}, 5.0^\circ\,\mathrm{E})$, where the old and new values differ by 10 hPa. We will see below that Richardson's value at this point is suspect. A similar table of initial values appears in Platzman (1967) in which two surface pressures at 46.8° N are question-marked. In fact, it is the orographic heights in Platzman's table that are incorrectly transcribed from WPNP.

Comparing the momenta in Tables 6.3 and 6.4, we see much more significant discrepancies. Although the overall flow suggested by the momenta is similar in each case, point values are radically different from each other, with variations as large as the values themselves and occasional differences of sign. These dissimilarities arise partly from the different analysis procedures used, but mainly from the large margin of error involved in the interpolation from the very few observations to the grid-points.

The investigation of the comparison between the old and new momentum values, using modern techniques of objective analysis, is an attractive possibility, but it will not be explored here.[4] Instead, in the forecast in Chapter 7, we have simply replaced the reanalysed values of all fields by Richardson's original values at the (few) gridpoints where the latter are available. The values in Table 6.4 are thus the initial values for both Richardson's forecast and the forecasts described in the following chapters. In consequence of this, the calculated tendencies at the central points of the domain will be found to be essentially the same as those obtained by Richardson.

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[4] Recently, ECMWF has completed a reanalysis back to 1957 (see §11.4 below). Perhaps some day 'in the dim future', they will reach back to 1910.

Table 6.3. *Initial Distribution:* Reanalysed Values. *The pressure (units hPa) at the base of each of the five layers is given for the white cells. The stratospheric temperature (units K) is also given. The eastward and northward components of momentum (units* $10^2 \times kg\, m^{-1} s^{-1}$*) for each of the five layers are tabulated in the black cells. The bottom number in each cell is the surface elevation (in metres). Latitude is indicated on the left-hand side and longitude in the top row.*

	$5^\circ E$	$8^\circ E$	$11^\circ E$	$14^\circ E$	$17^\circ E$
$54.0^\circ N$			**106** **-228** **120** **-144** **0** **-81** **-97** **0** **-221** **81** 0		
$52.2^\circ N$		**-62** **-138** **-133** **-135** **-155** 150	212 206 410 609 799 987 200	**-25** **-79** **-107** **-156** **-181** 100	
$50.4^\circ N$	**-175** **208** **-292** **263** **-249** **174** **-118** **99** **-88** **51** 200	216 205 409 607 796 983 200	**-105** **-182** **-268** **-38** **-201** **-18** **-199** **73** **-127** **73** 400	212 206 410 608 798 976 300	**-126** **-218** **-167** **-213** **-155** **-130** **-214** **0** **-175** **82** 300
$48.6^\circ N$	221 204 406 605 793 984 200	**-159** **-275** **-216** **-131** **-60** 400	214 206 410 608 796 961 400	**-131** **-205** **-147** **-129** **-81** 400	213 206 410 608 798 989 200
$46.8^\circ N$		217 204 405 604 794 872 1200	**-208** **18** **-289** **0** **-172** **172** **-45** **64** **-32** **38** 1800	213 205 407 606 796 842 1500	
$45.0^\circ N$			210 203 404 603 795 995 100		

Table 6.4. *Initial Distribution.* Richardson's Values. *The pressure (units hPa) at the base of each of the five layers is given for the white cells. The stratospheric temperature (units K) is also given. The eastward and northward components of momentum (units* $10^2 \times kg\, m^{-1} s^{-1}$*) for each of the five layers are tabulated in the black cells. The bottom number in each cell is the surface elevation (in metres). Latitude is indicated on the left-hand side and longitude in the top row.*

	$5^\circ E$	$8^\circ E$	$11^\circ E$	$14^\circ E$	$17^\circ E$
$54.0^\circ N$			**-65 8** **127 -104** **81 -25** **-81 0** **-198 84** 0		
$52.2^\circ N$		**-70** **-62** **-114** **-91** **-160** 150	214 205 409 609 798 988 200	**-160** **40** **-60** **-60** **-219** 100	
$50.4^\circ N$	**-30 -110** **-245 300** **-223 158** **-91 87** **-18 15** 200	212 205 408 607 795 983 200	**-56 -18** **-146 -62** **-95 29** **-52 58** **-110 55** 400	214 205 409 609 798 976 300	**-100 -32** **0 -260** **-55 -135** **-25 48** **-190 160** 300
$48.6^\circ N$	214 203 405 604 793 974 200	**27** **-328** **-136** **-33** **48** 400	212 205 409 608 796 963 400	**0** **-166** **-95** **-19** **-65** 400	214 204 408 607 798 988 200
$46.8^\circ N$		214 204 406 605 795 875 1200	**-50 80** **-280 41** **-175 150** **-105 80** **-155 40** 1800	214 204 408 607 797 846 1500	
$45.0^\circ N$			213 203 403 603 796 997 100		