Kelvin-Helmholtz-Waves above the Inn Basin – a Snapshot from Spacelab

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Abstract:
A space photograph of Southern Bavaria is presented, which was taken with the Metric Camera on December 5, 1983 during the first mission of the European Spacelab. Wave patterns in a stratus layer over the Inn basin are identified as Kelvin-Helmholtz waves and their wavelengths are compared with theoretical computations.

Zusammenfassung: Kelvin-Helmholtz-Wellen über dem Innbecken – ein Schnappschuß von Spacelab
Ein „Weltraumbild" von Südbayern wird vorgestellt, das mit der Metrischen Kamera am 5. Dezember 1983 während des Erstflugs des europäischen Spacelab aufgenommen wurde. Wellenmuster in einer Stratusschicht über dem Innbecken bei Rosenheim werden als Kelvin-Helmholtz-Wellen identifiziert und die gemessenen Wellenlängen mit theoretischen Berechnungen verglichen.

1 Introduction

From November 28 to December 7, 1983 the European Spacelab went on its first mission transported by the US Space Shuttle and accompanied by considerable public attention. As part of the earth observation payload a Metric Camera was flown with the scientific objectives of compiling maps of less developed regions of the earth, updating existing maps in developed regions and – of course – demonstrating for the first time the usage of a calibrated photogrammetric camera with standard aerial film (format 23 cm × 23 cm) in a spacecraft. After postprocessing a so called orthophoto results which displays the image details in the exact position of a map projection with correct geometry. Details of the camera system, operation and control, evaluation methods etc. are given in SCHROEDER and KONECNY (1983); interesting examples – including a stereo pair of the scene that is discussed here – can be found in KONECNY (1984).

One of the some thirty flight tracks, when the Space Shuttle was in an earth oriented attitude for metric camera operations, commenced over the western Sahara and led over Spain and southern France to the Alps and Bavaria. A portion of the picture taken in the morning of December 5 is reproduced in original size in Figure 1. The wealth of geographical details and the brilliant sharpness are remarkable. From a

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meteorological point of view our interest concentrates on the well organized wave structures which are impressed on the thin layer of stratus over the Inn basin near Rosenheim. The purpose of this paper is to bring one outstanding piece of space photography to the attention of the meteorological community and to compare the observed wavelengths with the predictions of the linearized theory attributed to KELVIN and HELMHOLTZ.

2 Description of Photograph and Ground Observations

Figure 1 presents a 120 km x 140 km portion of the 189 km x 189 km original photograph (scale 1:820000) taken with the Metric Camera at 09:01:50 GMT on December 5, 1983 with an exposure time between 1/250 and 1/500 s. The comparsion with Figure 2, where some geographical details are given in the same scale, aids the orientation.

The top of the photo is pointing towards NW (325°). In the plain north of the Alps a thin snow cover over the fields contrasts nicely with the dark forests (especially south of Munich), while within the Alps valley floors and mountain tops appear white and the wooded medium heights dark. The wealth of geographical details (lakes, rivers, urban areas, motorways, shapes of forests, valleys, mountain tops etc.) eases orientation when a precise map is at hand (e.g. Topographische Übersichtskarte 1:200000, Bayr. Landesvermessungsamt).

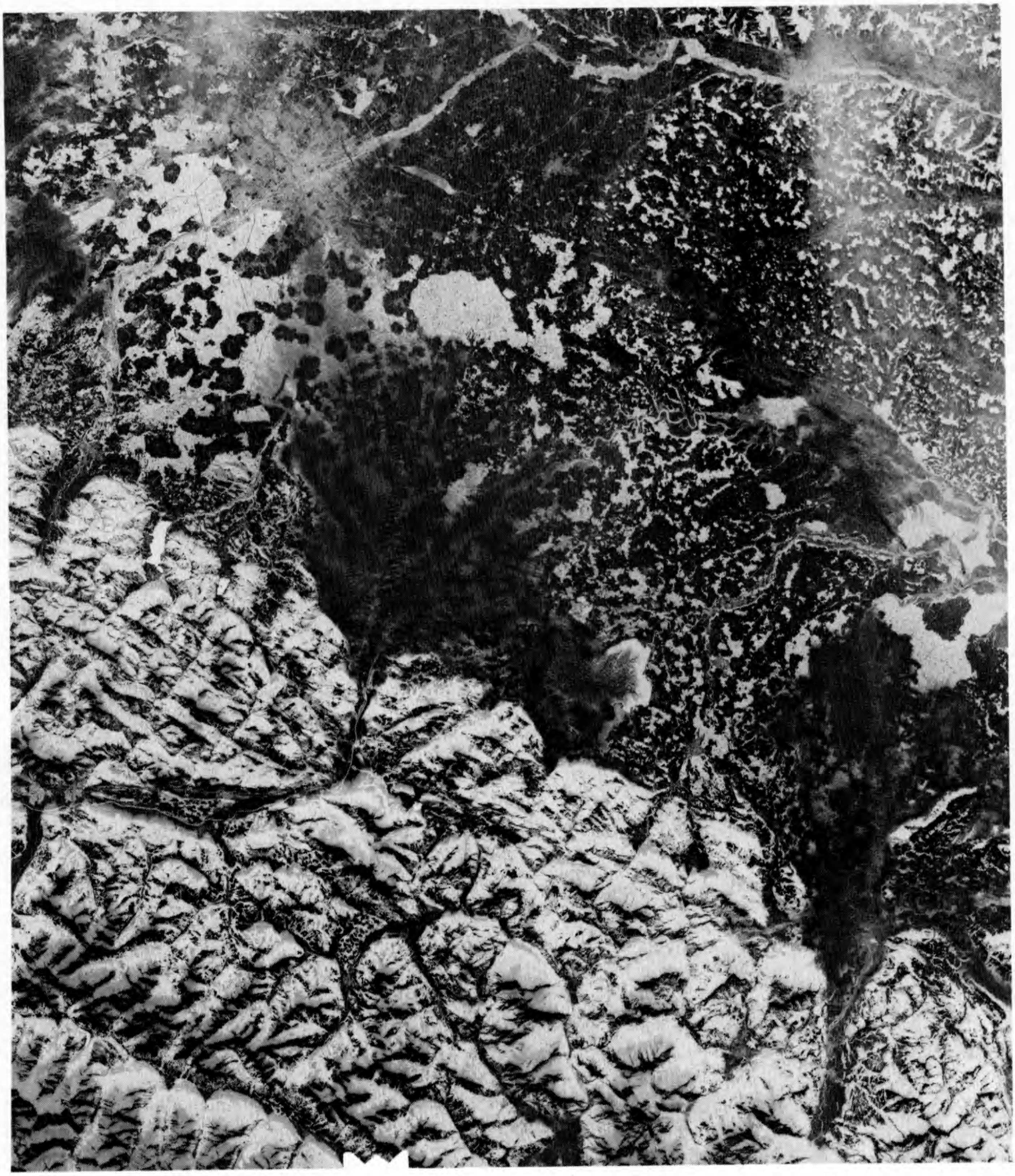
A layer of very thin stratus (mostly transparent) covers the Inn basin around Rosenheim. The mean extension amounts to approx. 25 km and roughly follows the 500 m contour line (above MSL) of the basin, while two tongues reach farther. One follows the river Inn over approx. 40 km and the other coincides with the wind direction reported from Wendelstein (towards 330° at 09 GMT) and extends with gradually decreasing thickness over 50 km the southeastern outskirts of Munich. The tops of the thin stratus are estimated to be 800 m above MSL (approx. 300 m above ground) as Hocheck and Samerberg (both 900 m above MSL) are well above the cloud layer.

Within the cloud cover several wave groups are clearly visible. They exhibit slightly different orientation and clearly different wavelengths. For groups 1 through 5 (see Figure 2) the mean wavelengths are measured in an enlarged copy of Figure 1. They vary between 320 and 620 m (± 30 m; see Table 1). Although the normals to the wavefronts (which themselves are not always straight) show a directional variability (between 310° and 340°; ± 10°), they lie in the sector which coincides with the directions of the last portion of the alpine Innvalley (335°) and of the chimney plume at the Unterföhring power station (305°; 150 m above ground). The wind directions at Wendelstein (towards 330° at 09 GMT in 1830 m above MSL) and above Oberschleißheim (towards 300° at 12 GMT in 850 m above MSL) fit also to that sector. In summary, the normals of the wavegroups seem to indicate the wind direction at the cloud surface. The simple model picture, that air flows out of the alpine part of the Innvalley ("Talauswind" in the morning) and gradually adopts the direction prevailing above the foreland, is intriguing; results from numerical simulations fit in this picture (WAGNER 1984, ULRICH 1984).

When the above values were obtained by the simple methods mentioned, the possibility arouse to check these estimates by photogrammetric, stereoscopic means. Measurements within a stereo image produced by exposures 884 (Figure 1) and 882 (taken 10 s earlier, e.g. approx. 75 km further west) reveal the

■ **Table 1** Characteristics of measured wavegroups (compare Figures 1 and 2).

Wavegroup Index i	1	2	3	4	5
Number of Troughs	10	8	20	10	10
Mean Wavelength L_i (m)	370	620	340	480	320
Orientation (⊥ to front; deg)	310	310	320	310	340



● **Figure 1** Parts of southern Bavaria and Austria; photograph shot on December 5, 1983 at 09:01:50 GMT from Spacelab. Courtesy M. SCHROEDER, Institute for Optoelectronics, DFVLR.

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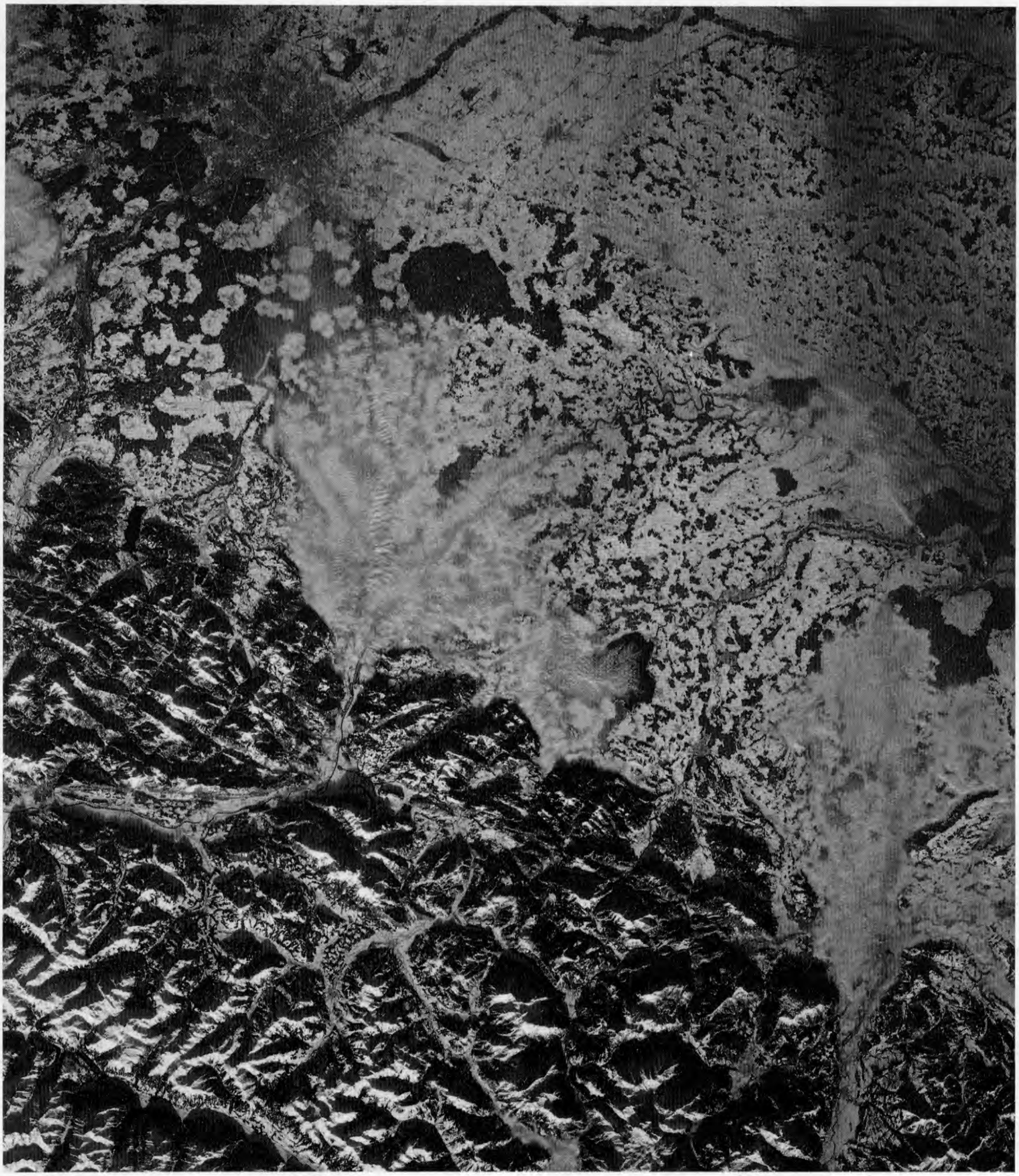

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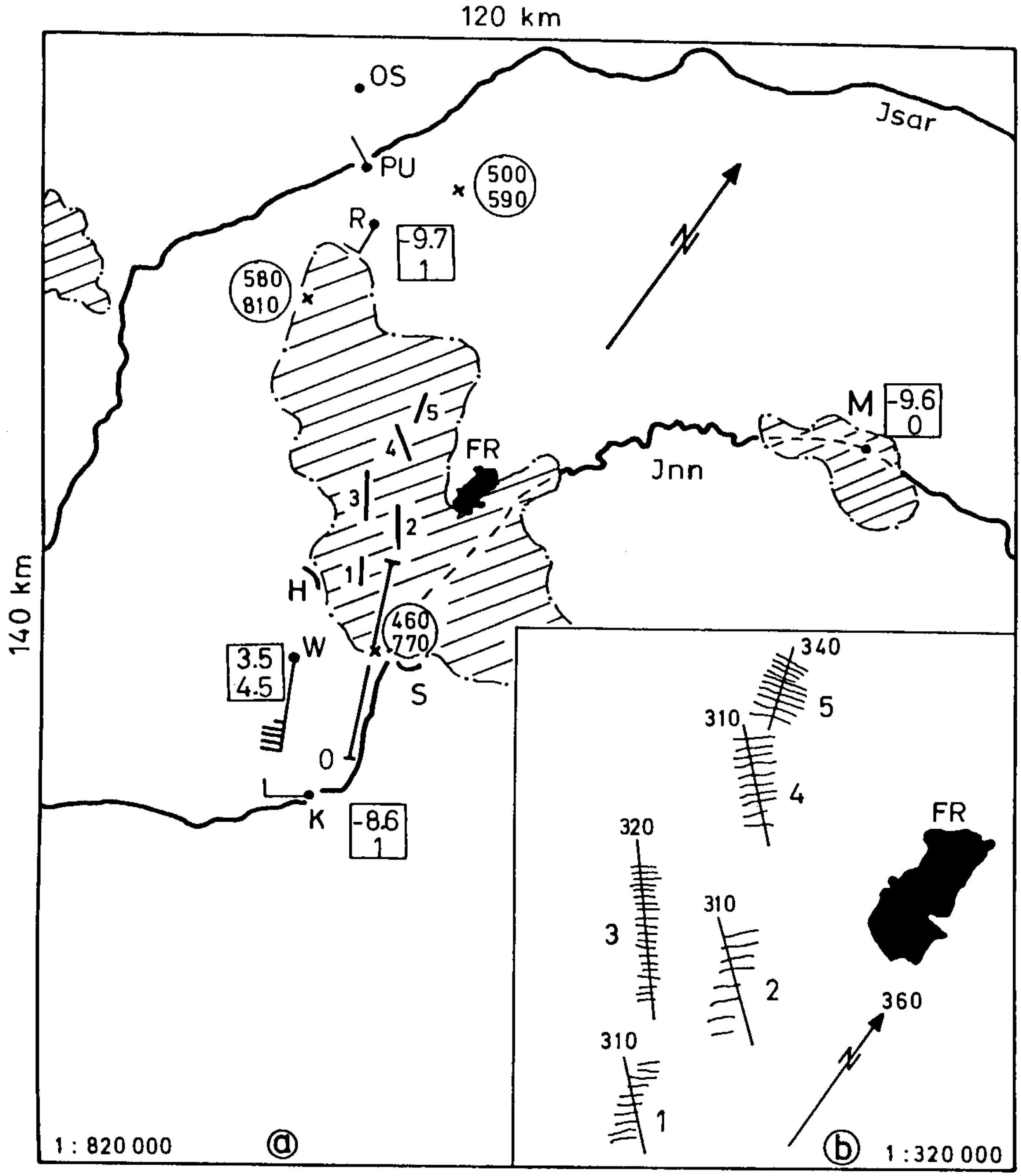

● **Figure 2** (a) Geographic details of Figure 1 in same size and scale (1:820000); (b) enlarged section with the troughlines of wave groups 1 to 5 (1:320000). Temperature (°C; above) and wind speed (m/s; below) for synoptic stations at 09 GMT are given in squares, ground elevation (m MSL; above) and elevation of the thin stratus layer (m MSL; below) in circles. Areas covered by stratus are hatched. The abbreviations stand for Oberschleißheim (OS), power station Unterföhring (PU; with plume), München-Riem (R), the forest near Rott am Inn (FR), Mühldorf (M), Hocheck (H; 896 m MSL), Samerberg (S; 910 m MSL), Wendelstein (W; 1835 m MSL), Oberaudorf (O), Kufstein (K). The baseline of Figure 3 is also indicated (⊢—⊣)

cloud layer height above ground (difference between the encircled numbers in Figure 2); they amount to 310 m east of Samerberg, to 230 m near the Brunnthal motorway junction and to only 90 m for the small mist feathers above the Speichersee in the northeast of Munich. Taking into account the surface elevations, we see that the cloud elevation is nearly constant (approx. 800 m above MSL) over a distance of 45 km (Samerberg ↔ Brunnthal). The stereo image shows clearly that the stratus is so thin (less than 20 m) that elevation equals top height while the thickness cannot be assessed. Only the most pronounced cloud portions in wavegroup 2 have a vertical extension of about 50 m. The figures for the wavelengths coincide with the estimates given above. The accuracy of these measurements lies in the order of ± 20 m, which confirms the figure (± 10 m) claimed by KONECNY (1984); nevertheless it should be kept in mind that due to reduced contrast and sharpness, measurements of clouds bear more uncertainties compared to the evaluation of topographic details.

For a comparison with theoretical predictions temperature and wind data are necessary. The corresponding values at 09 GMT from the synoptic stations München-Riem, Mühldorf, Kufstein und Wendelstein are included in Figure 2 (in squares). The radiosonde ascents at Oberschleißheim (00 and 12 GMT) reveal a thick stable layer at the ground (00 GMT: $\Delta p = 134$ hPa $\sim H = 1170$ m, $\Delta T = 15$ K; 12 GMT: $\Delta p = 97$ hPa $\sim H = 840$ m, $\Delta T = 13$ K). Its inversion descends by 300 m due to general subsidence caused by the region of high pressure over central and eastern Europe, but even at noon it was much too elevated (approx. 1300 m above MSL) to be connected which the stratus formation over the Inn basin. At 00 GMT an isothermic layer between 80 and 280 m above ground gives a hint for a density discontinuity in about 800 m above MSL within the stable ground layer. The next section attempts to compare the observed wavelengths with the ones at such an interface calculated from an idealizing theory.

3 Kelvin-Helmholtz-Waves

A very simple model for the attempt to explain waves as the observed ones can be found in CHANDRASEKHAR 1961 (§ 101). The validity of its assumptions is discussed below. We let two uniform fluids of densities ρ_1 and ρ_2 be separated by a horizontal boundary and we suppose that the lower fluid is more dense than the upper ($\rho_1 > \rho_2$) and at rest ($u_1 = 0$) while the upper is streaming with constant velocity u_2. After substitution of the usual normal mode ansatz $\exp[ik(x - ct)]$ into the linearized perturbation equations for an incompressible, inviscid fluid one obtains as relation between phase velocity c and wavenumber k:

$$c = au_2/(1 + a) \pm \sqrt{(g/k) \times (1 - a)/(1 + a) - au_2^2/(1 + a)^2} \tag{1}$$

where g stands for the acceleration of gravity and $a = \rho_2/\rho_1 = T_1/T_2$ (the second equality follows from the fact that the pressure is continuous at the interface).

Stable waves at the interface with a real phase velocity result for wavelengths L ($L = 2\pi/k$) with

$$L > L_{min} = (2\pi/g) \times u_2^2/(1 - a^2) \tag{2}$$

whereas the two assumptions $c = u_1 = 0$ and $c = u_2$ imply

$$\begin{aligned} L(c = 0) &= (2\pi/g) \times au_2^2/(1 - a) \\ L(c = u_2) &= (2\pi/g) \times u_2^2/(1 - a), \end{aligned} \tag{3}$$

respectively. For $a = 1 - \epsilon$ and $\epsilon < 0.05$ we get

$$L(c = 0) \cong L(c = u_2) \cong 2\,L_{min} \tag{4}$$

Table 2 L (c = 0), L_{min} and L (c = u_2) for different plausible values of u_2 and T_2; $u_1 = 0$ and $T_1 = 263$ K = − 10 °C are kept fixed (see text for details)

u_2 (m/s)	T_2 (K)	ΔT (K)	a	c (m/s)	L (m)
3.0	266	3	.989	0.0	505
				1.49	257
				3.0	511
	268	5	.981	0.0	303
				1.49	156
				3.0	309
	270	7	.974	0.0	217
				1.48	113
				3.0	223
4.5	266	3	.989	0.0	1140
				2.23	580
				4.5	1150
	268	5	.981	0.0	682
				2.23	351
				4.5	695
	270	7	.974	0.0	487
				2.22	253
				4.5	500

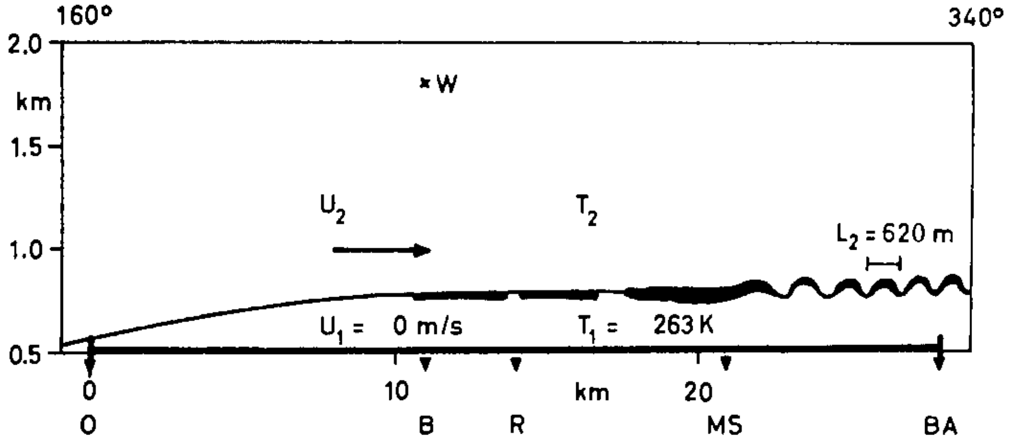

Figure 3 Schematic cross-section from Oberaudorf (O) to Bad Aibling (BA) oriented from 160° to 340° (see Figure 2). A 300 m thick layer of stagnant ($u_1 = 0$) cold air is assumed at the ground and moving air aloft ($u_2 > 0$; $T_2 > T_1$; see Table 2 for plausible values). Patches of thin stratus are observed between Brannenburg (B) and Reischenhart (R), whereas waves are found north of the motorway München-Salzburg (MS). The summit of Wendelstein (W) is also indicated, which lies 10 km to the west of the cross-section.

Table 2 gives computational wavelengths for two different values of u_2 (the observed value from Wendelstein and two thirds of it) and three values of each T_2 (plausible estimations) and the unknown phase velocity c, while T_1 and u_1 are kept fixed (the data from Mühldorf are assumed to be representative for the entire airbody in the Inn basin). What conclusions can be drawn? First, all estimates for L are in the same order of magnitude as the observed wavelengths. Further, for five out of the six given combinations the observed wavelengths (see Table 1) lie on the stable side of L_{min}. From Equation (2) it is clear that values as the observed ones are the further on the instable side of L_{min} the higher u_2 becomes and the more a approaches unity. Taking $\Delta T = 5$ K for granted, the observed differences in wavelength can be accounted for with either variations in phase velocity (at $u_2 = 4.5$ m/s) or with changes in u_2, if the wave pattern is supposed to be stationary (e.g. $c = 0$).

All together, it has to be admitted that the model as outlined above and schematically drawn in Figure 3 is quite sensitive on the input parameters u_1, T_1, u_2, T_2 and c. It even may be argued that it is not adequate at all, if the air coming from the alpine Innvaley does not flow over a pre-existing body of cooler, saturated air in the Rosenheim basin, but comes under that body of air, lifts it and thus leads to the formation of stratus. Stratus layers over Mühldorf, the Starnberger See, the Ammersee and the Lechfeld south of Augsburg (the latter two outside Figure 1, but still on the original picture) have led us to the assumption that on that particular day the formation of stratus is due to sufficiently wet surface conditions and independent of forced lifting.

It is obvious that vertical profiles of wind speed, wind direction and temperature would be necessary for a more profound interpretation and the application of a more realistic theory that takes into account a continuously stratified atmosphere. As those are not available, we should relax for a while, enjoy the beauty of the snapshot and just admire the complexity of nature.

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