Novaya Zemlya effect: analysis of an observation

W. H. Lehn and B. A. German

The Novaya Zemlya effect, historically identified with the premature rebirth of the sun during the polar night, is a long range optical ducting phenomenon in the lower atmosphere. An occurrence of the effect was observed at Tuktoyaktuk, Canada (69°26′N, 133°02′W) on 16 May 1979, when the minimum solar altitude was −1°34′. The sun's image remained above the horizon, within a gray horizontal band, and assumed the various expected shapes, ranging from a bright rectangle filling the band, to three flat suns stacked one over the other, to several thin vertically separated strips. A model for the corresponding atmospheric conditions was identified by matching the observations with images calculated from a computer simulation study.

I. Introduction

The Novaya Zemlya effect, an optical ducting phenomenon in the lower atmosphere, is historically associated with an anomalous appearance of the sun during the polar winter night. The first recorded observation[1] was made in 1597 from the island of Novaya Zemlya (76°12′N) when the icebound Barentz expedition witnessed a two-week early return of the sun. Modern observations have been reported by Shackleton[2] in 1915 and Liljequist[3] in 1951.

A model for atmospheric ducting was proposed by Wegener,[4] who assumed a temperature inversion with a sharp discontinuity some distance above the observer. The existence of inversions with suitable horizontal extent was verified by Visser.[5] Further development of the model and reconstruction of Liljequist's observation were carried out by Lehn.[6]

A typical Novaya Zemlya sequence was documented at Tuktoyaktuk, Canada, on 16 May 1979. The observations and photographs are presented in this paper. Analysis by means of a single-inversion atmospheric model enables identification of the corresponding average atmospheric properties.

II. Physical Model

A physical model for the Novaya Zemlya effect, discussed in detail in Ref. 6, is briefly as follows. In the presence of a temperature inversion in which most of the temperature rise occurs within a narrow range of elevation (a thermocline[7]), an optical duct is formed between the thermocline and the earth's surface. At the thermocline, the rapid drop in refractive index causes upward-heading rays with large angles of incidence to be returned back toward the earth, in a manner reminiscent of total internal reflection. Ducted rays suffering multiple returns can be guided for large distances along the earth's surface. The duct terminates where the thermocline ceases to exist. Beyond this point, ducted rays can finally escape into space, possibly

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with some additional refraction beyond that provided by normal astronomical refraction calculations (see Fig. 1).

To facilitate computer ray tracing and construction of image spaces, the direction of ray propagation is reversed. A ray bundle is considered to emanate from the observer's eye, exit from the duct, and finally escape into space. A plot of ray elevation angle at the observer against escape angle produces the transfer characteristic from which images of astronomical objects are calculated. The nonmonotonic characteristics typical of the Novaya Zemlya effect create images of extreme distortion.

Visually, the duct appears as a narrow horizontal band of increased density, in this case resting on the horizon. It can be thought of as a window in the atmosphere through which light from abnormally long distances reaches the eye.

The observations at Tuktoyaktuk necessitated two additions to the model. First, the upper and lower duct boundaries did not display the expected symmetry about the observer's horizontal reference ($\phi_0 = 0$). Assuming the thermocline layer to have a small constant slope relative to the earth's surface was sufficient to account for the asymmetry. Second, as the horizon was observed to be at an elevation of +1 min of arc, it was clear that rays with $\phi_0 < 1$ min of arc were not propagating in the duct; rather, such rays were being refracted downward to terminate on the earth's surface. Hence, it was necessary to assume a ground layer of strong refraction, extending from the surface approximately up to the observer's eye level.

III. Observations and Computer Simulation

The field station at Tuktoyaktuk, Canada (69°26′N, 133°02′W) offered unobstructed lines of sight northward over the Beaufort Sea. The dates for the expedition, 14–28 May 1979, were chosen in the hope of observing a midnight sun some days in advance of its calculated onset on 20 May. Such an appearance would be directly analogous to the classically observed premature return of the midday sun during the polar night.

On two successive nights we observed conditions favorable for a Novaya Zemlya appearance. On 15 May the sun sank with pronounced refractive flattening into a gray band resting on the horizon. This band had the typical appearance of a duct but transmitted no sun image; a thin ice fog within the inversion kept visibility below 20 km.

On 16 May a duct was again present, this time transparent, and the Novaya Zemlya effect brought about a midnight sun.[8] Our observations, extending over ~1½ h, were recorded on Kodachrome 64 film, using a 560-mm lens located 5.2 m above sea level. From this position, the upper edge of the duct was at elevation +14 min of arc, while the lower edge (and horizon) was at +1 min of arc.[9] The air was calm, and the surface temperature was about −2°C (from interpolation of meteorological station data).

An iterative process is used to identify the atmospheric temperature distribution responsible for the observations. A typical stage in this process begins with the choice of a trial temperature profile. Four variables can then be manipulated to investigate the refractive

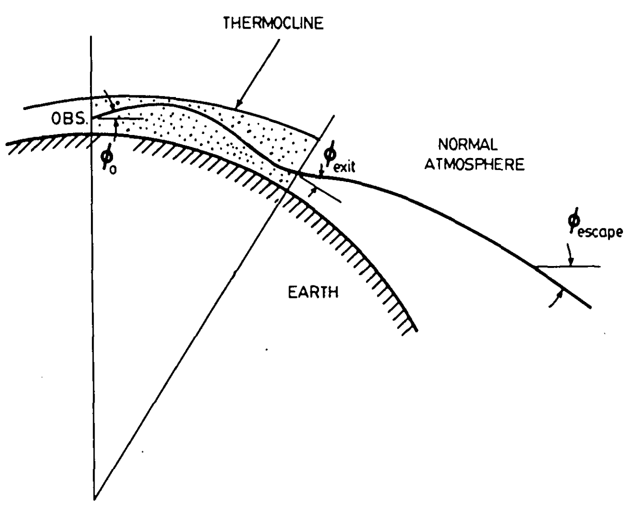

Fig. 1. Geometry of the Novaya Zemlya model. A light ray, with direction of propagation reversed for computational convenience, emanates from the observer's eye with elevation angle ϕ_0. After exiting from the duct, the ray undergoes the normal atmospheric refraction before escaping into space.

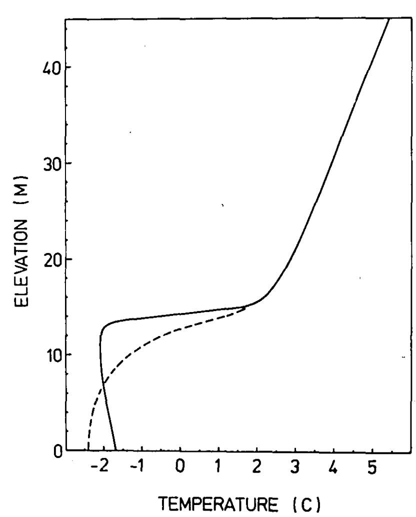

Fig. 2. Temperature profiles at the observer's location. The solid line represents the Wegener model of Phases I and III, while the dashed line gives rise to the Phase II observations.

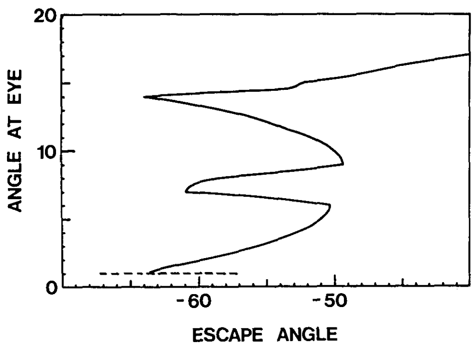

Fig. 3. Phase I transfer characteristic. The angles are in min of arc relative to the observer's coordinate system. The observer sees the duct extending from 1 to 14 min of arc in elevation.

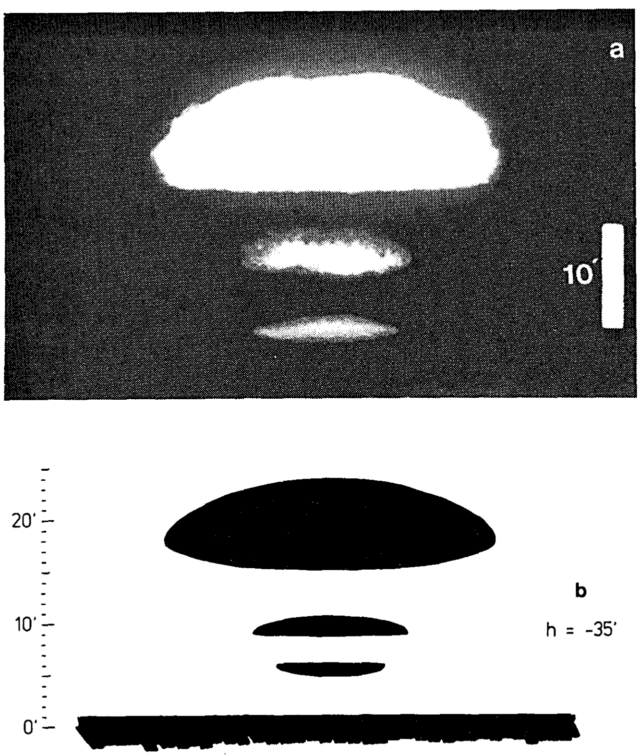

Fig. 4. (a) Image of the sun at 1:34 a.m. MDT. The calculated position of the sun's center is $h = -35$ min of arc. (b) Calculated appearance of the sun based on the Phase I transfer characteristic.

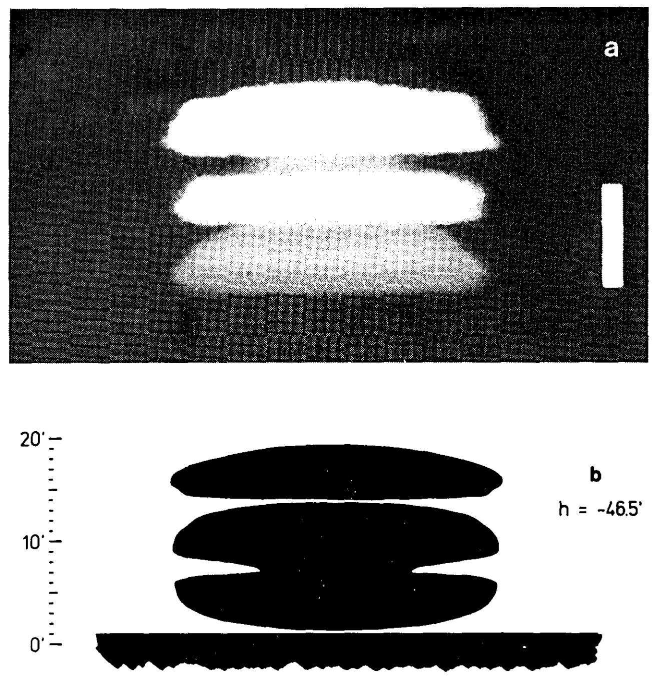

Fig. 5. (a) Image of the sun at 1:41½ a.m.; $h = -46.5$ min of arc. (b) Calculated appearance.

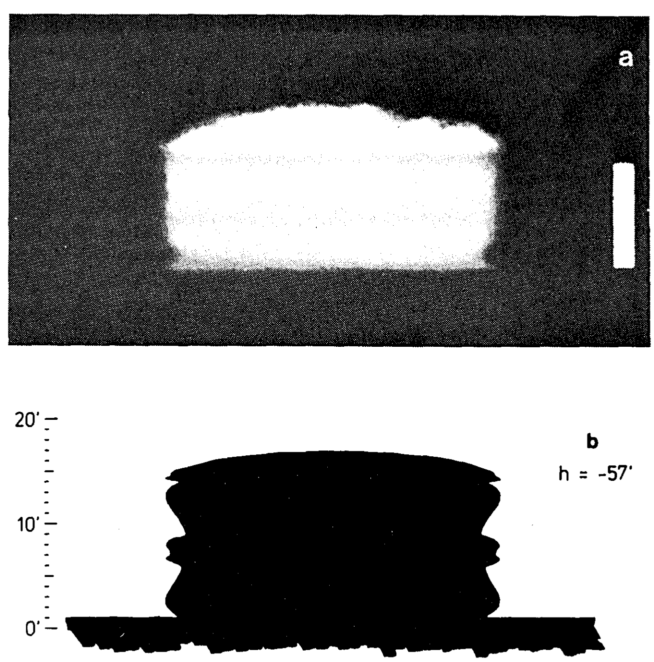

Fig. 6. (a) Image of the sun at 1:49 a.m.; $h = -57$ min of arc. (b) Calculated appearance.

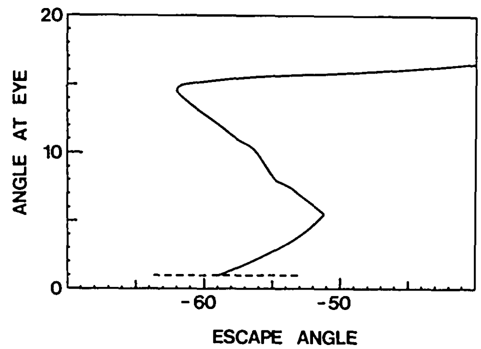

Fig. 7. Phase II transfer characteristic. The thermocline tilt is +8 min of arc in this case.

properties of this case: (1) duct length; (2) elevation of the thermocline above the observer; (3) tilt angle of the thermocline; and (4) refraction contributed by the atmosphere beyond the duct. For any simulation, the required tilt is the easiest to establish; because the calculations identify the initial elevation angle of the uppermost ducted ray, it is only necessary to tilt the coordinate system sufficiently to raise this initial angle to equal the observed +14 min of arc. The remaining variables are then adjusted in successive calculations to compile a cross section of possible transfer characteristics that describe the refractive properties of the assumed temperature profile.

It quickly became apparent that no single temperature profile could account for the complete set of observed images. Three distinct phases, requiring fundamentally different transfer characteristics, were identified from the analysis of the observations.

A. Phase I

The first phase commences when the sun's image enters the duct, 1:30 a.m. MDT, and lasts until the image completely fills the duct at 1:50 a.m. To start the analysis, values are assigned to the refraction beyond the duct on the basis of two considerations. First, the observed multiple images within the duct imply multiple returns of the sun's rays from the thermocline, a condition most easily achieved with a long duct. Second, the total refraction contributed by the duct (approximately proportional to duct length) and the atmosphere beyond the duct must add up to the difference between the sun's true and apparent positions, a difference that is not large during this phase. Hence minimum refraction, namely, the standard astonomical refraction tabulated for normal atmospheres,[4] is attributed to the atmosphere beyond the duct.

A deeply notched transfer characteristic is required to produce the images observed during this phase. An atmospheric model approaching that proposed by Wegener gives the best image reconstructions. The temperature profile is shown by the solid line in Fig. 2; its very steep temperature rise a few meters above the observer is not far different from Wegener's absolutely sharp temperature discontinuity. Figure 3 gives the resulting transfer characteristic for which the duct length and thermocline tilt were, respectively, 52.8 km and +6 min of arc. Tests of various departures from the chosen temperature profile demonstrate that this characteristic is quite sensitive to small changes and that only the Wegener model generates the necessary notches.

Photographs and reconstructions of the sun's image for Phase I are shown in Figs. 4–6. A vertical white bar representing an angle of 10 min of arc provides the scale. In Fig. 4, when the lower limb of the sun begins to send rays into the duct, the sun's center, relative to the observer's coordinates, is at $h = -35$ min of arc, and the lower limb is at -51 min of arc. If a vertical line at the escape angle value of -51 min of arc is drawn on the transfer characteristic of Fig. 3, five intersections with the curve can be seen at eye angles of 4.9, 6.1, 8.7, 10.6, and 15.2 min of arc. Thus the lower limb of the sun is imaged (seen by the eye or camera) at these five elevation angles. In the same way, the image elevation of any other point on the sun may be calculated.

It should be noted that the uppermost sun image arises from direct (nonducted) rays; its lower edge coincides with the upper edge of the duct.

As the sun sinks, a larger fraction of its lower disk is imaged within the duct, until finally the duct is filled by a complex pattern of rays to produce the almost rectangular image of Fig. 6.

The computations revealed a general trend that made the image-matching task somewhat easier. Duct length could be traded off against duct elevation, while maintaining essentially the same transfer characteristic. Thus, once a characteristic of the right shape was found, adjustment of duct length to obtain the necessary refraction angles was fairly straightforward.

B. Phase II

A continuation of Phase I would have shortly split the sun image into three thin horizontal strips within the duct. This process would have started at $h = -66$ min of arc when the upper limb elevation of -50 min of arc begins to intersect the rightward projections of the transfer characteristic (Fig. 3).

The development of the image over this interval, however, indicates that the duct transmission is entering a new phase, requiring a distinctly different transfer characteristic. A suitable shape, shown in Fig. 7, is obtained by rounding off the sharp corner in the temperature profile of Phase I. The dashed line in Fig. 2 gives the modified profile. The necessary duct length of 54 km has been kept close to that of Phase I, since it does not seem reasonable to assume major sudden changes in this parameter. Further, a slightly increased refraction is assumed beyond the duct, as a natural consequence of inversion development due to radiative cooling. An addition of 6 min of arc to the normal refraction is sufficient to match the elevation angles of corresponding photographs and calculations.

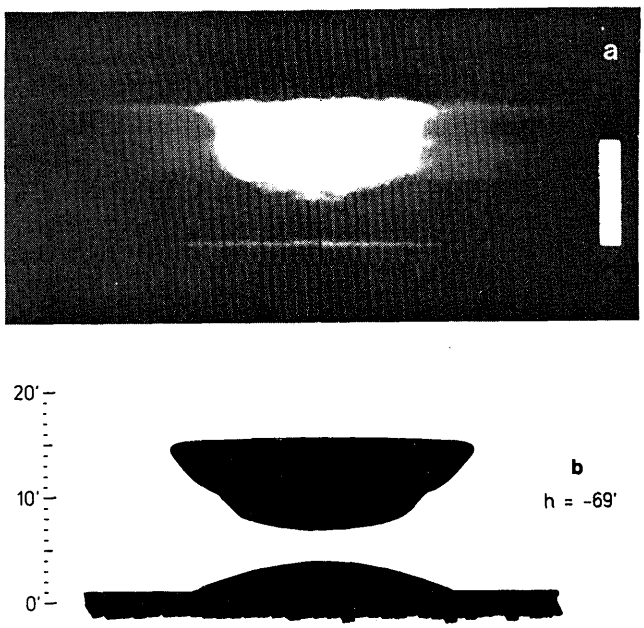

Fig. 8. (a) Image of the sun at 2:06 a.m.; $h = -75$ min of arc. (b) Appearance calculated from Phase II transfer characteristic (Fig. 7) for $h = -69$ min of arc. This shape agrees fairly well with the photograph; however, to obtain correspondence of the elevation angles, the atmosphere beyond the duct is assumed to contribute the needed extra 6 min of arc.

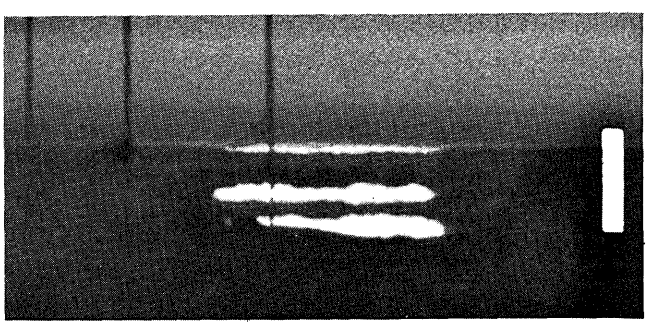

Fig. 9. Typical sun image observed during Phase III; 2:44 a.m., $h = -94$ min of arc, camera elevation = 2.5 m. This shape arises from a Wegener model with transfer characteristic like that of Fig. 3 (see text).

Figure 8 illustrates a typical case from this phase; the sun's elevation h is -75 min of arc. Phase II lasted from ~1:50 a.m. to 2:15 a.m.

C. Phase III

As the sun approaches its minimum elevation of $h = -94$ min of arc, the image (Fig. 9) reverts to the type expected from the Wegener model of Phase I. This case is not simulated in detail; however it could arise directly from the duct conditions of Phase I if the inversion beyond the duct (suggested in Phase II) continues to develop. Rays emerging from the duct with exit angles near zero are given a refraction of 20 min of arc in excess of the 35 min of arc provided by the normal atmosphere. This extends the leftmost projections of the transfer characteristic (Fig. 3) by 20 min of arc to much lower escape angles, so that the image calculated by placing the sun at $h = -94$ min of arc closely approaches Fig. 9.

IV. Conclusions

A recent occurrence of the Novaya Zemlya effect has been documented and analyzed. A fairly simple atmospheric model is adequate to describe the observed optical processes. The model contains one inversion with a single sloping layer of temperature discontinuity merging into a nearly normal atmosphere at some distance from the observer. Specific model parameters are identified to generate calculated sun images closely matching the photographic observations.

The success of this single-thermocline model should not, however, preclude the investigation of more complex atmospheric structures that contain multiple layers of temperature discontinuity.

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8. A photograph of a terrestrial subject, made on the same night, appears in W. H. Lehn, J. Atmos. Terr. Phys. **42,** 471 (1980).
9. The calculation of duct elevation angles, estimated to be accurate to ±1 min of arc, is based on measurements made on the original photographs.