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A winter anomaly campaign in Western Europe

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An integrated campaign of ground-based, balloon- and rocket-borne measurements was performed in Western Europe during winter 1975–76. The campaign was aimed at the study of the atmospheric–ionospheric coupling during pronounced disturbances of ionospheric D-region electron density (winter anomaly). Various atmospheric and ionospheric parameters were measured in the altitude regime 30–120 km. A large set of middle atmosphere temperature data as obtained from satellites is also available for the time period of the campaign. Some major aspects of the campaign are described and respective results presented as they are available at the present state of data evaluation.

Introduction

The D-region winter anomaly was detected many years ago by radio propagation measurements at medium latitudes. Radio-waves of suitable frequency passing through the ionospheric daytime D-region and being reflected from some higher ionospheric layers are attenuated (absorbed) in the D-region (75–95 km). The degree of absorption is dependent on the electron density and collision frequency in the D-region. The electron density is assumed to be mostly produced by photoionization of NO by solar Ly-α radiation. Therefore, a seasonal variation of the D-region absorption with a minimum in winter is to be expected. This is found, indeed, but superimposed on it there are frequent and sometimes very strong enhancements of absorption with a duration of one to several days. They are called 'winter anomaly events'. The intensity and distribution of these events has been studied by ground based radio propagation measurements for quite a number of years and at many places.

The events appear to occur in 'patches' with horizontal extensions of several hundreds of kilometers, and sometimes up to 2000 km. Latitudinal variations have been found as well as correlations with solar activity during the solar cycle. Short period variations frequently occur as wavelike structures with periods between 5 and 25 days. Coupling to other atmospheric or ionospheric layers are not infrequent, and there is also some influence of geomagnetic disturbances. When separating the geomagnetic and solar flare induced effects from the rest of the phenomena, one remains with a class of events which are called the 'meteorological type' of winter anomaly. Only this type will be considered here. (For a compilation of recent winter anomaly literature see Offermann (1979*a*)).

Campaign description

On the face of it the winter anomaly phenomenon appears to be a rather simple electron density effect. It turns out, however, to be very complicated as soon as one considers the reasons for the density variations. Many atmospheric and ionospheric parameters appear to influence them, and it is this fact that makes the winter anomaly so interesting for the study of atmospheric and ionospheric processes and of their interactions. The Western European Winter Anomaly Campaign described here therefore contained a large number of different experiments. They can be roughly grouped into five different categories:

1. definition and verification of meteorological type winter anomaly events;
2. determination of large scale structures (as winter anomaly patches or wind systems);
3. determination of the local thermodynamic structure (vertical wind, temperature, and density profiles);
4. measurements of the neutral atmosphere composition including trace constituents;
5. measurements of plasma parameters as electron density, ion composition, ion mobility and conductivity.

For a detailed description see Offermann (1977, 1979*b*). Each of these five groups contained ground-based, balloon-borne, and rocket-borne experiments. A number of remote sensing satellite experiments were also in operation during the campaign. The balloons and rockets were launched from the site 'El Arenosillo' in Southern Spain (37°6′ N; 6° 44′ W). The ground stations included several radio-wave propagation experiments as well as a number of meteor wind and incoherent scatter radars. They were located at various places in Spain, France, Great Britain, Italy, Austria and Germany. The campaign lasted from the end of December 1975 until mid-February 1976. A total of 22 scientific groups participated in it. They performed 38 different types of experiments on 47 rockets, 23 balloons, and in 12 ground-based stations. Quite a few of these experiments were performed not to study the D-region itself, but to explore the atmospheric layers below and above it to look for mutual couplings. The campaign yielded a large amount of data, which in part are still being evaluated. Only a few selected results are therefore summarized here.

Electron densities

Seventeen *in situ* electron density determinations were performed during the campaign (Friedrich *et al.* 1979). Good correlation with ground based radio-wave absorption measurements was found. The data show that there were density enhancements during winter anomaly events up to one order of magnitude, and that they essentially occurred in the altitude régime 75–95 km.

The reason for enhanced electron densities may be increased ion production rates as well as decreased recombination rates. Enhancements of the production rate may be caused by temperature changes, which affect the chemistry of minor atmospheric constituents. Other causes might be horizontal and/or vertical transports of minor constituents with low ionization potential (like NO). Decreases of the electron recombination rate, too, can be effected by temperature changes, for instance by the temperature sensitivity of the water cluster ion chemistry. Similar effects could be imagined to be produced by transports (horizontal and/or vertical) of suitable minor constituents (such as H_2O, etc.). Therefore the question arises whether the production rate was increased, or whether the recombination rate was decreased during the winter anomaly events found.

Ion production rates

Ion production rates were calculated by Thrane *et al.* (1979) for 2 days of the campaign (4 and 21 January, 1976) from *in situ* solar flux and particle precipitation measurements. They found that the two major production sources in the D-region were ionization of NO (by Ly-α) and of $O_2(^1\Delta_g)$. To determine whether the ion production rate from NO was normal or enhanced, one has to consider the solar Ly-α flux and the NO density. The Ly-α flux was found to have been normal. To make a similar statement about the NO density, a NO reference profile for undisturbed conditions is required. Such a profile does not exist. To obtain a rough idea of how it might look, figure 1 shows a collection of NO profiles inferred from ion spectrometer measurements under quiet conditions (Swider 1978). The data show considerable fluctuations.

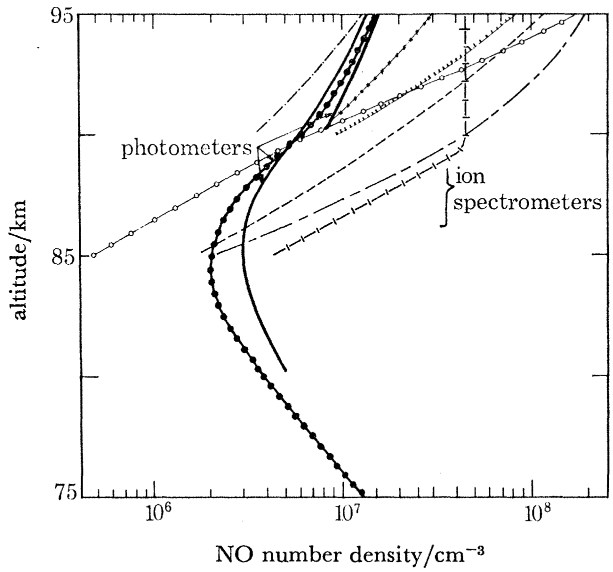

FIGURE 1. NO densities in the D-region during undisturbed conditions. The two heavy lines represent photometer measurements by Tohmatsu (1977), the heavy dotted profile is a photometer experiment of Baker *et al.* (1977), and the remaining seven profiles (thin lines) represent densities inferred from ion spectrometer measurements (Swider 1978).

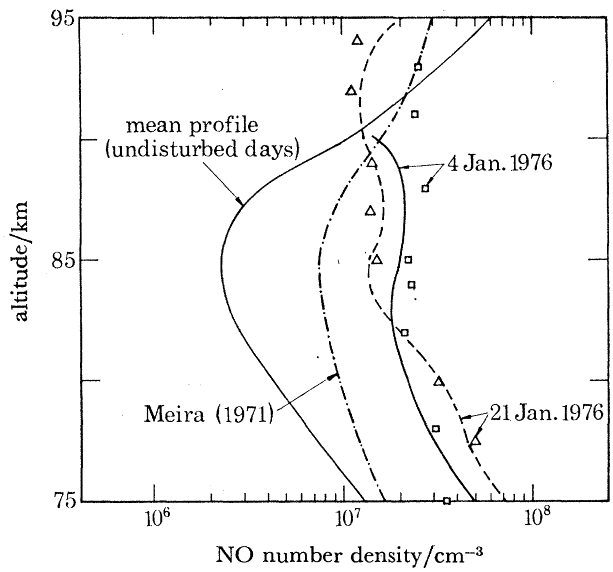

FIGURE 2. NO densities measured during the winter anomaly as compared to a mean quiet time profile derived from figure 1. The squares and triangles give densities obtained from ion spectrometers. Other data shown were measured by photometers. The profile of Meira (1971) is given for comparison.

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A number of quiet time NO measurements by photometers are also shown in figure 1 (Tohmatsu 1977; Baker *et al.* 1977). Despite the scatter of the data and although the different techniques may conceal different systematic errors, a mean curve was calculated from the data given in figure 1, and is shown in figure 2. This is, of course, a very crude method, and it is used only to obtain an approximate idea of what an undisturbed NO density profile might be. In figure 2 this mean profile is compared to NO densities as obtained on winter anomalous days (4 and 21 January 1976) during the campaign described here. Results of two photometers and two ion spectrometer measurements are shown. Meira's (1971) profile is also given for comparison. Figure 2 shows that in the important régime 80–90 km the NO densities were considerably enhanced on both days. This means that also the ion production rates calculated by Thrane *et al.* (1979) represent enhanced values.

$O_2(^1\Delta_g)$ densities were obtained from a 1.27 μm infrared experiment, and were also inferred from two ion spectrometer measurements during the campaign (Beran & Bangert 1979; Arnold & Krankowsky 1979). Ion production rates calculated on the basis of these densities are about a factor of 3 higher than one would normally expect for an undisturbed atmosphere. They are comparable to those obtained from NO (Thrane *et al.* 1979).

The conclusion, therefore, is that the ion production rate appears to have been enhanced during winter anomalous days of the campaign. It should be noted in this context that all NO measurements during winter anomaly days which are in the literature so far, do show considerable density enhancements in the D-region (Offermann 1979*a*). On the contrary respective $O_2(^1\Delta)$ enhancements appear to be present only occasionally. This makes it difficult to answer the question how these two types of enhancement come about. Combined action of two atmospheric parameters (as, for instance, temperature plus transport) may be required.

Electron loss rates

As mentioned above, another reason for enhanced D-region electron density may be a decrease of the electron loss rate. Effective loss rates were calculated by Thrane *et al.* (1979) from the ion production rates and the measured electron densities. In the régime 80–90 km the loss rate is found to be low, indeed. In the lowest part of the D-region (around 78 km) it shows, however, a steep increase by more than an order of magnitude on both days considered (4 and 21 January 1976). This is attributed to an important change in ion composition occurring at that altitude: ion spectrometer measurements show that at this level the number density of NO^+ ions became equal to the sum of the densities of the water cluster ions (Arnold & Krankowsky 1979). This height level is called the 'transition height' (below it the water cluster ions dominate). The transition height occurs at 83–85 km under normal conditions. During the winter anomaly it is found to be appreciably lowered on all occasions for which it was reported in the literature, sometimes even below the 78 km level reported here (Offermann 1979*a*).

The low transition height means that the water cluster ions essentially disappear from the D-region during winter anomaly. This indicates an explanation of the low loss rates reported here, because the recombination rate of the cluster ions is much larger than that of the NO^+ ions. Explanations of ion composition changes of this kind could be found in temperature changes or in transports of suitable minor constituents. As in the case of the production rate also here one is referred to the thermodynamic structure of the atmosphere for a more detailed understanding of the winter anomaly.

Thermodynamic structure of the atmosphere

Temperatures and winds measured during the campaign were analysed by Offermann *et al.* (1979), Rees *et al.* (1979) and Labitzke *et al.* (1979). As concerns the temperatures, strong wave-like structures were found in the vertical temperature profiles in the altitude régime 30–110 km above the rocket range on the 2 days considered above (4 and 21 January 1976, see Offermann *et al.* (1979)). These structures were very similar on those 2 days. An analysis of more rocket measurements and quite a number of satellite data at four different altitude levels between 31 and 80 km shows that these wavelike structures persisted in the altitude régime covered for at least 1 month. They contained short, medium, and long period components (periods of roughly 6–7 days, 12–15 days, and of the order of a month), which appeared to have fixed phase relations at the various altitude levels. This indicates that the thermodynamic state of the atmosphere was governed by pronounced wavelike disturbances during the entire campaign. In the 80 km temperature field these structures were horizontally extended to distances of at least 2000 km.

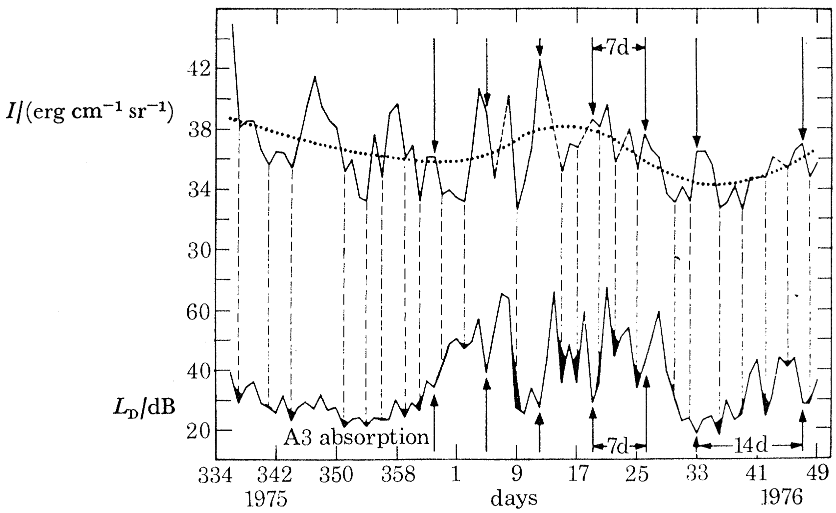

Figure 3. Comparison of winter anomaly activity and temperatures at 80 km. Strength of winter anomaly is represented by daily means L_D of A3 radio wave absorption. Infrared fluxes as measured by the p.m.r. experiment (channel 3000) of the Nimbus 6 satellite are taken as a measure of 80 km temperatures. The long term temperature trend is indicated by a dotted line; it roughly parallels the mean intensity of the winter anomaly activity. Good correspondence of short term fluctuations is found when connecting the minima in the two curves by vertical dashed lines. The respective correspondence of maxima is much less pronounced, and is definitely missing on a number of days, for instance, those indicated by arrows. (For a detailed discussion see Offermann *et al.* 1979).

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Disturbances of this kind could influence the D-region electron densities. The decrease of water cluster ion density discussed above would, for instance, be compatible with a temperature enhancement in the same altitude régime. Such enhancements in the D-region are found indeed in the vertical temperature profiles measured on 4 and 21 January 1976. Furthermore, the satellite data indicated generally increased temperatures around 80 km (long term enhancements) during those time periods of winter 1975–6 when the winter anomaly activity was strong. This is shown in figure 3. A more detailed correlation between variations of 80 km temperatures and winter anomaly activity (as represented by the strength of absorption of radiowaves L_D), i.e. a correlation of short term fluctuations was sought. As shown in figure 3, there appears to be a correspondence of low values of temperature and winter anomaly. High values, however, do not correlate regularly but only occasionally. From this, one may conclude that high temperature is a necessary condition for winter anomaly to occur, but not a sufficient one. Something else (a 'cofactor') is necessary in addition to the high temperature to produce winter anomaly events on this timescale (Offermann *et al.* 1979). There is some indication that this cofactor might be controlled by atmospheric dynamics. (Note the 7-day intervals between the days marked by arrows in figure 3.)

As regards the nature of the cofactor one could obviously think of some horizontal and/or vertical transport of a suitable atmospheric trace constituent. NO and $O_2(^1\Delta_g)$ (or related species) might be good candidates as they were found enhanced during winter anomaly. Horizontal NO transports from the auroral zones to medium latitudes by large scale wind systems have been suggested in the literature as an explanation of the winter anomaly. For the time of the campaign therefore a circulation analysis for the Northern Hemisphere was performed on the basis of temperature and wind data obtained from radiosondes, rockets, satellites, and meteor wind radars (Labitzke *et al.* 1979). Circulation charts were computed for 1 day per week, and a total of 6 weeks. The circulation was generally found to be highly variable. If one compares the wind speeds and directions obtained to the winter anomaly data discussed here one does not arrive at convincing evidence that horizontal transport alone is a sufficient means of explaining the winter anomaly events. In addition, the magnetic activity was generally low during the campaign (Offermann 1979*b*). Hence only moderate NO production in the auroral zone is expected for that time period, if one may assume that the results of Cravens & Stewart (1978) at 105 km are also indicative for the D-region.

Labitzke *et al.* (1979) also calculated mean vertical motions, which could transport, for instance, NO from the E-region reservoir into the D-region. The authors feel that combination of both horizontal and vertical motions may explain some winter anomaly events. It should be mentioned, however, that the analysis made by these authors refers to radio-wave absorption measurements taken at a different place and in a somewhat higher altitude régime than the data discussed here.

Vertical transport other than by mean motions could be effected by atmospheric turbulence. NO or O might be transported downward from the 100 km level by enhanced eddy diffusion. Enhanced O densities in the D-region could lead to enhanced ozone production and thereby to the increased $O_2(^1\Delta)$ densities mentioned above. A transport mechanism of this kind would have to be compatible with a number of constraints imposed by the following measurements:

(1) Enhancements of NO density appear to occur regularly during winter anomaly events, whereas $O_2(^1\Delta)$ density increases are not always found (see above). Furthermore, there are measurements of enhanced NO densities that were accompanied by high O densities, as well as other measurements that found high NO densities with decreased O densities (Krankowsky *et al.* 1979; Dickinson 1977). As NO and O are necessarily transported at the same time, it appears difficult to reconcile these different findings by a mechanism with only one free parameter (transport).

(2) Turbulence must be strong enough to effect strong D-region modifications sometimes in as short a time as half a day (see figure 3). When estimating the eddy coefficients, values of the order of 10^7 cm^2/s are obtained which must have been present in a large altitude régime during the campaign described here. The more serious problem, however, appears to be the removal – at the end of a winter anomaly event – of the large amounts of NO from the D-region, where

it is rather stable against photodissociation. The mechanism of removal has to be as fast as the build-up process, as is seen from figure 3. Turbulent downward transport into the stratosphere appears to be questionable, because the Richardson numbers calculated for the lower mesosphere (50–70 km) indicate that the region was rather stable during the campaign. This assumes, however, that turbulent conditions were similar above Spain and some surroundings. This assumption is not trivial, because wind speeds at D-region heights were large (Labitzke *et al.* 1979), and, therefore, vertical transports a few thousand kilometres away from Spain might have influenced the measurements above the rocket range. The ongoing data analysis will therefore have to check on this assumption. Vertical eddy diffusion also would have to be modulated, as only part of the winter anomaly variability shown in figure 3 can be attributed to temperature variations (see Offermann *et al.* 1979). Such modulation should be detectable by analysing the Richardson numbers measured in the D-region during the campaign. First results of this analysis indicate that turbulence in the D-region was strong throughout the campaign. It does, however, not appear to be modulated. (The same caveat concerning horizontal extension of turbulent conditions applies as above.)

In consequence, a vertical eddy transport model also appears to have its difficulties. The future data analysis will therefore have to carefully consider the interplay of horizontal wind systems, vertical mean motions, vertical eddy transport, and temperature changes. It will then hopefully improve the understanding of the role of minor constituents and of the cofactor during winter anomaly events.

Conclusions

During the Western European Winter Anomaly Campaign 1975–6, an indication was found that winter anomaly events (i.e. electron density enhancements in the D-region) were accompanied by enhancements of ion production rates as well as by decreases of electron loss rates in the D-region. Ion production rate increases were due to density enhancements of NO and $O_2(^1\Delta_g)$. Decreases of loss rates could be attributed to decreased densities of water cluster ions. Destruction of water cluster ions might have been caused, at least in part, by considerable temperature enhancements. Density variations of the minor constituents mentioned (NO, $O_2(^1\Delta_g)$, and related species) could be brought about by combined action of horizontal and vertical transports. This latter effect will be analysed in more detail during the future data evaluation.

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