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The *D* region winter anomaly at high and middle latitudes induced by planetary waves

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An observational study of the *D* region winter anomaly at high and middle latitudes has been made during the period of a sudden stratospheric warming of the 1967/1968 winter. From isopleth analysis of the absorption index, f_{min}, systematic large-scale distributions of the absorption are found at even higher latitudes than 60° geomagnetic latitude as well as at middle latitudes. On the basis of evidence that geostrophic winds induced by well-developed planetary waves extend to the upper *D* region, it is found that when southward winds are dominant, the absorptions become weaker at high latitude but stronger at middle latitude, indicating that abundant NO could be carried away from high-latitude source regions to middle-latitude sink regions. Thus large amplitude planetary waves in the *D* region could induce the winter anomaly through NO transport not only at middle but also at high latitudes.

1. INTRODUCTION

The winter anomaly of radio wave absorption in the *D* region (60–85 km), which is directly due to remarkable enhancement in the electron density, has been an important unresolved phenomenon in the lower ionosphere [*Offermann*, 1979]. According to *Arnold and Krankowsky* [1977], necessary conditions for the observed electron density increase are an about tenfold increase of ionization sources as NO (and $O_2(^1\Delta_g)$) and a temperature rise of a few tens of degrees Kelvin due to a strong temperature dependence of the conversion rate of molecular ion to cluster ion. Thus it is important to identify what processes could bring about these conditions in the winter *D* region.

With the use of a two-dimensional dynamical and chemical model, *Solomon et al.* [1982] simulated the winter anomaly at middle and high latitudes, resulting from a NO increase due to vertical transport from the lower thermosphere source region by eddy diffusion and meridional circulation. Their results are consistent with the regular component of the winter anomaly [*Schwentek*, 1971]. Furthermore, they pointed out the important contribution of aurora events to the high-latitude NO increase associated with energetic electron precipitations [*Kondo and Ogawa*, 1976]. Concerning the mechanism of the irregular component of the winter anomaly, *Offermann et al.* [1982] stressed the important role of vertical transport of NO by enhanced eddy diffusion. A recent numerical study by *Jones and Avery* [1984], on the other hand, demonstrates the role of planetary wave wind transport of NO from high latitudes in producing the irregular components. There are some inconsistencies in theoretical studies of irregular components.

An observational study by *Kawahira* [1982] of the winter anomaly at middle latitudes at sudden warmings has given observational evidences that a NO increase by well-developed planetary wave wind transports from the polar region, where NO is most abundant [*Cravens and Stewart*, 1978; *Iwagami and Ogawa*, 1980], could produce irregular components of the winter anomaly. Recent observational studies by *Pakhomov et al.* [1984] have also verified the effect of large-scale winds on the winter anomaly at middle latitudes.

These observational studies are confined to south of 60° geomagnetic latitude, south of aurora region. However, well-developed planetary waves in the mesosphere could induce a NO change by wind transport effects also at high latitudes, as shown by a numerical study by *Roble and Gray* [1979] in the case of NO transport in the lower thermospheric polar region. Indeed, recent LIMS satellite observations of NO_2 in winter high latitudes by *Russel et al.* [1984] find the large-scale distribution at polar winter night latitude above 70-km height. This first finding verifies a planetary wave effect on the *D* region chemical species, not only at middle but also at high latitudes. Although the high latitude winter anomaly has been studied mainly in relation to

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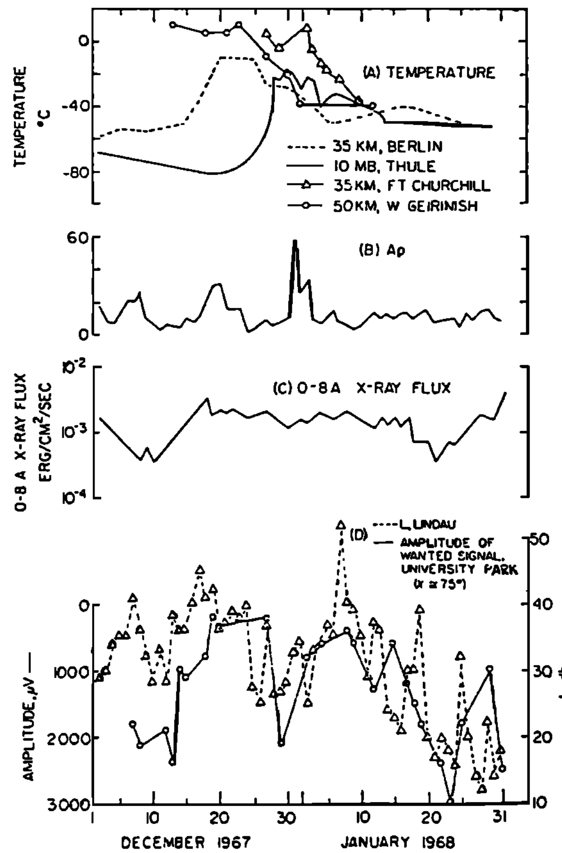

Fig. 1. Variations of geophysical and ionospheric parameters during December 1967 and January 1968 [after *Rowe et al.*, 1969].

dominant geomagnetic effects such as energetic electron precipitation [see review of *Thomas*, 1980], the present study aims to elucidate the dynamical effects of planetary waves on the winter anomaly at high latitudes from an observational analysis.

2. RESULTS

The present study concentrates on the winter anomaly which occurred during a sudden warming of the 1967/1968 winter from late December 1967 to early January 1968. Variations of geophysical and ionospheric parameters are shown in Figure 1 [*Rowe et al.*, 1969]. It is apparent that the absorptions enhance as the warmings develop, as seen in Figures 1*a* and 1*d*. According to Rowe et al., the electron density observed at Pennsylvania (40°N) reached its maximum at 75–80 km height during the period from December 25, 1967, to January 1, 1968. They further noticed that the winter anomaly has an intimate relationship to sudden warmings, but not to geomagnetic storms from the long-term comparison between *Ap* index and the absorption.

Kawahira [1982] proposed an observational evidence for the mechanism of this winter anomaly as a NO increase due to southward transport from high latitudes by well-developed planetary wave winds. A schematic picture of the mechanism is shown in Figure 2 [*Kawahira*, 1985]. These large-amplitude planetary waves in the mesosphere have been identified by satellite observations of temperatures [e.g., *Hirota and Barnett*, 1977]. Thus the figure shows a realistic pattern of geopotential height, especially its large variation along latitude circle, in the winter *D* region at the time of stratospheric sudden warmings. Then strong southward geostrophic winds could transport abundant NO from high to middle latitudes and here bring about an enhancement in NO concentration, resulting in the winter anomaly. On the other hand, northward winds could cause a decrease at middle latitudes. As suggested in Figure 2, even at higher latitudes than 60° geomagnetic latitude, there would be a large-scale wind effect on NO variations in addition to geomagnetic storm effects.

In order to elucidate the effect of planetary wave winds on the absorption, the isopleth analysis of $\Delta f_{\min}$, which is the deviation from monthly median value of $f_{\min}$, is made at high and middle latitudes including aurora region. The $\Delta f_{\min}$ is a good indicator of the absorption [*Sinno and Higashimura*, 1969], the isopleth of $\Delta f_{\min}$ corresponds to that of the electron density in *D* region produced by ionization of NO due to Lyman α solar radiation, because the analysis is confined to the south of the polar night latitude (70°N).

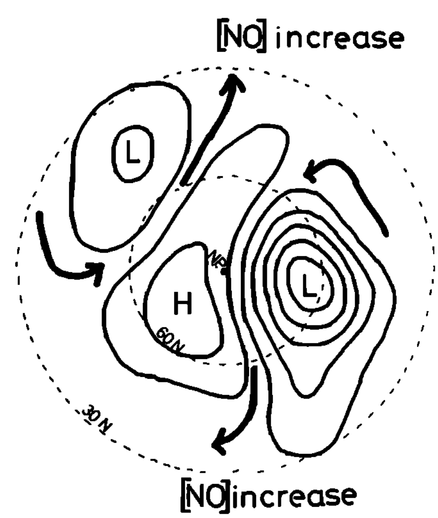

Fig. 2. A hemispheric chart of geopotential height in the winter *D* region at the period of sudden warmings, and schematic illustration for the mechanism of the winter anomaly [after *Kawahira*, 1985].

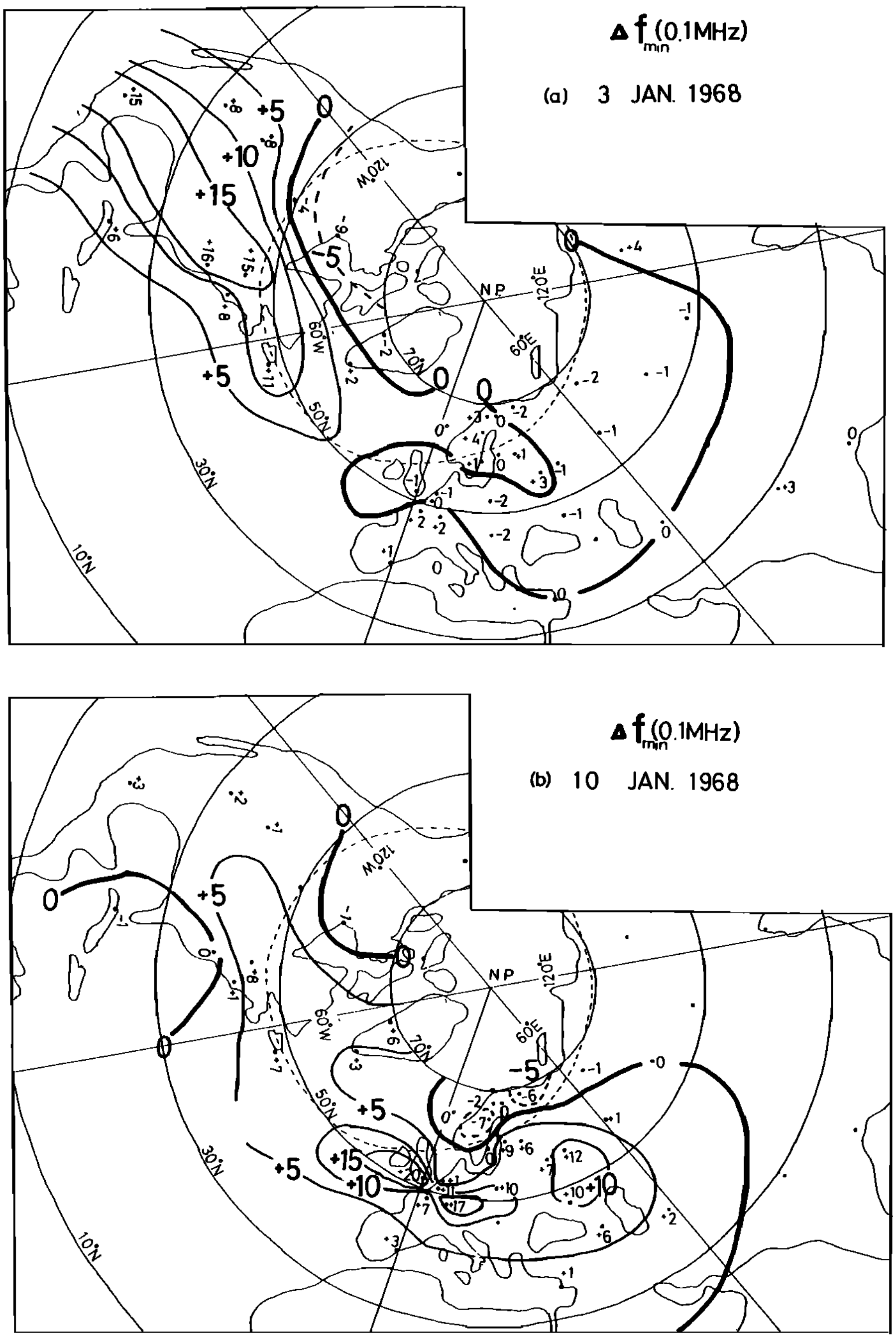

Fig. 3. Large-scale isopleth analysis of the absorption index, Δf_{min}, in the form of 3-day running means using the 3-hour average at 11, 12 and 13 local time of the deviation from the monthly median value of f_{min} (*a*) on January 3, 1968, and (*b*) on January 10, 1968. Positive area is an increase in absorption, and negative area is a decrease. Dotted line indicates 60° geomagnetic latitude ($\Lambda = 60°$).

The results of January 3 and 10, 1968, are shown in Figure 3, when the warming reached its peak and the absorption enhancement was remarkable [*Rowe et al.*, 1969; *Kawahira*, 1982]. A systematic and large-scale distribution of the absorption even at high latitudes is clearly detected; the scale is similar as that of planetary waves. It is noted that the distribution of Δf_{min} along 60°N is not uniform but shows a "wavy" pattern. Furthermore, there is a negative correlation of the absorption distributions between middle and

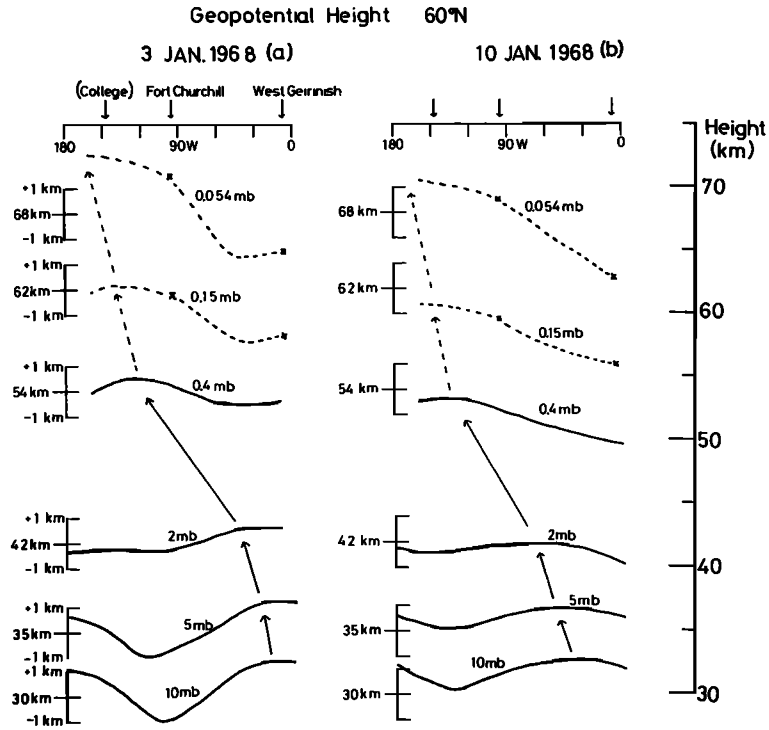

Fig. 4. Vertical profile of geopotential height along 60°N from 0°W to 180°W. Real height is shown in the right-hand side, and the scale of the geopotential height in the left-hand side is twice the real height. The thick line is after the Upper Air Synoptic Map (NOAA), and the dotted lines are estimated from hydrostatic balance with use of observed temperature at Fort Churchill and West Geirinish, (*a*) on January 3 and (*b*) on January 10, 1968 [after *Kawahira*, 1982].

high latitudes; e.g., along 90°W positive Δf_{min} is located south of 60°N and negative Δf_{min}, north of 60°N.

Then the evidence of large amplitude planetary waves in *D* region during the 2 days was given by *Kawahira* [1982] as shown in Figure 4, where geopotential height distributions along 60°N in western longitude from 0°W to 180°W are shown from 30 to 70 km height. It is apparent that over North America, geostrophic southward winds are dominant during the 2 days, since geopotential height become higher in west side than east side. The southward winds over North America are consistent with the winds observed at College by meteor radar by *Hook* [1972] as shown in Figure 5, where zonal and meridional components of the winds averaged between 75 and 105 km height reverse during the period of peak stratospheric warmings (Figure 1). In Figure 5, wind changes at White Sands by meteorological rocket soundings are also shown, which represent similar changes as those at College. It is evident that the southward winds in meteor height at College are consistent with geostrophic southward winds induced by planetary waves as shown in Figure 4. Thus the planetary wave induced winds would be dominant even up to the upper *D* region, because the data at College are the average between 75 and 105 km height layer.

Although there are no wind data in Europe, it can be suggested from Figure 4 that northward winds may have been dominant on January 3, since lowest geopotential height at 70 km is located near 10°W, but southward wind on January 10, since the monotonic increase toward west of geopotential height at 70 km is seen.

The comparison between Figures 3 and 4 indicates a tendency that southward winds (northward) would cause an increase (decrease) of the absorption at middle latitudes, but a decrease (increase) at high latitudes. Large-scale wave winds thus affect the distribution of *D* region NO even in the auroral region as has theoretically been studied by *Roble and Gray* [1979], because the life time of NO is comparable to that of atmospheric motion. It is to be noted that the wind directions at College (Figure 5), being south- and westward, are consistent with the distribution of

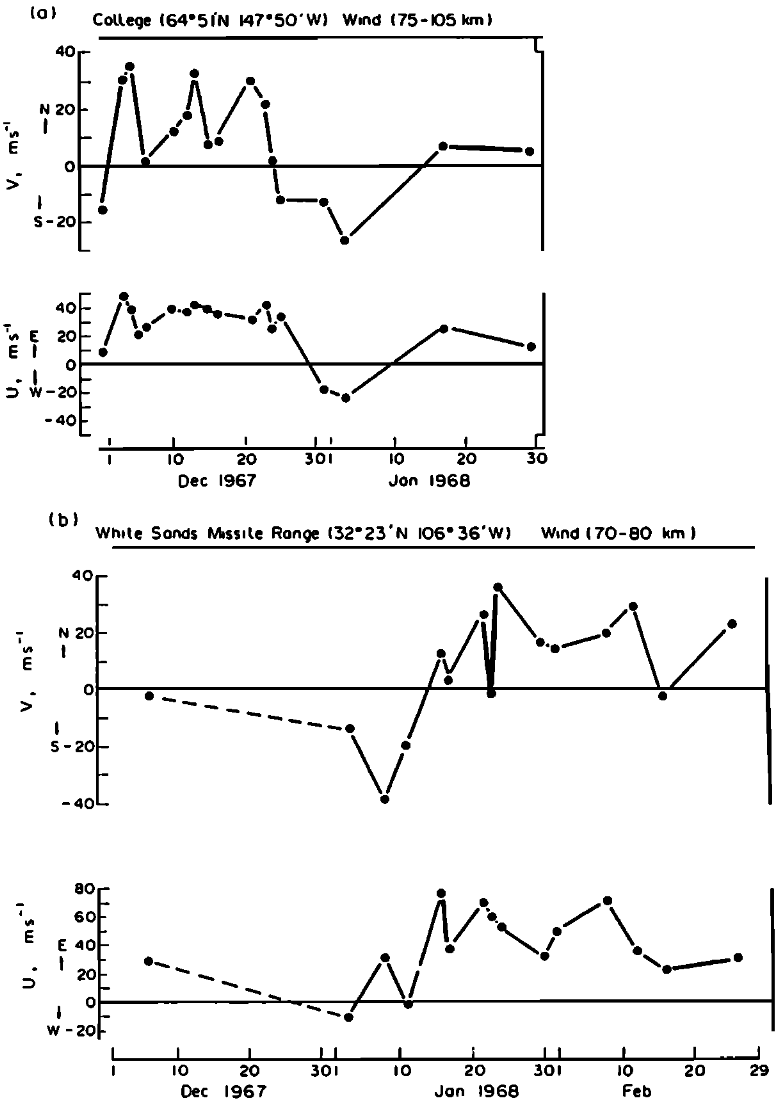

Fig. 5. Variations of winds in the upper mesosphere. W and E indicate the wind toward west and east, respectively, and likewise N and S toward north and south: (*a*) observed by meteor radar at College [after *Hook*, 1972]; (*b*) observed by meteorological rocket soundings at White Sands [after *Kawahira*, 1982].

the absorption maxima on January 3 and 10, being located from northeast to southwest over North America as seen in Figure 3. This fact would also support the planetary wave wind effect on the winter anomaly.

The effect of planetary waves on high-latitude *D* region is further investigated from the time change of the absorption and meridional winds as shown in Figure 6. Figure 6*b* shows the time change of Δf_{min} at the two stations, Fort Churchill, which is located north of 60° geomagnetic latitude, and Boulder, which is located south of that latitude. Thus variations of the absorption at Fort Churchill may be influenced by NO changes owing to energetic electron precipitation associated with geomagnetic storms, but at Boulder they may be influenced by NO changes owing to transport effects associated with neutral winds. In order to see these effects, there are shown the absorption changes observed by riometer at Dixon Island (Figure 6*a*) as an index of energetic electron precipitations, and the meridional winds at College and White Sands, respectively (Figures 6*c* and 6*d*).

The absorption changes at Fort Churchill seem to correlate well with that of the riometer absorption, which could indicate the NO enhancement through

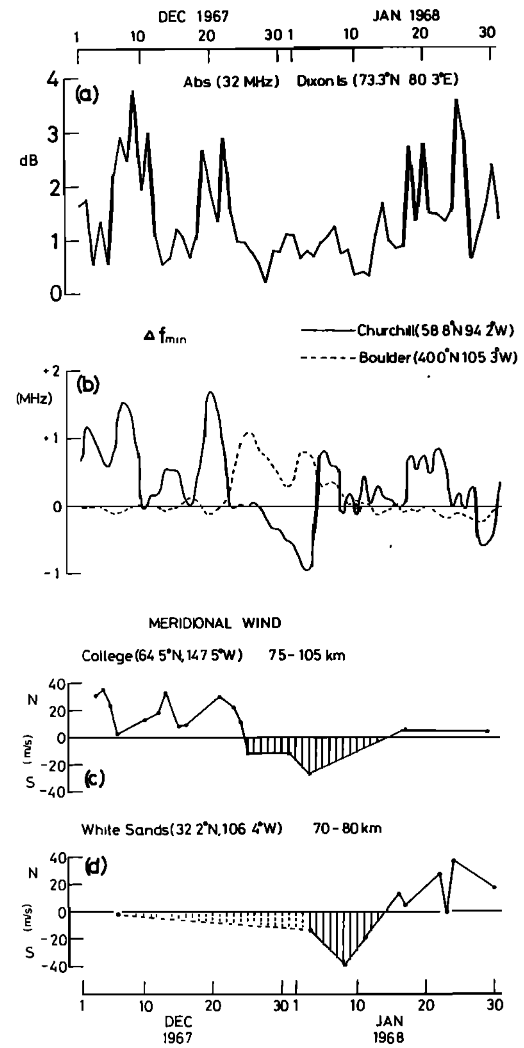

Fig. 6. Time changes of physical quantities. (*a*) The riometer absorption at Dixon Island (Λ = 63°) which is defined as a diurnal maximum value among every hourly observed ones. (*b*) Δf_{min} at Fort Churchill (Λ = 68.7°) and Boulder (Λ = 49.0°), respectively. (*c*) Meridional wind at College observed by meteor radar [*Hook*, 1972], and (*d*) meridional wind at White Sands observed by meteorological rocket soundings.

energetic electron precipitations [*Iwagami and Ogawa*, 1980]. Although the absorption at Boulder is not remarkable compared to that at Fort Churchill during nearly all periods, except during the period from late December to early January when the clear reversed changes are seen, the absorption at Boulder becomes stronger, but at Fort Churchill it becomes weaker, and furthermore then southward winds are dominant (Figure 6*c* and 6*d*). These results would indicate that the large-amplitude planetary wave southward winds carried away abundant NO from high-latitude source regions to middle-latitude sink regions. As a result of this effect, NO increases at middle latitude, but the decrease at high latitude is induced as suggested from the schematic picture of Figure 2; in other words, the meridional gradient of NO profile between middle and high latitudes becomes less steep.

The same analysis over Eurasia is shown in Figure 7. Some different features from Figure 6 are seen in that middle-latitude absorption (at Garchy) is comparable to that in high latitude (at Murmansk). This may be due to a difference in a NO distribution over the aurora region between North America and Eurasia [*Cravens and Stewart*, 1978]. However, during

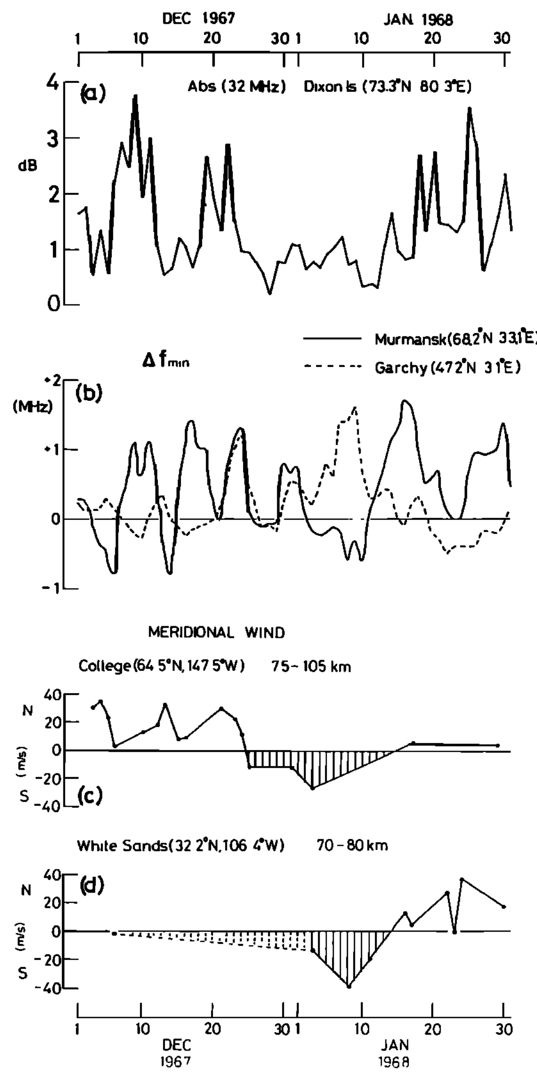

Fig. 7. Same as in Figure 6, but (Figure 7*b*) is at Murmansk (Λ = 63.5°) and Garchy (Λ = 49.6°).

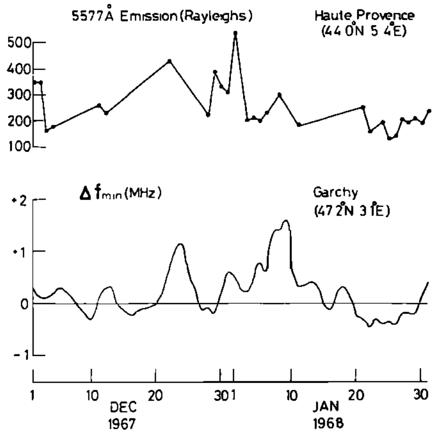

Fig. 8. Variations of 5577-Å airglow emission at Haute Provence [after *Fukuyama*, 1977] and of the absorption at Garchy.

the active period of planetary waves from late December to early January, a remarkable absorption increase at middle latitude and the decrease at high latitude are apparent as is seen in Figure 6.

These evidences show a direct effect of atmospheric motions on the lower ionosphere at high latitudes.

3. CONCLUDING REMARKS AND DISCUSSION

In the present paper, from meteorological and absorption data analysis at the high and middle latitudes, it is found that large-amplitude planetary wave winds transport NO-rich air from high to middle latitudes, resulting in a NO (absorption) increase at middle latitudes but a NO (absorption) decrease at high latitudes. However, during the period of less active planetary waves, the daily changes of the absorption at high latitude are similar to that of energetic electron precipitation, but those at middle latitudes are weak. These results show interesting effects of meteorological and geomagnetic disturbances on the high-latitude lower ionosphere.

Furthermore, the planetary wave wind transport from the polar region at the time of sudden warming can play an important role not only on NO but also on atomic oxygen (O) changes, because its lifetime is long enough to be affected by atmospheric motion and is abundant at higher latitudes. This effect has been recognized as a dramatic increase of airglow intensity at the time of sudden warmings as presented by *Fukuyama* [1977], where variations of the airglow intensity at Haute Provence (44°N, 6°E) at the time of the sudden warming of the 1967/1968 winter were also analyzed. In Figure 8, the variation of 5577 Å airglow emission at Haute Provences and the absorption at Garchy (47.2°N, 3.1°E) are compared. Similar changes of the two parameters would suggest that abundant atomic oxygen in the polar region could also be transported by southward winds associated with planetary waves.

It is to be noted that roles of eddy diffusion owing to breaking gravity waves [*Lindzen*, 1981] are still important as stressed by *Offermann et al.* [1982], because its continuous transport of NO from the lower thermosphere could maintain higher NO density in the polar region. Further eddy diffusion itself may be influenced at the time of sudden warmings due to zonal wind variations which affect vertical propagation of internal gravity waves as discussed by *Dunkerton and Butchart* [1984]. These variations will be studied in more detail.

In the present study, temperature rise effects on the absorption could not be elucidated. Temperature changes during the warming are seen as a rise in the stratosphere but a decline in the mesosphere [*Hirota and Barnett*, 1977]. Thus the absorption enhancement during the stratospheric warmings may be due to a NO increase. However, seasonally averaged temperatures of the winter *D* region are warmer than those of the summer. Thus the cluster ion density in winter would be far less than in summer even during sudden warmings. Therefore a warmer winter *D* region could give an adequate condition for electron enhancement [*Arnold and Krankowsky*, 1977].

The effect of atmospheric waves on the polar lower ionosphere, as discussed in the present paper, may be quite interesting and important in the aeronomy of the mesosphere and lower thermosphere. Since the polar region acts as the chemical source region of NO and O, which are produced by geomagnetic storms, the transport process in the polar region could be one of the important factors in the chemistry and thermodynamics of the mesosphere and even upper stratosphere at middle and high latitudes.

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