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by

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ABSTRACT

Global midday measurements of the primary ionic constituents of the earth's topside ionosphere between June and October, 1966, have revealed strong longitudinal variation in the altitude of the O^+-H^+ transition level resulting from a corresponding variation in the distribution of O^+. While the altitudinal variation of the transition level at European and Pacific longitudes is nearly symmetric about the geomagnetic equator, at American longitudes the level drops by almost 1000 km between the northern and southern hemispheres. This behavior is interpreted as an effect caused by atmospheric winds. Concentration profiles for O^+ and H^+ along a midlatitude field line in the northern and southern hemispheres have been calculated, considering the atmospheric wind field and its component parallel to the magnetic field. It is found that the ion-wind interaction produces an important interhemispheric proton flux, which is actually responsible for the asymmetry in the O^+-H^+ transition level observed at American longitudes.

THE EFFECT OF ATMOSPHERIC WINDS ON THE O^+-H^+ TRANSITION LEVEL

INTRODUCTION

For some time it has been thought that winds, caused by pressure gradients in the neutral atmosphere, may have significant effects on the ionosphere. King and Kohl [1965] suggested that certain ionospheric F-layer anomalies might be explained in terms of charged particle drifts produced by these winds. Later, these workers described a detailed calculation of the atmospheric wind system, based on data from the Jacchia [1964] model atmosphere [Kohl and King, 1967], and quantitatively demonstrated the importance of vertical ionospheric drifts produced by the neutral winds.

Data obtained from the Explorer 32 ion mass spectrometer indicate a strong longitudinal variation in the high altitude distributions of the heavy ions O^+ and N^+, which produces a corresponding variation in the altitude of the O^+-H^+ transition level. In this preliminary report these observations will be described, and the variation of the transition level with longitude and latitude will be interpreted as further evidence that winds in the neutral atmosphere, through neutral-ion drag, have an important effect on the distribution of ions in the topside ionosphere.

EXPLORER 32 INSTRUMENTATION AND ORBIT

The Explorer 32 satellite (Atmospheric Explorer-B) was launched on May 25, 1966, into an orbit with an inclination of 64.7°, perigee of 277 km, and apogee of 2725 km. The spacecraft carried an experiment complement designed to make in situ measurements of positive ion composition and concentration, electron concentration and temperature, and neutral particle composition, concentration, and temperature. The useful satellite lifetime of ten months permitted a global study of the diurnal variation of the atmosphere during two complete diurnal cycles.

The Bennett ion spectrometer was similar in design to the instruments flown on the OGO satellite series [Taylor et al., 1965]. The sweep voltage was programmed to cover the ion mass range 12 to 19 AMU, and 1 and 4 AMU, assuring detection of O^+, N^+, H^+, and He^+, the primary ionic constituents of the topside ionosphere. The range of measurable ion concentration was from 10^1 to 10^6 ions/cm^3. The satellite was spin stabilized, with the attitude of the spin axis maintained perpendicular to the orbit plane by magnetic control. The data upon which this paper is based were all obtained when the angle between the spectrometer axis and the satellite velocity vector was less than 10°. An earlier paper [Brinton et al., 1969b] includes a more extensive description of the Explorer 32 spacecraft and spectrometer, and a discussion of data interpretation techniques.

LONGITUDINAL VARIATION OF ION CONCENTRATIONS

A global study of ion composition at midday in the altitude range 500-2700 km has been made using Explorer 32 spectrometer data obtained between June and October, 1966. The primary ground stations which acquired data from the satellite lie in three longitude bands, and therefore, a comparison of the ion distributions at these three longitudes was possible. Because the earth's magnetic field strongly controls the ion distributions, as pointed out by Bowen et al. [1964], our data have been plotted in geomagnetic coordinates. Concentrations of O^+, N^+, and H^+ measured at midday (1000-1500 LT) in the geomagnetic longitude range -30° to +20° (America) were compared with corresponding data from the longitude intervals +70° to +120° (Europe) and -110° to -170° (Pacific).

While no significant longitudinal variation was noted for H^+, a pronounced effect was observed in the concentrations of O^+ and N^+. The distributions of O^+ and N^+ in the American longitude range were significantly different from those at European and Pacific longitudes, the latter two being essentially identical. At European and Pacific longitudes the O^+ and N^+ were observed to be nearly symmetric with respect to the geomagnetic equator. At American longitudes, however, measurements in the northern hemisphere at low and midlatitudes between 1000 and 2500 km indicate a higher O^+ concentration than at the same altitude and latitude at European and Pacific longitudes. The opposite is true in the southern hemisphere, where O^+ concentrations measured between 500

and 2700 km at American longitudes are lower than those at a comparable location in the European and Pacific longitude ranges. These longitudinal variations in concentration have been observed to be as great as a factor of five. The longitudinal behavior of N^+ was similar to that of O^+, with N^+ having a uniformly lower concentration. We will not discuss the behavior of N^+ further in this paper, but will assume that the mechanisms controlling the high altitude distribution of O^+ are effective for N^+ as well. Since He^+ was a minor constituent over the entire altitude range, and we have not as yet studied its longitudinal behavior, we will not discuss He^+ in this preliminary report.

LONGITUDINAL VARIATION OF O^+-H^+ TRANSITION LEVEL

Because a longitudinal variation has been observed in the global distribution of O^+, but not H^+, the altitude of the O^+-H^+ transition level exhibits a longitudinal dependence. The solid points in Figure 1 were obtained from altitude profiles of O^+ and H^+ at European and Pacific longitudes, each profile having been derived from ion concentrations measured in a ten degree interval of geomagnetic latitude; the open points represent data obtained in a similar manner at American longitudes. Each point indicates the altitude at which the predominant ionospheric constituent changes from O^+ to H^+, and the observed increase of this altitude with increasing latitude is consistent with the latitudinal variation of H^+ reported by Taylor et al. [1968]. Figure 1 illustrates clearly, however, that the latitudinal variation of the transition level observed at American longitudes is distinctly different from that

observed at European and Pacific longitudes. While the transition level variation at the latter two is nearly symmetric about the geomagnetic equator, at American longitudes the level drops by almost 1000 km between the northern and southern hemispheres.

DISCUSSION

The global variation of the magnetic field dip angle at 1000 km altitude in coordinates of geographic latitude and longitude is shown in Figure 2. This illustration immediately suggests the origin of the observed longitudinal effects in the ion composition, in that while the dip angle distribution is almost the same at European and Pacific longitudes it is significantly different over America, a pattern identical to that observed in the ion distributions. On this basis we assume that the longitudinal variation of ion composition is associated with the deviation of the magnetic dipole axis from the earth's rotational axis.

The ion measurements reported here were derived, at all longitudes, by averaging data obtained at midday during the period June-October, 1966. The sun was thus in a relatively fixed position with respect to the earth's rotational axis during the period of the measurements. So, when we describe the ionosphere using coordinates based on the earth's magnetic field (which is appropriate because of the field's constraint on the plasma), the relative position of the sun with respect to a given geomagnetic latitude changes as a function of longitude.

There are two known ways in which the relative position of the sun

influences the ionosphere:

(1) The attenuation of ionizing EUV radiation changes with solar zenith angle, with consequent effects on photoionization rates. This influence, however, is small at low and mid latitudes.

(2) The ionosphere is influenced by the neutral atmosphere, whose structure is strongly controlled by the solar zenith angle. The interactions between the neutral atmosphere and the ionosphere are two-fold: (a) Latitudinal variations in the neutral atmosphere affect photoionization rates and ion chemistry. For example, atmospheric phenomena like the helium bulge in the winter hemisphere, as discussed in the context of the helium ion anomaly by Taylor et al. [1969], may have significant effects on the global ionospheric distribution. Considering the problem at hand, oxygen ion chemistry depends on the three neutral constituents O_2, N_2, and O, while H^+ chemistry depends additionally on H. There is, unfortunately, little information on the global distribution of these neutral constituents. To assume that neutral composition variations could produce the observed effects in the O^+ and H^+ distributions would therefore be rather speculative, and thus as a working hypothesis we disregard this possibility; (b) the dynamics of the neutral atmosphere, and in particular atmospheric winds, can produce significant effects on the ionosphere. This was recognized by Kohl and King [1967], who showed that atmospheric winds can be important in determining ionospheric structure and behavior.

In the following it will be shown that, in fact, atmospheric winds

can also account for the observed longitudinal and latitudinal effects in the ion distributions described in this paper.

THE ATMOSPHERIC WIND FIELD

At present a theoretical three-dimensional model of the neutral atmosphere does not exist, and thus the atmospheric wind field can only be deduced from atmospheric density observations. Kohl and King [1967], Geisler [1967], and Volland and Mayr [1968] have derived the wind field from the Jacchia [1964] three-dimensional model which is based on satellite drag measurements. In the following we adopt the approach of Volland and Mayr [1968], who described the three-dimensional structure of the thermosphere by means of spherical functions. They have shown, in fact, that Jacchia's model and the resulting wind distribution can be reproduced by spherical functions of low degree, which greatly simplifies the analysis.

The large horizontal dimension of the neutral atmosphere, as compared to its small altitudinal extension, requires that in order to satisfy flow continuity, horizontal winds must be an order of magnitude larger than vertical winds. For this reason, primarily, we neglect vertical winds in our ionospheric study.

For illustrative purposes we will discuss the wind effects for equinox conditions. Our data, however, were obtained under northern hemisphere summer conditions which, as shown later, must be expected to produce even stronger longitudinal effects. Equinox requires that the following

conditions be fulfilled (Volland and Mayr, 1968):

(1) The meridional velocity must be zero at the subsolar point (for equinox conditions, the equator), where the atmospheric pressure bulge is observed at F_2-region heights.

(2) The meridional velocity must be symmetric with respect to the subsolar point (for equinox, the equator).

(3) At the poles the time independent terms in the velocity function must be zero, but the time dependent terms should be non-zero.

These postulates determine the form of the meridional velocity, u, which is approximated by two spherical functions of low degree [Volland and Mayr, 1968]:

$$u = u_{10}P_{10}\cos\lambda + u_{21}\frac{P_{21}}{\cos\lambda}\cos(\omega(\tau-\tau_{21})) \qquad (1)$$

where

$P_{10} = \sin\lambda$

$P_{21} = \frac{3}{2}\sin(2\lambda)$

λ = geographic latitude

$\tau = t + \frac{\ell}{\omega}$ (local time)

t = universal time

$\omega = \frac{2\pi}{\tau_0}$ (angular frequency with τ_0 the period of one day)

ℓ = geographic longitude

τ_{21} = 1400 local time (observed diurnal maximum in atmospheric density)

"u" is positive in the south direction.

Assuming that the altitudinal variations of "u" within the F_2-region are small, and therefore negligible, relation (1) is defined with the two parameters u_{10} and u_{21} which are, according to Volland and Mayr, of the order of $u_{10} \sim 10$ m/sec, and $u_{21} \sim 50$ m/sec.

Thus far we have described the wind field in the geographic coordinate frame, which is appropriate for the neutral atmosphere, considering the solar control of the thermospheric structure. For purposes of studying the ionosphere, however, it is of interest to describe the wind component parallel to the magnetic field as a function of geomagnetic latitude. This is straightforward for the two longitudes in which the earth's rotational and dipole axes and the earth-sun line lie in the same plane. As this is the situation for noontime at American and Pacific longitudes, and thus applies to the ion composition measurements under discussion, we shall describe the wind field for these two cases only.

At American longitudes the magnetic equator is south of the geographic equator and thus we can describe the wind field by substituting in equation (1) $\lambda = (\Theta + 15°)$, and similarly for Pacific longitudes $\lambda = (\Theta - 10°)$, where we define Θ as the geomagnetic latitude. If we denote the magnetic dip angle by I, then the wind component parallel to the magnetic field is $u_{\parallel} = u \cos I$, where the meridional velocity "u" is defined in (1). Although it is $u_{\parallel}$ which enters into the momentum transfer equation, it is actually the vertical component of $u_{\parallel}$ that is of significance for the ion continuity equations. Therefore, we shall discuss here the vertical wind component $u_{\perp} = u_{\parallel} \sin I$.

Figure 3 shows $u_\perp$ as a function of geomagnetic latitude at American and Pacific (European) longitudes for equinox conditions. Arrows indicate the subsolar points at which the horizontal wind velocity is zero. The horizontal winds, which according to (1) blow away from the subsolar point, increase symmetrically to the south and north with increasing distance from the equator. For this reason, at American longitudes the horizontal velocity is larger at southern geomagnetic latitudes than it is at northern latitudes. Similarly, the velocity is larger at northern geomagnetic latitudes for Pacific longitudes. This is evident in Figure 3, where it is also clear that the resulting downward wind components exhibit pronounced but opposite asymmetries at American and Pacific longitudes. It is also apparent that the degree of asymmetry varies as a function of latitude, the difference in velocity being most pronounced at about 20° geomagnetic latitude. This pattern is in excellent agreement with the ion composition observations shown in Figure 1, which indicate that for American longitudes the largest difference in the O^+-H^+ transition level between hemispheres occurs at approximately this latitude. It is also consistent that the greater downward velocity corresponds to the lower O^+-H^+ transition level.

As described earlier, the ion composition measurements do not reveal a significant asymmetry at European and Pacific longitudes. This is entirely understandable when we consider that these measurements were made during northern hemisphere summer, when the subsolar point almost coincided with the geomagnetic equator at these longitudes, thus producing

a symmetric wind field in the geomagnetic reference frame.

In the following section we shall quantitatively discuss the wind effects that have so far been described qualitatively.

IONOSPHERE MODEL

The ion composition observations reported here indicate that O^+ and H^+ were the major ionic constituents of the upper ionosphere at the time of the measurement. The distribution of O^+ is controlled by photoionization of O, loss through ion-molecule reactions involving N_2 and O_2, and diffusion of O^+ through O and H^+ with a transport velocity parallel to the magnetic field. The distribution of H^+ is chemically controlled by the charge exchange reaction

$$O^+ + H \rightleftarrows H^+ + O \qquad (2)$$

and by diffusion of H^+ through O^+ with a transport velocity parallel to the magnetic field. Considering these processes we have solved the ion and electron momentum and continuity equations along a field line that intersects the equator at an altitude of 2500 km.

The following boundary conditions were adopted: (1) At low altitudes (well below the F_2-peak for O^+ and well within the charge exchange region for H^+), we assumed that the solutions approach chemical equilibrium; (2) the ion velocities at the equator were determined such that the solutions for the northern and southern hemispheres yielded identical equatorial density values.

The theoretical investigation was performed for noontime and solar equinox conditions at American longitudes, the objective being to demonstrate how the asymmetry in the vertical wind component (with respect to the geomagnetic equator (Figure 3)) causes an asymmetry in the ion composition. As discussed earlier, these effects are dependent on the distance of the subsolar point from the geomagnetic equator; thus, during summer in the northern hemisphere (the time of our observations), the asymmetry at American longitudes would be enhanced relative to the equinox case, while the asymmetry at Pacific and European longitudes would be diminished.

We adopted values of required neutral atmosphere parameters from results of the Geoprobe rocket measurements which were carried out in March, 1966, under solar activity conditions similar to those at the time of the Explorer 32 ion measurements. The N_2 concentration and gas temperature were obtained from Pelz and Newton [1969], while the measurements by Hall et al. [1967] (simultaneous with the Geoprobe flight) provided information on O and O_2. The ion composition measurements by Brinton et al. [1969a] provided the H concentration, which was found to be significantly higher than model values. The loss coefficient for the $(O^+ + N_2)$ reaction was chosen to be 10^{-12} cm^3sec^{-1}, and for the reaction $(O^+ + O_2)$ to be 10^{-11} cm^3sec^{-1}. For incident photons, the ionization probability was assumed to be $6 \times 10^{-7}sec^{-1}$, their attenuation within the thermosphere having been taken into account. The charge transfer coefficient for reaction (2) was assumed to be $5 \times 10^{-12}T_i^{1/2}$ cm^3sec^{-1}. An electron and ion temperature model was adopted which

reflects the typical electron temperature values deduced by Brace et al. [1965]. For the atmospheric wind field we adopted the analytical form (1) which was previously discussed and for which the vertical wind components are shown in Figure 3.

The dashed profiles in Figure 4 are the computed ion composition profiles for northern and southern geomagnetic latitudes, plotted versus height along a field line that intersects the equator at 2500 km. It is apparent from the figure that in the southern hemisphere, where the downward wind component is stronger (see Figure 3), the O^+ concentration is significantly lower than it is in the northern hemisphere. As shown in the figure, this decrease results from both a relative decrease in F_2-maximum density and height, and a decrease in the O^+ scale height immediately above the F_2-peak. The dashed profiles, which describe quite properly the wind effects on the O^+ distribution, were derived under the assumption that ion fluxes at the equator from one hemisphere to the other are zero, thus prohibiting any interhemispheric ionization exchange. One implication of this artificial constraint is that the protonosphere is forced into a static state, and as a consequence the O^+-H^+ transition level occurs at almost the same altitude in both hemispheres, even though the O^+ distributions are distinctly different. This result is quite plausible when we consider that charge exchange equilibrium for H^+, which holds below the transition level, tends to fix the transition level as long as dynamic effects are insignificant. It is obvious from Figure 4 that the zero flux assumption is, of course,

entirely unrealistic, since both O^+ and H^+ are discontinuous at the equator, with higher concentrations in the northern hemisphere.

When our calculations are modified to consider ion fluxes across the equator from the northern to the southern hemisphere, such that the ion concentrations become continuous at the equator, the distributions indicated by the solid lines in Figure 4 result. Evidently, this interhemispheric coupling does not significantly affect the O^+ layer at lower altitudes, an understandable result when we consider that the critical flux for O^+ is an order of magnitude larger than the critical flux for protons. It is H^+, then, which contributes primarily to the ionization transport across the equator. The chief result of this proton transport is that the O^+-H^+ transition level is raised in the northern hemisphere due to an upward flux of H^+, and the level is lowered in the southern hemisphere due to a downward flux of protons. The combined effect is that the altitude of the transition level is significantly different in the two hemispheres (about 600 km higher in the northern hemisphere), which is quantitatively in fairly good agreement with the observed ion composition at American longitudes described earlier in this paper.

An additional feature of our composition model should be noted. Although there is no significant asymmetry apparent in the protonosphere (consistent with our observations), at lower altitudes the H^+ concentration is considerably lower in the northern hemisphere than in the southern hemisphere, whereas the O^+ density is much higher in the northern hemisphere than in the southern. This opposite trend in O^+ and H^+ is a

direct consequence of the dynamic state of this region and it emphasizes the complexity of the wind effects.

Figure 5 summarizes in schematic form the mechanisms by which the neutral wind interaction affects ionospheric composition. Horizontal atmospheric winds blow away from the subsolar point, which, for equinox conditions and American longitudes, does not coincide with the geomagnetic equator. The downward wind component is larger at southern than at northern magnetic latitudes, and as a consequence, the altitude of the O^+ layer is reduced at southern latitudes, where its density is decreased due to the enhanced recombination rate at lower altitudes. This represents an ion sink in the southern hemisphere which draws ionization across the equator in the form of proton fluxes tending to restore symmetry to the H^+ distribution in the protonosphere. As a consequence an asymmetry is produced in the O^+-H^+ transition level, which is consistent with our observations.

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We are very indebted to Professor H. Volland for valuable discussion concerning the atmospheric wind field.

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FIGURE CAPTIONS

FIGURE 1: Observed variation of O^+-H^+ transition level altitude. The solid points were derived from ion distributions measured at European and Pacific longitudes, while the open points are based on data obtained at American longitudes. The longitudinal variation is attributed to the effect of atmospheric winds on the ion distributions.

FIGURE 2: Global variation of magnetic field dip angle at 1000 km altitude. The southward shift of the isoclines at American longitudes contrasts with the uniform northward shift at European and Pacific longitudes.

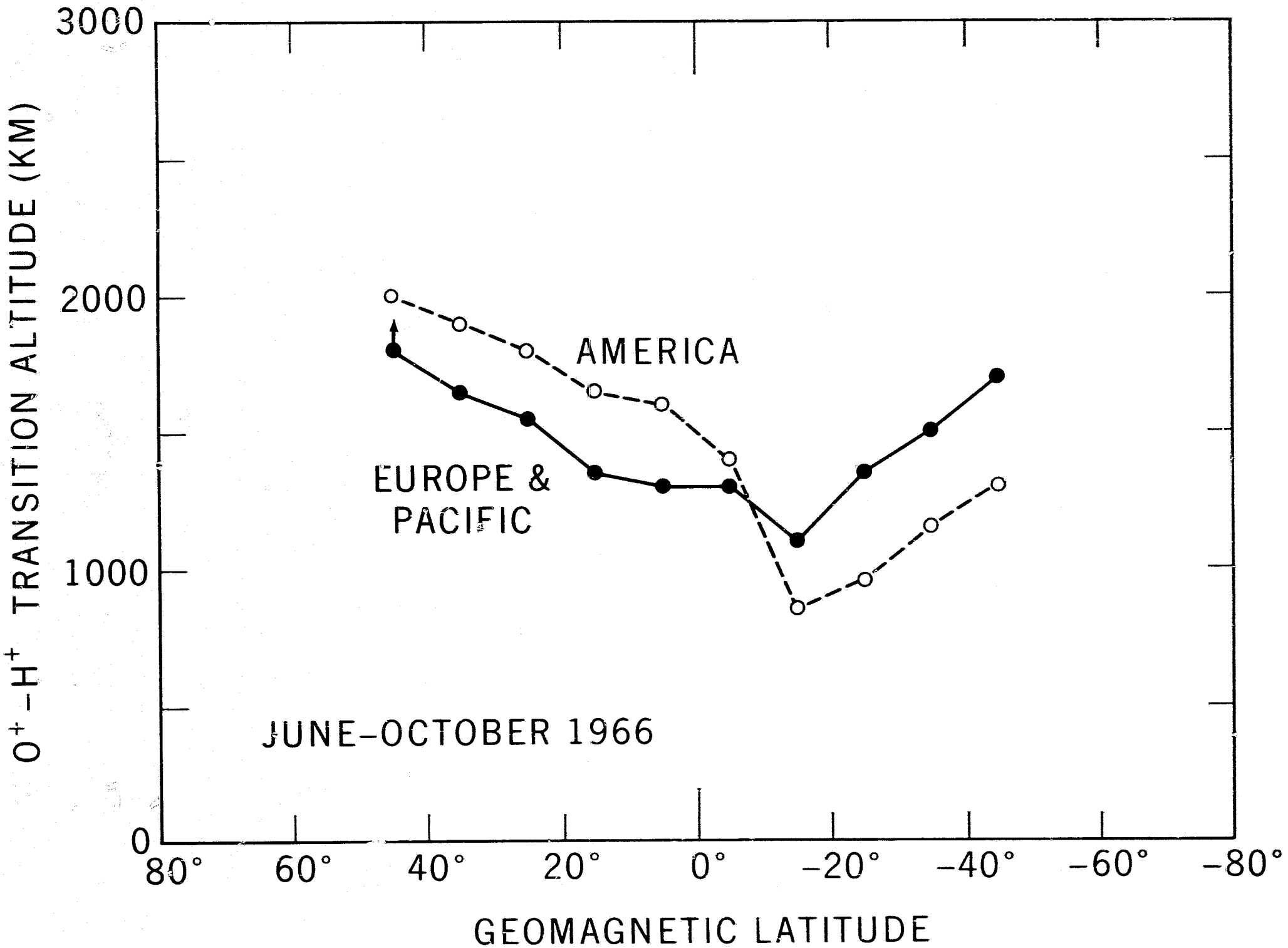
FIGURE 3: The vertical wind component $u_\perp$ for noontime equinox conditions for American and European (Pacific) longitudes. It was derived from the horizontal wind field described in equation (1) [Volland and Mayr, 1969].

FIGURE 4: Computed distributions of O^+ and H^+ along a field line which intersects the equator at 2500 km, for American longitudes. The wind field shown in Figure 3 is employed. Dashed lines indicate the distributions in which ionization transport between the two hemispheres was artificially suppressed. The solid lines describe the ion composition derived by considering interhemispheric flow of ionization, required to satisfy the boundary condition of continuous ion distributions across

the equator.

FIGURE 5: Schematic representation of the effects of ion-wind interaction. Horizontal arrows pointing away from the subsolar point indicate the wind velocity, which increases toward higher latitudes; wind components parallel to magnetic field lines are asymmetric in the magnetic coordinate system. The ion structure is illustrated by lines of constant density whose thickness decreases with decreasing concentrations. The larger downward wind in the southern hemisphere produces an asymmetry in the O^+ distribution. Coupled to and floating on the O^+ layer is the protonosphere, in which H^+ fluxes tend to compensate the wind effect and thus maintain near-symmetry in the proton concentrations about the equator. As a result, a pronounced asymmetry develops in the O^+-H^+ transition level, in agreement with our observations.

FIGURE 1


3000
2000
1000
0
O^+–H^+ TRANSITION ALTITUDE (KM)
AMERICA
EUROPE &
PACIFIC
JUNE–OCTOBER 1966
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40°
20°
0°
–20°
–40°
–60°
–80°
GEOMAGNETIC LATITUDE

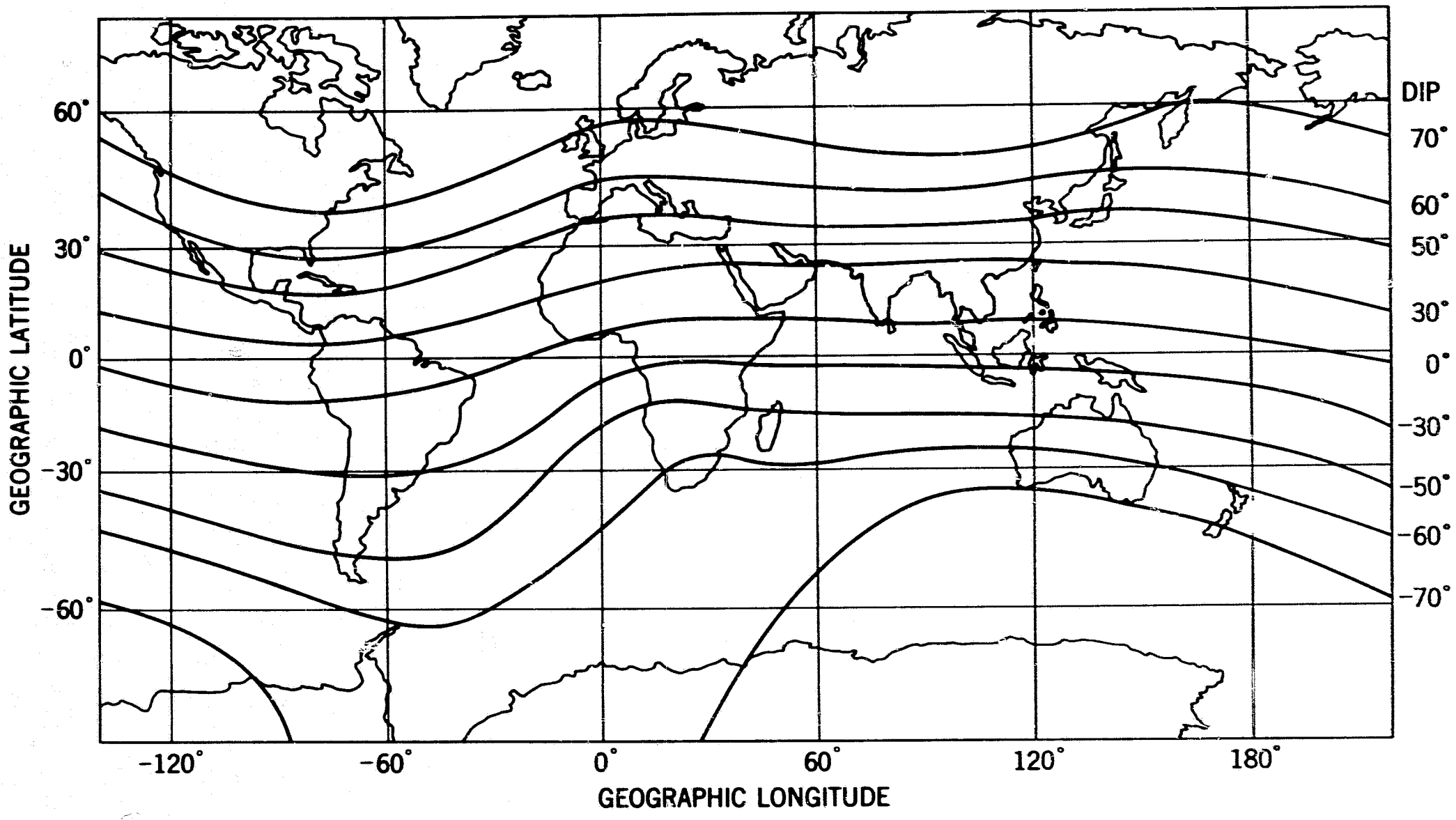
60°
30°
0°
-30°
-60°
GEOGRAPHIC LATITUDE
DIP
70°
60°
50°
30°
0°
-30°
-50°
-60°
-70°
-120°
-60°
0°
60°
120°
180°
GEOGRAPHIC LONGITUDE

FIGURE 2

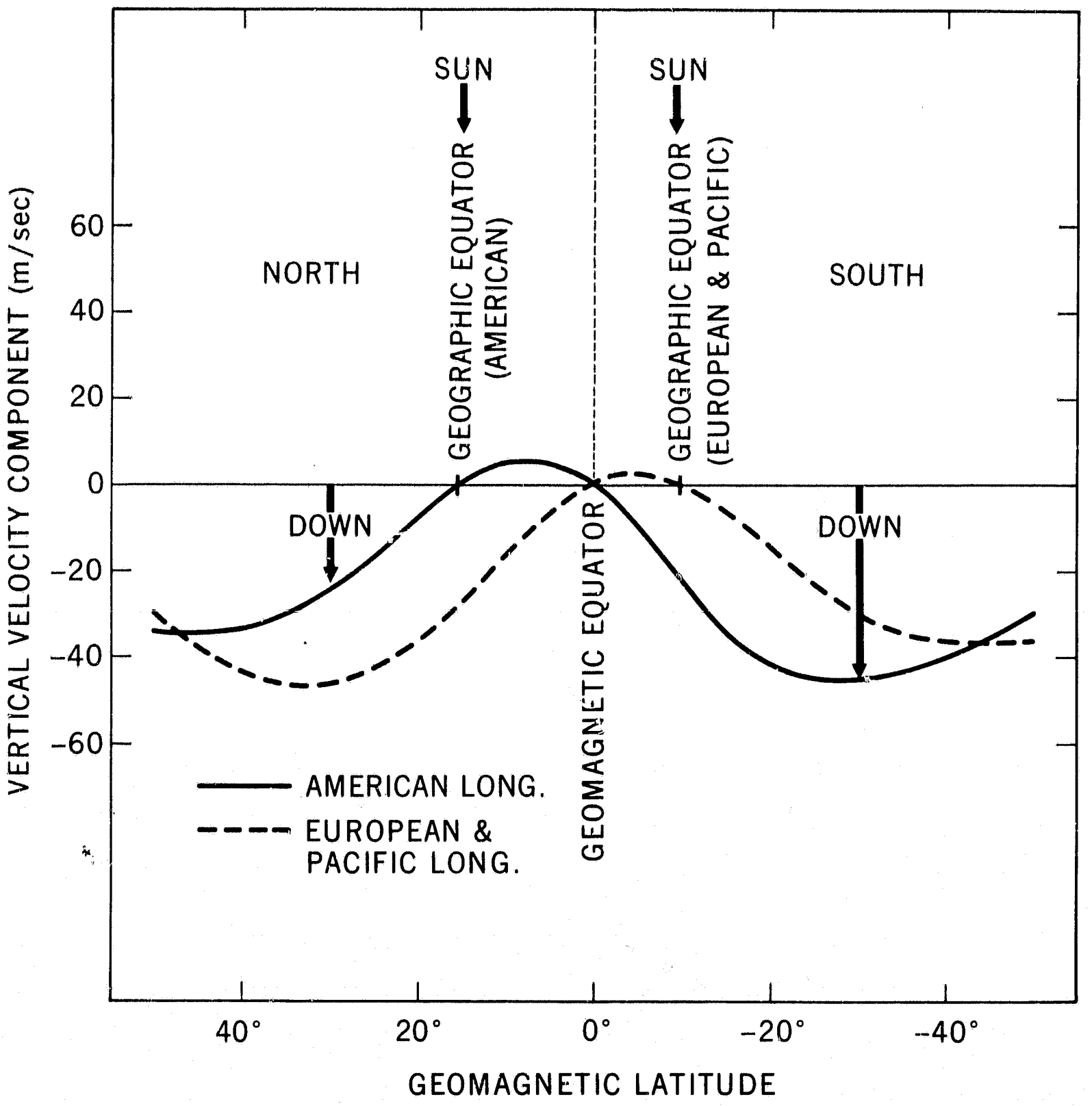
VERTICAL VELOCITY COMPONENT (m/sec)
60
40
20
0
-20
-40
-60
NORTH
SOUTH
SUN
SUN
GEOGRAPHIC EQUATOR
(AMERICAN)
GEOGRAPHIC EQUATOR
(EUROPEAN & PACIFIC)
DOWN
DOWN
GEOMAGNETIC EQUATOR
AMERICAN LONG.
EUROPEAN &
PACIFIC LONG.
40°
20°
0°
-20°
-40°
GEOMAGNETIC LATITUDE

FIGURE 3

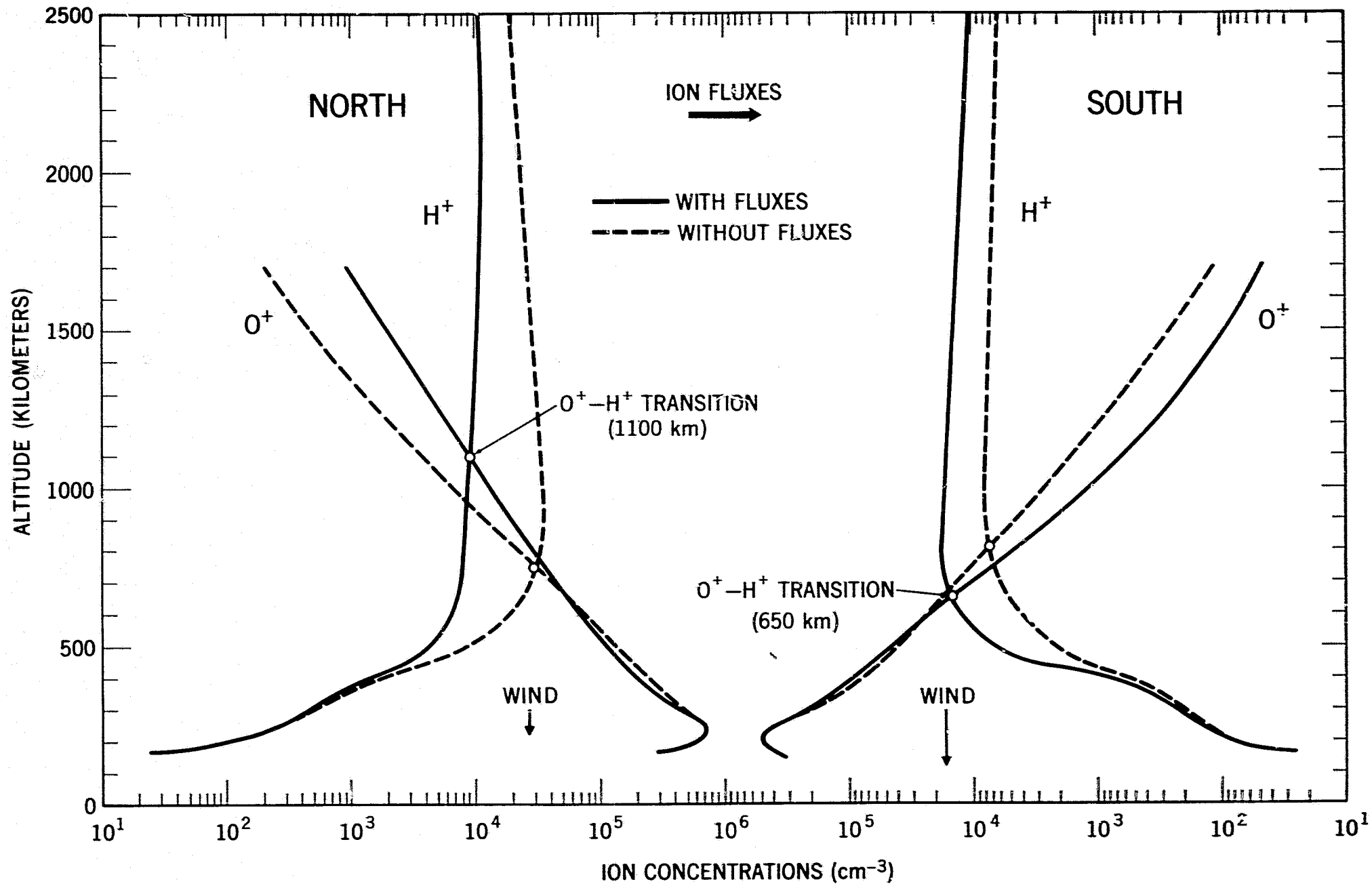
NORTH
SOUTH
ION FLUXES
WITH FLUXES
WITHOUT FLUXES
H+
O+
O+–H+ TRANSITION
(1100 km)
O+–H+ TRANSITION
(650 km)
WIND
WIND
ALTITUDE (KILOMETERS)
2500
2000
1500
1000
500
0
10^1
10^2
10^3
10^4
10^5
10^6
10^5
10^4
10^3
10^2
10^1
ION CONCENTRATIONS (cm^-3)

FIGURE 4

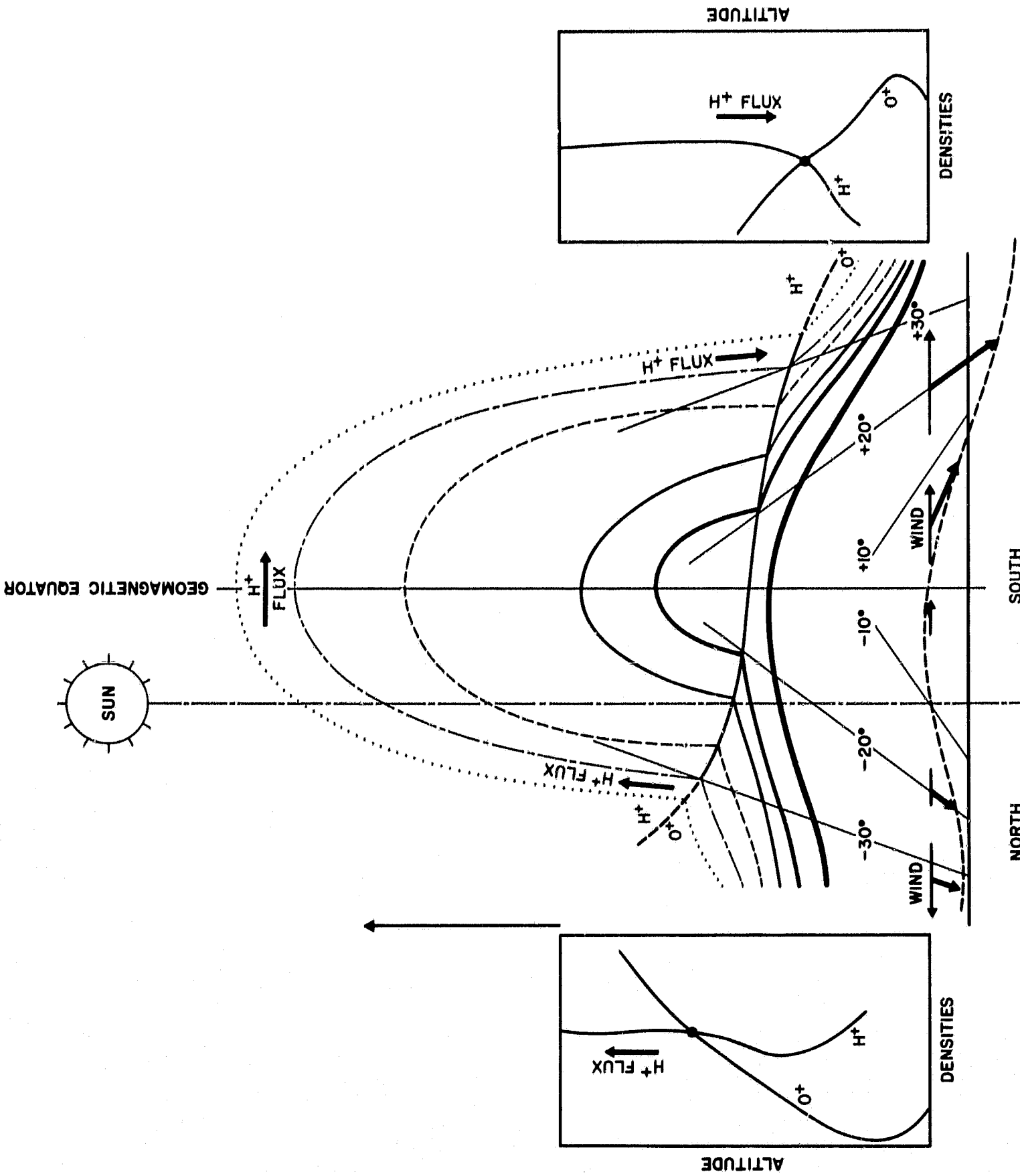
ALTITUDE
H+ FLUX
O+
H+
DENSITIES
O+
H+
H+ FLUX
+30°
+20°
+10°
WIND
SOUTH
GEOMAGNETIC EQUATOR
H+ FLUX
SUN
H+ FLUX
H+
O+
-10°
-20°
-30°
WIND
NORTH
H+ FLUX
H+
O+
DENSITIES
ALTITUDE

FIGURE 5