JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. A9, PAGES 7495–7508, SEPTEMBER 1, 1984

Ion-Neutral Coupling in the High-Latitude *F* Region: Evaluation of Ion Heating Terms From Dynamics Explorer 2

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We study a set of south (summer) polar passes from the Dynamics Explorer 2 data base that provide measurements of ion and neutral velocities along the track of the spacecraft for various geomagnetic conditions. The ion velocities are obtained from the ion drift meter and the retarding potential analyzer instruments; the neutral velocities are obtained from the Fabry-Perot interferometer and the wind and temperature spectrometer instruments. These data enable a direct determination of the in situ ion-neutral difference velocity. Simultaneous measurements of atmospheric composition using the neutral atmosphere composition spectrometer and of electron temperatures and densities using the Langmuir probe enable the ion heating and cooling rates to be determined. The rates are discussed in relationship to values for the electron, ion, and neutral kinetic temperatures. The comprehensive nature of the data set allows for a quantitative study of ion-neutral coupling and, in particular, affords a more rigorous test of the common assumptions used in the ion energy equation than has been previously possible. From our study we find the following: (1) The ion-neutral difference velocities, which drive the Joule heating, have a complex morphology that depends on the stability of the high-latitude ion convection and the inertia of the neutral gas. (2) Ionospheric "hot spots" are observed to be related to large perpendicular electric fields that give rise to frictional (Joule) heating. (3) These events are often seen to occur in conjunction with troughs in the electron density and with decreases in the ratio of atomic oxygen to molecular nitrogen. In such cases, momentum transfer to the neutral gas is reduced, and the ion-neutral velocity difference and associated Joule heating can be maintained over longer time periods. (4) An approximate balance between local frictional heating of the ions and local cooling of the ions to the neutrals is seen in regions of strong ion convection. The commonly used approximate form of the ion energy equation involving only local processes appears at times, however, to be inadequate for large regions of the summer polar cap. The ion temperatures observed in these regions are higher than expected from simple local heating/local cooling arguments. Additional source(s) of ion heating would be required to provide energy balance.

1. INTRODUCTION

The interaction between the ionospheric plasma and the neutral atmosphere at high latitudes is known to be complex, and sophisticated large-scale numerical models have been developed to enable better understanding of the energy and momentum transfer processes involved. Three-dimensional, time-dependent models of the thermosphere [*Fuller-Rowell and Rees*, 1980; *Dickinson et al.*, 1981] are now available that solve the coupled energy and momentum equations for the neutral species based on empirical and semiempirical inputs describing the ionospheric composition and dynamics. These models have been used to examine the predicted behavior of the neutral thermosphere for various different geophysical situations [*Roble et al.*, 1982, 1983, 1984; *Fuller-Rowell and Rees*, 1981; *Fuller-Rowell et al.*, 1984; *Rees et al.*, 1980, 1983; *Killeen and Roble*, 1984]. In addition, extensive theoretical studies of the convecting high-latitude ionosphere have been performed [*Schunk and Raitt*, 1980; *Sojka et al.*, 1981, 1982; *Quegan et al.*, 1982] using models that incorporate many chemical and transport processes and that are based on experimental evidence [e.g., *Heppner*, 1977; *Volland*, 1978; *Heelis and Hanson*, 1980; *Heelis et al.*, 1982] concerning the ion convective flow.

These and other studies have shown that the global *F* region neutral wind circulation is driven by a combination of pressure gradient forces set up by local and global heating and drag forces produced by momentum transfer collisions between the ions and the neutral gas. At high latitudes the ion drag force is of primary importance, as has been illustrated by numerous experimental investigations of the neutral winds [*Rees*, 1973; *Meriwether et al.*, 1973; *Nagy et al.*, 1974; *Kelley et al.*, 1977; *Rees et al.*, 1980; *Spencer et al.*, 1982; *Mikkelsen et al.*, 1981; *Killeen et al.*, 1982, 1983, 1984; *Hays et al.*, 1979, 1984]. One significant difficulty in the study of ion-neutral coupling at high latitudes has been the paucity of direct, simultaneous measurements of ion and neutral velocities. Such data are required to assess the frictional (Joule) heating rate to the thermosphere, which varies with the square of the difference velocity, as well as the direct, collisional exchange of momentum between the ions and neutrals (ion drag). A realistic parameterization of the ion-neutral coupling is needed for the large numerical models since, to a significant degree, this coupling controls the global energy budget of the thermosphere as well as the dynamical processes that redistribute the energy.

Paper number 4A0682.
0148-0227/84/004A-0682$05.00

Direct measurements of ion and neutral velocities have been made previously using barium and strontium chemical release rocket experiments [*Haerendel et al.*, 1967; *Meriwether et al.*, 1973; *Kelley et al.*, 1977; *Heppner and Miller*, 1982]. These data, although necessarily limited in scope, have illustrated directly the strong ion-neutral coupling present at high latitudes. Another source of such data has been from joint observations using ground-based Fabry-Perot interferometers and incoherent scatter radar facilities [*Nagy et al.*, 1974; *Hays et al.*, 1979; *Burnside et al.*, 1983; *Rees et al.*, 1984; V. B. Wickwar et al., unpublished manuscript, 1984]. These powerful techniques have proved useful in illustrating long-term trends in the response of the nighttime neutral winds to forcing by the convecting ions. They have been less useful, however, in defining the details of the relative ion-neutral motion for more limited periods of time and more local regions of space.

Other, indirect techniques have been develped that use incoherent scatter radar data to infer the neutral winds and temperatures [*Bauer et al.*, 1970; *Roble et al.*, 1974; *Salah and Holt*, 1974; *Emery*, 1978; *Alcaydé et al.*, 1983; *Baron and Wand*, 1983]. The indirect methods have been successful in providing important information on wind fields and Joule heating rates, but they have had to rely on largely untested assumptions concerning the validity of the approximations in the theory used to relate the ionospheric measurements to inferred neutral atmospheric behavior. A similar situation exists for the analysis of satellite data from Atmosphere Explorer [*St.-Maurice and Hanson*, 1982, 1983] where full vector neutral wind measurements have not been available.

The need for high-resolution (both temporal and spatial) measurements of simultaneous ion and neutral velocities follows from a consideration of the time scales for (1) the ionospheric response to magnetospheric forcing and (2) the response of the neutral atmosphere to forcing by the convecting ions. The "classical" patterns of high-latitude ion convection [*Heppner*, 1977; *Volland*, 1978, 1979; *Heelis et al.*, 1982] involving two polar vortices are known to be only "representative" or average depictions of the real ion drifts in the *F* region. Satellite measurements show that the ion drifts covary with the rapid fluctuations of the magnetospheric dynamo electric fields. While the response of the ions to imposed electric fields is near instantaneous, the transfer of momentum to the more numerous neutrals is much slower with time constants being measured in tens or even hundreds of minutes depending on the local ion density. The neutrals therefore tend to filter out the high spatial and temporal frequencies present in the ion motion at high latitudes. The degree of filtering of the input "spectrum" of ion velocities due to the inertia of the neutral gas, in large part, determines the morphology of Joule heating.

The data from the Dynamics Explorer satellite [*Hoffman et al.*, 1981] enable a significant improvement in the experimental description of high-latitude ion-neutral coupling. The instrument complement of the low-altitude, polar-orbiting Dynamics Explorer 2 (DE 2) spacecraft is unique in that full vector measurements of the velocities of both the ionic and neutral components of the upper atmosphere are possible. The Fabry-Perot interferometer (FPI) [*Hays et al.*, 1981] measures the meridional component of the neutral wind, and the wind and temperature spectrometer (WATS) [*Spencer et al.*, 1981] measures the zonal component. The ion velocity measurements are made by the ion drift meter (IDM) [*Heelis et al.*, 1981] and the retarding potential analyzer (RPA) [*Hanson et al.*, 1981], which give the zonal and meridional components, respectively. In addition to the direct measurements of dynamics the neutral constituent abundances are monitored using the neutral atmosphere composition spectrometer (NACS) [*Carignan et al.*, 1981], and the electron temperatures and densities are monitored using the Langmuir probe (LANG) [*Krehbiel et al.*, 1981]. The comprehensive set of measurements provides, for the first time on a global basis, direct information on the detailed dynamical coupling between the neutral atmosphere and the ionospheric plasma at *F* region altitudes. This paper presents first results from a study of the simultaneous ion and neutral motions in the high-latitude thermosphere using measurements from Dynamics Explorer.

A total of six passes of DE 2 over the southern hemisphere polar cap from October 1981 have been selected from a larger data base to illustrate different features of the coupling for conditions of high ion density (sunlit pole). We discuss the measured ion-neutral difference velocities using all other relevant observables from DE 2 with two main objectives: first, to show the variety of coupling regimes that can exist and the consequences on the neutral atmospheric composition, dynamics, and thermodynamics and, second, to study the validity of the commonly used approximation to the ion energy balance equation through an evaluation of individual ion heating and cooling terms.

In section 2 we present the theoretical background for the ion energy balance problem and define a time constant for the ion-neutral momentum exchange process that will be used as a quantitative measure of the strength of the coupling. In section 3 we present the satellite observations. In section 4 we relate the in situ Joule heating measurements to the observed neutral atmospheric response and discuss the morphology of *F* region Joule heating. In section 5 we discuss the ion energy balance for all passes studied, giving particular attention to orbit 1174. Finally, in section 6 we summarize our findings.

2. THEORETICAL BACKGROUND

Ion Energy Balance Equation

The general form of the equation governing the exchange of energy between *F* region ions and the other atmospheric constituents is given by [e.g., *Banks and Kockarts*, 1973; *Schunk*, 1977; *Banks*, 1980; *St.-Maurice and Hanson*, 1982]

$$\frac{D}{Dt}(\tfrac{3}{2}p_i) + \tfrac{5}{2}p_i(\nabla \cdot \mathbf{v}_i) + \nabla \cdot \mathbf{q}_i + \mathbf{P}_i : \nabla \mathbf{v}_i = \sum_{j=1}^{N} \frac{n_i m_i \nu_{ij}}{(m_i + m_j)} [3k(T_j - T_i)\Psi_{ij} + m_j(\mathbf{v}_i - \mathbf{v}_j)^2 \Phi_{ij}] \quad (1)$$

Here D/Dt is the total time derivative, $[(\partial/\partial t) + \mathbf{v}_i \cdot \nabla]$, including the advective derivative; p_i is the ion gas kinetic pressure for the *i*th ionic constituent, $p_i = n_i k T_i$; $\mathbf{v}_i$ is the ion velocity vector; $\mathbf{q}_i$ is the heat flux vector; $\mathbf{P}_i$ is the ion stress tensor; n_i is the ion number density; m_i and m_j are the masses of the *i*th ionic and *j*th atmospheric constituents, respectively; ν_{ij} is the collision frequency for momentum transfer from the *i*th to the *j*th constituent; k is Boltzmann's constant; T_i and T_j are kinetic temperatures; and Ψ_{ij} and Φ_{ij} are correction factors given by the velocity dependence of the collisional cross sections used [e.g., *Banks and Kockarts*, 1973; *Schunk*, 1975]. For a polarization collision model these factors are both equal to unity. The terms on the left-hand side of equation (1) are (1) the total time derivative including advective processes, (2) the divergence of the ion velocity, (3) heat conduction, and (4) viscous heating. The right-hand side of equation (1) represents a summation of the effects of frictional heating (proportional to $(\mathbf{v}_i - \mathbf{v}_j)^2$) and collisional heat transfer (proportional to $(T_i - T_j)$) over all N atmospheric constituents.

Approximations

In studies of F region ion temperatures an approximation to (1) is generally used in which all terms on the left-hand side of the equation are neglected. The reasons for this have been reviewed by *Schunk* [1977] and, more recently, by *St.-Maurice and Hanson* [1982], and here we will only briefly mention the more significant assumptions made. First, the term involving the total derivative is assumed to be small, since the effects due to the partial $\partial/\partial t$ can be neglected for events occuring on time scales longer than $1/\nu_{ij}$ (approximately seconds at the altitude of interest). The advective derivative is more problematical, but recent theoretical studies of the ion energy balance by *Schunk and Sojka* [1982] have indicated that heat advection and heat conduction both have small effects on the energy balance below ~400 km for the wide range of geophysical conditions considered in their work. The divergence of $\mathbf{v}_i$ is neglected, since the ion gas is essentially incompressible [*Rishbeth and Hanson*, 1974]. The viscous heating term is expected, from theoretical considerations, to be small for spatial lengths greater than $(\mathbf{v}_i - \mathbf{v}_j)/\nu_{ij}$ (approximately a few kilometers in the F region) [*Schunk*, 1975].

In addition, the summation appearing on the right-hand side of (1) is usually evaluated assuming that the neutral atmospheric composition is dominated by a single species (atomic oxygen). Similarly, the ion composition is assumed to be dominated by O^+. Heat exchange between the ions and electrons is sometimes also neglected but will be included in the level of approximation tested in this work since it can be determined quantitatively using the DE 2 measurements.

With the above assumptions, the ion energy balance equation may be written (following *St.-Maurice and Hanson* [1982]) as

$$(\mathbf{v}_i - \mathbf{v}_n)^2 = \frac{\Psi_{in}}{\Phi_{in}} \frac{3k}{m_n} (T_i - T_{eq}) \tag{2}$$

where

$$T_{eq} = T_n + (T_e - T_n) \frac{\nu_{ie}}{\nu_{in}} \left(\frac{(m_i + m_n)}{m_i \Psi_{in}} \right) \tag{3}$$

Here the subscripts n and e refer to the neutral species (atomic oxygen) and electrons, respectively, and the further assumption has been made that there is no frictional heat exchange between the ion and electron gases since large differences in $\mathbf{v}_i$ and $\mathbf{v}_e$ are unlikely to exist perpendicular to the magnetic field. Equations (2) and (3) can be most simply written as

$$Q_{ei} = Q_{in} \tag{4}$$

with

$$Q_{ei} = 3kn_i\nu_{ei}(T_e - T_i) \tag{5}$$

$$Q_{in} = \frac{n_e}{2} \nu_{in}[3k(T_i - T_n) - m_n(\mathbf{v}_i - \mathbf{v}_n)^2] \tag{6}$$

This is the form used by *Bauer et al.* [1970] and *Alcaydé et al.* [1983] in their studies using incoherent scatter ion temperature measurements to infer neutral temperatures. In the derivation of (4), Ψ_{in} and Φ_{in} have both been set to unity, implying use of a polarization collision cross section with no velocity dependence. Alternatively, (4) may be solved for the ion temperature T_i,

$$T_i = T_n\left(\frac{\nu_{in}}{\nu_{in} + \nu_{ie}}\right) + T_e\left(\frac{2\nu_{ie}}{\nu_{in} + \nu_{ie}}\right) + \frac{\nu_{in} m_O}{3k(\nu_{in} + \nu_{ie})} (\mathbf{v}_i - \mathbf{v}_n)^2 \tag{7}$$

TABLE 1. Assumptions Used in the Ion Energy Balance Equation

Term	Approximation	Comments
$\mathbf{P}_i : \nabla \mathbf{v}_i$	neglected	Viscous heating small for scale lengths greater than $(\mathbf{v}_i - \mathbf{v}_n)/\nu_{in}$ (few kilometers).
$\partial/\partial T$	neglected	For events occurring on time scales $> 1/\nu_{in}$ ($\simeq$ few seconds).
$\nabla \cdot \mathbf{v}_i$	neglected	Ion motion incompressible.
$\mathbf{v}_i \cdot \nabla p_i$	neglected	Small below 400–500 km on the basis of theoretical modeling of high-latitude ionosphere [*Schunk and Sojka*, 1982].
$\nabla \cdot \mathbf{q}_i$	neglected	Same as for $\mathbf{v}_i \cdot \nabla p_i$, above.
$(\mathbf{v}_i - \mathbf{v}_e)^2$	neglected	Ion-electron relative drift perpendicular to field lines small.
i	$= O^+$	Sole ion at F region altitude.
j	$=$ O, e	Neutral atmosphere dominated by neutral O; electron-ion frictional heating considered.
Ψ, Φ	= unity	Reasonable for small relative ion-neutral drifts. True for a polarization collision model.

Table 1 lists the assumptions used to simplify the ion energy balance equation at F region altitude. We note that certain geophysical measurements previously reported, e.g., neutral temperatures measured using incoherent scatter radar data, are dependent on the validity of (4). Since the parameters T_i, T_e, T_n, n_O, n_{N_2}, n_i $(= n_e)$, $\mathbf{v}_i$, and $\mathbf{v}_n$ are all measured by instruments on DE 2, both sides of (4) can be independently assessed to test the validity of the approximations inherent in its usage. In fact, the satellite measurements provide a near-ideal data set to test these assumptions, since the measurements are made rapidly enough to define finer details of the ion-neutral coupling than would be resolvable from the ground. Also, there are fewer problems with fields of view or uncertainties in the altitude of the measurements than would pertain to a ground-based study.

Ion-Neutral Coupling Time Constant

The equation governing the exchange of momentum between the ion and neutral populations has been given in full by *Dickinson et al.* [1981] as well as by others. Recently, in a theoretical study using the National Center for Atmospheric Research thermospheric general circulation model, *Killeen and Roble* [1984] have shown that the ion drag term in the momentum equation is often dominant for typical forcing conditions in the summer polar F region. If other terms (i.e., Coriolis, pressure gradient, and momentum advection) can be neglected, the momentum equation is simply

$$\frac{\partial \mathbf{v}_n}{\partial t} = \frac{n_i}{n_n} \nu_{in}(\mathbf{v}_i - \mathbf{v}_n) \tag{8}$$

From this expression a time constant τ_{ni} may be defined that describes the e-folding time taken for the velocity of the neutral gas to approach the velocity of the ions following an instantaneous change in the ion drift; τ_{ni} may be written [*Baron and Wand*, 1983]

$$\tau_{ni} = \frac{n_n}{n_i \nu_{in}} \tag{9}$$

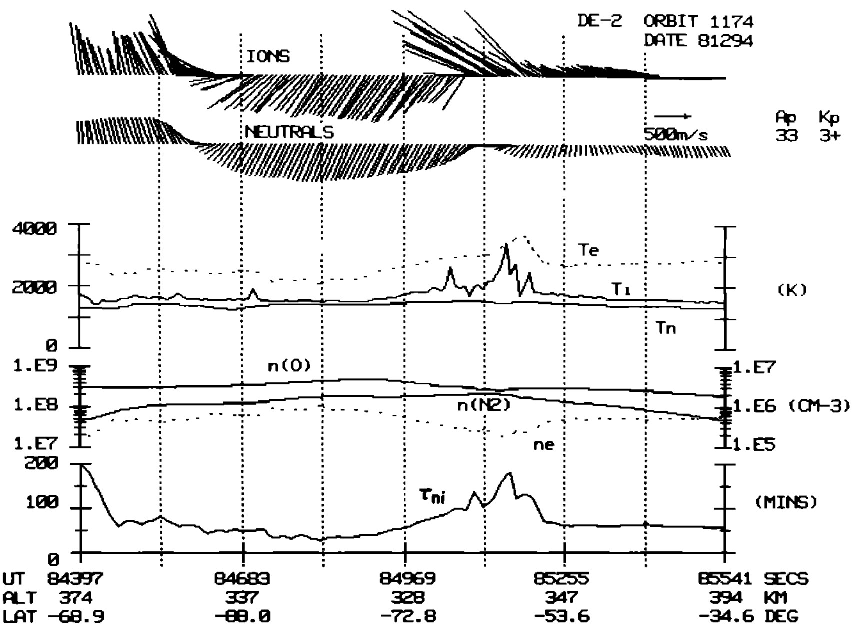

Fig. 1. Geophysical observables measured along the track of Dynamics Explorer 2 during orbit 1174. The ion drifts and the neutral winds are shown in the top two traces plotted against time, altitude, and latitude of the spacecraft. The second panel shows the electron ion and neutral temperatures measured along the track, and the third panel shows the atomic oxygen and molecular nitrogen number densities (left-hand scale) and the electron density (right-hand scale). The bottom trace shows the ion-neutral coupling time constant measured along the track (see text).

We calculate τ_{ni} along the track of DE 2 to provide a quantitative measure of the tightness of the ion-neutral coupling. Since ν_{in} is directly proportional to n_n, the time constant τ_{ni} is essentially inversely proportional to the electron (ion) density.

We note here that a more rigorous definition of the ion-neutral momentum transfer time constant would require consideration of the viscous forcing time scale corresponding to the diffusion of momentum through the neutral gas. The "viscous" coupling between the ions and neutrals might be expected to maximize near sharp temporal or spatial boundaries in the ion flow where large second derivatives in the neutral velocity field can result [*St.-Maurice and Schunk*, 1981; *Fuller-Rowell*, 1984]. Since such viscous forcing effects are likely to have relatively short scale lengths and since the appropriate second derivatives are difficult to estimate experimentally, we neglect such effects in our simple calculation for the ion-neutral time constants.

In all calculations involving collision frequencies we have adopted the formulae presented in a recent review by *Schunk and Nagy* [1980] and have used measured values for the relevant number densities.

3. OBSERVATIONS

Simultaneous measurements of ion and neutral velocities from six south polar passes of DE 2 during October 1981 are shown in Plate 1. The passes selected were centered near perigee to afford best coverage for the neutral atmosphere measurements. The neutral winds are measured by appropriately merging the meridional wind component measurements obtained by the FPI with the zonal wind component measured by the WATS. The data handling technique for this merging has been discussed in detail by *Killeen et al.* [1982]. We note that the spatial resolution (i.e, latitudinal resolution) is different for these two instruments since the FPI is a limb-scanning, remote sensing device while the WATS is an in situ sensor. Because of the lower spatial resolution of the FPI (approximately 2°–4° of latitude), fewer neutral wind vectors are plotted in Plate 1 than ion drift vectors. The ion drifts are measured using the RPA and IDM instruments, which are both in situ sensors. The electron and ion temperatures are measured by the LANG and the RPA, respectively. The neutral temperatures are measured by the FPI using the Doppler width of the 6300-Å emission feature. The FPI temperatures used are averages for data samples taken at tangent point altitudes (along the line of sight of the instrument) between 200 and 400 km. Each FPI temperature data point is adjusted up to an exospheric value using a simple Bates model (S parameter = 0.02 km^{-1}). The average exospheric neutral temperatures so obtained are then shifted in time to match the data from the in situ instruments, as are the meridional wind measurements [*Killeen et al.*, 1982]. The NACS instrument is used to provide O and N_2 abundances along the track of DE 2. The electron (ion) densities are obtained from the LANG instrument.

The ion and neutral velocity vectors in Plate 1 are coded by red bars and yellow arrows, respectively, and are plotted in geographic polar coordinates (latitude and local solar time). All six passes correspond to segments of the DE 2 orbit near perigee, and the altitudes sampled range between 300 and 360 km. The solar terminator is denoted by the curved shaded line, and the location of the invariant pole is given by the symbol S for each pass. Plates 1*a* and 1*b* for orbits 1174 and 1187, respectively, show data near the same UT (~2100 hours) but separated by one day. For both cases, the invariant pole is situated on the dawnside of the geographic pole, and the measured ion drifts show a classical form with steady antisolar flow over the geomagnetic polar cap bounded on both the dawnside and the duskside by more local regions of sunward flow. For orbit 1174 the ion drift velocities on the dawnside are the stronger, being in excess of 1000 m s^{-1} in a narrow convection channel. The situation is reversed for orbit 1187, where the dusk, sunward ion drift velocities are the stronger.

The response of the neutral gas to the changes in ion flow direction is also shown in Plate 1 (yellow arrows). For orbit 1174 the neutral wind vectors show a flow pattern similar to that of the ions as the neutral gas follows with remarkable fidelity the ion flow reversal near the dusk boundary of the polar cap. Indeed, the neutral and ion vectors show near agreement in both magnitude and direction throughout the dusk auroral zone and polar cap regions. In sharp contrast to this behavior are the large difference velocities observed in the dawn convection channel and, to a lesser extent, in the mid-latitude, midmorning sector where the neutral winds moderate in response to the sunward ion flow but do not acquire the full ion velocity. The significance of the large difference velocities in the dawn convection channel is discussed in greater detail below. For orbit 1187 the neutrals also follow the basic ion convection pattern with generally smaller magnitudes. For this orbit, the largest difference velocities occur on the duskside of the polar cap, and the neutral velocity moderation due to the sunward convecting ions on the morningside is less pronounced than for orbit 1174.

Plates 1*c* and 1*d* show two passes separated by 3 hours. For these orbits, 1161 and 1163, respectively, the invariant pole was situated on the dayside of the geographic south pole. In both cases the neutral wind pattern is similar, with a high-speed region of antisunward neutral flow over the polar cap, a well-defined reversal to sunward flow in the morning sector, and a less smooth and well-defined reversal on the eveningside near the solar terminator. The pattern of ion convection for these two closely spaced passes is, however, dramatically different. The ion drifts measured during orbit 1161 show a similar form to those for orbit 1174. The drifts for orbit 1163, by contrast, show no well-structured antisolar flow region over the polar cap but generally exhibit a larger degree of turbulent flow throughout the polar regions. In these two passes, therefore, we have an interesting case study of a situation where a substantial change in the ion convection pattern has occurred over a time scale that is of the order of the ion-neutral momentum exchange time constant, τ_{ni}. The similarity of the neutral flow associated with two quite different ion drift flows is a good illustration of the filtering effect of the neutral thermosphere due to the long time constants involved in the transfer of momentum between the ionized and neutral constituents (see below). In the case of orbit 1163, the direction of the neutral flow is clearly not determined by the instantaneous forcing observed at the time of the satellite pass but rather is determined by the time history of the ion drag forcing over a period of many minutes preceding the pass. The inertial continuation of the neutral gas flow during periods of varying ion drifts has important consequences on the structure of *F* region Joule heating as evidenced by the observed enhancements in the ion temperatures (see next section).

In Plate 1*e* we show data from an orbit that passed near the cusp region on the dayside of the magnetic polar cap. For this pass, orbit 1200, there is evident a turning of both neutral and ion flows from the sunward direction as the satellite "skims" the cusp region near the geographic pole. Away from the convection-dominated region at mid-latitudes near 0900 LST, both ion and neutral wind speeds abate. The largest difference velocities occur in the duskside sunward flow region and in the region of the rotational reversal associated with the cusp. As for several of the other passes shown, the remnant, antisunward neutral flow at mid-latitudes on the morningside is consistent with the global wind system set up by solar UV and EUV heating of the thermosphere.

To provide a contrast to the coupling regimes discussed above which correspond to passes occurring during relatively active geomagnetic conditions (see *Ap* and *Kp* values in Plate 1), we show in Plate 1*f* observations made during a period of very low magnetic activity ($Kp = 2-$, $Ap = 4$). In this orbit, the neutral velocities measured are generally much smaller than those of the five orbits discussed previously. Also, the measured ion drifts show a more irregular and spatially confined signature of forcing due to electric fields of magnetospheric origin. The relatively "noisy" ion drift pattern observed on this pass is typical for a geomagnetically quiet situation (N. C. Maynard, personal communication, 1983). There remains, however, a clear indication of momentum coupling between the ions and neutrals in, for example, the local, antisunward flow region near 80° latitude. There is no evidence that the neutrals respond significantly to the large, but highly localized "spikes" in the ion drift observed between 50° and 60° latitude on the eveningside near the solar terminator. This lack of a measured neutral response to the ion drift spikes, while being in agreement with the general theoretical conclusions of *St.-Maurice and Schunk* [1981], could be due, in part, to the spatial averaging inherent in the FPI measurement of the meridional wind component (~2°–4° latitude). Such averaging tends to smear and deemphasize small-scale structure in the meridional wind.

4. F REGION FRICTIONAL HEATING AND NEUTRAL ATMOSPHERIC RESPONSE

The full set of measurements afforded by the DE 2 instrumentation used in this work is illustrated in Figure 1 where the ion and neutral wind vectors are plotted for orbit 1174 as a function of time and latitude (top panel). Simultaneously measured electron, ion, and neutral temperatures are plotted in the second panel, and the [O], [N_2], and electron number densities are plotted in the third panel. The bottom panel shows the calculated ion-neutral time constant τ_{nt} in minutes. From such an array of measurements it is possible to estimate directly the frictional and collisional heat exchange rates between the neutral, ionic, and electron gases.

In the case of orbit 1174 shown in Figure 1, as mentioned earlier, the ions and neutrals have similar velocities except in the region of the dawn convection channel near 62°S latitude (~85,040 s UT). In this region the neutral air driven by solar tidal forcing first encounters the rapid stream of sunward convecting ions. Clearly, inside this channel there is insufficient time available during the interaction between the convecting ions and any given parcel of neutral gas for the neutral wind to acquire an appreciable fraction of the ion velocity. There is, however, a moderation and turning of the neutral flow in response to the convection channel in the ionosphere. The difference velocity ($\mathbf{v}_i - \mathbf{v}_n$) here is large (~1000 m s^{-1}), and, consequently, one would expect to see significant frictional heating. This heating is present and is evident most obviously in the measured ion temperatures which show an increase of more than 1000 K in the channel. The electron temperature also shows a local increase by a similar margin, but the neutrals, on the other hand, show a much smaller increase, spread over a broader region. The reason for the different response of the ion and neutral temperatures is the much larger heat capacity of the neutral gas. The heating event is also evident in the neutral composition data where a large decrease in the

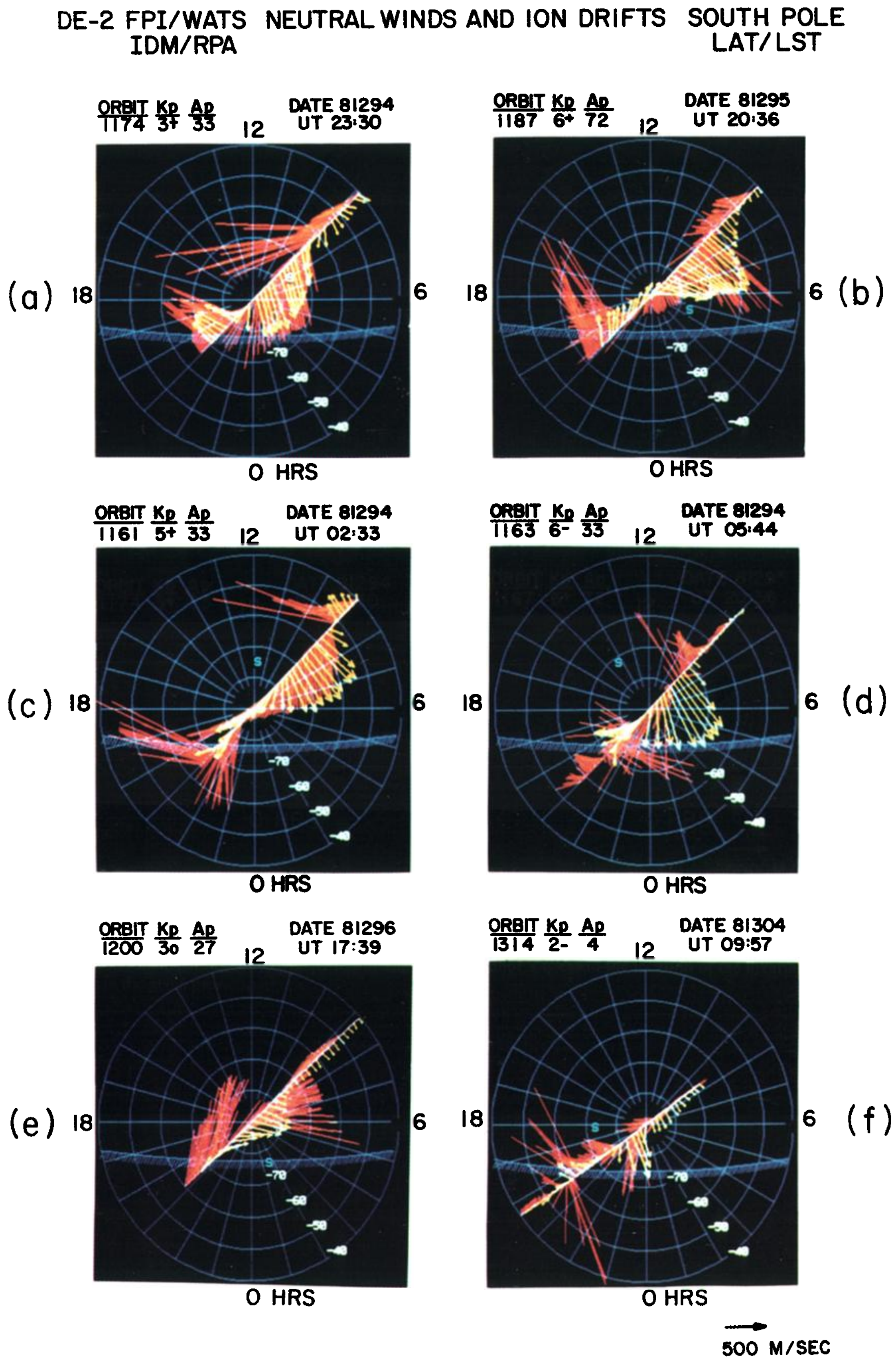

Plate 1. Neutral wind and ion drift vectors measured using instrumentation on Dynamics Explorer 2 for six perigee passes over the southern polar region are plotted in geographic polar coordinates (latitude, pole to 40°S; local solar time). The neutral winds are coded by the yellow arrows, and the ion drifts are coded by the red bars. The curved line represents the location of the solar terminator (90° solar zenith angle). The symbol S refers to the location of the invariant pole at the universal time of the given pass.

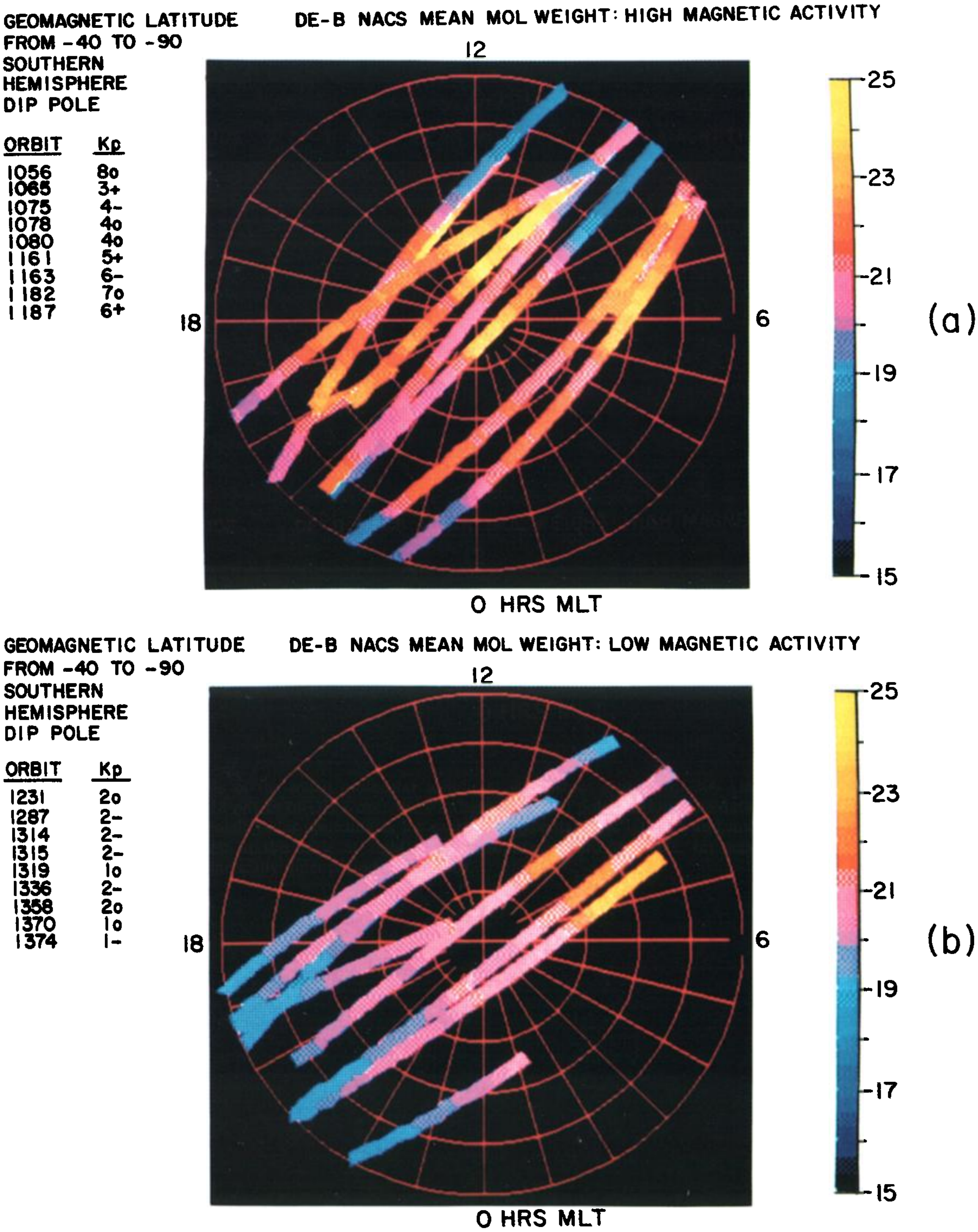

Plate 2. Measurements of the mean molecular weight at a constant altitude of 300 km obtained from the NACS instrument for a total of 18 passes of DE 2 over the southern (summer) polar region. The data are plotted along the track of the satellite in geomagnetic polar coordinates for each orbit (geomagnetic latitude and magnetic local time). The data are color coded according to the scale at right and are separated into two sets: (*a*) geomagnetically active periods ($Kp > 3o$) and (*b*) geomagnetically quiet periods ($Kp < 3o$).

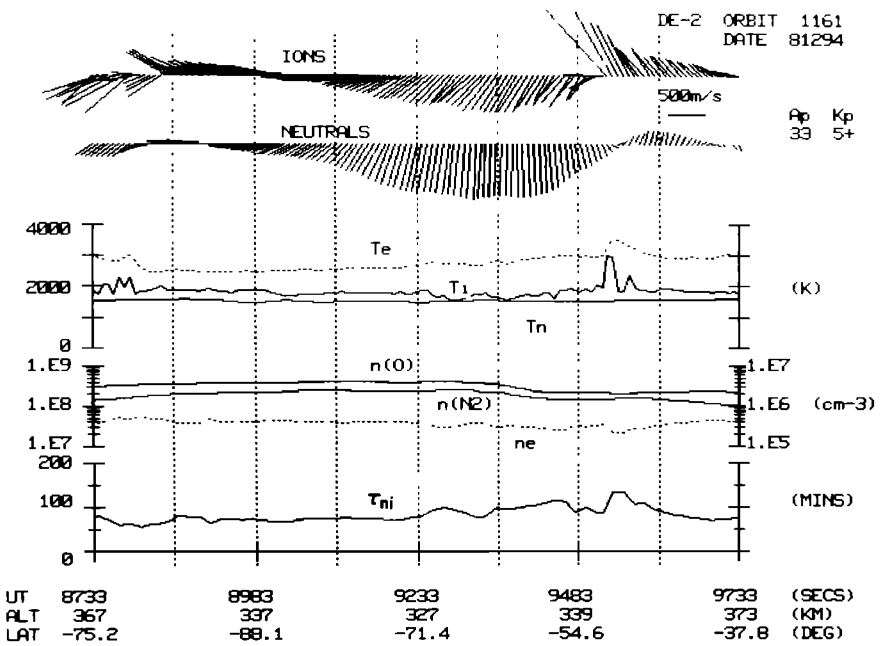

Fig. 2. Same caption as for Figure 1 except for orbit 1161.

[O]/[N_2] ratio is observed near the channel (corresponding to an increase in the mean molecular weight (MMW) of the atmosphere at constant altitude). This change is caused by upwelling of the neutral atmosphere initiated by the integrated effect of Joule heating occurring at all altitudes below the spacecraft [e.g., *Hays et al.*, 1973; *Volland*, 1983]. It can also be seen from Figure 1 that the region of frictional heating is associated with a large trough in the electron density. This type of association has been noted many times in the DE data base, and it leads us to describe a feedback mechanism which acts through the neutral atmospheric response to frictional heating to prolong such a heating event by reducing the collisional coupling between the ions and the neutrals.

The mechanism which relates the observations is assumed to work as follows. Immediately after the onset of a large and steady **E** x **B** ion drift, large ion-neutral difference velocities are set up that give rise to frictional heating in the *F* region and in the *E* region. The consequence of the former is to raise the ion temperatures rapidly, while the consequence of the latter is to produce an upwelling of the neutral gas which brings air rich in molecular nitrogen to *F* region altitudes [*Hays et al.*, 1973]. The magnitude of the perturbation to the neutral atmosphere is dependent on the *E* region conductivity and therefore on the extent to which particle precipitation processes enhance that conductivity. The effect of both the ion temperature increase and the increase in N_2 density is to raise the ionospheric recombination rate by enhancing the ion-atom exchange reaction rates [*Banks et al.*, 1974; *Schunk et al*, 1975], producing molecular ions that rapidly dissociatively recombine. Ionospheric troughs are produced whose geometries are dependent on the trajectories followed by the convecting plasma flux tubes. This effect has been discussed in the literature, but what has not been generally recognized is that these processes also prolong the duration of the heating event and modify the neutral winds by slowing down the exchange of momentum from the ions to the neutral gas. The effective momentum decoupling is illustrated in Figure 1 by the large increase in τ_{ni} associated with the heating region. For this orbit, τ_{ni} increases by nearly a factor of 3, going from ~50–60 min outside the heating region to ~180 min inside. The momentum decoupling of the ions and neutrals in regions of strong ion convection could have profound effects on the global thermospheric dynamical system and clearly needs to be addressed theoretically. Full understanding of this process would, of course, require detailed consideration of the time history for the individual convecting ionospheric flux tubes using a model such as that used by *Sojka et al.* [1982] in addition to a self-consistent theory for the ion-neutral interactions using a model such as that used by *Roble et al.* [1984].

Figures 2 and 3 show data from orbits 1161 and 1163, respectively, in the same format. Orbit 1161 has similar characteristics to orbit 1174 with a well-defined convection channel near the dawnside auroral oval (cf. Plate 1*c*) associated with an enhanced ion temperature, a change in the [O]/[N_2] ratio, and a small increase in the ion-neutral coupling time constant. Three hours later, on orbit 1163, the ion drift pattern has changed substantially, and the measured difference velocities are clearly controlled, in large part, by the inertia of the neutrals. In essence, the neutrals have not had sufficient time to accommodate to the new regime of ion drifts, and therefore they retain the imprint of prior ion drag forcing. For this orbit, the frictional heating is no longer confined principally to the dawn auroral zone but is spread over the entire polar cap. Large-scale increases in both T_i and the (MMW) are observed corresponding to a large electron density trough and very significant momentum decoupling of the ions to the neutrals (τ_{ni} increases to values of >170 min). From a comparison of these two data sets (1161 and 1163) it is clear that the morphology of *F* region Joule heating is highly dependent on the time scales for the ion and neutral response to their respective forcing processes. For orbit 1161 the ion drifts determine the location of the frictional heating, whereas for orbit 1163 the inertia of the neutral air mass is the controlling factor in the changed environment of ion convection.

Since in the data of Figures 1–3 and in other examples not shown, there is evident a clear correlation between large ion-neutral difference velocities and enhancements in MMW as measured by the NACS instrument, we can use the MMW

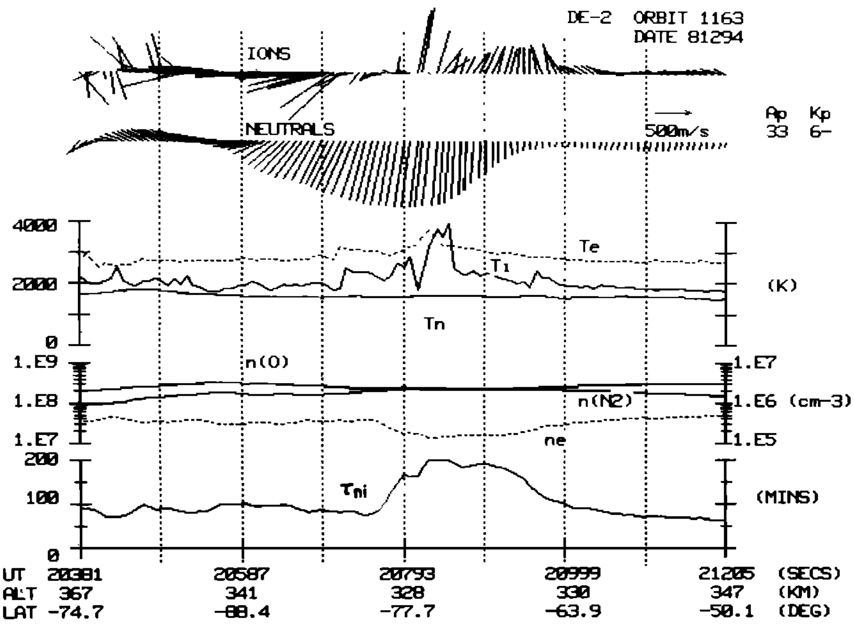

Fig. 3. Same caption as for Figure 1 except for orbit 1163.

measurement as a rough indicator for the presence or absence of frictional heating. In Plate 2 we show values for the MMW obtained by NACS for a total of 18 passes of DE 2 over the summer polar region during October 1981. The MMW values are adjusted down to a constant altitude of 300 km using a simple scale height extrapolation from satellite altitude. The data are separated into active ($Kp > 3o$, Plate 2*a*) and quiet ($Kp < 3o$, Plate 2*b*) cases, are color coded according to the scale at right, and are plotted in geomagnetic polar coordinates (magnetic latitude, magnetic local time). There is a clear dependence of the MMW on geomagnetic activity as can be seen by comparing Plates 2*a* and 2*b*. Typical values for the MMW for low geomagnetic activity are in the range 18–21, whereas typical values for the high activity cases are in the range 21–24. In addition to the obvious general upwelling of the neutral atmosphere in response to high levels of geomagnetic activity, there are indications of the changing morphology of high-latitude Joule heating in this data set. For the low-activity cases, the enhancements in MMW occur in the morning auroral zone, whereas for the high-activity cases, enhancements are spread over the entire polar region, at times occurring in the duskside auroral zone, at times in the dawnside auroral zone, and at other times in the geomagnetic polar cap. The tendency for the heating disturbance to become more complex in terms of its morphology with increasing activity is attributed to the importance of the inertia of the neutral gas in determining the locations for the large ion-neutral difference velocities in situations where the ion convection pattern is changing rapidly (in relation to τ_{ni}). Clearly, to attain a realistic parameterization of Joule heating in the high-latitude upper atmosphere for use in the numerical models, the temporal and spatial variability of the ion drifts, the inertia of the neutrals, and the feedback effects on the electron density via the neutral atmosphere discussed above will all have to be taken into account.

From a study of the data shown in Figures 1–3 it can be seen that *F* region heating at high latitudes in the summer hemisphere has a complex morphology, with the regions of strong heating at times confined to "hot spots" near convection channels in the dawn auroral zone (orbits 1174 and 1161), at times spread over the entire magnetic polar cap (orbit 1163), and at times present predominantly in the eveningside auroral zone (orbit 1187). This complexity is also seen in the neutral composition variability illustrated in Plate 2. From our study of the neutral winds, ion drifts, and other observables from DE 2 we conclude that the morphology of frictional heating is controlled by a combination of factors: (1) the temporal and spatial variability of the $\mathbf{E} \times \mathbf{B}$ ion drifts, (2) the local electron (ion) density and composition of the neutral atmosphere, and (3) the time taken for the neutral gas to acquire the available momentum from the drifting ions for any given quasi-stable convection pattern, and therefore the time history of the neutral forcing.

Further work using the extensive data base from DE 2 will, it is hoped, reveal the details of the interplay between the above factors for different geophysical circumstances. Such a study is considered essential to enable realistic parameterizations of the spectrum of high-latitude energy and momentum forcings to be made available for inclusion in the numerical models of these processes.

5. *F* REGION ION ENERGY BALANCE

As discussed above, the comprehensive set of measurements from DE 2 enables an evaluation of all individual heating terms used in the standard approximate form of the ion energy balance equation (equation (4)). Here, we use the data already presented from orbits 1174, 1161, and 1163 of DE 2 to test this theory. The approach taken is to view the problem from three different standpoints. First, we use the entire set of relevant satellite measurements, and we calculate the heating rate to the ions due to a combination of electron-ion collisional heating and ion-neutral frictional heating (Q_{in}) and the cooling rate of the ions due to collisions with the ambient neutral gas (Q_{out}). If the approximate form of (4) is valid, these rates should be equal in magnitude, since the ion temperatures are controlled by purely local collisional processes. Second, we compare the measured ion temperatures with "predicted" ion temperatures calculated using the theory of (7) and DE measurements of the dynamics and neutral composition. This comparison is of interest since it illustrates the sensitivity of

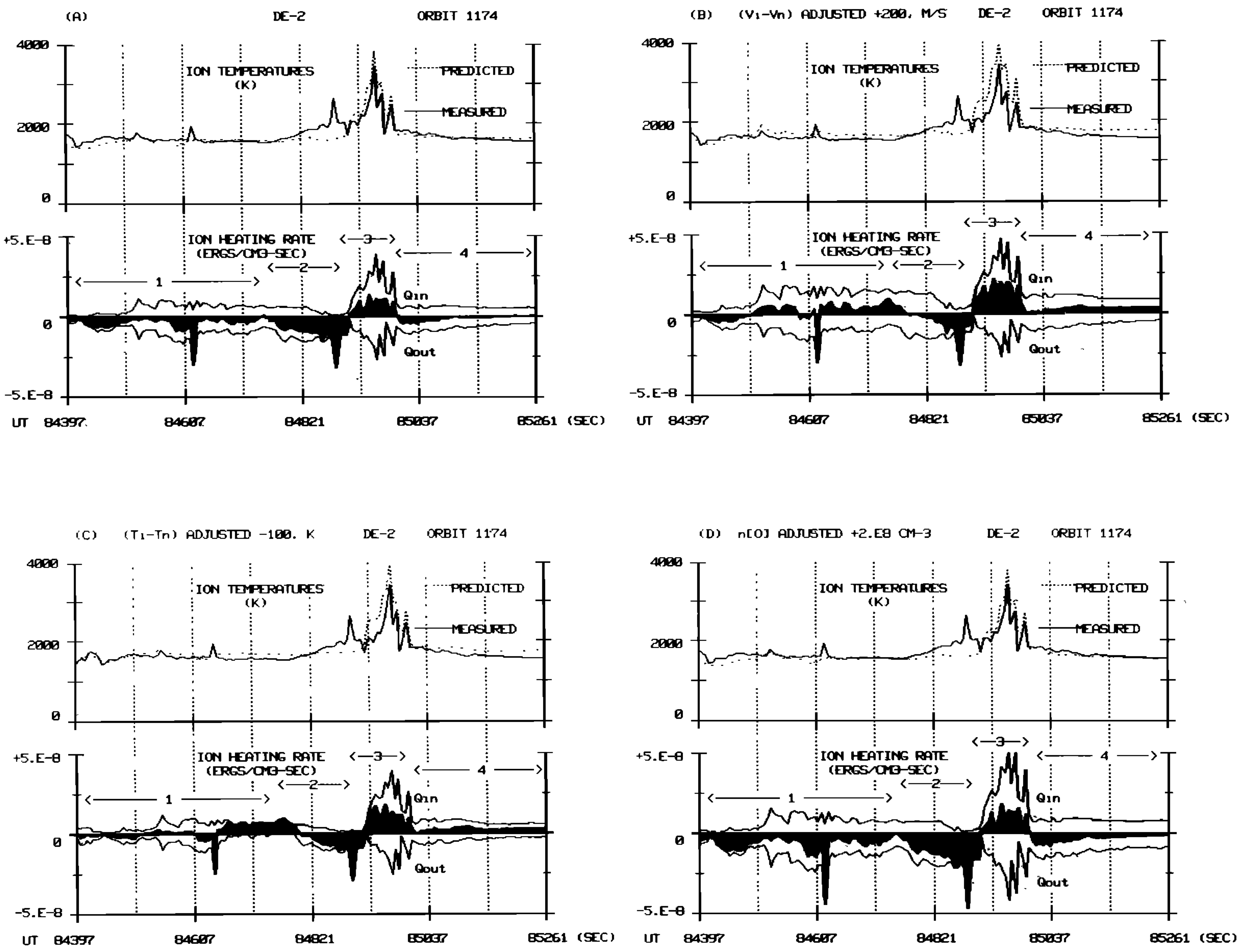

Fig. 4. (*a*) Top panel: measured (solid line) and predicted (dotted line) ion temperatures along the track of Dynamics Explorer 2 plotted as a function of universal time for orbit 1174. Bottom panel: calculated heating rate to the ions (Q_{in}) and the calculated cooling rate (Q_{out}) of the ions based on the approximate ion energy balance terms discussed in the text. Heating and cooling rates plotted as a function of time along the track. The solid portion illustrates the difference ($Q_{in} - Q_{out}$). (*b–d*) Same as for Figure 4*a* with arbitrary adjustments in the ion-neutral difference velocity, the ion-neutral difference temperature, and the neutral composition, respectively (see text for details).

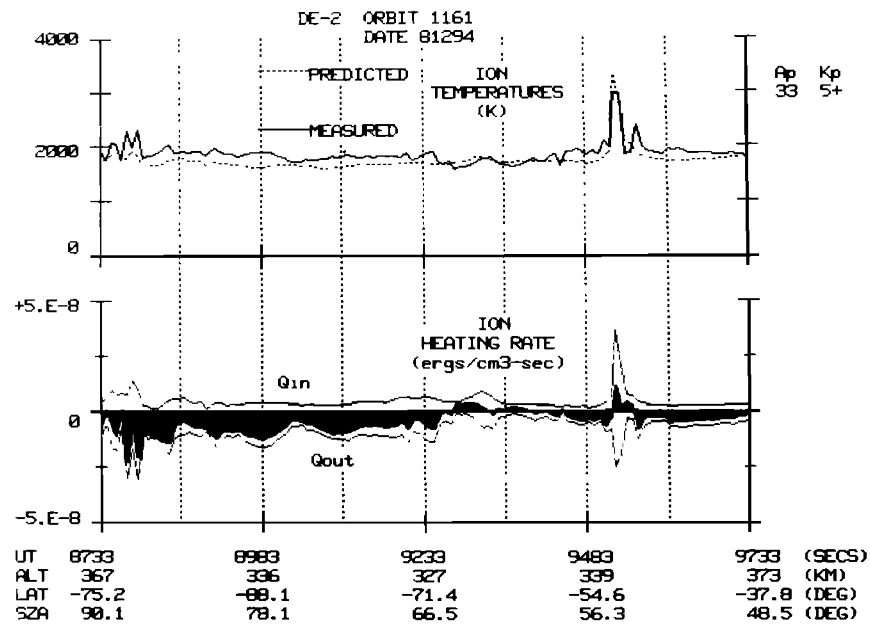

Fig. 5. Same caption as for Figure 4*a* except for orbit 1161.

our test to the measured neutral and ion temperatures ((T_i − T_n) being the critical parameter in (6)) as well as indicating directly the utility of the approximate theory in predicting temperatures. Third, since the theory of ion heating is nonlinear (being dependent on the square of the ion-neutral difference velocity), we study the sensitivity of our test to the various measured observables to see what the consequences of systematic experimental error would be on our conclusions.

In Figure 4*a* are plotted measured and predicted values of the ion temperature for orbit 1174 (top panel) using RPA observations and equation (7), respectively. In the bottom panel are plotted the calculated heating rate to the ions (Q_{in}) and the calculated cooling rate of the ions (Q_{out}). The heating and cooling rates are in units of ergs cm^{-3} s^{-1} with Q_{in} being positive and Q_{out} negative. The difference, ($Q_{err} = Q_{in} - Q_{out}$), which represents the degree to which (4) does not provide an adequate approximation to the real case, is given by the solid portions in the bottom panel. We note that sharp spike features in the ion heating curves are not considered of significance to this study, since they correspond to single, possibly spurious data points. Our comments will be restricted to a discussion of regions where sustained smooth values are obtained.

We discuss first the heating rate calculations. The frictional heating of the ions in the morningside convection channel is evident in the sharp local increase in Q_{in} to values of $\sim 2 \times 10^{-8}$ ergs cm^{-3} s^{-1}. This heating is largely balanced by local cooling to the neutrals (Q_{out}). At lower latitudes on the morningside there is some heating due in part to electron-ion collisions and in part to frictional heating (cf. Figure 1) that is balanced by cooling to the neutrals. In this region (on the right-hand side of Figure 4*a*) the theory of (4) is seen to be working, as the calculated heating and cooling rates are of equal magnitude (little or no solid portion). To the left of the convection channel (i.e., in the polar cap) the calculated cooling rate exceeds the calculated heating rate in general, although there are regions where the rates are in reasonable agreement. In the convection channel itself, the calculated heating rate is greater than the cooling rate, and the solid portion becomes positive. Turning our attention to the top panel of the figure, we see that there is general good agreement between the measured and predicted values of T_i for most of the pass with the exceptions of the convection channel, where the predicted values exceed the measured values by $\sim$200 K, and the region just to the left of the channel in the figure, where the measured values exceed the predicted values by $\sim$100–200 K.

To discuss in greater detail the comparison of data with theory for this pass, we select the four regions indicated in Figure 4*a*. Region 1 corresponds to the eveningside auroral zone and a large part of the polar cap. In this region, Q_{err} is generally negative. This discrepancy is, however, not thought to be significant, since as can be seen from the top panel, the measured and predicted temperatures differ by only a few tens of degrees. This means that an experimental error in ($T_i - T_n$) of that magnitude would explain the discrepancy. Since the ion and neutral temperatures are measured by different instruments with typical statistical accuracies of $\sim$20 K, we consider the measurements taken in region 1 to be in good agreement with the theory of (4). In region 2, however, there is a significant disagreement with the approximate theory. In this zone we observe an increase in both T_i and T_e that does not correspond to a commensurate increase in T_n. Here, the ions cool rapidly to the relatively cold neutrals, and yet their temperature is higher by $\sim$200 K than would be expected from the measured difference velocities (cf. Figure 1). Such a large temperature error would be difficult to explain experimentally, particularly in view of the good agreement with theory elsewhere. In region 3 the disagreement is in the opposite sense, with the measured ion temperatures being somewhat cooler than would be expected from the known amount of frictional heating present. This is, however, a region of large ion velocities, and it is likely that the velocity dependence of the ion-neutral collision cross section might be of importance (see, for example, *St.-Maurice and Hanson* [1982, Appendix A], where, by comparing a polarization collision model with a hard sphere model, it was shown that the ion temperature could be underestimated by several hundreds of degrees by using the

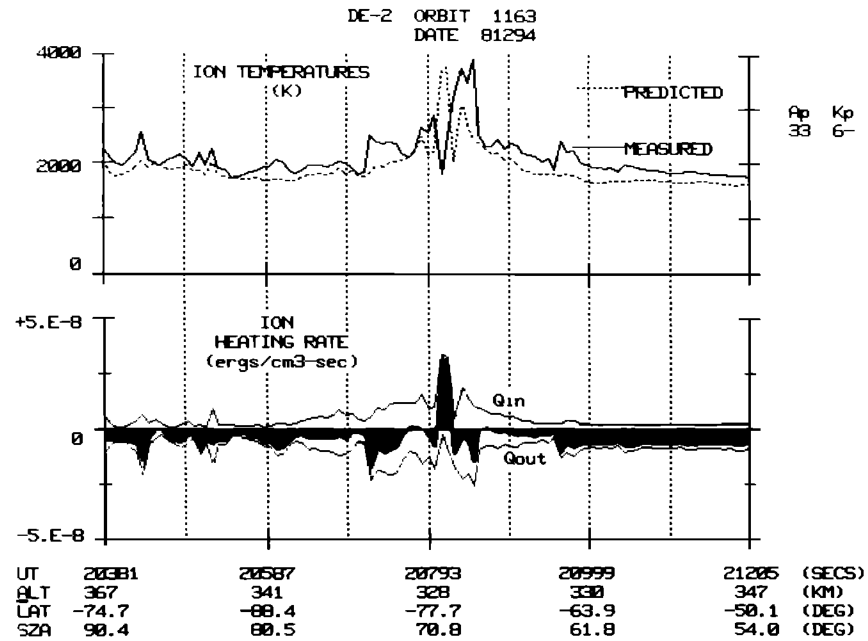

Fig. 6. Same caption as for Figure 4*a* except for orbit 1163.

approximation $\Psi_{in} = \Phi_{in} = 1$ for the case of high ion velocity). It is considered that the likely cause of the disagreement with the approximate theory in region 3 is the neglect of this velocity dependence in the collision cross section. An alternative explanation of the discrepancy in region 3 could be related to the increased sensitivity of the calculation for Q_{in} to the ion-neutral difference velocity in regions of high ion drift speed (equation (6)). An underestimation, by $\sim$15–20%, of the extent to which the neutral wind follows the ion drift would eliminate a large portion of the discrepancy within the convection channel (region 3). Such an underestimate could conceivably occur because of the spatial averaging inherent in the FPI measurement of meridional neutral wind. Elsewhere, in regions where the ion-neutral velocity difference is relatively small, such smearing due to the remote sensing technique would have little consequence. The region marked 4 in Figure 4*a*, as mentioned earlier, shows good agreement between the measurements and the approximate theory.

Since the problem highlighted by region 2 of orbit 1174 was so significant, a large effort was undertaken to ensure that no obvious experimental errors could account for the disagreement. First, an exhaustive survey of individual spectra obtained from both the RPA and FPI instruments in this region was undertaken, and no anomalies were found. Second, neutral temperatures from the WATS instrument were used in place of the FPI temperatures, and although there were small differences in values between the FPI and WATS measurements (approximately tens of degrees), the lack of an increase in T_n associated with the T_i increase was also apparent in the WATS data. Third, the heating and cooling rate calculations were repeated incorporating N_2 collisions in the theory using the measured N_2 density. It was found that the calculated rates were insensitive to neutral composition. Finally, arbitrary offsets in the measurements for the individual observables were included in the calculations to see what experimental error would be required to explain the discrepancy. In Figures 4*b*, 4*c*, and 4*d* we show three of these attempts, where we arbitrarily adjusted $(\mathbf{v}_i - \mathbf{v}_n)$ by 200 m s^{-1}, $(T_i - T_n)$ by 100 K, and n[O] by 2.0×10^8 cm^{-3}, respectively. In all cases, although it was possible to vary the "integral" of Q_{err}, the relative difference between region 2 and region 4 persisted. To explain the result would require unlikely changes in instrument calibration along the track of the satellite. We conclude that in region 2 there appears to be a missing heat source to the ions that is not considered in the standard approximate form of the ion energy balance equation.

From a consideration of the terms listed in Table 1, it is not clear what could provide such a heat source. An attempt was made to evaluate the heat advection term using measured values for the one-dimensional derivative of the ion velocity. This source appears to be too small, particularly in region 2, where the ion velocities are relatively steady (Figure 1) and the derivatives consequently small. One possibility is heat conduction; in regions of strong Joule heating some heat might well be conducted to the ions from below. However, in region 2 the difference velocities are small, and there is unlikely to be significant Joule heating occurring at *E* region altitude. Conduction from above is also unlikely, on the basis of the theoretical work of *Schunk and Sojka* [1982], who showed that heat from the magnetospheric populations of suprathermal ions does not reach altitudes below $\sim$400 km at solar minimum and $\sim$500 km or more at solar maximum. Another possibility which requires further work is the suggestion that wave-particle interactions could account for additional ion heating at *F* region altitude (J.-P. St.-Maurice, personal communication, 1983).

In Figures 5 and 6 we show further examples of the ion energy balance calculations for orbits 1161 and 1163, respectively. For orbit 1161 there is a significant discrepancy between the measured and predicted ion temperatures in a large region of the polar cap, although as before, there is good agreement elsewhere. The other pass (1163) shows a larger degree of structure in the difference velocities, and once again there are regions of agreement and of disagreement. For all orbits studied, there is rough (first order) agreement between the approximate theory and measurement, with discrepancies, where they occur, attributable to temperature differences rarely exceeding 100–200 K in magnitude. The discrepancies are, however, significant, since they cannot be easily explained in terms of experimental error and in the negative solid regions they require the existence of a source or sources of ion heating that have not been considered previously in experimental studies of high-latitude *F* region ion energetics.

6. CONCLUSIONS

We have used data from several instruments aboard the Dynamics Explorer 2 satellite to perform a study of the details of ion-neutral dynamical coupling in the high-latitude summer *F* region. Direct measurements of ion and neutral vector winds have been made for a set of polar passes of the spacecraft and have been discussed in the light of supporting observations of the composition and kinetic temperatures of both neutral and ionic constituents. The comprehensive nature of the data set has enabled the dynamical, thermodynamical, and compositional aspects of ion-neutral coupling to be investigated experimentally. The measurements have also been used to perform an experimental test of the standard approximate form of the ion energy balance equation. Our principal findings may be listed as follows:

1. Ion-neutral difference velocities, and therefore the *F* region frictional (Joule) heating, have a complex morphology which is dependent on the time constants for ion-neutral collisional momentum transfer. This complexity is also evident in the observed response of the neutral atmospheric composition to the heating.

2. Ionospheric "hot spots" are observed where ion temperature enhancements are colocated with large difference velocities.

3. A feedback mechanism acting on the ion-neutral coupling due to neutral compositional changes and enhanced ionospheric recombination has been postulated. This mechanism has the effect of causing significant momentum decoupling of the ions to the neutrals during a Joule heating event. The effect of such a mechanism on the dynamics of the upper atmosphere at high latitudes needs to be addressed theoretically. It is suggested that the combination of a self-consistent ionospheric model, incorporating transport effects, with a three-dimensional, time-dependent general circulation model of the neutral atmosphere would provide the most suitable theoretical tool for such a study.

4. A first-order agreement is observed between measured ion heating rates and temperatures and the conventional, approximate theory based on the ion energy balance equation. There are, however, important disagreements that are difficult to explain by experimental error. The discrepancies observed would imply the presence of a missing ion heat source (or sources) in the high-latitude *F* region. Such a source has not been previously considered in studies of the neutral dynamics and thermodynamics, on the basis of inferences made using the approximate theory. Additional experimental work using comprehensive data sets and careful error analyses is clearly called for to study more fully this issue in *F* region ion energetics.

Acknowledgments. Much of this work was carried out under NASA grant NAS5 26152 to the University of Michigan. Work at the University of Texas at Dallas was supported by NASA grants NAG 5-305 and NAG 5-306. Valuable discussions with J.-P. St.-Maurice, R. G. Roble, B. A. Emery, and T. J. Fuller-Rowell are gratefully acknowledged as well as encouragement from members of the Dynamics Explorer Science Team.

The Editor thanks J. J. Sojka and T. J. Fuller-Rowell for their assistance in evaluating this paper.

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(Received February 6, 1984;
revised April 30, 1984;
accepted May 2, 1984.)