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Interhemispheric plasma flows in the equatorial topside ionosphere

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Abstract. Latitudinal, longitudinal, and seasonal variations in the field-aligned and perpendicular flows measured at an altitude near 830 km, by the Defense Meteorological Satellite Program *F*10 satellite are examined. These profiles are studied during the nighttime (2100 magnetic local time) for solstice periods in 1991 when the solar activity is high. Latitude and longitude variations show the influence of *F* region winds in modulating the observed field-aligned flows. At night, large downward field-aligned flows of the order 400-600 ms^{-1} are observed in the winter hemisphere and coincide in longitude with the location of previously identified adiabatic heating effects studied by *Venkatraman and Heelis* [1999a]. Interhemispheric flows at 2100 hours local time are seen to extend up to apex heights of ~ 1000 km during times of high solar activity. Perpendicular drifts, however are relatively invariant with latitude as expected.

1. Introduction

In the last 30 years, great progress has been made in the study of plasma temperatures and velocities in the topside ionosphere. Extensive in situ and radar measurements [*Hanson et al.*, 1970; *Hanson and Sanatani*, 1970; *Nagy et al.*, 1972; *Hanson et al.*, 1973; *Heelis et al.*, 1978; *Heelis and Hanson*, 1980; *Sulzer and González*, 1996; *MacPherson et al.*, 1998] have established that the dynamics of this region may be controlled by a number of coupled processes involving diffusion, **E** × **B** drifts, and thermospheric neutral winds.

Recognizing the importance of dynamics and energetics of this region, extensive theoretical and modeling work has also been pursued in the study of the topside ionosphere. Studies conducted in this region using computational methods [*Balan et al.*, 1997; *Bailey et al.*, 1973; *Brace and Theis*, 1981] reveal the importance of field-aligned plasma transport and the associated adiabatic heating and cooling of the plasma. Recent observations by *Venkatraman and Heelis* [1999a, b] (hereafter referred to as VHA and VHB, respectively) show the longitude and seasonal dependence in ion temperature that would be expected from heating and cooling effects induced by *F* region winds. Here we investigate the same data set to extract the ion drift velocity and to examine the behavior of the field-aligned ion motions.

2. Observations

VHA have shown that the latitude variation in the ion temperature near 830 km is consistent with the anticipated behavior of field-aligned ion flows produced by *F* region neutral winds. Their study focused on the observed features of ion temperature (T_i) and the ion composition (N_i) during the months of January, March, and June in 1991. It was shown that adiabatic heating and cooling effects are prominent during solstices in longitude regions where the *F* region meridional and zonal winds are expected to enhance field-aligned transport of plasma. Temperature variations as large as 500°K are attributed to the effects of plasma transport. The purpose of this paper is to demonstrate the existence of field-aligned plasma flows that are consistent with these variations. Data are obtained from the Defense Meteorological Satellite Program (DMSP) satellite *F*10 at 2100 hours local time. This satellite orbits the Earth in an elliptical orbit at an altitude of ~ 830 km. The orbital period of 101 min yields about 14 passes a day separated in longitude by ~ 25°.

Environmental sensors on board the *F*10 satellite include the retarding potential analyzer (RPA) which measures the in-track ion drift studied in this work in addition to ion densities and ion temperatures. The cross-track ion drifts are measured by the ion drift meter (IDM). Owing to discrepancies in the vehicle attitude and corrections to the ram velocity as will be shown later, the behavior of the topside ionosphere is best characterized when the velocities are at their largest, i.e., during solstices. Furthermore, in order to contrast the dynamical behavior of the topside ionosphere with the temperature variations described by VHA we have restricted our investigation to the solstice periods in 1991 examined by VH. During this period of high solar activity, the ionosphere near 830 km altitude is always comprised of more than 90% O$^+$. When the satellite passes supersonically through the gas, it provides accurate measures of the cross-track ion drifts from the

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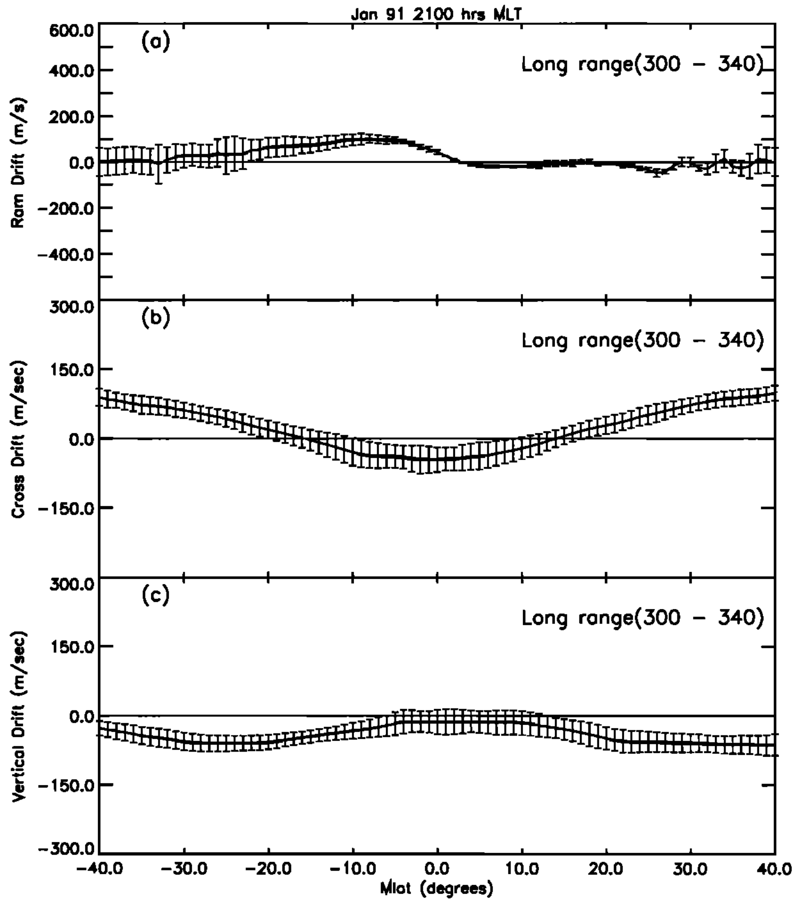


Figure 1. Averaged latitude profiles of (a) ram, (b) cross-track, and (c) vertical drifts in the 300°-340° longitude region for January 1991.

IDM and the in-track (ram) drifts from the RPA. With only a single ion present, the derivation of the ram drift from the RPA may be compromised by lack of information about the vehicle potential with respect to the plasma. However, previous studies have shown that the vehicle potential is a first-order function of the electron temperature [*Anderson et al.*, 1994], and this information is used to establish the relationship for the data set under consideration. Specifically, we assume that at a magnetic latitude of 40° in the summer hemisphere, the ram drift is very small and that the current-voltage characteristics from the RPA can be used to accurately determine the vehicle potential. These data together with a measure of the electron temperature from the Langmuir probe are used to establish a functional relationship of the form

$$\phi = -A\frac{kT_e}{e}\ln[\frac{8kT_e}{\pi m_e {v_s}^2}]^{1/2} \qquad (1)$$

Here ϕ is the sensor potential, k is the Boltzmann's constant, T_e is the electron temperature, e is the elementary charge, m_e is the electron mass, and v_s is the spacecraft velocity. The constant **A** is derived from the condition at 40° in the summer hemisphere and then this relationship is used to derive the ram drift at lower latitudes. In order to account for the uncertainties in the ram drift due to discrepancies in the satellite attitude, we further adjust the baseline velocity for the ram drift by making it almost zero at midlatitudes of ±40° and obtain the corrected ram drift.

2.1. Ram, Cross, and Vertical Drift Velocities

To confirm the presence of field-aligned flows associated with temperature enhancements, we have studied the ion drift velocity measured by DMSP in a manner identical to the way VHA studied plasma temperatures. Figure 1 shows the three mutually perpendicular ion drifts observed in January 1991 for the longitude region where the field-aligned motions are expected to be a minimum. Here the latitude variations at 2100 hours local time are plotted. Since the satellite is almost in a polar orbit, drifts labeled ram, cross, and vertical are positive when aligned approximately along the north, east, and radially outward directions, respectively. It should be emphasized that the ram drift is subject to uncertainties in the absolute zero produced by the accuracy in the determination of the sensor plane potential with respect to the plasma. The cross and vertical drifts also have some uncertainties in the absolute zero due to inadequacies in the specification of the spacecraft attitude. However, the latitude variations shown in the figure do not result from these uncertainties and may thus

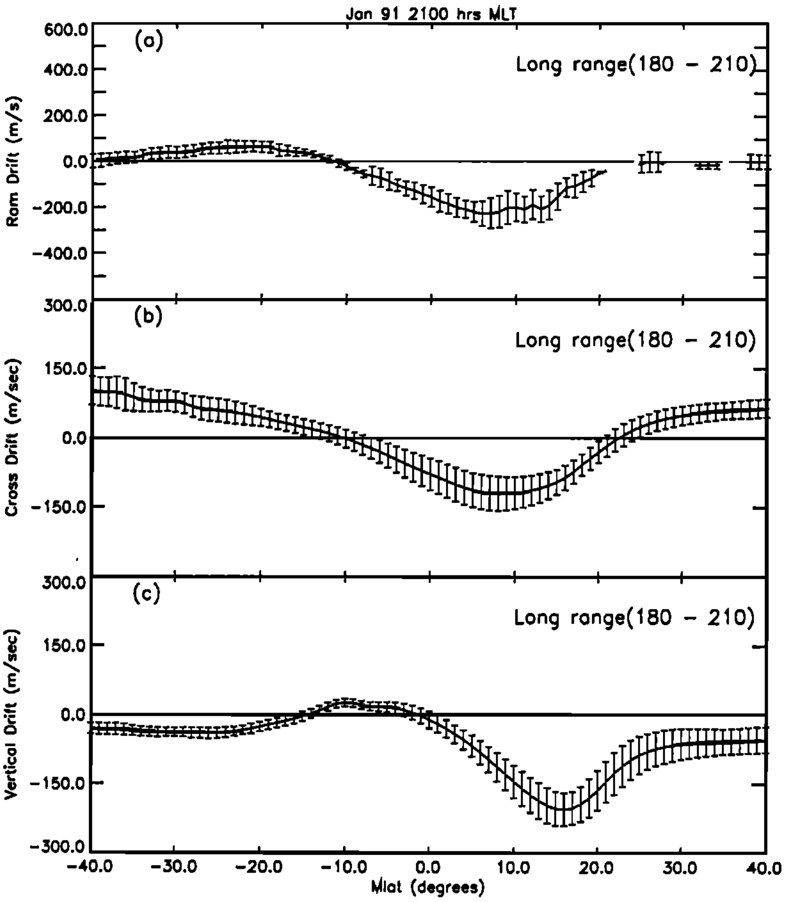


Figure 2. Averaged latitude profiles of (a) ram, (b) cross-track, and (c) vertical drifts in the 180°-210° longitude region for January 1991.

be interpreted in terms of geophysical variations. Note that near the magnetic equator, the cross drift is quite small but directed to the west at a local time when we expect the drift to be eastward. This discrepancy is due to inadequate specification of the satellite attitude with an uncertainty as small as 0.5°, but as we shall see it does not invalidate our overall conclusions. The feature of note here is the lack of large latitudinal variations within ±40° of the magnetic equator. Figure 2 shows the latitudinal variations observed in January 1991 for the longitude region where the field-aligned motions are expected to be a maximum. Rather dramatic latitudinal variations are seen consistent with the expectation that summer to winter interhemispheric transport exists in concert with large downward field-aligned flows in the winter. Figures 3 and 4 show data in a format the same as those in Figures 1 and 2. Here the data for June 1991 are shown for the same two longitude regions. In this case the behavior of the latitude variations is essentially reversed, in agreement with the expectations based on the role of interhemispheric transport induced by *F* region neutral winds. Note that for the longitude region where we expect interhemispheric transport to be minimized, the vertical drift at low-magnetic latitudes is again quite small and vertically upward at a local time when we expect these drifts to be downward. This discrepancy is again due to inadequate specification of spacecraft attitude.

2.2. Field-Aligned and Perpendicular Drifts

More insight into the behavior of the plasma may be obtained by resolving the observed velocity into the magnetic meridian plane and separately examining the plasma flows perpendicular and parallel to the magnetic field. For the nighttime crossings shown here, the *F*10 satellite moves from south to north and slightly westward in longitude. The International Geophysical Reference Field [*Langel,* 1991] is used to derive the components of the magnetic field in the spacecraft reference frame. The horizontal ion drift in the magnetic meridian, v_m, is first computed by the expression

$$v_m = -(v_x \cos\alpha + v_y \sin\alpha), \qquad (2)$$

where α is a small angle between the magnetic meridian and the sensor look direction and v_x and v_y are the ram and cross track velocities, respectively. Then the perpendicular and the parallel ion flow components are computed from the expressions

$$v_{\parallel} = v_z \cos I + v_m \sin I \qquad (3)$$

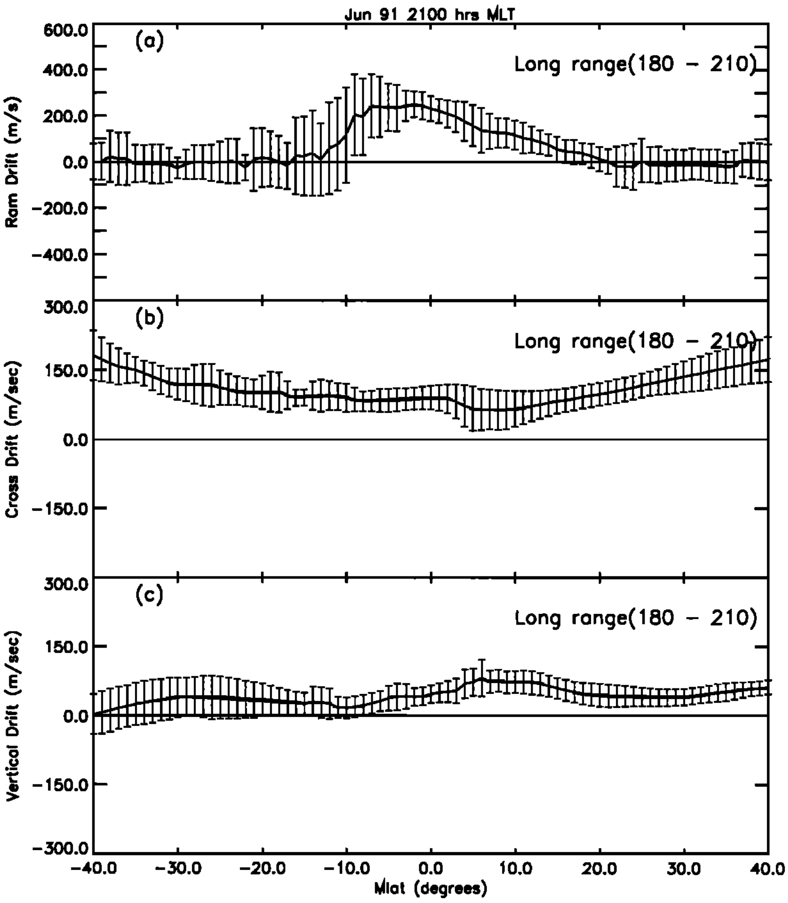


Figure 3. Averaged latitude profiles of (a) ram, (b) cross-track, and (c) vertical drifts in the 180°-210° longitude region for June 1991.

and

$$v_\perp = v_m \cos I - v_z \sin I, \tag{4}$$

where I is the angle of inclination and is positive in the north and negative in the south. Here $v_\parallel$ and $v_\perp$ are the field-aligned and perpendicular (in the magnetic meridian) components of the plasma drift, respectively, and v_z is the vertical drift. Note that $v_\parallel$ is positive along the direction of the magnetic field and $v_\perp$ is positive upward and perpendicular to the magnetic field.

Figure 5 shows the parallel and perpendicular flows computed from the data shown in Figures 1 and 2. Note that the perpendicular drift is relatively invariant with latitude as should be expected. At 2100 hours this drift is small in magnitude and mostly downward as expected. In the longitude region between 300° and 340° (Figure 5b) the field-aligned flows are small and directed downward in both the Northern and Southern Hemispheres. This is consistent with the expectation that interhemispheric transport plays a minor role and plasma is diffusing down the field lines in response to recombination at lower altitudes in both hemispheres. Notice that the downward flows in the winter hemisphere in the longitude region between 180° and 210° (Figure 5c), shows a strong latitude variability. At the highest magnetic latitudes, plasma flows down in both the hemispheres. However, equatorward of 15° latitude in the Southern Hemisphere (summer), the flow is directed upward along the magnetic field prior to flowing rapidly down the field lines in the Northern Hemisphere (winter). Field-aligned flows maximize to ~ 300 ms^{-1} near 10° magnetic latitude in the Northern Hemisphere.

Figure 6 show features similar to those in Figure 5 but at different longitudes. Here the flows are computed from the data in Figures 3 and 4, respectively. Similar to the northern winter case, the perpendicular drift at 2100 hours is small and relatively invariant with latitude as expected. At the southernmost latitudes the increasing presence of H$^+$ ions may produce a large uncertainty in the absolute value of the cross and vertical ion drifts, but ion composition measurements (as shown by VHA) show that this is not a significant factor in the summer hemisphere or equatorward of 25° magnetic latitude. In the 180° – 210° longitude region shown in Figure 6a, the field-aligned flows vary very little, consistent with our expectation that interhemispheric plasma transport plays a minor role in this longitude region during northern summer. A small amount of interhemispheric flow seen in this case can be attributed to a discrepancy in the spacecraft attitude, thus affecting the vertical velocity, which in turn translates to uncertainties in the parallel flow. In the 300°–340° longitude region (Figure 6b), the parallel ion flow shows a strong latitude dependence especially at lower magnetic latitudes. Equator-

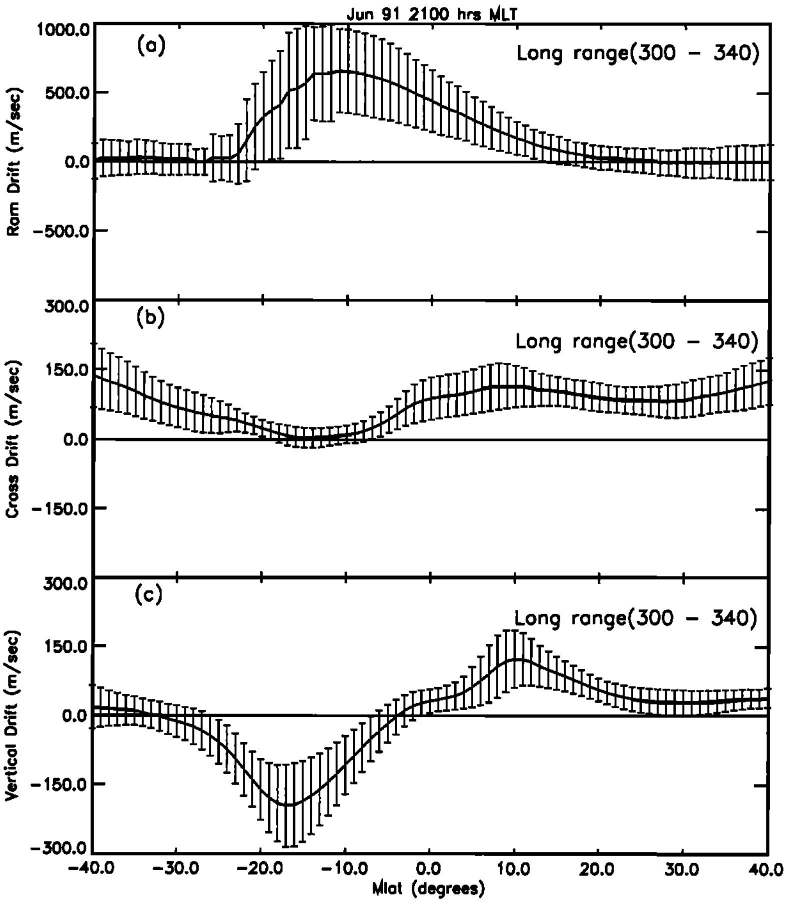


Figure 4. Averaged latitude profiles of (a) ram, (b) cross-track, and (c) vertical drifts in the 300°-340° longitude region for June 1991.

ward of ~ 18° magnetic latitude in the Northern Hemisphere (summer), the flow is directed upward along the magnetic field and flows rapidly downward in the Southern Hemisphere (winter). Field-aligned flows maximize at ~ 600 ms^{-1} near 10° magnetic latitude in the winter (southern) hemisphere.

3. Discussion

Figure 7 is a schematic illustration showing the direction of field-aligned flows and perpendicular drifts at 830 km during the period of study. Examination of field-aligned and perpendicular ion motion during the time of adiabatic heating and cooling observed by VHA confirm the existence of field-aligned plasma motions. The field-aligned flows are organized by season and longitude in accord with the roles played by meridional and zonal neutral F region winds. During northern winter, the meridional and zonal winds combine to maximize plasma transport and its effects in the 180° – 210° longitude region where the magnetic declination is positive. In this longitude region, field-aligned flows of the order of 200 ms^{-1} are seen near the magnetic equator at 830 km altitude. Further, it was shown by VHB that these flows maximize in an O^+ dominant plasma with the flux tube apex height just below the transition height. For this northern winter case, these flows directed from summer to winter are seen equatorward of 15° magnetic latitude in the summer hemisphere. This suggests that indeed interhemispheric transport of plasma occurs on flux tubes with apex heights less than ~ 1000 km, i.e., below the transition height. These field-aligned flows maximize near 10° magnetic latitude in the winter hemisphere with average flow values close to 300 ms^{-1} at 830 km altitude. These flow velocities correspond to downward fluxes of ~ 6×10^9 cm^{-2} s^{-1}. Similar examination of field-aligned flows during northern summer shows that the longitude regions for maximum field-aligned flows are changed. Here the meridional and zonal winds maximize plasma transport, and its effects in the 300° – 340° longitude region where the magnetic declination is negative. In this longitude region, field-aligned flows of the order of 400 ms^{-1} are seen near the magnetic equator at 830 km altitude. These flows directed from summer to winter are seen equatorward of 18° magnetic latitude in the summer hemisphere suggesting that interhemispheric transport of plasma in this case occurs on flux tubes with apex heights less than 1500 km. Similar to the northern winter case, field-aligned flows maximize near 10° magnetic latitude in the winter hemisphere with average flow values close to 600 ms^{-1} at 830 km altitude. These flow velocities correspond to downward fluxes of about 12×10^9 cm^{-2} s^{-1}. Note that the maximum in the field-aligned

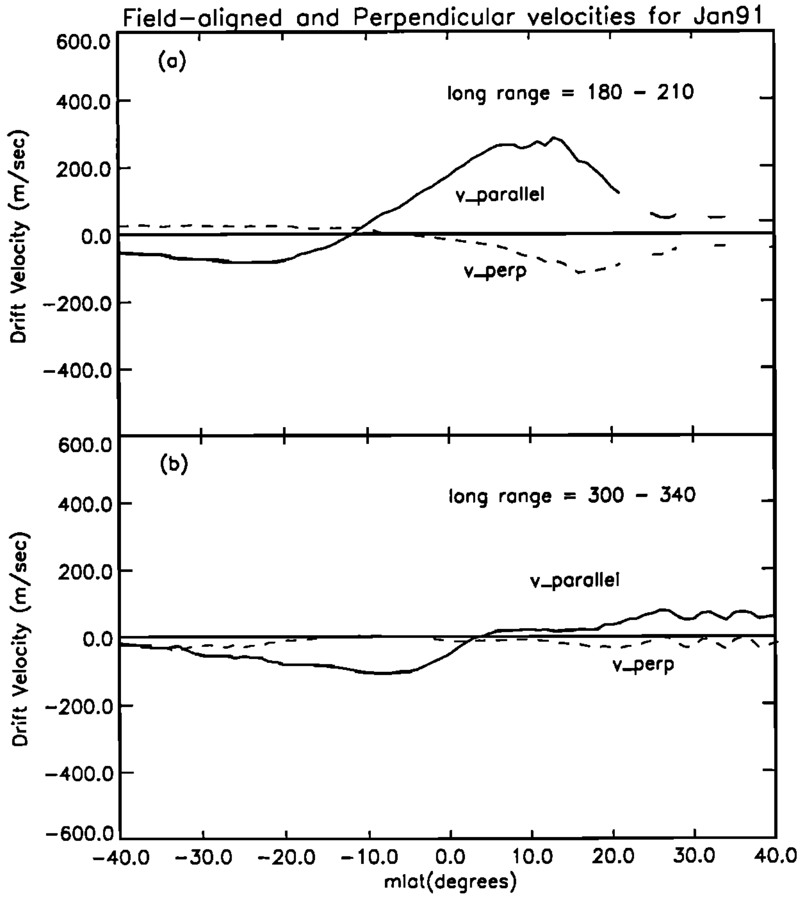


Figure 5. Averaged latitude profiles of field-aligned and perpendicular flows in the longitude regions (a) 180°-210° and (b) 300°-340° for January 1991.

velocity is displaced to the winter hemisphere and corresponds well to the regions of adiabatic heating observed by VHB. Also, the field-aligned flows vary little with latitude in longitude regions where nighttime *F* region meridional and zonal winds have opposing components in the magnetic meridian. The corresponding adiabatic heating effect in these longitude regions is also a minimum. We have thus confirmed both the effects of declination on field-aligned plasma transport and the associated heating. In addition to downward flow due to interhemispheric transport, nighttime downward diffusion due to recombination at lower altitudes can further enhance downward plasma flow. Note that interhemispheric transport is indicated when the flows in one hemisphere are upward while at corresponding latitudes in the other hemisphere they are downward. Evidence for such flows in these data are confined to flux tubes with apex altitudes below ~ 1000 km. Of course the plasma is not in diffusive equilibrium in such cases but the apex altitude limit is close to the estimated O^+/H^+ transition altitude. Thus the data support the notion that interhemispheric flows are largely confined to regions where O^+ is the dominant ion throughout the magnetic flux tube.

Our results are in general agreement with what is expected based on previous studies of field-aligned velocities and ion temperatures. Observations of field-aligned velocities from mathematical models [*Bailey and Heelis*, 1980] suggest that a neutral air wind of 100 ms^{-1} in the magnetic meridian will result in average field-aligned velocities of the order of 200 ms^{-1} near the magnetic equator and peak to trough temperature differences of 400°K. These results are comparable to those seen here, but whether the *F* region neutral winds are in accord with the model requirements must await a study of the other data sources.

4. Conclusions

Observations from the RPA and IDM aboard the DMSP *F*10 satellite have confirmed field-aligned velocities consistent with our expectations based on interhemispheric transport of plasma from summer to winter hemisphere. In this study we examined velocity data for the months of January and June in 1991. A study of field-aligned and perpendicular flows clearly shows longitudinal and seasonal variations consistent with the behavior of *F* region neutral winds. A study of the longitudinal variation in field-aligned flows suggest that these flows maximize in regions where the effects of the *F* region neutral meridional and zonal winds maximize. Thus in January they maximize in the 180° – 210°

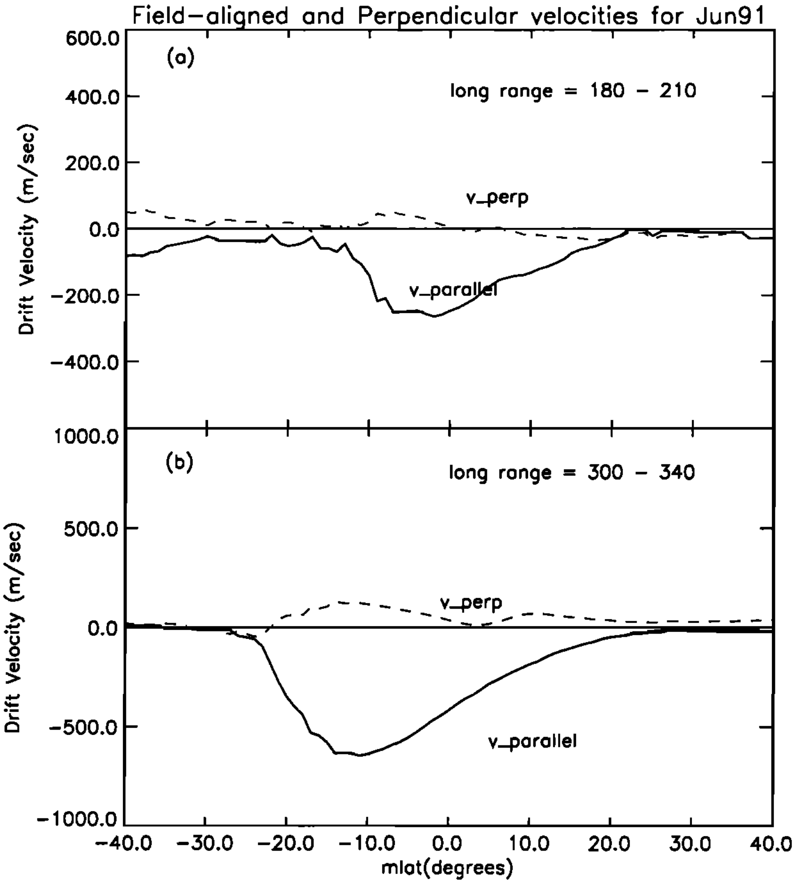
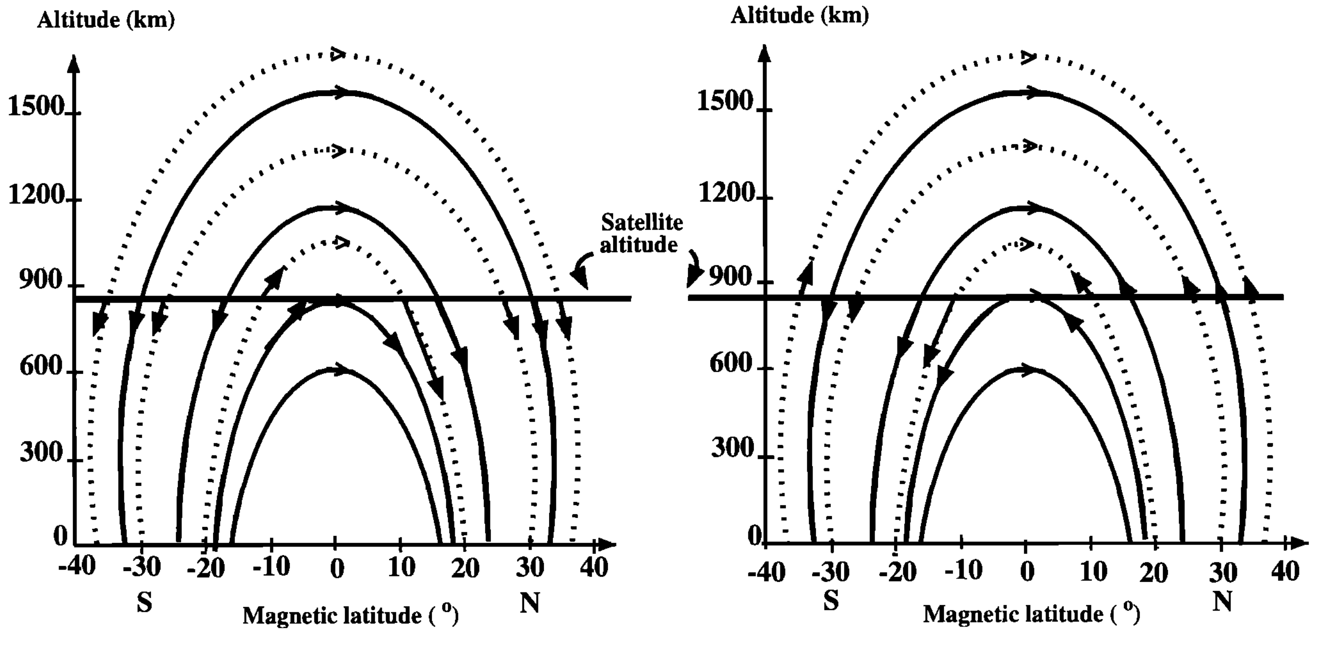


Figure 6. Averaged latitude profiles of field-aligned and perpendicular flows in the longitude regions (a) 180°-210° and (b) 300°-340° for June 1991.



January 1991 (180° - 210°)

June 1991 (300° - 340°)

Figure 7. Interhemispheric plasma flows in the topside ionosphere.

longitude region, while in June they maximize in the 300° – 340° longitude region. More importantly these flows maximize at low-magnetic latitudes close to the dip equator for flux tubes with apex heights below the O^+/H^+ transition height. The morphological behavior of the field-aligned ion flows and the magnitude of the observed flows are consistent with previously observed ion temperature variations and will require F region neutral winds in the magnetic meridian of ~ 100 ms^{-1} near the dip equator.

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