Out-of-Ecliptic Tests of the Inverse Correlation Between Solar Wind Speed and Coronal Expansion Factor

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In this paper we address the question of whether out-of-ecliptic measurements satisfy the inverse correlation between wind speed at 1 AU and flux tube divergence in the corona, already found from measurements in the ecliptic. Using the in-ecliptic calibration, we derive out-of-ecliptic speeds from coronal expansion factors determined from global observations of photospheric field and their current-free coronal extension. These derived speeds are compared with speeds inferred from interplanetary scintillation measurements during 1972–1988 and with in situ speeds measured by the Pioneer 11 spacecraft at 16°N latitude during 1984–1988. These three sets of wind speed show the same overall variation with latitude and time during the sunspot cycle, with higher latitudes having more years of fast wind than lower latitudes and all latitudes having slow wind at sunspot maximum. Although some detailed discrepancies are also present, the overall agreement is comparable to that achieved in the ecliptic plane.

1. Introduction

Complementary synoptic measurements of near-Earth solar wind speed and photospheric magnetic field now span more than two sunspot cycles. In an attempt to understand these measurements, *Wang and Sheeley* [1990a] recently verified that the wind speed at Earth is inversely correlated with the flux tube divergence rate in the corona, a result that *Levine et al.* [1977] had obtained previously using observations during 2 months of the Skylab mission in 1973. Regions of low divergence, derived from a current-free extension of Mount Wilson Observatory (MWO) measurements, corresponded to fast wind at Earth, and regions of high divergence corresponded to slow wind. This relation remained valid through all phases of two consecutive sunspot cycles. Furthermore, for an idealized axisymmetric field, the sense of the correlation was unchanged when a more realistic current sheet model was substituted for the current-free model originally used by Levine et al. As will be discussed in section 4, a physical explanation for this correlation has recently been proposed by *Wang and Sheeley* [1991], who showed that the result is consistent with simple models in which Alfvén waves boost the wind to high speeds.

An inverse relation between wind speed and coronal expansion factor has several observational implications [*Wang and Sheeley*, 1990b; *Wang et al.*, 1990; *Sheeley and Wang*, 1991]. The fastest wind ought to occur on field lines that are rooted in local minima of the large-scale photospheric field, where coronal holes are about to break apart or where neighboring holes of like polarity are about to join. Such low-divergence regions include the neck of a polar hole lobe during the declining phase of the sunspot cycle and the high-latitude edge of an azimuthal hole just after polar field reversal. On the basis of in-ecliptic comparisons with the observed wind speed, these low-divergence regions ought to produce wind that is about 100 km s^{-1} faster than the 600 km

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s^{-1} speed expected from the centers of the polar holes at sunspot minimum.

A definitive test of such out-of-ecliptic predictions must await in situ measurements from the Ulysses spacecraft now en route to high latitudes via the planet Jupiter [*Wenzel et al.*, 1989; *Wang et al.*, 1990]. However, in the meantime, a preliminary test can be made using out-of-ecliptic speeds inferred from radio interplanetary scintillation (IPS) measurements and speeds measured from the Pioneer and Voyager spacecraft, whose encounters with the outer planets have left them on out-of-ecliptic trajectories. The objective of this paper is to describe the results of such a preliminary test.

2. Sources of Wind Speed Data

Multistation IPS measurements were obtained by the groups at the University of California at San Diego (UCSD) and at the Research Institute of Atmospherics of Nagoya University and were provided to us by B. J. Rickett and M. Kojima, respectively. The UCSD measurements were obtained at 74 MHz during April 1972 to September 1982 [*Coles and Rickett*, 1976; *Coles et al.*, 1980; *Rickett and Coles*, 1982, 1991], and the Nagoya measurements were obtained at 327 MHz during 1983–1988 [*Kojima and Kakinuma*, 1986, 1987, 1990]. Like the UCSD group (who also analyzed Nagoya data) and like the Nagoya group itself, we excluded Nagoya measurements that originated close to the Sun, in our case within 0.3 AU. This selection removed some sporadic "glitches" and annual variations from the data. It also made the range of heliocentric distances comparable to that obtained for the UCSD measurements and avoided mapping problems that might arise from possible accelerations close to the sun [*Rickett and Coles*, 1991; *Scott et al.*, 1983; *Kakinuma and Kojima*, 1984; *Armstrong et al.*, 1985].

At present, the most suitable out-of-ecliptic spacecraft measurements are from Pioneer 11 (P11), which has been approaching 16°N latitude since its encounter with Saturn in 1979. By comparison, Pioneer 10 has been on a relatively low latitude trajectory at 3°N since its encounter with Jupiter in 1973. Voyager 1 has been approaching the much higher latitude of 38°N, but its plasma detector failed shortly after

the Saturn encounter in 1980. Finally, although Voyager 2 (V2) has been on a steep ascent into the southern hemisphere since its encounter with Neptune in August 1989, several years will be required before it will reach even 16°S latitude at this relatively great heliocentric distance of 30 AU. Consequently, we shall use only the P11 measurements to supplement the IPS-inferred speeds and leave the V2 measurements (prior to 1989) for an in-ecliptic comparison. These P11 and V2 speeds have been compared previously by *Gazis et al.* [1988] and *Barnes et al.* [1989] and were provided by P. R. Gazis (NASA Ames Research Center) and L. A. Villanueva (Massachusetts Institute of Technology (MIT)), respectively.

Our magnetically derived proxy for solar wind speed was based on solar magnetic field measurements obtained at the Mount Wilson Observatory during 1967–1989 and at the Wilcox Solar Observatory (WSO) during 1976–1989. The procedure for deriving this "speed" from photospheric measurements has been described in detail elsewhere [*Wang and Sheeley*, 1990a; *Wang et al.*, 1990]. Briefly, the observed line-of-sight photospheric field is divided by the sine of the observed latitude to convert it to a radial field, which is then used as the photospheric constraint on the field's current-free extension into the corona. The outer boundary condition is prescribed at a spherical source surface located at 2.5 R_S, where the nonradial components are forced to vanish. The flux tube expansion factor is evaluated at 5° intervals of latitude and longitude on this surface from the ratio of the field strength there and at the corresponding photospheric foot point. Finally, a calibration is obtained by comparing the in-ecliptic source-surface expansion factor and the in situ wind speed near Earth a few days later, depending on the Sun-Earth transit time. A range of expansion factors from 3.5 to 18 was found to correspond to a range of wind speeds from 650 km s^{-1} to 450 km s^{-1}.

Our procedure for deriving the coronal field differs from that of *Hoeksema et al.* [1982, 1983]. We assume that the large-scale field is radial at the photosphere, as supported for example by the measurements of *Howard and LaBonte* [1981] and *Svalgaard et al.* [1978], whereas Hoeksema et al. use a rigorous matching between the line-of-sight components of the observed and calculated field as the inner boundary condition on the current-free field. This latter procedure underestimates the strengths of the polar fields around sunspot minimum and causes the source-surface neutral line to lie farther from the equator than the coronal intensity pattern with which it is thought to be associated. Consequently, in the years around sunspot minimum, Hoeksema et al. supplemented their derived field with a strongly peaked polar field similar to the one that Svalgaard et al. deduced from WSO measurements in 1976. Our simpler, but less rigorous, procedure gives strong, highly peaked polar fields automatically, so that further enhancement is not necessary.

All of the above solar wind speeds were transformed to 1 AU for comparison with each other and with the in situ speed measured by the Los Alamos and MIT plasma experiments on the VELA, IMP, and ISEE 3/ICE series of spacecraft. The transit times were calculated using the observed speed, with multiple-valued entries being averaged when they occurred. Some of these wind speed measurements were obtained from the National Space Science Data Center [see *Couzens and King*, 1986], while other more recent speeds were obtained directly from the experiment teams at Los Alamos and MIT, courtesy of R. D. Zwickl (now at National Oceanic and Atmospheric Administration) and J. T. Gosling, and A. J. Lazarus and P. A. Milligan, respectively.

Initially, we displayed the IPS speeds in a Bartels format at several latitudes to see if we could identify the occurrence and evolution of individual high-speed streams and relate them to corresponding patterns of in situ and magnetically derived speed. Although some patterns of IPS speed were visible in the ecliptic, especially during 1973 and 1974, in general they were not visible at higher latitudes or even in the ecliptic after 1982, apparently owing to the numerous data gaps that were present at those latitudes and times. Also, at this initial stage of the study, it was unclear how to combine the UCSD and Nagoya measurements into a single display because different correction factors were required to bring them into agreement with the in situ spacecraft measurements. When they were applied, these corrections gave inconsistent results at high latitudes.

Consequently, we turned to a quantitative study in which the speed profiles were condensed into 27-day Carrington averages and further smoothed in six-rotation running means. Such running means were necessary for the IPS speeds, which were relatively "noisy" owing to the limited number of suitable radio sources, especially at high latitudes and southern heliographic latitudes. In addition, the IPS measurements were placed in relatively wide latitude bins, ±10° around the desired latitude, as a compromise between our desire for improved statistics and latitudinal resolution. By comparison, the magnetically derived speeds were not averaged in latitude or longitude; rather, they simply refer to the indicated location with a resolution of approximately 5° in latitude and longitude.

3. RESULTS

3.1. *Comparisons with IPS-Inferred Speed*

In this section, we compare magnetically derived wind speeds with speeds inferred from IPS measurements. For this purpose, we subdivide the interval 1972–1989 into two parts: 1972–1982, for which UCSD and MWO data are both available, and 1983–1989, for which Nagoya and WSO data are available. The MWO data were also available during this second interval, but they were noisier (i.e., had more random errors) than the WSO data and contained a calibration error that has only recently been discovered and corrected [*Wang and Sheeley*, 1988; R. Ulrich and J. Boyden, private communication, 1989]. Although our objective is to learn how well the IPS speeds and magnetically derived speeds are related at high latitude, we shall begin by calibrating them against in-ecliptic measurements by near-Earth spacecraft.

Figure 1 shows six-rotation running means of the UCSD, MWO, and spacecraft speeds. (We emphasize that the UCSD and MWO data shown here refer to the ecliptic latitude of Earth, as distinguished from 0° heliographic latitude.) In the top panel the UCSD speed (solid line) is well correlated with the in situ speed (dashed line) but lies about 12% lower, consistent with previous analyses [*Coles et al.*, 1978; *Watanabe*, 1989]. The correlation coefficient is 0.87. The middle panel shows the agreement when the UCSD speed has been increased by 12%. Only slight discrepancies
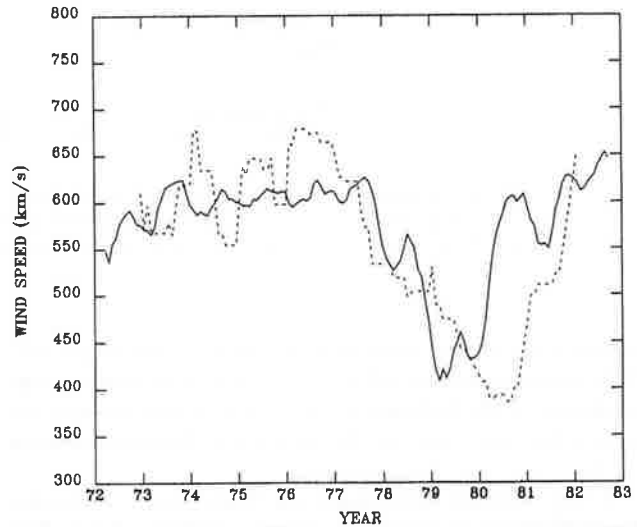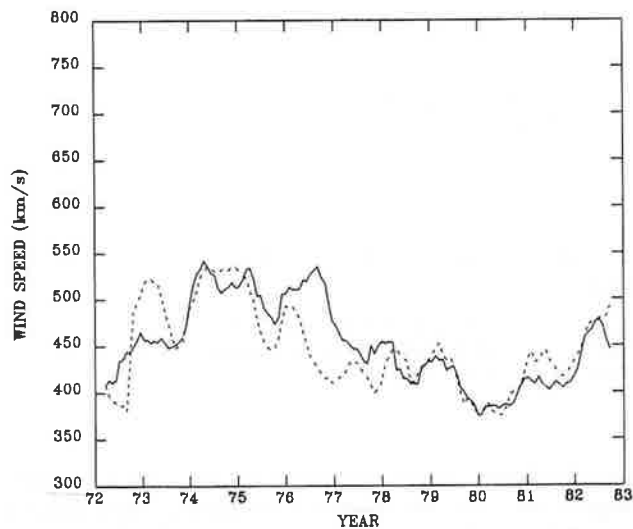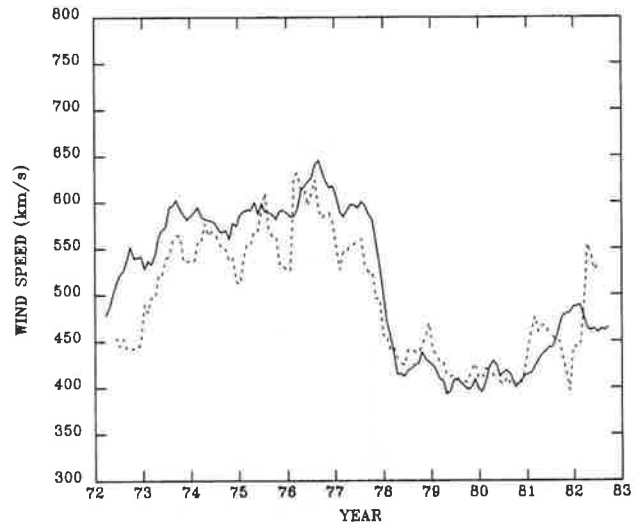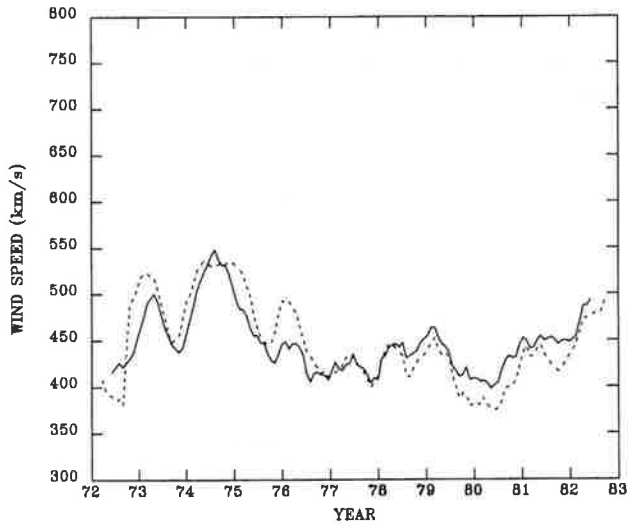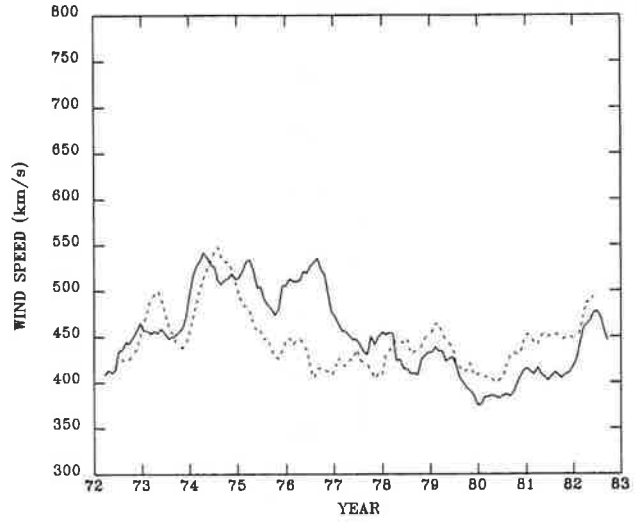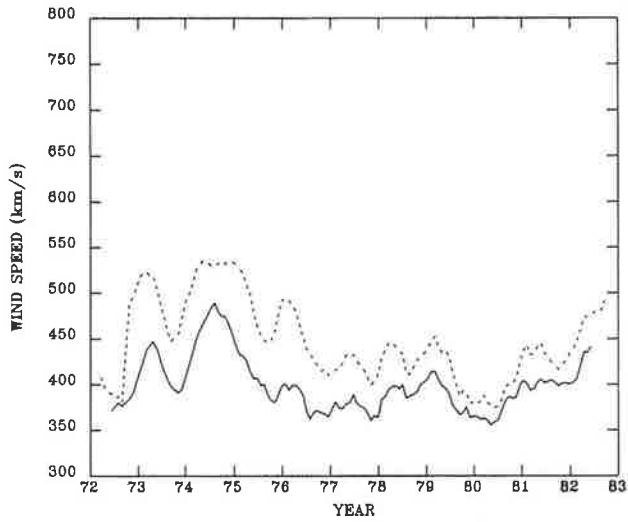
Fig. 1. Six-rotation running means of in-ecliptic wind speed inferred from UCSD IPS measurements and derived from MWO magnetic field measurements, showing how these quantities compare with in situ measurements during 1972–1982. (Top) Uncorrected IPS speed (solid line) and in situ speed (dashed line). (Middle) Same as top panel except IPS speed has been increased by 12%. (Bottom) Magnetically derived speed (solid line) and in situ speed (dashed line).

Fig. 2. A comparison of the corrected IPS speeds (dashed lines) and the magnetically derived speeds (solid lines) during 1972–1982 (top) in the ecliptic, (middle) at 30°N, and (bottom) at 60°N.
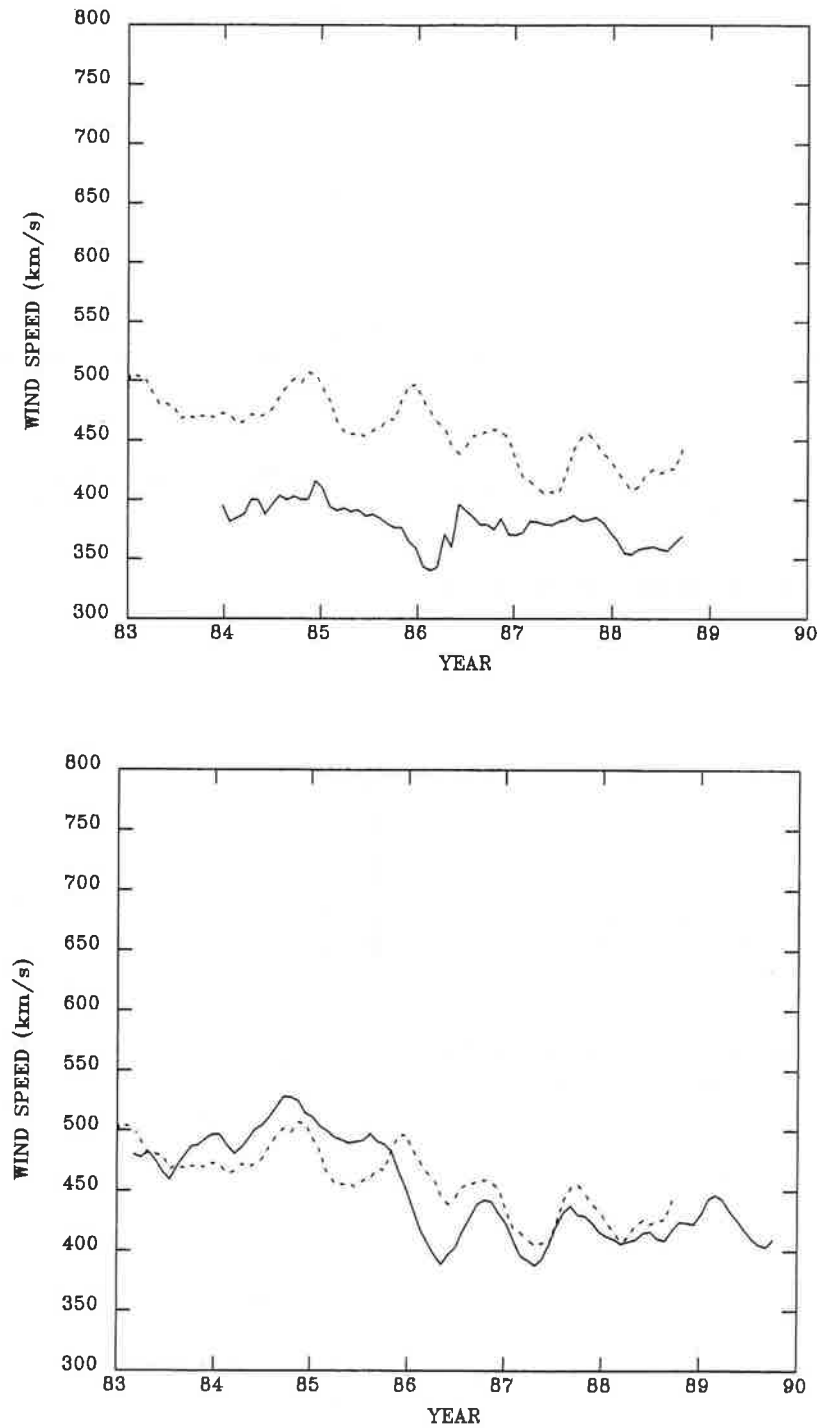
Fig. 3. Six-rotation running means of in-ecliptic wind speed inferred from Nagoya IPS measurements and derived from WSO magnetic field measurements during 1983–1989. (Top) Uncorrected IPS speed (solid line) and in situ speed (dashed line). (Bottom) Magnetically derived speed (solid line) and in situ speed (dashed line).

remain in the short-term variations. In the bottom panel the MWO speed (solid line) shows an overall agreement with the in situ speed (dashed line) but has some short-term discrepancies that give rise to the lower correlation coefficient (0.74).

Having seen how the UCSD and MWO speeds each compare with the in situ speed, we next see in Figure 2 how they compare with each other, both in the ecliptic and at 30°N and 60°N latitude. In the ecliptic (top panel), the gradual rise and

fall of the MWO speed (solid line) during the sunspot cycle is roughly matched by that of the UCSD speed (dashed line), but several short-term discrepancies are also present. The correlation coefficient is only 0.51. At 30°N latitude (middle panel), the speeds show a more pronounced variation that is nearly bimodal, with fast wind centered around 1975 near sunspot minimum and slow wind around 1980 near sunspot maximum. This greater range of speeds is partly responsible for the relatively high correlation coefficient of 0.89.
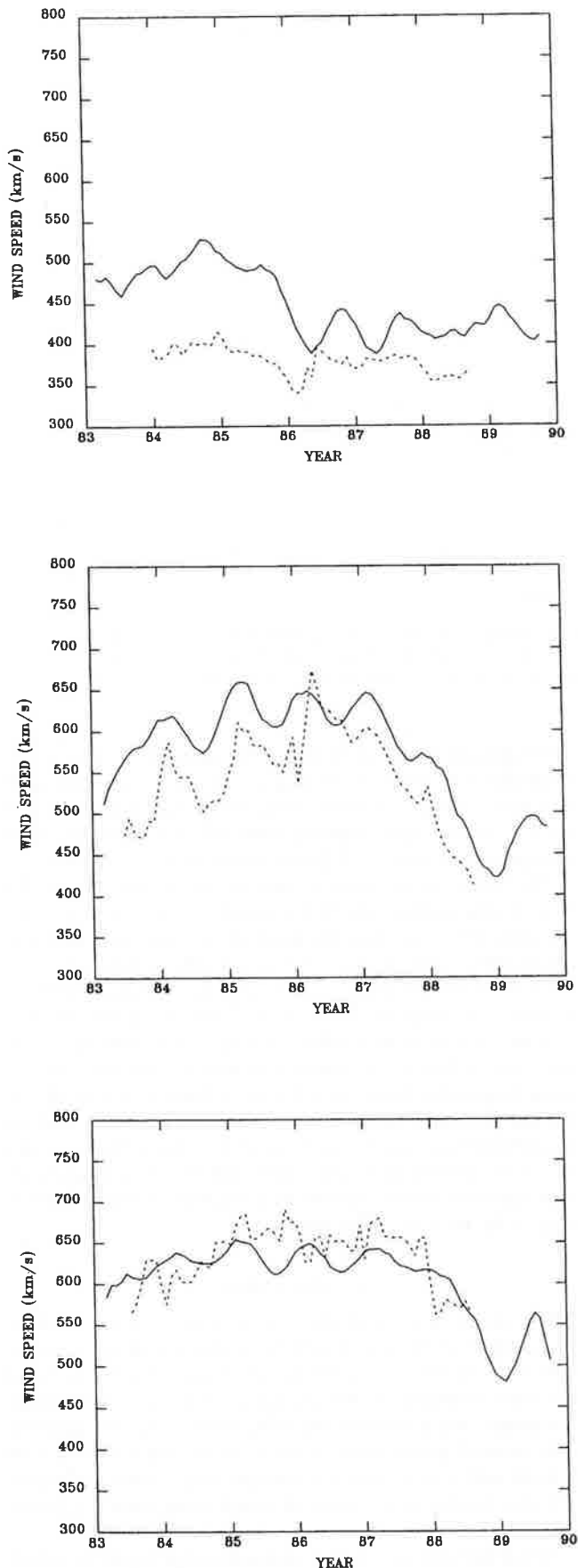
At 60°N latitude (bottom panel), fast wind tends to fill in the temporal profile, leaving only a few years of low speed around sunspot maximum. This filling-in is more pronounced for the MWO speed, principally owing to its faster recovery in 1981, reducing the correlation coefficient to 0.58. Although we do not know the reason for this faster recovery, we know that it also occurred in the WSO-derived speed, so that it is not an artifact of the MWO observations alone. Also, the discrepancy is probably not the result of the greater latitudinal resolution of the magnetically derived speeds because little change occurs when the MWO speeds at 60°N latitude are averaged with those at 50°N and 70°N.

Next, we proceed to the Nagoya-inferred and WSO-derived speeds during 1983–1989. Figure 3 compares these speeds with the in-ecliptic speed near Earth, again using six-rotation running means. In the top panel the Nagoya speed (solid line) and the in situ speed (dashed line) both show a slight downward trend, but the Nagoya speed is 19% smaller. Also, the Nagoya speed does not show the quasi-annual enhancements visible in the profile of in situ speed during these years around sunspot minimum. This lack of short-term agreement combines with the relatively low range of speeds to produce a correlation coefficient of only 0.44.

In the bottom panel the WSO speed (solid line) is relatively well correlated with the in situ speed (dashed line), showing the same downward trend and nearly synchronous annual variations. This agreement on the short time scale is apparently responsible for the relatively large correlation coefficient of 0.80, despite the relatively small range of speeds. Corresponding in-ecliptic variations are also present in the MWO-derived speed during this time (not shown here). We might expect such annual variations of wind speed in these years around sunspot minimum as the Earth wanders back and forth across the strong latitudinal gradient near the Sun's equator.

Next, in Figure 4, we show how the WSO and Nagoya speeds compare with each other, again using six-rotation running means. (Because the Nagoya speed required such a large in-ecliptic correction (19%) and because it was so poorly correlated with the in situ speed, we have not applied this correction in the comparison with the WSO speeds in Figure 4.) The in-ecliptic comparison (top panel) has a correlation coefficient of 0.66, which is probably fortuitously high, given the correlation coefficient of 0.44 that we found between the Nagoya and the in situ speeds shown in the top panel of Figure 3.

At 30°N latitude (middle panel), the agreement is much better (0.84), perhaps owing in part to the wider range of speed and in part to the presence of similar annual variations. However, annual variations are not expected in such heliographic displays, suggesting that they must be spurious in both data sets. Although we do not know the origin of the WSO annual variations, we suspect that they result from rebinning coarse measurements that were originally obtained in the ecliptic coordinate system. The higher-resolution MWO measurements do not show such pronounced out-of-ecliptic variations, except at latitudes greater than 60°, where the poorly determined polar fields begin to exert their influence. Although we do not know the origin of the IPS variations either, we suppose that they reflect the seasonal availability of acceptable radio sources.

At 30°N latitude, both profiles show fast speed in the years around sunspot minimum and low speed near sunspot maximum in 1989. In general, the WSO speed is greater than the

Fig. 4. A comparison of the uncorrected Nagoya IPS speeds (dashed lines) and the WSO magnetically derived speeds (solid lines) as follows: (top) in the ecliptic, (middle) at 30°N, and (bottom) at 60°N.
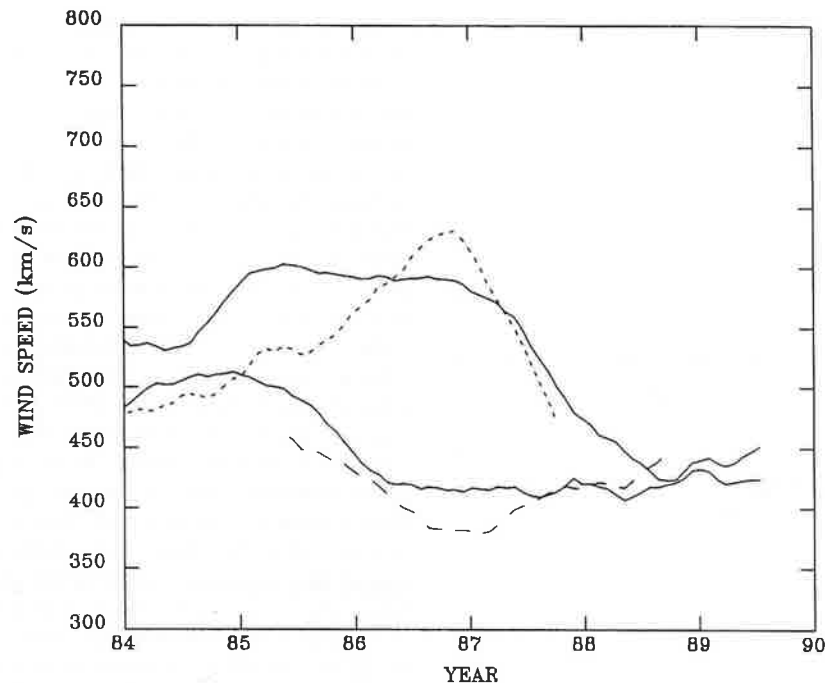
Fig. 5. Thirteen-rotation running means of wind speed in the ecliptic and at 16°N during the years around sunspot minimum. The Voyager 2 in-ecliptic observations (long-dashed line) and the Pioneer 11 observations at 16°N (short-dashed line) are compared with WSO magnetically derived speeds at the corresponding latitudes (solid lines).

Nagoya speed, but the overall correction factor of 8% is much less than the 19% that was required in the ecliptic plane. Also, the speed during 1989 is somewhat higher than that obtained with the MWO and UCSD speeds at the time of the 1980 sunspot maximum (compare Figure 2, middle panel). We suppose that this is a real difference, perhaps indicating that the minimum-speed era had not quite arrived by 1989, or perhaps simply indicating a more frequent occurrence of long-lived coronal holes and accompanying wind streams during the recent era.

At 60°N latitude (bottom panel), both profiles are dominated by fast wind, except in 1989, where the WSO speed (solid line) falls to a minimum value of about 470 km s^{-1} (which again is considerably larger than the previous minimum value of only 400 km s^{-1} in 1980 (compare Figure 2, bottom panel)). Although the WSO and Nagoya speed profiles seem to be in relatively close overall agreement at this latitude, their short-term variations and low speed ranges conspire to produce a correlation coefficient of only 0.60.

3.2. Comparisons With Out-of-Ecliptic Spacecraft Measurements

In this section, we compare magnetically derived wind speeds with in situ speeds measured by the Pioneer 11 and Voyager 2 spacecraft during 1984–1988. During this time, P11 was moving out of the heliosphere at a nearly constant heliographic latitude of 16°N. Its longitude and its radial distance at about 20 AU were comparable to those of V2, which was still in the ecliptic plane moving toward an August 1989 encounter with Neptune. Thus during 1984–1988, wind speed measurements from V2 provide a useful in-ecliptic contrast with the P11 measurements at 16°N.

Figure 5 shows wind speed from P11 (short-dashed line) and V2 (long-dashed line) during 1984–1988 and corresponding WSO-derived speeds at 16°N latitude and in the ecliptic plane (solid lines). One-year (13-rotation) running means were used to remove annual variations. The obvious separation between the P11 and V2 speeds during 1985–1987 has been described previously by *Gazis et al.* [1988] and *Barnes et al.* [1989].

The WSO speeds have a similar separation during this time. In the ecliptic the WSO speed is only slightly faster than the V2 speed through most of this interval, and it is comparable to the in situ speed near Earth (not shown here). At 16°N the WSO speed is about 50 km s^{-1} larger than the P11 speed during 1985 and 25 km s^{-1} smaller toward the end of 1986. The overall tendency for the in-ecliptic speed to decrease suddenly at sunspot minimum and the higher-latitude speed to decrease a few years later was also shown by the IPS measurements, as seen in Figure 4 and as described previously by *Coles et al.* [1980] and *Kojima and Kakinuma* [1987]. It is consistent with the global pattern of WSO-derived speed shown in a multiple-latitude Bartels display by *Wang et al.* [1990].

4. DISCUSSION

The main purpose of this study was to learn whether currently available out-of-ecliptic measurements are consistent with the inverse correlation between wind speed and flux tube divergence, already obtained for in-ecliptic measurements. We found that the IPS, Pioneer 11, and magnetically derived speeds showed the same overall variation with latitude and time during the sunspot cycle, with the higher latitudes having more years of faster wind than the lower latitudes.

This long-term variation is summarized in Figure 6, which combines UCSD and MWO speeds from Figure 2 with Nagoya and WSO speeds from Figure 4. Also, the MWO-derived speed has been extended to 1987 and thus provides
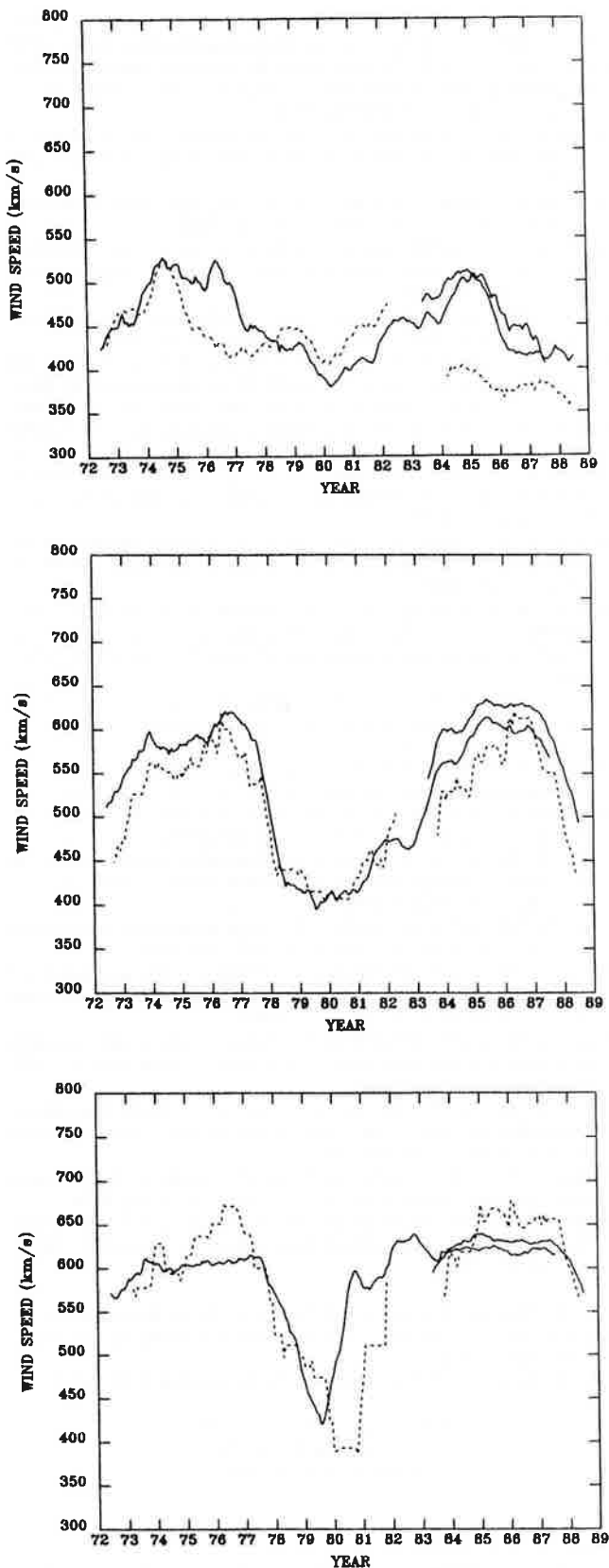
Fig. 6. Thirteen-rotation running means of IPS speed (dashed lines) and magnetically derived speed (solid lines) for the combined interval 1972–1988, illustrating the variation during the sunspot cycle. (Top) In-ecliptic speeds. (Middle) Speeds at 30°N. (Bottom) Speeds at 60°N. At each latitude the UCSD speeds have the same 12% correction shown in the preceding figures, and the Nagoya speeds are uncorrected. During 1983–1987 the overlapping plots of WSO and MWO speed differ by less than about 25 km s⁻¹.

a 5-year overlap with the WSO speed. Consistent with Figures 2 and 4 and as discussed below, the UCSD speeds have been corrected (increased) by 12% at all latitudes, whereas the Nagoya speeds are uncorrected. Thirteen-month running means have been used to remove the annual variations that were present in the preceding figures.

. Overall, the IPS and magnetically derived speeds (dashed and solid lines, respectively) both show the familiar pattern of high speed in the years around sunspot minimum and low speed at sunspot maximum. The amplitude of this 11-year variation becomes more pronounced away from the ecliptic, and at 30°N latitude the rise to maximum speed takes a few years longer than the fall to minimum speed (consistent with the fact that the rise to maximum speed occurs during the declining phase of the sunspot cycle, which is longer than the rising phase). At 60°N latitude the speeds were always fast except for a brief interval at sunspot maximum.

Although Figure 6 illustrates the overall agreement between the magnetically derived speeds (solid lines) and the IPS speeds (dashed lines), it also illustrates our difficulty in reconciling the Nagoya speeds at high and low latitude during 1984–1988. The application of a 19% correction would remove the obvious in-ecliptic discrepancy (top panel) but destroy the agreement already obtained at 30°N and 60°N latitude (middle and bottom panels, respectively). In fact, the resulting high-latitude discrepancy would be so great that it could not be removed by changing the calibration of the MWO and WSO speeds without simultaneously destroying their agreement with the in situ speed in the ecliptic plane and with the UCSD speed at all latitudes. It is interesting to note that the published maps of uncorrected Nagoya speed during 1984–1986 also show relatively low values in the ecliptic plane [*Kojima and Kakinuma*, 1986, 1987]. As was discussed recently by *Rickett and Coles* [1991], there are a number of effects that may potentially bias the IPS speeds when the signals originate from regions of differing velocity along the line of sight. In such cases, one would not expect a single correction factor to reconcile differences between IPS and in situ speeds.

Another of our objectives was to see if we could find localized pockets of very fast wind that arise from regions of low flux tube divergence and are a signature of this inverse relation between wind speed and coronal flux tube divergence. We would have expected them to appear at high latitudes just after polar field reversal and then to migrate equatorward as the sunspot cycle progressed [see *Wang et al.*, 1990]. Toward sunspot minimum, their signatures become visible in the ecliptic as the familiar recurrent high-speed streams [*Wang and Sheeley*, 1990a, b; *Sheeley and Wang*, 1991]. Such in-ecliptic streams have been well documented in temporally resolved IPS data (see, e.g., *Rickett and Coles* [1991]) but are not visible in the figures of this paper owing to the large amount of spatial and temporal averaging. Although the higher-latitude IPS data may require some averaging owing to their lower sampling rate, it is still possible to resolve longer-lived solar wind features provided that spatial resolution is retained in the temporal averaging. Indeed, some out-of-ecliptic concentrations of fast wind are visible in 6-month averages of IPS speed during 1973–1986 [*Kojima and Kakinuma*, 1986, 1987], and it seems likely that similar features would have been visible in corresponding displays of magnetically derived speed.

Finally, we note that during the preparation of this paper,

Wang and Sheeley [1991] found a way to understand the inverse correlation between wind speed and coronal expansion factor in terms of a model in which Alfvén waves boost the wind to high speeds. In essence, they explain the correlation in terms of a photospheric constraint on the wave energy flux, which they assume is distributed approximately uniformly over the coronal base, and a coronal constraint on the mass flux, which is determined by the requirement that the flow pass through the solar wind critical point and thus be independent of the coronal expansion factor. Consequently, a low-divergence flux tube would have an enhanced energy flow at the critical point without having an enhanced mass flow there and would thereby give rise to relatively fast wind as the wave energy is converted into bulk flow at greater radial distances. If this explanation proves to be correct, it will provide further motivation for comparing out-of-ecliptic wind speeds with corresponding speeds derived from observations of the Sun's photospheric magnetic field.

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