Comparison of Winds Derived from the LIMS Satellite Instrument with Rocket Observations

Anne K. Smith
This report contains statistical comparisons of horizontal winds derived from the LIMS satellite instrument with wind profiles from a large number of meteorological rocket soundings. Several methods of determining winds from geopotential height fields are included. The results give an indication of the accuracy of horizontal wind fields computed from satellite data.

P. L. Bailey supplied the rocket wind profiles in an accessible format. L. V. Lyjak smoothed the LIMS geopotential height fields and computed the mean meridional winds. Partial support for this work was provided by NASA Grant W-15439.
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INTRODUCTION

This report evaluates the accuracy of winds derived from daily mapped fields of data from the Limb Infrared Monitor of the Stratosphere (LIMS). There are two matters which are considered: 1) the determination of the best of several algorithms for computing horizontal winds from the LIMS data, and 2) the evaluation of the computed LIMS winds compared with in situ rocket measurements. Section II of this report discusses the data sets used in the comparisons. Sections III and IV explain the methods used for computing zonal and meridional winds from the LIMS data, and present a few individual profiles which illustrate the different methods. These are used to subjectively select the best method for determining horizontal winds.

Overall results are contained in Section V, which presents average zonal and meridional winds and rms errors for each of 4 latitude zones (20°S-20°N, 20°N-40°N, 40°N-60°N, and 60°N-80°N) and 7 periods (25 October-30 November 1978, and monthly for December 1978 through May 1979). The LIMS winds presented include both the geostrophic wind and that which includes higher order terms. As can be seen from these figures, the wind calculated with additional terms is sometimes, but not always, superior to the geostrophic wind.
Chapter 1: Data

Geopotential height data from LIMS are available in synoptic form daily at 1200 GMT for the period 25 October 1978 through 28 May 1979. The data have 13 spectral coefficients (zonal mean and 6 zonal wave-numbers) for every 4° latitude between 64°S and 84°N. There are 17 pressure levels: 100, 70, 50, 30, 16, 10, 7, 5, 3, 2, 1.5, 1, 0.7, 0.5, 0.4, 0.2, and 0.1 mb. Leovy et al. discuss the comparison of the temperature and height fields with NMC data and with selected rocket profiles. The geopotential heights used here have been smoothed in latitude with a least squares cubic spline, applied independently for each spectral coefficient and pressure level. Smoothing of some kind was found to be necessary to reduce the random noise in meridional derivatives used in computing the zonal wind. LIMS profiles were interpolated linearly to the latitudes of the rocket stations. No interpolation in time was performed, so LIMS and rocket soundings can be as much as 12 hours apart.

The comparison data consist of all available rocket soundings which include measurements of pressure and horizontal winds. Rawinsondes which coincided with rocket soundings are also included in the comparisons. The comparisons include data from 14 stations which range from the tropics to high northern latitudes. Table 1 lists the latitudes and longitudes of the rocket stations, and the number of soundings per month. These data were interpolated in log pressure to the 17 pressure levels at which LIMS data were available. No vertical extrapolation was performed, so many of the rocket soundings do not cover the full range from 100 to 0.1 mb.
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A few rocket profiles (about 10 out of a total of more than 800) were rejected because of obvious bad points. Most of these were at high latitudes (primarily Thule, Greenland and Primrose Lake, Canada). In addition, single bad points were disregarded from soundings at other stations. There were a number of other soundings which were not rejected, but which appeared to be excessively noisy, especially in the upper stratosphere and lower mesosphere. While the contribution of this noise to differences in LIMS and rocket winds averaged over a large number of soundings is probably small, the contribution to the rms difference is large.

Table 2 gives the average time difference between the LIMS and rocket soundings for each time period and station. All LIMS soundings are at the map time of 1200 GMT; the rocket times are variable. The time interval is greatest for stations closest to the international dateline (Kwajalein, Barking Sands, Shemya, and Poker Flats). No clear correlation between average time difference and mean or rms error was found.
Table 2.

<table>
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Chapter 2: Zonal Wind Calculations

The simplest and most commonly used method of computing winds from satellite data is to use the geostrophic approximation. For this, the instantaneous horizontal structure of the geopotential is needed. There are additional terms that can be incorporated into the determination of zonal \((u)\) or meridional \((v)\) wind, while still only requiring knowledge of the instantaneous height field at a particular level. The gradient wind correction to the zonal wind is sometimes used for calculating the zonal mean wind (e.g., Kohri, 1981; Leovy et al., 1984). The gradient wind includes the centrifugal force as well as the pressure gradient and Coriolis forces. For horizontal wind that is purely zonal, the centrifugal force results from flow around a particular latitude on a sphere.

\[
f_u + u^2 \tan \theta \frac{\tan \theta}{a} + \frac{1}{a} \frac{\partial \phi}{\partial \theta} = 0
\]  

(1)

where \(f\) = Coriolus parameter

\(\theta\) = latitude

\(a\) = radius of the earth

\(\phi\) = geopotential

The gradient wind is given by

\[
u = \frac{fa}{2 \tan \theta} \left[ -1 + \sqrt{1 + \frac{4 \tan \theta}{fa} u_{geo}} \right]
\]

(2)

where \(u_{geo}\) is the geostrophic zonal wind. It is clear from Eq. 1 that the gradient wind is always less (more easterly) than the geostrophic zonal wind.

Quiroz (1981) found that the zonal mean gradient wind differed from the zonal mean geostrophic wind by up to 8 m s\(^{-1}\) in the high latitude
winter stratosphere. Kohri (1981) found differences of more than 15% (more than 15 m s\(^{-1}\)) in the jet core for the mean wind of December 1975, as well as large percentage differences (15-20%) at high latitudes. Since the gradient wind is always less than the geostrophic wind, there are systematic differences between them even when averaging over a large number of soundings.

All of the terms which have been neglected from the horizontal momentum equation in order to get (1) depend on the meridional or vertical velocity. These cannot be included without considerable complication to the calculations. With the scaling normally assumed for the winter stratosphere, which is that the mean zonal wind is an order of magnitude larger than the meridional and vertical wind and the eddy zonal wind, neglect of these terms should still give approximately correct results for \(u\). However, the gradient wind differs most from the geostrophic wind in high latitudes, which is the region in which linearization around the zonal mean wind is least valid (i.e., the approximation \(|u'| \ll |\bar{u}|\) is poorest where \(\bar{u} = \frac{1}{2\pi} \int_0^{2\pi} u \, d\lambda\) and \(u = \bar{u} + u'\)). Eq. 1 is sometimes linearized, so that

\[
\frac{f \bar{u}}{\bar{u}^2} \frac{\tan \theta}{a} + \frac{1}{a} \frac{\partial \bar{u}}{\partial \theta} = 0,
\]

and

\[
\bar{u} = \frac{fa}{2\tan \theta} \left[ -1 + \sqrt{1 + \frac{4\tan \theta}{fa} \bar{u}_{geo}} \right]. \tag{3}
\]
In high latitudes this linearization can cause errors that are as
dlarge or larger than the gradient correction itself. This is illustrated
in Fig. 1 for Thule, 10 January. The geostrophic wind is superior to
the wind calculated using Eq. 3. (The gradient wind calculated from
Eq. 2 is almost identical to the geostrophic wind.) The zonal mean
wind is clearly different by a large amount from the local zonal wind
speed. Because of this problem, I suggest that the gradient wind
correction not be used as given in (3). The correct form of the zonal
mean gradient wind is

\[ \bar{u} = \frac{f_a}{2\tan \theta} \left[ -1 + \sqrt{1 + \frac{4\tan \theta}{f_a} \left( \bar{u}_{\text{geo}} - \frac{\tan \theta}{f_a} \bar{u}'^2 \right)} \right]. \]

Using the geostrophic approximation to determine \( \bar{u}'^2 \) should be adequate.

Both geostrophic and gradient (see Eq. 2) zonal winds are shown on
the comparison figures in Section V. In general the gradient correction
results in small systematic improvements in the LIMS winds, although in
a few cases the geostrophic wind is better.
Fig. 1. Zonal wind at Thule on 10 January 1979.
Chapter 3: Meridional Wind Calculations

The relative angular momentum gradient, as well as that due to planetary rotation (Coriolus force), can be included in the determination of the meridional wind \(v\).

\[
v \frac{\partial u \cos \theta}{\partial \theta} - fv + \frac{1}{\cos \theta} \frac{\partial \phi}{\partial \lambda} = 0
\]

which gives

\[
v = \frac{1}{\gamma} \frac{1}{\cos \theta} \frac{\partial \phi}{\partial \lambda}
\]

Equation 4 gives only the eddy component (\(v'\)) of the meridional wind; the zonal mean component (\(\bar{v}\)) is identically zero. The \(v'\) from Eq. 4 will be smaller than the geostrophic wind on the equatorward side of a zonal jet, and larger on the poleward side. The relative difference is largest in low latitudes where the magnitude of the relative change \((f-\gamma)/f\) is largest. In particular, where \(\gamma \approx 0\), Eq. 4 can approach infinity. While the correction given by Eq. 4 can result in improvements in \(v\), especially in low and middle latitudes, it can cause severe problems for particular soundings. Figure 2a, which is a sounding at Kwajalein (8.7°N), illustrates this problem. There is obviously a large error in the meridional wind at 50 mb calculated from Eq. 4, which results from a small value of \(\gamma\).

In some instances the meridional wind calculated from Eq. 4 is superior to the geostrophic wind (Fig. 3a, also for Kwajalein). In
Fig. 2a. Meridional wind at Kwajalein on 10 January 1979.
The LIMS higher order \( v \) is derived from Eq. 4.
Fig. 2b. As in Fig. 2a, except that the LIMS higher order $v$ is derived from Eq. 5 with $\varepsilon = 0.5$. 

A = LIMS geostrophic $v$
B = rocket $v$
C = rawinsonde $v$
D = LIMS higher order $v$
Fig. 3a. As in Fig. 2a, but for Kwajalein on 13 December 1978.
Fig. 3b. As in Fig. 3a, except that the LIMS higher order $v$ is derived from Eq. 5 with $\epsilon = 0.5$. 
order not to neglect this additional information, a cutoff limit for $f$ was used. The ratio $|\hat{f}|/|f|$ was restrained to be less than or equal to the cutoff

$$|\hat{f}| = \frac{1}{\cos \theta} \frac{3}{\theta} u \cos \theta \quad |\hat{f}| \geq \epsilon |f|^3$$

(5)

|\hat{f}| = \epsilon |f| \quad \text{otherwise}

(sign of $\hat{f}$ determined by sign of $f - \frac{1}{\cos \theta} \frac{3}{\theta} u \cos \theta$)

Experiments with this cutoff limit showed that $\epsilon = 0.1$ was too small, but that with values of $\epsilon = 0.33$ and $\epsilon = 0.5$ there were no severe problems. The best overall results (i.e., the results with the smallest mean error) are obtained with $\epsilon = 0.5$, and this value will be used hereafter. Figures 2b and 3b show the same soundings as in Fig. 2a, 3a but $\hat{f}$ defined by Eq. 5. The spike in the 10 January wind has been eliminated while the 13 December winds remain the same. The meridional wind is now superior to the geostrophic wind in both cases.

It should be noted that while the limit $\epsilon = 0.5$ eliminated the problem cases for the $v$ calculated to coincide with available rockets, there is no guarantee that problems would not exist at other times and/or locations than those examined. Therefore calculation of $v$ using Eqs. 4-5 should be done with caution for tropical latitudes.

The zonal mean meridional wind determined from the geostrophic approximation (or from Eq. 4) is identically zero. However, the mean meridional circulation during active periods in the winter high-latitude
stratosphere can be quite strong. The effect of \( \bar{v} \) on the meridional wind comparisons was determined by computing the mean meridional circulation. Using the geostrophic \( u \) and \( v \), the thermodynamic equation was used to determine the vertical wind \( w \) as a residual.

\[
\left( \frac{\partial}{\partial t} + \frac{u}{\cos \theta} \frac{\partial}{\partial \lambda} + \frac{v}{a} \frac{\partial}{\partial \theta} \right) T + w \left( \frac{\partial T}{\partial z} - \frac{\kappa T}{H} \right) = J
\]

where \( z \) is log pressure, \( J \) is diabatic heating rate. For this calculation, the three dimensional structure and temporal change of the temperature field, and the diabatic heating rate are required. The zonal mean vertical wind was then used in the continuity equation to determine \( \bar{v} \).

\[
\frac{1}{\cos \theta} \frac{\partial}{\partial \theta} \bar{v} \cos \theta + \frac{1}{\rho} \frac{\partial}{\partial z} \rho \bar{w} = 0
\]

The appropriate boundary condition is \( \bar{v} = 0 \) at \( \theta = 90^\circ \).

The typical structure of the mean meridional circulation in the winter stratosphere has poleward \( \bar{v} \) in low and middle latitudes (Hadley cell) and equatorward \( \bar{v} \) in high latitudes (Ferrel cell). This results in changes to the calculated \( v \) in middle and high latitudes which tend to be of opposite sign to those due to Eq. 4. A comparison of these changes in computing \( v \) is shown in Fig. 4 for a high latitude case during the period in which \( \bar{v} \) was strongest. The mean meridional circulation on this date was probably larger than would be encountered in the stratosphere except during sudden warmings.
Fig. 4. Meridional wind at Thule for 22 January 1979. The LIMS higher order v includes the geostrophic v and the zonal mean v (Eq. 6).
The meridional wind profiles shown in the next section include the correction due to $\bar{v}$, and the change in $v'$ from Eqs. 4-5. The higher order meridional wind is given by

$$v = \bar{v} + \frac{1}{\gamma} \frac{1}{\cos \theta} \frac{\partial \phi}{\partial \lambda}$$

$$\gamma = f - \frac{1}{\cos \theta} \frac{\partial}{\partial \theta} \frac{\partial \phi}{\partial \lambda}$$

for $|\gamma| \leq .5|f|$ \hspace{1cm} (7)

$$|\gamma| = \epsilon |f| \text{ for } |\gamma| < .5|f|$$
Chapter 5: Statistical Results

Plots in this section are statistical results involving all rocket soundings and the corresponding LIMS geostrophic and higher order winds. The higher order winds are determined from Eq. 2 (zonal) and Eq. 7 (meridional). Results are presented separately for each latitude zone and month (with October 25-31 included in the November averages). Mean values and rms differences of zonal and meridional winds are included. In determining the mean u and v, the only LIMS winds used are those at levels sampled by either the rocket or rawinsonde (or both) on that day. Since many of the rocket/rawinsonde soundings do not extend over the entire vertical range, the means at any particular level can contain less than the total number of soundings (indicated by the value of N given at the top of each plot). The large rms differences are at least in part due to the jagged nature of the rocket profiles (c.f. Figs. 1-4).

An estimate of the daily variations in rocket measurements can be determined from a study by Kao and Schmidlin (1976). They used wind data from meteorological rockets which were launched at 3 hour intervals over a 24 hour period, and determined variance as a function of height at two tropical stations: Natal, Brazil and Kourou, French Guiana. They found variance in the zonal and meridional wind speeds in the range of 5-50 m$^2$/sec$^2$, with a maximum of >75 m$^2$/sec$^2$ for the meridional wind speed at 60 km at Kourou. The variance includes the effects of instrument noise and of temporal changes (including tides and atmospheric turbulence). These measurements suggest that some of the LIMS-rocket rms differences (up to 7-8 m/sec) may be attributed to temporal variations and/or to variability in the rocket measurements.
In general the mean winds compare quite well at all latitude zones and months. Differences in geostrophic and higher order LIMS winds are not large, but the added terms give significant improvement in some cases (see December mean $u$ at 20°-40°N, and mean and rms $v$ at 20°S-20°N). The gradient correction to the zonal wind is simple to incorporate, and results in an overall improvement in the comparisons. The ageostrophic contributions to the meridional wind are more difficult to apply, but can result in substantial changes to the estimated wind speed.

Suggestions for deriving winds from satellite data are:

1) If the actual zonal wind speeds are needed, include the gradient correction to $u$; if a qualitative picture of spatial or temporal variations is needed, the geostrophic wind is probably adequate. Depending on the degree of smoothing implicit in the method of synoptic mapping, some latitudinal smoothing of the height fields may be necessary before differentiation.

2) Computation of the mean meridional circulation is sometimes necessary for understanding transports or dynamical processes. However, $\bar{v}$ is generally small compared with $v$; so it does not have a large effect on local wind speed variations derived from satellite data.

3) The relative rotation rate contribution to $v'$ is sometimes substantial, especially in the tropics and subtropics. If accurate meridional winds in these regions are needed, then some way of evaluating the contribution of this additional term would be advised. The method suggested in this report is
one possible way of including the effects of zonal wind shear while avoiding singularities which can result from the formulation. Overall, no clear improvement (and no degradation) in the rms error is gained by including this higher order term.


A = LIMS geostrophic $u$
B = rocket $u$
C = rawinsonde $u$
D = LIMS gradient $u$

A = LIMS geostrophic - rocket $u$
B = LIMS geostrophic - rawinsonde $u$
C = LIMS gradient - rocket $u$
D = LIMS gradient - rawinsonde $u$
A = LIMS geostrophic $v$
B = rocket $v$
C = rawinsonde $v$
D = LIMS higher order $v$
LATITUDE BAND 20N-40N
OCT-NOV MEAN U N=44

LATITUDE BAND 20N-40N
OCT-NOV U RMS DIFF N=44

A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
LATITUDE BAND 20N-40N
OCT-NOV MEAN V N=44

LATITUDE BAND 20N-40N
OCT-NOV V RMS DIFF N=44

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
LATITUDE BAND 40N-60N
OCT-NOV MEAN V N=43

LATITUDE BAND 40N-60N
OCT-NOV V RMS DIFF N=43

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v
A = LIMS geostrophic $u$
B = rocket $u$
C = rawinsonde $u$
D = LIMS gradient $u$

A = LIMS geostrophic - rocket $u$
B = LIMS geostrophic - rawinsonde $u$
C = LIMS gradient - rocket $u$
D = LIMS gradient - rawinsonde $u$
LATITUDE BAND 20N-40N
DECEMBER MEAN V N=35
LATITUDE BAND 20N-40N
DECEMBER V RMS DIFF N=35

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
LATITUDE BAND 40N-60N
DECEMBER MEAN U N=20

LATITUDE BAND 40N-60N
DECEMBER U RMS DIFF N=20

A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
A = LIMS geostrophic \( v \)
B = rocket \( v \)
C = rawinsonde \( v \)
D = LIMS higher order \( v \)
A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
LATITUDE BAND 60N-80N
DECEMBER MEAN V N=9

LATITUDE BAND 60N-80N
DECEMBER V RMS DIFF N=9

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
A = LIMS geostrophic \( u \)
B = rocket \( u \)
C = rawinsonde \( u \)
D = LIMS gradient \( u \)

A = LIMS geostrophic - rocket \( u \)
B = LIMS geostrophic - rawinsonde \( u \)
C = LIMS gradient - rocket \( u \)
D = LIMS gradient - rawinsonde \( u \)
LATITUDE BAND 20S-20N
JANUARY MEAN V N=39

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

LATITUDE BAND 20S-20N
JANUARY V RMS DIFF N=39

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
A = LIMS geostrophic \( v \)
B = rocket \( v \)
C = rawinsonde \( v \)
D = LIMS higher order \( v \)
A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
LATITUDE BAND 40N-60N
JANUARY MEAN V N=29

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

LATITUDE BAND 40N-60N
JANUARY V RMS DIFF N=29

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
LATITUDE BAND 6ON-8ON

JANUARY MEAN V N 8

\( A = \text{LIMS geostrophic v} \)
\( B = \text{rocket v} \)
\( C = \text{rawinsonde v} \)
\( D = \text{LIMS higher order v} \)

LATITUDE BAND 6ON-8ON

JANUARY V RMS DIFF N 8

\( A = \text{LIMS geostrophic - rocket v} \)
\( B = \text{LIMS geostrophic - rawinsonde v} \)
\( C = \text{LIMS higher order - rocket v} \)
\( D = \text{LIMS higher order - rawinsonde v} \)
LATITUDE BAND 20S-20N
FEBRUARY MEAN U N=42

A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

LATITUDE BAND 20S-20N
FEBRUARY RMS DIFF N=42

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
LATITUDE BAND 20S-20N
FEBRUARY MEAN V N=42

LATITUDE BAND 20S-20N
FEBRUARY V RMS DIFF N=42

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
LATITUDE BAND 20N-40N
FEBRUARY MEAN U N=37

LATITUDE BAND 20N-40N
FEBRUARY U RMS DIFF N=37

A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
LATITUDE BAND 20N-40N
FEBRUARY MEAN V N=37

LATITUDE BAND 20N-40N
FEBRUARY V RMS DIFF N=37

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
LATITUDE BAND 40N-60N
FEBRUARY MEAN U N=33

LATITUDE BAND 40N-60N
FEBRUARY RMS DIFF N=33

A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
LATITUDE BAND 40N-60N
FEBRUARY MEAN V N=33
LATITUDE BAND 40N-60N
FEBRUARY V RMS DIFF N=33

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
A = LIMS geostrophic u  
B = rocket u  
C = rawinsonde u  
D = LIMS gradient u  

A = LIMS geostrophic - rocket u  
B = LIMS geostrophic - rawinsonde u  
C = LIMS gradient - rocket u  
D = LIMS gradient - rawinsonde u
A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
A = LIMS geostrophic \( v \)
B = rocket \( v \)
C = rawinsonde \( v \)
D = LIMS higher order \( v \)
A = LIMS geostrophic $u$
B = rocket $u$
C = rawinsonde $u$
D = LIMS gradient $u$
LATITUDE BAND 20N-40N
MARCH MEAN V N=40

LATITUDE BAND 20N-40N
MARCH V RMS DIFF N=40

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
LATITUDE BAND 40N-60N
MARCH MEAN U N=20

LATITUDE BAND 40N-60N
MARCH U RMS DIFF N=20

A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
LATITUDE BAND 40N-60N
MARCH MEAN V N=20

LATITUDE BAND 40N-60N
MARCH V RMS DIFF N=20

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v
A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
LATITUDE BAND 60°N-80°N
MARCH MEAN V N=22

LATITUDE BAND 60°N-80°N
MARCH V RMS DIFF N=22

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
LATITUDE BAND 20S-20N
APRIL MEAN U N=30

LATITUDE BAND 20S-20N
APRIL U RMS DIFF N=30

A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
LATITUDE BAND 20S-20N
APRIL MEAN V N=30

LATITUDE BAND 20S-20N
APRIL V RMS DIFF N=30

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v
A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u
LATITUDE BAND 20N-40N
APRIL MEAN V N=43

LATITUDE BAND 20N-40N
APRIL V RMS DIFF N=43

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
A = LIMS geostrophic \( u \)
B = rocket \( u \)
C = rawinsonde \( u \)
D = LIMS gradient \( u \)

A = LIMS geostrophic - rocket \( u \)
B = LIMS geostrophic - rawinsonde \( u \)
C = LIMS gradient - rocket \( u \)
D = LIMS gradient - rawinsonde \( u \)
LATITUDE BAND 40N-60N
APRIL MEAN V N=16

LATITUDE BAND 40N-60N
APRIL V RMS DIFF N=16

A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
\[ A = \text{LIMS geostrophic } u \]
\[ B = \text{rocket } u \]
\[ C = \text{rawinsonde } u \]
\[ D = \text{LIMS gradient } u \]
A = LIMS geostrophic $v$
B = rocket $v$
C = rawinsonde $v$
D = LIMS higher order $v$
LATITUDE BAND 20S-20N
MAY MEAN U N=34

LATITUDE BAND 20S-20N
MAY U RMS DIFF N=34

A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u

A = LIMS geostrophic - rocket u
B = LIMS geostrophic - rawinsonde u
C = LIMS gradient - rocket u
D = LIMS gradient - rawinsonde u
A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v
LATITUDE BAND 20N-40N

MAY MEAN U N=45

LATITUDE BAND 20N-40N

U RMS DIFF N=45

\[ A = \text{LIMS geostrophic} \ u \]
\[ B = \text{rocket} \ u \]
\[ C = \text{rawinsonde} \ u \]
\[ D = \text{LIMS gradient} \ u \]
A = LIMS geostrophic v
B = rocket v
C = rawinsonde v
D = LIMS higher order v

A = LIMS geostrophic - rocket v
B = LIMS geostrophic - rawinsonde v
C = LIMS higher order - rocket v
D = LIMS higher order - rawinsonde v
A = LIMS geostrophic $u$
B = rocket $u$
C = rawinsonde $u$
D = LIMS gradient $u$
A = LIMS geostrophic $v$
B = rocket $v$
C = rawinsonde $v$
D = LIMS higher order $v$
LATITUDE BAND 60N-80N
MAY MEAN U N=21

LATITUDE BAND 60N-80N
MAY U RMS DIFF N=21

A = LIMS geostrophic u
B = rocket u
C = rawinsonde u
D = LIMS gradient u
A = LIMS geostrophic \( v \)
B = rocket \( v \)
C = rawinsonde \( v \)
D = LIMS higher order \( v \)

A = LIMS geostrophic - rocket \( v \)
B = LIMS geostrophic - rawinsonde \( v \)
C = LIMS higher order - rocket \( v \)
D = LIMS higher order - rawinsonde \( v \)
References


