Long-Period Oscillations in Mesospheric and Lower Thermospheric Winds (60–110 km) at Saskatoon (52°N, 107°W, $L=4.3$)

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Winds from a medium-frequency radar (2.2 MHz) are available in tidally corrected form, on a daily basis, for 28 months from September 1978–December 1980. These data have excellent temporal resolution, and there are few gaps in the sequence. The amplitudes and phase progressions with height (60–110 km) are shown for the QBO, annual, semi-annual, terannual, 3-mth, and 27-d waves. The results for the first three oscillations are consistent with those from CIRA (1972) model data to near 100 km; above there are disagreements which are likely due to tidal contamination in that model.

1. Introduction

In an earlier study winds from this same location for heights from 65–118 km, and for the years 1969–76, were analysed (BELMONT and NASTROM, 1979): the features of the quasi-biennial and the first four harmonics of the annual wave were discussed. The winds were derived from a Medium Frequency Radar (2.2 MHz), operating in the partial reflection drift mode. All of the data were for local noon conditions, meaning that tidal influences (12-, 24-h) were present and could have contaminated the findings. Also, the method of analysis used for much of the data was a simple one, and as early as 1975 was replaced by the preferred “Full correlation analysis” method (MEEK *et al.*, 1979).

During 1978 a real-time processing and analysis system was developed (GREGORY *et al.*, 1979; MEEK, 1980; MEEK and SOIFERMAN, 1979), and beginning in September 1978 continuous winds data have become available. Wind calculations are made every 5 min for all suitable echoes in height ranges from ~60–110 km during the day, and ~75–110 km during the night. There is some seasonal variation in the heights of occurrence of suitable echoes, and more details are given elsewhere (GREGORY *et al.*, 1981). These winds data are available with very few gaps until early 1981 (the time of writing this report).

Some of the characteristics of these data have been extensively reported elsewhere. The winds have been combined into 1-h means, in 9 km vertical layers, and harmonic analyses applied to 24-h blocks. It has been found that providing at least 16 of the 24 hours are represented, the daily means and amplitudes and phases of the 24-, 12-h tides can be obtained. Layers at 80 km (75.5–84.5 km) and above are amenable to such

treatment. The monthly mean profiles of these exist for 1978/79 (MANSON *et al.*, 1981a; GREGORY *et al.*, 1981) and for 1979/80 (MANSON *et al.*, 1981b): there are typically 20 or more values for each layer of the monthly profiles. The data evidence great regularity of seasonal variation—a climatology has emerged—but underlying there is great variability of shorter period waves (e.g., gravity waves, $\tau \lesssim 6$ h) and longer period waves (planetary waves, $\tau \gtrsim 2$ d).

Here, for the first time, we use the daily mean, tidally corrected winds (~ 75 – 110 km) from a data set which is unique in its length (28 months) and continuity to ascertain features of long-period waves ($\tau \gtrsim 1$ mth). There are typically 500–600 days available for each layer, of a possible 850 days, so that all harmonics studied are very adequately represented. In the 60 to ~ 75 km region tidal corrections cannot be made on a daily basis throughout the year, so to match the temporal resolution above those heights, daily noon values (1-h mean) are used there. Our other studies, e.g., MANSON *et al.* (1981a, b), show the tidal amplitudes to be small there (~ 5 ms⁻¹) so little error is expected. The transition between these two regions will be carefully studied, below, for any indications of tidal contamination. In order to estimate the amplitudes and phases (time of maximum eastward and northward speed) of the QBO, the first four harmonics of the annual wave, and the 27-d wave, harmonic analysis was applied to the long data set of daily values: this is somewhat similar to that used by BELMONT and DARTT (1973). We also used spectral analysis to ascertain the sharpness or uniqueness of the peaks sought by the harmonic analysis.

2. Quasi-Biennial Oscillation (QBO)

As noted by BELMONT and NASTROM (1979), now called Paper 1, a QBO in zonal wind speed, in the lower thermosphere (~ 95 km), has been reported by workers in Berlin (VLF drifts), Japan (airglow), Adelaide (meteor winds), and Saskatoon (M.F. radar). Periods are typically 19–28 mths and amplitudes 1–15 ms⁻¹.

Fig. 1. The Quasi-Biennial Oscillation from zonal daily values (means, or noons). The times of eastward maxima are shown for the first day of each plotted month. The phase of the QBO ($\lesssim 80$ km) extrapolated from 1969–75 data (BELMONT and NASTROM, 1979) is shown.

Using our new data, tests with sinusoidal waves having periods ranging from 24–28 mths showed similar amplitudes and phases—however, we preferred 26 mths as the signal to noise of the fit (amplitude compared to residual) was largest there. The profiles in Fig. 1, show a mean amplitude of 2.5 ms^{-1} and a range of $1\text{--}3.5 \text{ ms}^{-1}$. The phases are fairly stable from 60–80 km, then change by -120° or $+240^\circ$ for 90–110 km (note the points on the graph are centres of 9 km layers). There is excellent agreement with Paper 1: they show a 180° phase shift near 90 km; and their phase dates of maximum speed near 80 km, extrapolated forward to 1979, assuming $\tau = 26 \text{ mth}$, matches our values well. This argues for a mean period of 26-mth. The only differences are their larger amplitudes above 110 km, which we prefer not to incorporate, as these data lie above the theoretical reflection height for our 2.2 MHz radio waves. Virtual height corrections and *E*-region data interpretation has not yet been possible locally (MANSON *et al.*, 1981a, b). The amplitudes of the meridional QBO are less than 1 ms^{-1} .

3. Annual Wave

It is immediately instructive to study the monthly mean profiles of daily zonal wind speeds (u) above $\sim 80 \text{ km}$, shown in cross-section form in Fig. 2 for 1979. Below 80 km noon values have to be used: the continuity across this height testifies to the smallness of tidal effects there. There is evidence for a strong annual wave below $\sim 90 \text{ km}$, and a weaker wave of reversed phase above that height. For comparison we show in Fig. 3, the cross-section for the noon zonal wind speed. Even up to 90 km there is little difference,

Fig. 2. Monthly mean zonal winds (ms^{-1}) for 1979: positive is the eastward flow. Daily mean values are used for heights $\geq 80 \text{ km}$.

Fig. 3. Monthly mean zonal winds (ms^{-1}) for 1979, using only local noon values.

Fig. 4. Monthly mean meridional winds (ms^{-1}) for 1979: positive is the northward flow.

but above, as the tidal amplitudes grow the differences become highly significant: the annual wave evident in Fig. 3 above 90 km is mainly due to tides. A careful assessment of the tides for 1979 (MANSON *et al.*, 1981a) show that the positive, eastward cell above 90 km in summer is due to the seasonal variation in phase of the 24-h diurnal tide, whose

Fig. 5. Amplitudes and phases of the zonal (EW) and meridional (NS) components of the annual, semi-annual, and 3-month waves.

amplitude is larger ($\sim 20 \text{ ms}^{-1}$) and phase more stable than many authors have suggested. The strong negative westward cell above 90 km, in summer months, is due to both 12- and 24-h tides. Note that the noon data of Belmont and Nastrom for 1969–76 has a similar seasonal variation to our Fig. 3, as is expected. The zonal winds at 50°N , in CIRA (1972), also show strong eastward values above 90 km in summer, again suggesting tidal contamination. For completeness we show the monthly mean meridional wind speeds in Fig. 4. There are systematic differences with the wind cross-sections shown in Paper 1.

In Fig. 5, we show the results of the harmonic analysis for zonal and meridional components. For the zonal, amplitudes are large and near 40 ms^{-1} up to 80 km, but decrease rapidly to a minimum near 100 km. As expected from Fig. 2, they do not increase strongly above 100 km. Up to 90 km the phase date is in December, but $\sim 100 \text{ km}$ is in the summer solstice. Our results compare well in amplitude and phase with those of GROVES (1972) up to $\sim 100 \text{ km}$, but we do not show his second maximum of 20 ms^{-1} near 105 km.

It is likely that this was due to tidal contamination, as demonstrated above in Figs. 2 and 3. Similarly, the amplitudes above 100 km in Paper 1 appear too large: our phase agreement is good up to there however.

Significantly, the amplitudes we show here below 90 km and also the strength of the winter eastward jet near 60 km (Figs. 2, 3), are now consistent with expectations from rocket data (BELMONT *et al.*, 1975). In contrast, in Paper 1, the jet and the annual wave amplitude were much smaller ($\sim 20 \text{ ms}^{-1}$) for 1969–76. A number of the possible causes listed there may now be eliminated:

1) The winds from the M.F. radar are now not too low (e.g., Figs. 2, 3, 5). Also, detailed comparisons of noon values of radar and rocket data from Primrose Lake (54°N), show excellent agreement (GREGORY *et al.*, 1981).

2) Tides are not an important factor below ~ 80 km. This is clear from the continuity of results in Figs. 2, 4, 5; and our earlier papers on tides.

The problem of the earlier smaller amplitudes remains unresolved: possible remaining explanations include the averaging of many years of data, each with different stratwarm influences; the use of data of poorer quality (MEEK *et al.*, 1979); and the possibility of a strong trend in the strength and altitude range of the winter jet over intervals of ~ 5 years.

For the first time the meridional annual wave is shown: amplitudes are small ($1\text{--}5 \text{ ms}^{-1}$) and the phase similar to the zonal.

4. Semi-Annual Wave

The strength and phase of this wave can be predicted from Figs. 2, 4: the harmonic results are in Fig. 5. The zonal amplitudes are somewhat larger at $\sim 15 \text{ ms}^{-1}$, than in Paper 1, up to 80 km; and we show a strong maximum at 70 km, with a weaker poorly resolved maximum near 100 km. The phase dates are early April and October up to near 80 km, and there is then a strong phase gradient (10 km mth^{-1}) to mid-January, -July phase dates from $\sim 100\text{--}110$ km. This corresponds to a vertical wavelength of 60 km. Up to ~ 100 km, this agrees very well with Paper 1: above that height, tidal effects and vertical height corrections make their results uncertain. Again there is sensible agreement with GROVES (1972) to ~ 100 km, although we define the phase gradient in much more detail; the data near 50°N was not well distributed in height in his data set (CIRA, 1972). Finally, the spectral analysis upon the wind series were entirely consistent with the harmonic analysis: periods were 180-d, and the phase progression with height was consistent with Fig. 5. The meridional component shown there is very small ($\lesssim 2 \text{ ms}^{-1}$): the phase is similar but more erratic than the zonal phase.

5. Three-Month Wave

This is the second harmonic of the semi-annual wave. From Fig. 5, its amplitudes for zonal and meridional winds are approximately half those of the 6 month wave. The phase gradient of the zonal wind above 80 km is $\sim 20 \text{ km month}^{-1}$, which is twice that of the semi-annual wave, again equivalent to a vertical wavelength of 60 km. Belmont and

Nastrom also found this phase gradient feature. There is also good agreement with actual phase days and amplitude values (they only show the zonal data). The identification of this period oscillation is thus confirmed. Finally we note that the spectral analysis of the data set does not systematically give a spectral peak at this period for all heights and components. The phase coherence near 90-d was usually fairly constant, however, and not inconsistent with the harmonic analysis-derived phase progression.

6. Terannual Wave (4 mth)

This component was also not evident in the spectral analysis. When called for in harmonic analysis, amplitudes were $\leq 1 \text{ ms}^{-1}$ at all heights for both components (zonal and meridional). The phase varied consistently with height however, and showed a very large phase gradient ($\sim 60 \text{ km mth}^{-1}$). The phase dates lie in February, June, and October.

7. 27-Day Oscillation

Such a component could be due to solar/geomagnetic coupling and is certainly worth seeking. It was not clearly present in the spectral analysis of the 28-mth sequence. The harmonic analysis of the zonal wind, (Fig. 6), shows a maximum of 3 ms^{-1} at 80 km, and $\sim 1 \text{ ms}^{-1}$ at other heights. The phase is remarkably consistent with height; we have chosen August/September 1979 arbitrarily for the graph, as the oscillation is repetitive at 27-d. Waves of period near this have similar amplitudes, but in general, less consistent phase variations with height: we also show the results for a 35-d wave. No phase progression is really expected. In conclusion, we must note that comparison of our winds above 80 km, with magnetic disturbances on a major event basis or statistically, do not show a strong coupling: it is weak at best.

Fig. 6. Amplitudes and phases of 27-, 35-day waves in the zonal wind.

8. Conclusion

1) A weak QBO (2–3 m/s) exists from 60–110 km— there is a large phase shift from below 80 km to above 90 km.

2) The annual zonal wave is very large ($\sim 40 \text{ ms}^{-1}$) up to 80 km, falling to less than 5 ms^{-1} near 100 km. There is a phase shift of $\sim 180^\circ$ from below 80 km (phase dates in December), to above 100 km (phase dates in Summer solstice). The amplitudes below 90 km are much bigger than during 1969–76, (BELMONT and NASTROM, 1979) for still unknown reasons.

3) The semi-annual zonal wave varies in amplitude from near 15 ms^{-1} below 80 km, to $\sim 8 \text{ ms}^{-1}$ above ~ 90 km. The phase progression is consistent with a vertical wavelength of ~ 60 km, again giving a phase shift of $\sim 180^\circ$ between upper and lower ranges of the altitudes studies.

4) The weak 3-month has again been detected (cf. BELMONT and NASTROM, 1979): its amplitude is half that of the 6-mth wave, and its vertical wavelength is the same, giving double the gradient in km per month.

5) The terannual (4-mth) and 27-d waves were weak ($\sim 1 \text{ ms}^{-1}$ most heights) but had regular phase variations with height.

6) The effect of the removal of tidal components above 80 km, had a dramatic effect upon the amplitudes of summer and winter monthly circulation cells above 90 km, when compared to noon data. The characteristics of long-period waves obtained by Belmont and Nastrom using noon data is likely in error above ~ 100 km in both amplitude and phase. There are indications that the data used by GROVES (1972) in CIRA (1972) were also tidally contaminated above ~ 90 km.

7) Below 90 km, and especially 80 km, the tidal influences are small and appear not significant for this analysis. The phases of the various long-period waves are very similar for the early 1969–76 noon data, and this 1978–80 set of daily data. However, the amplitudes of summer and winter monthly circulation cells, and the amplitudes of annual and semi-annual waves are much larger ($\sim$ twice) than in the earlier set of data. As such they are consistent with rocket data from near 60 km (GREGORY *et al.*, 1981).

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