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Semidiurnal Hough Mode Extensions in the Thermosphere and Their Application

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Semidiurnal tidal modes propagate vertically without change of meridional structure in the lower atmosphere. However, in the thermosphere where viscosity, ion drag, and other processes assume importance, individual tidal modes, propagating into the thermosphere from below, begin to change meridional structure as they propagate vertically. In addition, the modes are subject to attenuation. The extent of meridional alteration and vertical attenuation depends on the mean thermal structure of the thermosphere and the degree of ionization, both of which vary during the → next page

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20. Abstract (Continued)

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solar cycle. This note gives the results of numerical calculations of the explicit behavior of the 2,2, 2,3, 2,4, and 2,5 Hough modes within the thermosphere under conditions typical of sunspot maximum and minimum. In addition we present a numerical description of semidiurnal tides excited within the thermosphere. For the convenience of the reader a copy of a paper by Hong and Lindzen giving details of the numerical program is included. The present report can be considered an extensive addendum to this paper.

CONTENTS

SEMIDIURNAL HOUGH MODE EXTENSIONS IN THE THERMOSPHERE AND THEIR APPLICATION

I. Introduction

In Hong and Lindzen (1976) a general computation of the semidiurnal tide in the thermosphere was presented in detail. It was noted in that paper that the semidiurnal tide in the thermosphere was primarily forced from below, though at sunspot maximum tides from below were severely attenuated in the thermosphere so that in situ thermospheric forcing was of comparable importance for the semidiurnal tide in the upper thermosphere (above 200 km). In all cases, the lower thermosphere was dominated by higher order Hough modes whose origin is primarily the troposphere and mesosphere. The presentation of results in Hong and Lindzen (1976) was made particularly difficult by the fact the amplitudes and phases of the higher order modes (2,3: 2,4: 2,5) were sensitive to detailed variations of the wind and temperature below 100 km - variations which could occur within a single season. To a lesser extent this sensitivity holds for the 2,2 mode itself. Thus, it was obvious that observers might need information on the upward extension of individual Hough modes incident on the thermosphere at, say, 100 km. Such information could permit observers to deduce the global implications of observations at a

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few stations. Unfortunately, it is difficult to present such information in a compact form since the linearized equations for tides in the thermosphere are no longer separable in their latitude and altitude dependence due to the presence of ion drag and molecular viscosity; i.e., the latitude structure of a given mode forced below 100 km will change with height above 100 km or; equivalently, vertical structure will vary with latitude. Moreover, such 2-dimensional structures will vary with solar cycle insofar as ion drag (proportional to electron density) and neutral temperature vary with the solar cycle. To present the upward extension of a single mode at sunspot minimum and maximum has required 24 fairly detailed diagrams, and extensions of four modes are necessary. In addition we must include 16 additional diagrams which display the atmospheric response to in situ EUV and Schumann-Runge forcing within the thermosphere during sunspot maximum and minimum. One hundred and twelve diagrams exceed the tolerance of most editors, and generally interfere with the convenient reading of a paper. However, for specialists these diagrams are of considerable use. We have, therefore, prepared this report wherein the above mentioned diagrams are presented as a supplement to our paper.

II. Brief Description of Results

In view of the non-separability of the tidal equations in the thermosphere, the use of the term, Hough mode, is by no means unambiguous. What we shall mean by the term is that configuration of fields in the thermosphere forced by an upcoming wave at 100 km consisting in that Hough mode alone. Note that Hough modes in the conventional sense (Chapman and Lindzen, 1970) are well defined at 100 km. To distinguish the Hough mode in the thermosphere from the conventionally defined Hough mode, we will use the term, Hough mode extension, (HME). Computational details are given in Hong and Lindzen (1976), which is included as an appendix.

Figures 1a, 2a, 3a, and 4a show the vertical variation of the amplitude of the 2,2 Hough mode extensions, at various latitudes at sunspot minimum, for the temperature, northerly velocity, westerly velocity and vertical velocity fields, respectively; while Figures 1b, 2b, 3b, and 4b show the vertical variation of the phase of the 2,2 Hough mode extension (HME) in each of these fields for the same latitudes and sunspot conditions. Figures 5-8 show the same quantities at sunspot maximum. The assumed conditions at sunspot maximum and minimum are described in Hong and Lindzen (1976). Note that for a given HME, all amplitudes are arbitrary to within a <u>single</u> constant factor (appropriate to all fields to all altitudes and latitudes) while all phases are arbitrary to within a <u>single</u> constant phase displacement. In other words, Figures 1-8 give only relative amplitudes and phases for the 2,2 HME under sunspot minimum and maximum conditions. Figures 1-8 offer results for only a limited number of latitudes (0°, 15°, 30°, 45°, and 60°). In order to aid the reader in interpolating these results to other latitudes we present in Figures 9-12 the variations of amplitudes and phases with latitude at specific altitudes. These altitudes have been chosen as representative of the lower and upper thermosphere and of an intermediate level. Results are shown for both sunspot maximum and minimum conditions. All amplitudes in

Figures 9-12 have been normalized by maximum values at a given altitude. Hence, these values must be calibrated by values from Figures 1-8. Figures 9-12 show clearly the extent to which non-separability affects HME's in the thermosphere. In classical tidal theory (Chapman and Lindzen, 1970) latitudinal structures are independent of altitude and phases are independent of latitude.

The conterparts of Figures 1-12 for the 2,3 HME are shown in Figures 13-24. Note that since the 2,3 mode is antisymmetric about the equator, temperature, westerly velocity and vertical velocity amplitudes are zero at the equator while northerly velocity amplitudes are non-zero there. The counterparts of Figures 1-12 for the 2,4 HME are shown in Figures 25-36, and the counterparts for the 2,5 mode are shown in Figures 37-48.

A caveat is in order concerning accuracy. The calculations used for this report had somewhat better numerical resolution than those in Hong and Lindzen (1976). Nevertheless, we estimate tha accuracy of our results for the 2,2 and 2,3 HME's to be only 5% of maximum values at any altitude; for the 2,4 and 2,5 HME's the corresponding accuracy is only about 10%. We believe these accuracy estimates to be conservative. However, small relative amplitudes at any given altitude are naturally suspect, as are the phases corresponding to such small relative amplitudes. In most practical problems, this should be of little consequence.

Finally, in Figures 49-52 we show the amplitudes and phases of the semidiurnal tidal fields, as functions of height at various latitudes, due to in situ thermospheric forcing at sunspot minimum.

Figures 53-56 give the corresponding results for sunspot maximum. The heating functions are described in Hong and Lindzen (1976). For sunspot maximum we used the lower values for the flux in the Schumann-Runge continuum. We approximated the latitude dependence of the in situ heating by a classical 2,2 Hough function. This, in fact, accounts for the bulk of the heating; and since the resulting amplitudes are, in general, relatively small, we do not feel that the corrections to our simple heating structure will prove significant. Similarly, we have not included any detailed latitude destributions of in situ response. In general, this response is very smooth and interpolation directly from Figures 49-56 should prove adequate.

III. Remarks

As already noted in Hong and Lindzen (1976), as concerns height of maximum amplitude, attenuation of amplitude from maximum to top of thermosphere, and phase variation with height, the 2,2 and 2,3 modes are quite similar and would be hard to distinguish at a single station. The same degree of similarily exists between the 2,4 and 2,5 modes. It is not so surprising that essentially similar modes should occur in pairs differing only in symmetry.

IV. Applications

The main use of the present report will be to deduce global implications from observations of semidiurnal tides at a few stations. An example of how this may be done may be found in a recent paper (Lindzen, 1976) wherein lower thermospheric data from Millstone Hill (46.6°N), St. Santin (45°N) and Arecibo (18°N) were used to determine the amplitudes and phases of the 2,4 and 2,5 modes which dominate the semidiurnal tide below 120 km. Lindzen (1976) used classical Hough modes, whereas with the present work it will be possible to repeat this work with the more appropriate Hough mode extensions. It is our intention to use data from the above stations for the upper and lower thermosphere to deduce the amplitudes and phases of all the HME's in this report, using the following procedure:

(1) It is now well established that the semidiurnal tide in the lower thermosphere is dominated by the 2,4 and 2,5 modes. Thus data from these levels may be used to calibrate these HME's in a manner entirely analogous to that used in Lindzen (1976).

(2) Using results in this report for the thermospherically-forced semidiurnal tide (Figures 48-56), the results from item 1 above, and the 2,4 and 2,5 HME's from this report, we can calculate the combined contribution from in situ forcing and the 2,4 and 2,5 modes to the semidiurnal tide in the upper thermosphere where the 2,2 and 2,3 modes assume considerable prominence. Thus, the difference between the above contributions and upper thermospheric observation will permit us to evaluate the contributions from the 2,2 and 2,3 modes forced from below the thermosphere.

(3) The results from item 2, above, can be used to improve the results from item 1, above, and so on.

The above observationally based estimates will permit not only the generation of global models on the basis of limited observations, but will also provide reasonable tests of the predictions provided by models for the generation of tides in the lower atmosphere such as that of Lindzen and Hong (1974).

A complete picture of daily variations in the thermosphere will require a knowledge of the diurnal as well as the semidiurnal tide in the thermosphere. The former will not require any counterpart of the present semidiurnal HME's because it can be shown that the diurnal tide in the thermosphere is almost entirely forced in situ (Lindzen, 1971), primarily by EUV absorption. One of the present authors (J. Forbes) is currently completing a calculation of the thermospherically-forced diurnal tide similar to the calculations of Hong and Lindzen (1976) for the semidiurnal tide. It is hoped that the diurnal caculations will be sufficiently accurate to improve our current knowledge of the EUV flux, and hence, among other things, improve our calculations of the thermospherically-forced semidiurnal tide.

Acknowledgements

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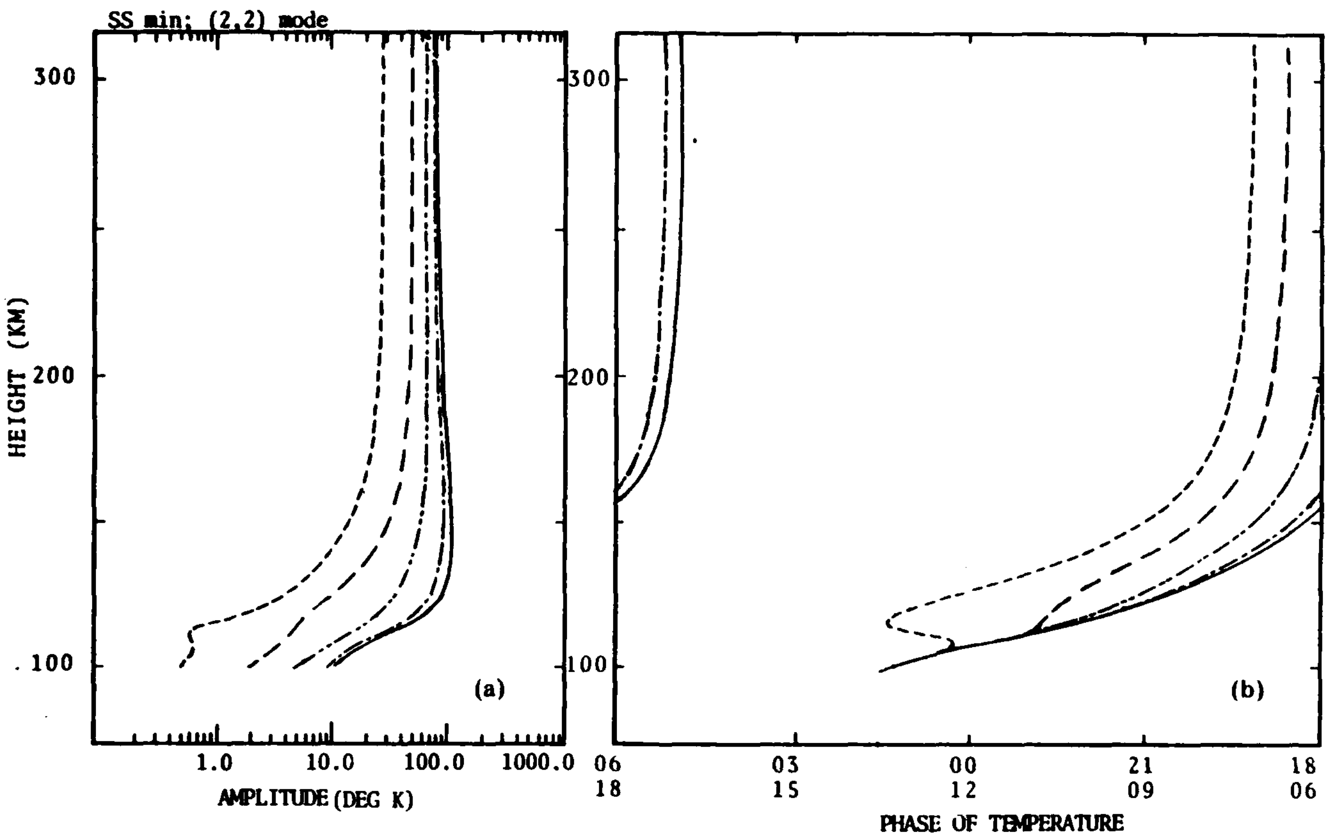


Fig. 1 — (a) Amplitude of temperature oscillation of the 2,2 Hough mode extension (HME) as a function of altitude for various latitudes under minimum sunspot conditions. Different line conventions apply to different latitudes as follows: ——, 0°; — — —, 15°; — — — —, 30°; — — —, 45°; – – – –, 60°. (b) Phase of temperature oscillation (hour of maximum, local time) of the 2,2 Hough mode extension (HME) as a function of altitude for various latitudes under minimum sunspot conditions. Line convention as in (1a).

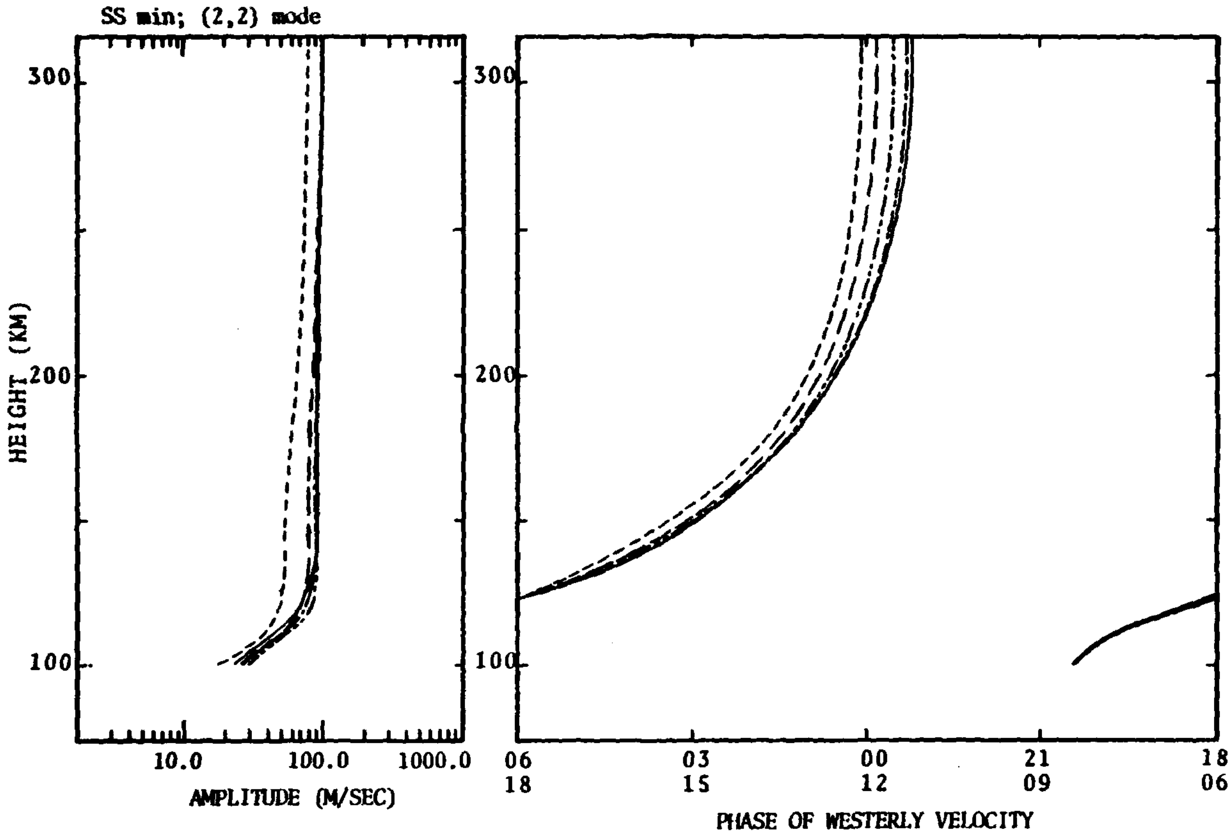


Fig. 2 — Same as Fig. 1, but for the westerly velocity oscillation of the 2,2 HME under minimum sunspot conditions

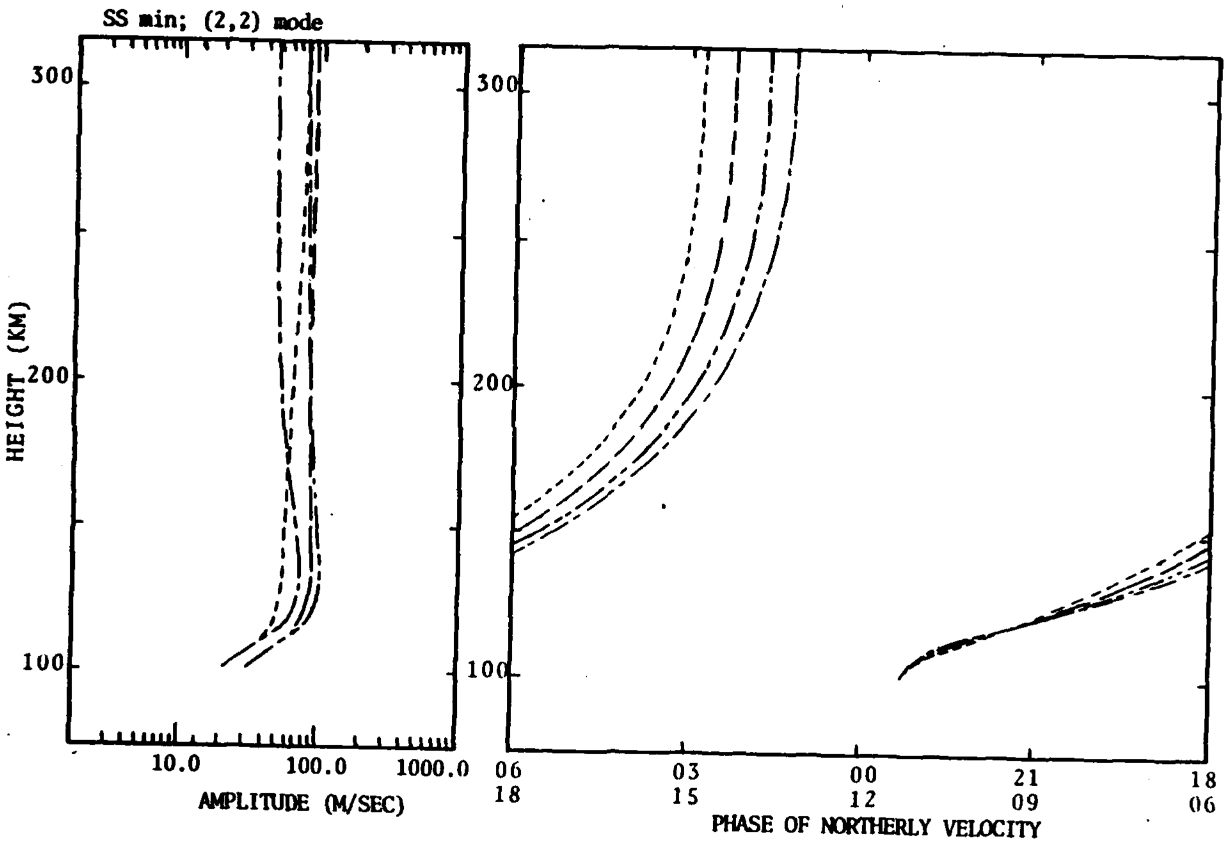


Fig. 3 — Same as Fig. 1, but for the northerly velocity oscillation of the 2,2 HME under minimum sunspot conditions

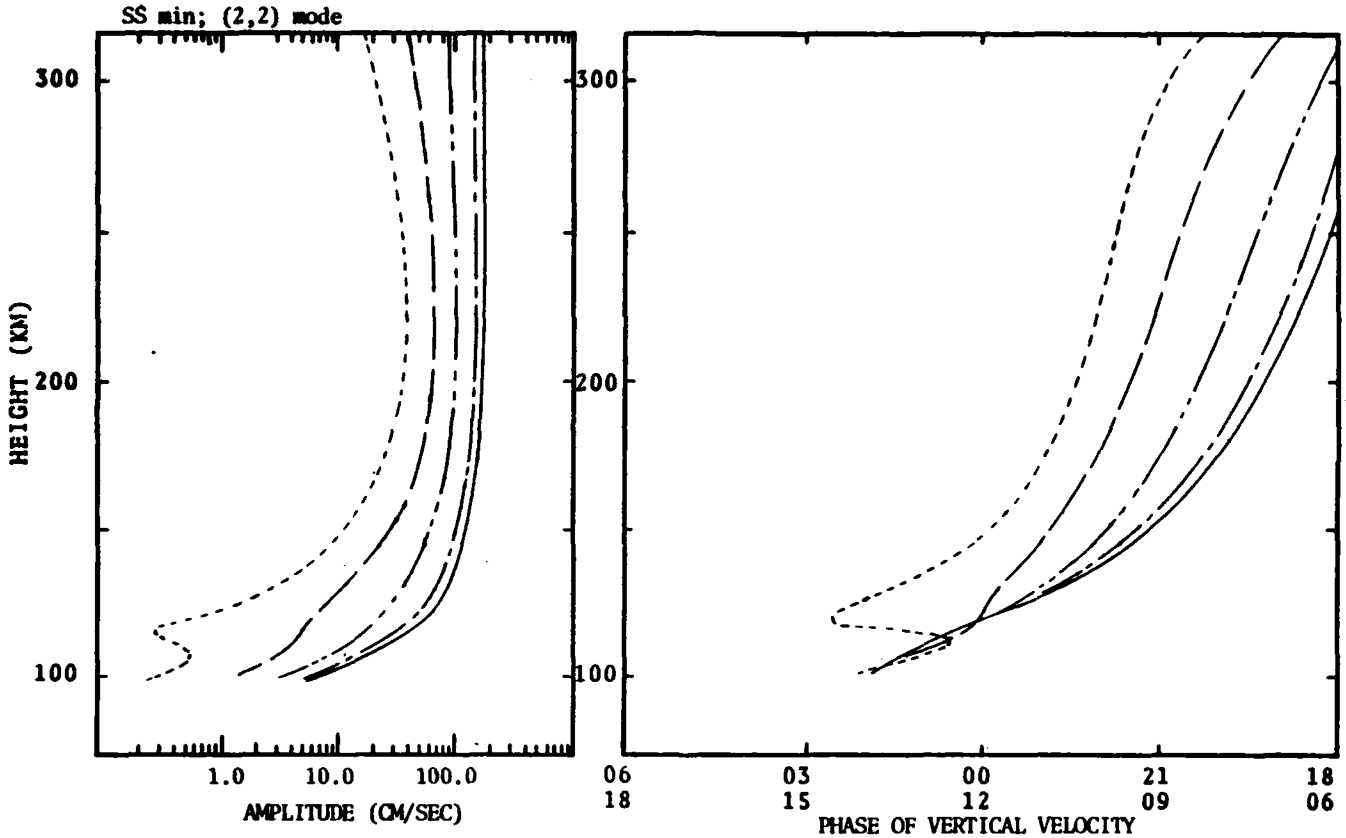


Fig. 4 — Same as Fig. 1, but for the vertical velocity oscillation of the 2,2 HME under minimum sunspot conditions

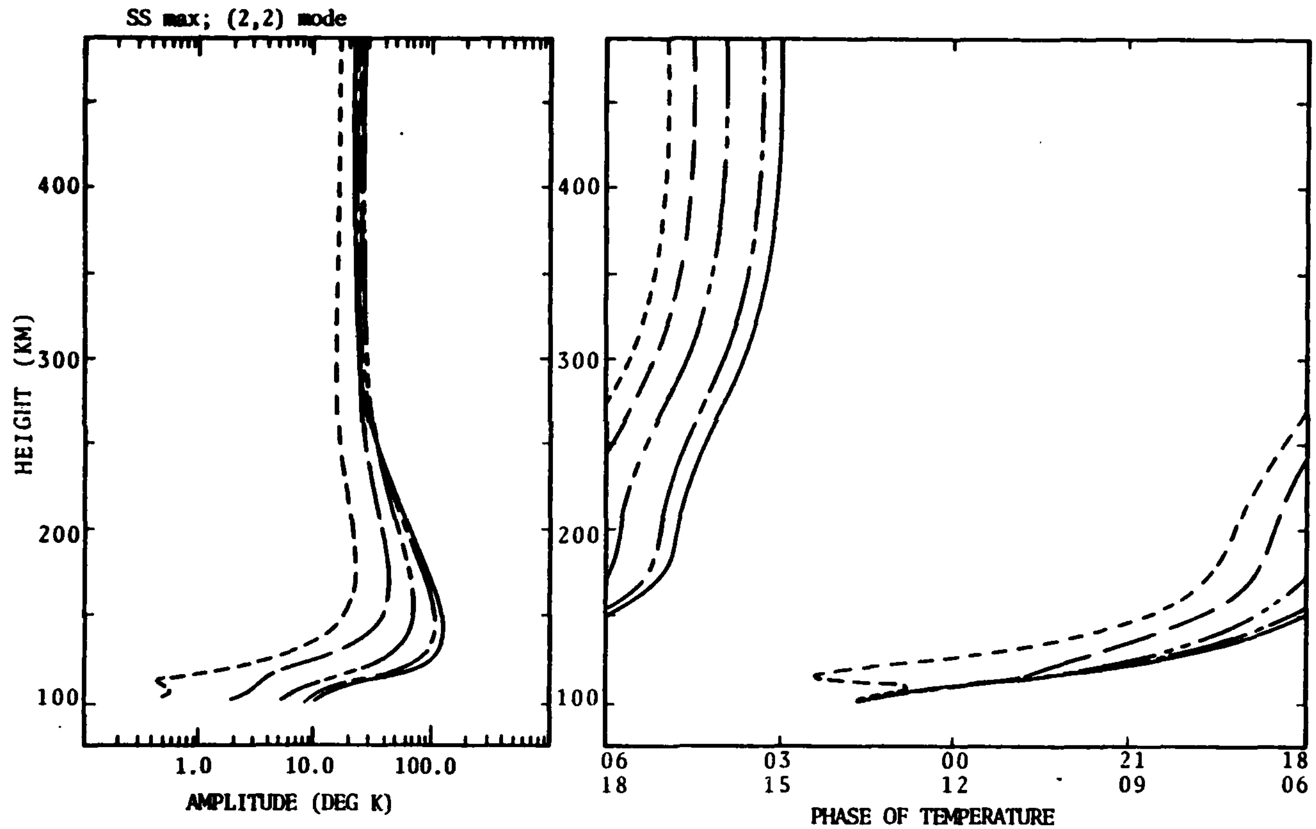


Fig. 5 — Same as Fig. 1 but for maximum sunspot conditions

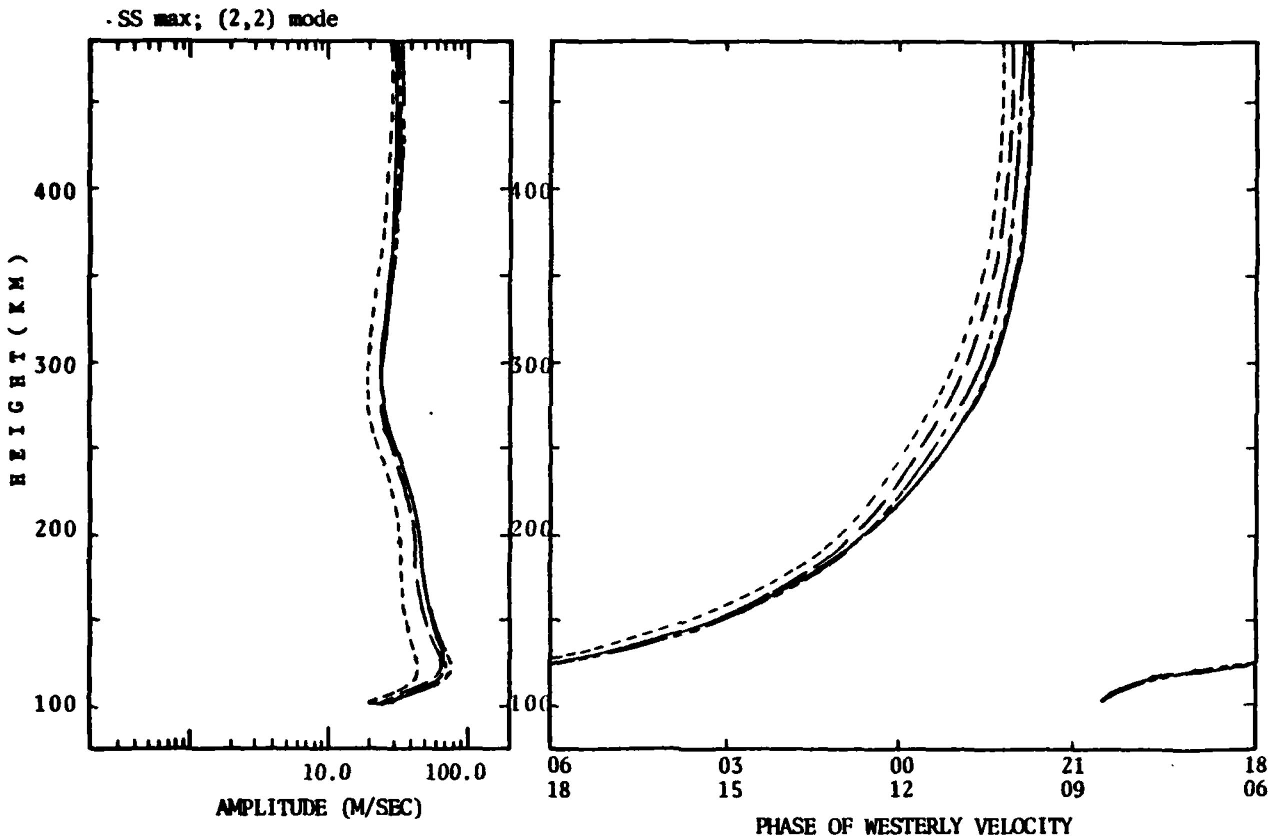


Fig. 6 — Same as Fig. 2 but for maximum sunspot conditions

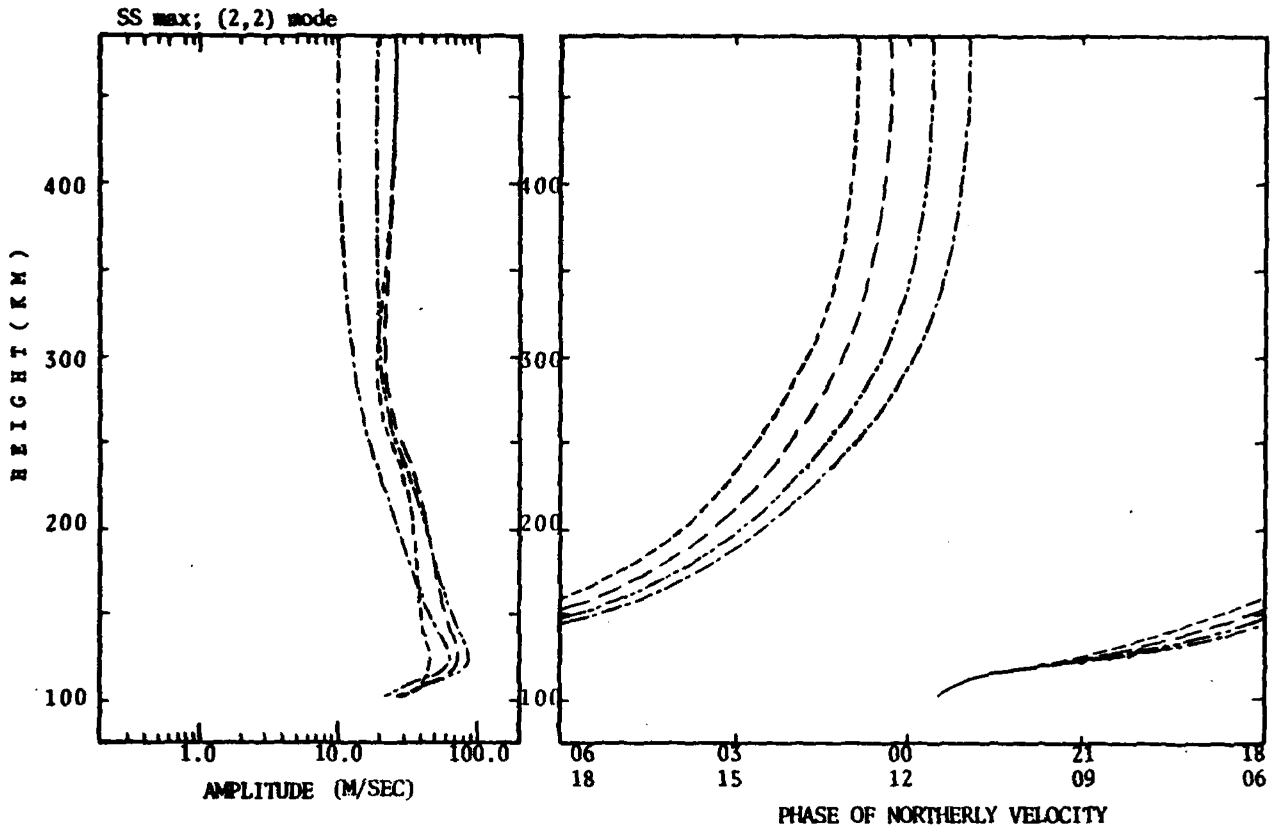


Fig. 7 — Same as Fig. 3 but for maximum sunspot conditions

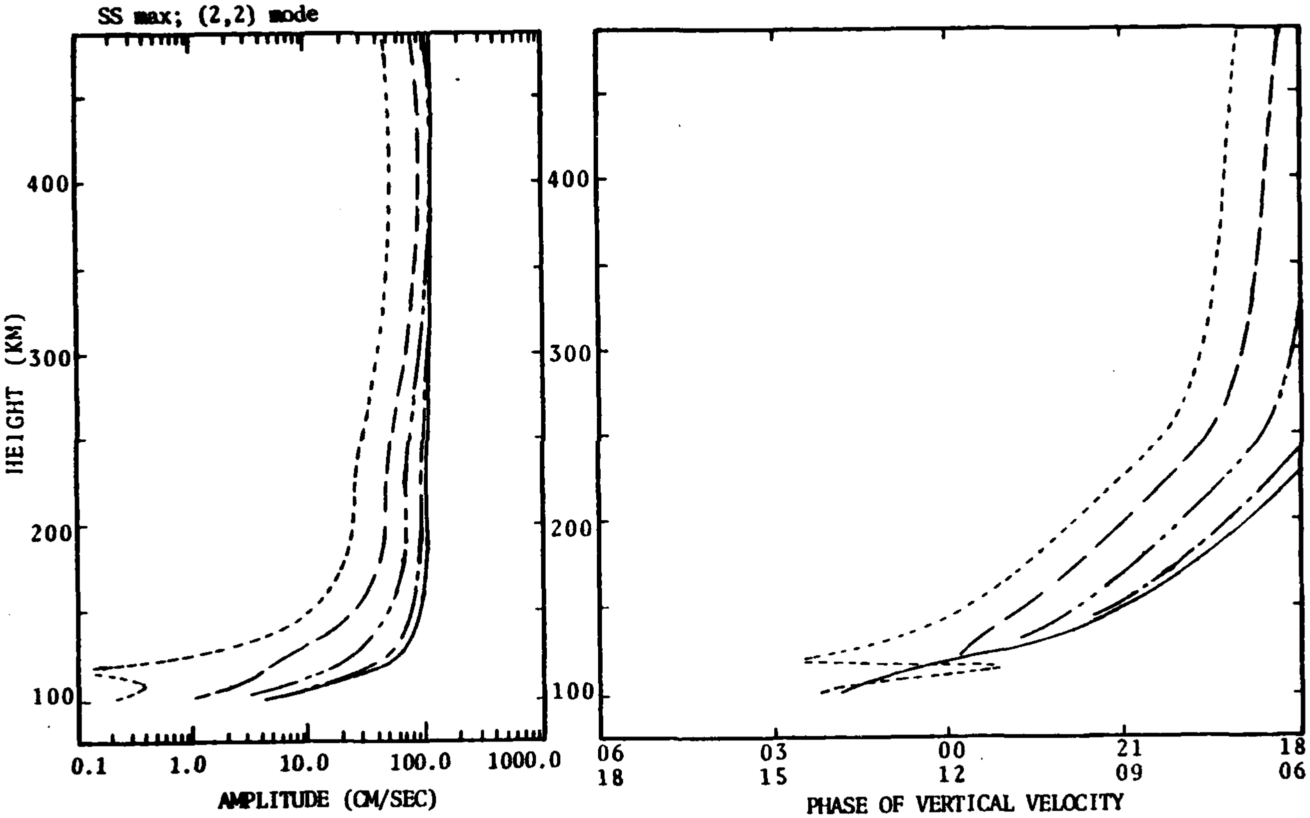


Fig. 8 — Same as Fig. 4 but for maximum sunspot conditions

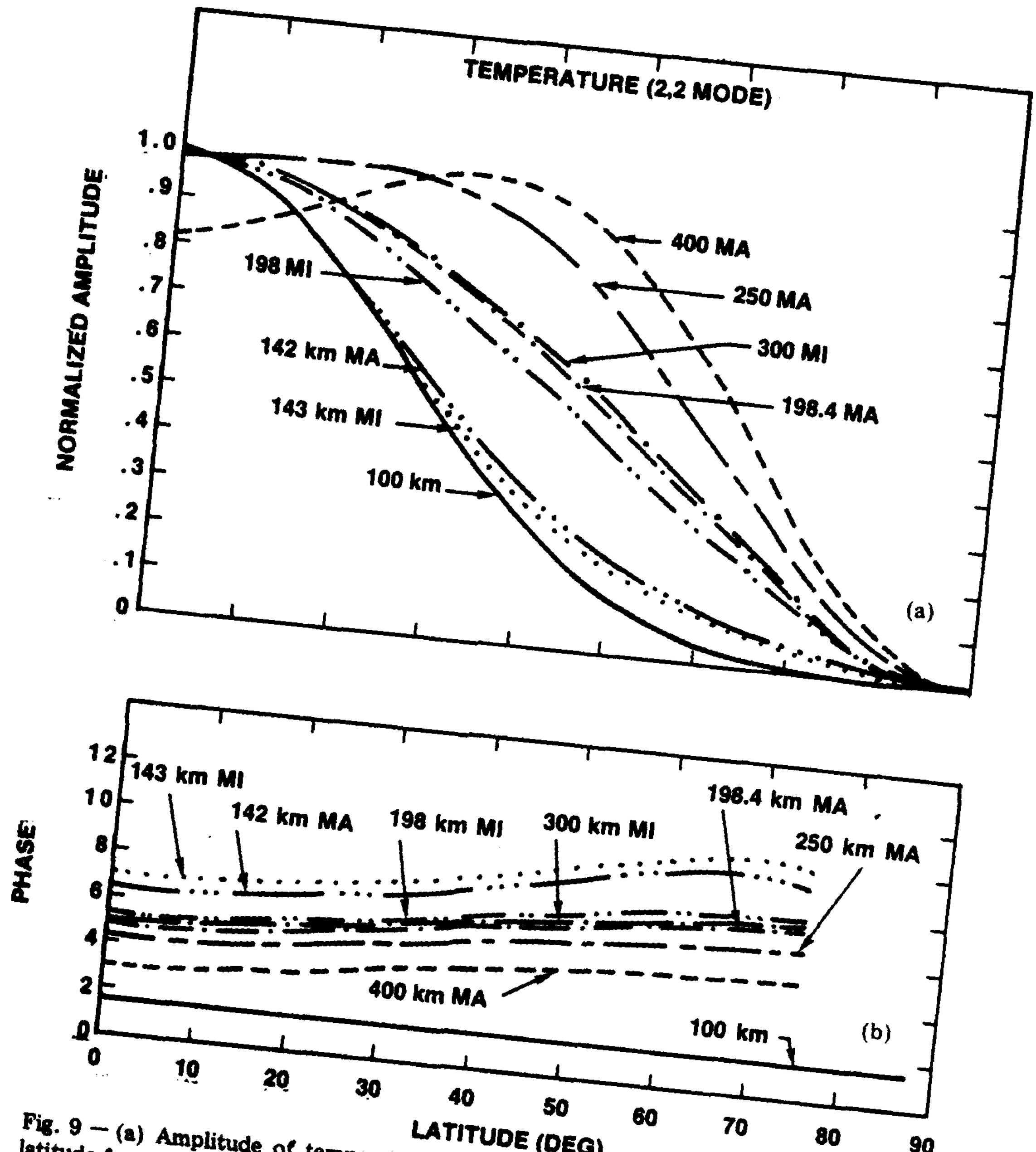


Fig. 9 — (a) Amplitude of temperature oscillation of the 2,2 HME as a function of latitude for selected altitudes and sunspot conditions (values normalized by maximum value at each altitude). MI refers to sunspot minimum; MA refers to sunspot maximum. Values at 100 km are essentially independent of sunspot conditions. (b) Phase of temperature oscillation (time of maximum, local time) of the 2,2 HME as a function of latitude for selected altitudes and sunspot conditions.

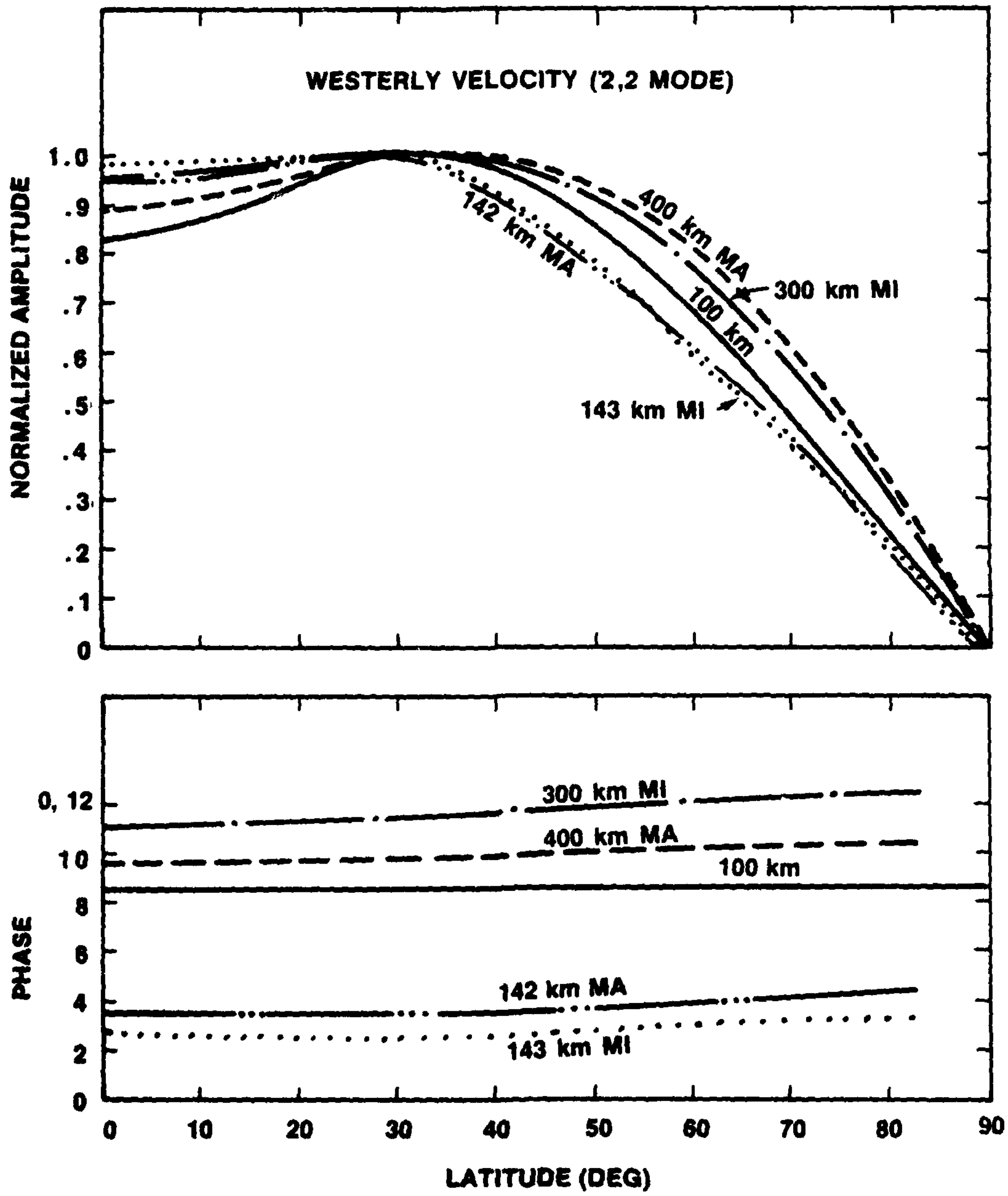


Fig. 10 — Same as 9, but for the westerly velocity oscillation of the 2,2 HME

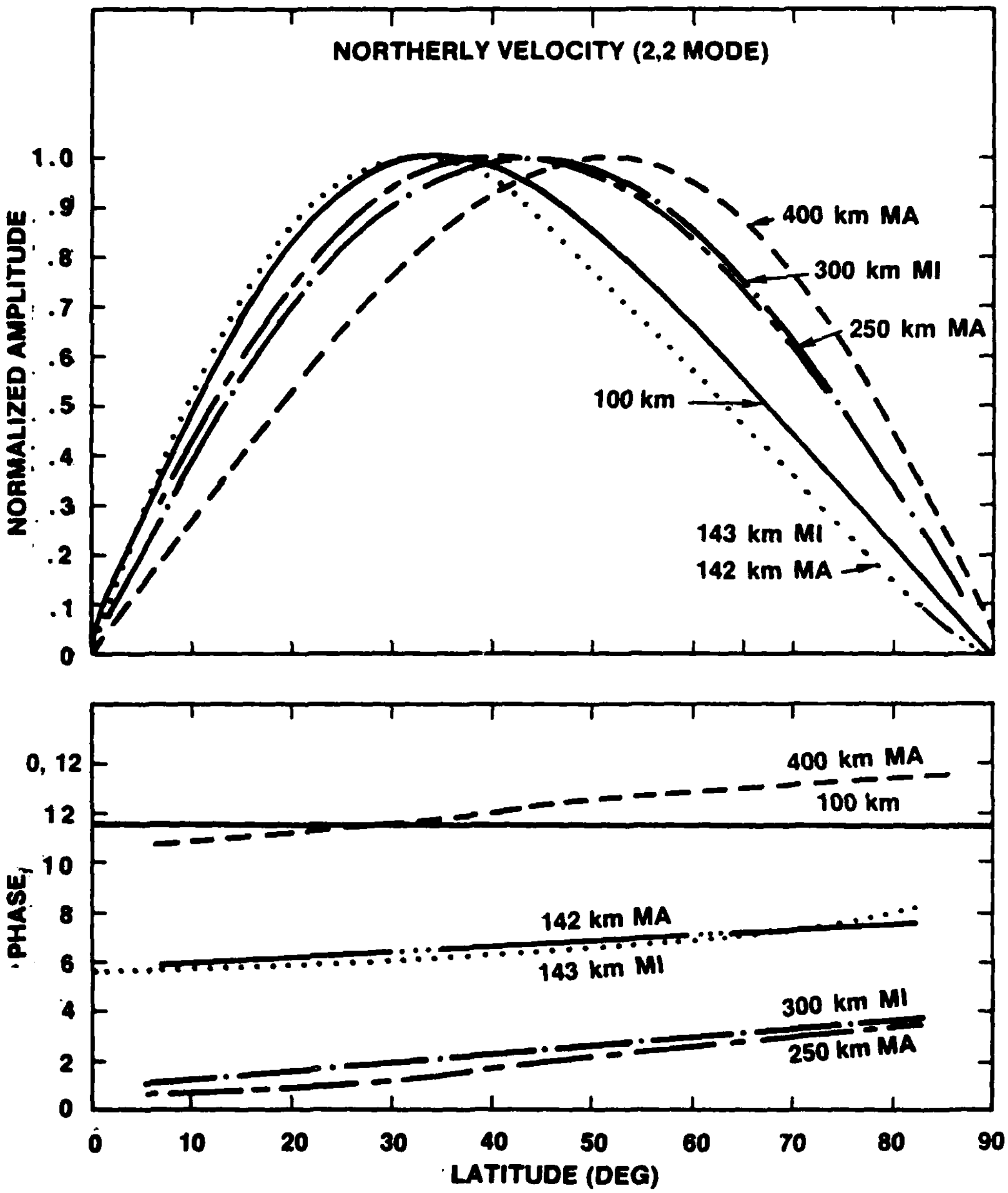


Fig. 11 — Same as 9 but for the northerly velocity oscillation of the 2,2 HME

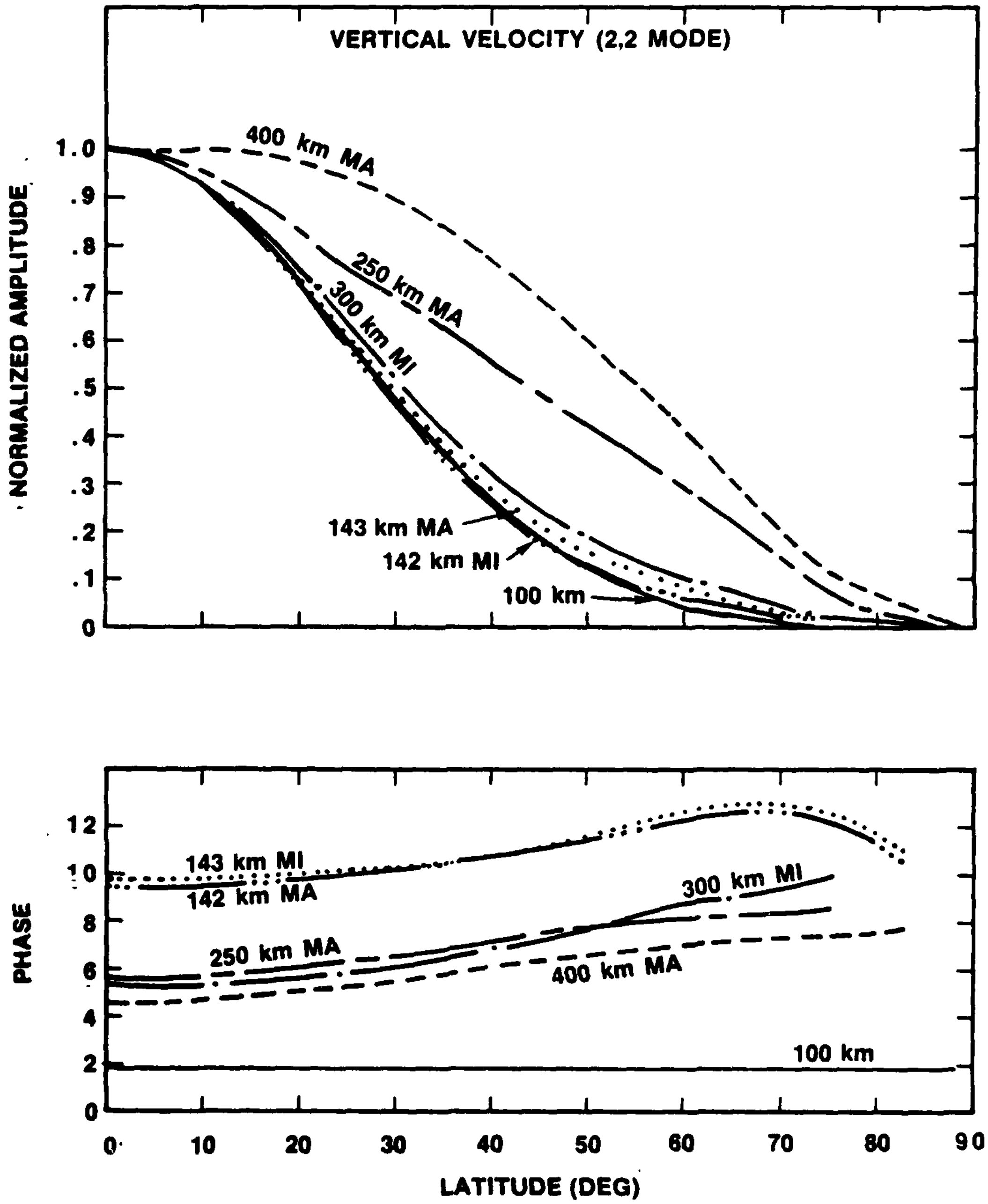


Fig. 12 — Same as 9 but for the vertical velocity oscillation of the 2,2 HME

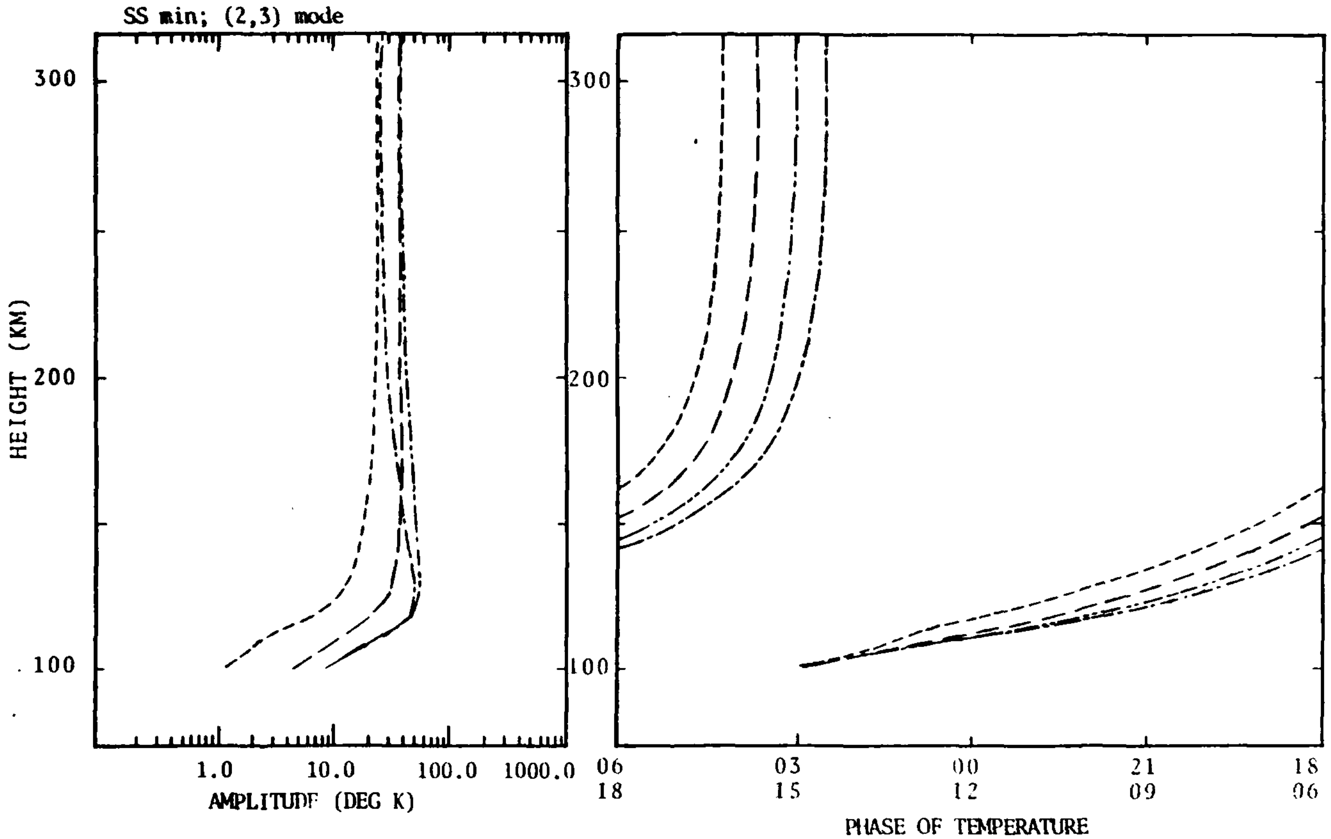


Fig. 13 — Same as 1 but for the 2,3 HME

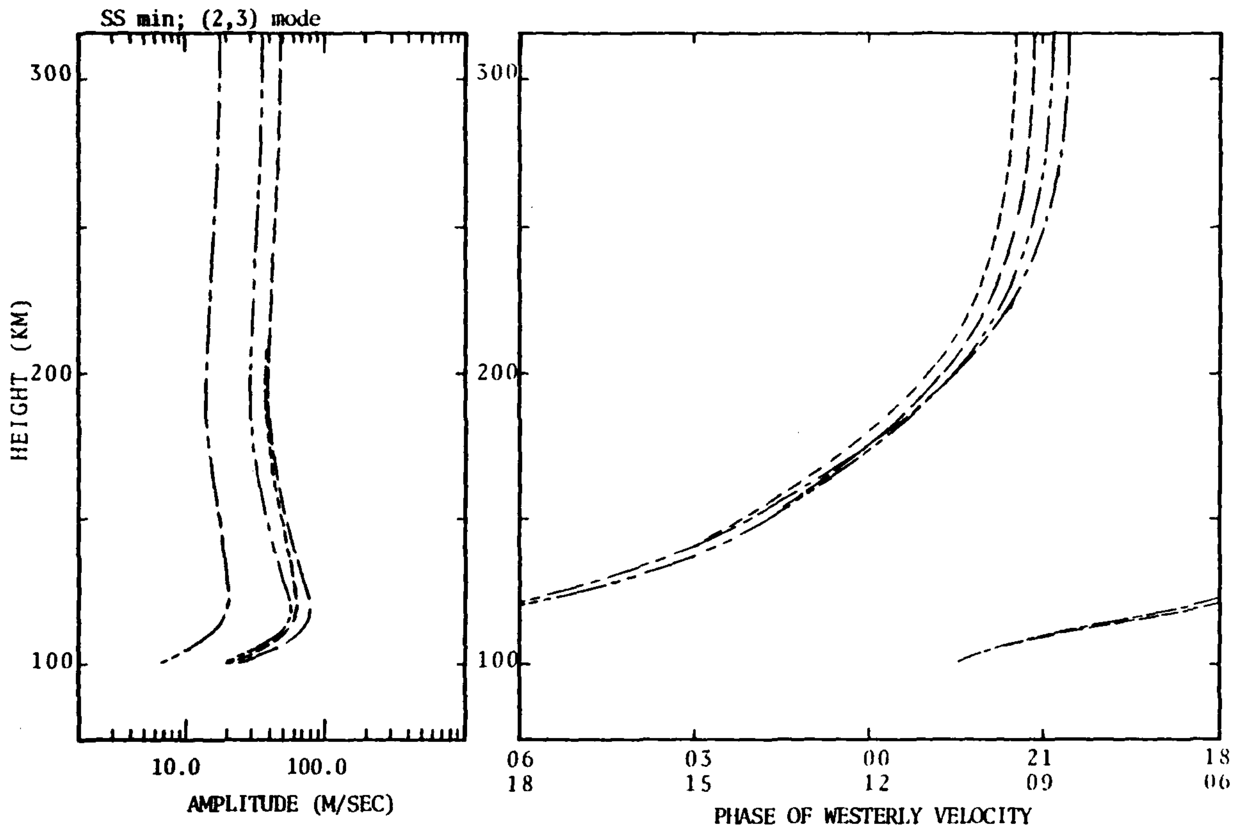


Fig. 14 — Same as 2 but for the 2,3 HME

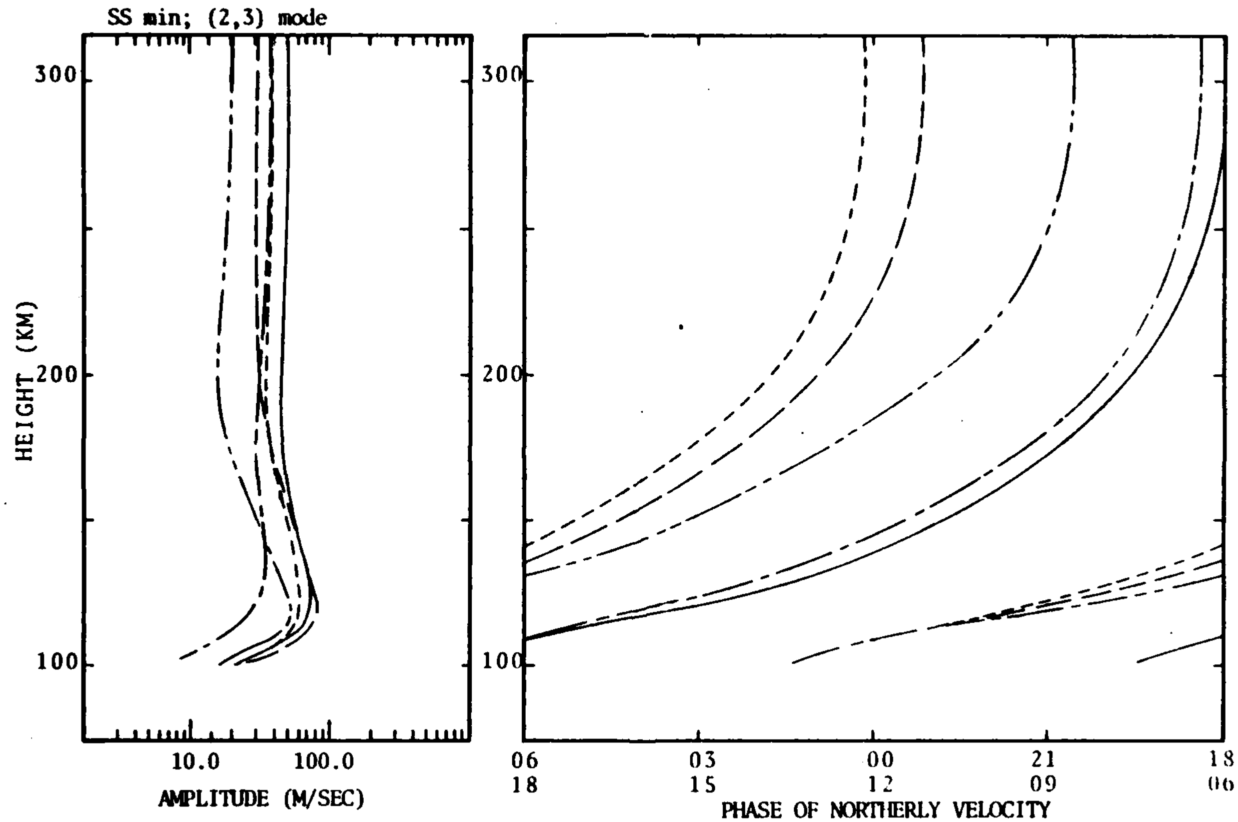


Fig. 15 — Same as 3 but for the 2,3 HME

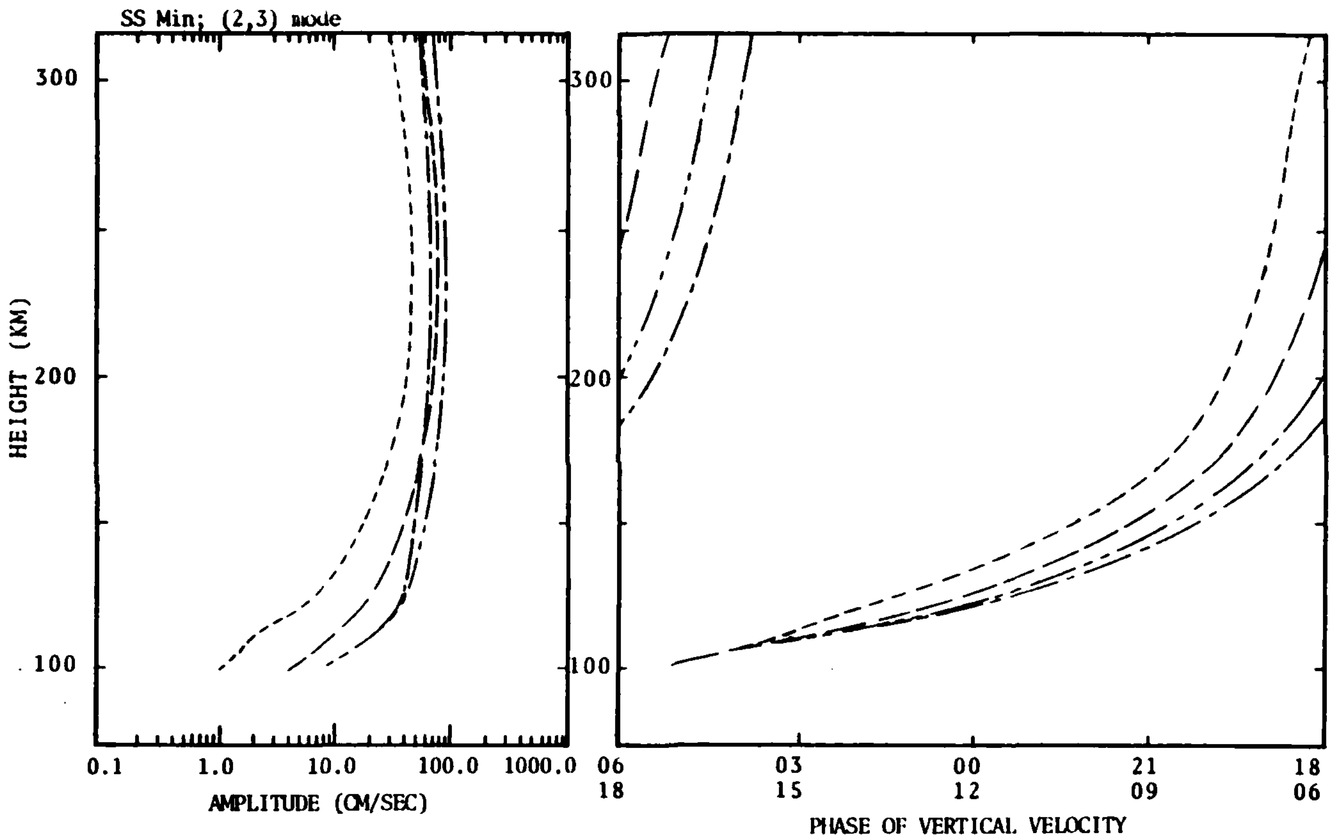


Fig. 16 — Same as 4 but for the 2,3 HME

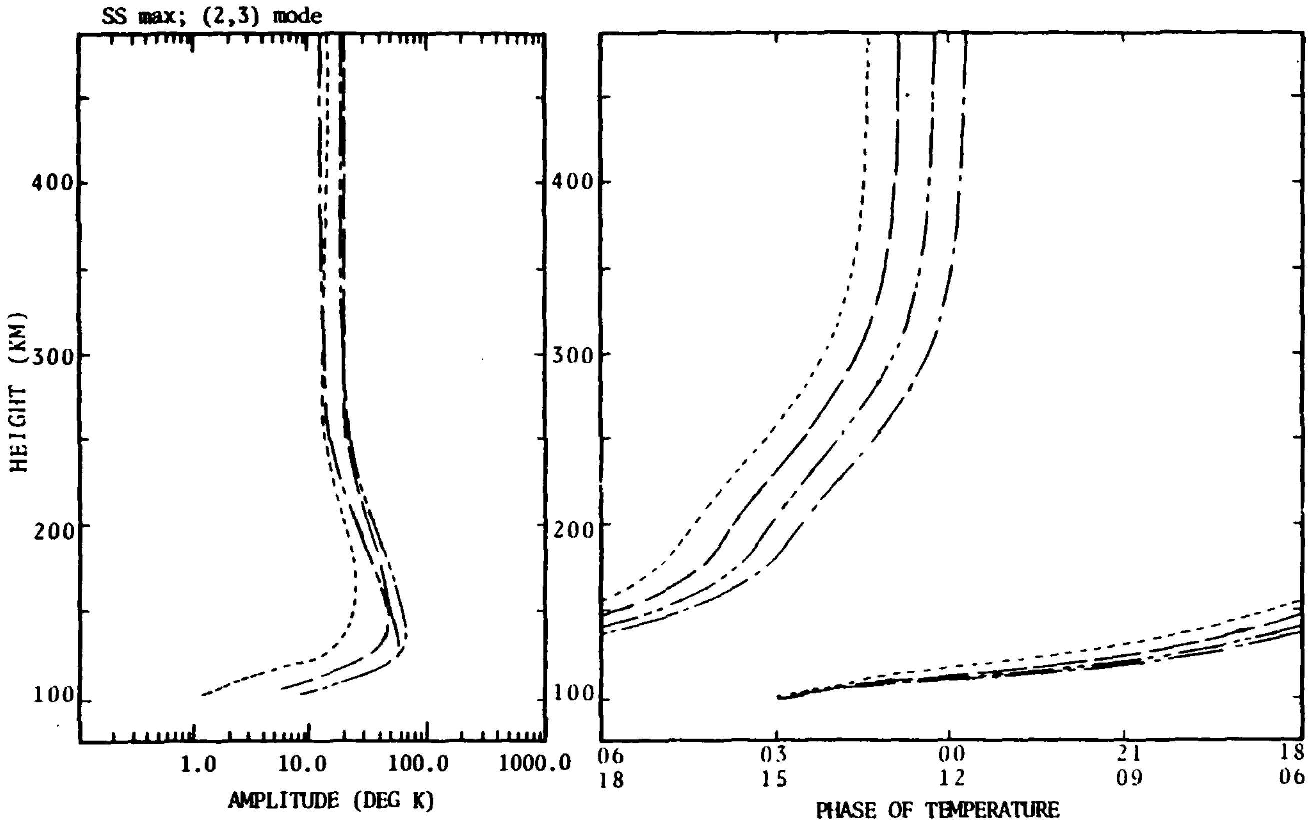


Fig. 17 — Same as 5 but for the 2,3 HME

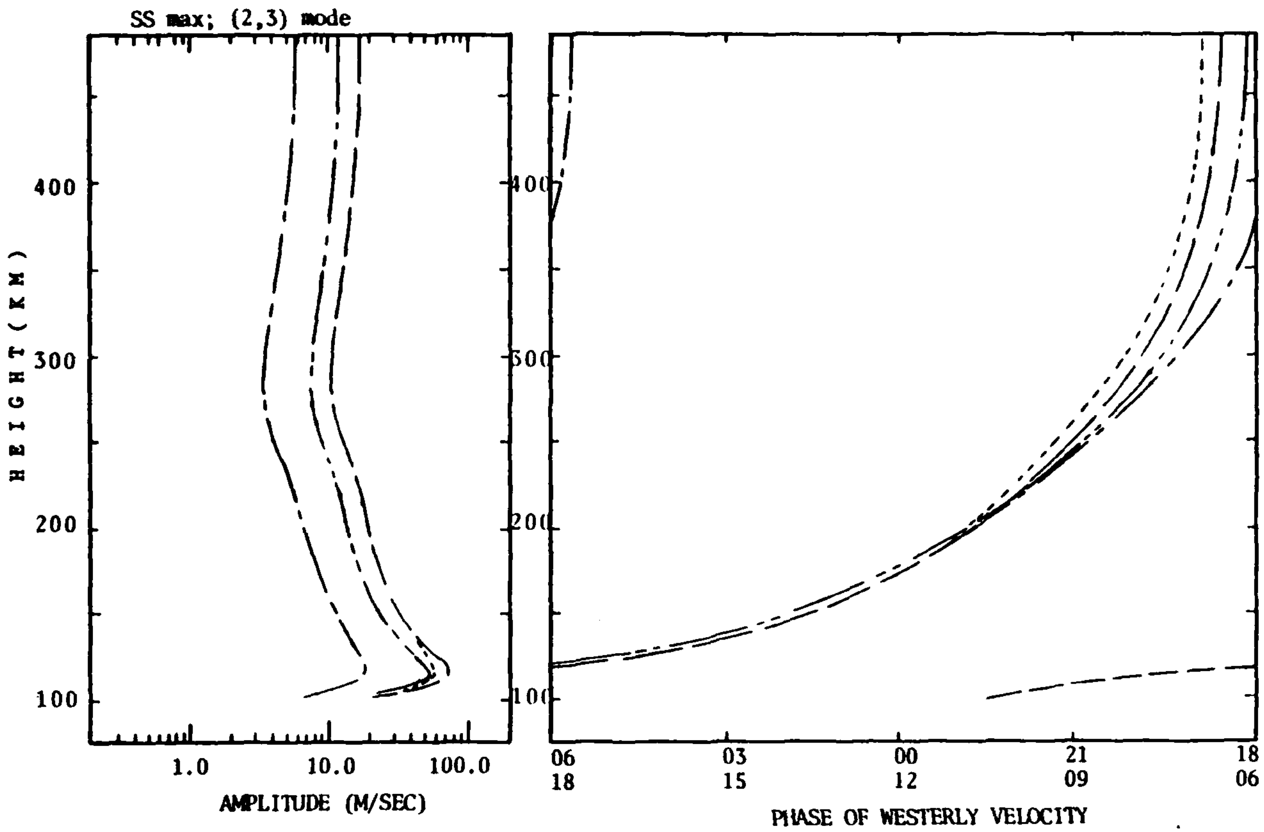


Fig. 18 — Same as 6 but for the 2,3 HME

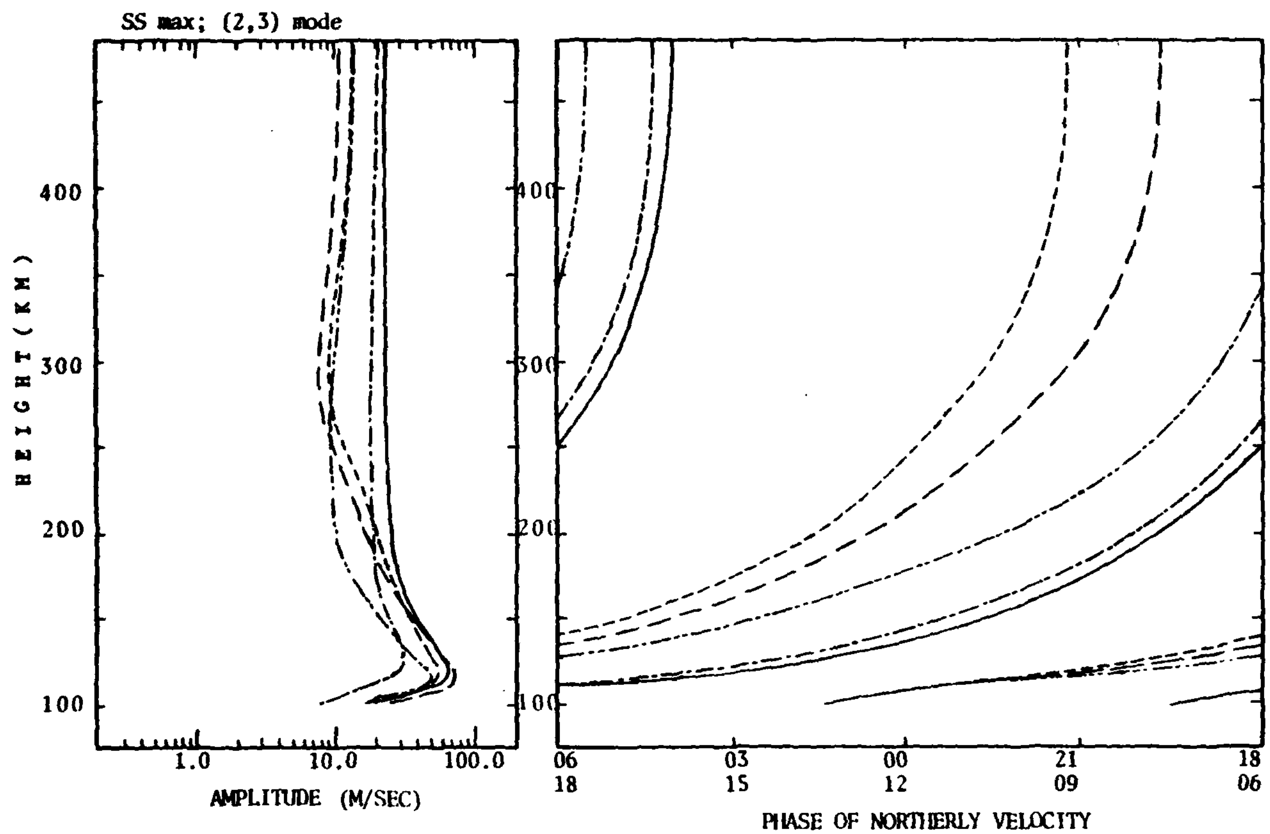


Fig. 19 — Same as 7 but for the 2,3 HME

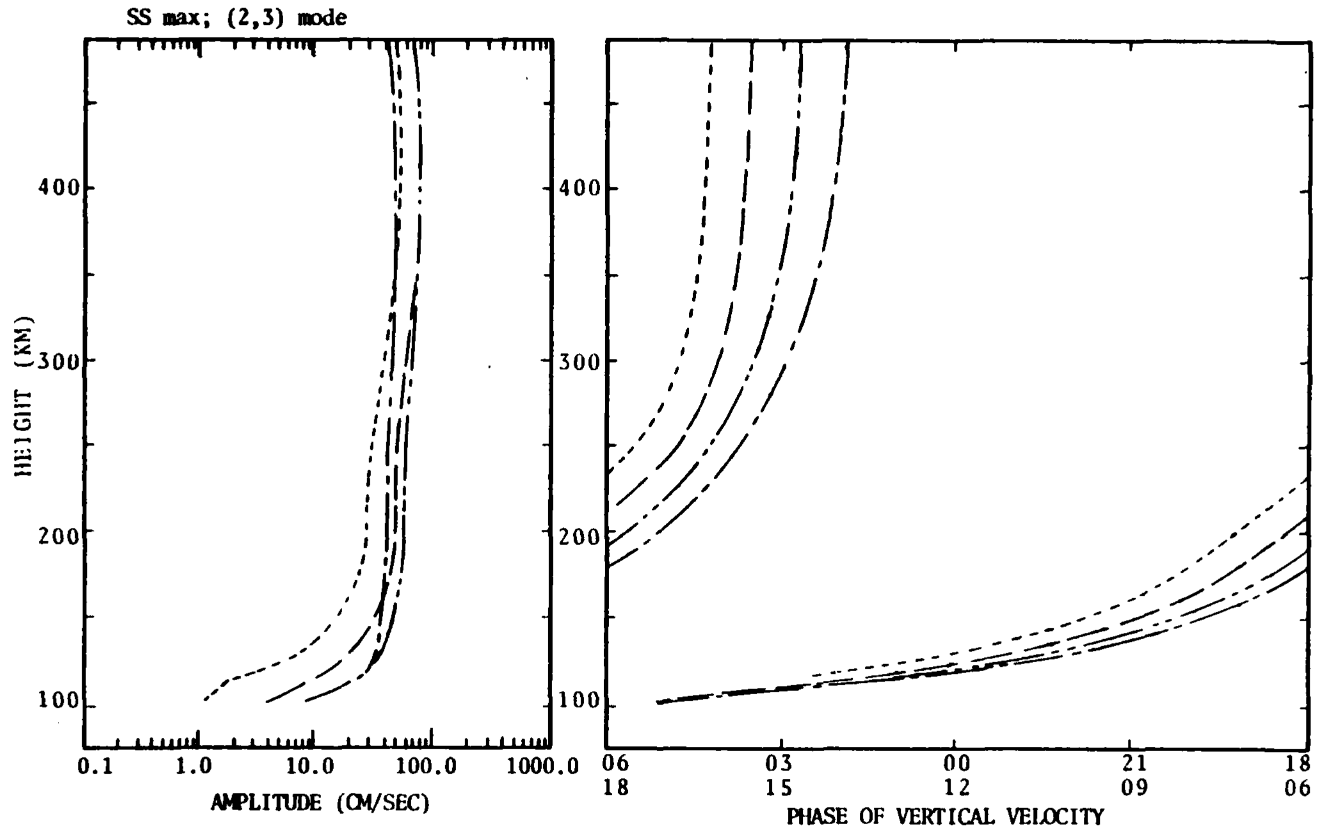
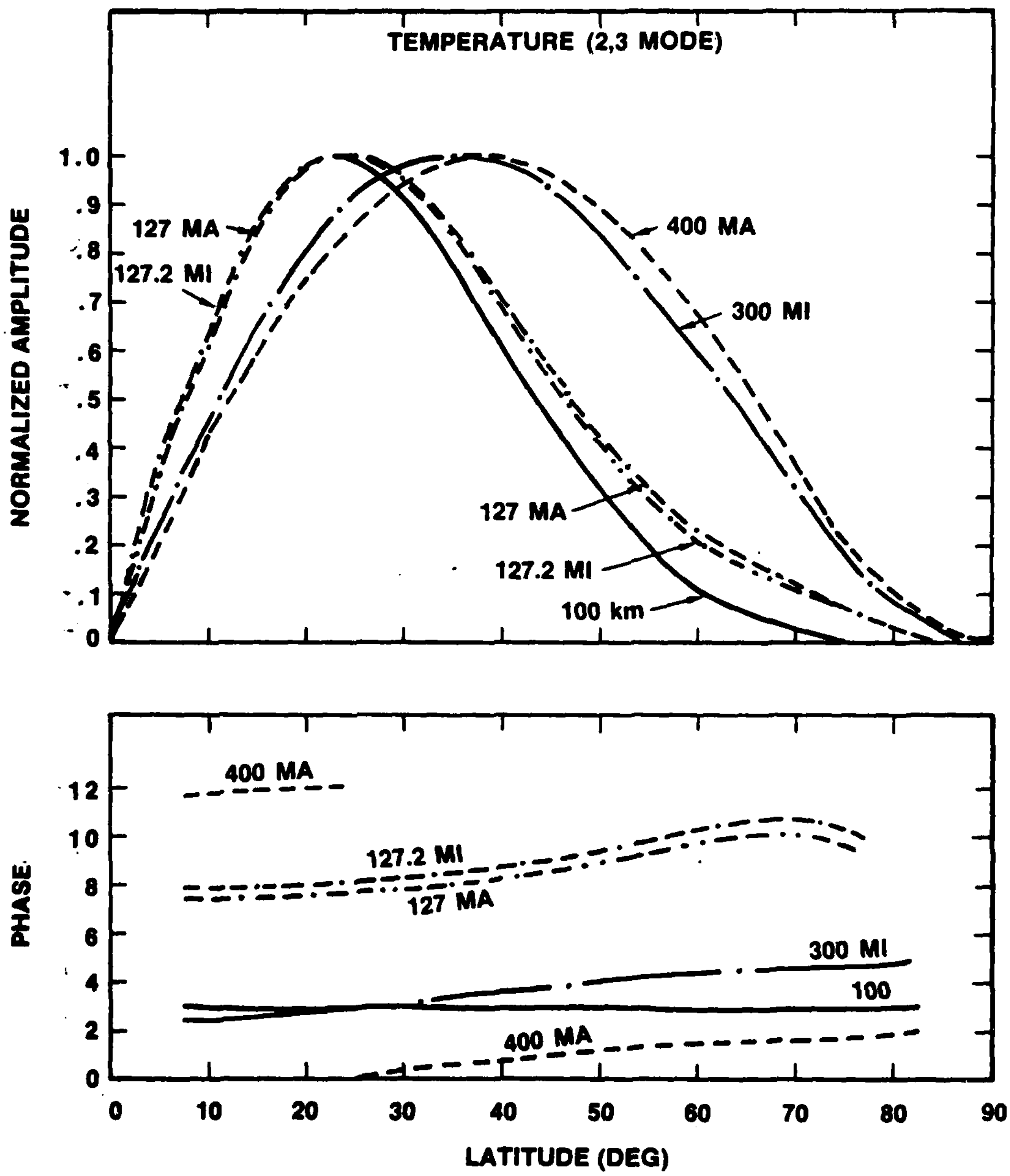


Fig. 20 — Same as 8 but for the 2,3 HME



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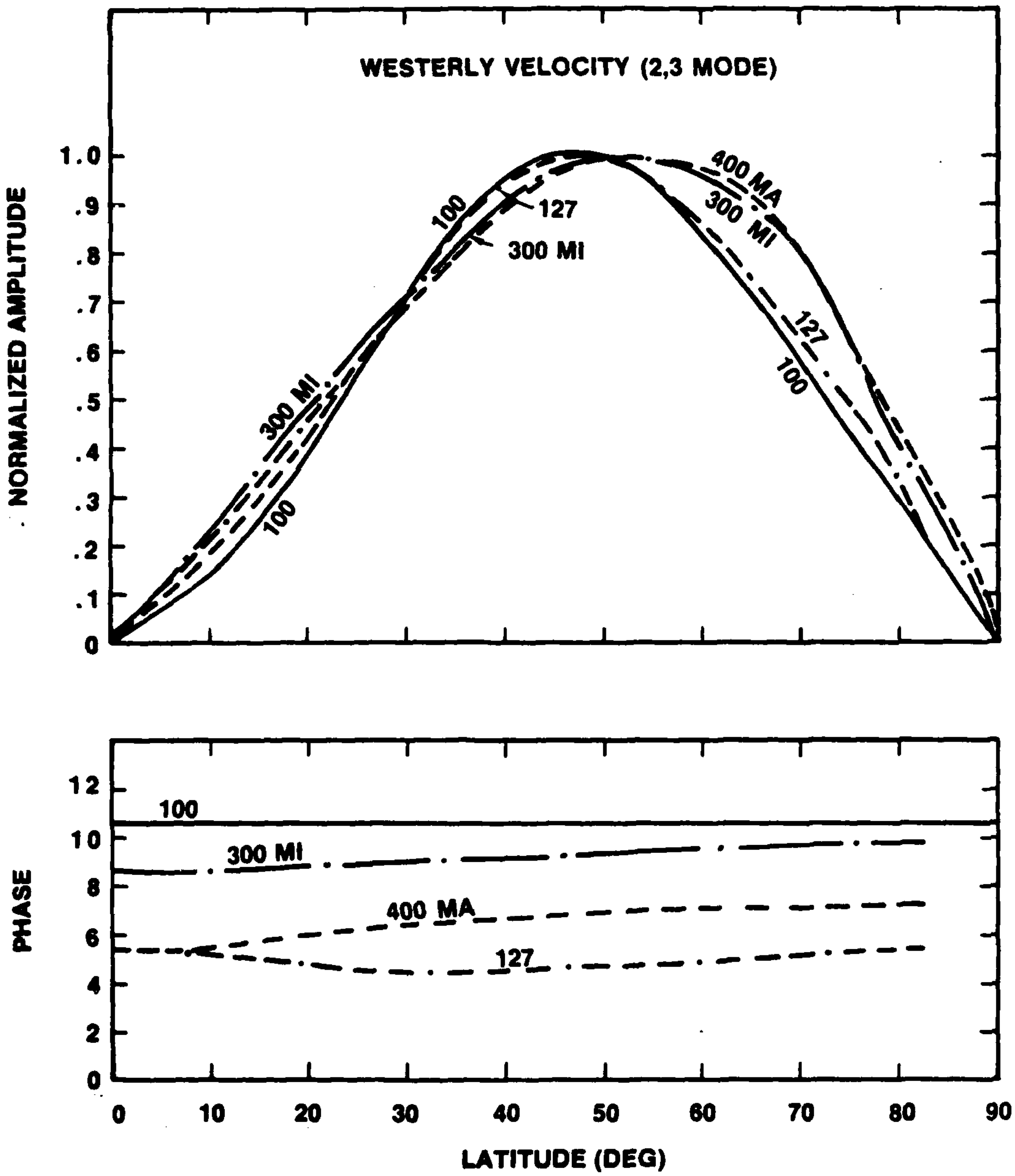


Fig. 22 — Same as 10 but for the 2,3 HME

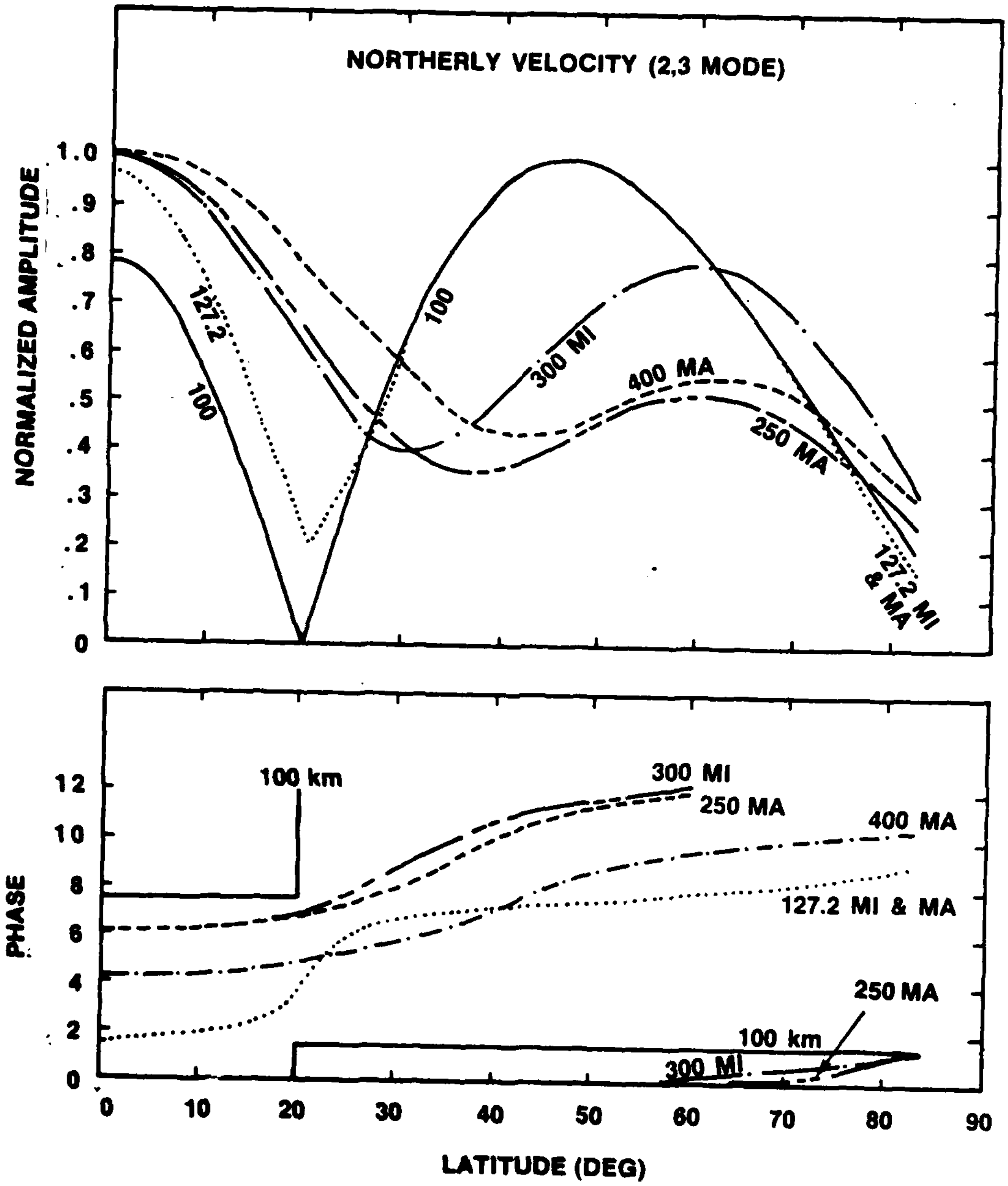


Fig. 23 — Same as 11 but for the 2,3 HME

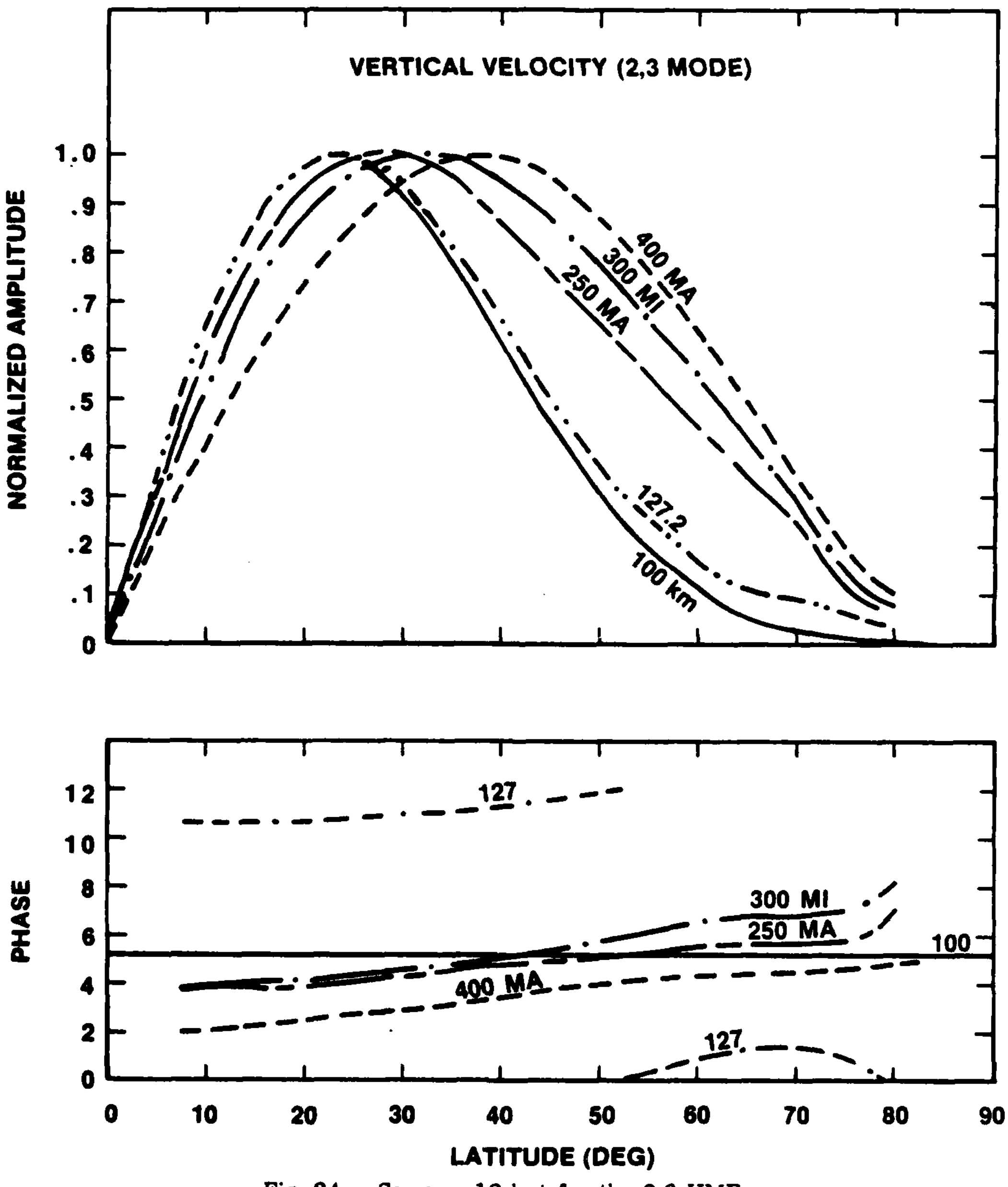


Fig. 24 — Same as 12 but for the 2,3 HME

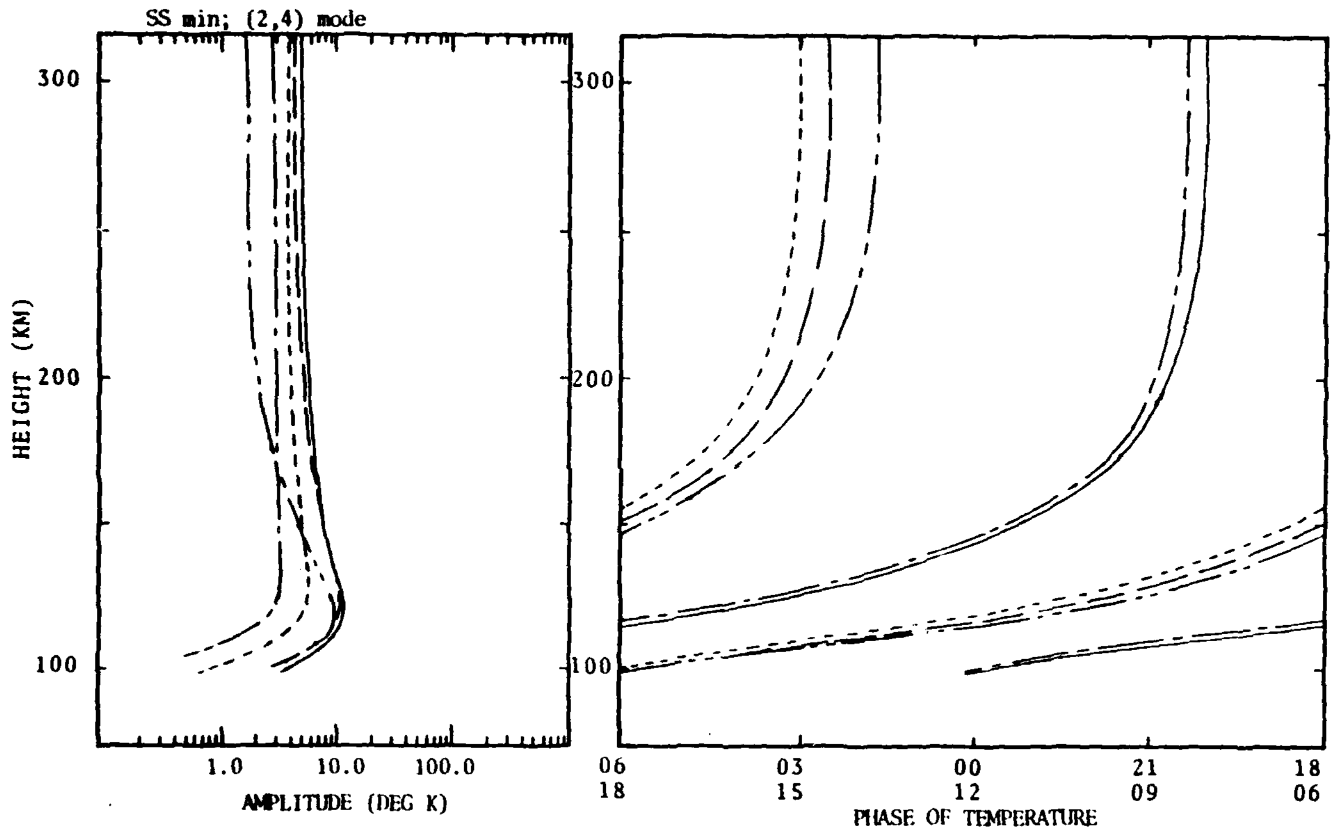


Fig. 25 — Same as 1 but for the 2,4 HME

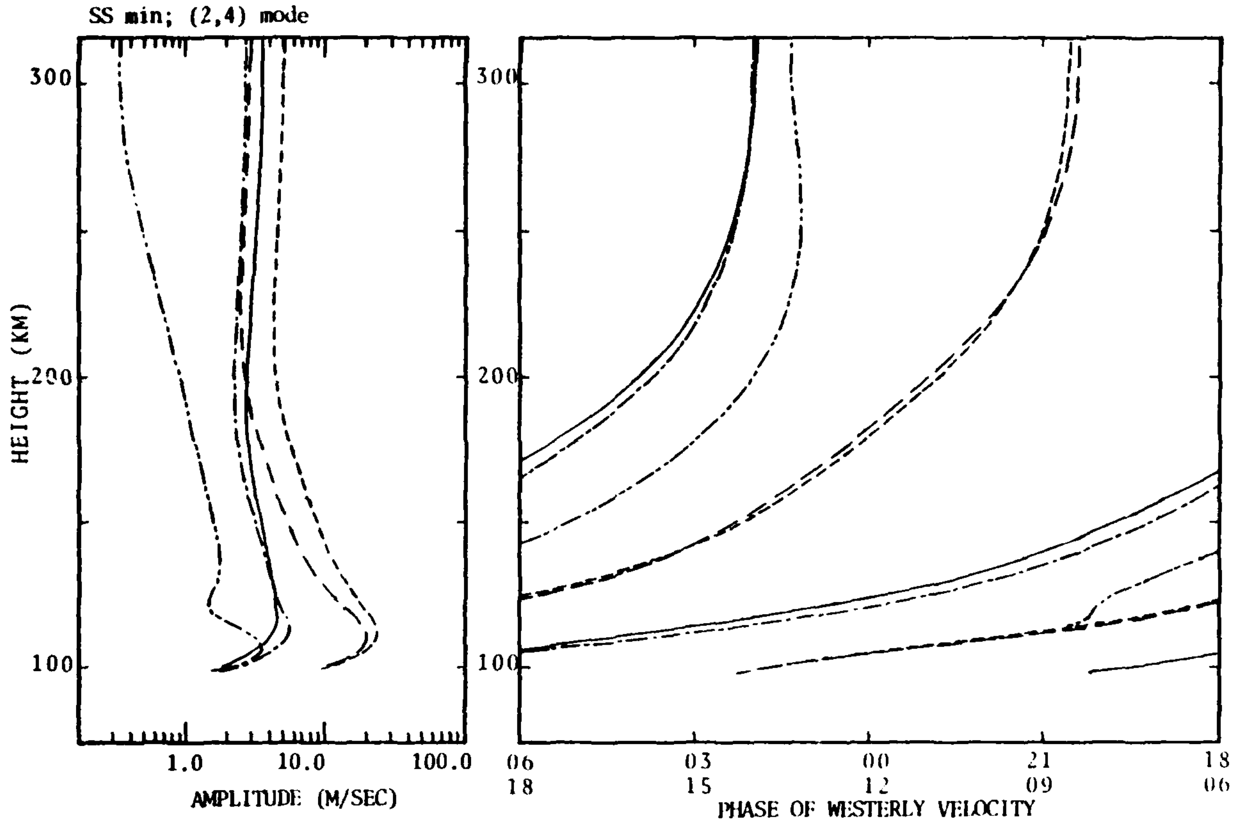


Fig. 26 — Same as 2 but for the 2,4 HME

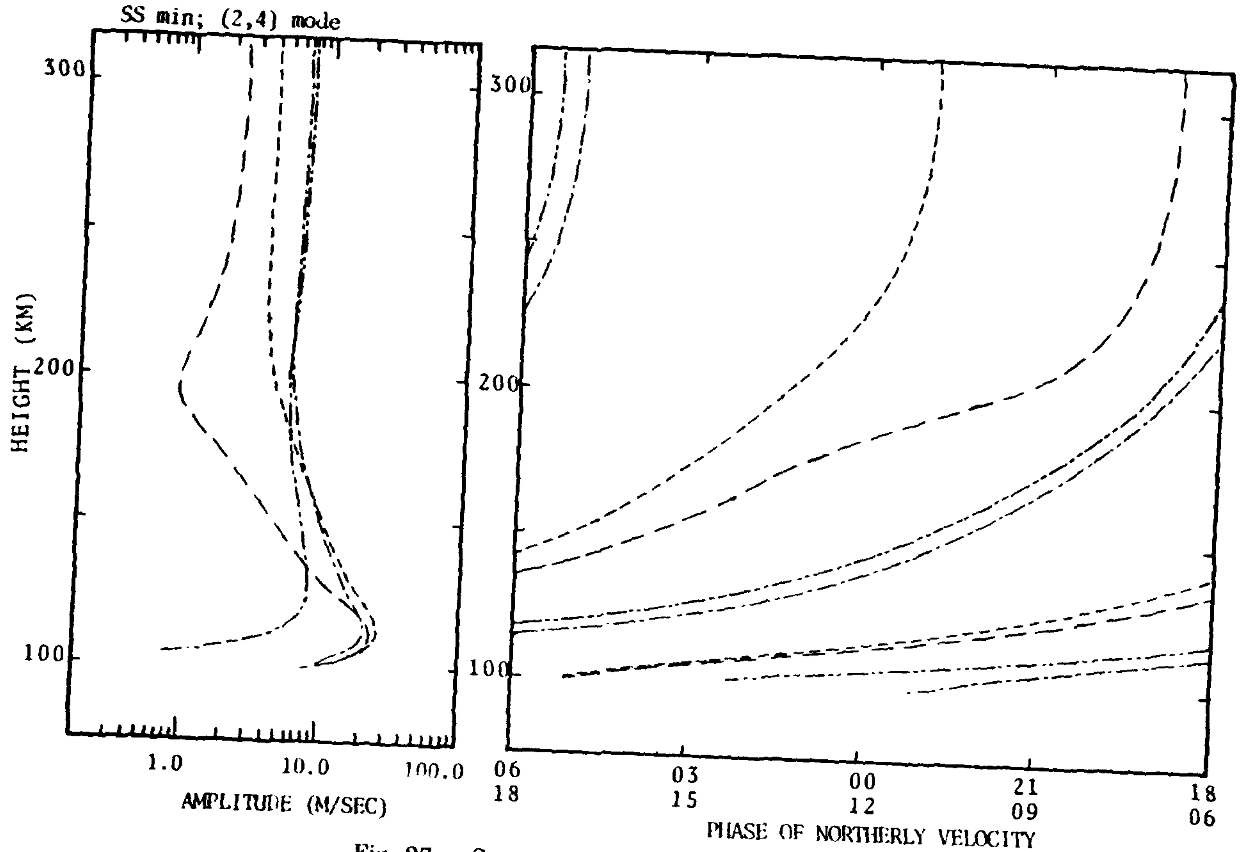


Fig. 27 — Same as 3 but for the 2,4 HME

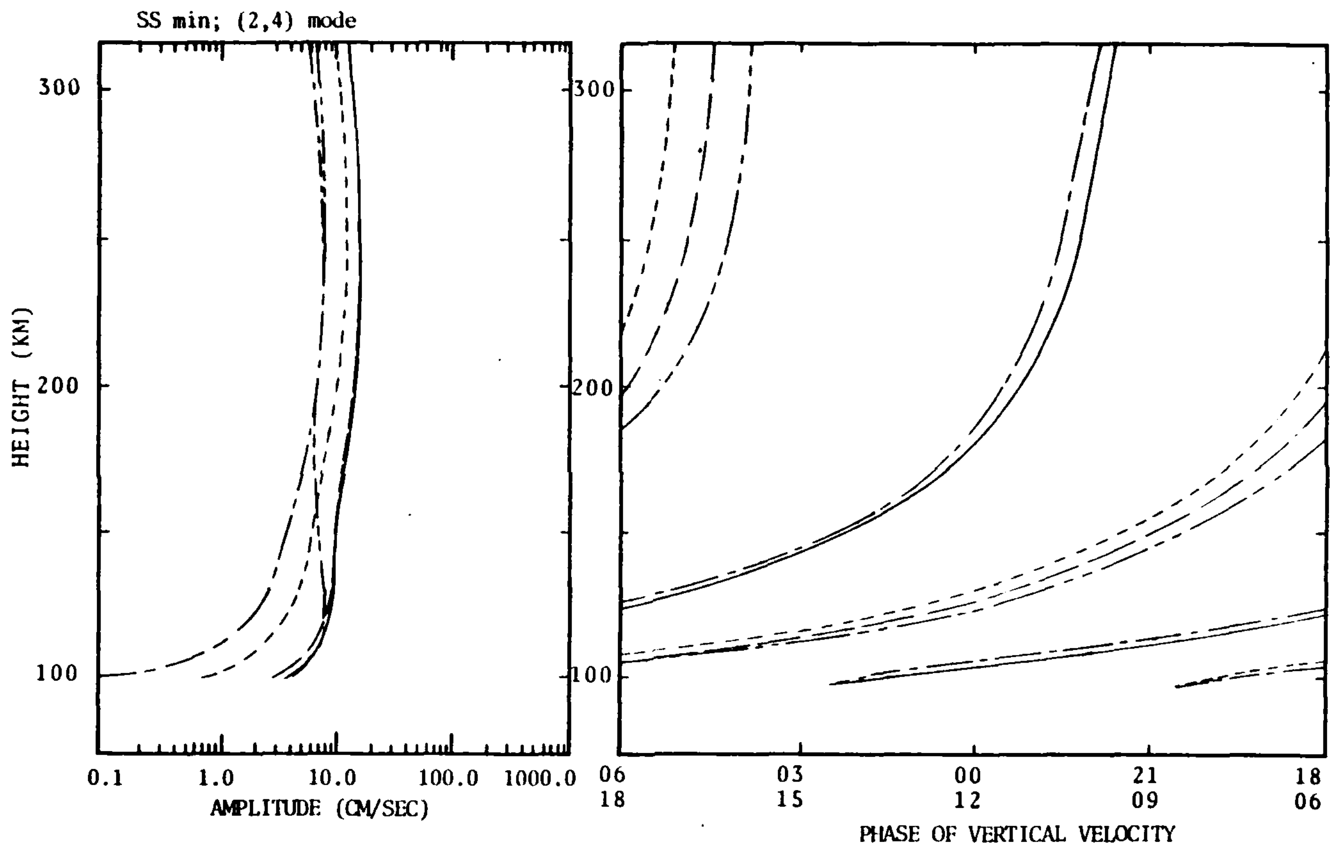
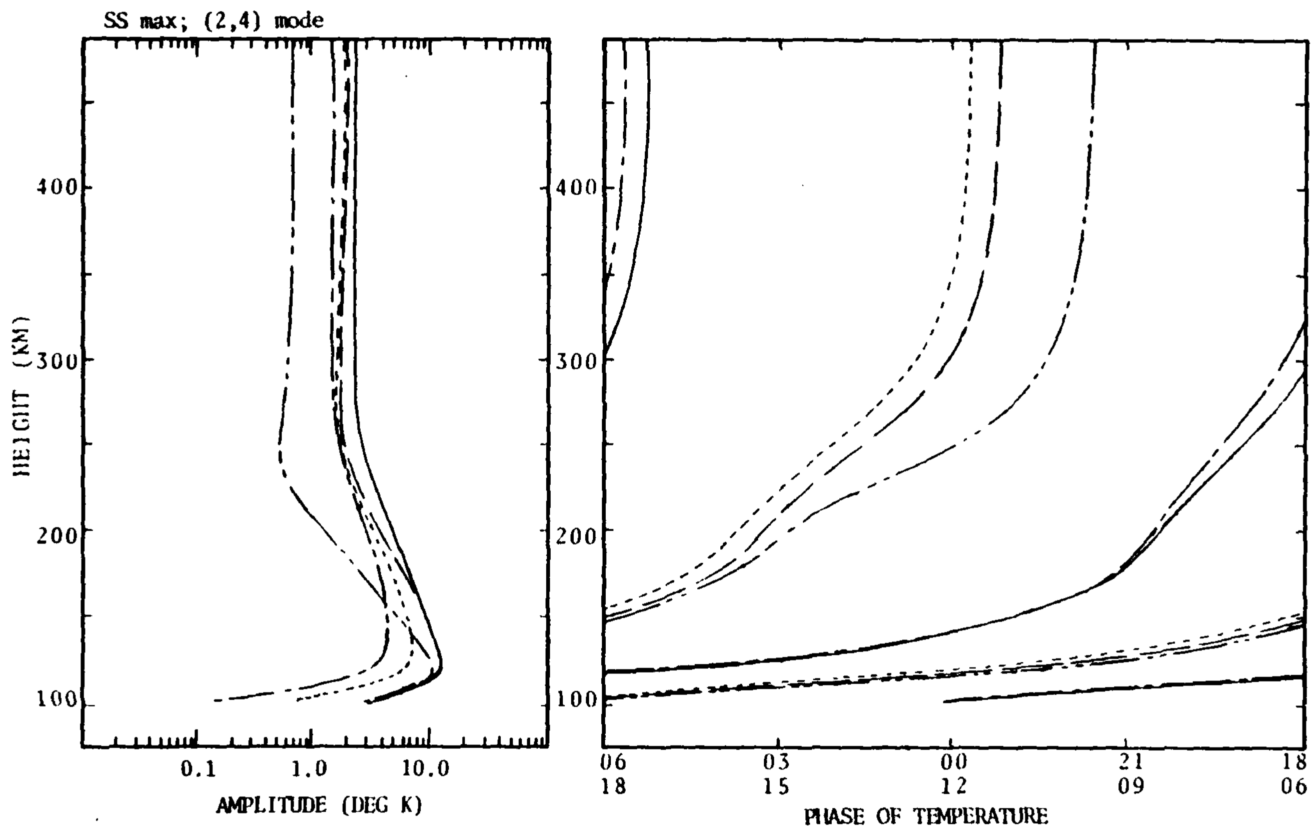


Fig. 28 — Same as 4 but for the 2,4 HME



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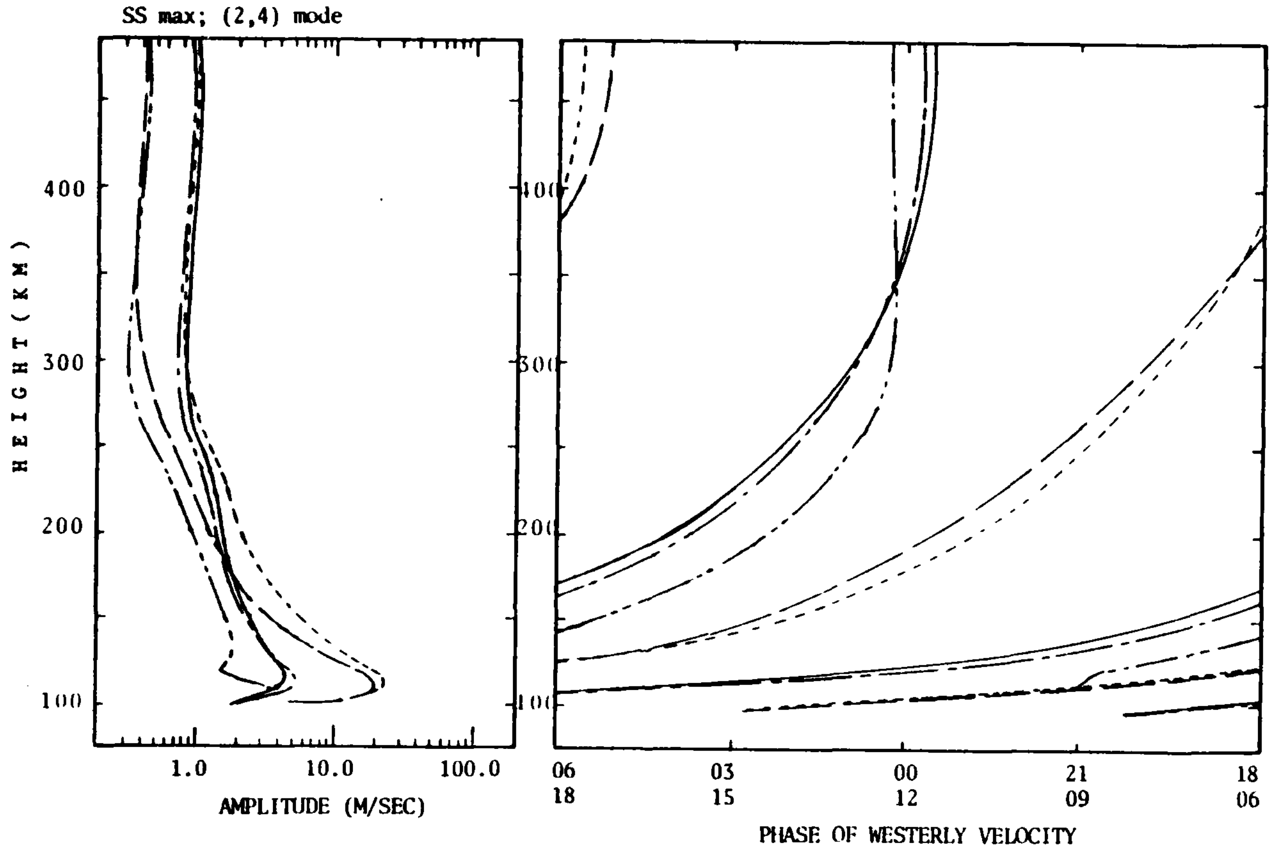

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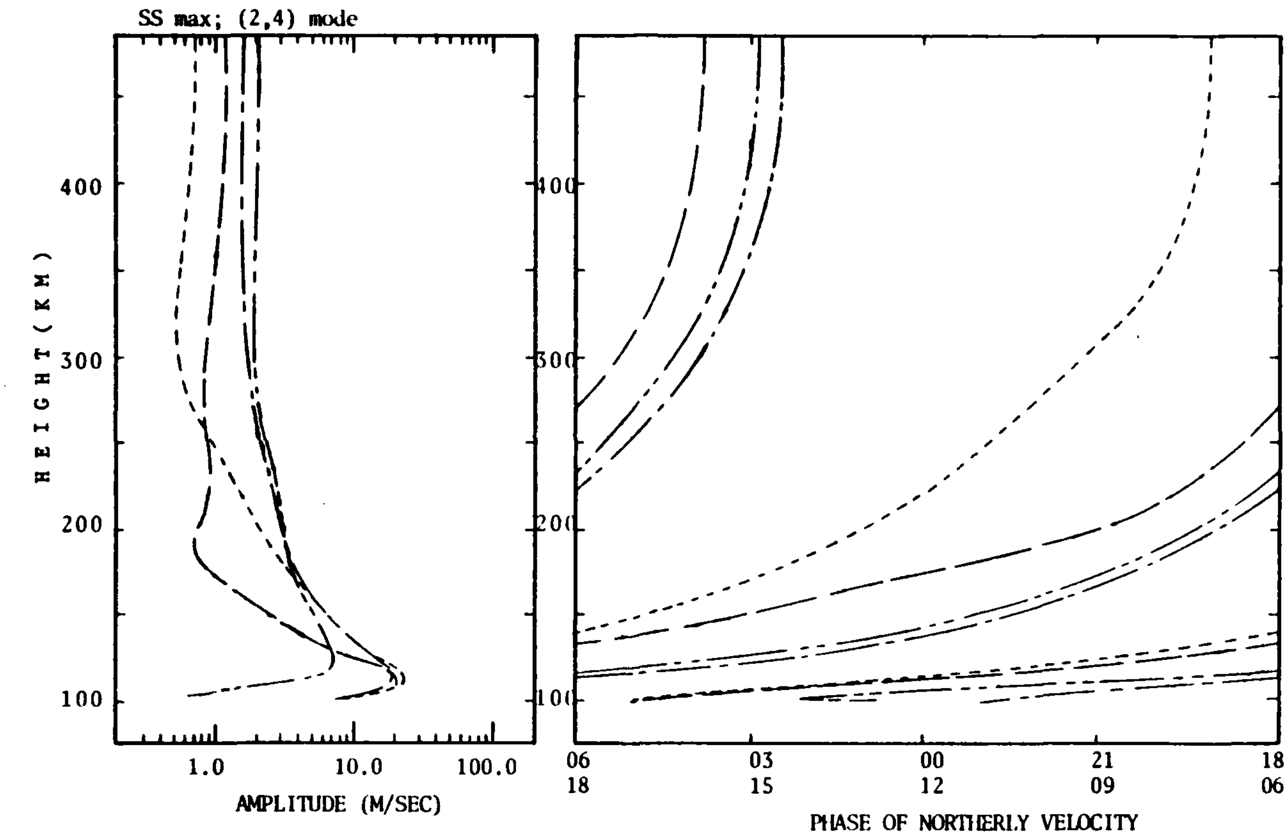

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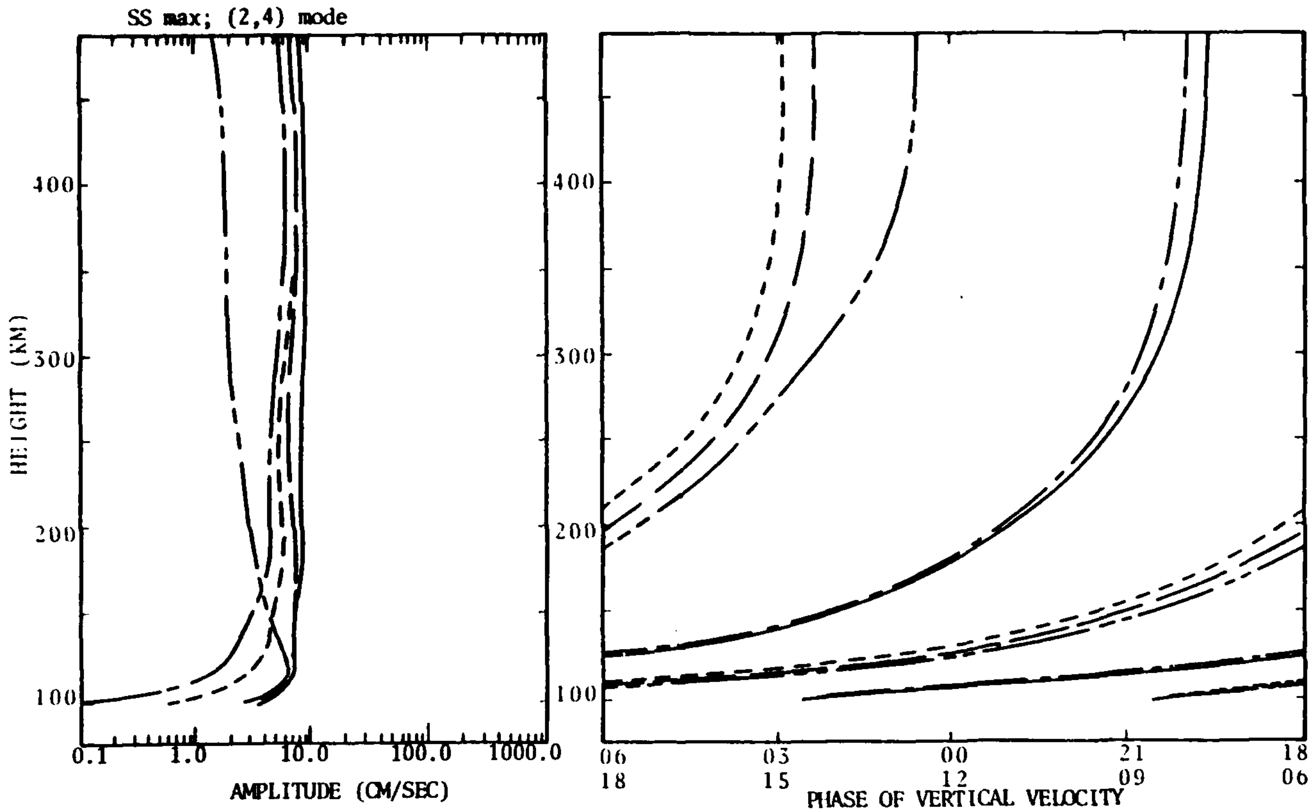

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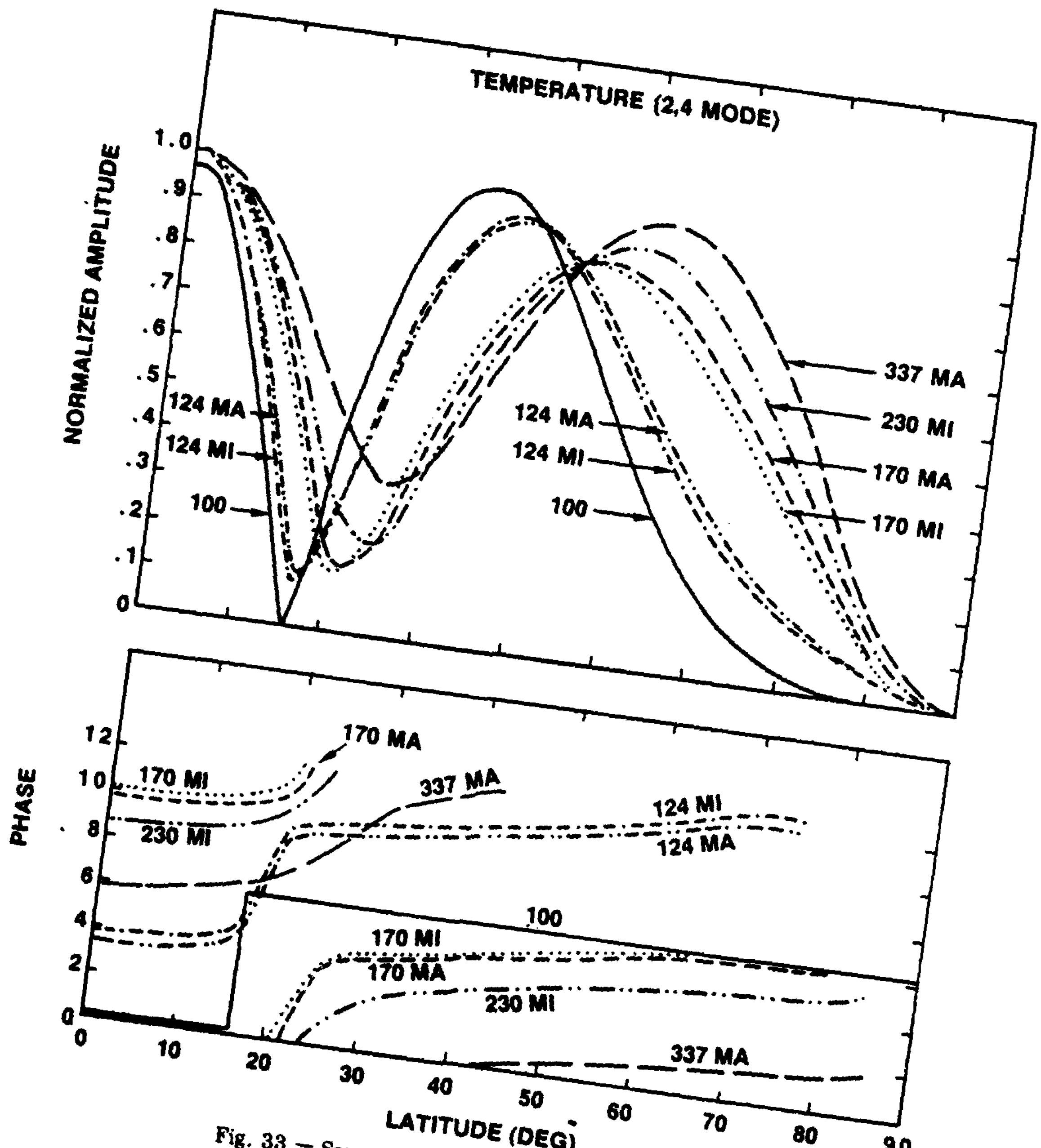

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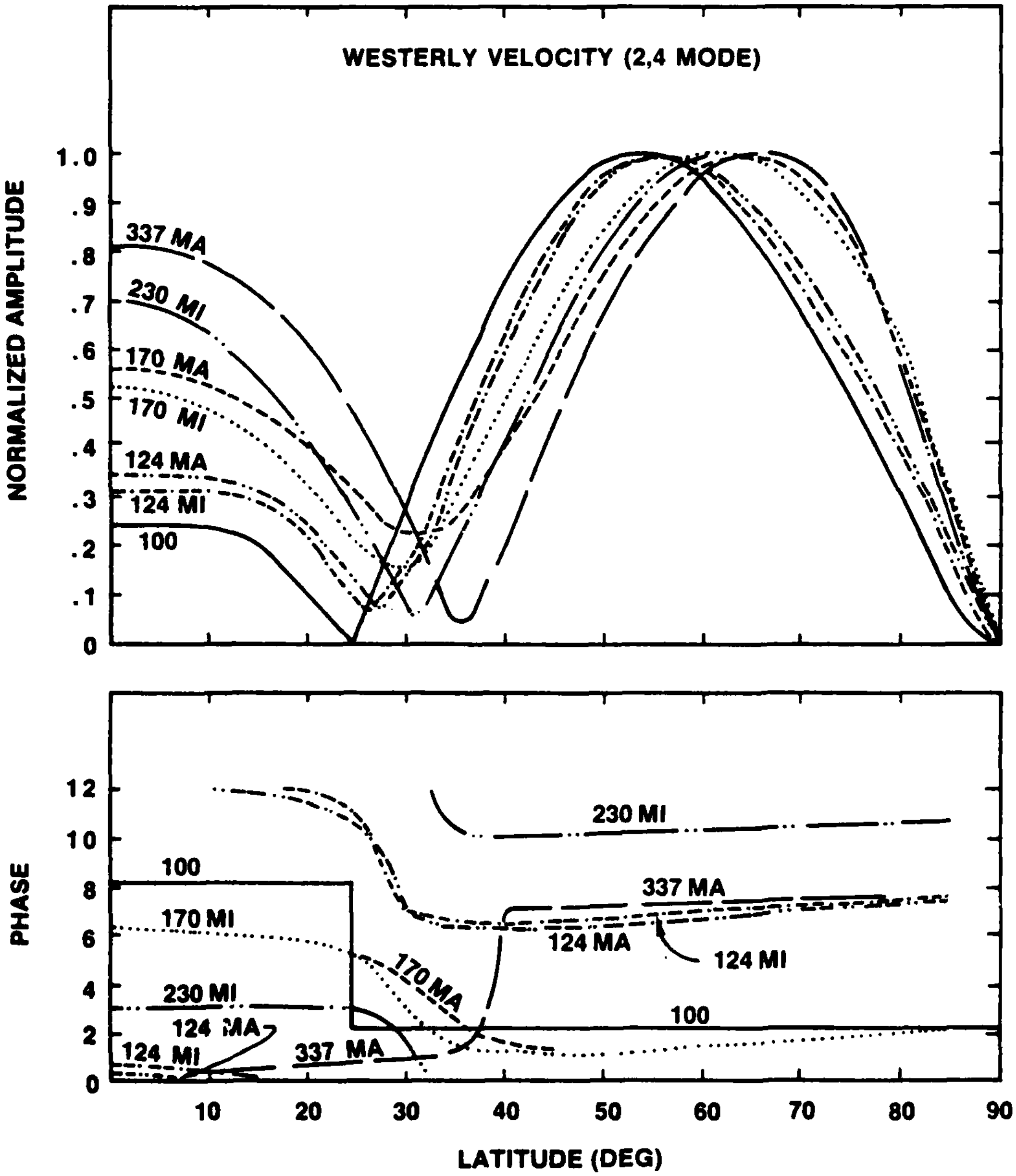

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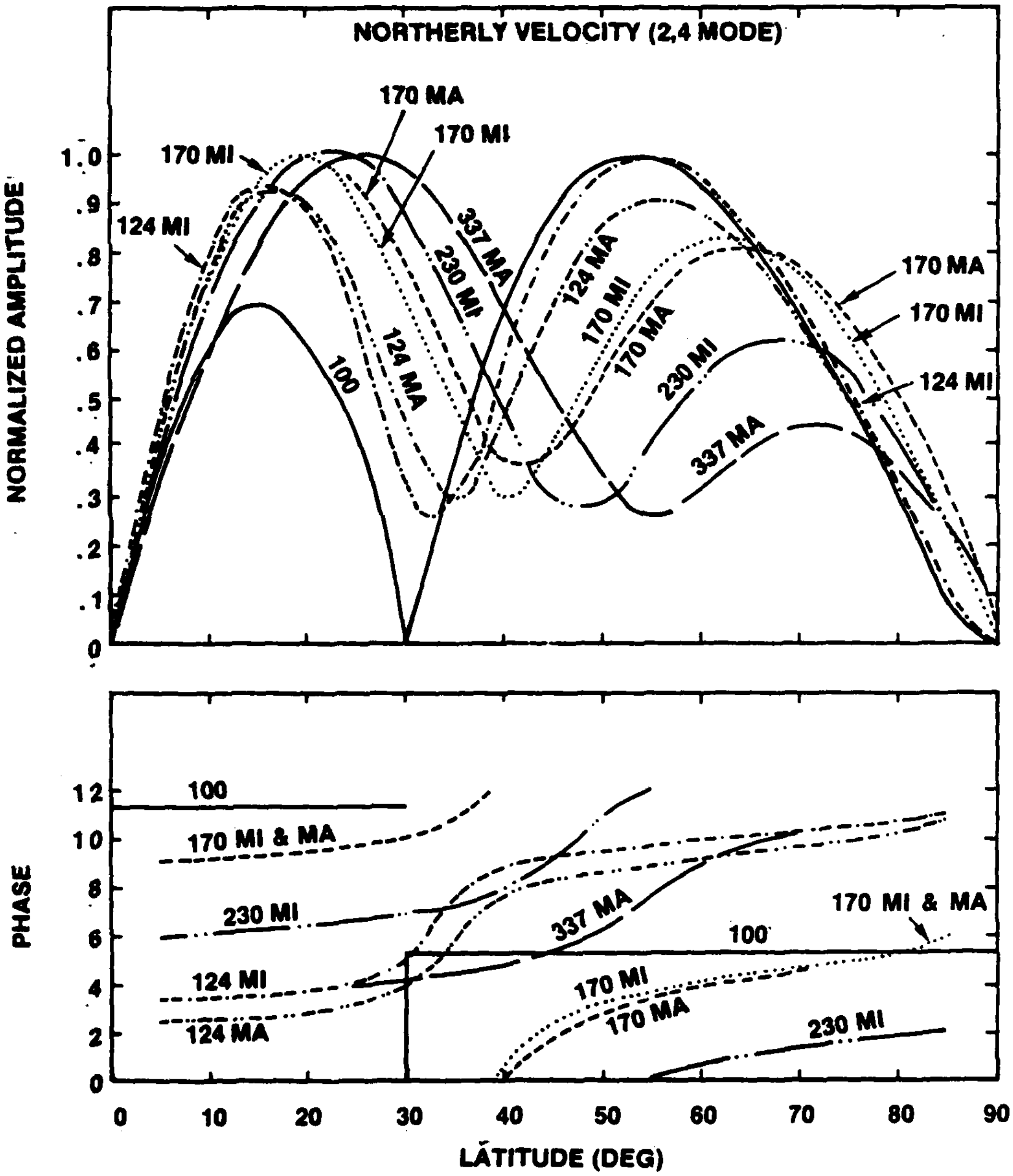

Fig. 35 — Same as 11 but for the 2,4 HME

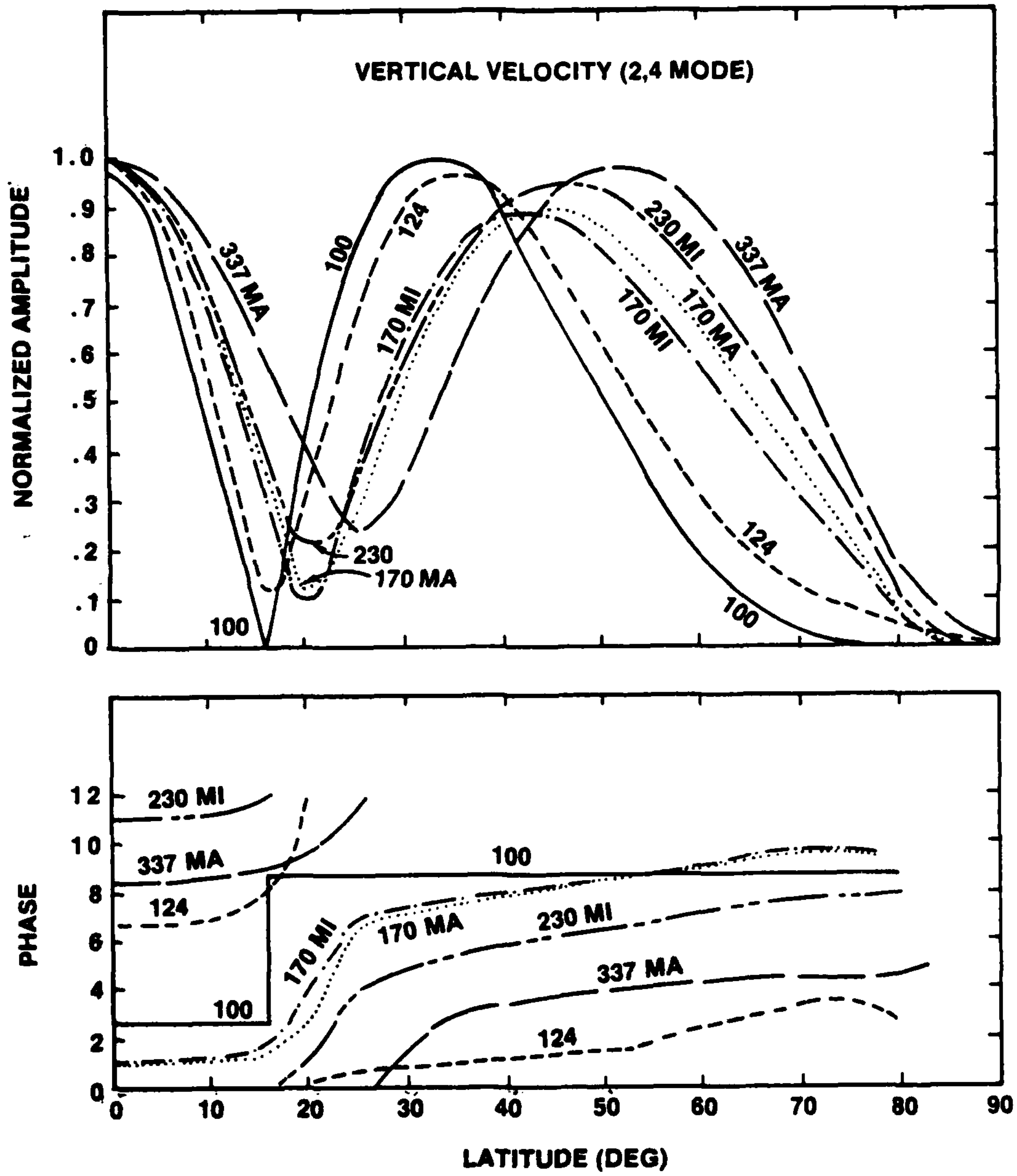

Fig. 36 — Same as 12 but for the 2,4 HME

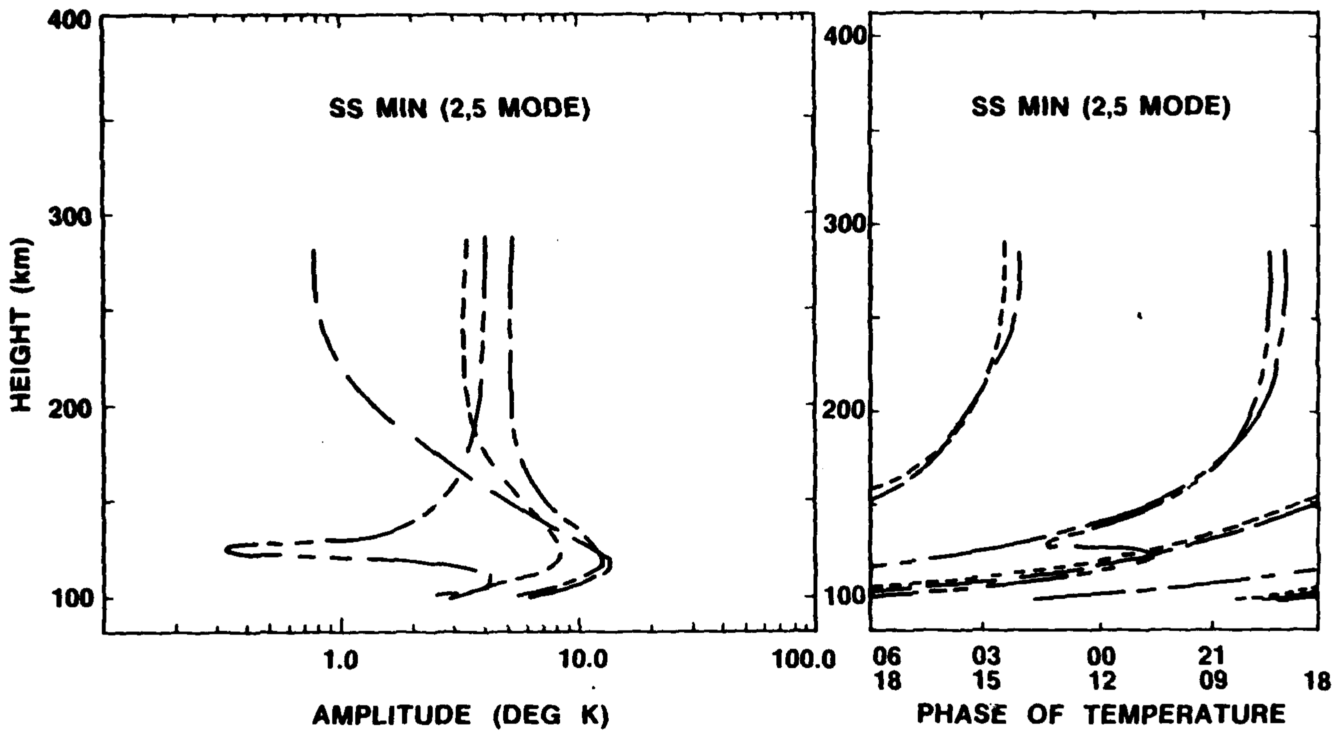

Fig. 37 — Same as 1 but for the 2,5 HME

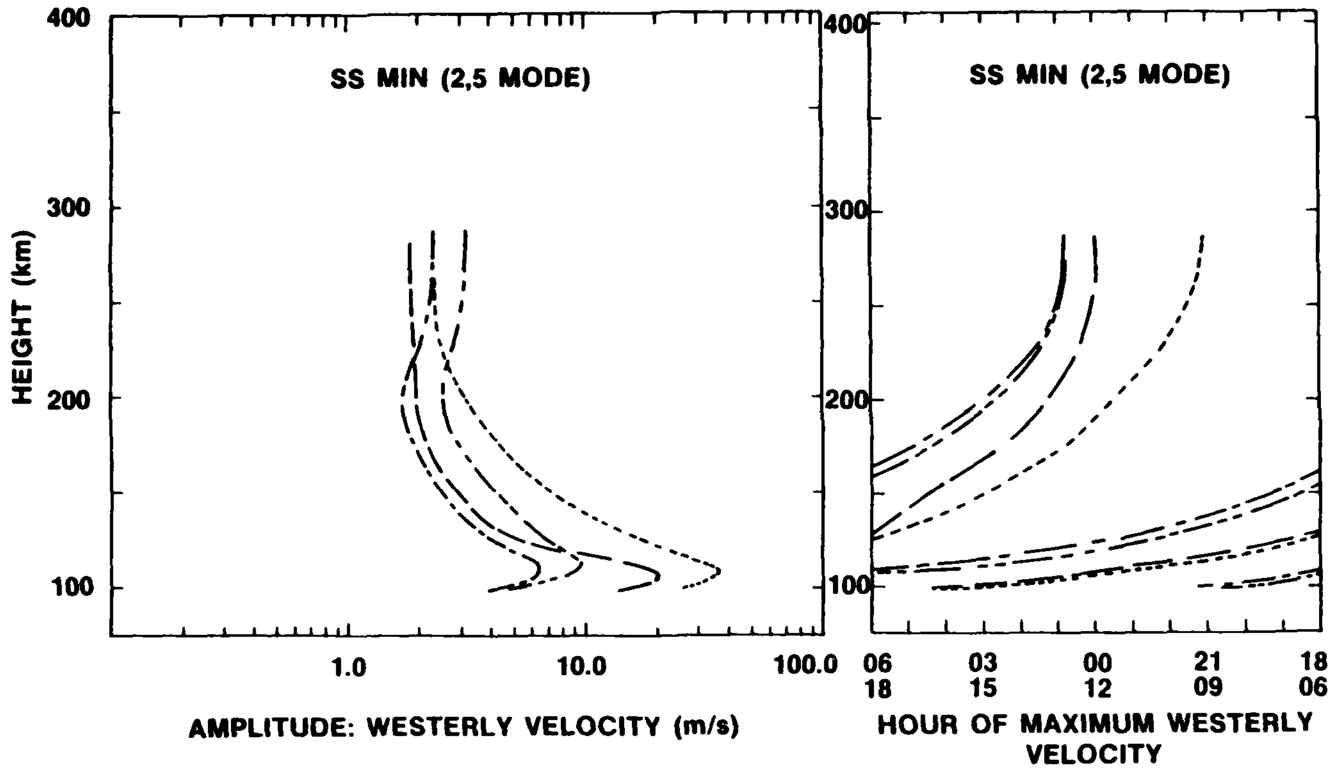

Fig. 38 — Same as 2 but for the 2,5 HME

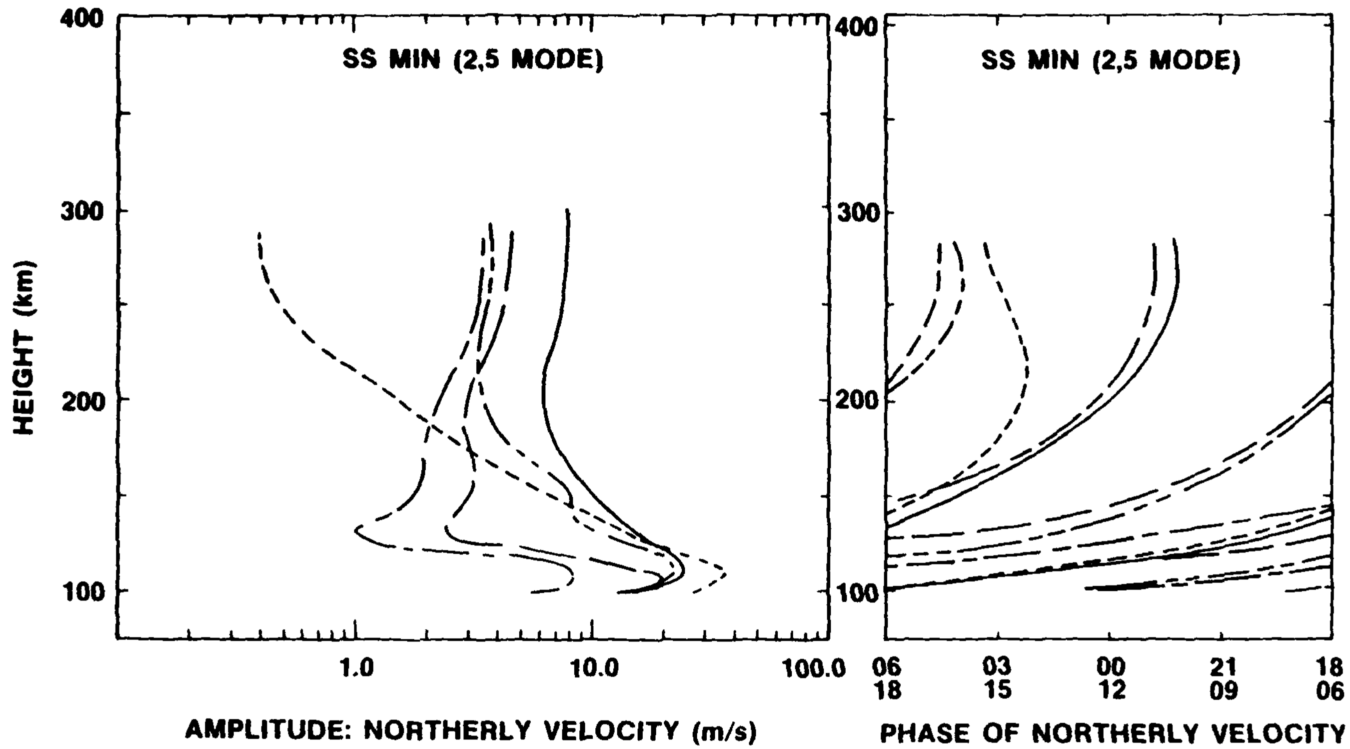

Fig. 39 — Same as 3 but for the 2,5 HME

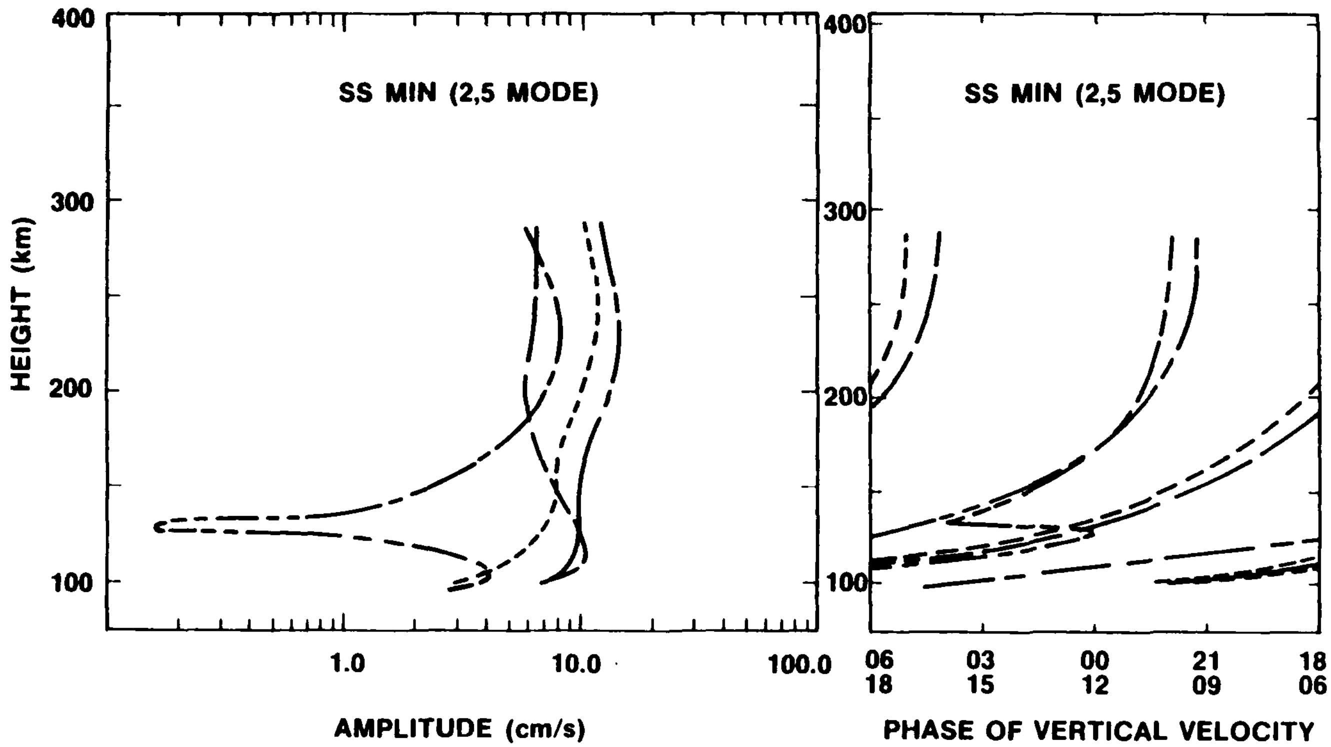

Fig. 40 — Same as 4 but for the 2,5 HME

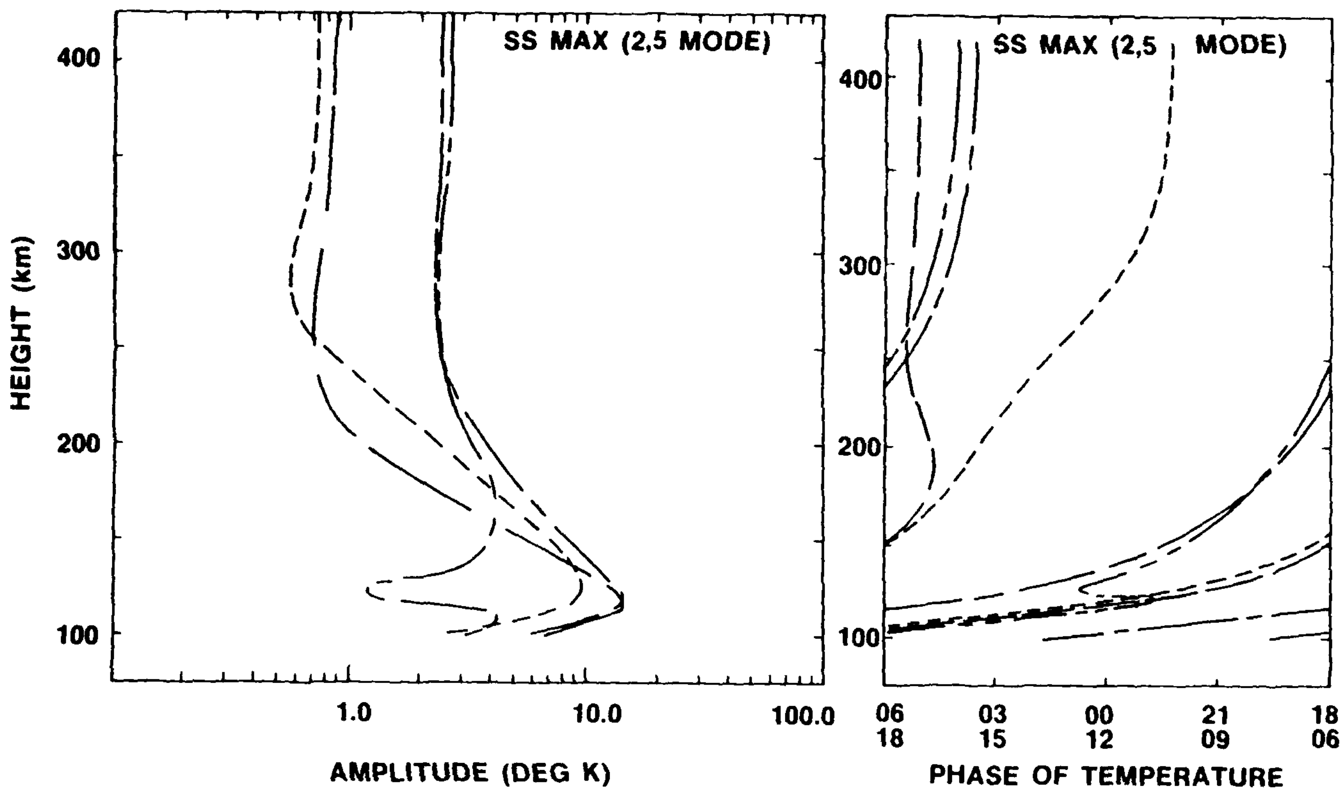

Fig. 41 — Same as 5 but for the 2,5 HME

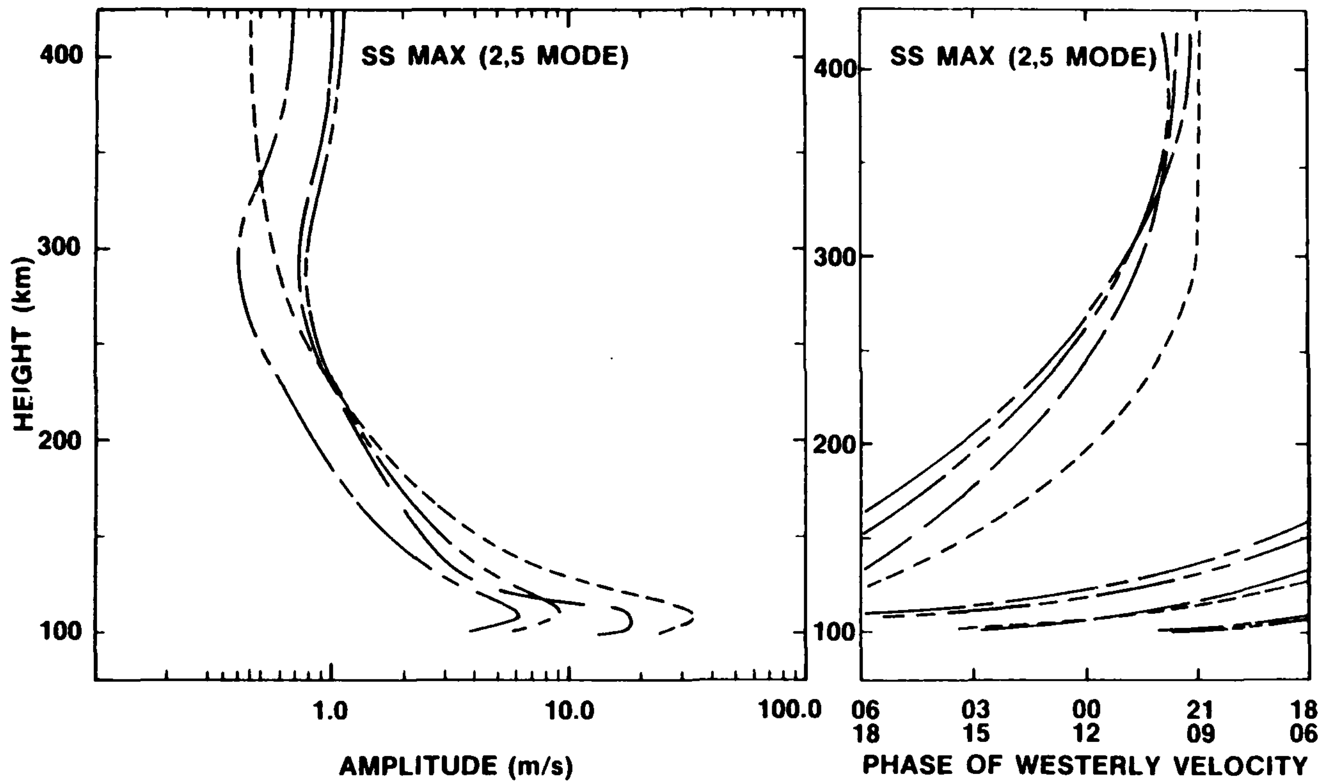

Fig. 42 — Same as 6 but for the 2,5 HME

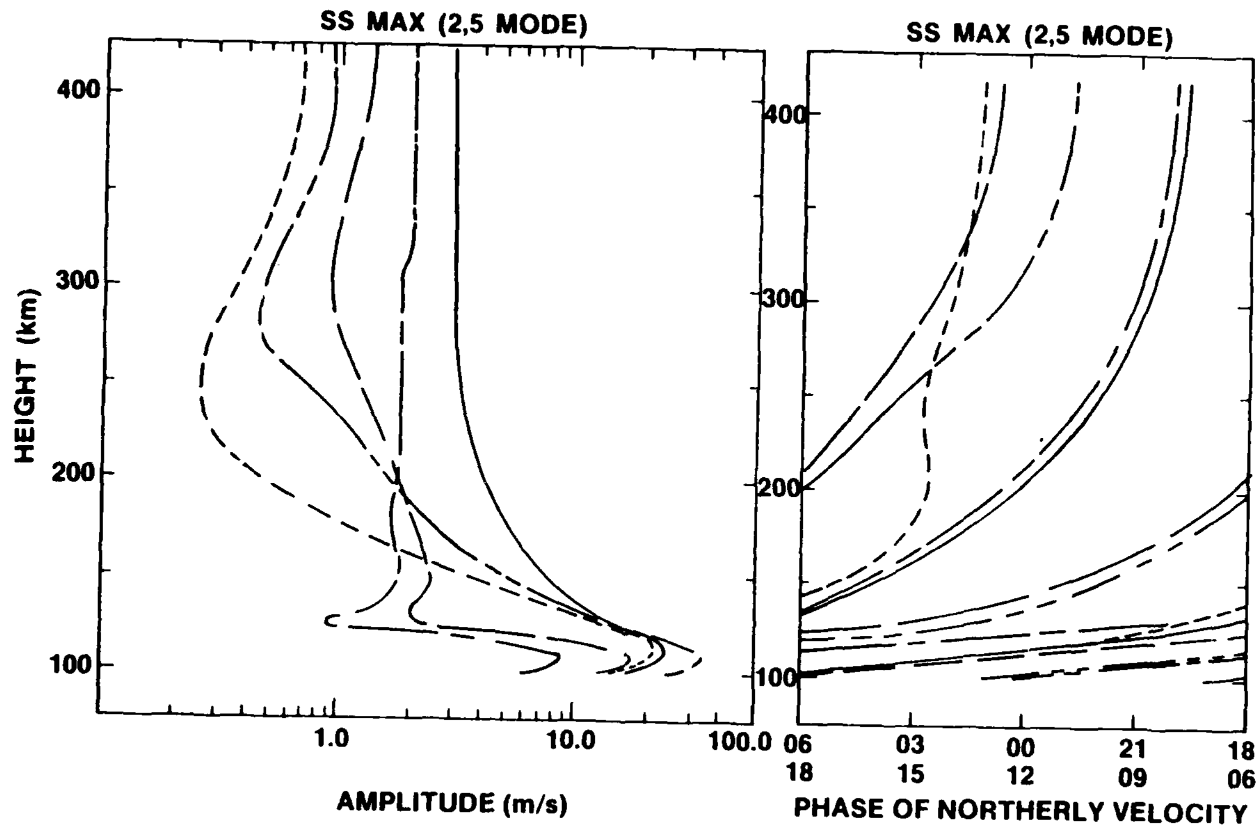

Fig. 43 — Same as 7 but for the 2,5 HME

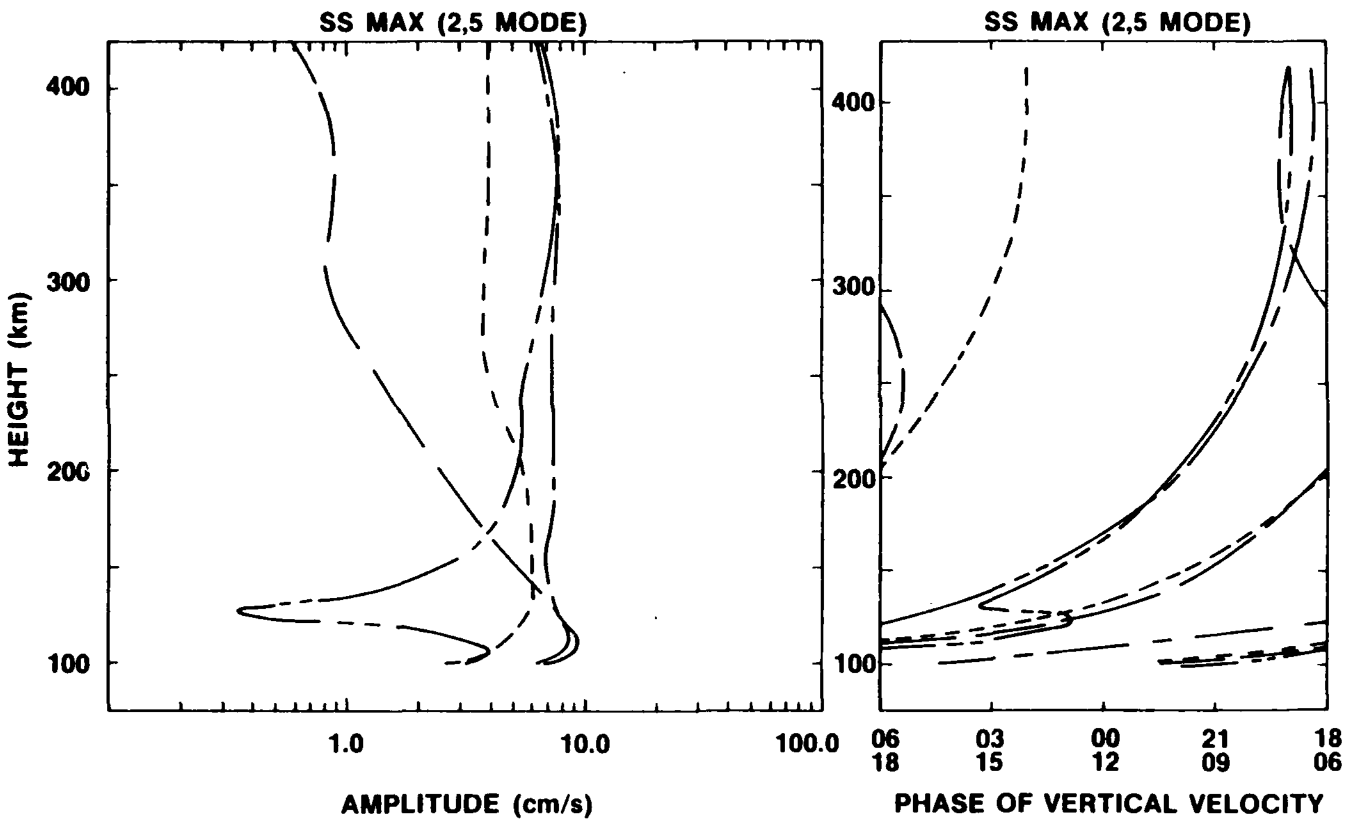

Fig. 44 — Same as 8 but for the 2,5 HME

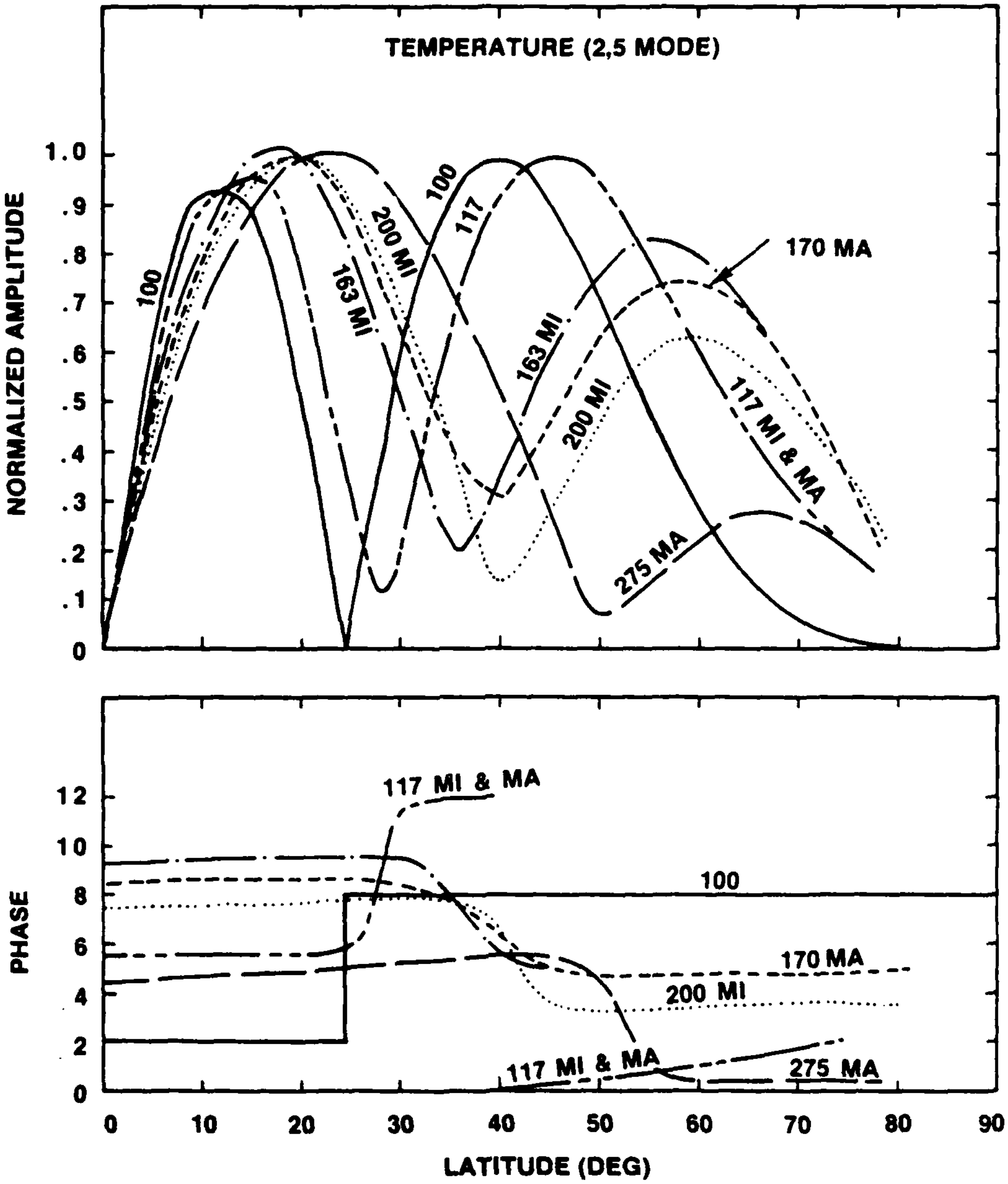

Fig. 45 — Same as 9 but for the 2,5 HME

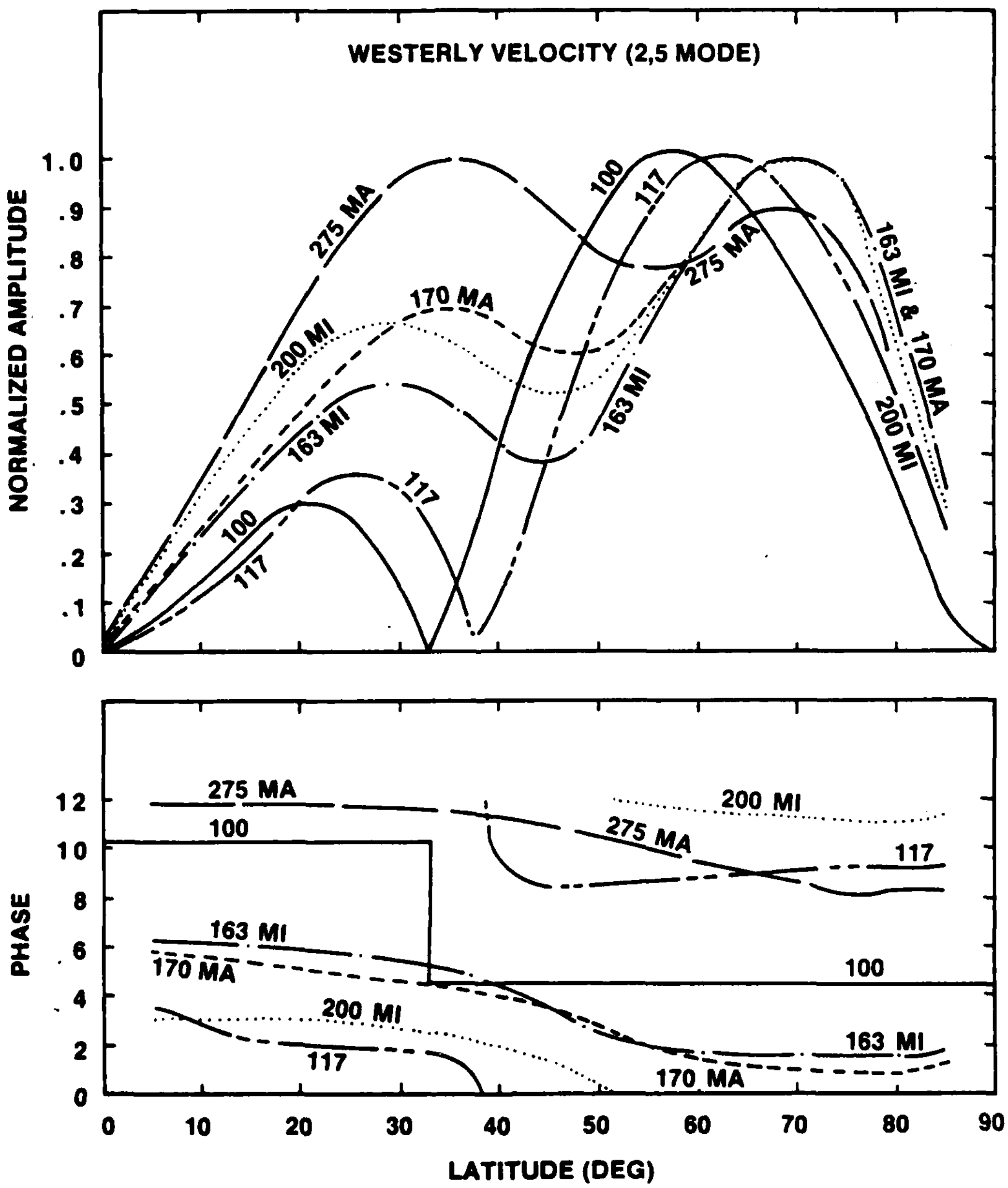

Fig. 46 — Same as 10 but for the 2,5 HME

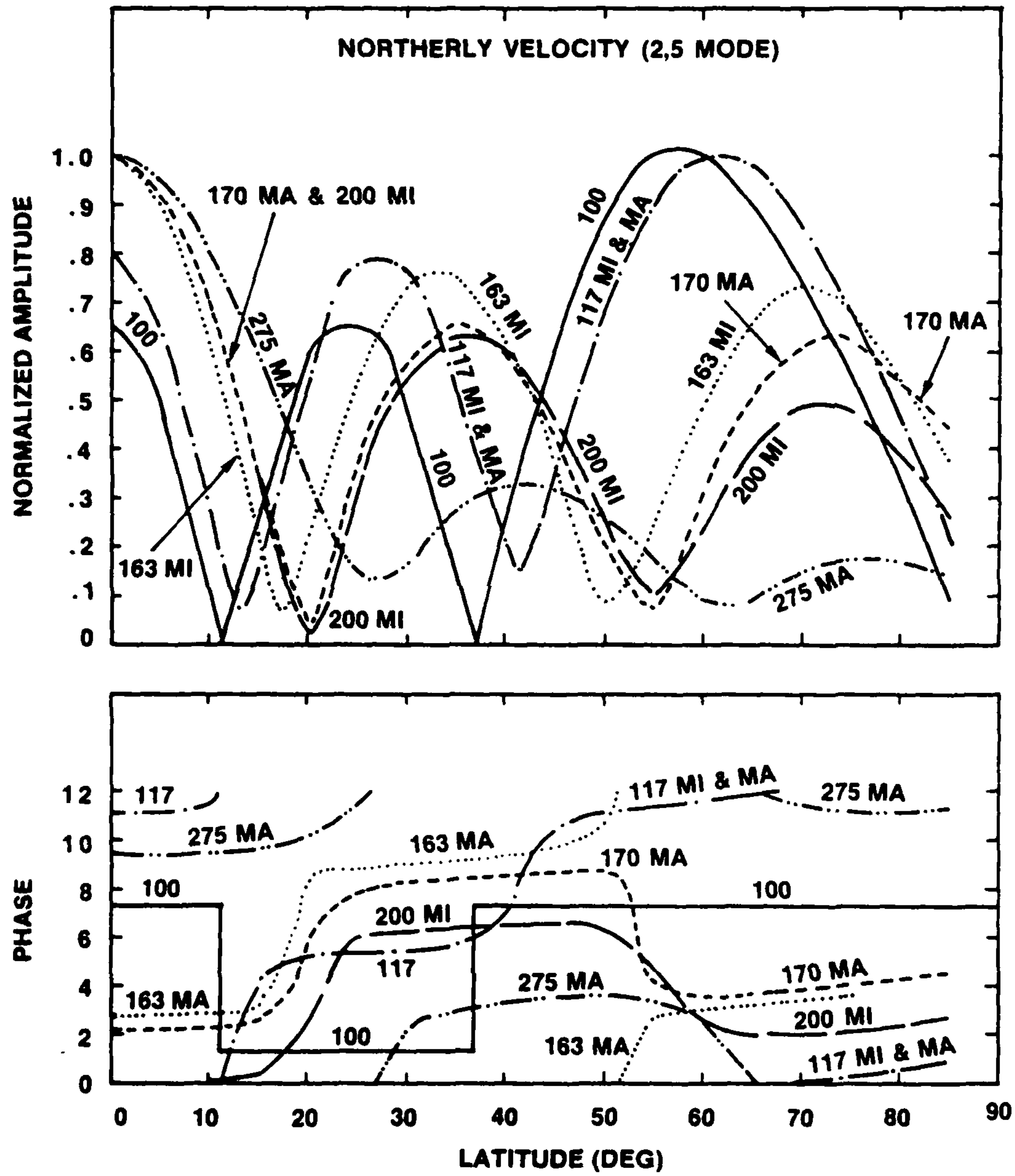

Fig. 47 — Same as 11 but for the 2,5 HME

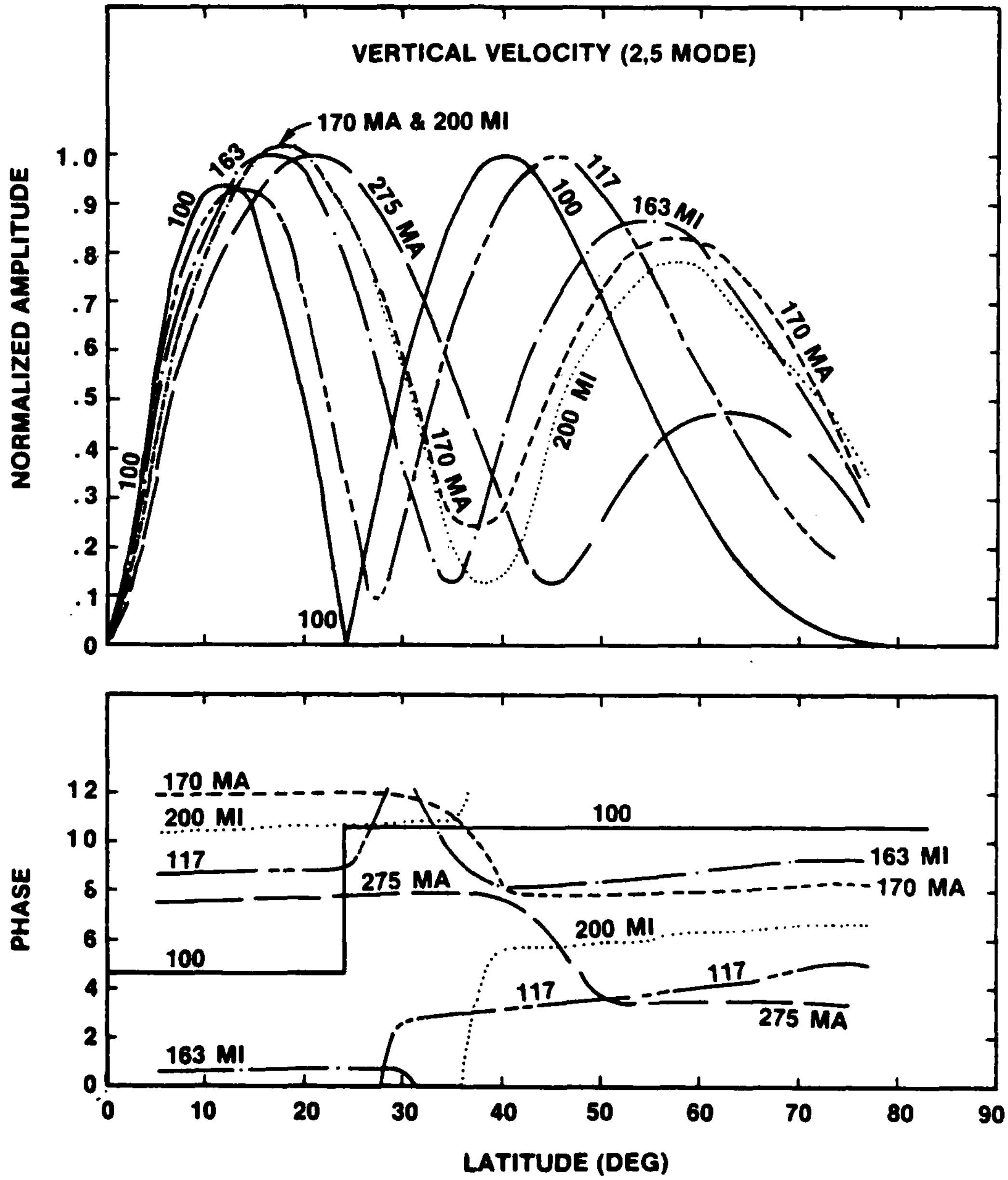

Fig. 48 — Same as 12 but for the 2,5 HME

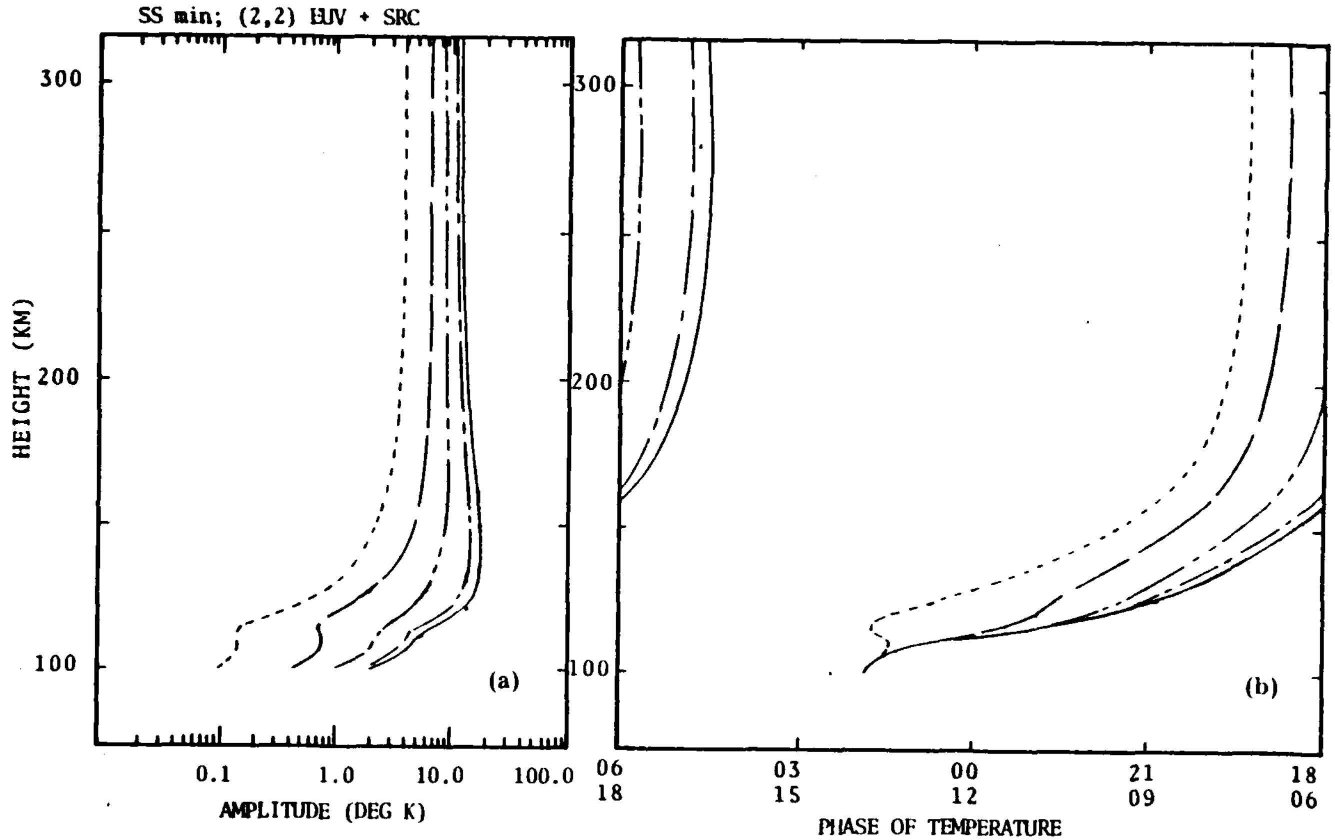

Fig. 49 — (a) Amplitude of the semidiurnal temperature oscillation forced by absorption in the EUV and Schuemann-Runge continuum as a function of altitude at selected latitudes for sunspot minimum conditions. See Fig. 1 for line conventions. See text for further details. (b) Phase (hour of maximum, local time) of the semidiurnal temperature oscillation described in 49(a).

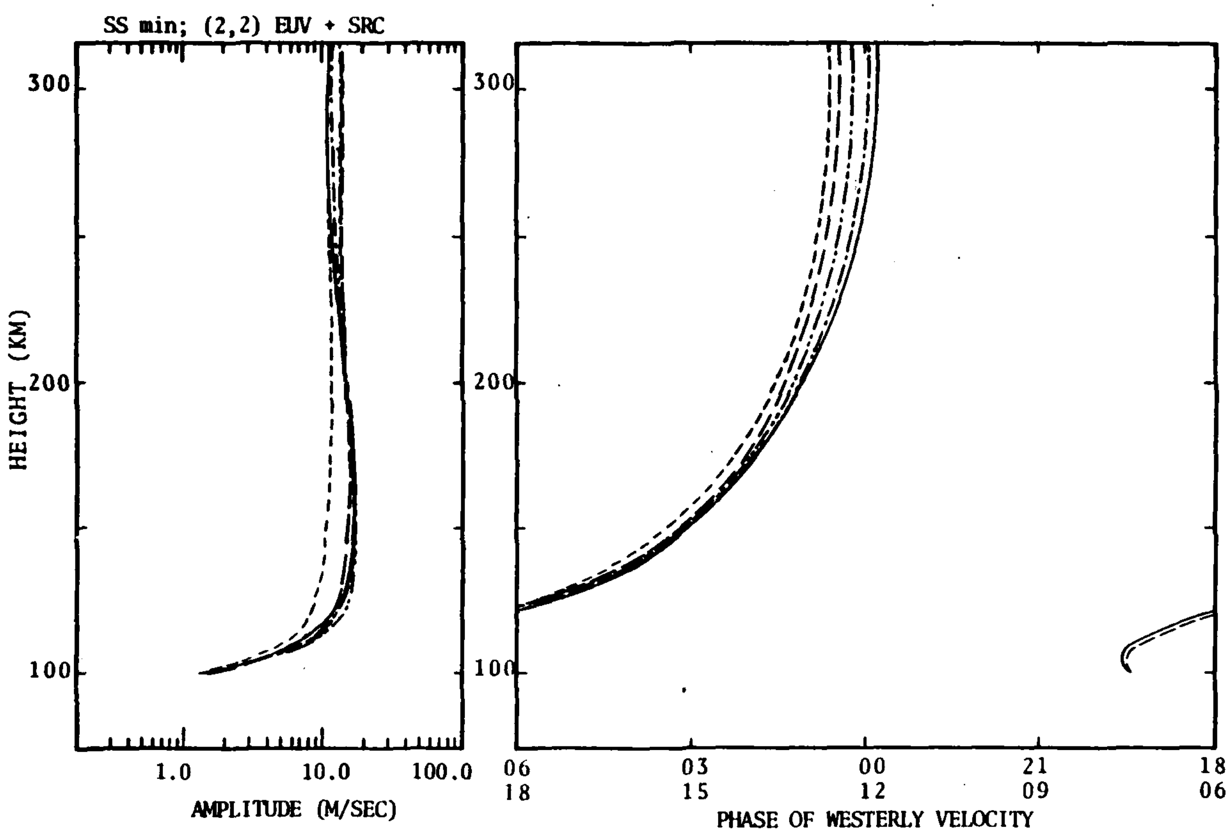

Fig. 50 — Same as 49 but for the westerly velocity oscillation

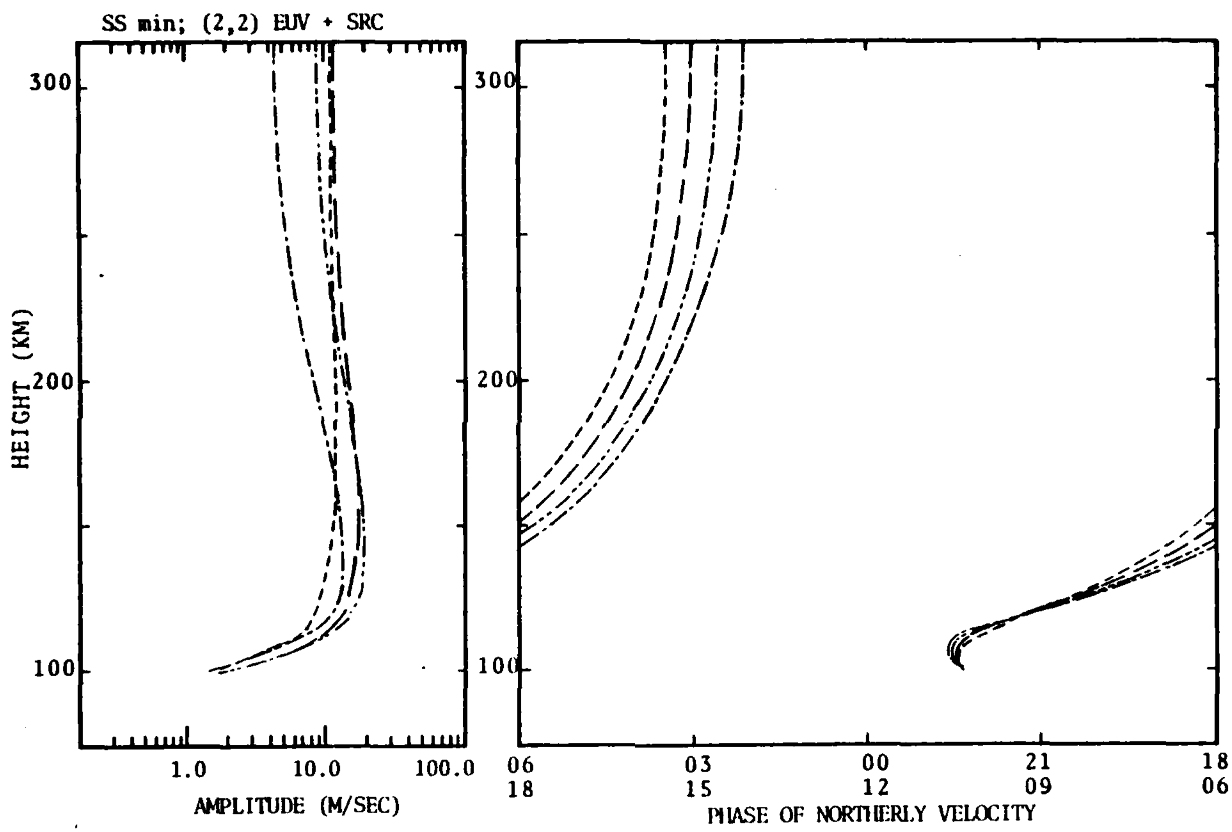

Fig. 51 — Same as 49 but for the northerly velocity oscillation

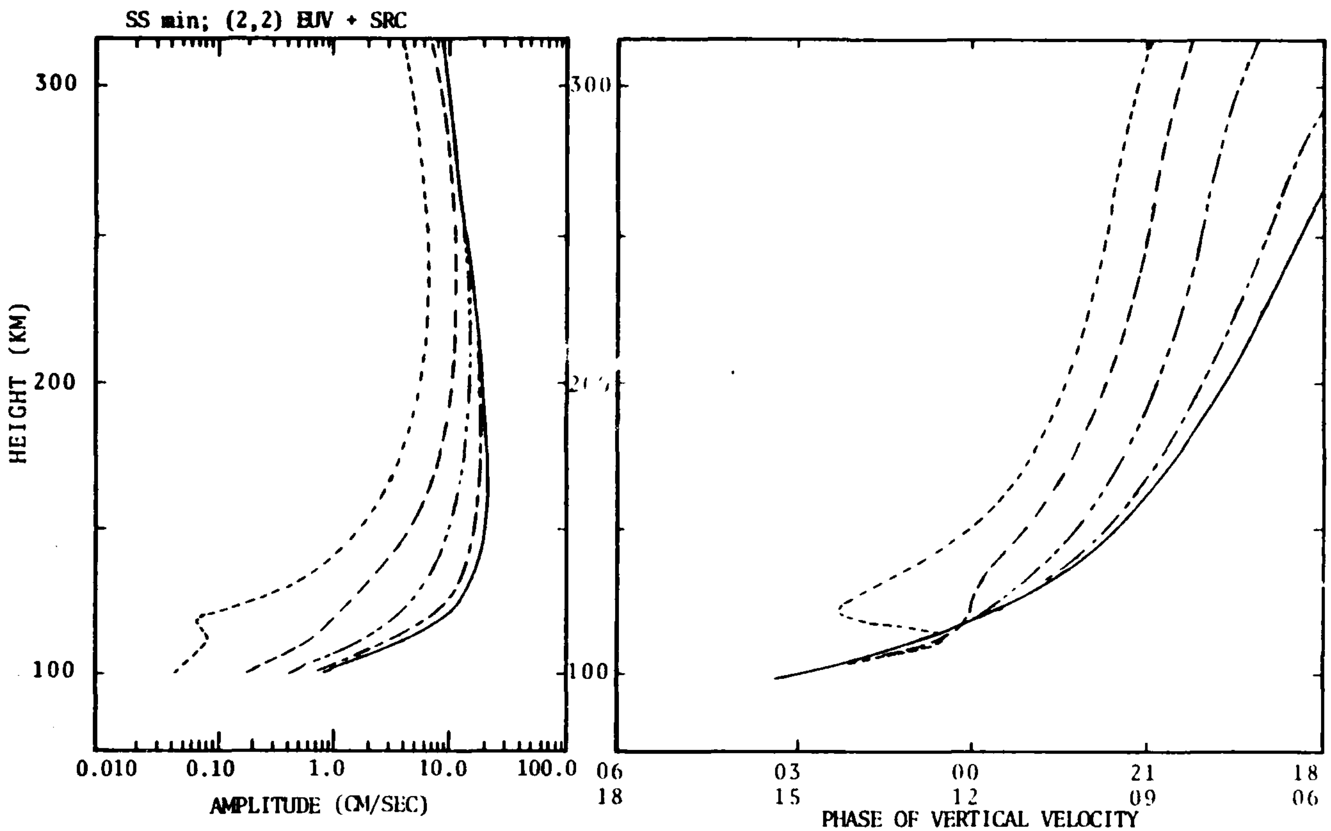

Fig. 52 — Same as 49 but for the vertical velocity oscillation

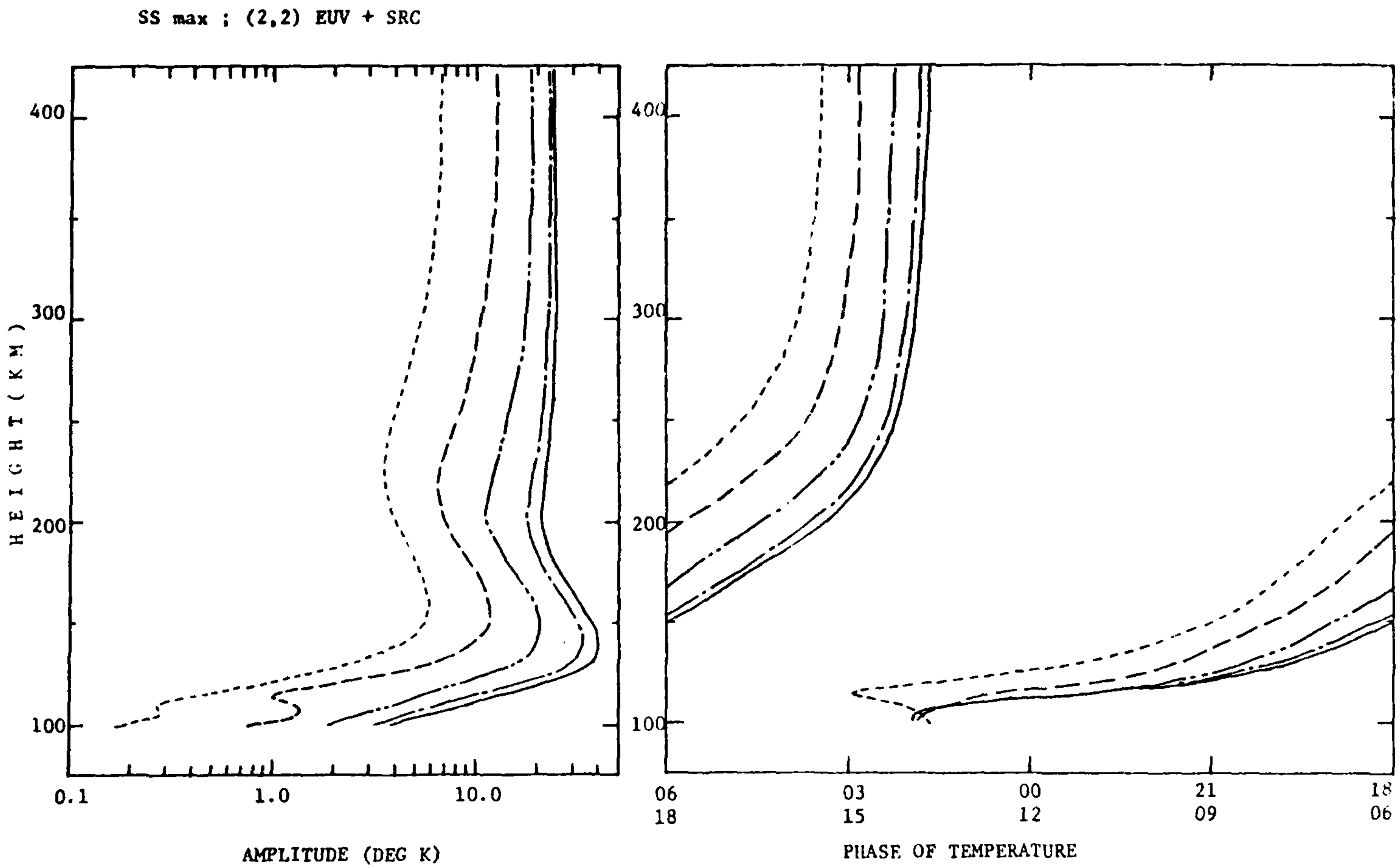

Fig. 53 — Same as 49 but for sunspot maximum conditions

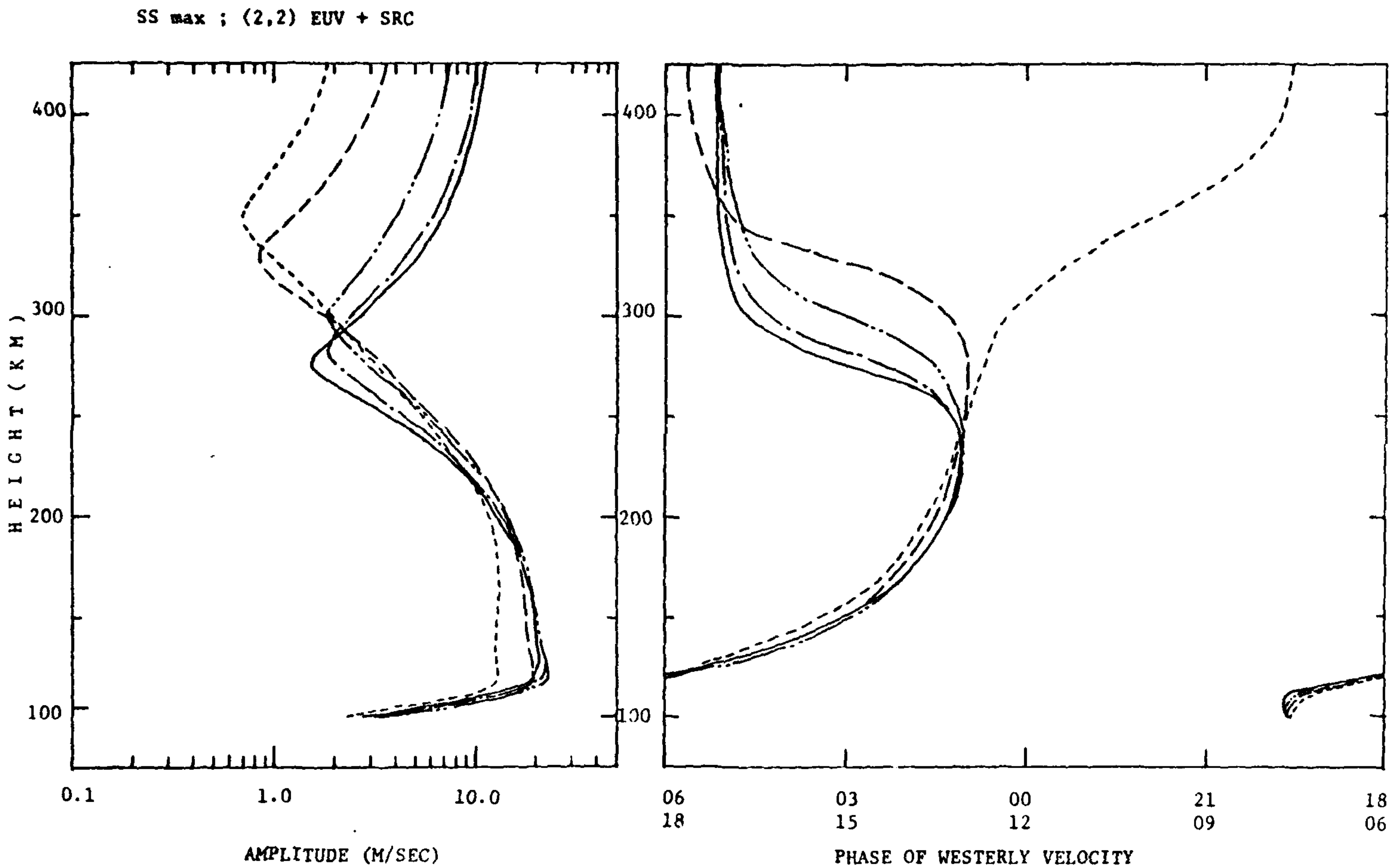

Fig. 54 — Same as 50 but for sunspot maximum conditions

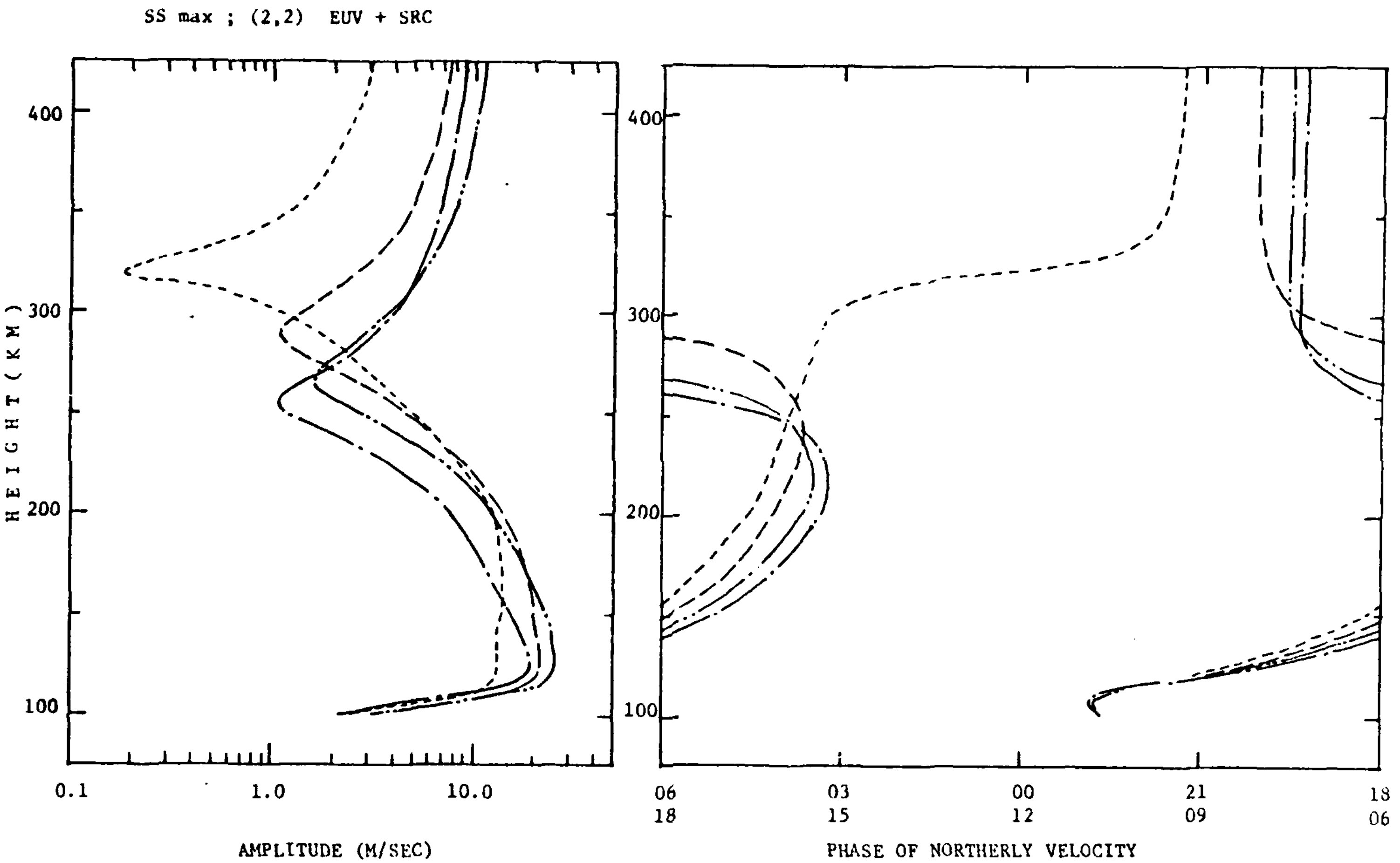

Fig. 55 — Same as 51 but for sunspot maximum conditions

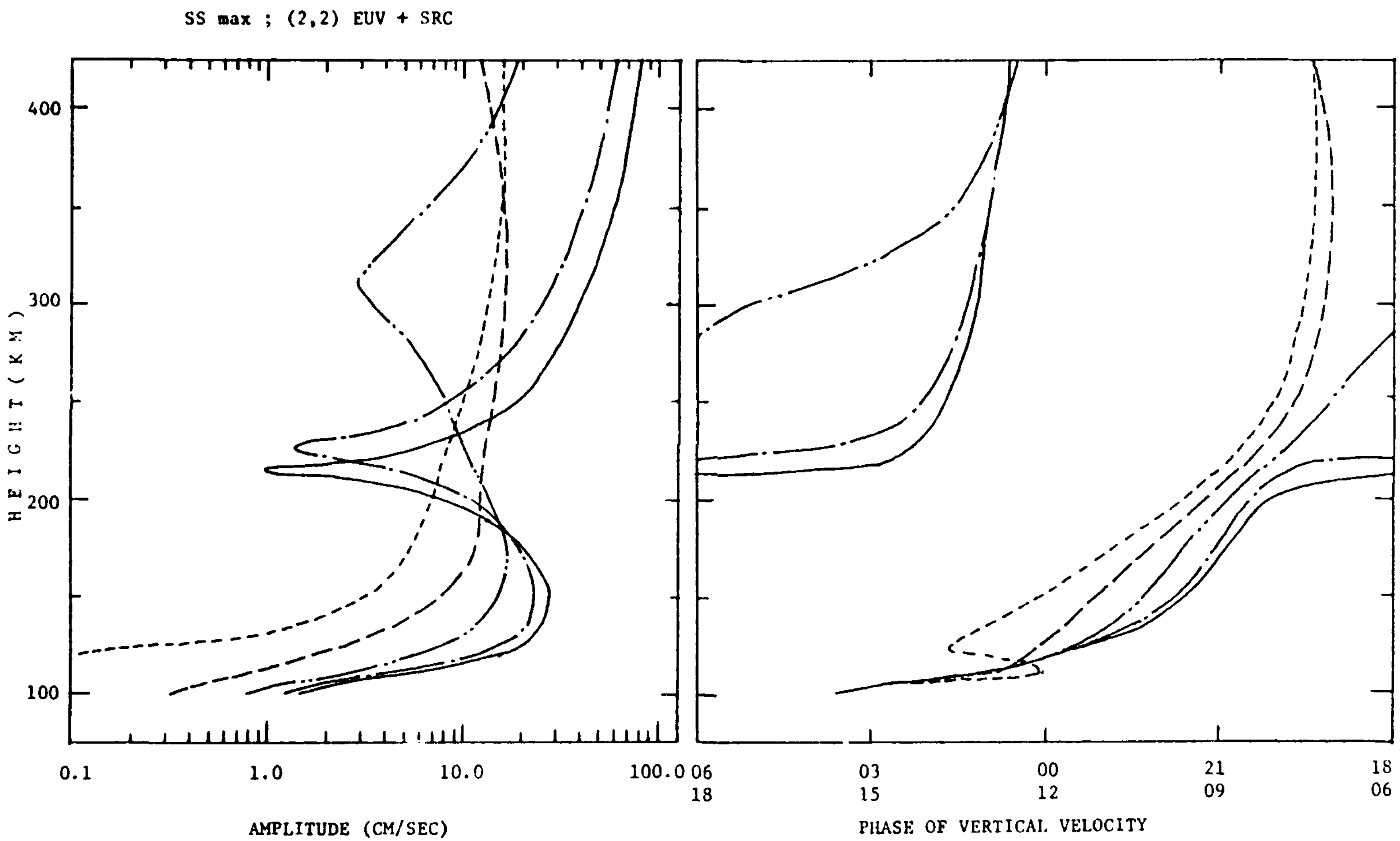

Fig. 56 — Same as 52 but for sunspot maximum conditions

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