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LAYER OF MAXIMUM WIND
ANALYSIS TECHNIQUE

David B. Spiegler

August 1966

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433L SYSTEM PROGRAM OFFICE
ELECTRONICS SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
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FOREWORD

System 433L: project 3.0; task 3.1. This TR has been prepared for the 433L System Program Office under Contract No. AF19(628)-4924 by THE TRAVELERS RESEARCH CENTER, INC., 250 Constitution Plaza, Hartford, Conn. The Research Center's publication number is 7479-230. Robert L. Houghten, Lt. Colonel, USAF, is System Program Director. This report covers the period 1 October 1965—15 July 1966, and was submitted for approval on July 29, 1966.

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ABSTRACT

An objective layer of maximum wind (LRMW) analysis technique is described and evaluated. The evaluation indicates that the technique represents a significant improvement over the previously developed level of maximum wind (LMW) analysis technique [Spiegler, D. B., and J. T. Ball, et al., 1965: Techniques for objective hemispheric analysis and prediction of the jet stream. Technical Report 7463-176 (ESD-TR-65-13), The Travelers Research Center, Inc.].

A categorization procedure for wind profiles that results in nine jet stream categories is designed and used for the derivation of regression equations that supply the initial-guess fields for each of five LRMW parameters. The stratification of the profiles into nine categories is a refinement of the previous seven categories developed for the LMW analysis technique. The initial-guess LRMW equations are stable in tests with independent data and are capable of specifying, very well, the general characteristics of the LRMW profile. They also provide realistic values for the LRMW parameters over no-data areas that are consistent with the entire analysis area.

The analysis technique locates jet cores between grid points and generates observations along these cores by using models of horizontal jet profiles.

Thickness of the LRMW as one of the analysis fields in conjunction with the wind-speed maximum, mean height of the LRMW, and vector shears below and above the LRMW enable the generation of a three-dimensional picture of the wind field in the vicinity of the jet stream.

Over the data areas, where a comparison between objective and subjective analyses can be made, the objective LRMW analyses compare favorably with the subjective analyses.

REVIEW AND APPROVAL

Publication of this technical report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Robert L Houghten

Robert L. Houghten
Lt. Colonel, USAF
System Program Director

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SECTION I

INTRODUCTION

An objective hemispheric analysis technique for five level-of-maximum-wind (LMW) parameters was described and evaluated in a previous report [6]. The five LMW parameters are: the wind direction at the LMW, the wind speed at the LMW, the height of the LMW, and the scalar shears 10,000 ft above and below the LMW. The evaluation indicated that the analysis technique produces high quality analyses, particularly of the wind speed, but that there are a few areas of the hemisphere near jet streams where the height of the LMW and the vertical shears are not specified properly. These areas are usually associated with wind profiles that exhibit a thick layer of high wind speeds (i.e., cases where there is more than one distinct maximum, such as in areas where both the polar and subtropical jet are observed). Because the analysis technique requires a level of maximum wind, a particular level is selected somewhere in the thick layer, although the level selected is not meaningful for these cases. The analyses and verifications of the height and vertical shears are sensitive to where in the layer the LMW is specified. Because of this, it was concluded that the analysis technique should be refined to present a more realistic three-dimensional picture of the jet stream and its associated parameters. To accomplish this refinement, a layer of maximum wind (LRMW) was defined (similar to that discussed by Reiter [5]) and the analysis of six LRMW parameters was performed. These parameters are:

(a) the mean altitude of the LRMW (bounded by levels where the wind speed is 85% of the maximum speed in the layer), $\bar{Z}$ (LR),
(b) the thickness of the LRMW, h (LR),
(c) the maximum wind speed in the LRMW, W_{sM}
(d) the mean wind direction in the LRMW, $\bar{W}_d$(LR),
(e) the vertical vector shear below the LRMW, $\vec{S}_b$, and
(f) the vertical vector shear above the LRMW, $\vec{S}_a$.

The mean altitude of the layer of maximum wind replaces the height of the level of maximum wind in the analysis technique. The thickness of the LRMW is a new field. Vector shears above and below the LRMW, instead of scalar shears above and below the LMW, complete the more realistic three-dimensional analysis. The LRMW analysis technique is similar to that described for the LMW [6]; that is (a) initial-guess fields are supplied by using an established relationship between the LRMW parameters and the information available from constant-pressure-surface analyses of wind, temperature, and geopotential height, and (b) the initial-guess fields are adjusted using station values of the LRMW parameters (computed by a preprocessor program) and the successive approximation analysis technique (SAT) [1].

Section II describes the experiments performed and the analysis technique, and Section III discusses the results of the tests and the evaluation of the technique.

SECTION II

EXPERIMENTS FOR LAYER OF MAXIMUM WIND INITIAL-GUESS EQUATIONS, AND THE PROCEDURE FOR ANALYSIS

1. Selection of LRMW Categories

In previous work on the objective analysis of the jet stream [6], seven jet-stream categories were defined based on wind speeds at 200 and 300 mb [$W_s(2)$ and $W_s(3)$], latitude, and a combination of both wind speeds and latitude. These categories were: no jet, subtropical jet[1], subtropical—polar jet[1], and polar jet[1].

The "subtropical—polar" jets are characterized by either a single maximum somewhere between 200 and 300 mb, or by multiple maxima (e.g., polar jet in the vicinity of 300 mb and subtropical jet in the vicinity of 200 mb). Thus, it was advantageous to further separate the two subtropical-polar categories into single- and multiple-type wind maxima. The resulting nine categories and the associated criteria for each are listed in Table I.

Latitude, which had previously been included as one of the criteria, was omitted because it was noted that the jets to the north of strong mid- to high-latitude ridges, or blocking anticyclones, had characteristics of subtropical jets, even though located north of 45° (e.g., the height of the maximum wind speed was around 40,000 ft). Conversely, the polar jet was sometimes observed in the subtropics at a latitude below 30° (30°N and 45°N had previously been the limiting latitudes for polar and subtropical jets [6]).

Thickness of the LRMW[2], h(LR), was included in the criteria for the subtropical—polar jets for the reasons previously discussed. A 12,000-ft thickness was chosen as the separation limit between single and multiple maxima after considerable testing with 8,000- and 10,000-ft thicknesses.

Criteria established for the nine jet-stream categories should help to overcome the problem of accurately specifying the shears and mean height of the layer of maximum wind caused by a thick LRMW.

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[1] Two categories: "weak—moderate", and "strong".

[2] Thickness of the LRMW is defined by the height difference between the two levels, above and below the wind speed maximum, at which the wind speed is equal to 85% of the wind speed maximum.

TABLE I
JET-STREAM CATEGORIES AND THEIR DEFINITIONS

Jet-stream category	Description	Definition						
		$W_s(3)^*$		$W_s(2)^*$	$W_s(2) - W_s(3)^*$		$W_s(3) - W_s(2)^*$	$h(LR)^\dagger$
1	No jet	< 60	and	< 60	—		—	—
2	Weak—moderate subtropical jet	> 100	or	> 100	> 15		—	—
3	Strong subtropical jet	> 100	or	> 100	> 20		—	—
4	Single weak—moderate subtropical jet	60—100	or	60—100	≤ 15	and	≤ 15	≤ 12000
5	Single strong subtropical—polar jet	> 100	or	> 100	≤ 20	and	≤ 20	≤ 12000
6	Multiple weak—moderate subtropical—polar jet	60—100	or	60—100	≤ 15	and	≤ 15	> 12000
7	Multiple strong subtropical—polar jet	> 100	or	> 100	≤ 20	and	≤ 20	> 12000
8	Weak—moderate polar jet	60—100	or	60—100			> 15	—
9	Strong polar jet	> 100	or	> 100			> 20	—

* Measured in knots.

† Measured in ft.

2. LRMW Screening Regression Experiments

The initial-guess fields to the LRMW analyses are provided by regression equations derived for the nine jet-stream categories described in Section 1.

To derive these regression equations, a three-month sample of winter upper-air data (Dec 1963, Jan and Feb 1964) received from the National Meteorological Center (NMC) was completely error checked and processed through three programs before the screening experiments were run. The first of these programs selects and computes LRMW parameters from rawinsonde and radiosonde station data. The second processor program computes a list of specifiers, which may be selected for use in the derived LRMW equations. The specifiers are:

(a) temperature, winds, and heights at mandatory constant-pressure surfaces from 700 to 100 mb;

(b) thickness, temperature differences, shears, and mean temperatures of layers bounded by mandatory constant-pressure surfaces;

(c) thicknesses between the mean height of the LRMW and the height of constant-pressure surfaces from 500 to 100 mb;

(d) wind shears between the maximum wind speed and the wind speed at mandatory constant-pressure surfaces; and

(e) an estimated thickness of the LRMW (computed from constant-pressure-surface winds and heights; the details of the computation are in Section 3).

These specifiers are listed in Table II.

TABLE II
SPECIFIERS USED IN LRMW SCREENING REGRESSION EXPERIMENTS*

$Z(7)$, $T(7)$, $W_d(7)$, $W_s(7)$

$Z(5)$, $T(5)$, $W_d(5)$, $W_s(5)$

$Z(4)$, $T(4)$, $W_d(4)$, $W_s(4)$

$Z(3)$, $T(3)$, $W_d(3)$, $W_s(3)$

$Z(1)$, $T(1)$, $W_d(1)$, $W_s(1)$

$h(7-5)$, $\Delta T(7-5)$, $\Delta W_s(7-5)$, $\Delta T/\Delta n(7-5)$

$h(5-4)$, $\Delta T(5-4)$, $W_s(5-4)$, $\Delta T/\Delta n(5-4)$

$h(5-3)$, $\Delta T(5-3)$, $\Delta W_s(5-3)$, $\Delta T/\Delta n(5-3)$

$h(4-3)$, $\Delta T(4-3)$, $\Delta W_s(4-3)$, $\Delta T/\Delta n(4-3)$

$h(2-1)$, $\Delta T(2-1)$, $\Delta W_s(2-1)$, $\Delta T/\Delta n(2-1)$

$h(5-M)$, $W_s(5-M)$, S_5

$h(3-M)$, $W_s(3-M)$, S_3

$h(1-M)$, $W_s(1-M)$, S_1

$W_s(L)$

$h(LR)$, $h_e(LR)$, $W_d(LR)$, $\overline{Z}(LR)$, $\vec{S}_b$, $\vec{S}_a$, $\vec{S}_{bM}$, $\vec{S}_{aM}$

*Z = altitude; $\overline{Z}$ = mean altitude; T = temperature; ΔT = temperature difference; W_d = wind direction; W_s = wind speed; ΔW_s = wind shear; h = thickness; h_e = estimated thickness; $\Delta T/\Delta n$ = thermal wind; $S_x = [W_s(x\text{-}M)]/[Z(x)-\overline{Z}(LR)]$; $\vec{S}_a$ and $\vec{S}_b$ = vector shears above and below; $\vec{S}_{aM}$ and $\vec{S}_{bM}$ = maximum $\vec{S}_a$ and $\vec{S}_b$; parenthetic numbers refer to level in 100 mb.

The third processor program separates the data into the nine categories discussed in the previous section.

3. The LRMW Analysis Procedure

The regression equations for the nine jet-stream categories provide the initial guesses (grid-point values) for the analyses of all LRMW fields except wind direction. The procedures for obtaining grid-point values for each of the LRMW parameters are as follows.

3.1 Wind direction for the LRMW, $W_d(LR)$

(a) For subtropical-jet categories (2 and 3),

$$W_d(LR) = W_d(2)$$

because height of the subtropical jet is generally near 200 mb.

(b) For polar-jet categories (8 and 9),

$$W_d(LR) = W_d(3)$$

because height of the polar jet is generally near 300 mb.

(c) For subtropical—polar and no-jet categories (4—7 and 1),

$$W_d(LR) = \frac{W_d(3) + W_d(2)}{2}$$

because a subtropical—polar jet is generally located between 300 and 200 mb; for no-jet categories, "maxima" may be anywhere in the sounding, and the average of wind directions at 300 and 200 mb is a good approximation.

3.2 Maximum wind speed within the LRMW, W_{sM}

The jet-stream category for each grid point is determined in order to generate initial guesses for the maximum wind field. This is not a straightforward procedure for categories 4 through 7, because thickness of the LRMW [h (LR)] is part of the category criteria and also an LRMW parameter to be analyzed, but is not available at this point. Categories 1, 2, 3, 8, and 9, on the other hand, are uniquely determined by 300- and 200-mb wind speeds and their differences.

Category 4 is different from Category 6 only in the thickness criteria (similary for Categories 5 and 7). The solution to the problem is the computation of an estimated thickness of the LRMW [$h_e(LR)$] to classify uniquely grid points for Categories 4 and 6 and Categories 5 and 7. The only information available (at all grid points) for the computation is constant-pressure-surface data. The estimated thickness is computed as follows.

The level of maximum wind (LMW) is assumed to be at 36,000 ft for Categories 4, 5, 6, and 7 (as this was the mean height to the nearest thousand feet of the LMW for subtropical—polar jet categories {1840 cases} [6]). For a grid point that may be in either Category 4 or 6, based on the 300- and 200-mb wind criteria, the wind-speed maximum is computed for both categories and the average value is used as an aid in obtaining an estimated thickness. Eight-five percent of the averaged wind-speed maximum defines the boundaries of the layer of maximum wind. A simple interpolation between the heights of constant-pressure surfaces above and below the LMW and their associated wind speeds determines the heights at which the wind speed is 85% of the maximum speed. The estimated thickness of the LRMW is obtained by subtracting the interpolated height of the lower boundary of the layer from the interpolated height of the upper boundary of the layer. The proper category for the grid point can then be determined with the estimated thickness. A similar procedure is employed for grid points that initially could be in Category 5 or 7.

The suitability of this method for properly categorizing a grid point was tested on the 3-month upper-air data sample. The number of cases placed in the proper category using the estimated thickness is given in Table III; the actual number of cases in a category was determined by using winds-aloft station data (dependent) to arrive at the true thickness [h(LR)].

The results in Table III indicate that the method of estimating the thickness of the LRMW works well.

With all grid points now uniquely defined by category, the initial guess of W_{sM} is generated by the appropriate regression equations. The initial guess is "corrected" by using the processed station observations and the successive approximation analysis (SAT) technique [1].

After a specified number of passes through the data, the jet cores are located (first at grid points, and then between grid points through a parabola fitting routine). "Observations" are generated along core segments by using Endlich and McLean's jet-stream model [2], which relates the wind speed at the core to the wind speed at some specified perpendicular distance from the core. This model was first derived from aircraft flights in the southeastern U.S. and results were recently corroborated by similar flights into jet streams in the central U.S. [3].

TABLE III
NUMBER OF CASES PLACED IN PROPER CATEGORY USING h_e(LR)—DEPENDENT DATA

Jet-stream category*	No. of cases h_e(LR) computation	No. of cases, h(LR) computation	% correct
4	798	935	85.3
5	231	267	86.5
6	534	779	75.5
7	368	468	78.6
Total	1931	2449	78.8

*See Table I for definitions.

An additional pass is then made using both the generated data and the actual station data, and a relatively small influence radius. The generated wind-speed "observations" may be assigned a weight relative to the actual data for this pass.

Verification of W_{sM}

The areal-mean rms (ARMS) error method is used for verification purposes [7]. Although it was described in the previous report [6] (and elsewhere), it is described here because verification is considered one of the important aspects of the analysis evaluation. The ARMS error method approximates an area integral of the error over the analysis area by withholding some percentage of the observations and verifying them against the withheld- and analysis-station observations, which are equally weighted. The withheld-station observations approximate the maximum error points in the analysis field, but the number of withheld stations required by the ARMS error method usually does not equal the number of maximum error points. Therefore, the withheld stations were selected to represent equally the entire spectrum of maximum errors over the analysis area. The assumption is that the maximum error is inversely proportional to the density of the data.

The "density" of each station is computed prior to the analysis (see [7] for details of the density computation), and withheld stations are selected on the basis of three maximum-wind-speed and three station-density categories as outlined in Table IV.

TABLE IV

SELECTION OF WITHHELD STATIONS ON THE BASIS OF STATION DENSITY AND WIND SPEED MAXIMUM

Density (ρ)	No. of withheld stations		
	A [$W_{sM} > 100$ knots]	B [$W_{sM} = 60$—100 knots]	C [$W_{sM} < 60$ knots]
Low (0.11—0.32)	3	4	3
Medium (0.33—0.43)	4	3	3
High ($\geq$0.44)	3	3	4

3.3 Thickness of the LRMW, h(LR)

This field is analyzed at all grid points except those in Category 1. The initial guess for h(LR) is generated by regression equations after determining the jet-stream category for each grid point. The range of thickness for Category-1 data is too large to produce meaningful values. The SAT technique is then used with the station data for h(LR) to adjust the initial-guess field. No station is selected for corrections to grid points where $W_{sM} < 60$ knots at the station.

Verification of h(LR)

Thickness of the LRMW is verified using the ARMS error method and the identical set of withheld stations used in the verification of W_{sM} with the exception of verification Category C [$W_{sM} < 60$ knots].

3.4 Mean height of the LRMW, $\overline{Z}$(LR)

The procedure for generating the initial-guess field to the analysis, the "correction" to grid points, and the verification is identical to that for the thickness of the LRMW.

3.5 Vector shears below and above the LRMW, $\vec{S}_b$ and $\vec{S}_a$

The vector shears below and above the LRMW are analyzed separately, with the analysis for the shear below performed first.

The initial guesses, the analysis, and the verifications are the same as those for the maximum wind speed in the LRMW (i.e., analysis and verifications at all grid points).

On the shear-below and shear-above printout charts, station locations where maximum vector shears (anywhere in the wind profile) exceed 10 knots per thousand feet are indicated by code letters. The code letters correspond to a list of stations that is printed with the corresponding maximum shear values and the levels at which the maximum shear is observed.

SECTION III

RESULTS FROM LRMW EXPERIMENTS

The quality of the LRMW analysis technique was determined from: (a) testing the equations that provide the initial guesses to the analyses with independent station data, and (b) evaluating a series of objective analyses using both the ARMS error method and comparisons with subjective analyses of LRMW parameters. The test and evaluation of these items is described in the following two sections.

4. LRMW Initial-guess Equations—Test and Evaluation

The list of possible specifiers for the LRMW parameters includes those specifiers directly available on a routine basis from data tapes (e.g., winds and temperatures at constant-pressure surfaces), those that are computed from constant-pressure-surface wind and height data (e.g., thermal winds, thicknesses), and those that contain one or two LRMW parameters[3], either alone or as some arithmetic expression with constant-pressure-surface data (e.g., wind speed maximum, or shear between the wind at the LMW and at a constant-pressure surface).

Several screening regression experiments were performed for each specificand in each category. The primary objective in designing several experiments was to determine what combination of possible specifiers would yield the best results (some experiments used only directly available parameters as possible specifiers; others used only computed parameters; and still others used various combinations of directly-available and computed parameters as possible specifiers).

Table V lists the specificands, selected specifiers and their associated per cent reduction of variance (% red.), number of cases, rms errors, and standard deviations for each jet category for both dependent and independent data. Figure 1 illustrates the dependent and independent rms errors for each LRMW pararmeter. A study of the table reveals that:

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[3] These specifiers assume (for a particular LRMW parameter) that the analysis of the parameters proceeds in a particular sequential order (which it does—sec Section 3). Thus, the wind speed may be a possible specifier for all other LRMW parameters because it is analyzed first.

TABLE V
RESULTS OF LRMW INITIAL-GUESS EQUATIONS ON DEPENDENT AND INDEPENDENT DATA

Category	Specificand	Selected specifiers & % red.	Total % red.	No. of cases		Specificand mean		Rms error		Std. dev.		Units
				Dep.	Ind.	Dep.	Ind.	Dep.	Ind.	Dep.	Ind.	
1	W_{sM}	$W_s(2)$, $W_s(3)$, $W_s(1)$ 45.4 12.1 4.9	62.4	3316	533	49.5	50.9	8.5	9.1	13.9	14.4	knots
	$\vec{S}_b$	$W_s(5\text{-}M)$, $W_s(2\text{-}M)$, $W_s(3\text{-}M)$ 17.3 4.5 1.0	22.9	3316	533	3.28	3.27	1.74	1.76	2.03	1.97	kt 10^{-3} ft^{-1}
	$\vec{S}_a$	$W_s(1\text{-}M)$, $W_s(2\text{-}M)$, $T(1)$ 14.5 5.8 1.4	21.7	3316	533	-2.95	-3.34	1.85	2.19	2.09	2.41	kt 10^{-3} ft^{-1}
2	W_{sM}	$W_s(2)$, $W_s(1)$ 62.7 2.1	64.8	954	206	87.3	88.0	8.5	7.7	14.2	13.3	knots
	h(LR)	h_e, h(3-2) 33.1 2.3	35.4	954	206	9368	9599	3287	3579	4089	4375	ft
	$\overline{Z}$(LR)	$W_s(1)$, $W_s(3)$, T(5), h(LR), $W_s(2)$, W_{sM} 11.1 11.1 8.1 3.2 1.1 5.3	39.9	954	206	40764	40146	2335	2372	3013	2950	ft
	$\vec{S}_b$	$W_s(3\text{-}M)$, $\overline{Z}$(LR), $W_s(5)$, h(LR) 26.6 7.4 3.2 2.4	39.4	954	206	4.53	4.51	1.95	2.09	2.50	2.67	kt 10^{-3} ft^{-1}
	$\vec{S}_a$	W_{sM}, $W_s(1)$, $\overline{Z}$(LR) 8.9 15.1 5.3	29.3	954	206	-4.03	-4.15	2.18	2.38	2.60	2.66	kt 10^{-3} ft^{-1}
3	W_{sM}	$W_s(2)$ 83.0	83.0	785	97	133.9	132.6	8.9	6.3	21.5	24.1	knots
	h(LR)	h_e, T(2) 40.2 5.6	45.8	758	97	9826	8699	2914	2781	3960	3994	ft
	$\overline{Z}$(LR)	$[\Delta T/\Delta n](2\text{-}1)$, $W_s(3\text{-}M)$, h(LR), T(5) 17.3 5.1 6.6 3.0	32.0	758	97	39729	38907	1872	1601	2270	1830	ft
	$\vec{S}_b$	S_3, h(LR), $W_s(5\text{-}M)$, $W_s(3)$ 37.9 3.9 2.8 1.6	46.2	758	97	6.03	5.91	2.22	1.79	3.02	2.88	kt 10^{-3} ft^{-1}
	$\vec{S}_a$	W_{sM}, $W_s(1)$, $\overline{Z}$(LR) 14.4 15.9 5.8	36.1	758	97	-6.10	-6.35	2.61	2.47	3.26	3.25	kt 10^{-3} ft^{-1}

TABLE V (Continued)

Category	Specificand	Selected specifiers & % red.	Total % red.	No. of cases		Specificand mean		Rms error		Std. dev.		Units
				Dep.	Ind.	Dep.	Ind.	Dep.	Ind.	Dep.	Ind.	
4	W_{sM}	$W_s(2)$, $W_s(3)$, $W_s(1)$ 55.8 8.1 1.9	65.8	935	196	89.7	89.7	9.3	9.5	15.9	14.7	knots
	h(LR)	$W_s(2\text{-}M)$, $W_s(3)$, $W_s(2)$ 29.1 5.1 1.3	35.5	935	196	7364	7389	2204	2383	2744	2784	ft
	$\overline{Z}$(LR)	T(5), $W_s(1)$, $W_s(3)$, $W_s(2)$, $W_s(5)$ 19.3 6.8 4.5 7.8 1.6	40.0	935	196	35359	36526	4270	5089	5516	6094	ft
	$\vec{S}_b$	$\Delta W(5\text{-}3)$, $\overline{Z}$(LR), $W_s(M)$, $W_s(5)$ 16.1 5.7 5.8 7.0	34.6	935	196	3.79	3.52	2.10	2.05	2.60	2.39	kt 10^{-3} ft^{-1}
	$\vec{S}_a$	S_1, $W_s(1\text{-}M)$, $W_s(3\text{-}M)$ 22.6 3.2 1.7	27.5	935	196	-3.96	-4.19	2.34	2.42	2.75	2.78	kt 10^{-3} ft^{-1}
5	W_{sM}	$W_s(3)$, $W_s(2)$ 53.6 5.3	59.0	267	49	132.3	126.8	13.0	11.3	20.3	18.0	knots
	h(LR)	h_e, $W_s(2\text{-}M)$ 39.6 2.4	42.0	267	49	8083	7907	2061	2730	2706	3459	ft
	$\overline{Z}$(LR)	h(5-3), $\Delta W(3\text{-}2)$, h(LR), $\lvert\Delta T/\Delta n\rvert(2\text{-}1)$ 23.6 10.3 5.0 4.5	43.4	267	49	36382	35572	3167	3851	4211	4983	ft
	$\vec{S}_b$	S_5, $W_s(2\text{-}M)$ 32.7 2.2	34.9	267	49	5.00	5.52	2.54	2.92	3.15	3.64	kt 10^{-3} ft^{-1}
	$\vec{S}_a$	S_1, T(2), $W_s(3\text{-}M)$ 28.4 4.3 1.8	34.5	267	49	-5.75	-5.78	3.05	2.51	3.77	3.28	kt 10^{-3} ft^{-1}
6	W_{sM}	$W_s(2)$, $W_s(3)$, $W_s(1)$ 77.5 6.0 1.5	85.0	779	192	82.6	84.9	4.8	6.0	12.5	12.6	knots
	h(LR)	h_e, $\Delta W(7\text{-}5)$, $W_s(1\text{-}M)$ 14.6 1.0 0.9	16.5	779	192	16904	17117	3025	3111	3311	3520	ft
	$\overline{Z}$(LR)	$W_s(5)$, $W_s(1)$, T(5), $W_s(3)$, $W_s(2)$ 16.6 16.5 13.8 2.8 10.6	60.3	779	192	35424	37523	2890	3711	4583	5341	ft
	$\vec{S}_b$	S_5, h(LR), $\overline{Z}$(LR), $W_s(7)$, T(3) 23.9 3.1 2.9 2.3 1.7	33.9	779	192	3.63	3.39	1.81	1.77	2.22	2.17	kt 10^{-3} ft^{-1}
	$\vec{S}_a$	S_1 24.6	24.6	779	192	-3.30	-3.30	1.85	2.78	2.13	2.19	kt 10^{-3} ft^{-1}

TABLE V (Continued)

Category	Specificand	Selected specifiers & % red.	Total % red.	No. of cases		Specificand mean		Rms error		Std. dev.		Units
				Dep.	Ind.	Dep.	Ind.	Dep.	Ind.	Dep.	Ind.	
7	W_{sM}	$W_s(2)$, $W_s(3)$ 85.6 5.6	91.2	468	95	131.8	130.7	6.1	5.3	20.5	24.4	knots
	h(LR)	h_e, $W_s(5)$, ΔW(2-1), h(3-2) 33.4 2.1 1.5 1.9	38.9	468	95	17021	16982	2479	3057	3171	3353	ft
	$\overline{Z}$(LR)	ΔW(3-2), h(7-5), $W_s(1)$, $W_s(5)$, h(LR), $W_s(2-M)$ 31.6 9.8 5.5 4.5 3.4 8.0	62.8	468	95	36600	35601	1645	2637	22695	3466	ft
	$\vec{S}_b$	ΔW(5-3), $\overline{Z}$(LR) 43.7 6.3	50.0	468	95	5.59	53.6	1.81	2.28	2.51	2.98	kt 10^{-3} ft^{-1}
	$\vec{S}_a$	S_1, $W_s(1-M)$, $W_s(5)$ 35.4 1.7 1.0	38.1	468	95	-5.04	-5.19	2.14	2.45	2.72	2.92	kt 10^{-3} ft^{-1}
8	W_{sM}	$W_s(3)$ 68.7	68.7	813	108	85.7	86.1	7.9	10.6	14.1	14.5	knots
	h(LR)	h_e, $W_s(5)$ 34.2 3.2	37.4	813	108	8202	8138	3005	3485	3800	4262	ft
	$\overline{Z}$(LR)	T(5), $W_s(5-M)$, $W_s(1-M)$, T(2) 22.7 14.9 4.3 1.5	42.4	813	108	29313	30427	2469	3021	3254	3826	ft
	$\vec{S}_b$	S_5, h(LR) 27.7 6.0	33.7	813	108	4.64	5.23	2.07	2.49	2.54	2.89	kt 10^{-3} ft^{-1}
	$\vec{S}_a$	$W_s(2)$, W_{sM}, $\overline{Z}$(LR), $W_s(1)$ 7.9 16.7 2.1 0.9	27.7	813	108	-4.95	-5.07	2.33	2.59	2.74	3.12	kt 10^{-3} ft^{-1}
9	W_{sM}	$W_s(3)$ 79.4	79.4	315	28	127.1	132.8	9.0	11.6	19.8	22.5	knots
	h(LR)	h_e, ΔW(3-2), h(5-3) 32.9 2.1 1.5	36.5	315	28	8335	9410	2803	2410	3519	4155	ft
	$\overline{Z}$(LR)	T(5) $W_s(5)$ $W_s(2)$ 26.9 6.5 9.6	43.0	315	28	29933	30027	1831	1305	2426	2725	ft
	$\vec{S}_b$	S_5, h(LR) 45.4 7.1	52.5	315	28	6.48	6.70	2.19	2.19	3.18	3.30	kt 10^{-3} ft^{-1}
	$\vec{S}_a$	$W_s(2-M)$, S_1, $W_s(1-M)$ 44.4 5.3 2.2	51.9	315	28	-6.25	-4.86	2.61	2.00	3.76	2.56	kt 10^{-3} ft^{-1}

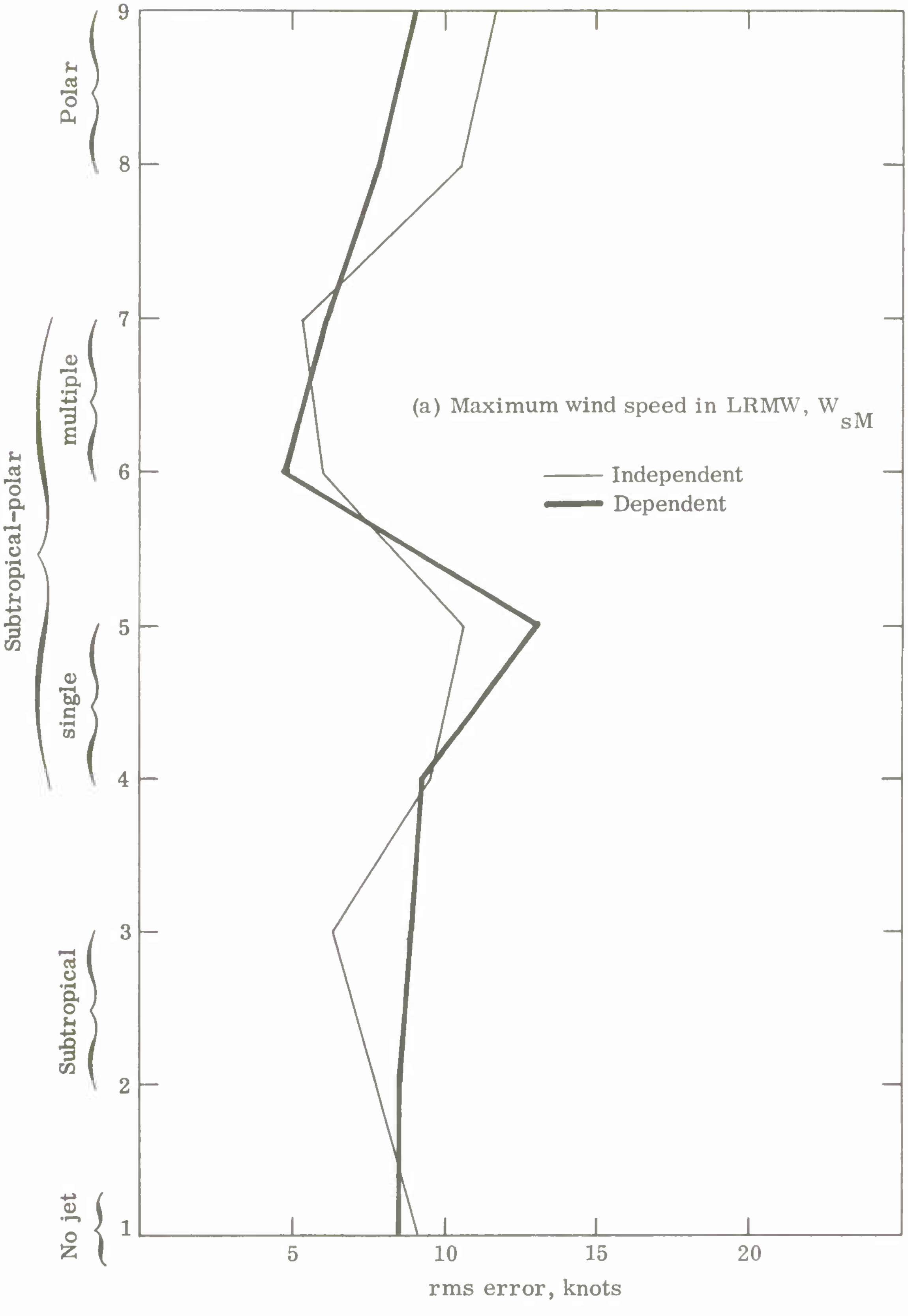
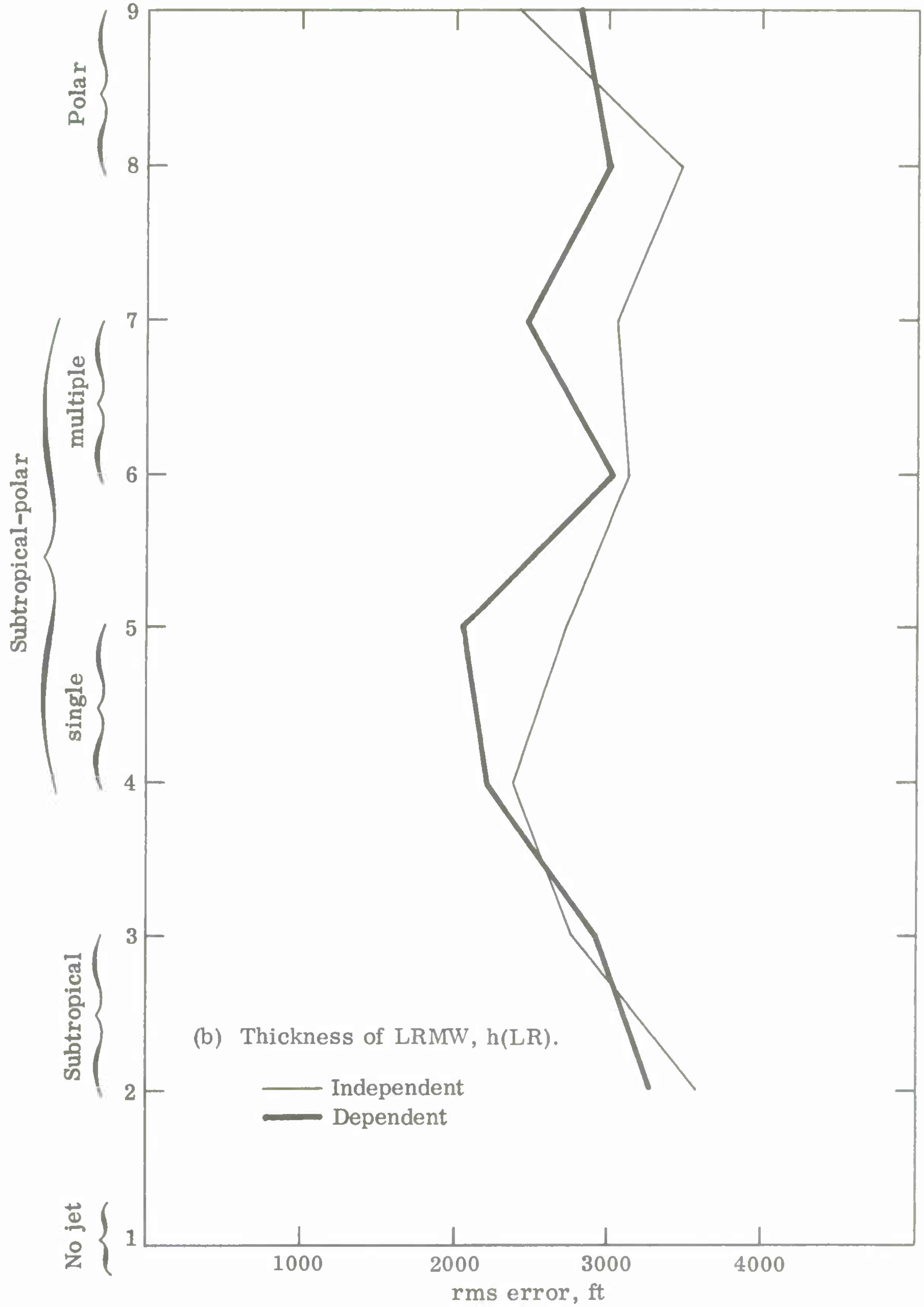


Fig. 1. Root-mean-square errors of LRMW parameters.



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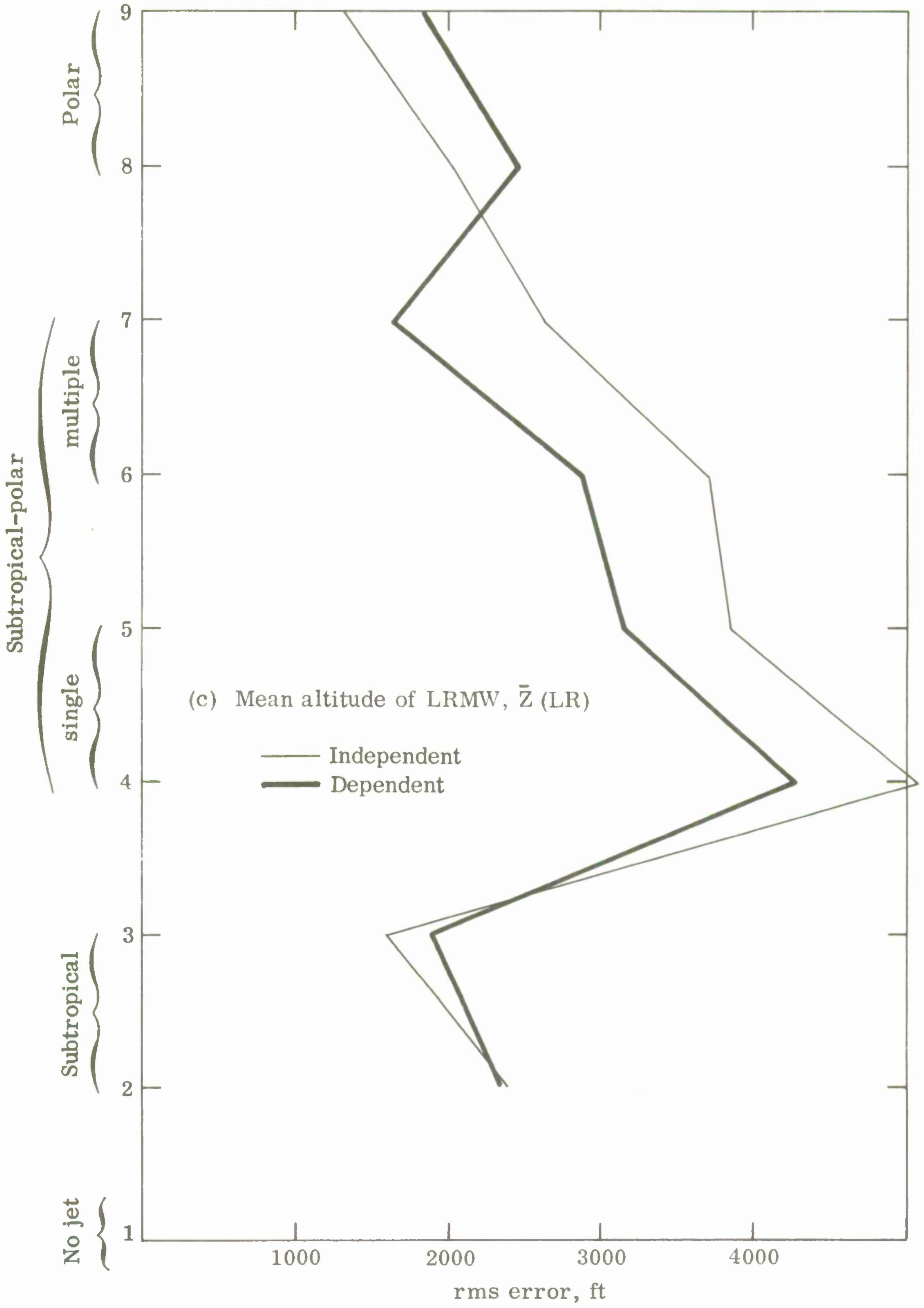

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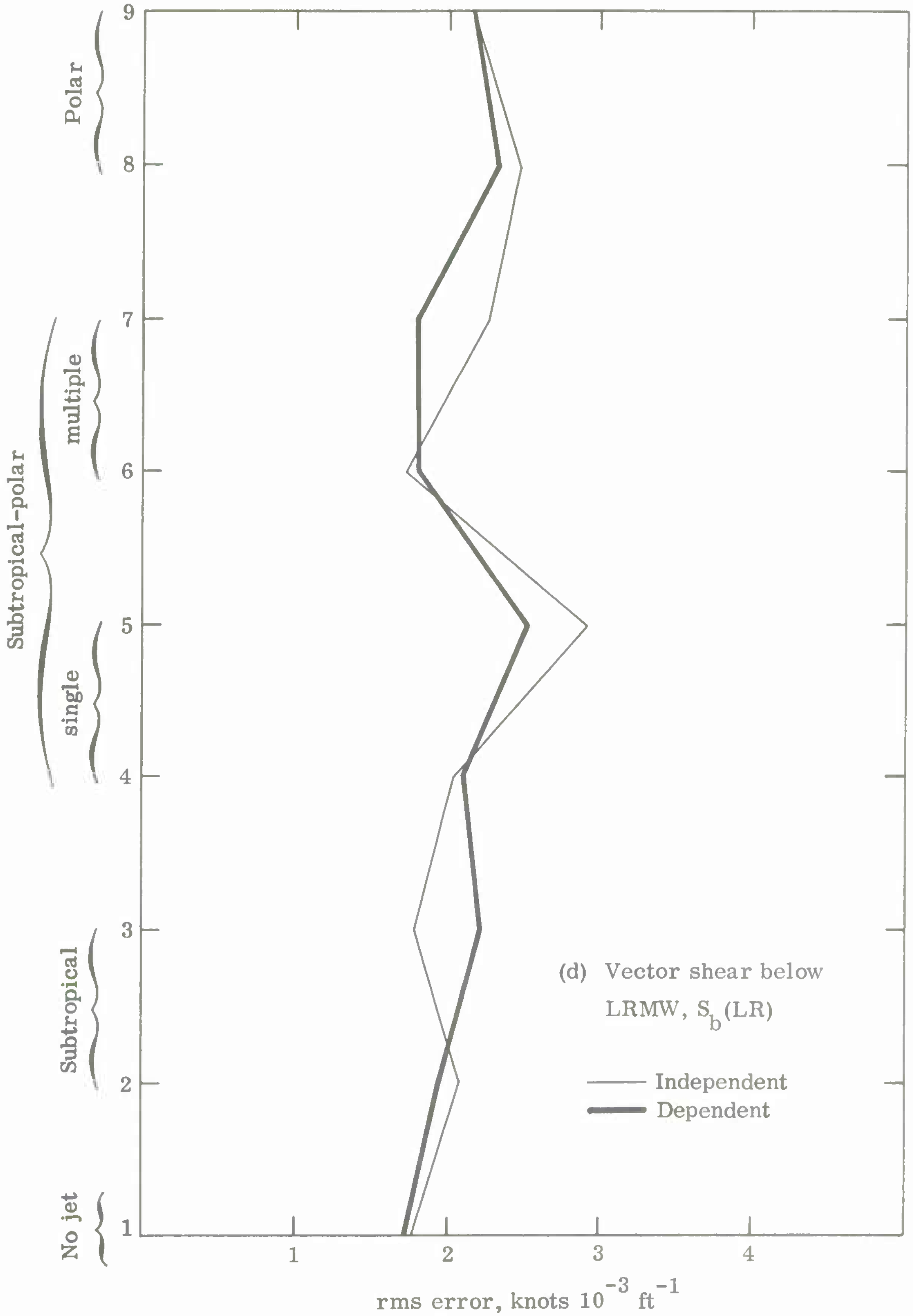

Fig. 1. Continued.

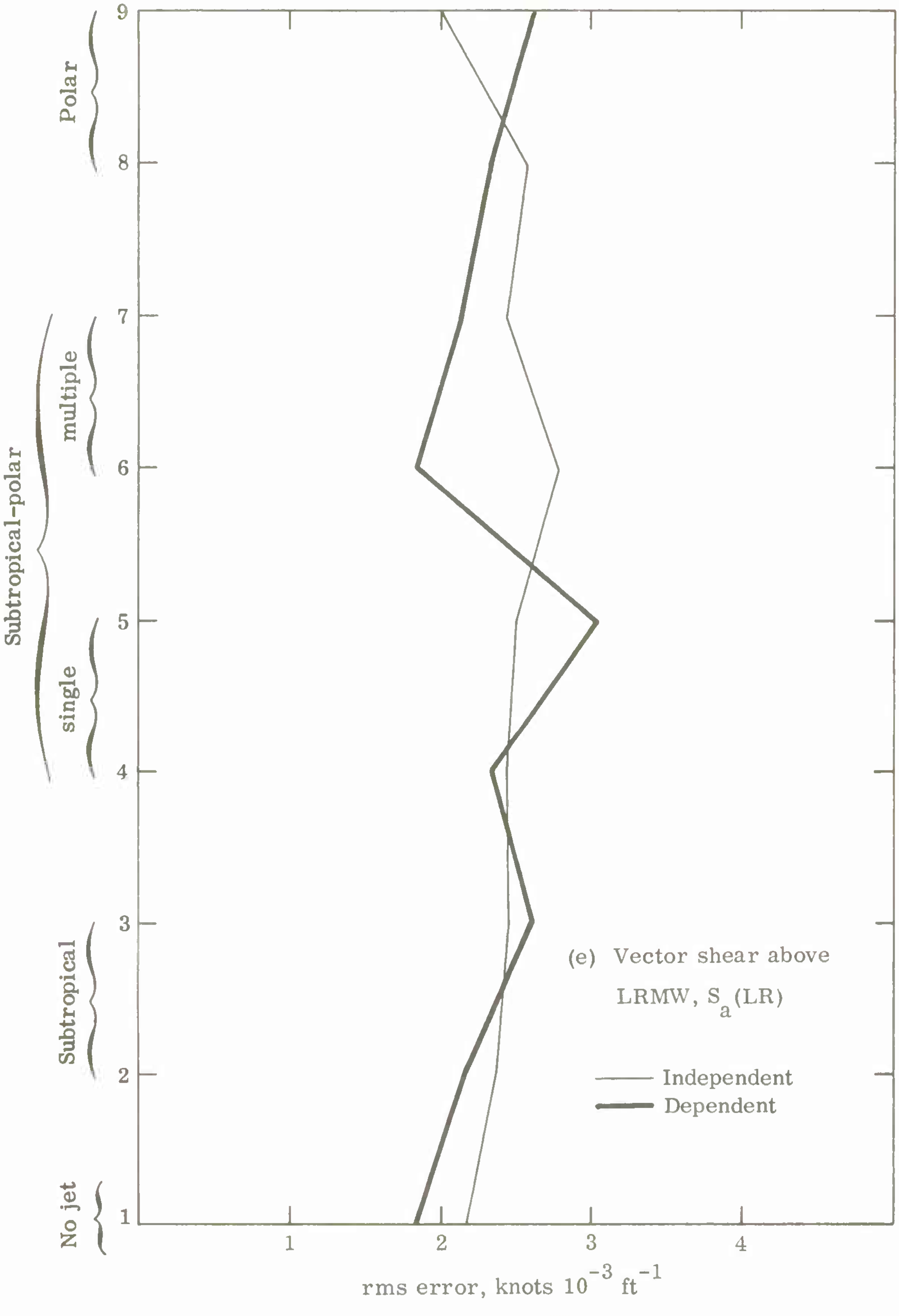

Fig. 1. Continued.

(a) The equations are stable with independent data because independent rms errors are frequently near the rms dependent errors; where the independent errors are higher (or lower) than the dependent errors, the standard deviation of the independent sample is also higher (or lower), except for $\vec{S}_a$, Category 6.

(b) In general, the specifiers selected by the screening program[4] are those that one might expect to be selected from synoptic experience with vertical wind profiles, i.e., (1) the specifiers selected for the maximum wind speed for all categories are one or more of the directly available constant-pressure-surface winds at 300, 200, and 100 mb. Considerable skill is demonstrated in specifying the maximum wind, as evidenced by the large % red.in both the independent and dependent samples; (2) for thickness of the LRMW, the estimated thickness is one of the selected specifiers for seven of eight LRMW categories (thickness not specified for no jet, Category 1); (3) for vector wind shears below and above the LRMW, the computed wind shears between constant-pressure surfaces and between the maximum wind level and constant-pressure surfaces are invariably among the selected specifiers; (4) the mean height of the LRMW is best specified by a combination of wind and temperature information at 500, 200, and 100 mb for most of the LRMW categories.

(c) There is a significant difference in the mean thicknesses of the LRMW for the single- and multiple-maxima subtropical—polar jet categories, i.e., the mean thicknesses are not just below and above the limiting value of 12,000 ft given by the definitions; the mean thicknesses for the multiple jet categories (6 and 7) are above twice that for the single jet

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[4] The cut-off criteria for selection is a combination of the modified F-test described by Miller [4] and practical considerations involving the optimum number of specifiers to use on an operational basis (e.g., a specifier may have been computed to be significant by the modified F-test, but may not have been included with those listed in Table V if the % red. and the lowering of the dependent rms error was considered to be small enough to make little difference in specification accuracy, considering the increased storage and computer time required for its use).

categories (4 and 5). Thus, the stratification into single and multiple jet categories is justified by the data and is a desirable revision of the subtropical–polar jet categories defined in the earlier report [6], where thickness was not a criterion.

Table VI shows the percentage of cases within specified error limits for the independent-data test of the LRMW equations. The error limits in the table were selected as representing a range of errors that is quite low considering that the LRMW equations were derived to provide initial-guess fields to analyses of LRMW parameters. It can be seen from the table that a very high percentage of the specification errors fall within these limits.

4.1 Subtropical and Polar Jets with h (LR) > 12,000 ft

It was recognized that the thickness of the layer of maximum wind could exceed 12,000 ft for a wind profile that clearly indicated either a subtropical jet or a polar jet.

TABLE VI
PERCENTAGE OF CASES WITHIN SPECIFIED ERROR LIMITS
FOR LRMW PARAMETERS (Independent data)

Jet-stream category	Total number of cases	Error Limits				
		W_{sM} ± 10 knots	h(LR) ± 4000 ft	$\overline{Z}$(LR) ± 4000 ft	$\vec{S}_b$ ± 2 knots	$\vec{S}_a$ 10^{-3} ft^{-1}
1	533	81.3	—	—	77.8	76.0
2	206	88.8	79.1	89.3	79.6	72.8
3	97	94.9	87.6	99.0	80.3	65.9
4	196	74.0	90.3	73.5	74.0	66.9
5	49	61.2	87.8	81.6	61.2	51.0
6	192	93.7	78.6	79.1	75.5	62.1
7	95	96.8	85.3	92.6	70.5	77.9
8	108	81.5	79.6	91.6	63.9	63.0
9	28	85.7	96.4	100.0	53.5	67.9

To determine the frequency of occurrence of these events, the dependent data sample for Categories 2 and 3 (subtropical) and Categories 8 and 9 (polar) were separated into cases where h(LR) ≤ 12,000 ft and cases where h(LR) > 12,000 ft. Table VII shows the breakdown of cases.

TABLE VII
NUMBER AND PERCENTAGE OF CASES WHERE h(LR) > 12,000 ft FOR JET-STREAM CATEGORIES 2, 3, 8, AND 9

(Dependent data)

Jet-stream category*	No. of cases		Total no. of cases	% cases h(LR) > 12,000 ft
	h(LR) ≤ 12,000 ft	h(LR) > 12,000 ft		
2	741	213	954	22.3
3	541	217	758	28.6
8	687	126	813	15.5
9	272	43	315	13.7

*See Table I for definitions.

It is readily apparent that thicknesses greater than 12,000 ft occur relatively infrequently for these categories. To determine if the equations derived for the entire category would perform satisfactorily on the subset of data given by the cases where h(LR) > 12,000 ft, the equations were tested with the subset. The statistics appear in Table VIII.

An examination of Table VIII and a comparison of it with Table V indicates that the rms errors are very close to or lower than the errors for all cases in the category for all LRMW parameters except the thickness of the LRMW. It is not surprising that the thickness is not specified well for these cases, because the mean thicknesses are about 5000 to nearly 7000 ft higher than the mean for the total number of cases in the categories.

Considering the stability of the equations on the subset of data for four of the five LRMW parameters, the relatively infrequent occurrence of thickness > 12,000 ft for the polar and subtropical jet categories, and the resultant small data sample available from one entire winter's data, it was concluded that separate equations were not warranted for these cases.

TABLE VIII
RESULTS OF TESTING SUBTROPICAL- AND POLAR-JET-STREAM EQUATIONS ON CASES WHERE h(LR) > 12,000 ft
(Dependent data)

Jet-stream category	Specificand	No. of cases*	Mean	Rms error	Units
2	W_{sM}	212	84.7	5.8	knots
	h(LR)		15133	4349	ft
	$\overline{Z}$(LR)		41727	2174	ft
	$\vec{S}_b$		3.96	1.62	knots 10^{-3} ft^{-1}
	$\vec{S}_a$		-3.82	1.92	knots 10^{-3} ft^{-1}
3	W_{sM}	216	135.8	5.7	knots
	h(LR)		14723	3390	ft
	$\overline{Z}$(LR)		40308	1554	ft
	$\vec{S}_b$		5.24	1.77	knots 10^{-3} ft^{-1}
	$\vec{S}_a$		-5.88	2.03	knots 10^{-3} ft^{-1}
8	W_{sM}	126	84.2	5.7	knots
	h(LR)		14795	5150	ft
	$\overline{Z}$(LR)		28744	2885	ft
	$\vec{S}_b$		4.73	2.43	knot 10^{-3} ft^{-1}
	$\vec{S}_a$		-4.25	2.42	knots 10^{-3} ft^{-1}
9	W_{sM}	43	121.5	6.6	knots
	h(LR)		14785	5247	ft
	$\overline{Z}$(LR)		30976	2758	ft
	$\vec{S}_b$		6.66	2.28	knots 10^{-3} ft^{-1}
	$\vec{S}_a$		-5.45	2.08	knots 10^{-3} ft^{-1}

*Where the number of cases differs from that given in Table VII, a case was eliminated due to data error.

4.2 Estimated h(LR) Resulting in Placing Cases in Wrong Category

For jet-stream Categories 4 through 7, part of the category definition is given by the thickness of the LRMW. For reasons discussed in Section 3, it is necessary to compute an estimated thickness of the LRMW. Table III lists the number of cases placed in the proper category using $h_e(LR)$, where the total number of cases in a category was determined by using winds-aloft station data (dependent) to arrive at the real thickness. About 79% of the cases were in the proper category for the four jet-stream categories. A similar determination was made for the station data from the independent sample (see Table IX). Then, the equation for the categories into which cases were misplaced [using $h_e(LR)$] were used with the data from the categories into which the cases should have been placed [according to the use of h(LR)] to determine how well the equations would perform for these misplaced cases. The results are given in Table X.

TABLE IX
NUMBER OF CASES PLACED IN PROPER CATEGORY USING $h_e(LR)$—INDEPENDENT DATA

Jet-stream category	No. of cases, $h_e(LR)$ computation	No. of cases, h(LR) computation	% correct
4	163*	196	83.2
5	39†	49	79.6
6	160‡	193	82.9
7	85¶	95	89.5
Total	447	533	83.9

*33 cases fell into Category 6.
†10 cases fell into Category 7.
‡33 cases fell into Category 4.
¶10 cases fell into Category 5.

It can be seen that applying the LRMW equations to the cases where erroneous categories are assigned leads to large errors in the estimation of $\overline{Z}(LR)$. However, the

TABLE X
ERRORS RESULTING FROM ASSIGNING WRONG CATEGORIES—INDEPENDENT DATA

Jet-stream category		Specificand	No. of cases	Mean	Rms error	Units
Equation	Data					
6	4	W_{sM}	33	83.3	3.3	knots
		$h(LR)$		9012	9583	ft
		$\bar{Z}(LR)$		35848	6208	ft
		$\vec{S}_b$		3.43	2.42	knots 10^{-3} ft^{-1}
		$\vec{S}_a$		-3.06	3.14	knots 10^{-3} ft^{-1}
7	5	W_{sM}	10	114.9	3.0	knots
		$h(LR)$		8669	8724	ft
		$\bar{Z}(LR)$		35571	4370	ft
		$\vec{S}_b$		2.99	1.91	knots 10^{-3} ft^{-1}
		$\vec{S}_a$		-4.20	1.87	knots 10^{-3} ft^{-1}
4	6	W_{sM}	33	85.7	6.1	knots
		$h(LR)$		15309	8097	ft
		$\bar{Z}(LR)$		37871	4211	ft
		$\vec{S}_b$		3.78	1.99	knots 10^{-3} ft^{-1}
		$\vec{S}_a$		-3.92	2.38	knots 10^{-3} ft^{-1}
5	7	W_{sM}	10	126.1	8.2	knots
		$h(LR)$		14809	6849	ft
		$\bar{Z}(LR)$		37080	4326	ft
		$\vec{S}_b$		5.12	2.35	knots 10^{-3} ft^{-1}
		$\vec{S}_a$		-5.64	1.38	knots 10^{-3} ft^{-1}

other LRMW parameter specifications are reasonably good. These results are not difficult to interpret. As given by the definitions of the categories and the means of the LRMW parameters, the major difference between Category 4 and Category 6 is the thickness of the LRMW, and similarly for Category 5 and Category 7. Other differences in LRMW parameters for these categories are not readily detectable. Thus, when the mean thickness of the LRMW is about 8,000 ft and a thickness-specification equation from a category where the mean thickness is about 16,000 ft is used, a large specification error is likely.

As noted in Section 3, computation of an estimated thickness of the LRMW must use constant-pressure-surface information. The large number of cases in each of Categories 4 through 7 warrants the use of separate LRMW equations for each of these categories. The small percentage of times (< 20%) that erroneous categories are assigned should not seriously affect the initial guess for four of the five LRMW analyses, but will affect the initial-guess field for thickness of the LRMW over 10 to 25% of the grid points where the 300- or 200-mb wind speed is ≥ 60 knots. However, the analysis will reduce considerably the number of grid points affected, because the station data will adjust the grid-point values.

4.3 Category Modeling of Wind Profiles (Categories 4—7)

It is well known that an almost infinite variety of vertical wind profiles is possible. A categorization of wind profiles for the purpose of an objective hemispheric analysis technique for LRMW parameters is, of necessity, based on constant-pressure-surface data which limits the sophistication of the categorization procedure. Our attempt to achieve modeling sophistication was made by introducing thickness of the LRMW as one of the criteria for defining the profiles that were other than "pure" subtropical or polar jets.

The logic for using 300- to 200-mb wind-speed differences as another part of the category criteria is straightforward. If there is a relatively small difference, either the maximum wind is between 300 and 200 mb or there are maxima near both of these levels. The thickness of the LRMW criteria is designed to separate these either/or cases; i.e., if the thickness is ≤ 12,000 ft, the maxima should be between 300 and 200 mb, and if it is > 12,000 ft, there may be maxima near 300 and 200 mb with a minimum in between or, if the maximum is between 300 and 200 mb, it must be a broad maximum (blunt nose jet) by definition.

Where there is a relatively large difference between the 300 and 200 mb wind speeds (Categories 2, 3, 8 and 9), the maximum wind is probably near the constant-pressure surface having the higher of the wind speeds.

To determine how closely the wind profiles from Categories 4 through 7 followed the logic of the criteria established for them, twenty-five profiles were plotted from station data of winds aloft and constant-pressure-surface winds.

Table XI lists the number of profiles that fell within the criteria limits described above for each of Categories 4 through 7.

TABLE XI
LEVEL OF MAXIMUM WIND LOCATIONS FOR
CATEGORIES 4 THROUGH 7

Jet-stream category	No. of cases W_{sM} located:					Minimum between 300 and 200 mb (between 2 maxima)
	Below 300 mb	At 300 mb	Between 300 and 200 mb	At 200 mb	Above 200 mb	
4	2	—	16	2	5	—
5	—	2	17	—	6	—
6	3	—	12	2	8	5
7	1	3	12	5	4	3

For the single jets, 65% of the (25) profiles contain maximum winds between 300 and 200 mb. There are cases where the difference between the 300 and 200 mb wind speeds is not large enough to place the profiles in the subtropical- or polar-jet categories, but where the speed increases above 200 mb or below 300 mb to result in the maximum being located outside the 300- to 200-mb layer.

For the multiple jets, just under 50% of the profiles contain maxima between 300 and 200 mb, and about 40% contain maxima at or above 200 mb. Sixteen percent of the cases exhibit a minimum between 200 and 300 mb. These cases are in the statistics twice, with maxima at or near 200 or 300 mb. Figures 2 through 5 show examples of profiles for each category and maximum wind-speed classification.

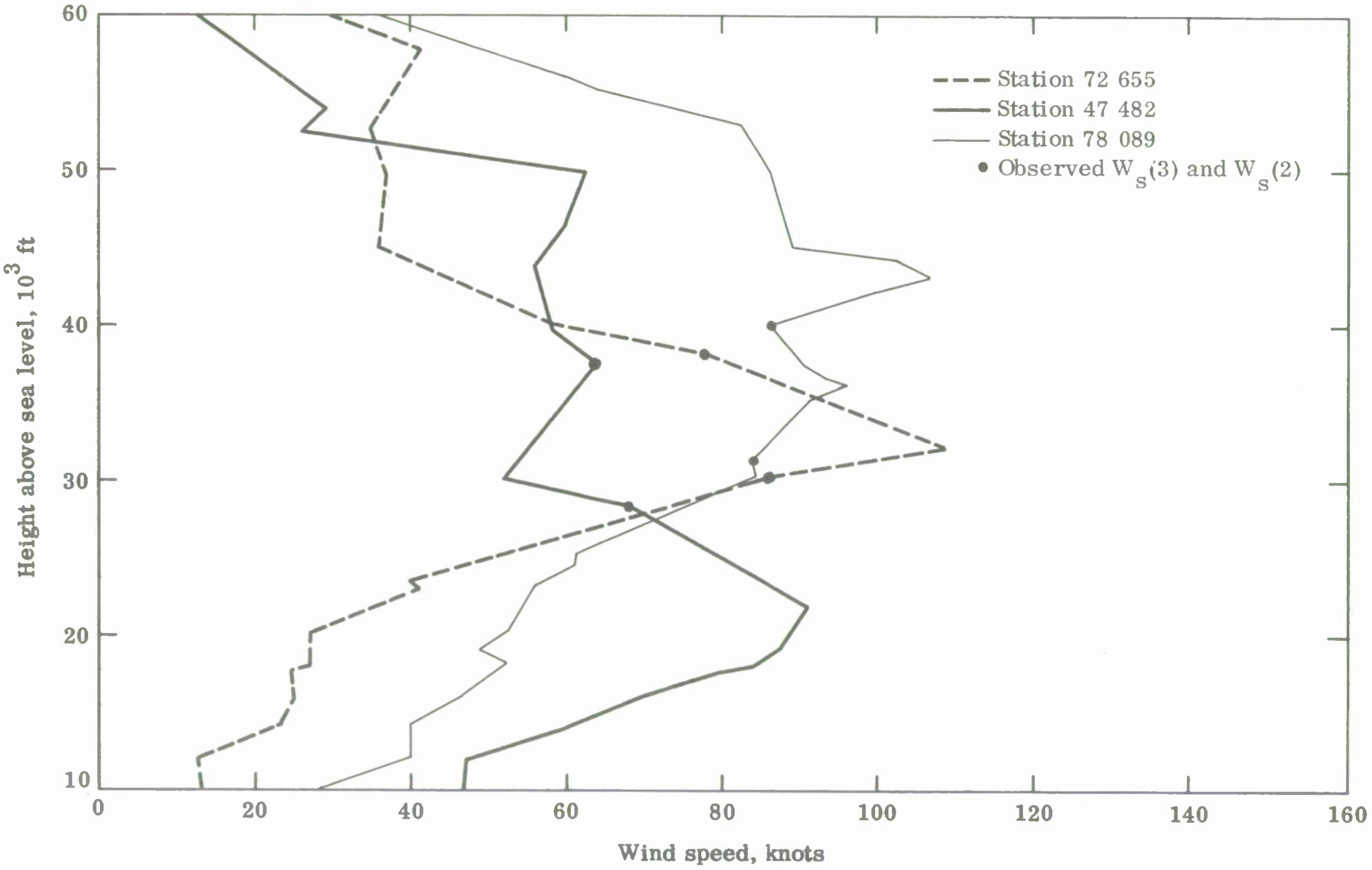

Fig. 2. Examples of wind profiles: Category 4, Single, moderate subtropical—polar jet.

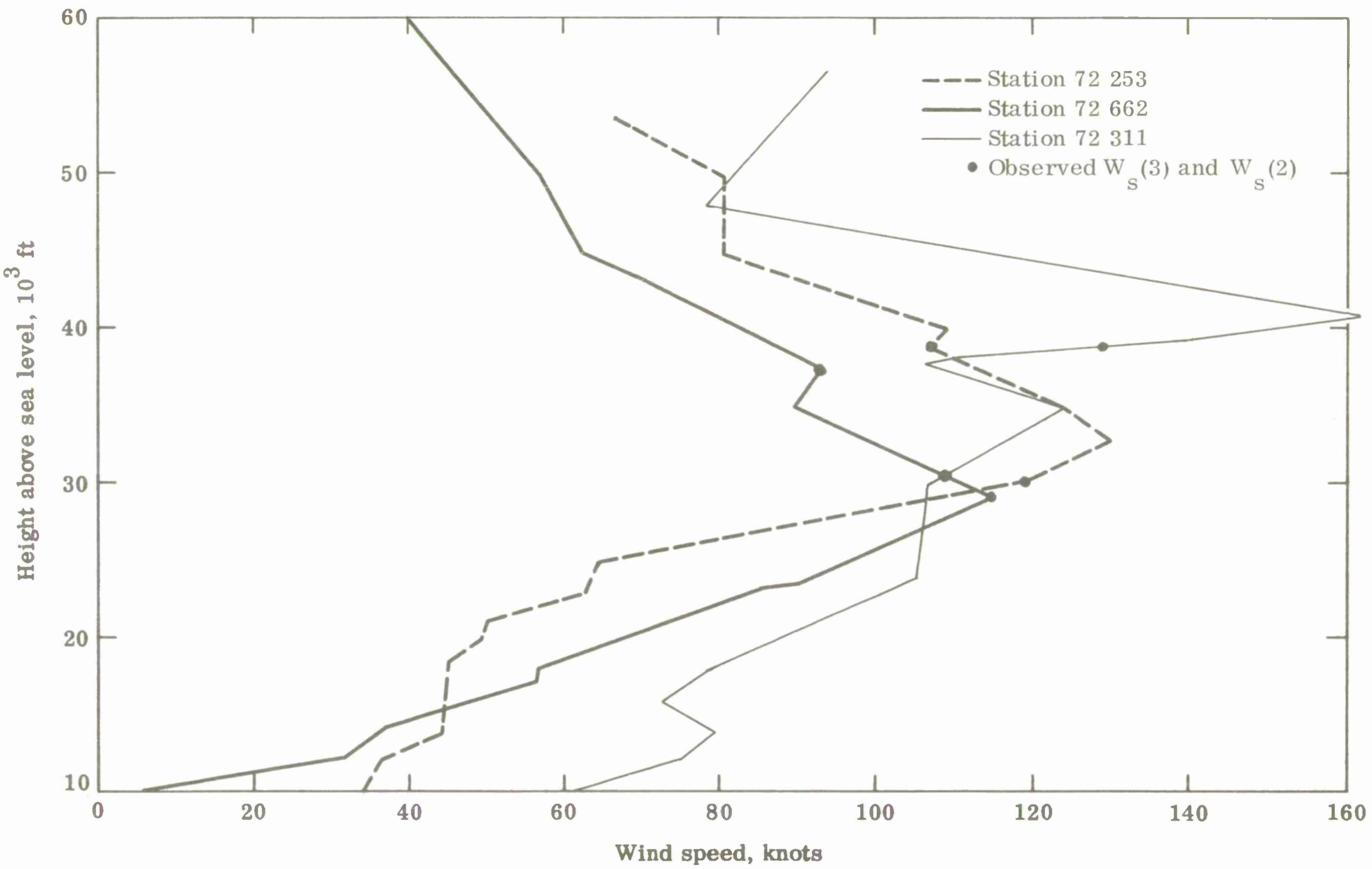

Fig. 3. Examples of wind profiles: Category 5, Single, strong subtropical—polar jet.

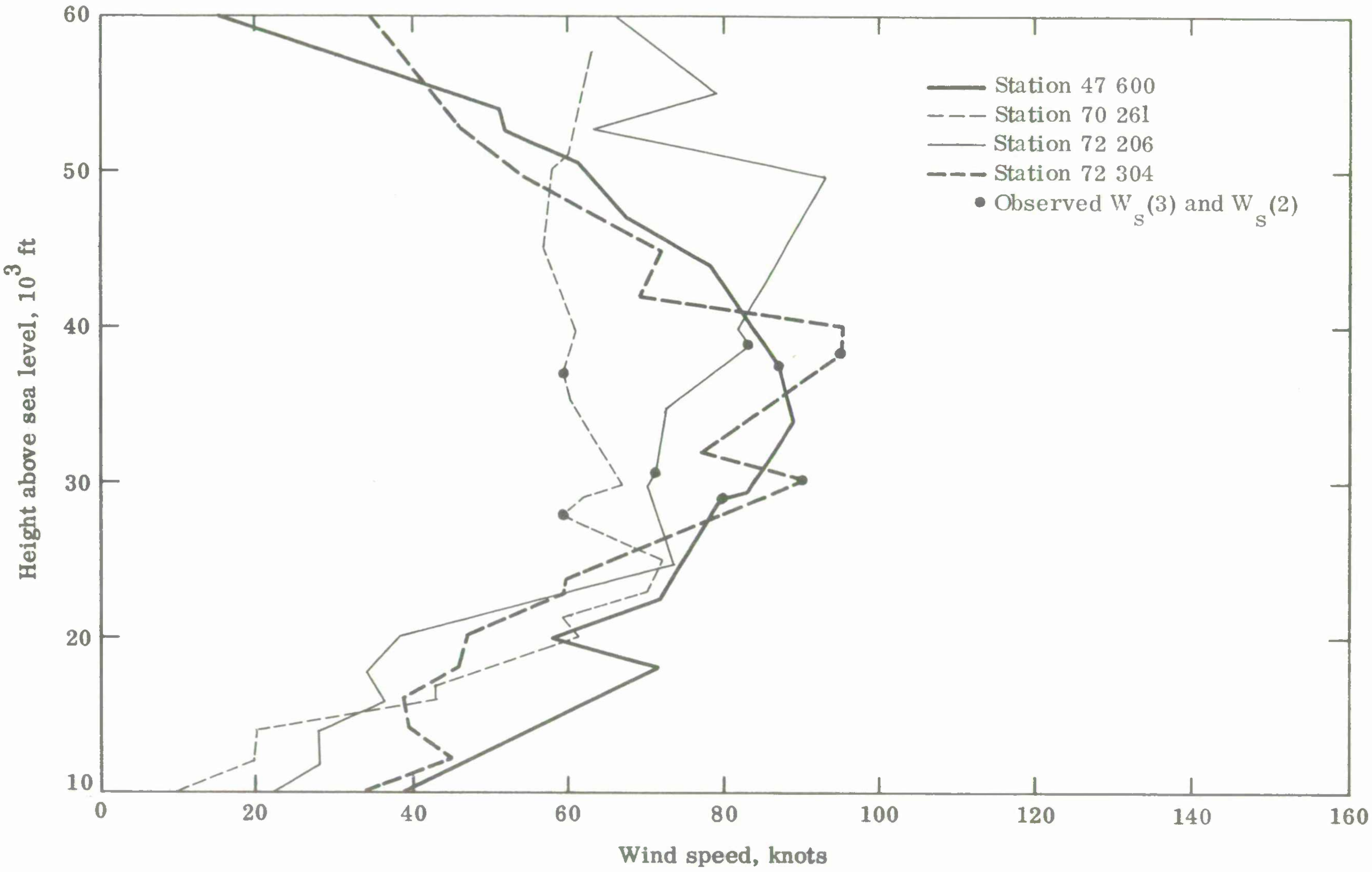

Fig. 4. Examples of wind profiles: Category 6, multiple, moderate subtropical—polar jet.

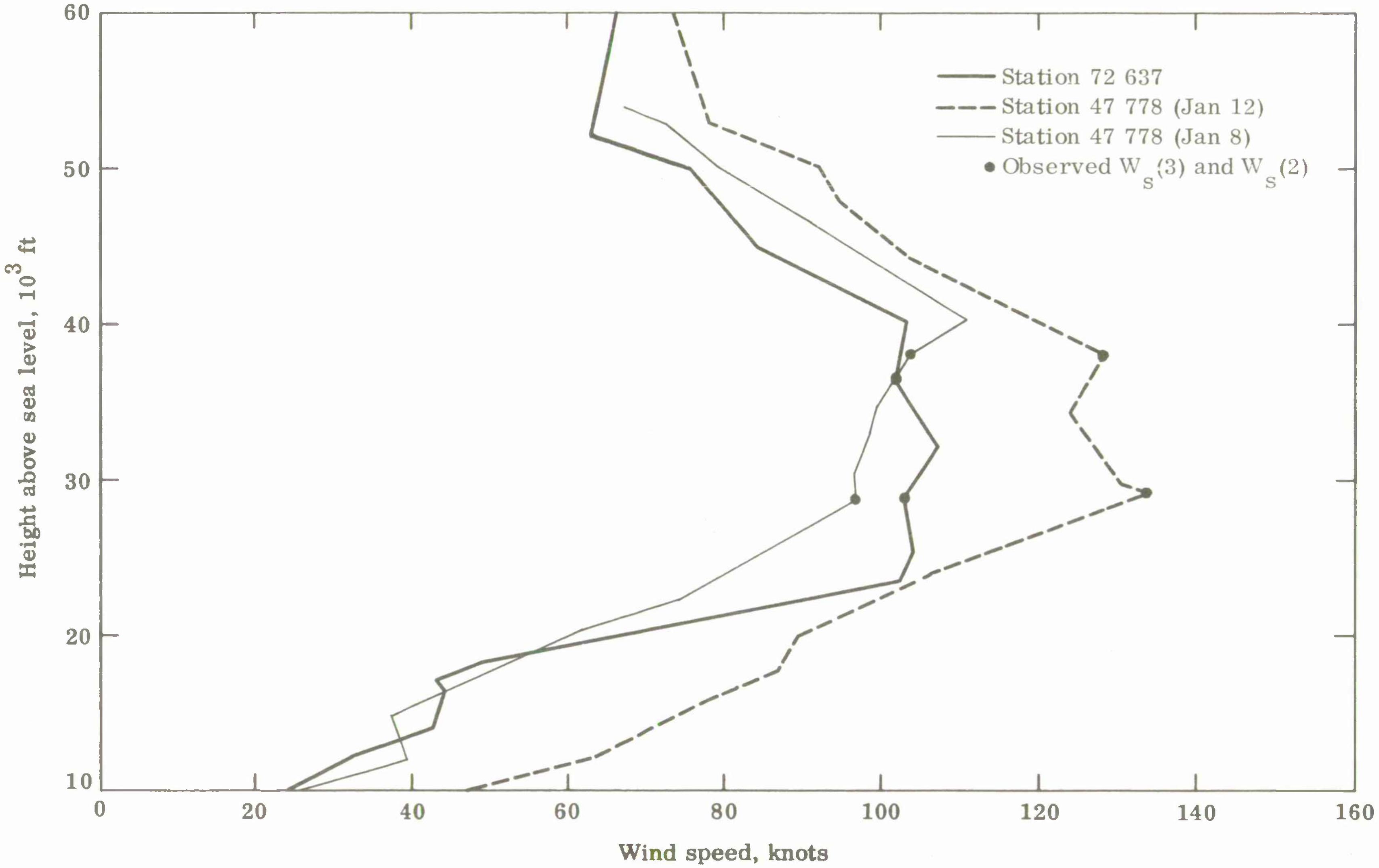

Fig. 5. Examples of wind profiles: Category 7, multiple, strong subtropical—polar jet.

In general, the wind profiles follow the logic for the category criteria, but, as noted, there are instances where a profile for a particular LRMW category deviates from the "model" conceived for that category.

The major point being made in this discussion of category modeling of wind profiles is that the wind profiles cannot be adequately stratified to include all types of profiles, at least when using only the constant-pressure-surface information (as required by the nature of the objective LRMW analysis technique). This is not considered serious, because the category equations supply only the initial-guess field for the LRMW parameters, and the initial guess is "corrected" over the data areas by the analysis procedure.

It is concluded that the LRMW categories defined here represent the near optimum stratification of wind profiles, considering that the definitions must be based on constant-pressure-surface information.

4.4 Verification of Different Types of Wind Profiles (Categories 4—7)

The wind profiles in Figs. 2 through 5 were chosen to illustrate some of the variety of wind profiles that are possible within particular categories. Subsequent to their selection it was decided to look for the individual verifications to determine whether the equations were capable of "capturing" some of the differences in the wind profiles. For each of the profiles in Figs. 2 through 5, it is possible to draw portions of the wind profiles from the information specified by the LRMW equations. Figures 6 through 9 represent the actual observed profiles and portions of the profiles constructed from the values given by the equations for the LRMW parameters. On these figures the maximum wind speed in the LRMW is plotted at the level of the mean height of the LRMW, but it does not necessarily follow that the maximum speed is actually at that level—it may be anywhere in the layer. A study of the figures and specification errors reveals that the specification of LRMW parameters as given by the equations is, in general, very good. Discussing the results by individual categories:

Category 4: single, moderate subtropical—polar jet

The equations are seen to be capable of specifying the mean height of the LRMW [$\overline{Z}$(LR)] above 200 mb, below 300 mb, and inbetween 300 and 200 mb. For these single jets, it may be assumed, in most cases, that the maximum is located very near $\overline{Z}$(LR)

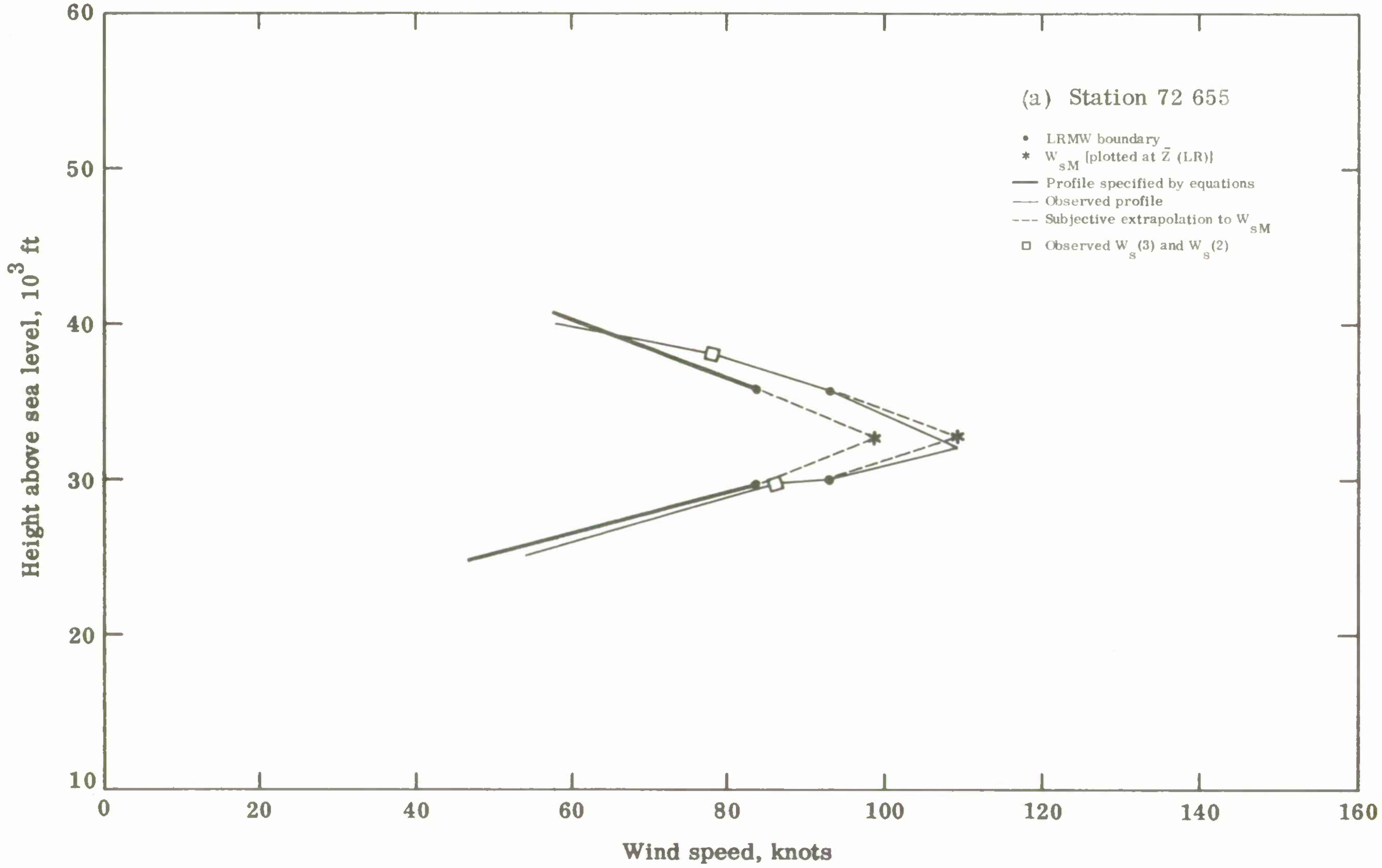

Fig. 6. LRMW profiles constructed from equations and observed data—Category 4.

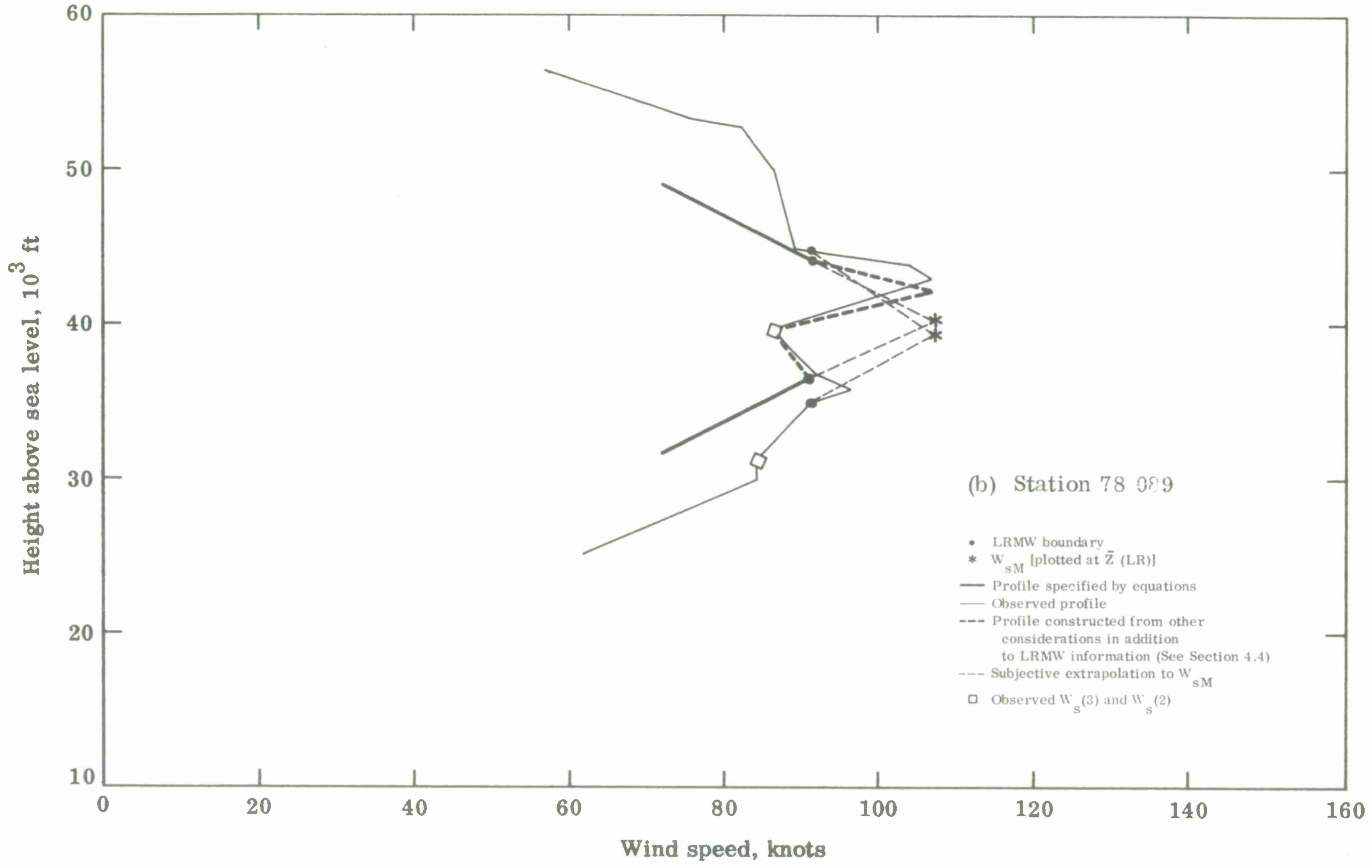

Fig. 6. Continued.

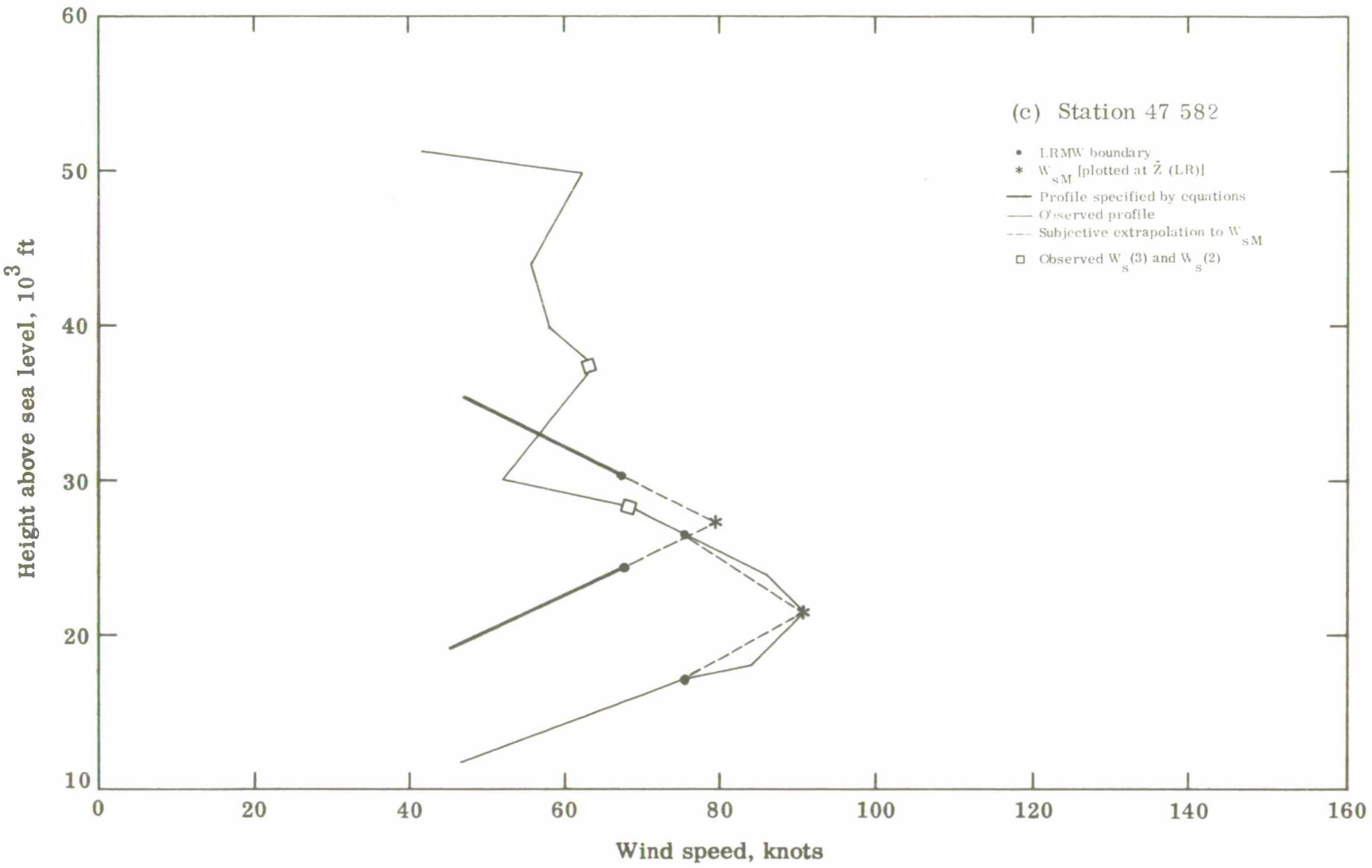

Fig. 6. Continued.

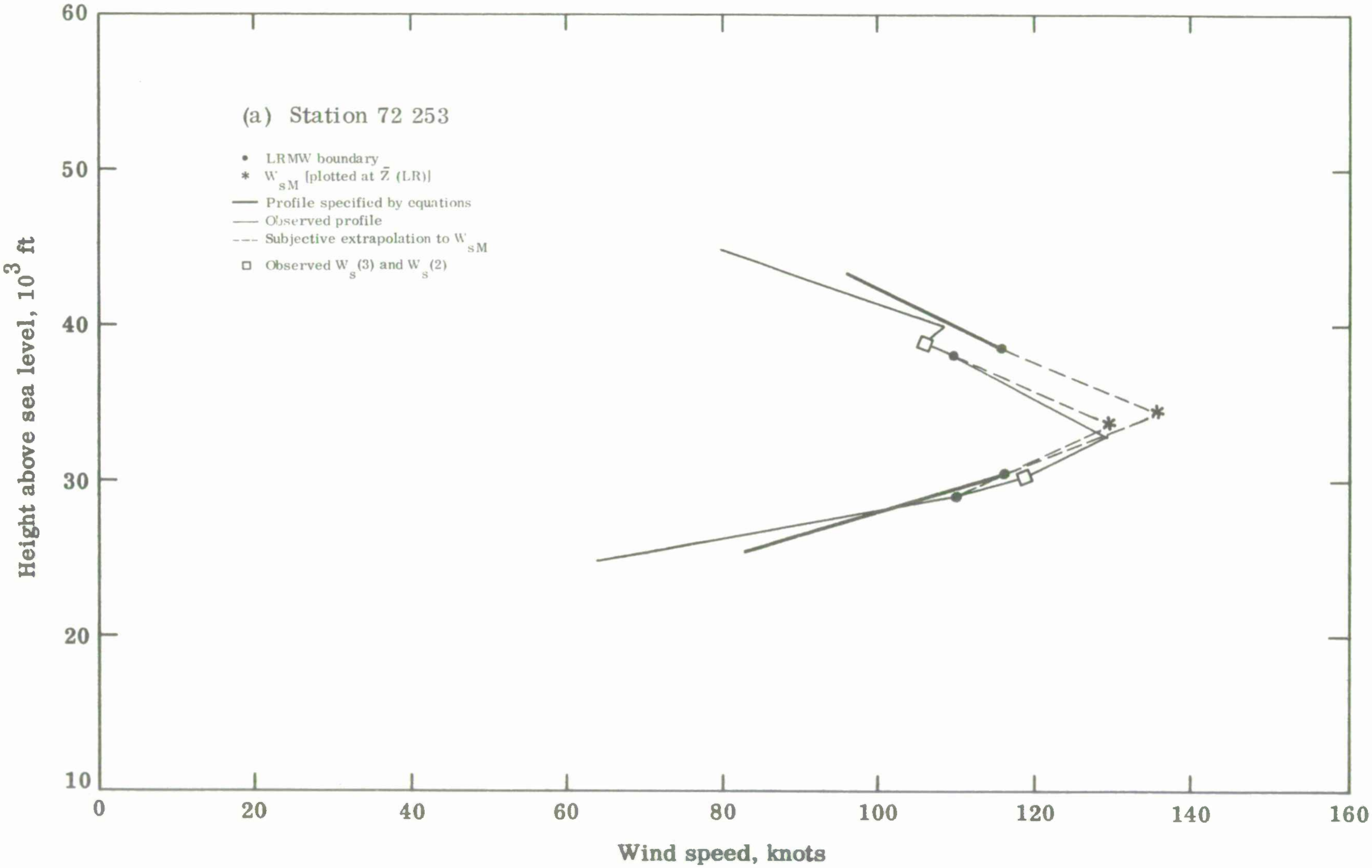

Fig. 7. LRMW profiles constructed from equations and observed data—Category 5.

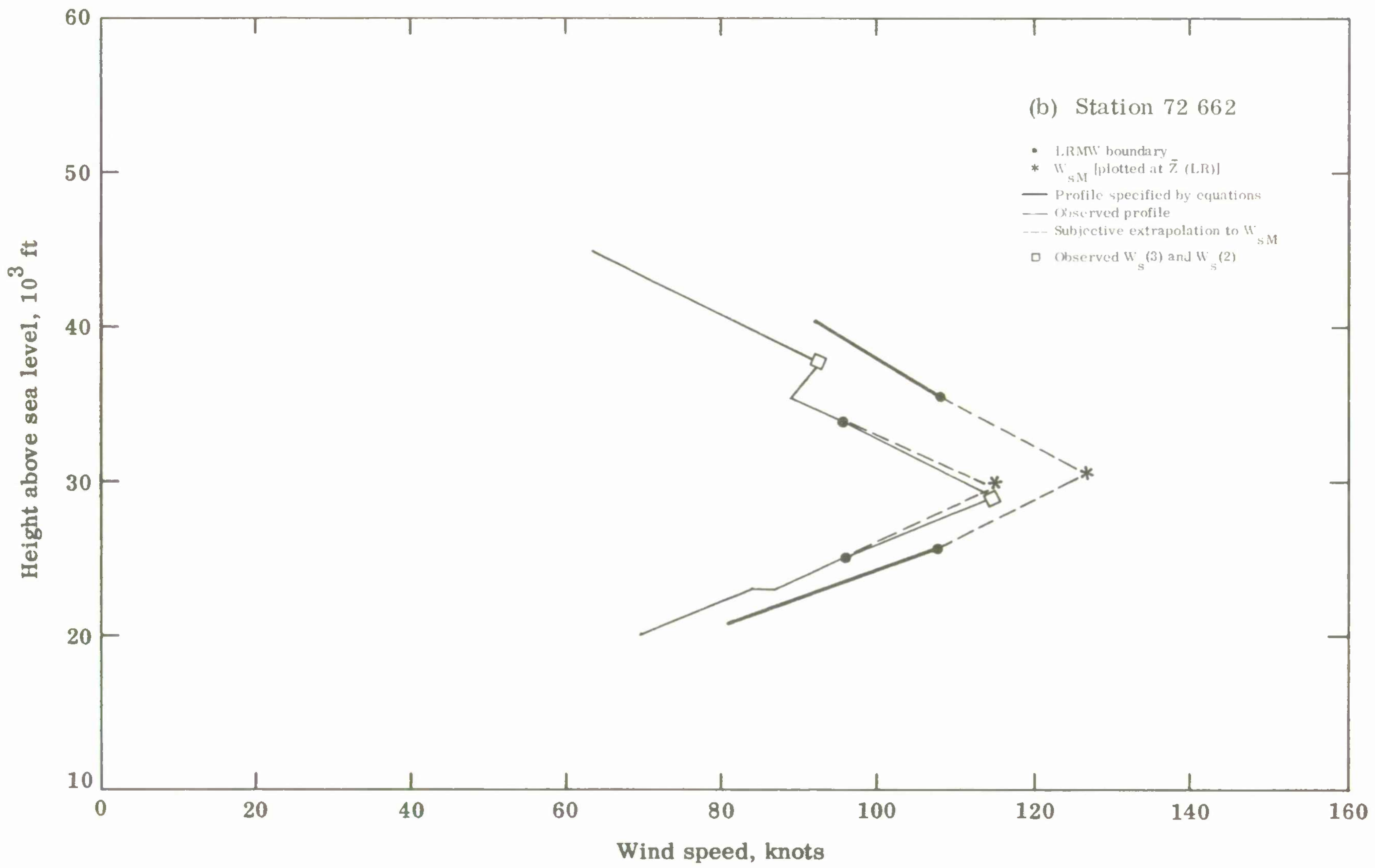

Fig. 7. Continued.

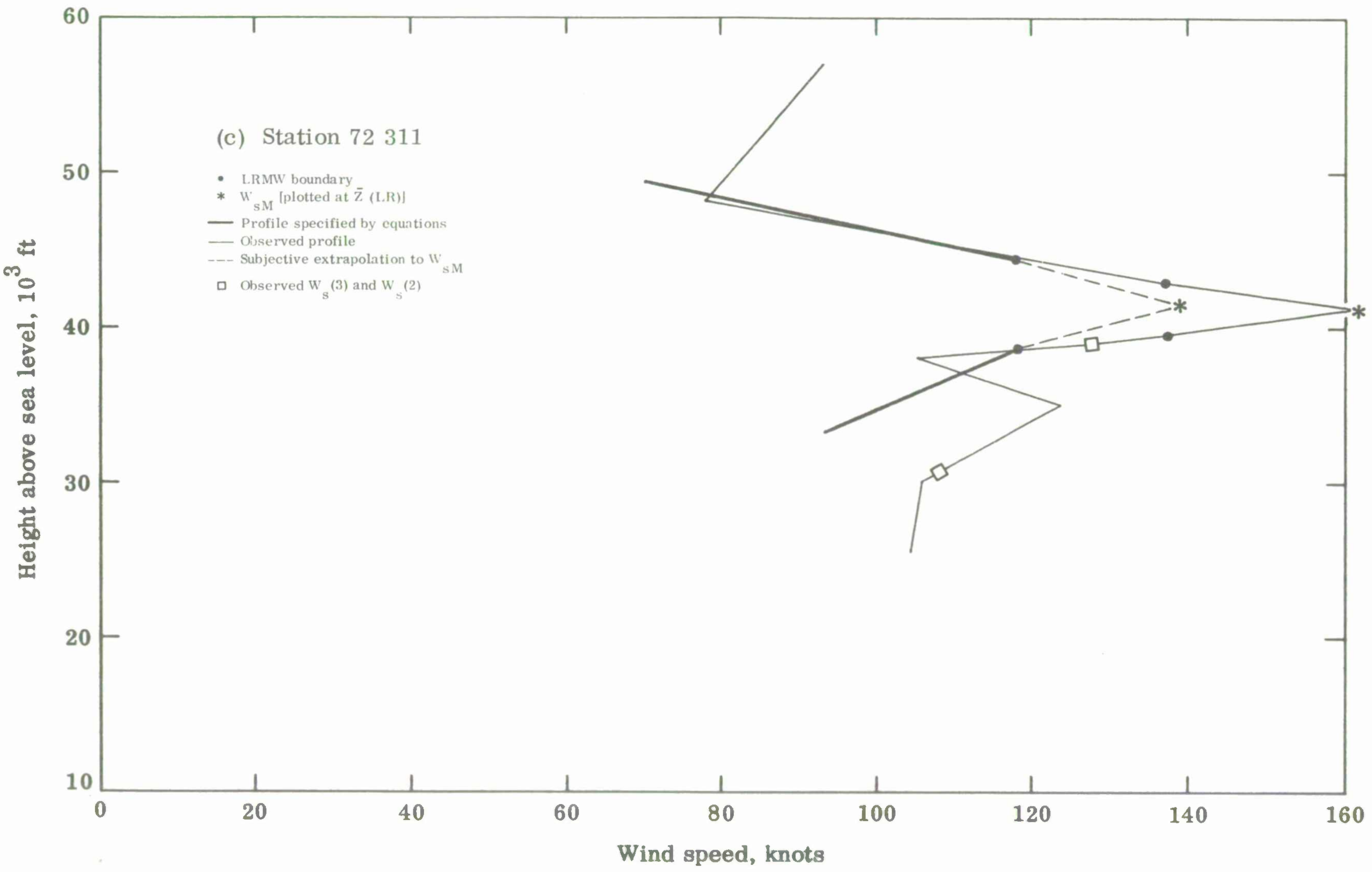

Fig. 7. Continued.

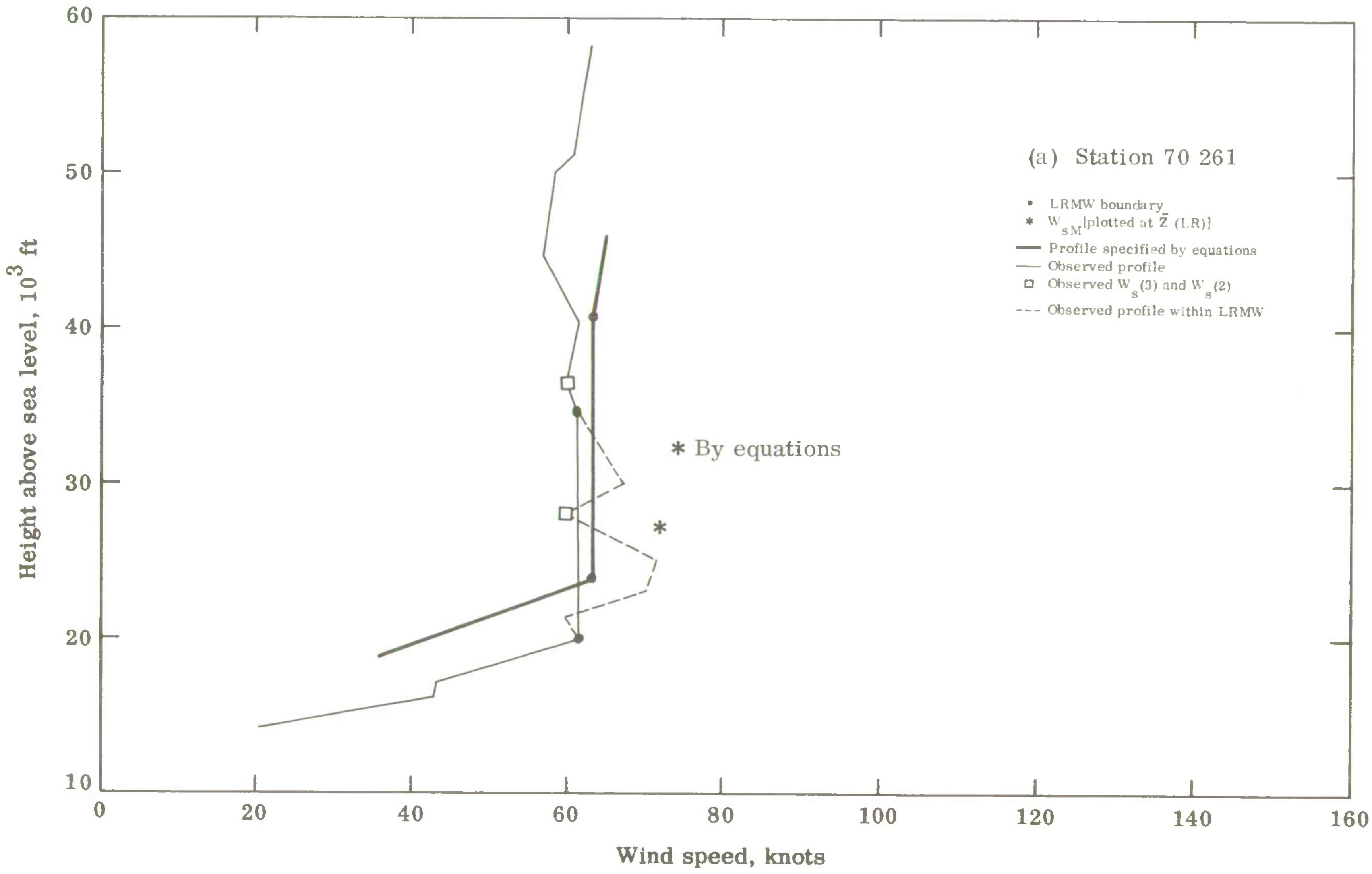

Fig. 8. LRMW profiles constructed from equations and observed data—Category 6 (boundaries of LRMW connected by solid vertical line to indicate thickness).

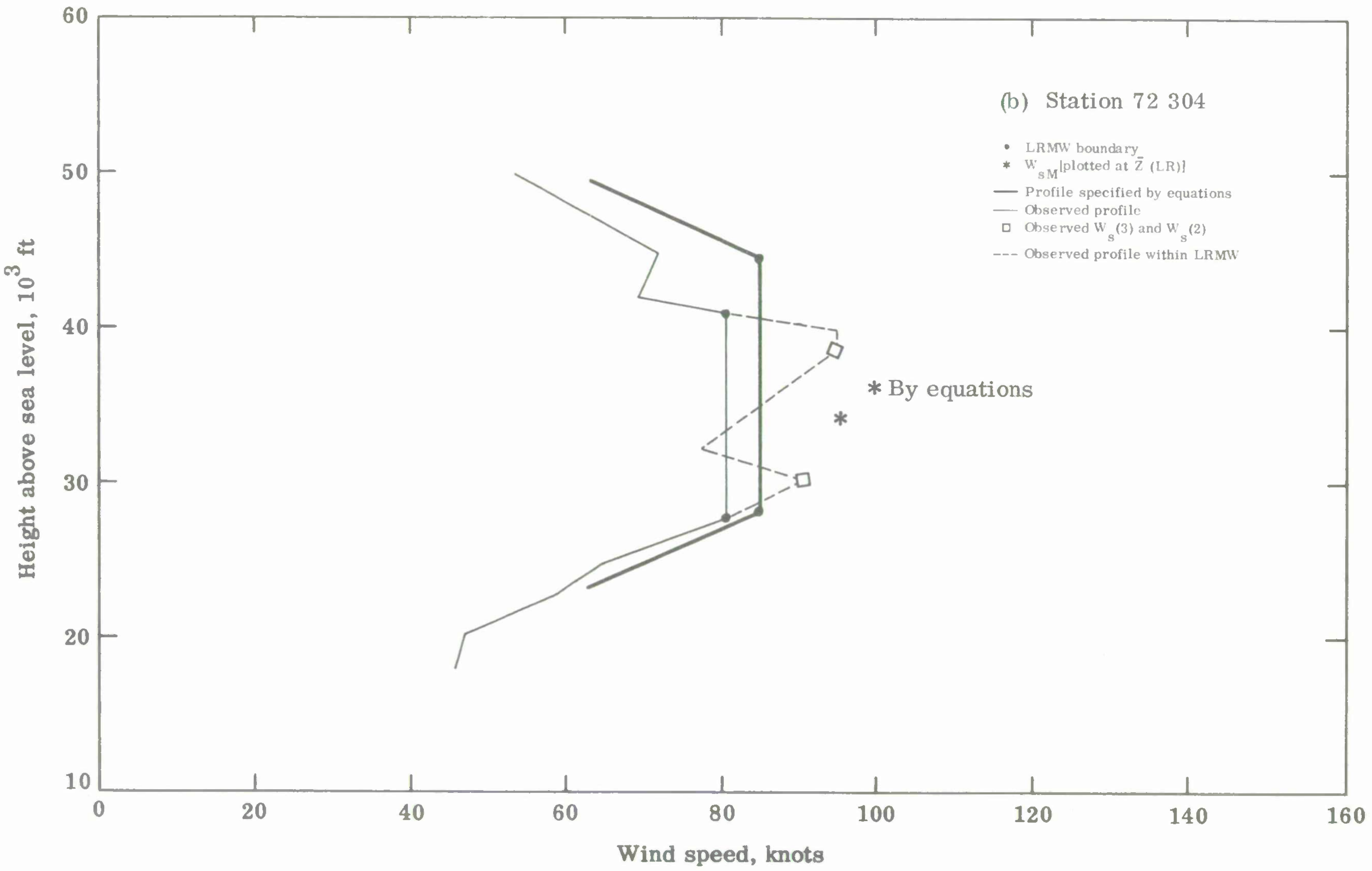

Fig. 8. Continued.

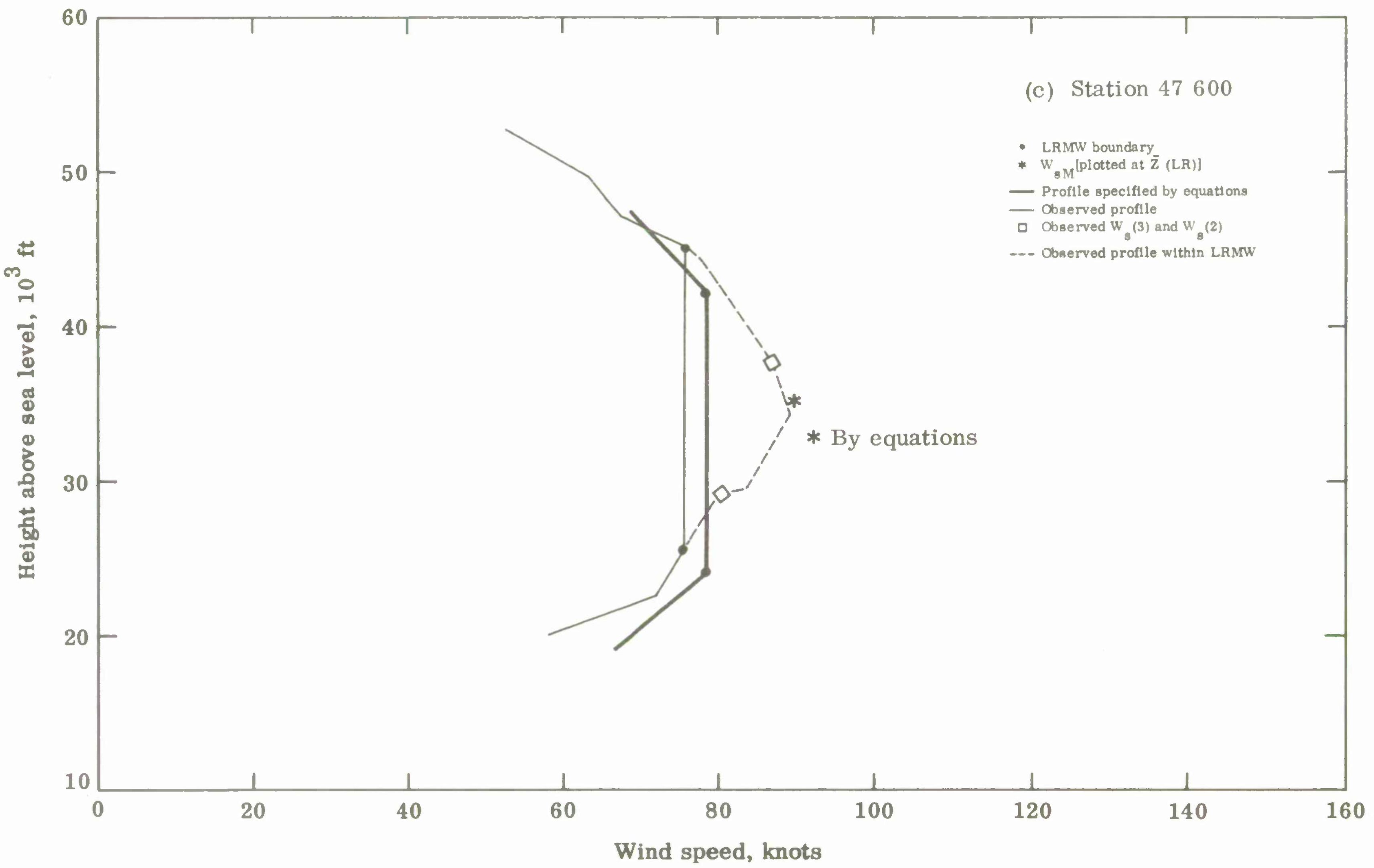

Fig. 8. Continued.

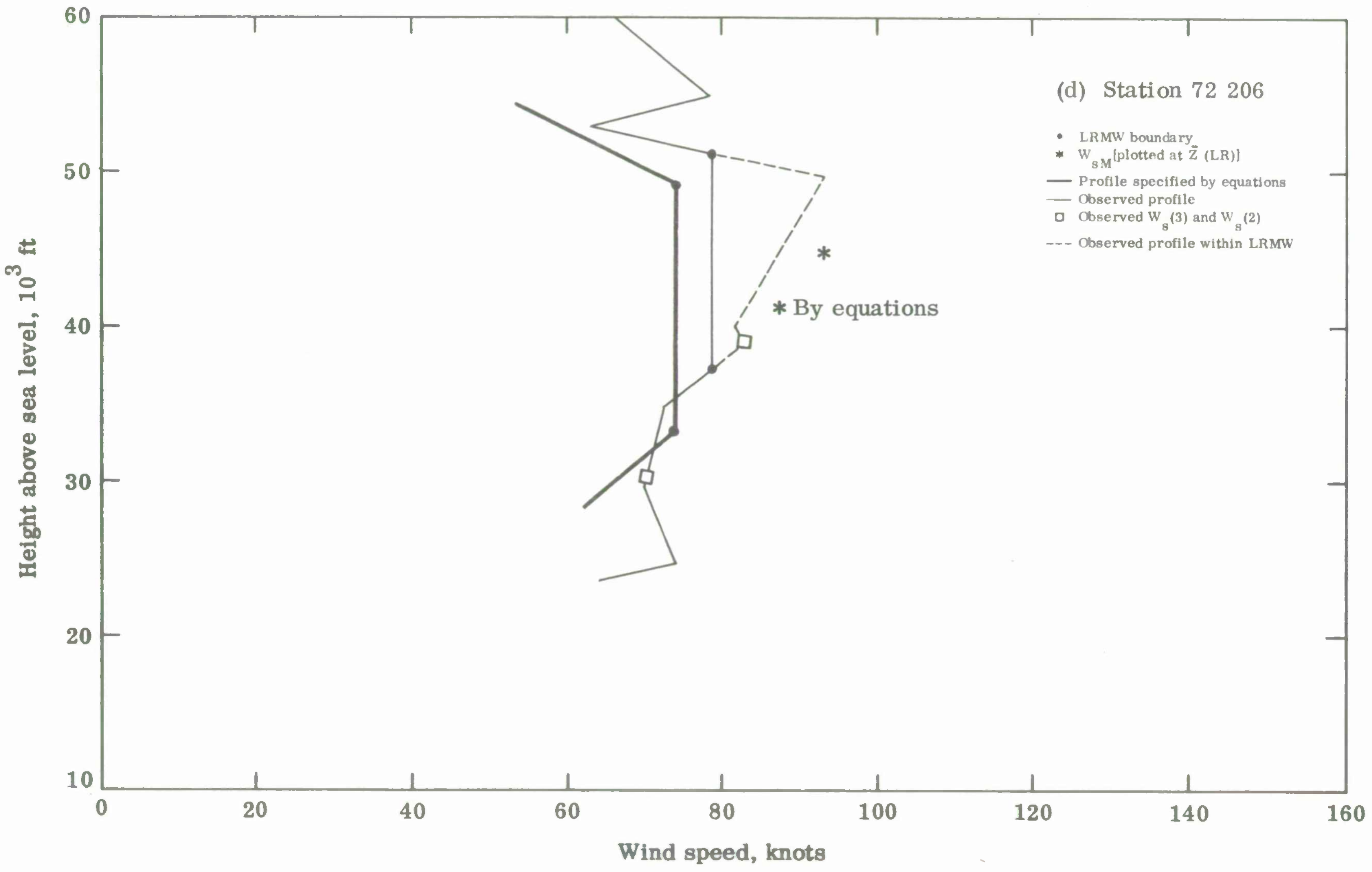

Fig. 8. Continued.

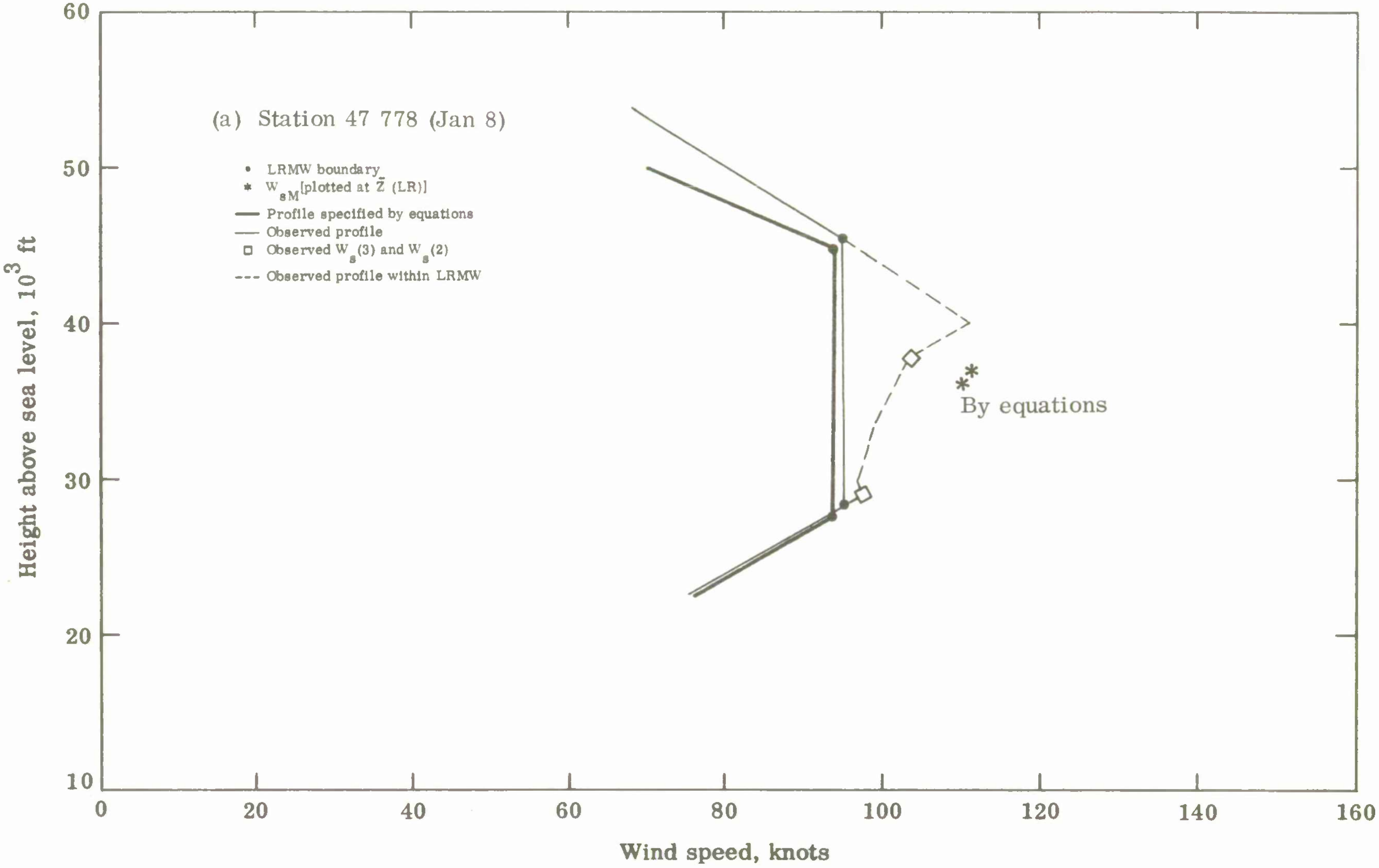

Fig. 9. LRMW profiles constructed from equations and observed data—Category 7 (boundaries of LRMW connected by solid vertical line to indicate thickness).

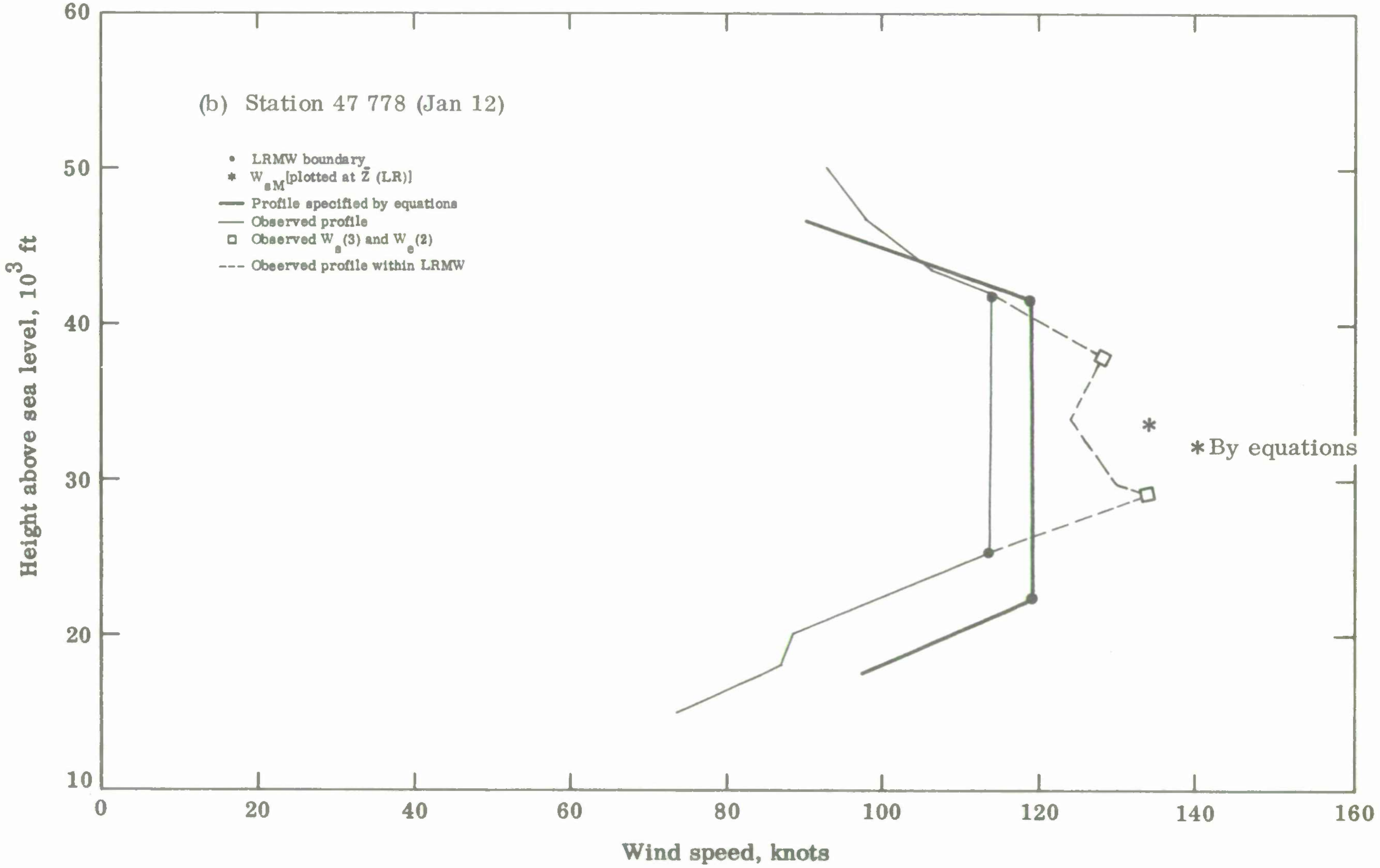

Fig. 9. Continued.

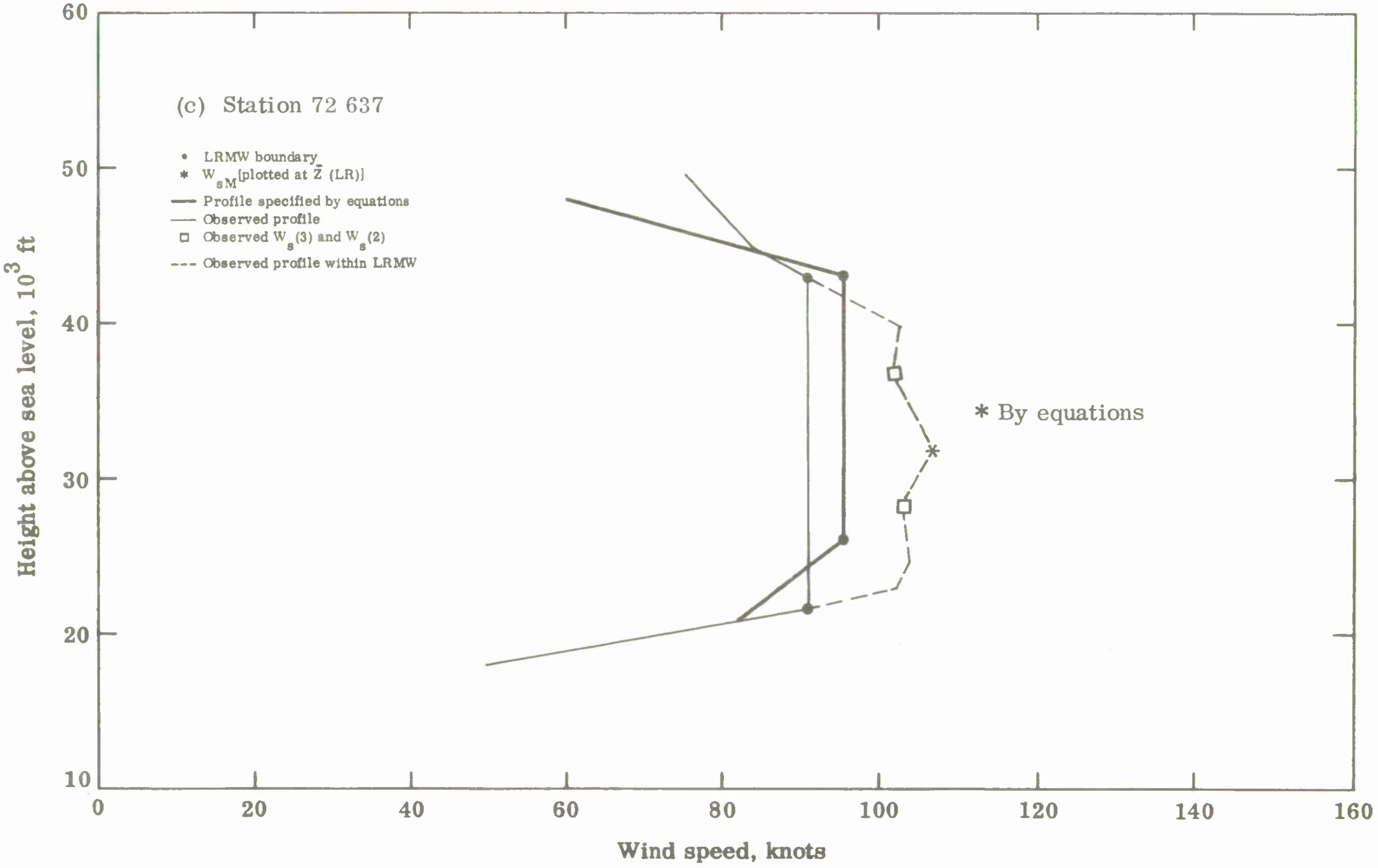

Fig. 9. Continued.

except where other information makes this unlikely [e.g., Station 78 089 has a wind speed of 86 knots at the 200-mb level, which is within 1000 ft of $\overline{Z}$(LR); thus, it is nearly impossible for the maximum of 107 knots to be at the specified $\overline{Z}$(LR) of 40557 ft. With the information of the boundaries of the LRMW given by the thickness in conjunction with the known 200-mb wind speed, it is very likely that the maximum wind speed is located between 200 mb and the upper boundary. This approximates the actual profile very well]. For Station 47 582, $\overline{Z}$(LR) is specified to be at a level lower than 300 mb, but the available 500-mb wind speed (which is higher than the maximum speed specified by the equations, and 16 knots greater than the 300-mb speed) strongly suggests that the maximum is closer to 500 mb than 300 mb, and that $\overline{Z}$(LR) is probably specified somewhat high. There is no information to indicate that the shears are in error; thus, the profile constructed from the LRMW equations can be subjectively displaced to a lower elevation somewhere between 500 and 300 mb to give a better approximation of the true profile. Station 72 655 exhibits a close relationship between the observed profile and that specified by the LRMW equations.

Category 5: single, strong subtropical—polar jet

The profiles obtained from the LRMW information approximate rather closely the observed profiles, despite the observed range of the mean height of the LRMW from 29551 to 41213 ft. Although the maximum wind speed for Station 72 311 was not specified to be as high as observed, most of the sharpness of the profile was indicated by the strong vertical shears and the relatively thin layer of maximum wind given by the LRMW equations.

Category 6: multiple, moderate subtropical—polar jet

In this category the vector shears above and below the LRMW, as well as the other LRMW parameters, are specified quite well (see Fig. 8). The maximum will frequently not differ by an appreciable amount from the 300- and 200-mb wind speeds; i.e., the definition of the category precludes a sharpness to the profile. The details within the thick LRMW, of course, are not specified.

Category 7: multiple, strong subtropical—polar jet

The comments made for Category 6 apply here. LRMW parameters are specified very well.

The major outcome of the verification results for these assorted profiles is an increase in confidence in the ability of the LRMW equations to closely approximate the observed values of the LRMW parameters despite the incongruity of profile types within a category.

5. LRMW Objective Analysis Technique—Test and Evaluation

The analysis procedure described in Section II was used with data from 12 observation times in January 1963 (a time period not within the three month sample used to derive the initial-guess equations). The LRMW analyses for the 12 observation times were verified using the ARMS error method. The evaluation consisted of (a) an interpretation of the verification statistics and comparison with verification statistics from LMW analyses described in the previous report, (b) a comparison of the computer analyses with hand-analyzed charts, and (c) a determination of the consistency between LRMW analyses for each observation time.

5.1 ARMS -error-method Statistics

Table XII presents the overall rms errors (both initial guess and final pass) for five LRMW parameters for twelve observation times during January 1963.

Four of the five LRMW parameter verification statistics are not directly comparable to the LMW parameter verification statistics because three of them are defined differently (as discussed in Section I) and thickness of the LRMW is a new parameter. The only direct comparison with the LMW verification statistics that can be made is for the wind speed maximum.

Because the analysis procedures for both the LRMW and the LMW are identical for the wind speed maximum after the initial-guess field has been generated, the comparison was made with the statistics obtained from the initial-guess fields (the January 1963 data was used as input to both). Table XIII lists the analysis and withheld station rms errors for the initial guess of W_{sM} for verification Category A (W_{sM} > 100 knots) for each of the 12 observation times. It is seen that the LRMW

TABLE XII
OVERALL RMS ERRORS FOR LRMW PARAMETERS FOR 12 OBSERVATION TIMES

Parameter	Verification category	Error (initial guess/final pass)		
		Total rms error	Analysis rms error*	Withheld rms error†
W_{sM}	A	16.4 13.4	16.5 4.8	16.4 18.4
	B	12.4 10.2	11.5 3.0	13.2 14.1
	C	10.0 7.2	9.7 2.0	10.4 10.0
h(LR)	A	6021 4523	5440 766	6552 6351
	B	6126 4146	5499 1225	6695 5734
$\overline{Z}$(LR)	A	4476 3139	4345 774	4604 4372
	B	4476 3615	3789 790	5070 5051
$\vec{S}_b$	A	2.88 2.07	2.90 0.66	2.85 2.85
	B	2.23 1.61	2.19 0.56	2.26 2.21
	C	1.52 1.19	1.37 0.31	1.66 1.66
$\vec{S}_a$	A	2.81 2.14	2.52 0.57	3.08 2.97
	B	1.91 1.48	1.94 0.47	1.87 2.04
	C	1.31 1.03	1.26 0.28	1.36 1.43

*Verified back to stations used in the analysis.

†Verified to those stations that were withheld from the analysis.

equations result in lower rms errors for 11 of 12 times for the analysis stations (in one case, the error is the same) and 10 of 12 times for the withheld stations. To test the significance of the better result given by the new equations, the data were subjected to the Student's t-test for paired comparisons [8]. It was found to be significant at less than the 1% level (i.e., highly significant). It is concluded that the newly defined jet-stream categories and newly derived equations produce higher quality initial guesses when $W_{sM} > 100$ knots than the LMW equations. For the lower wind speed verification categories (i.e., $W_{sM} = 60$—100 knots and < 60 knots), the difference in the LRMW and LMW errors for the initial-guess fields was insignificant.

For the other four LRMW fields, the error statistics are considered to be low enough to indicate that the analyses are of high quality although the errors for h(LR) are higher than one might hope for. The computation of an estimated thickness that may produce relatively large errors over about 20% of the analysis area is probably the prime reason for the relatively high errors. The discussion of the analyses of the LRMW parameters presented in the next section shows an example of a h(LR) map and suggests a method for detecting areas where large errors are likely, and a solution to the problem.

The verification statistics for all the LRMW parameters show that the reduction of the total rms error from the initial guess to the final pass is due almost entirely to the reduction of the rms error at analysis stations. At times, the withheld station rms error is somewhat higher for the final pass than it was for the initial guess. Similar results were obtained for the LMW technique. Logical reasons were presented in the previous report [6] and are repeated here:

> "(a) The analysis station rms error essentially indicates how well the analysis technique fits the observations (and these stations may be considered as minimum error points over the analysis area).
>
> "(b) The withheld stations, which approximate maximum error points do not contribute to the analysis, by definition. A station withheld over a sparse data area may be the only station in the area (e.g., a stationary weather ship in the ocean) and the analysis over that area will remain unchanged from the initial guess to the final pass.
>
> "(c) Withheld stations over a medium or high data-density area are not allowed to influence the analysis. The surrounding analysis stations, however, may change the analysis to the extent that the point at which there is a with-

held station observation may actually be in less agreement with the final analysis than it was with the initial-guess analysis."

One of the deficiencies of the previous LMW technique was the difficulty of specifying the height of the level of maximum wind, Z(L),because sometimes high wind speeds were evident over a thick layer. This was especially true when the maxima were between 50 and 100 knots with the height of the LMW varying widely over adjacent grid points or stations. Thus, the rms errors for the initial guess and final pass of Z(L) for verification categories A and B were: A (> 100 knots)—4818 ft and 3533 ft, respectively; B (50—100 knots)—7378 ft and 5738 ft, respectively.

The mean height of the layer of maximum wind, $\overline{Z}$(LR), is easier to specify and more meaningful, particularly for verification Category B, as is apparent from comparison of the $\overline{Z}$(LR) errors with the Z(L) errors.

For the shears below and above the LRMW, the rms errors are about the same as those that were associated with the LMW. It is indicative of a very good specification of the LRMW shear field because this result was achieved in spite of the fact that they are vector shears for the layer 5,000 ft below and above the LRMW instead of scalar shears for the layer 10,000 ft below and above the LMW. The difference in the shear criteria (LRMW and LMW) result in higher average values for shears (by 2 knots 10^{-3} ft^{-1}) and generally higher standard deviations (by 1—2 knots 10^{-3} ft^{-1}) for the LRMW shears over the LMW shears (see Table V of this report and Table IV of [6]).

5.2 Objective (computer) versus Subjective (man) LRMW Analysis Comparison

Figures 10—14 illustrate objective and subjective analyses of LRMW parameters. In general, these charts and others reveal that there are only minor differences in the analyses over the dense data areas (e.g., the U.S.), but differences are more noticeable over the sparse data areas (e.g., Canada). These differences are attributed primarily to the human analyst drawing to the available data which results in a tendency for maxima and minima to be positioned close to the observing stations when, in reality, they may be some distance away.

The objective thickness of the LRMW clearly indicates some unrealistically strong gradients over small areas of the western Pacific [Fig. 11 (a)]. These are

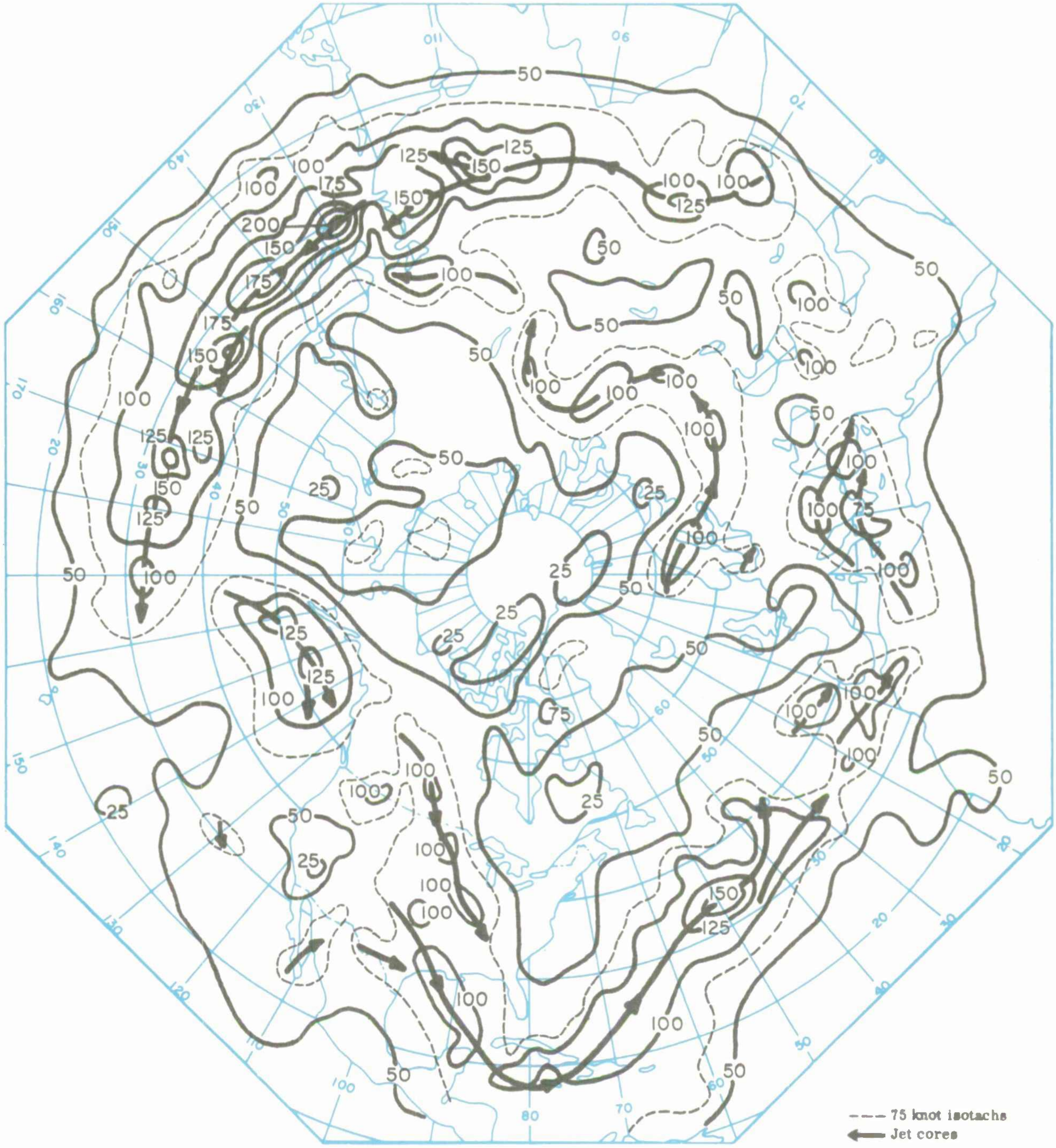

Fig. 10(a). Objective maximum wind speed, 1200Z, 3 January 1963.

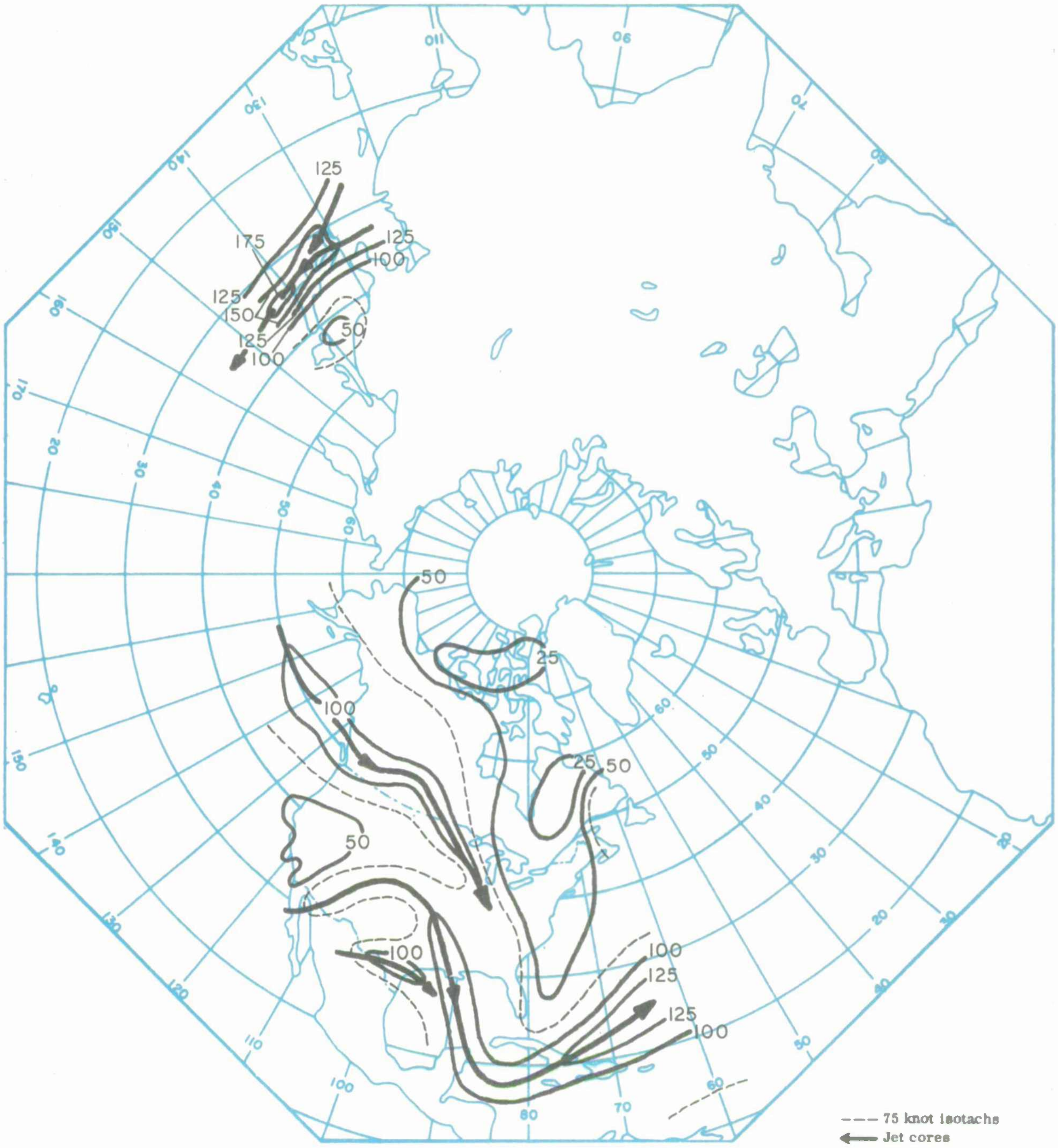

Fig. 10(b). Subjective maximum wind speed, 1200Z, 3 January 1963.

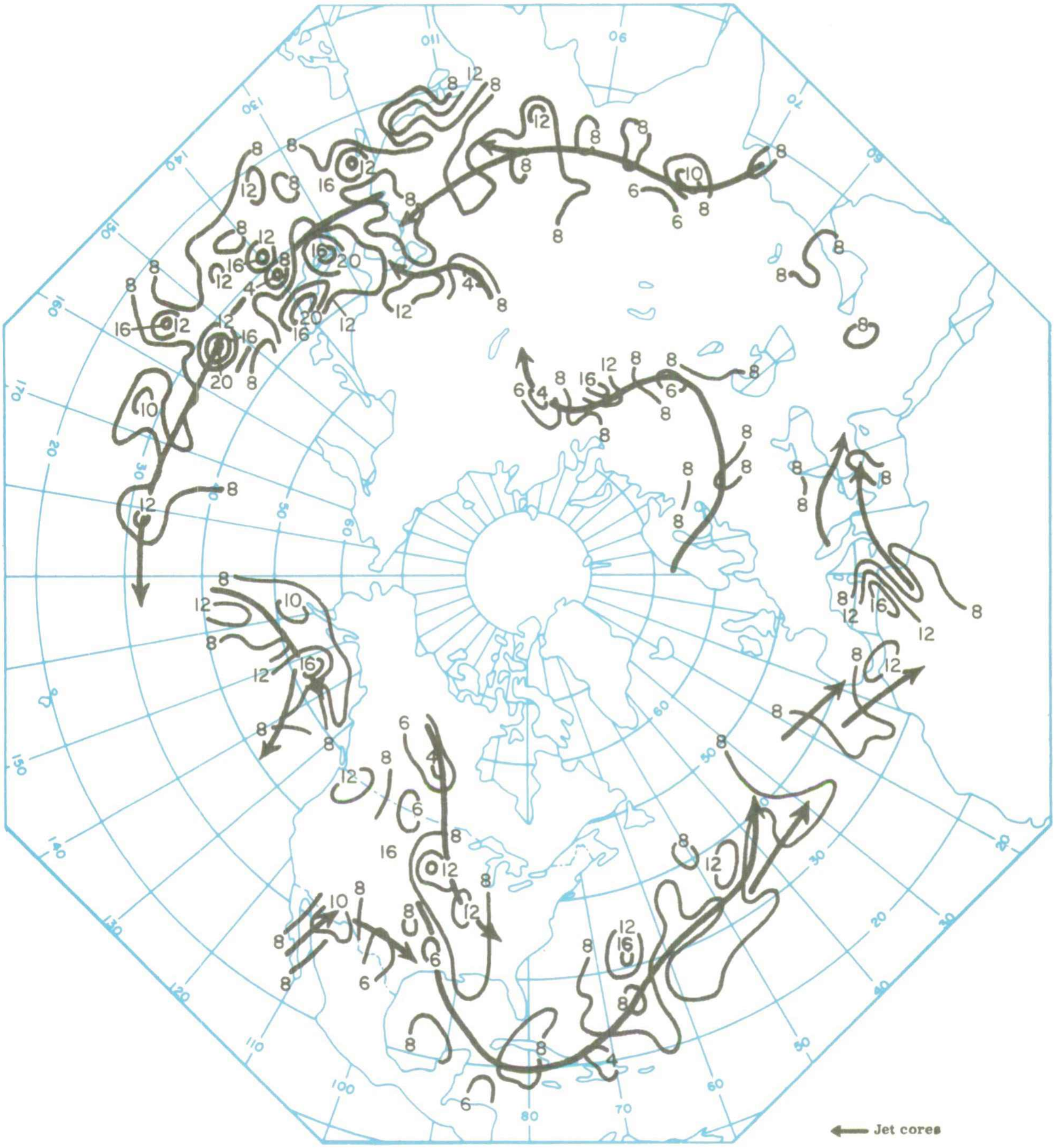

Fig. 11(a). Objective thickness of LRMW, 1200Z, 3 January 1963.

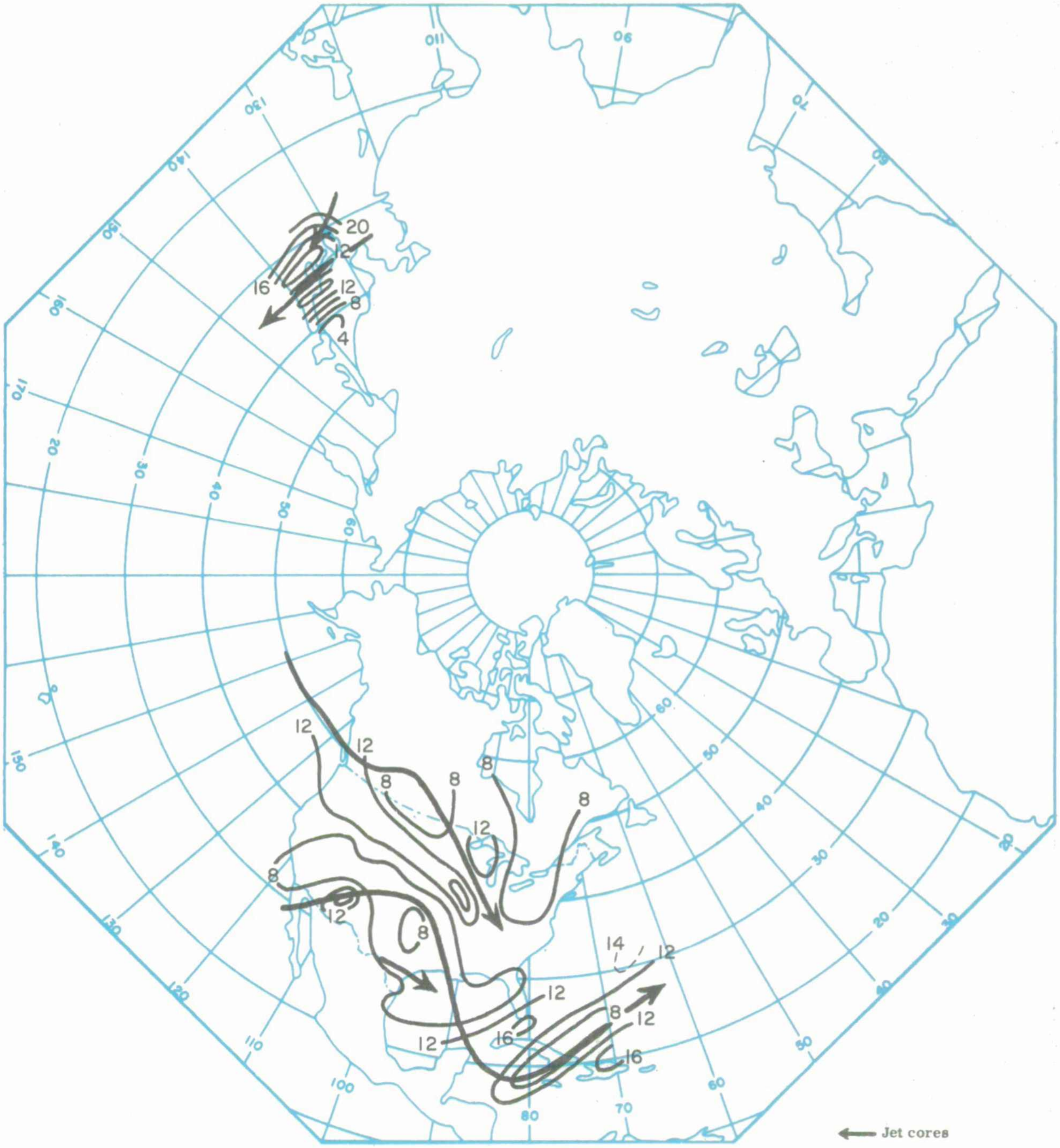

Fig. 11(b). Subjective thickness of LRMW, 1200Z, 3 January 1963.

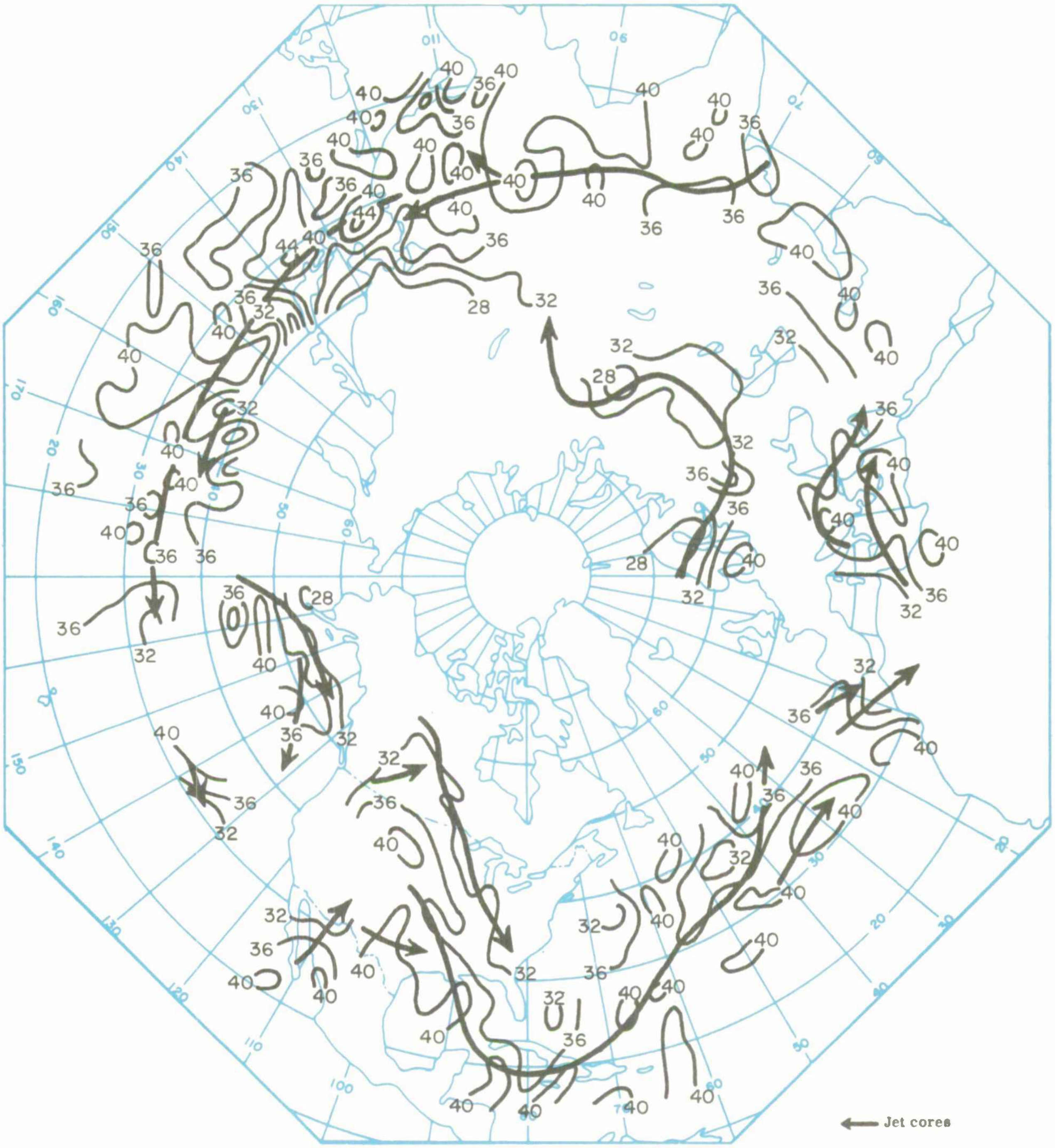

Fig. 12(a). Objective mean height of LRMW, 1200Z, 3 January 1963.

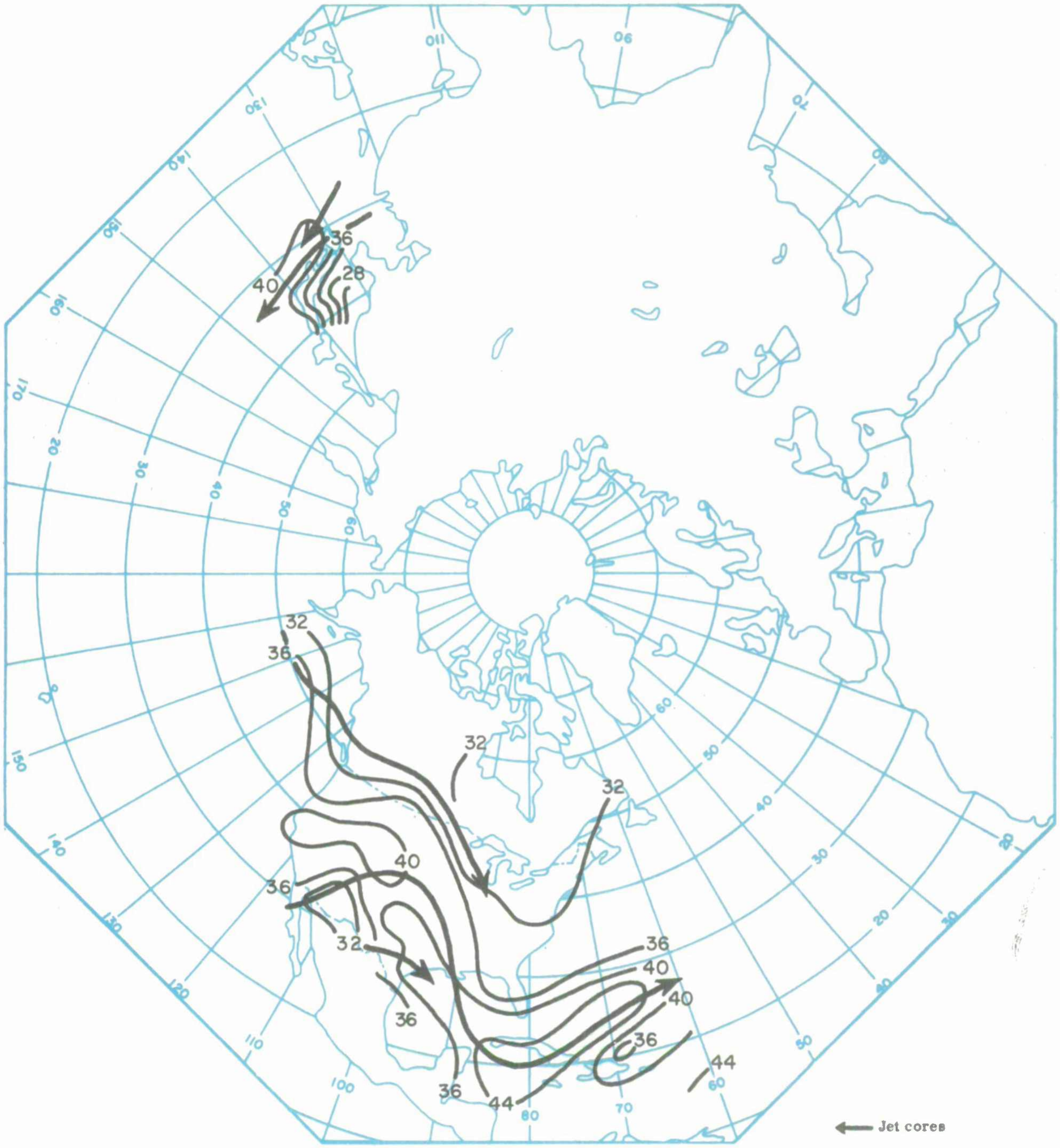

Fig. 12(b). Subjective mean height of LRMW, 1200Z, 3 January 1963.

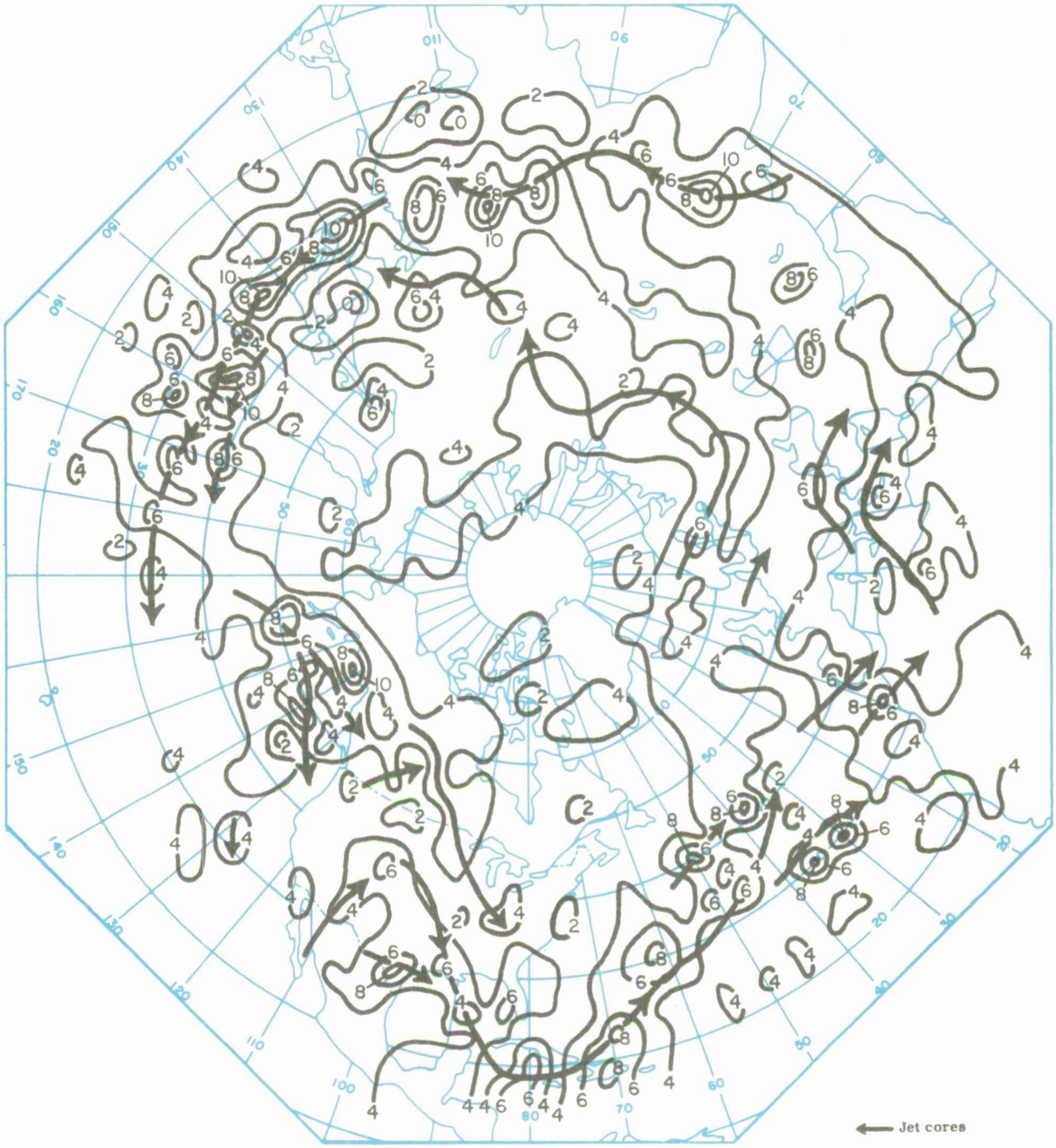

Fig. 13(a). Objective vector shear below the LRMW, 1200Z, 3 January 1963.

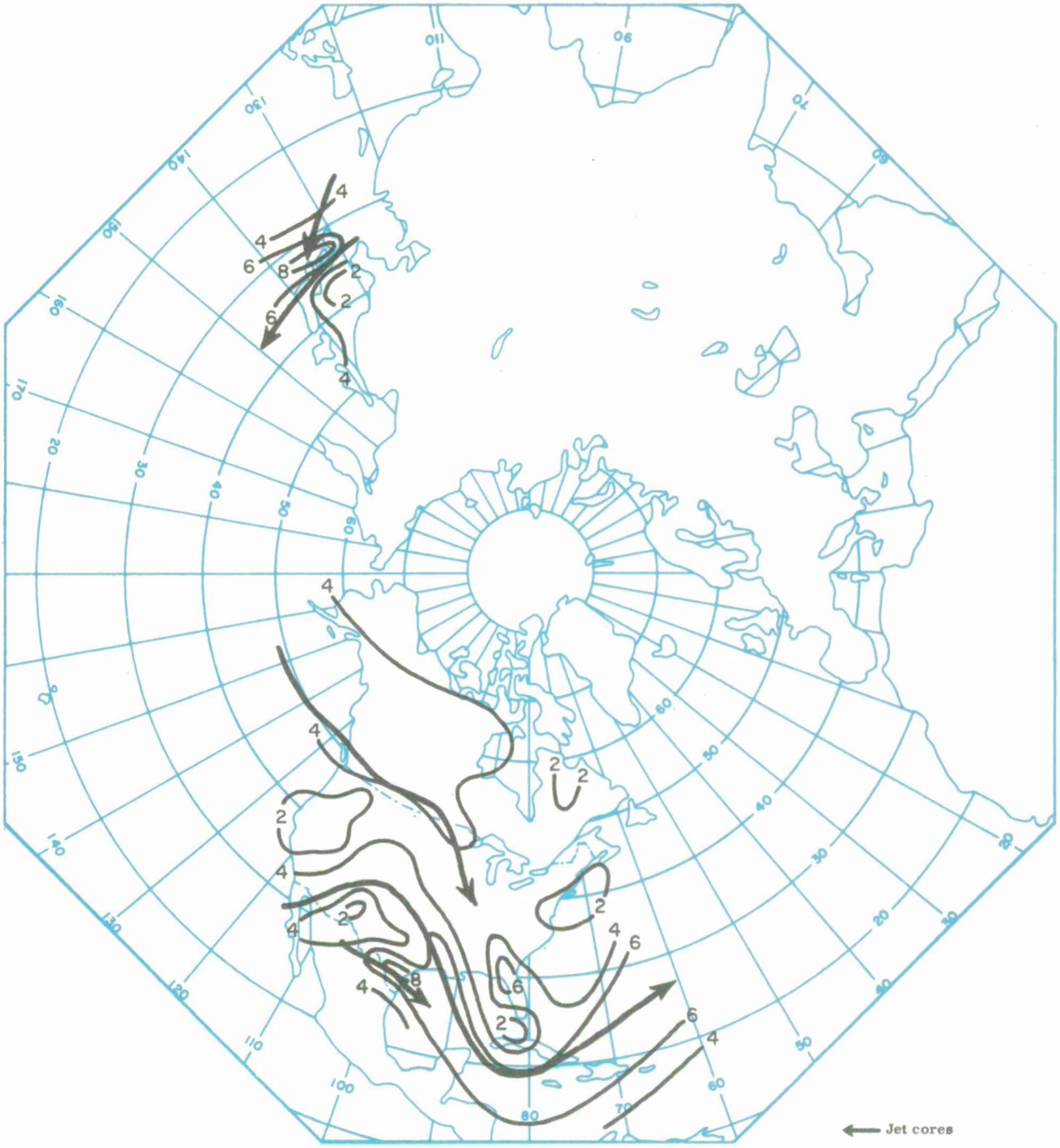

Fig. 13(b). Subjective vector shear below the LRMW, 1200Z, 3 January 1963.

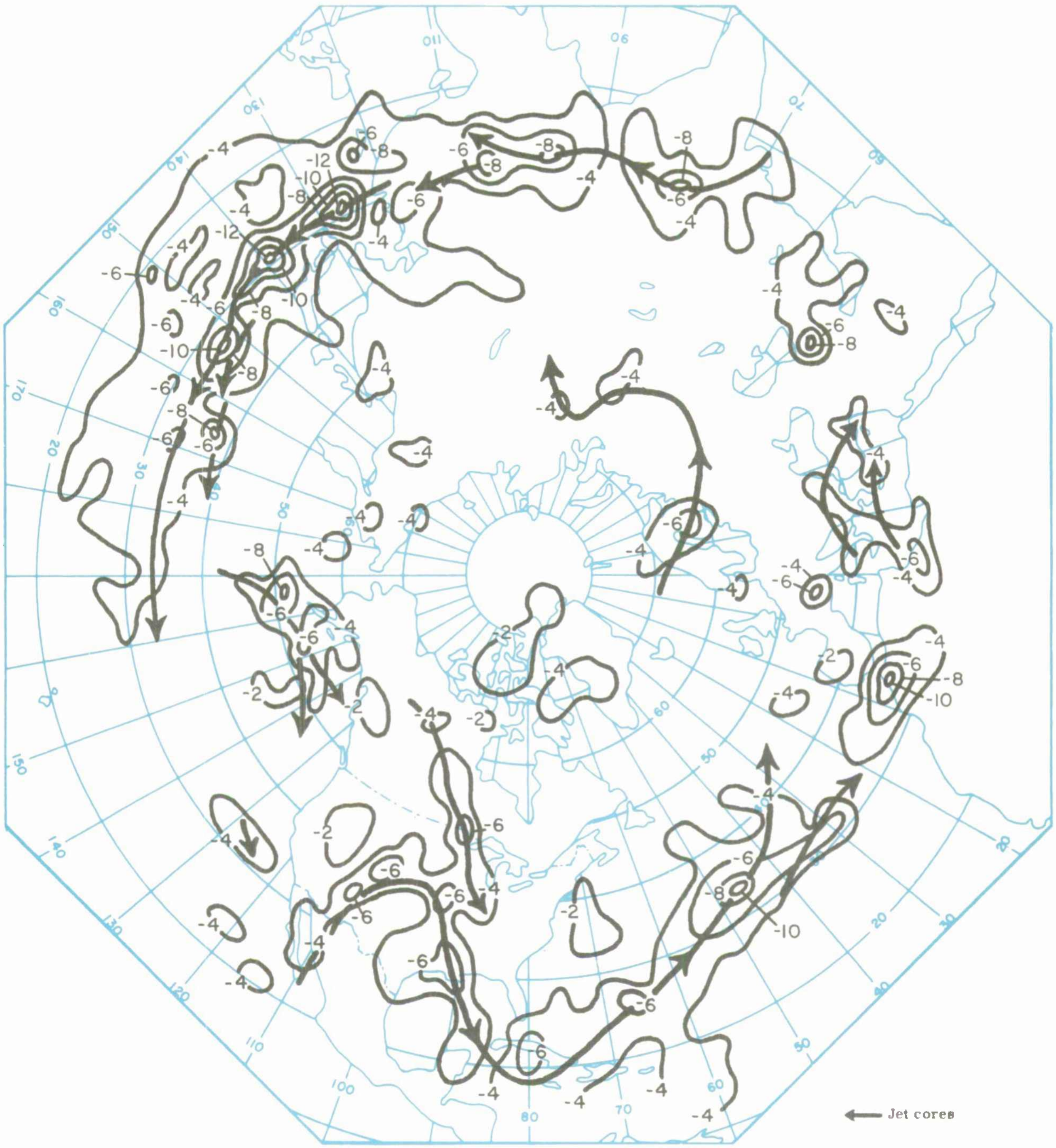

Fig. 14(a). Objective vector shear above the LRMW, 1200Z, 3 January 1963.

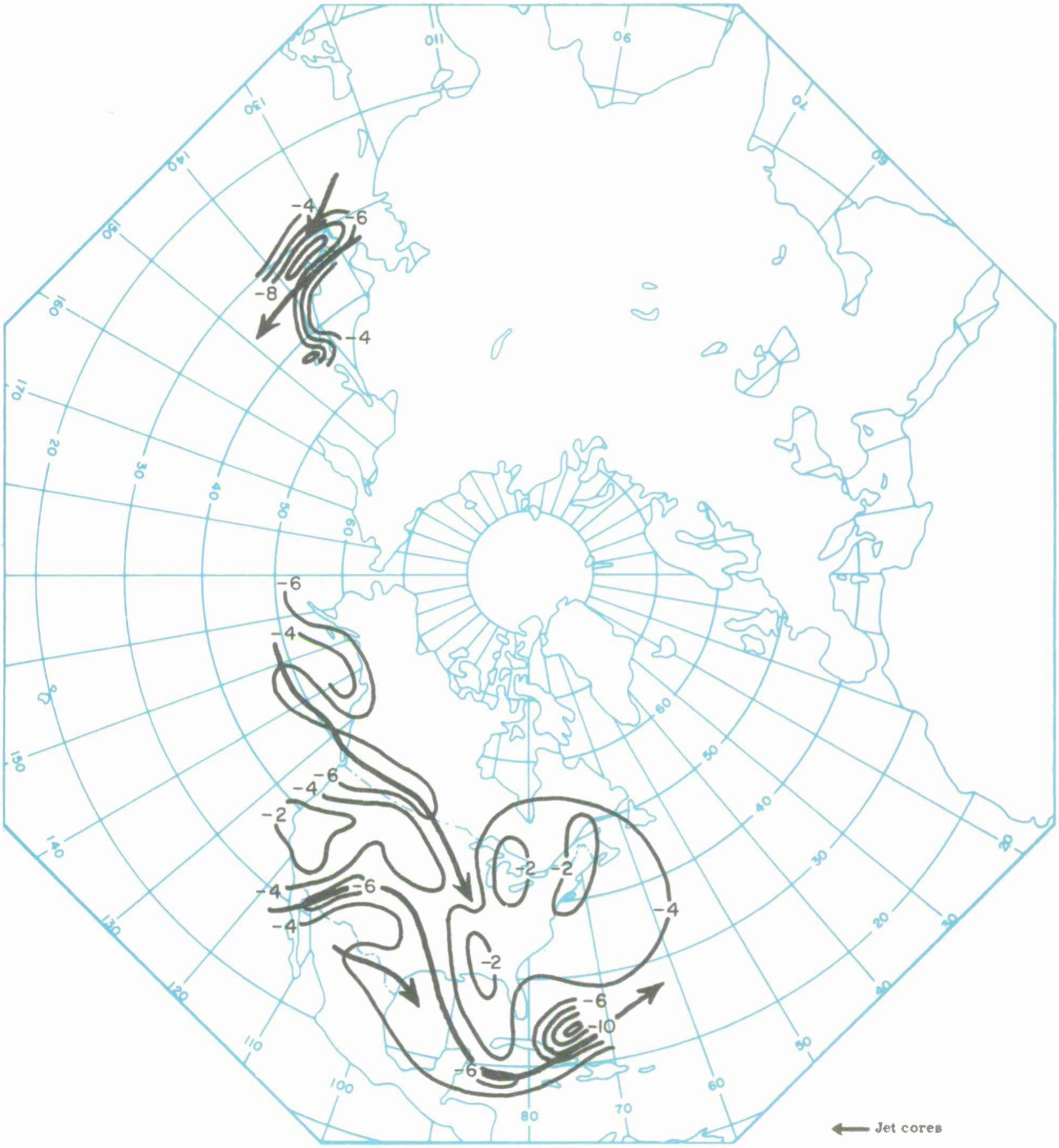

Fig. 14(b). Subjective vector shear above the LRMW, 1200Z, 3 January 1963.

TABLE XIII
LRMW VERSUS LMW COMPARISON: CATEGORY A ($W_{sM} > 100$ knots)
INITIAL-GUESS VERIFICATION STATISTICS

Date	Analysis LRMW	Station rms error LMW	Withheld station rms error	
			LRMW	LMW
Jan 1	14.3	22.3	20.2	23.4
Jan 2	16.3	22.1	11.9	17.3
Jan 3	27.1	27.1	9.2	19.7
Jan 4	19.3	22.4	21.2	20.2
Jan 5	16.5	24.4	20.3	26.3
Jan 6	18.2	21.2	21.1	26.3
Jan 7	18.7	28.0	13.9	15.6
Jan 8	15.0	30.0	13.2	23.6
Jan 9	5.8	7.6	18.4	19.8
Jan 12	13.7	27.0	18.8	20.7
Jan 13	15.2	21.4	14.0	11.0
Jan 14	15.2	19.7	13.5	19.6

entirely due to a value at one grid point that is in considerable variance with the surrounding grid points. The average of the four points surrounding the central point, for each of the four areas of strong gradients, is > 11,000 ft different than the value for the central point. It is very likely that these are instances where the wrong category equation is used, as discussed in Sections II and III. The analyses over these areas can be subjectively (or objectively) adjusted to be more consistent with the surrounding grid points and a high degree of confidence may be placed in the adjusted analysis if the strong gradient is due to a single grid point value (as it is for these cases).

5.3 Consistency between LRMW Parameters

A study of the LRMW objective analyses showed that they were consistent with one another. For example: (a) the maximum vertical shears correspond closely to the jet cores [Figs. 13 (a) and 14 (a)]; (b) the mean height of the LRMW is at low elevation for the mid- and high-latitude polar jets (as well as for polar jets at the lower end of deep troughs that extend into the subtropics) [Fig. 12(a)],and (c) the mean height of the LRMW is at higher elevations for subtropical jets in the lower latitudes (as well as for jets located to the north of mid- or high-latitude anticyclones) [Fig. 12(a)].

The problem of low shear values sometimes appearing near jet cores in the analysis of the LMW parameters [6] was largely eliminated by the specification of shears below and above the <u>LRMW</u> instead of below and above the LMW. (The LMW was difficult to specify in cases of thick vertical layers of high wind speed, and either the shear below, above, or both were sometimes computed to be relatively low values depending on where in the layer the level of maximum wind was specified.)

The thickness of the LRMW is usually $<$ 10,000 ft near the jet cores for the series of maps, and thickness maxima are often located between two jet cores; this is in agreement with what is known to occur. For example, over the north central U.S. on January 3, 1963 at 1200Z there is a polar jet core [$\overline{Z}$(LR) ~ 32,000 ft] and the subtropical jet is located over the south-central U.S. and extends into the Central Gulf of Mexico [$\overline{Z}$(LR) ~ 40,000 ft]. The thickness of the LRMW shows minima (~ 8,000 ft) along both cores and a maximum of 16,000 ft between the two cores, probably indicating the presence of both jets in this area, with the $\overline{Z}$(LR) at about 36,000 ft.

On the wind speed maximum analysis charts, the generated observations along the jet cores tend to elongate the maximum wind isotachs from those isotachs on the initial-guess chart. The purpose of the generated observations is to give a better representation of the wind field in the vicinity of the jet. In some areas on some charts in the series, withheld-station observations near jet cores permitted a check on whether this was being carried out. It was determined that for most cases the generated observations did give a better representation of the wind field.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

The definition and objective analysis of a layer of maximum wind (LRMW) and its associated parameters of wind speed maximum, thickness, mean height, and vector shears below and above the LRMW leads to a realistic three-dimensional picture of the jet stream.

The categorization procedures for wind profiles that result in nine jet-stream categories for which initial-guess regression equations were derived provide high quality initial-guess fields for the LRMW parameters.

A significant improvement is achieved in the initial-guess specification of the wind speed maximum, in areas where the speed exceeds 100 knots, over that given by the level of maximum wind (LMW) equations [6]. This is due to the refinement in the categorization procedure that includes an estimated thickness of the LRMW as part of the definition criteria.

Tests of the LRMW equations on independent data indicate that they are stable and capable of specifying very well the general characteristics of the LRMW profile.

The ability of the analysis technique to locate jet cores and generate "observations" along core segments results in better definition of the wind field in the vicinity of the jet stream than that given by the initial-guess "analysis". Over the data areas, where a comparison between objective and subjective analyses can be made, the objective LRMW analyses compare favorably with the subjective analyses.

Because the LRMW initial-guess regression equations require constant-pressure-surface information to specify the LRMW parameters, they are purely diagnostic equations, but may be used with prognostic fields to produce jet-stream predictions.

It is recommended that the LRMW diagnostic equations be applied to a series of prognostic constant-pressure-surface fields obtained from an operational numerical model. The resulting LRMW predictions should be verified and evaluated. If they are satisfactory, the equations can provide a relatively simple prediction technique for the LRMW parameters.

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APPENDIX

LRMW INITIAL-GUESS EQUATIONS

CATEGORY 1: NO JET

$$W_{sM} = 12.865 + 0.39483[W_s(2)] + 0.38694[W_s(3)] + 0.28719[W_s(1)]$$

$$\vec{S}_b = 1.4408 - 0.054367[W_s(5\text{-}M)] - 0.038540[W_s(2\text{-}M)] - 0.020353[W_s(3\text{-}M)]$$

$$\vec{S}_a = 0.17568 + 0.042254[W_s(1\text{-}M)] + 0.054752[W_s(2\text{-}M)] + 0.026165[T(1)]$$

CATEGORY 2: MODERATE SUBTROPICAL JET

$$W_{sM} = 9.8839 + 0.87219[W_s(2)] + 0.15047[W_s(1)]$$

$$h(LR) = -2969.4 + 0.68185h_e + 3.8081[h(3\text{-}2)]$$

$$\overline{Z}(LR) = 4156.5 + 7.6357[W_s(1)] - 6.5161[W_s(3)] + 12.964[T(5)] + 0.22620[h(LR)] - 11.49[W_s(2)] + 9.2997[W_{sM}]$$

$$\vec{S}_b = 12.569 - 0.11389[W_s(3\text{-}M)] - 0.0028825[\overline{Z}(LR)] - 0.036523[W_s(5)] + 0.0010659[h(LR)]$$

$$\vec{S}_a = 8.2556 - 0.09569[W_{sM}] + 0.092069[W_s(1)] - 0.0021269[\overline{Z}(LR)]$$

CATEGORY 3: STRONG SUBTROPICAL JET

$$W_{sM} = 17.385 + 0.90854[W_s(2)]$$

$$h(LR) = 1302.2 + 0.70960h_e + 18.102[T(2)]$$

$$\overline{Z}(LR) = 3899.9 + 45.540[\Delta T/\Delta n(2\text{-}1)] - 4.7480[W_s(3\text{-}M)] + 0.19228[h(LR)] + 7.9590[T(5)]$$

$$\vec{S}_b = -1.0689 + 77.530S_3 + 0.0019941[h(LR)] - 0.037482[W_s(5\text{-}M)] - 0.02065[W_s(3)]$$

$$\vec{S}_a = 15.124 - 0.093949[W_{sM}] + 0.083590[W_s(1)] - 0.00368[\overline{Z}(LR)]$$

CATEGORY 4: SINGLE, MODERATE SUBTROPICAL—POLAR JET

$$W_{sM} = 6.8307 + 0.49099[W_s(2)] + 0.55503[W_s(3)] + 0.15625[W_s(1)]$$

$$h(LR) = 706.54 + 16.776[W_s(2\text{-}M)] + 8.5505[W_s(3)] - 4.1051[W_s(2)]$$

$$\overline{Z}(LR) = 4034.5 + 26.611[T(5)] + 9.3408[W_s(1)] - 22.734[W_s(3)] + 20.991[W_s(2)] - 5.1075[W_s(5)]$$

$$\vec{S}_b = 6.6065 - 0.02205[\Delta W(5\text{-}3)] - 0.0017313[\overline{Z}(LR)] + 0.094231[W_{sM}] - 0.10067[W_s(5)]$$

$$\vec{S}_a = -0.48251 + 50.086S_1 + 0.033009[W_s(1\text{-}M)] + 0.03936[W_s(3\text{-}M)]$$

CATEGORY 5: SINGLE, STRONG SUBTROPICAL—POLAR JET

$$W_{sM} = 12.373 + 0.67147[W_s(3)] + 0.42204[W_s(2)]$$

$$h(LR) = 529.61 + 0.40014h_e + 4.2752[W_s(2\text{-}M)]$$

$$\overline{Z}(LR) = -\,1389.7 + 4.5992[h(5-3)] + 14.266[\Delta W(3-2)] - 0.35100[h(LR)] + 53.791[\Delta T/\Delta n(2-1)]$$

$$\vec{S}_b = -\,0.36367 + 108.92S_5 - 0.032949[W_s(2\text{-}M)]$$

$$\vec{S}_a = 6.2663 + 77.157S_1 + 0.13921\,[T(2)] + 0.044702[W_s(3\text{-}M)]$$

CATEGORY 6: MULTIPLE, MODERATE SUBTROPICAL—POLAR JET

$$W_{sM} = 6.3829 + 0.50841[W_s(2)] + 0.43791[W_s(3)] + 0.11974[W_s(1)]$$

$$h(LR) = 1363.0 + 0.24537h_e + 3.1464[\Delta W(7-5)] + 2.5430[W_s(1\text{-}M)]$$

$$\overline{Z}(LR) = 4014.6 - 11.804[W_s(5)] + 10.889[W_s(1)] + 16.757[T(5)] - 23.391[W_s(3)] + 22.043[W_s(2)]$$

$$\vec{S}_b = 6.8636 + 126.47S_5 + 0.0011678[h(LR)] - 0.0012614[\overline{Z}(LR)] - 0.02789[W_s(7)] + 0.053647[T(3)]$$

$$\vec{S}_a = -\,0.85393 + 129.06S_1$$

CATEGORY 7: MULTIPLE, STRONG SUBTROPICAL—POLAR JET

$$W_{sM} = 11.248 + 0.50325[W_s(2)] + 0.48457[W_s(3)]$$

$$h(LR) = -\,1079.1 + 0.42786h_e + 2.9815[W_s(5)] + 2.8140[\Delta W(2-1)] + 2.3720[h(3-2)]$$

$$\overline{Z}(LR) = -\,402.90 + 18.137[\Delta W(3-2)] + 4.1145[h(7-5)] + 2.7292[W_s(1)] - 4.3702[W_s(5)] + 0.29092[h(LR)] - 13.770[W_s(2\text{-}M)]$$

$$\vec{S}_b = 9.7026 + 0.084459[\Delta W(5-3)] - 0.0023900[\overline{Z}(LR)]$$

$$\vec{S}_a = 0.29497 + 221.09S_1 - 0.055363[W_s(1\text{-}M)] - 0.015380[W_s(5)]$$

CATEGORY 8: MODERATE POLAR JET

$$\begin{aligned}
W_{sM} &= 3.4559 + 1.0407[W_s(3)] \\
h(LR) &= 176.37 + 0.57071h_e + 4.9137[W_s(5)] \\
\bar{Z}(LR) &= 2988.4 + 25.356[T(5)] - 8.8904[W_s(5\text{-}M)] + 4.0343[W_s(1\text{-}M)] \\
&\quad - 9.0366[T(2)] \\
\vec{S}_b &= -0.59366 + 111.33S_5 + 0.0017857[h(LR)] \\
\vec{S}_a &= 0.71950 + 0.11020[W_s(2)] - 0.094667W_{sM} - 0.0013345[\bar{Z}(LR)] \\
&\quad + 0.020708[W_s(1)]
\end{aligned}$$

CATEGORY 9: STRONG POLAR JET

$$\begin{aligned}
W_{sM} &= 9.7510 + 0.97260[W_s(3)] \\
h(LR) &= -1635.3 + 0.64580h_e + 2.9689[\Delta W(3\text{-}2)] + 1.8193[h(5\text{-}3)] \\
\bar{Z}(LR) &= 3566.6 + 21.726[T(5)] - 4.6704[W_s(5)] + 3.7669[W_s(2)] \\
\vec{S}_b &= -3.6220 + 152.50S_5 + 0.0027131[h(LR)] \\
\vec{S}_a &= 1.1766 + 0.12513[W_s(2\text{-}M)] + 188.36S_1 - 0.064509[W_s(1\text{-}M)]
\end{aligned}$$

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13. ABSTRACT

An objective layer of maximum wind (LRMW) analysis technique is described and evaluated. The evaluation indicates that the technique represents a significant improvement over the previously developed level of maximum wind (LMW) analysis technique [Spiegler, D. B., and J. T. Ball, et al., 1965: Techniques for objective hemispheric analysis and prediction of the jet stream. Technical Report 7463-176 (ESD-TR-65-13), The Travelers Research Center, Inc.].

A categorization procedure for wind profiles that results in nine jet stream categories is designed and used for the derivation of regression equations that supply the initial-guess fields for each of five LRMW parameters. The stratification of the profiles into nine categories is a refinement of the previous seven categories developed for the LMW analysis technique. The initial-guess LRMW equations are stable in tests with independent data and are capable of specifying, very well, the general characteristics of the LRMW profile. They also provide realistic values for the LRMW parameters over no-data areas that are consistent with the entire analysis area.

The analysis technique locates jet cores between grid points and generates observations along these cores by using models of horizontal jet profiles.

Thickness of the LRMW as one of the analysis fields in conjunction with the wind-speed maximum, mean height of the LRMW, and vector shears below and above the LRMW enable the generation of a three-dimensional picture of the wind field in the vicinity of the jet stream.

Over the data areas, where a comparison between objective and subjective analyses can be made, the objective LRMW analyses compare favorably with the subjective analyses.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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