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CEDAR Prize Lecture

by Gary Swenson
University of Illinois

A Model for Calculating Acoustic Gravity Wave Energy and Momentum Flux in the Mesosphere from OH Airglow

CEDAR TUTORIAL, June 8, 1998.

"A model for calculating Acoustic Gravity Wave energy and momentum flux in the mesosphere from OH airglow"

Swenson, G. and A.Z. Liu, GRL, 25, 477, 1998.
{University of Illinois, Urbana, IL 61801; swenson1@uiuc.edu}

* Vertical flux of horizontal momentum, $F_M \propto \frac{\lambda_Z}{\lambda_X}\left\langle\left(\frac{T'}{\bar{T}}\right)^2\right\rangle$

* OH Airglow, Dynamic Response to AGWs

$$\frac{\rho'}{\rho} = -\frac{T'}{T}, \quad \left|\frac{I'/I}{\rho'/\rho}\right| \sim 3 \Rightarrow \text{CF (for large } \lambda_z)$$

[Swenson and Gardner, JGR-Atmospheres, 103, 6271, 1998]

* Starfire 95' Data- 5 nights (2/2, 2/3, 4/1, 4/2, 4/4, 1995)

-161 Waves, Intrinsic Parameters

λ_x=28.8 km

C_o=33.4 m/s, C_I=61.4 m/s

τ_I=7.8 minutes

λ_z=26.6 km

I'/I=3.8%

$|F_M|=21.9\ m^2s^{-2}$

$F_{M.ZONAL}=-5.3\ m^2s^{-2}$, $F_{M.MERIDIONAL}=6.1\ m^2s^{-2}$

[Swenson, Haque, Yang and Gardner, JGR, Submitted, 1998]

* Summary and 'Where do we go from here?'

$$\rho'/\rho \simeq \underline{\varepsilon\, e^{\beta(z - z_{OH})}} \cos\,[\omega t - kx + m(z - z_{OH})]$$

where,

ρ' is the change to ρ, the undisturbed mass density,

ε is the wave amplitude at altitude z_{OH} (88 km),

<u>$1/\beta$ is the amplitude growth length (= $2H$ for undamped waves),</u>

ω is the intrinsic frequency,

$m = 2\pi/\lambda_z$ is the vertical wave number,

$k = 2\pi/\lambda_x$ is the horizontal wave number,

λ_z is the vertical wavelength, and

λ_x is the horizontal wavelength.

$$\mathbf{F}_E = \frac{-\rho_o \lambda_{\mathbf{z}}^2}{\lambda_{\mathbf{x}} \tau_{BV}} \frac{g^2}{\mathbf{N}^2} \left\langle \left(\frac{T'}{\overline{\overline{T}}} \right)^2 \right\rangle \tag{1}$$

$$\mathbf{F}_M = \frac{\lambda_{\mathbf{z}}}{\lambda_{\mathbf{x}}} \frac{g^2}{\mathbf{N}^2} \left\langle \left(\frac{T'}{\overline{\overline{T}}} \right)^2 \right\rangle \tag{2}$$

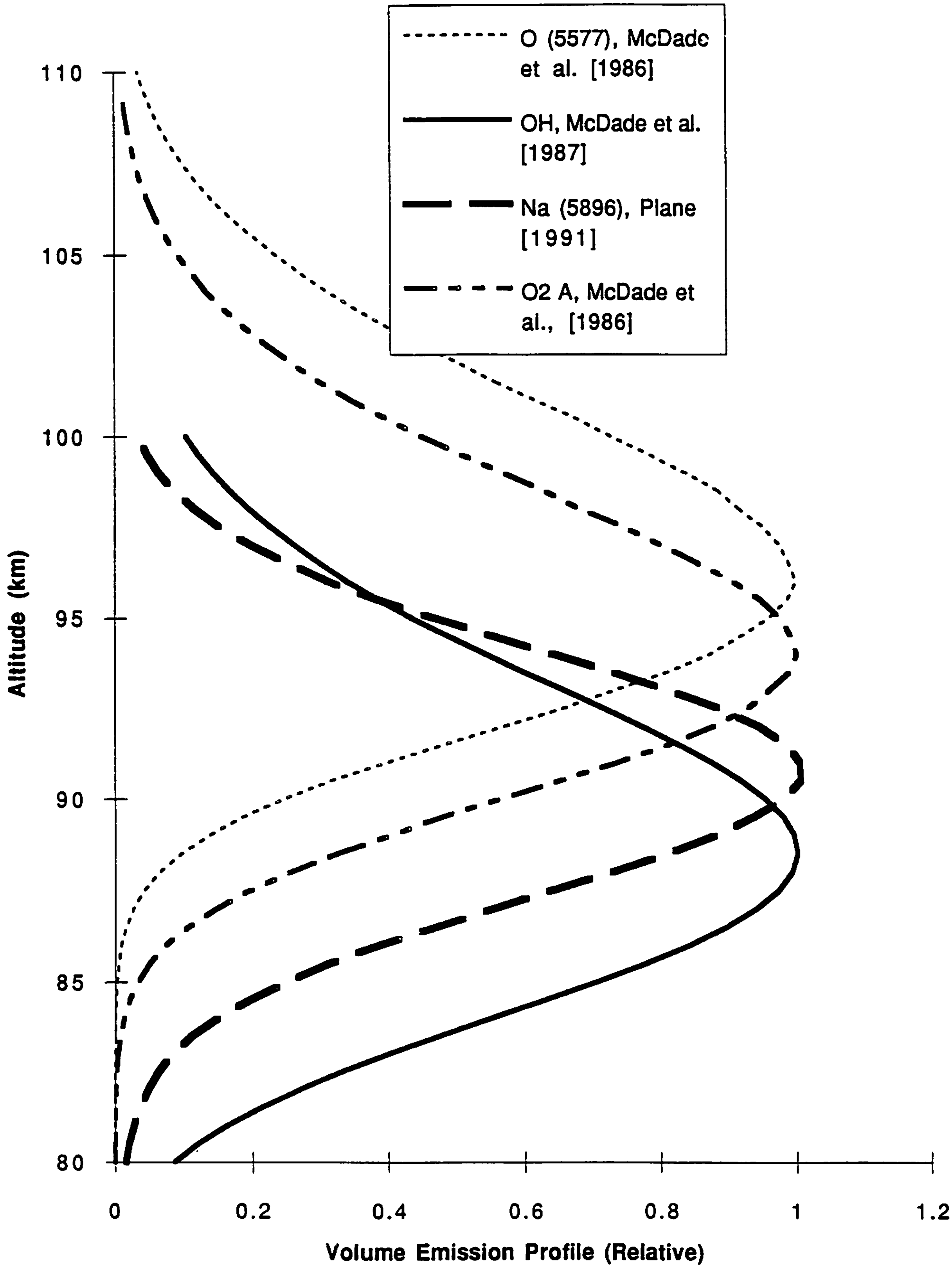
substitute

$$\frac{T'}{T} = \frac{I'_{OH}}{I_{OH}} \cdot \frac{1}{CF} \tag{3}$$

$$\mathbf{F}_{E,87km} = \frac{2.3 \cdot 10^{-3} \lambda_{\mathbf{z}}^2}{\lambda_{\mathbf{x}} \cdot CF^2} \frac{(I'_{OH})^2}{(I_{OH})^2} \quad (W\ m^{-2}) \tag{4}$$

$$\mathbf{F}_{M,87km} = \frac{6 \cdot 10^4 \lambda_{\mathbf{z}}}{CF^2\ \lambda_{\mathbf{x}}} \frac{(I'_{OH})^2}{(I_{OH})^2} \quad (m^2 s^{-2}) \tag{5}$$

$$CF(\lambda_z) = 3.5 - (3.5 - .01) \cdot e^{-.0055 \cdot (\lambda_z(km) - 6)^2} \tag{6}$$


O (5577), McDade et al. [1986]
OH, McDade et al. [1987]
Na (5896), Plane [1991]
O2 A, McDade et al., [1986]
110
105
100
95
90
85
80
Altitude (km)
0
0.2
0.4
0.6
0.8
1
1.2
Volume Emission Profile (Relative)

$$H + O_3 \overset{k_4}{\Rightarrow} OH^* + O_2. \quad (1)$$

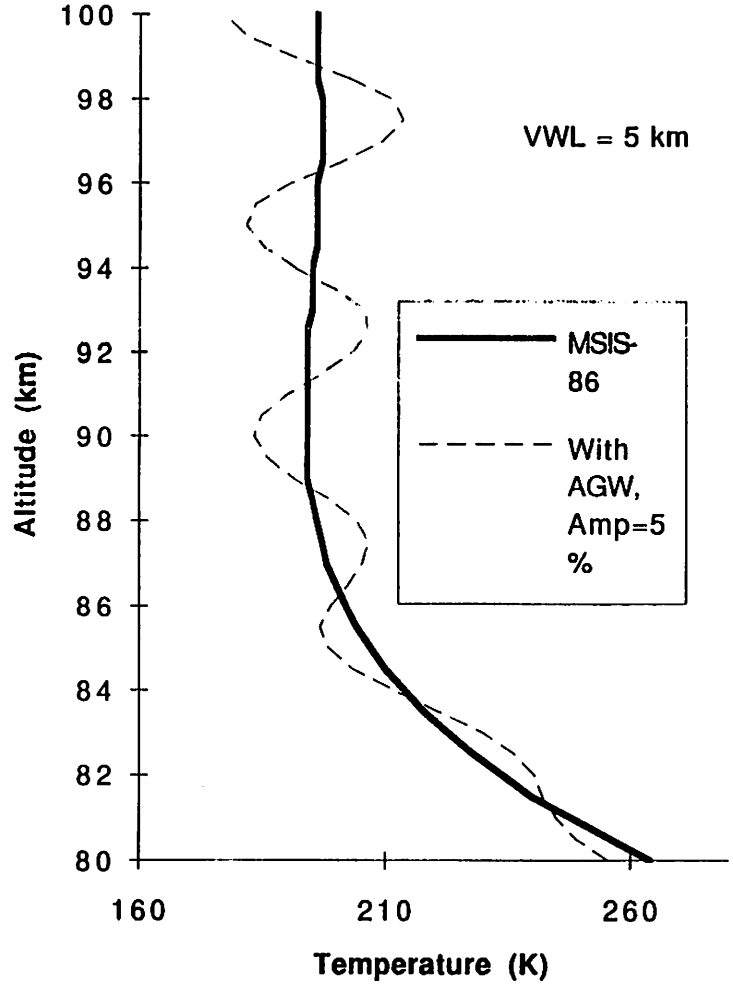
$$V(8,3) = \frac{K_1[O]\,[O_2]^2\,(200/T)^{2.5}}{(1 + 7.7 \times 10^{-14}\ \mathrm{cm}^3\,[O_2])} \quad (2)$$

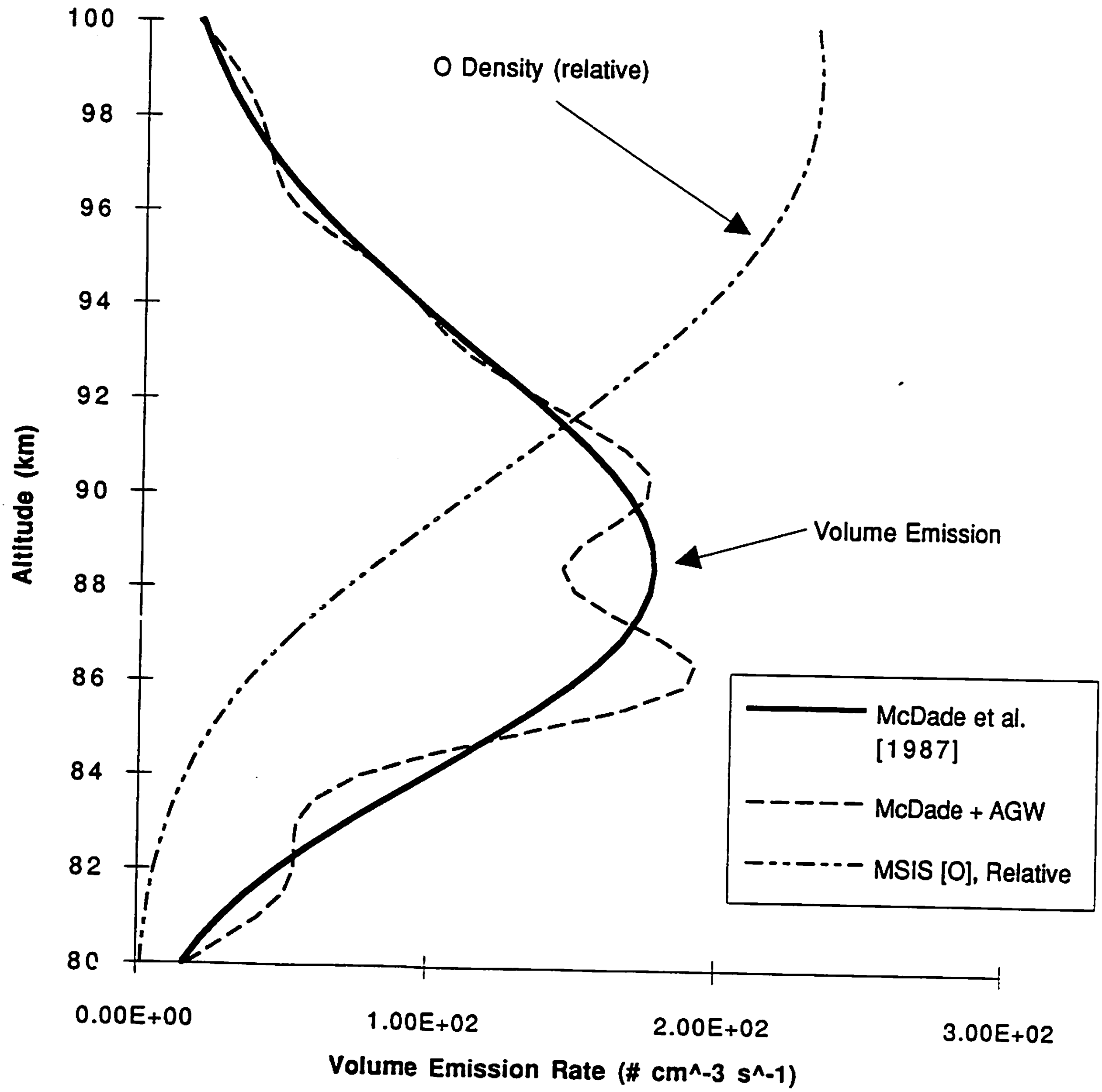
$$\rho'/\rho \simeq \varepsilon\, e^{\beta(z - z_{OH})} \cos\,[\omega t - kx + m(z - z_{OH})] \quad (3)$$

$$m^2 = \frac{(N^2 - \omega^2)}{(\omega^2 - f^2)} k^2 \quad (4)$$

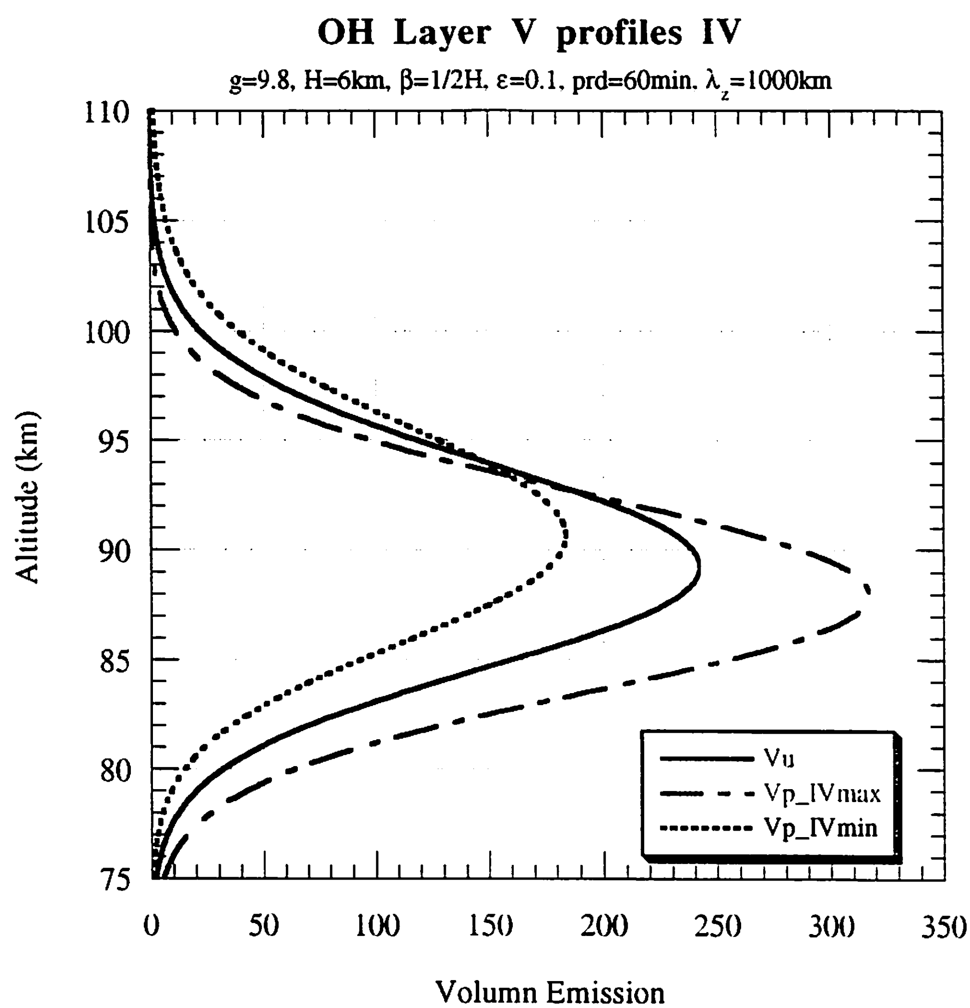
$$\Delta V(8,3) \simeq \quad (5)$$

$$\left(\frac{\Delta[O]}{[O]} + \frac{(2 + 7.7 \times 10^{-14}\,\mathrm{cm}^3[O_2])}{(1 + 7.7 \times 10^{-14}\,\mathrm{cm}^3[O_2])} \frac{\Delta[O_2]}{[O_2]} - 2.5 \frac{\Delta T}{T} \right) V(8,3)$$

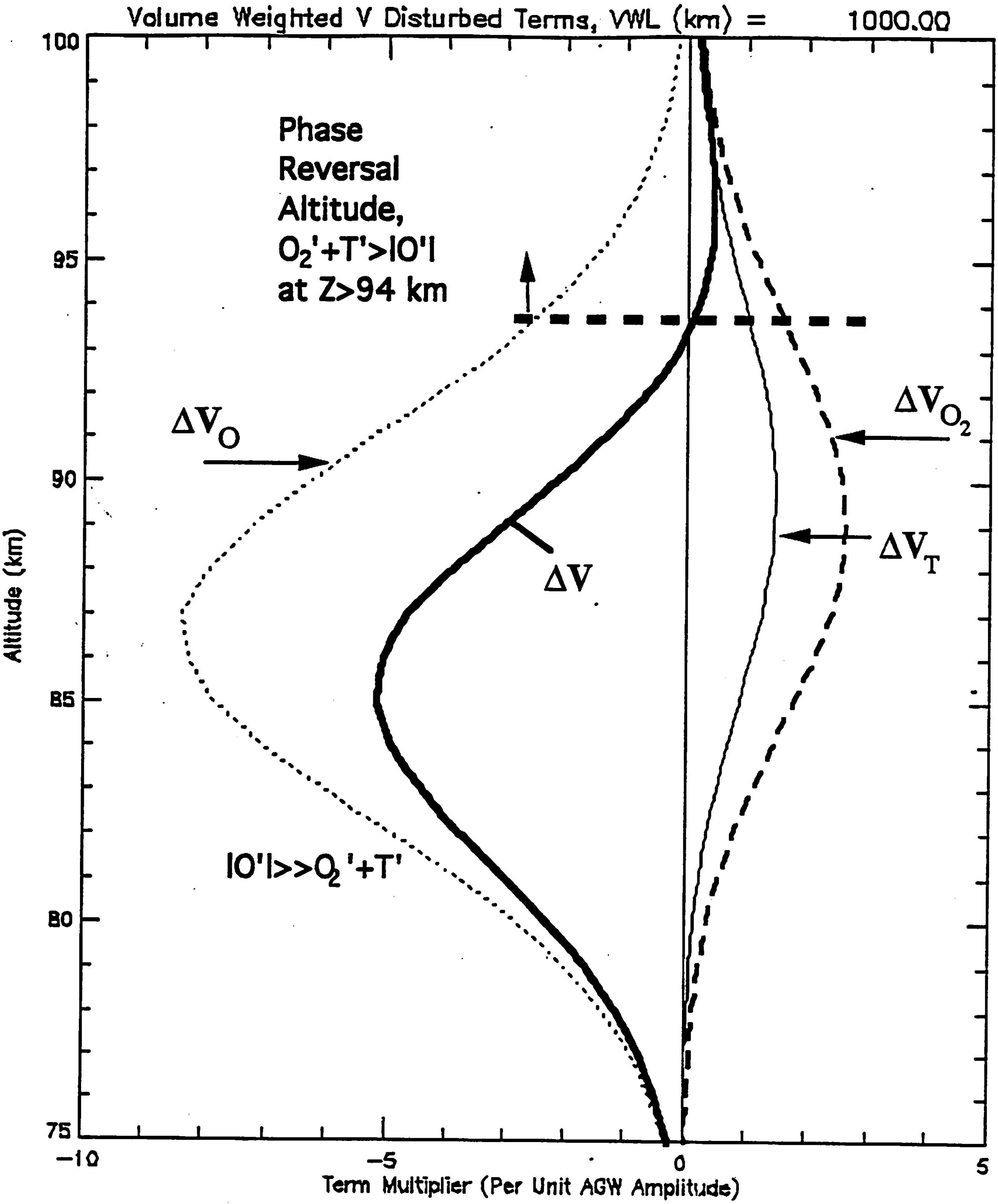

100
98
96
94
92
90
88
86
84
82
80
Altitude (km)
160
210
260
Temperature (K)
VWL = 5 km
MSIS-86
With AGW, Amp=5 %



100
98
96
94
92
90
88
86
84
82
80
Altitude (km)
O Density (relative)
Volume Emission
McDade et al. [1987]
McDade + AGW
MSIS [O], Relative
0.00E+00
1.00E+02
2.00E+02
3.00E+02
Volume Emission Rate (# cm^-3 s^-1)

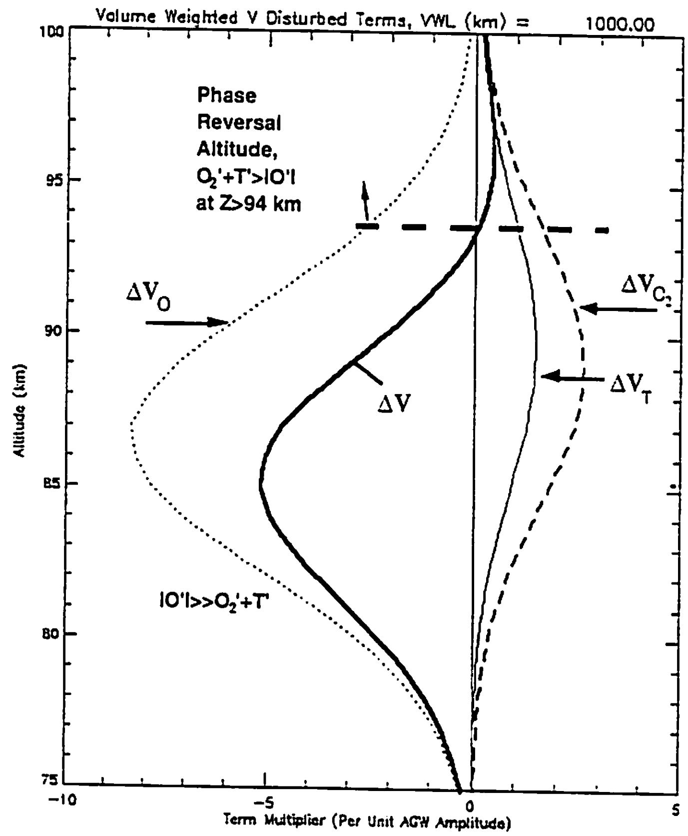


OH Layer V profiles IV
g=9.8, H=6km, β=1/2H, ε=0.1, prd=60min, λz=1000km
110
105
100
95
90
85
80
75
Altitude (km)
0
50
100
150
200
250
300
350
Volumn Emission
Vu
Vp_IVmax
Vp_IVmin



Volume Weighted V Disturbed Terms, VWL (km) = 1000.00
Phase
Reversal
Altitude,
O2'+T'>lO'l
at Z>94 km
ΔVO
ΔV
ΔVO2
ΔVT
lO'l>>O2'+T'
Altitude (km)
Term Multiplier (Per Unit AGW Amplitude)
100
95
90
85
80
75
-10
-5
0
5

(a)


Volume Weighted V Disturbed Terms, VWL (km) = 1000.00
Phase
Reversal
Altitude,
O2'+T'>lO'l
at Z>94 km
ΔVO
ΔVO2
ΔV
ΔVT
lO'l>>O2'+T'
Altitude (km)
Term Multiplier (Per Unit AGW Amplitude)

(b)

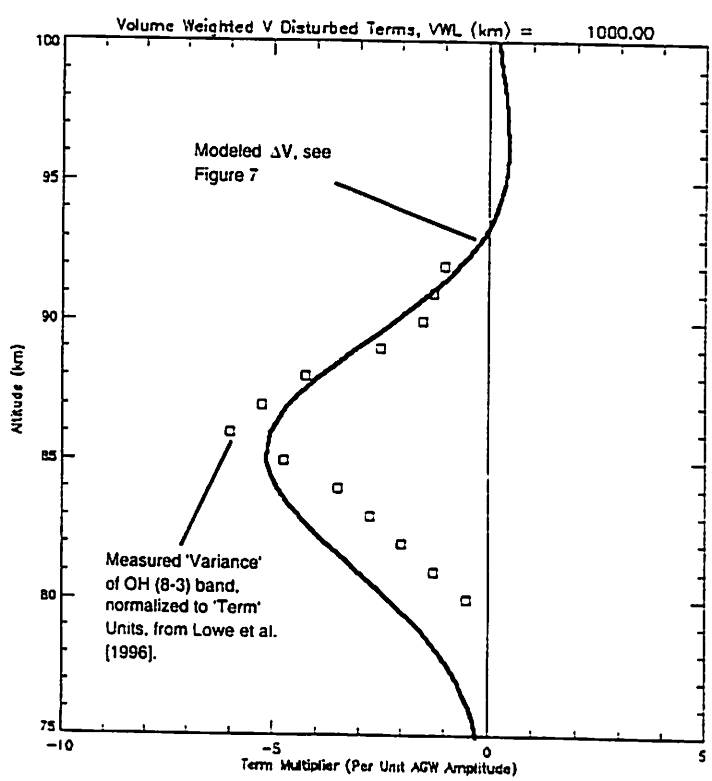
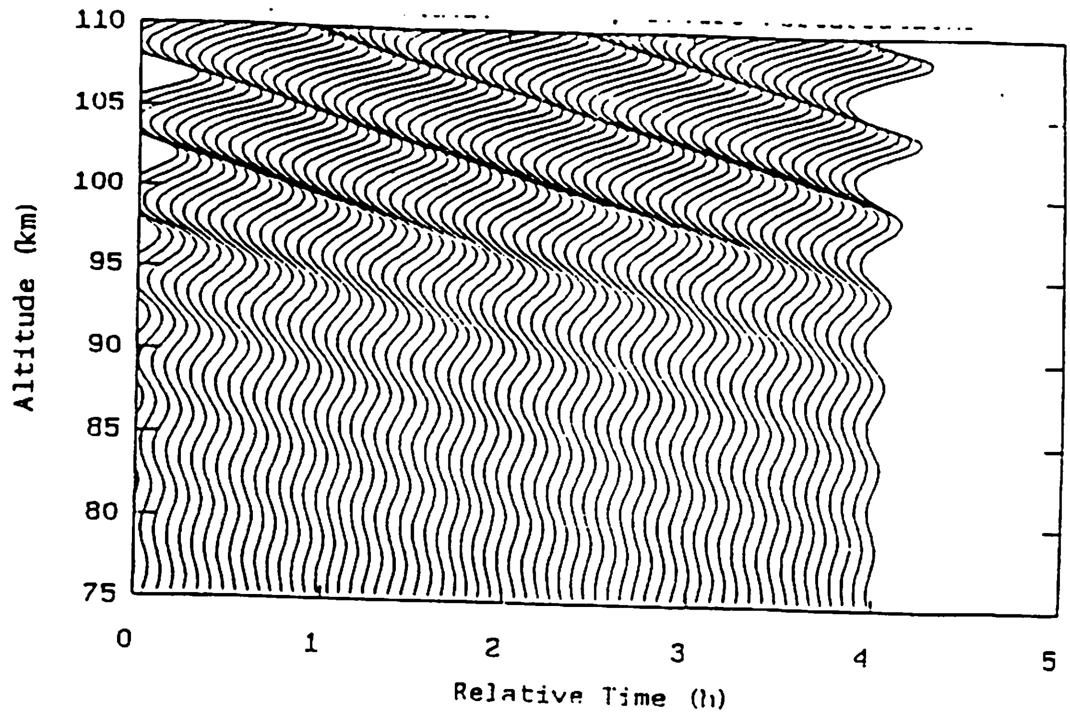
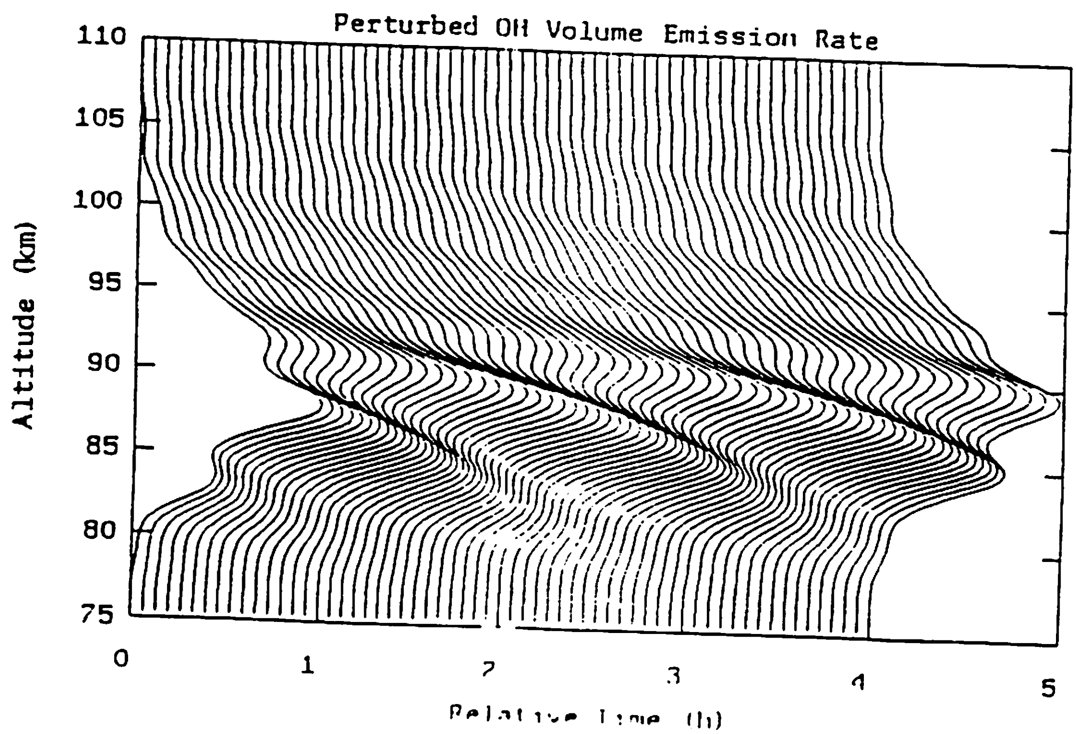
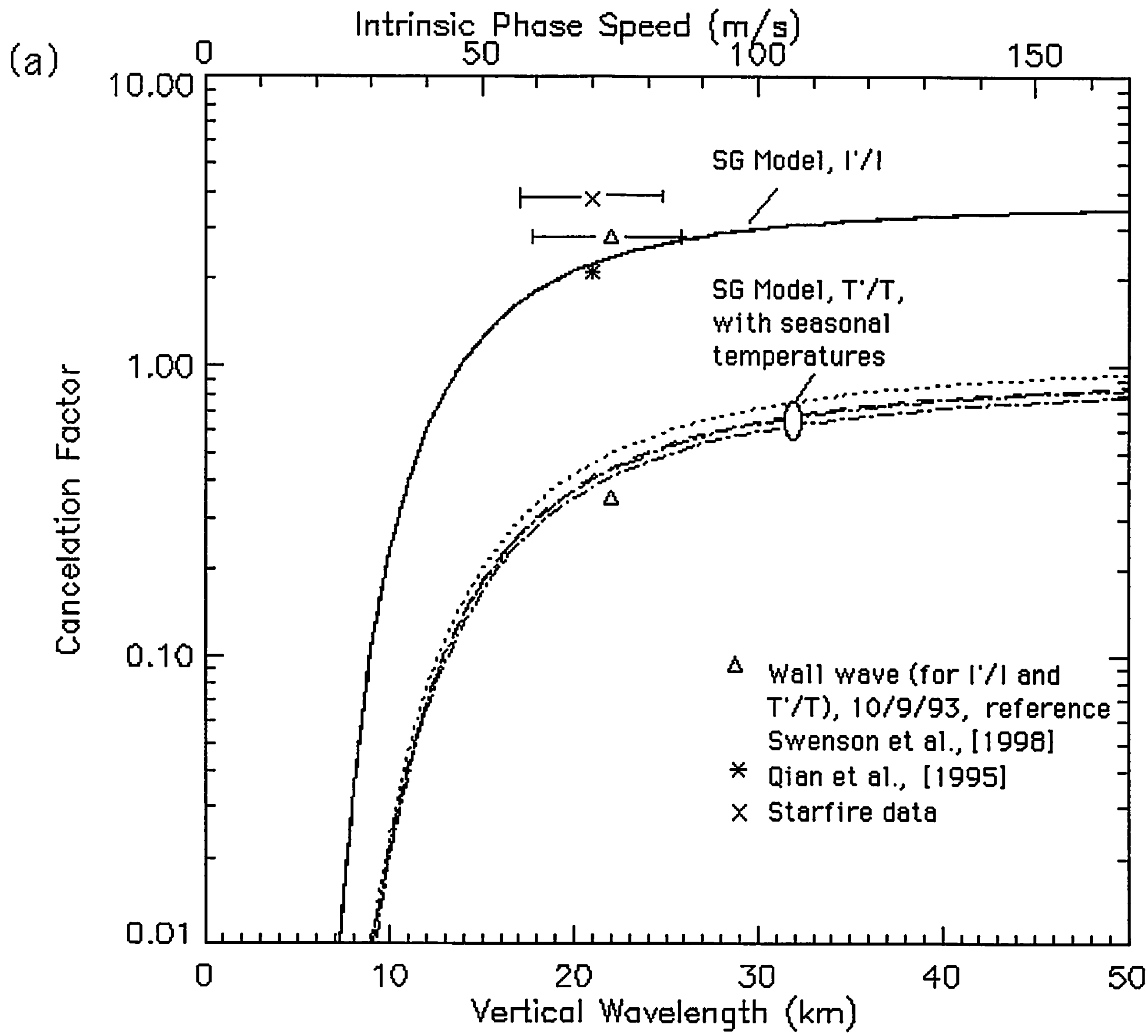

Volume Weighted V Disturbed Terms, VWL (km) = 1000.00
Modeled ΔV, see
Figure 7
Measured 'Variance'
of OH (8-3) band,
normalized to 'Term'
Units, from Lowe et al.
[1996].
Altitude (km)
Term Multiplier (Per Unit AGW Amplitude)

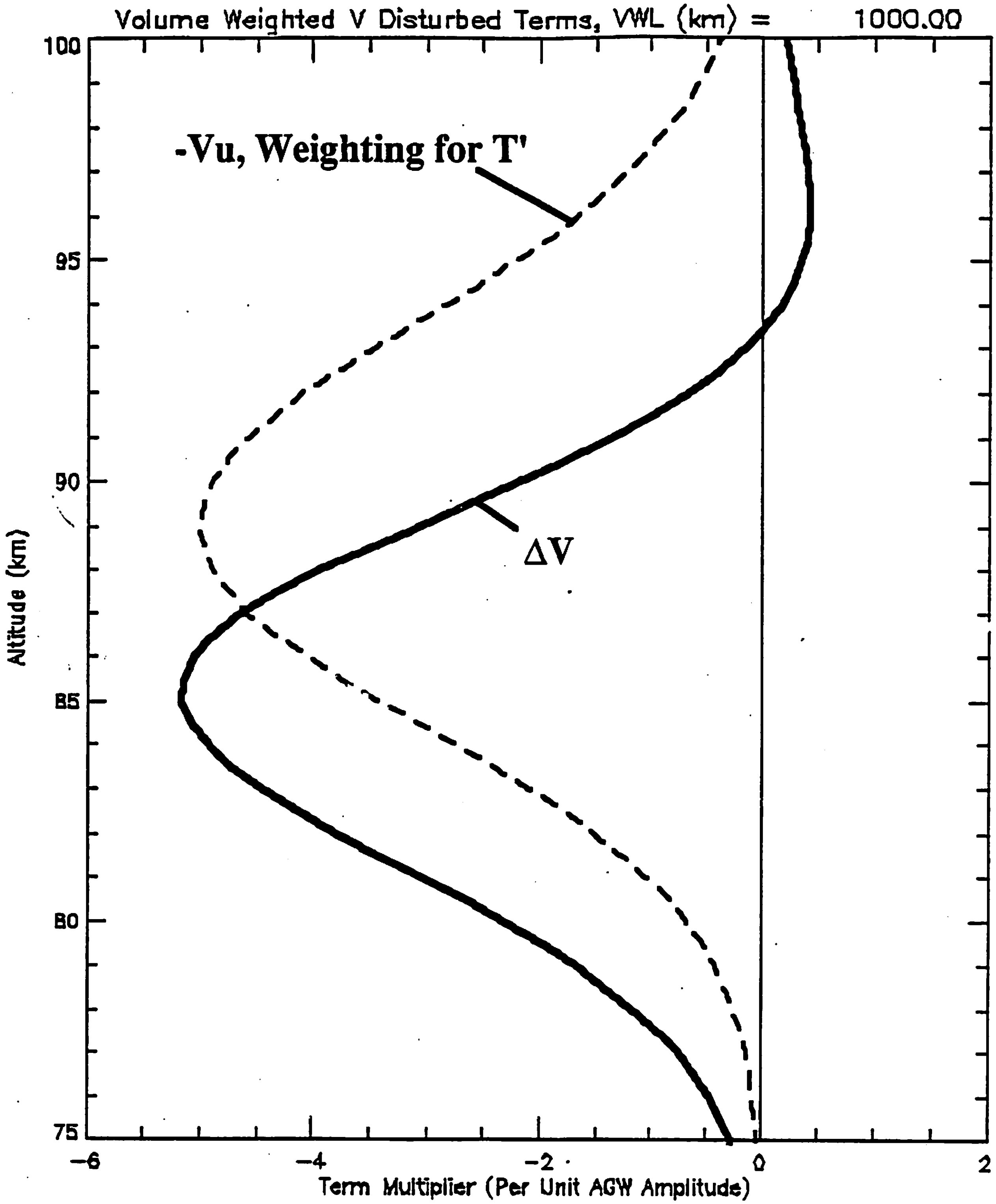
Figure 7


110
105
100
95
90
85
80
75
Altitude (km)
0
1
2
3
4
5
Relative Time (h)

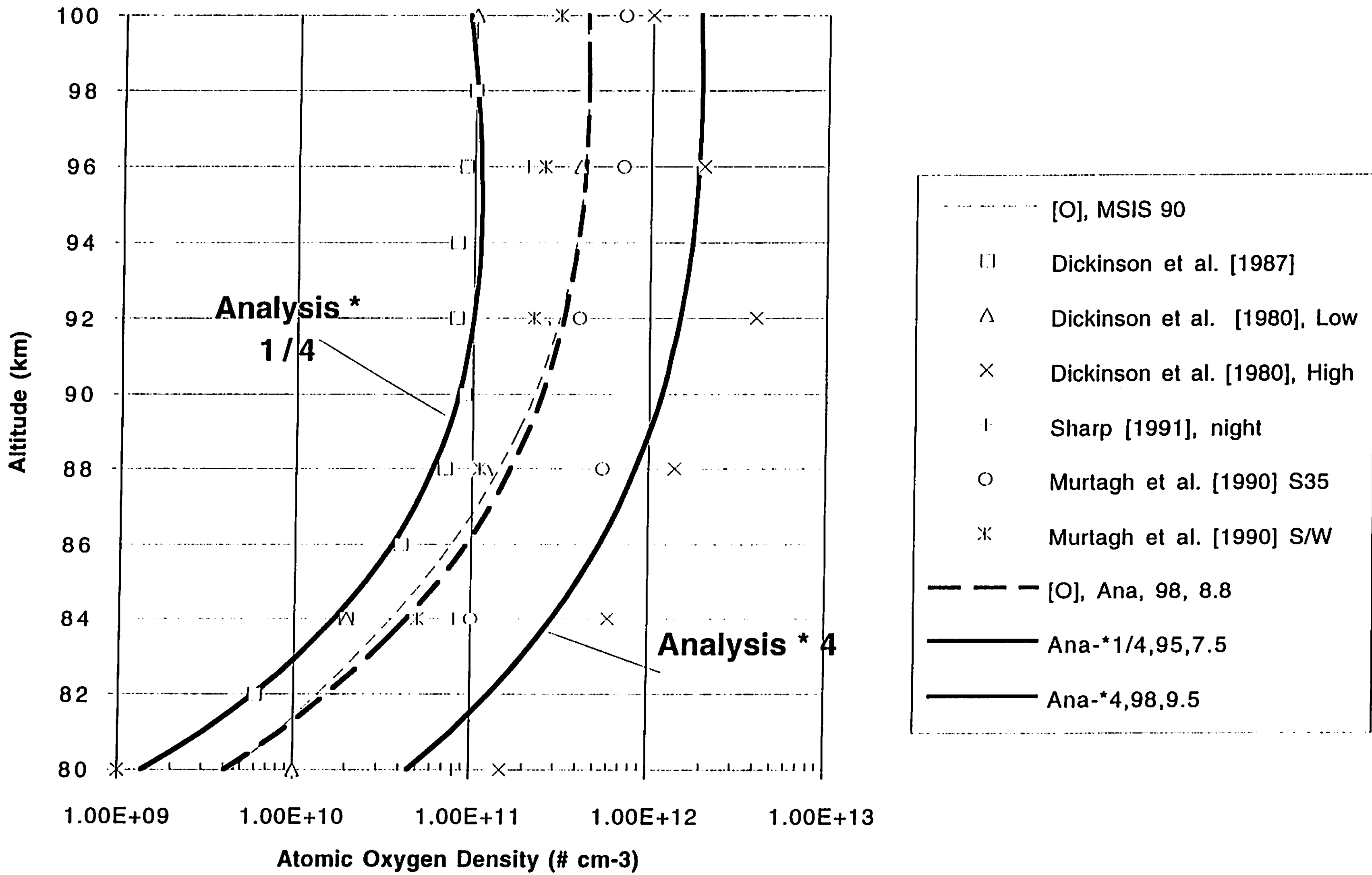

Perturbed OH Volume Emission Rate
110
105
100
95
90
85
80
75
Altitude (km)
0
1
2
3
4
5



(a)
Intrinsic Phase Speed (m/s)
0
50
100
150
10.00
1.00
0.10
0.01
Cancelation Factor
SG Model, I'/I
SG Model, T'/T, with seasonal temperatures
Wall wave (for I'/I and T'/T), 10/9/93, reference Swenson et al., [1998]
Qian et al., [1995]
Starfire data
0
10
20
30
40
50
Vertical Wavelength (km)

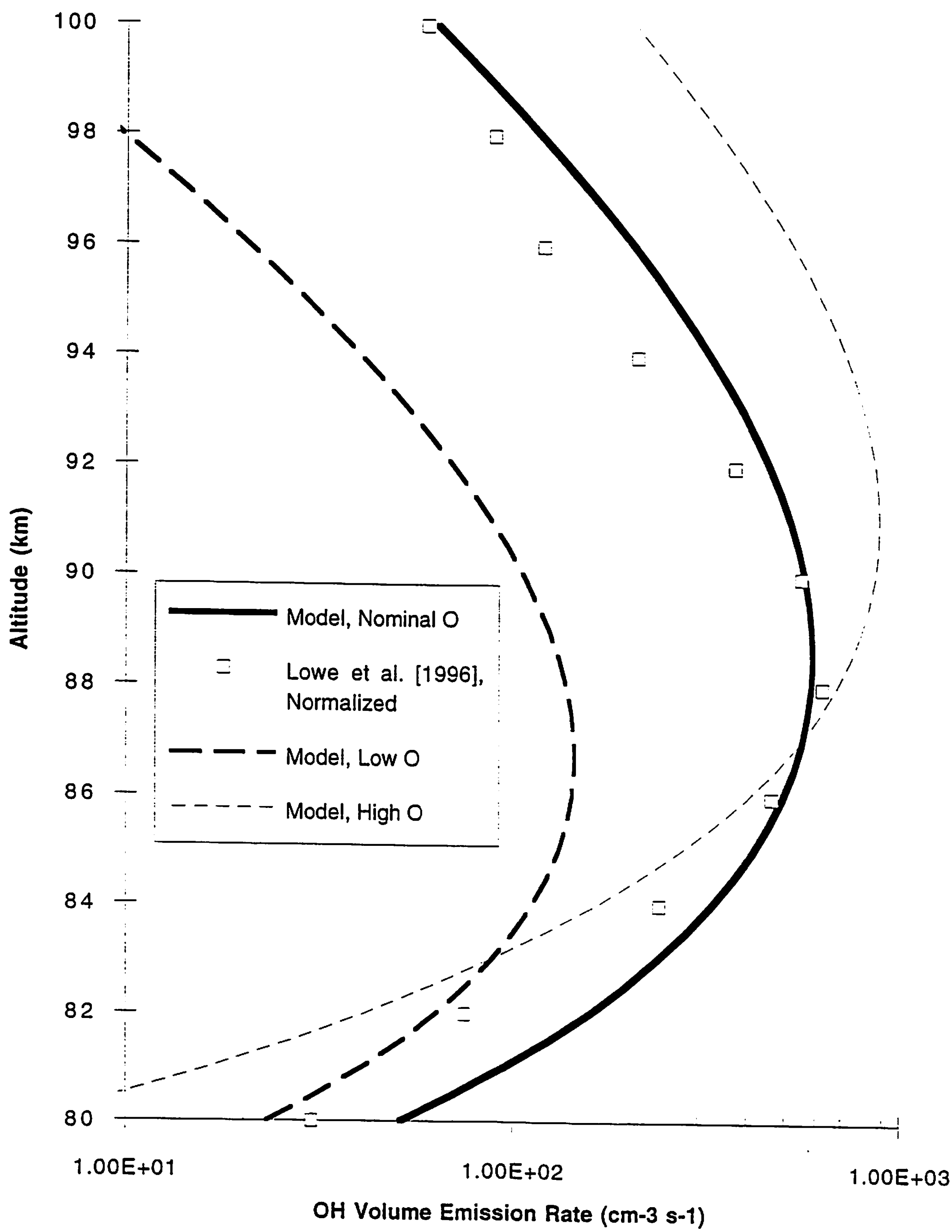


Volume Weighted V Disturbed Terms, VWL (km) = 1000.00
-Vu, Weighting for T'
ΔV
Altitude (km)
100
95
90
85
80
75
−6
−4
−2
0
2
Term Multiplier (Per Unit AGW Amplitude)

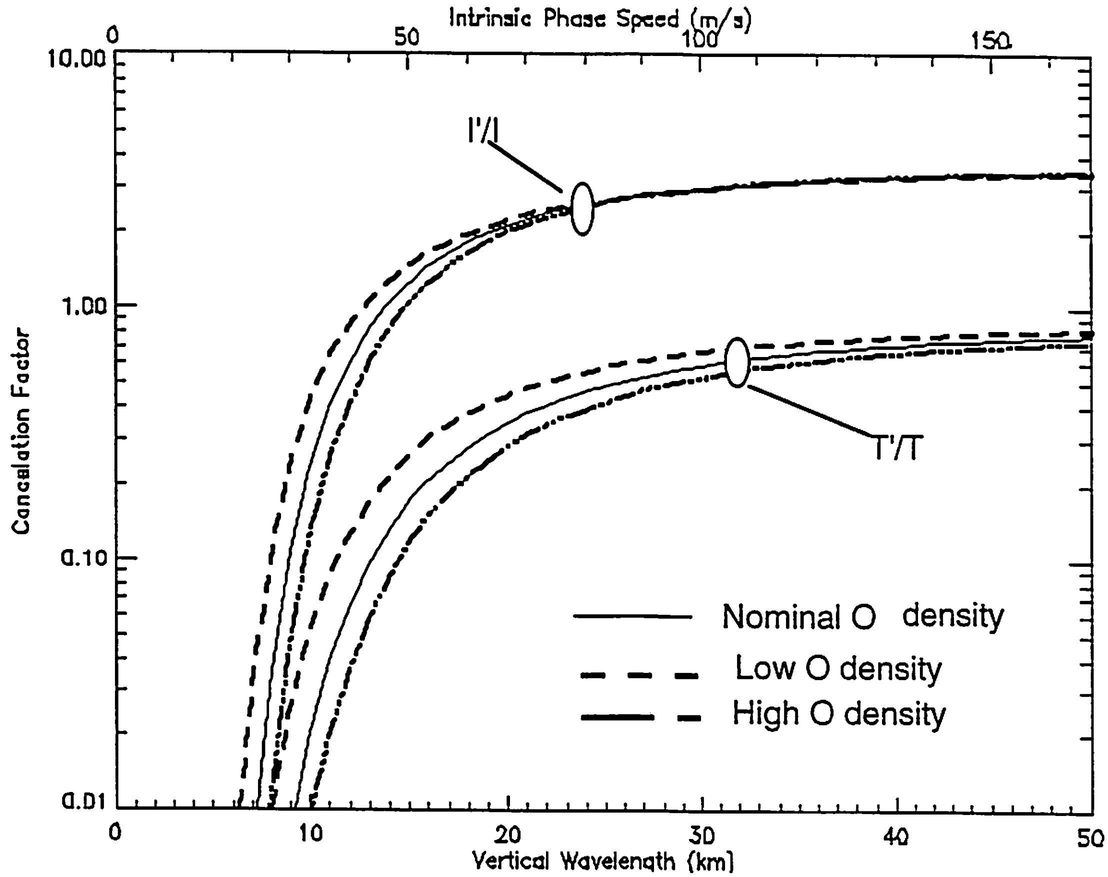


100
98
96
94
92
90
88
86
84
82
80
Altitude (km)
1.00E+09
1.00E+10
1.00E+11
1.00E+12
1.00E+13
Atomic Oxygen Density (# cm-3)
Analysis * 1 / 4
Analysis * 4
[O], MSIS 90
Dickinson et al. [1987]
Dickinson et al. [1980], Low
Dickinson et al. [1980], High
Sharp [1991], night
Murtagh et al. [1990] S35
Murtagh et al. [1990] S/W
[O], Ana, 98, 8.8
Ana-*1/4,95,7.5
Ana-*4,98,9.5

Fig XX, OH extreme, from O

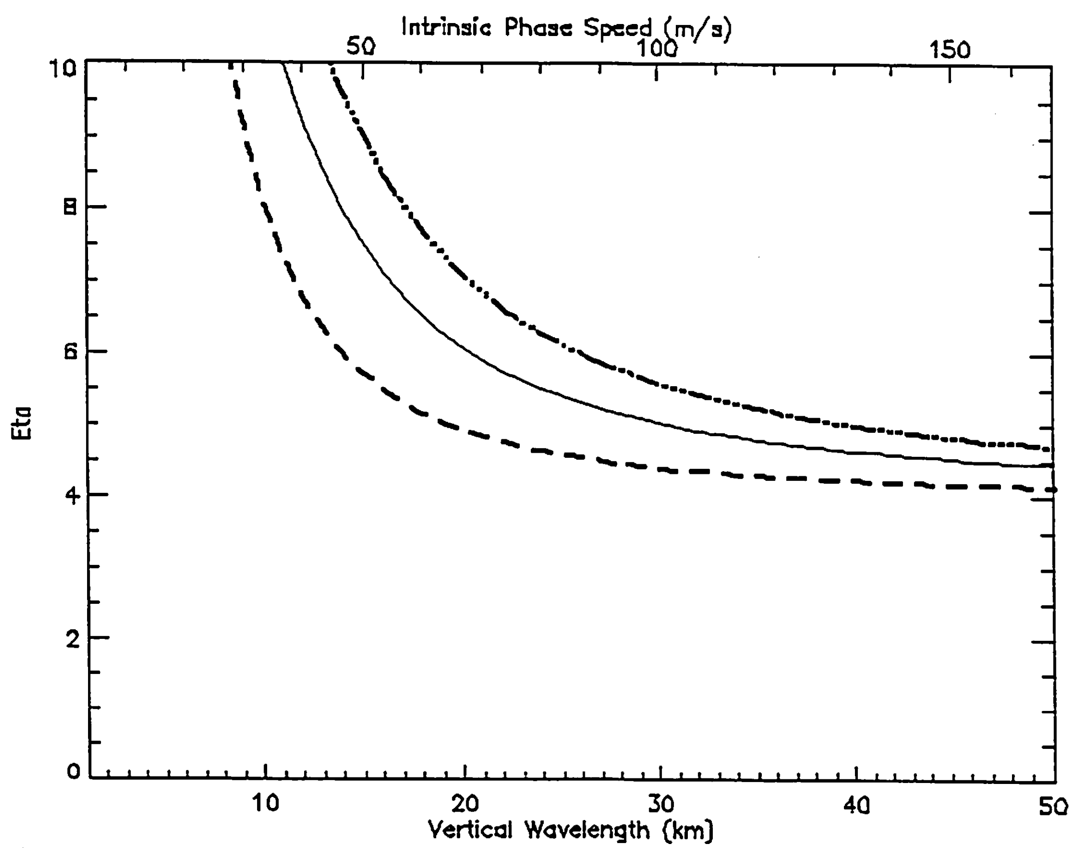


(a)



Intrinsic Phase Speed (m/s)
0
50
100
150
10.00
1.00
0.10
0.01
Cancelation Factor
I'/I
T'/T
Nominal O density
Low O density
High O density
0
10
20
30
40
50
Vertical Wavelength (km)

(b)



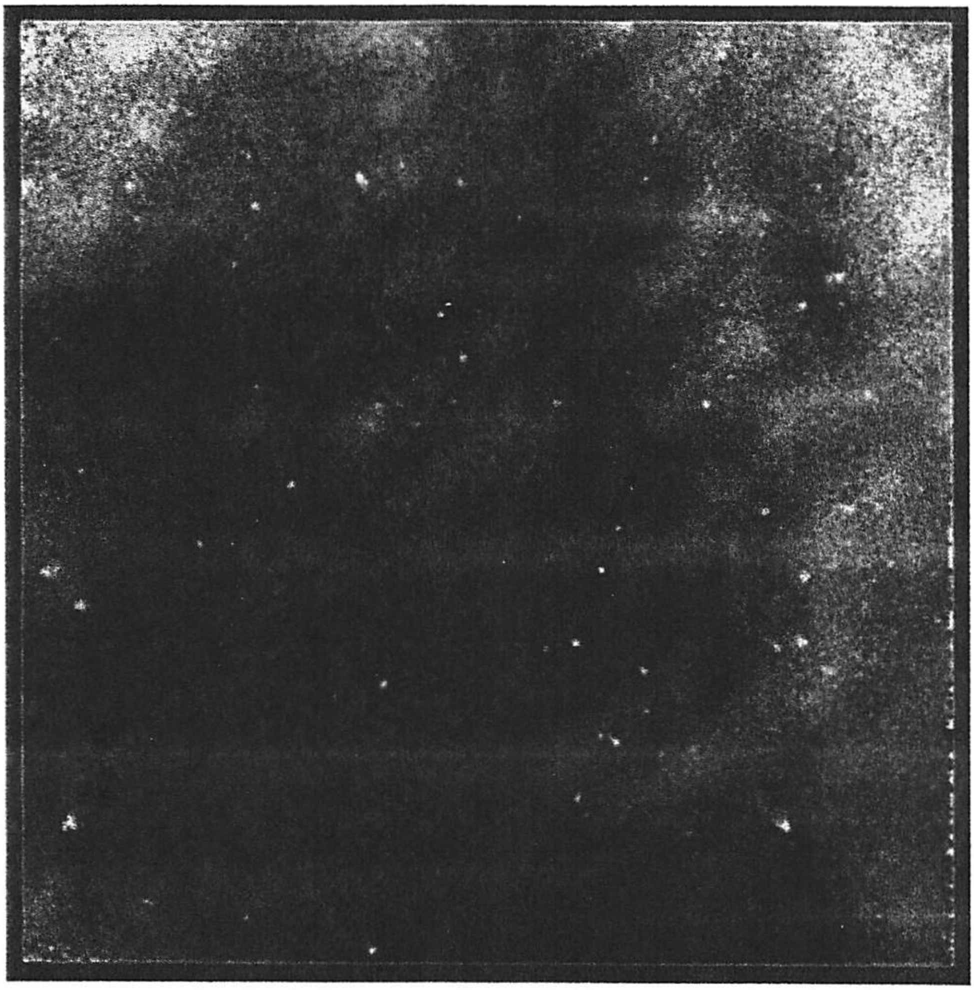
Intrinsic Phase Speed (m/s)
50
100
150
10
8
6
4
2
0
Eta
10
20
30
40
50
Vertical Wavelength (km)

$$F_M = \frac{\lambda_z}{\lambda_x} \frac{g^2}{N^2} \left\langle \left(\frac{T'}{\overline{T}} \right)^2 \right\rangle \qquad (1)$$

$$\rho' / \rho = -T' / \overline{T}$$

$$= \varepsilon \cdot e^{\beta(z - z_{OH})} \cdot \cos(\omega t - kx + m(z - z_{OH})) \qquad (2)$$

IR (1.5 Micron) OH Image, Nicmos Array
U of Illinois and U C Berkeley, (Astronomy)



UCSD Telescope; March, 1998
S/N ~ 200, IT=60 S

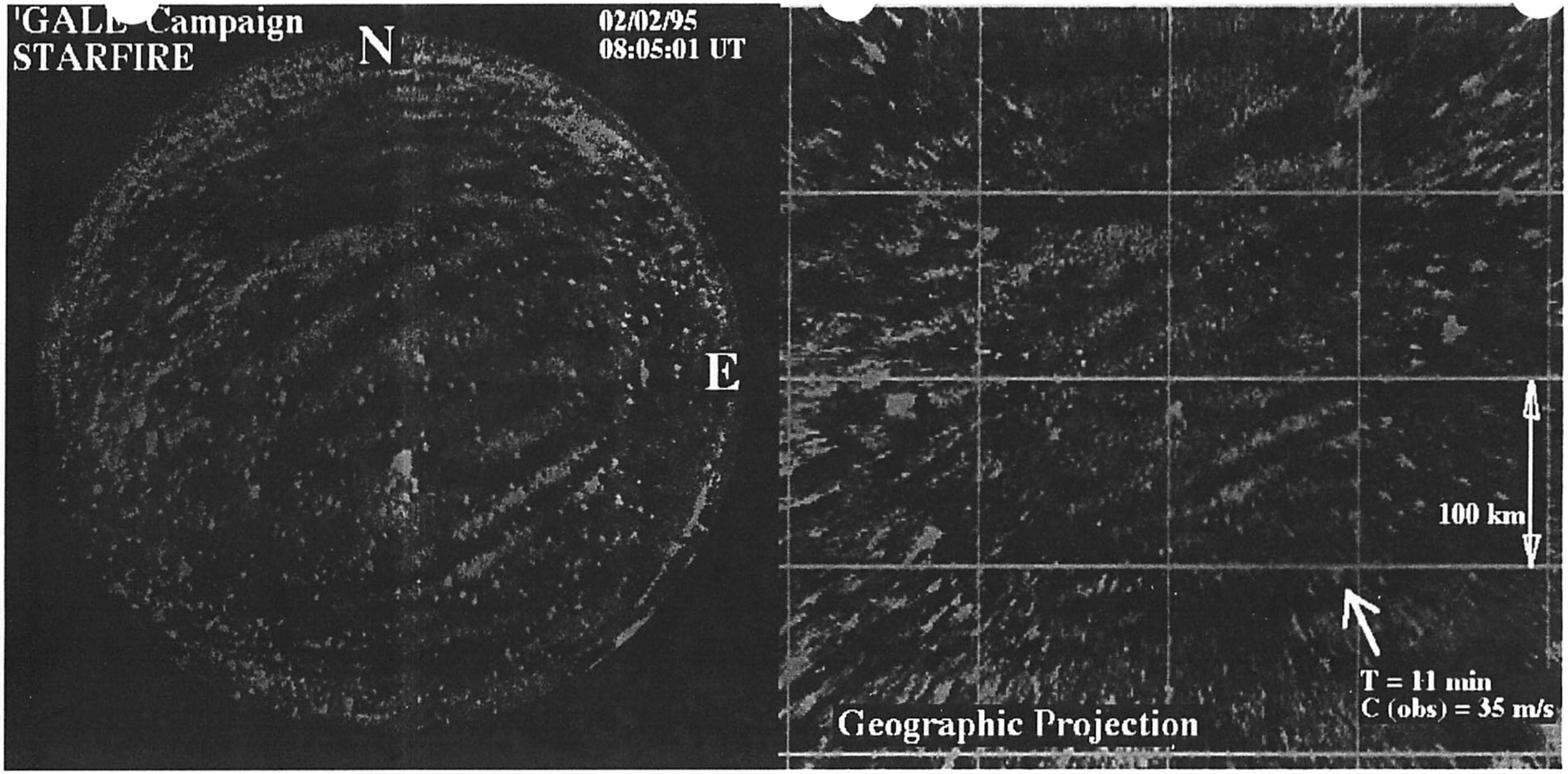
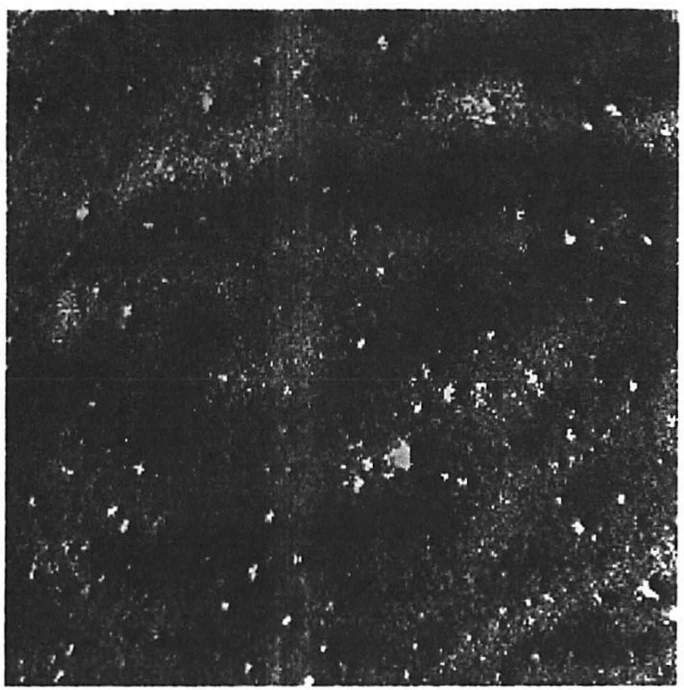

'GALE' Campaign
STARFIRE
N
02/02/95
08:05:01 UT
E
100 km
T = 11 min
C (obs) = 35 m/s
Geographic Projection

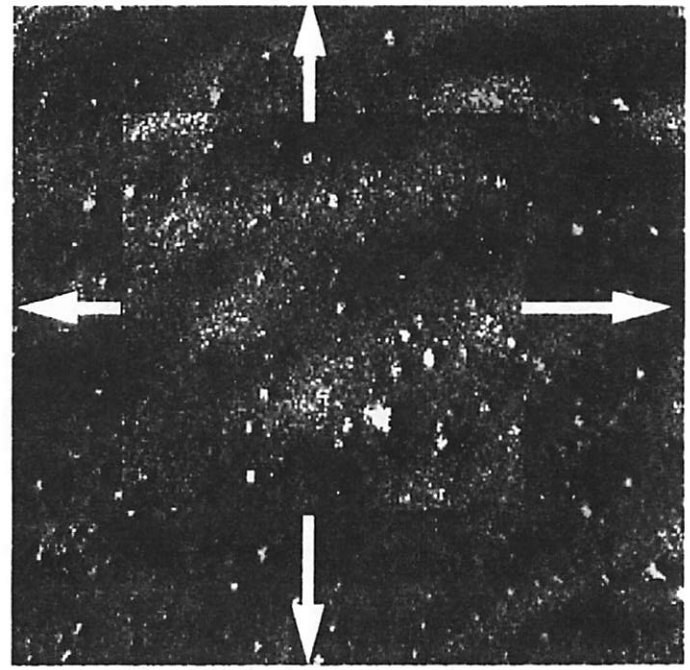
Table for Horizontal Wavelength λ_x

Date	Horizontal Wavelength (km)		
	Mean	Std. Deviation	Std. Error
02/02/95	37.3	13.9	2.5
02/03/95	36.4	11.2	1.2
04/01/95	22.7	4.1	0.7
04/02/95	22.3	9.4	2.1
04/04/95	24.6	13.7	2.1
Overall Mean	28.8	13.0	1.0

- **150x150 pixel frame($Frame_1$) taken at time $T_o + t$**



- **250x250 pixel frame($Frame_2$) taken at time T_o**



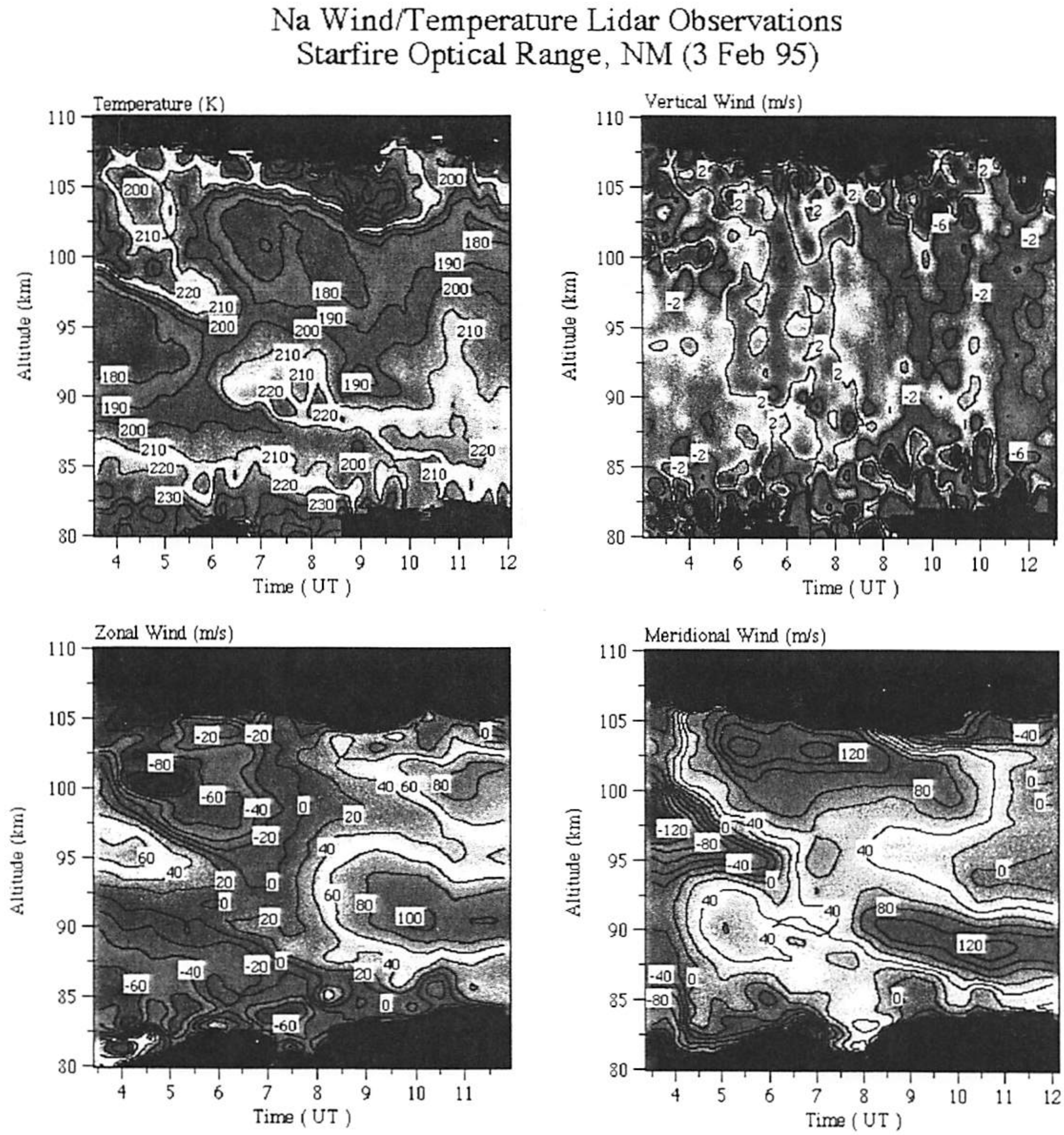
Finding the best match on the basis of root-mean square value, equivalent to correlation function in our case, between the two frames, i.e. $Frame_1$ and $Frame_2$.

$$RootMeanSquare = \sqrt{\left[(1/N_1N_2)\sum(I_1 - I_2)^2\right]}$$

where N_1 = Number of pixels in $Frame_1$.

N_2 = Number of pixels in $Frame_2$.

I_1, I_2 = Intensity values of each pixel



Na Wind/Temperature Lidar Observations
Starfire Optical Range, NM (3 Feb 95)
Temperature (K)
Vertical Wind (m/s)
Zonal Wind (m/s)
Meridional Wind (m/s)
Altitude (km)
Time (UT)

Figure 1

Na Wind/Temperature Lidar Observations
Starfire Optical Range, NM

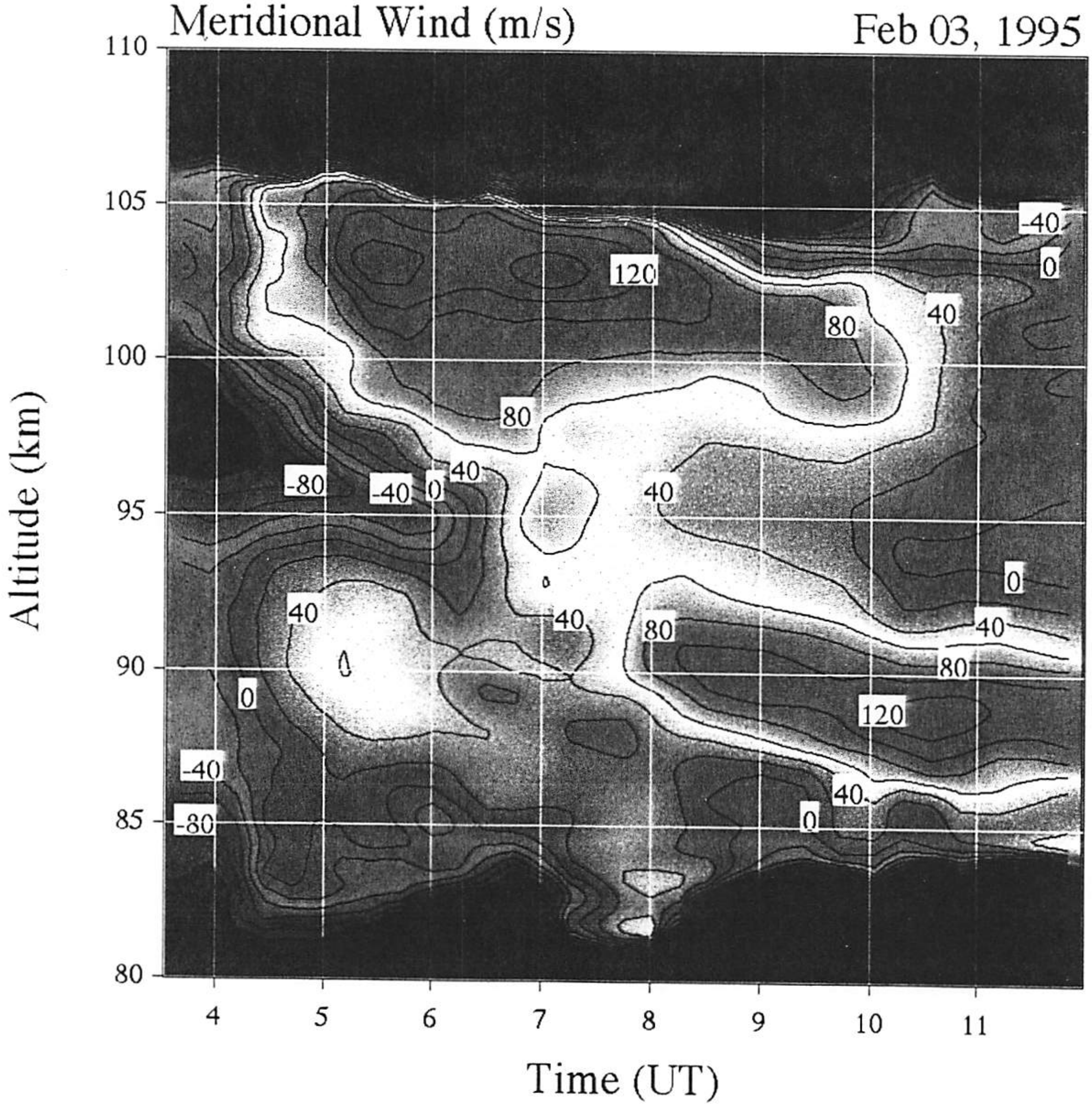
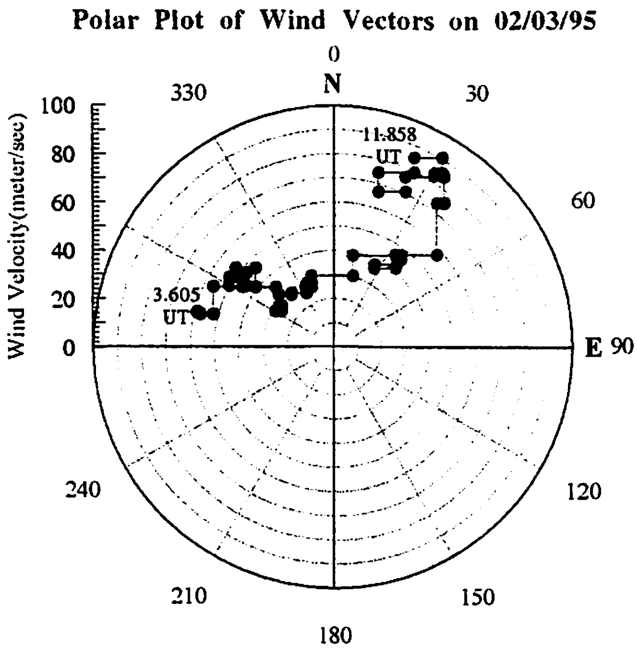


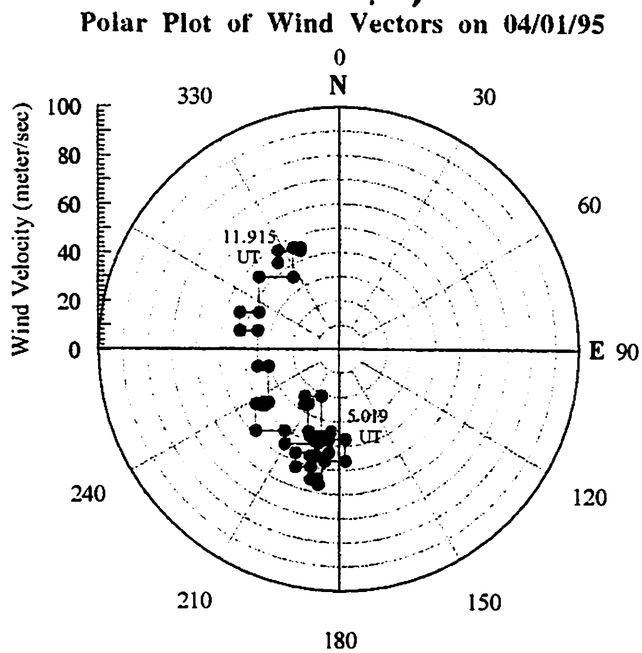
Table for Brunt-Vaisala Periods

Date	Brunt-Vaisala Period (minute)
02/02/95	6.2
02/03/95	5.7
04/01/95	4.7
04/02/95	4.6
04/04/95	4.3
Mean	5.1


Polar Plot of Wind Vectors on 02/03/95
0
N
330
30
60
E 90
120
150
180
210
240
100
80
60
40
20
0
Wind Velocity(meter/sec)
11.858
UT
3.605
UT

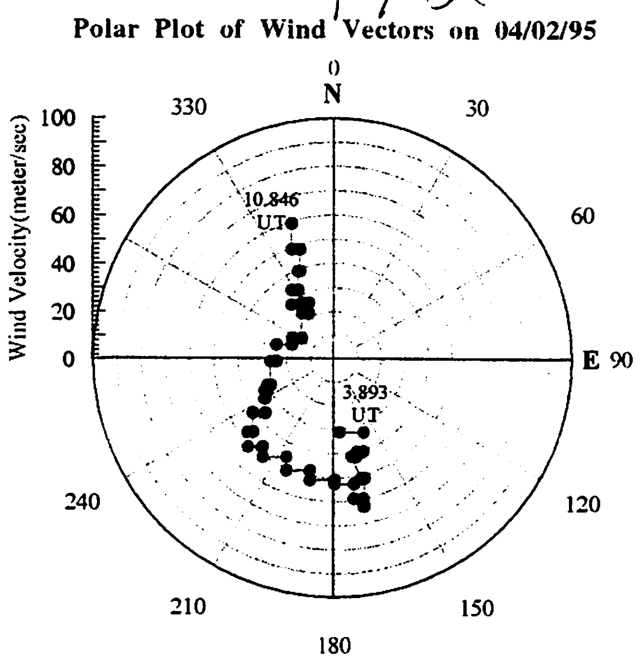
(a)

4/1


Polar Plot of Wind Vectors on 04/01/95
0
N
330
30
60
E 90
120
150
180
210
240
100
80
60
40
20
0
Wind Velocity (meter/sec)
11.915
UT
5.019
UT

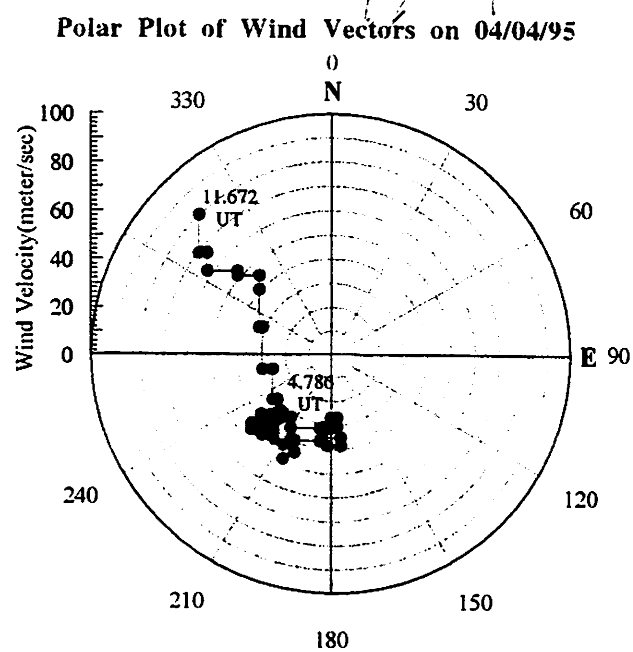
(b)

4/2

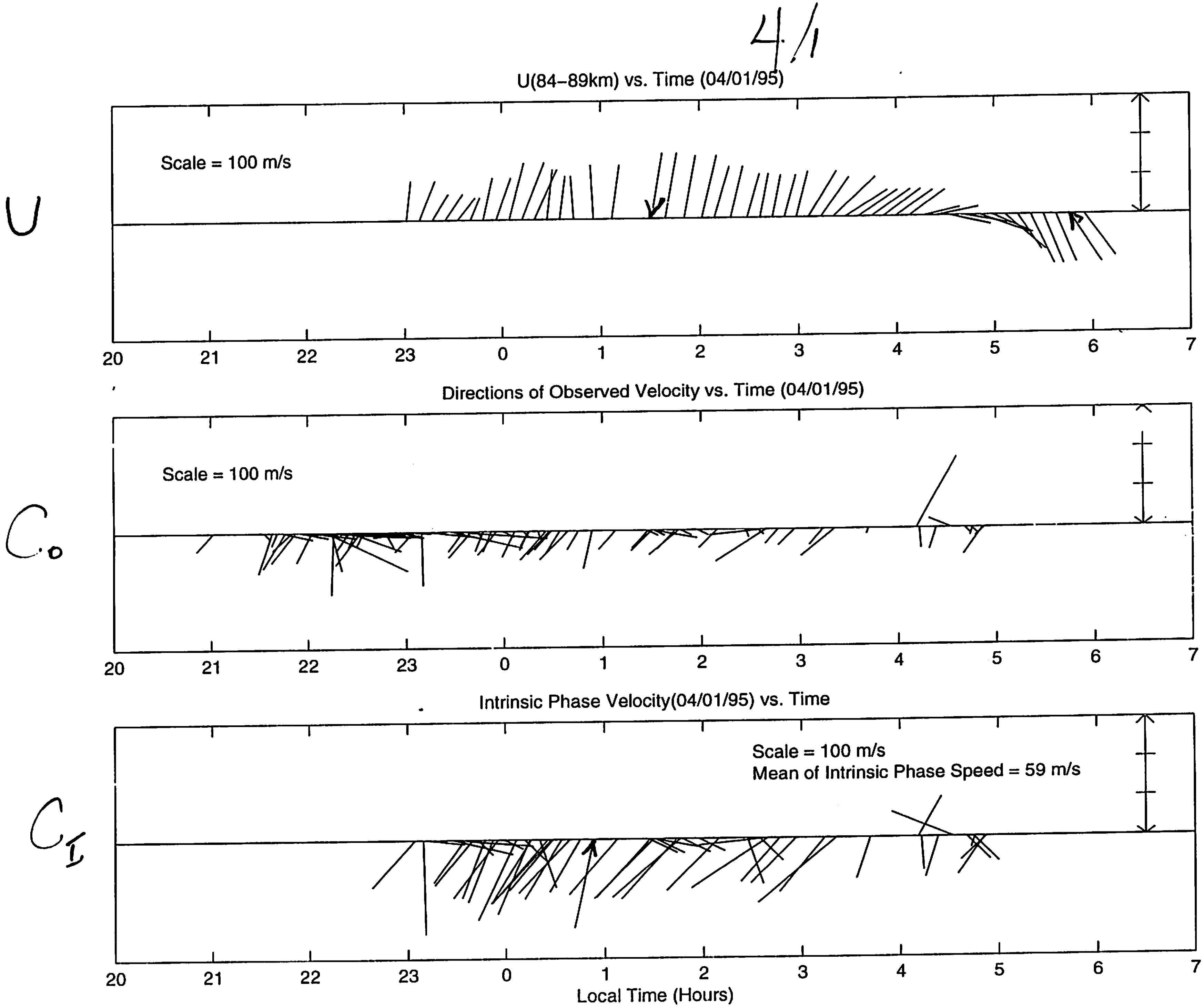

Polar Plot of Wind Vectors on 04/02/95
0
N
330
30
60
E 90
120
150
180
210
240
100
80
60
40
20
0
Wind Velocity(meter/sec)
10.846
UT
3.893
UT

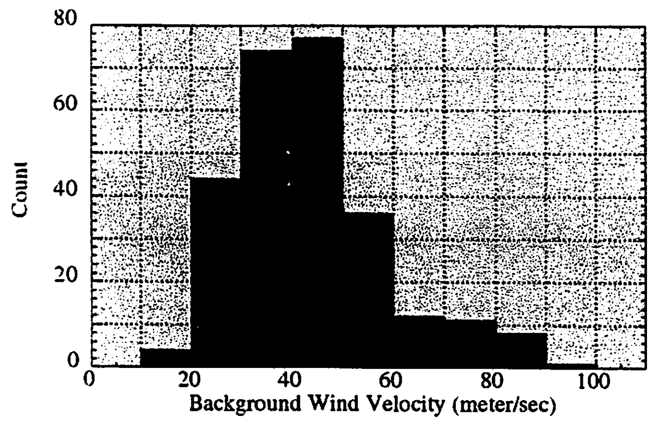
(c)

4/4

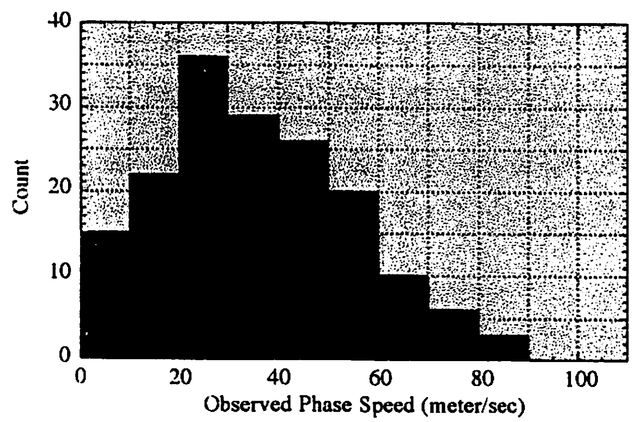

Polar Plot of Wind Vectors on 04/04/95
0
N
330
30
60
E 90
120
150
180
210
240
100
80
60
40
20
0
Wind Velocity(meter/sec)
11.672
UT
4.786
UT

(d)

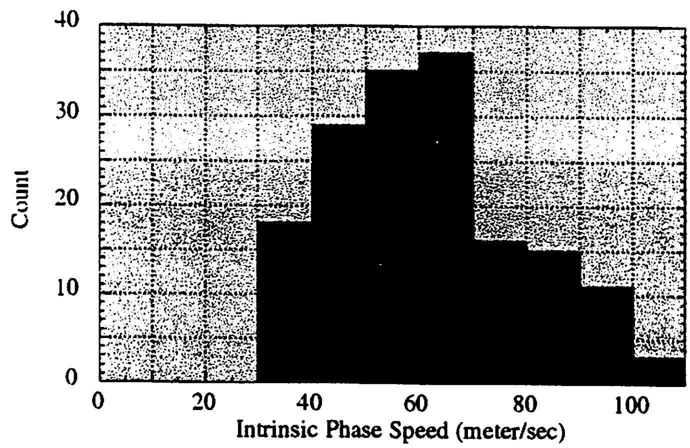

4/1
U(84–89km) vs. Time (04/01/95)
Scale = 100 m/s
U
20
21
22
23
0
1
2
3
4
5
6
7
Directions of Observed Velocity vs. Time (04/01/95)
Scale = 100 m/s
C.o
20
21
22
23
0
1
2
3
4
5
6
7
Intrinsic Phase Velocity(04/01/95) vs. Time
Scale = 100 m/s
Mean of Intrinsic Phase Speed = 59 m/s
C_I
20
21
22
23
0
1
2
3
4
5
6
7
Local Time (Hours)


80
60
40
20
0
Count
0
20
40
60
80
100
Background Wind Velocity (meter/sec)

U


40
30
20
10
0
Count
0
20
40
60
80
100
Observed Phase Speed (meter/sec)

C_o


40
30
20
10
0
Count
0
20
40
60
80
100
Intrinsic Phase Speed (meter/sec)

C_I

Intrinsic phase speed on all the five nights (02/02/95, 02/03/95, 04/01/95, 04/02/95, 04/04/95) as a function of time. The hourly mean of the five nights is shown as a bold line.

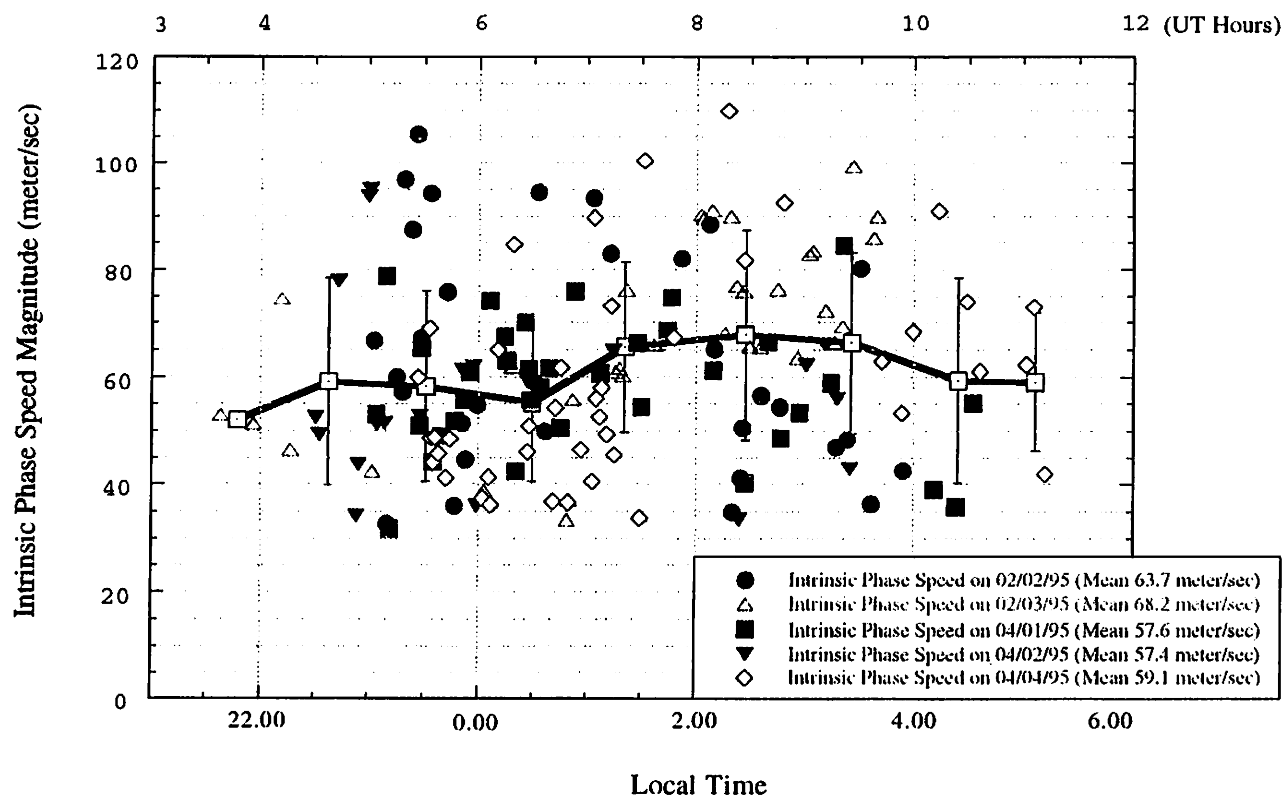
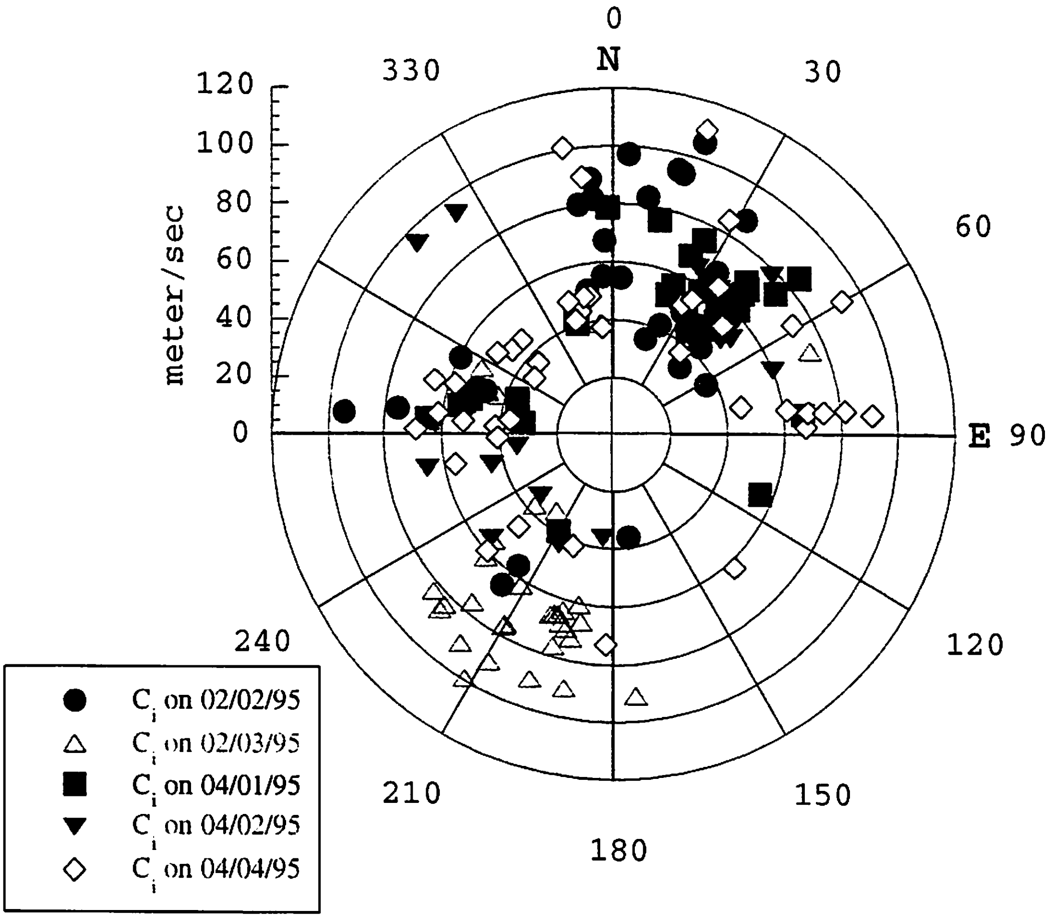


Table of Intrinsic Phase Speed C_i

Date	Intrinsic Phase Speed (m/sec)		
	Mean	Std. Deviation	Std. Error
02/02/95	63.7	21.1	3.7
02/03/95	68.2	17.0	2.9
04/01/95	57.6	12.5	2.1
04/02/95	57.4	17.0	3.8
04/04/95	59.1	18.8	2.9
Overall Mean	61.4	17.8	1.4



Intrinsic phase speed (C_i) on all the five nights (02/02/95, 02/03/95, 04/01/95, 04/02/95, 04/04/95) in a polar plot. The Y-Axis is represented as meter/sec and indicates the magnitude of C_i.

The frequency and wave numbers are related through the dispersion relation

$$m^2 = \frac{(N^2 - \omega^2)}{(\omega^2 - f^2)} k^2 \tag{1}$$

N - buoyancy frequency
f- inertial frequency .

For Albuquerque imager data, $N > \omega >> f$, or $\tau_{B\text{-}V} < \tau_I << \tau_f$

$$m^2 = \frac{(N^2 - \omega^2)}{(\omega^2)} k^2 = \left(\frac{N^2}{\omega^2} - 1\right) k^2 \tag{2}$$

Therefore:

$$\lambda_z = \frac{\tau_I C_I}{\sqrt{\frac{(\tau_I)^2}{(\tau_{B-V})^2} - 1}} \tag{3}$$

$\tau_{B\text{-}V}$ - Brunt-Vaisala period.

The mean conditions observed here result in

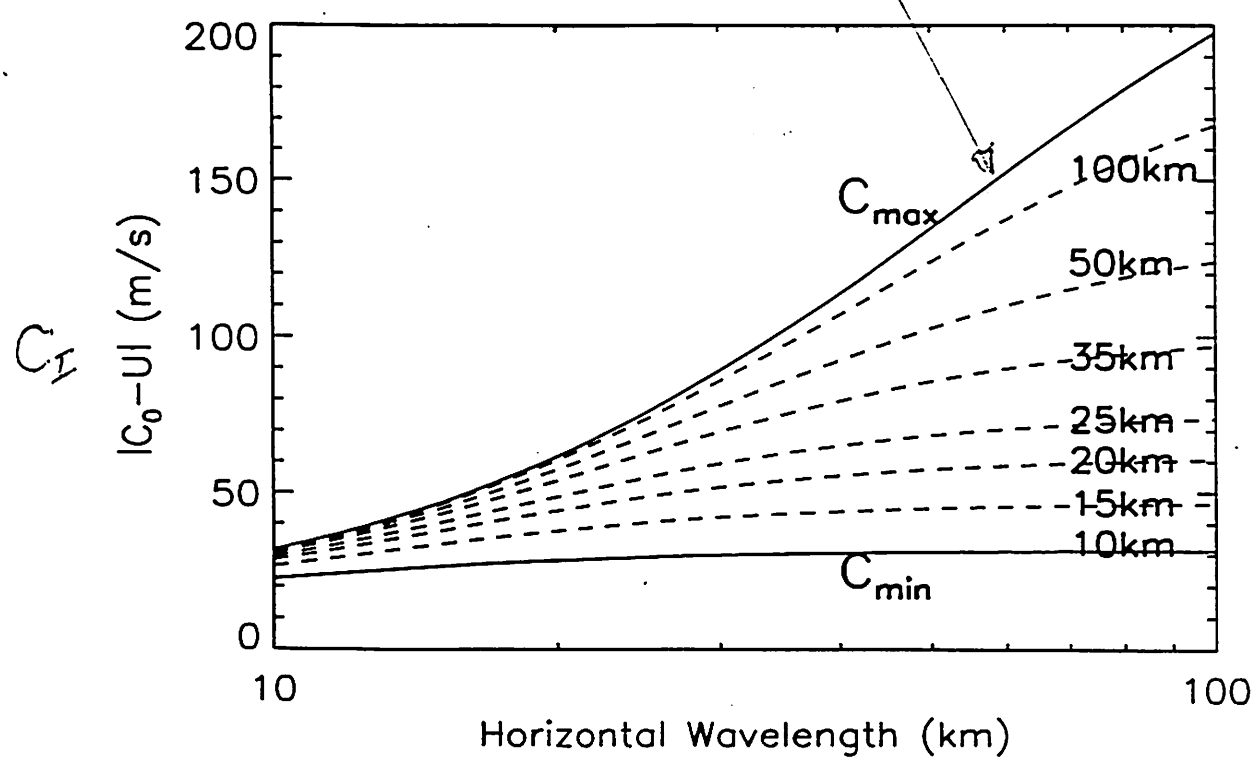
$$\lambda_z \sim 1.3 \tau_{B-V} C_I \tag{4}$$

Table of Vertical Wavelengths λ_z

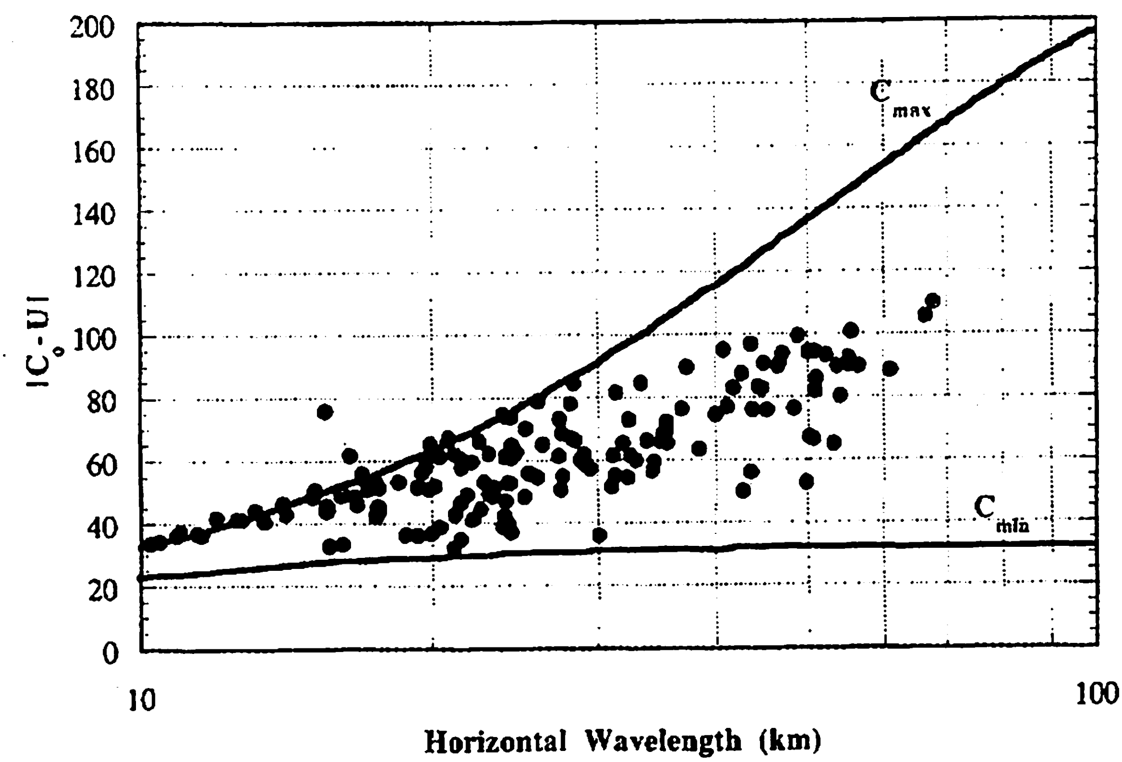
Date	Vertical Wavelength (km)		
	Mean	Std. Deviation	Std. Error
02/02/95	32.5	11.8	2.1
02/03/95	30.9	7.0	1.2
04/01/95	23.3	10.6	1.8
04/02/95	25.0	5.0	1.1
04/04/95	22.3	4.8	0.7
Overall Mean	26.6	9.4	0.7

(Alexander, pc)

$$C_{max} = \frac{N}{\sqrt{k^2 + \frac{1}{4H^2}}}$$



Horizontal Wavelength (λ_h) and C_i From StarFire Campaign



$$F_M = \frac{\lambda_z}{\lambda_x}\frac{g^2}{N^2}\left\langle\left(\frac{T'}{\bar{T}}\right)^2\right\rangle \qquad (1)$$

$$\rho'/\rho = -T'/\bar{T}$$
$$= \varepsilon \cdot e^{\beta(z - z_{oh})} \cdot \cos(\omega t - kx + m(z - z_{OH})) \qquad (2)$$

{where var(ρ'/ρ)= var(-T'/$\bar{T}$) = $<(\varepsilon \cos[])^2>$
and for monochromatic waves ≅ .5 ε^2}

substitute
$$\frac{T'}{T} = \frac{I'_{OH}}{I_{OH}} \cdot \frac{1}{CF} \qquad (3)$$

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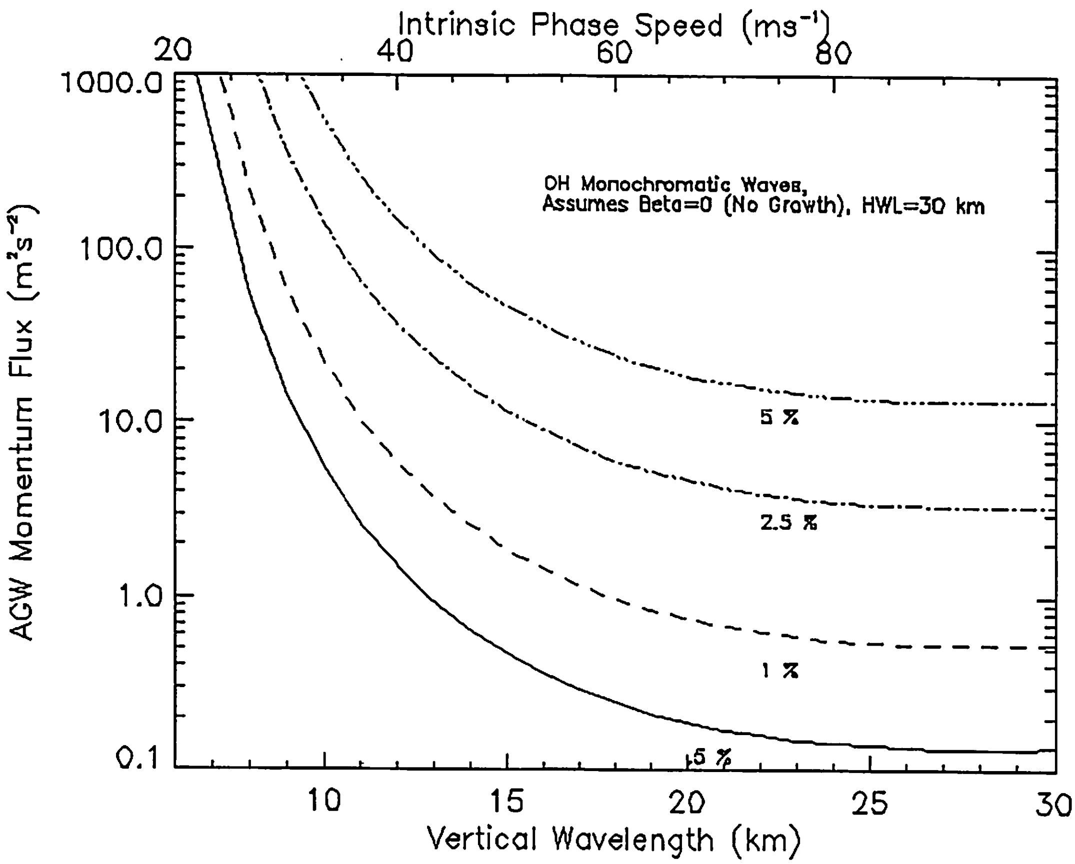
$$\mathbf{F}_{M,87km} = \frac{6 \cdot 10^4 \lambda_z \quad (I'_{OH})^2}{CF^2 \ \lambda_x \quad (I_{OH})^2} \qquad (m^2 s^{-2}) \qquad (4)$$

$$CF(\lambda_z) = 3.5(1 - e^{-0.0055 \cdot (\lambda_z(km) - 6)^2}) \qquad (5)$$

(Assumes 'No Growth', i.e. β=0)



Intrinsic Phase Speed (ms^{-1})
20
40
60
80
1000.0
100.0
10.0
1.0
0.1
AGW Momentum Flux (m^{2}s^{-2})
OH Monochromatic Waves,
Assumes Beta=0 (No Growth), HWL=30 km
5 %
2.5 %
1 %
.5 %
10
15
20
25
30
Vertical Wavelength (km)

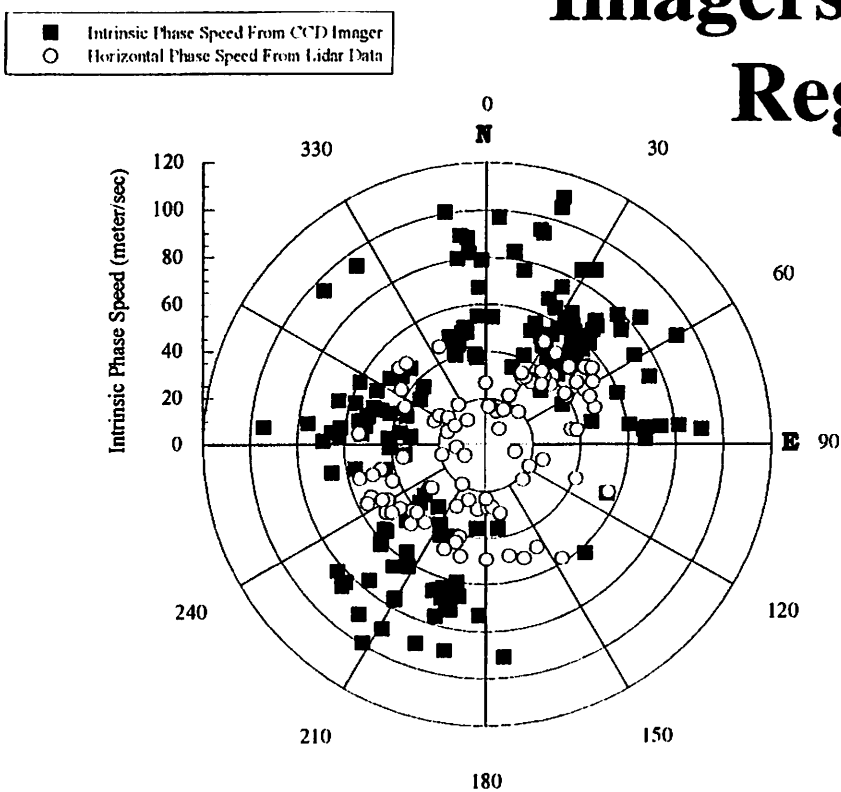
Table of Vertical Fluxes of Horizontal Momentum

Date	Momentum Flux (m^2/s^2)	
	Zonal Component	Meridional Component
02/02/95	2.4	7.9
02/03/95	-5.4	-3.0
04/01/95	-10.0	12.7
04/02/95	-3.2	1.3
04/04/95	-8.2	8.6
Mean	-5.3	6.1

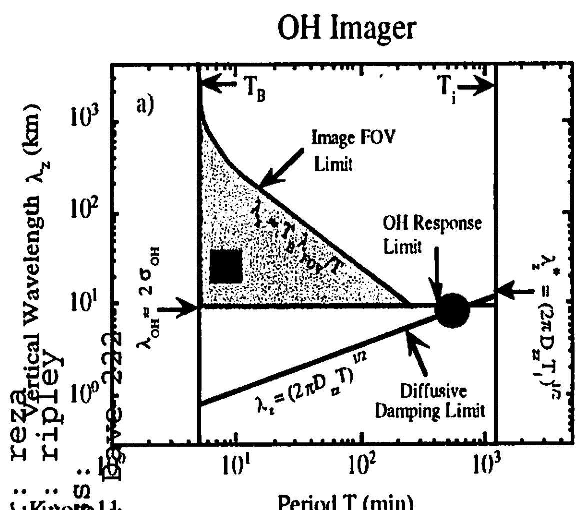
Table of Overall Means of Different Parameters

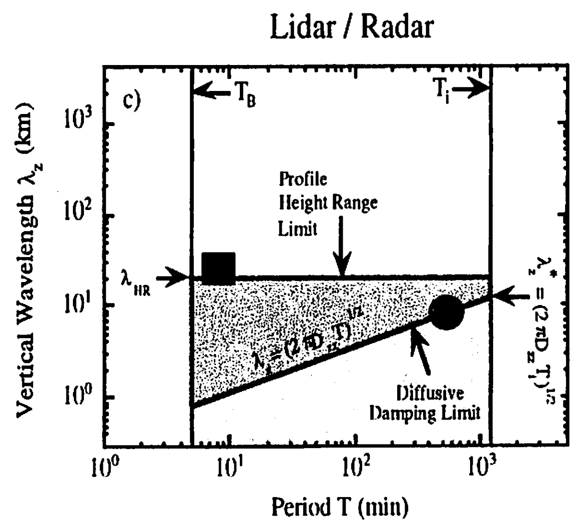
Parameters	Overall Mean
a) Horizontal Wavelength (λ_x)	28.8 km
b) Observed Phase Speed (C_o)	33.4 m/s
c) Relative Perturbed Airglow Intensity (I'/I)	3.8%
d) Intrinsic Phase Speed (C_i)	61.4 m/s
e) Intrinsic Period (τ_i)	7.8 minute
f) Brunt-Vaisala Period (τ_B)	5.1 minute
g) Vertical Wavelength (λ_z)	26.6 km
h) Vertical Phase Speed (C_z)	61.5 m/s
i) Momentum Flux (F_m)	21.9 m^2/s^2
j) Zonal Component of F_m	-5.3 m^2/s^2
k) Meridional Component of F_m	6.1 m^2/s^2

Imagers & Lidars Observe Different Regions of Wave Spectrum



	Imager	Lidar
C_h	61.4 m/s	27.7 m/s
λ_z	26.6 km	9.4 km
τ_{in}	7.8 min	8.8 hr
C_z	61.5 m/s	0.49 m/s
λ_h	28.8 km	1230 km





For lidar waves vertical diffusion vel

$mD_{zz} = 0.21 m/s < C_z$

$D_{zz} = 320\ m^2/s$

$\lambda_z = 9.4$ km

Summary

* Vertical flux of AGW **momentum flux**

-deduce from **intrinsinc wave parameters** (λ_x, λ_z) and amplitudes, as implied from I'/I of OH airglow.

-deduce **zonal and meridional components** from propagation directions observed in **imager time sequences.**

* It is <u>**crucial**</u> to measure all parameters, **including the wind vector** in the volume to establish the intrinsic phase speed (i.e. λ_z).

It is also <u>**crucial**</u> to calculate λ_z using the approximation for the **dispersion relationship** as:

$$m^2 = k^2\left(\frac{N^2}{\omega^2} - 1\right)$$

* 5 nights of data from Albuquerque, NM (Feb-April, 95), with 161 wave observations from the imager, with mean values for

λ_h=28.8 km

C_o=33.4 m/s

C_I=61.4 m/s

τ_I=7.8 minutes

λ_z=26.6 km

C_z=61.5 m/s

$|F_M|$=21.9 m/s

$F_{M.ZONAL}$=-5.3 m^2s^{-2}, $F_{M.MERIDIONAL}$=6.1 m^2s^{-2}

*Planned-2 Year Campaign at Albuquerque

* Needs
- Continued refinement of CF factor
  - OH, O2 Atmospheric, OI 557.7
- Develop a phase of I'/I to AGW
  - *AGW Growth with altitude
  - *Vertical wavelength (here U is unavailable)
- Develop spectral methods of extracting F_M from I'/I
  - *which includes compensation for U
- Continue evolution of improved data quality
  - *Background measurements, continuum
  - *Clouds, Contrails, Stars
- Develop a climatology of F_M