Prologue

80-110 km Altitude Region
Upper Mesosphere and Lower Thermosphere (UMALT)
MALT or MLT

1. Atomic Oxygen (O) Density Peaks (95-100 km)
    - Chemically Active
        - Heat Balance
        - Airglow (OH (87 km), O2A(92 km), OI(95km))
            - Atmospheric Structures (Waves/Instabilities)

2. Coldest Part of the Atmosphere (83km (June) 97 km (Dec))
  - Inherent Negative Temperature Gradient
    - Instabilities

3. Large Amplitude Gravity Waves(GW) and Tides
  - Temperature perturbations (1-10%)
  - Large Wind Shears (>40 m/s/km)
    - Unstable Regions
      - Wave-Like Turbulent Structures
        - Turbulence
        - Enhanced Energy Dissipation
        - Enhanced Eddy Diffusion

          Altitude Distribution of O

TOMEX
Turbulent Oxygen Mixing Experiment

A Rocket/Ground-Based Experiment to Study Instabilities over the MALT - Starfire Optical Range/WSMR 10/2000

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M. Larsen and R. Bishop (Clemson)

R. Roble (NCAR)

OUTLINE

- Conceptual Background- Atmospheric Stability
- Previous Work That Motivated TOMEX
- TOMEX Experiment
- Post TOMEX Work

Atmospheric Stability

Potential Temperature (Θ)- Temperature of an air parcel moved to a reference pressure adiabatically (entropy is constant).

1. $d\Theta/dz > 0$ (background temperature gradient with altitude is less than adiabatic lapse rate). Parcel moved up(down) is cooler(warmer) than surrounding air and sinks(rises). Stable.
2. $d\Theta/dz < 0$ (background temperature gradient is greater than adiabatic lapse rate). Parcel moved up(down) is warmer(cooler) than surrounding air and rises(sinks). Unstable.

Brunt-Vaisala Frequency (N)

Frequency associated with this Motion

$N^2=(g/\Theta)(d\Theta/dz)$

$=g/T(dT/dz+g/Cp)$

Cp is the specific heat of the atmosphere

T is the Temperature

-g/Cp is the adiabatic lapse rate (~-9.5K/km at 90 km)

$N^2>0$ Stable (4×10^{-4} sec^{-2} $\rightarrow$ Buoyancy Pd. of 5 min)

$N^2<0$ Unstable (Convective Instability)-Heavy Air Over Light Air

Richardson Number (Ri)

$$Ri = N^2/(\Delta u/ \Delta z)^2$$

where u is a wind speed, z is an altitude and thus $\Delta u/ \Delta z$ is the magnitude of the wind shear

$N^2 \propto$ PE of the Buoyancy Osc- Stability

$(\Delta u/ \Delta z)^2 \propto$ KE of the Wind Shear-Destabilizing

$Ri < 1$ Should Indicate Instability

Critical Ri

Ratio of the Work (W) Required to Interchange Two Parcels of Air to the Kinetic Energy(KE) Available to Do that Work

$W = \rho N^2 \Delta z^2$

$KE = (1/4)\rho(\Delta u)^2$

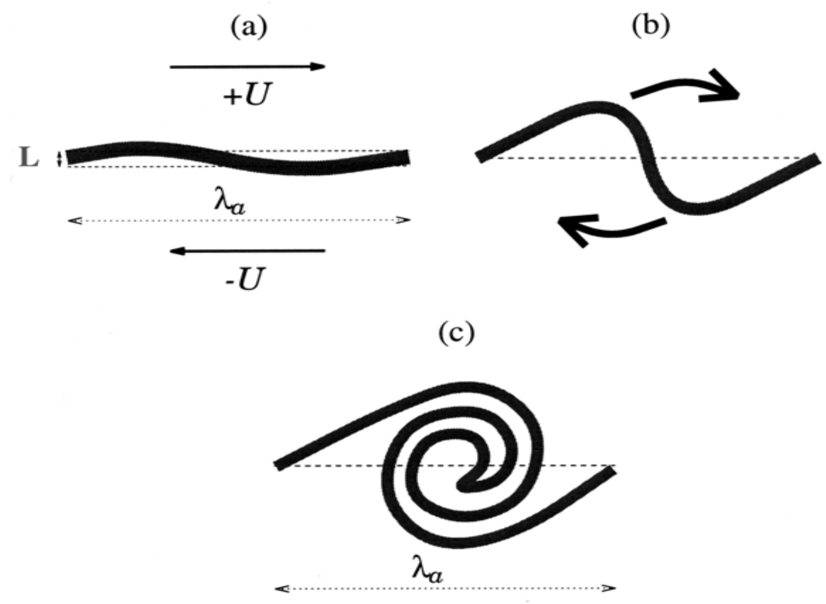
KE > W Implies Instability

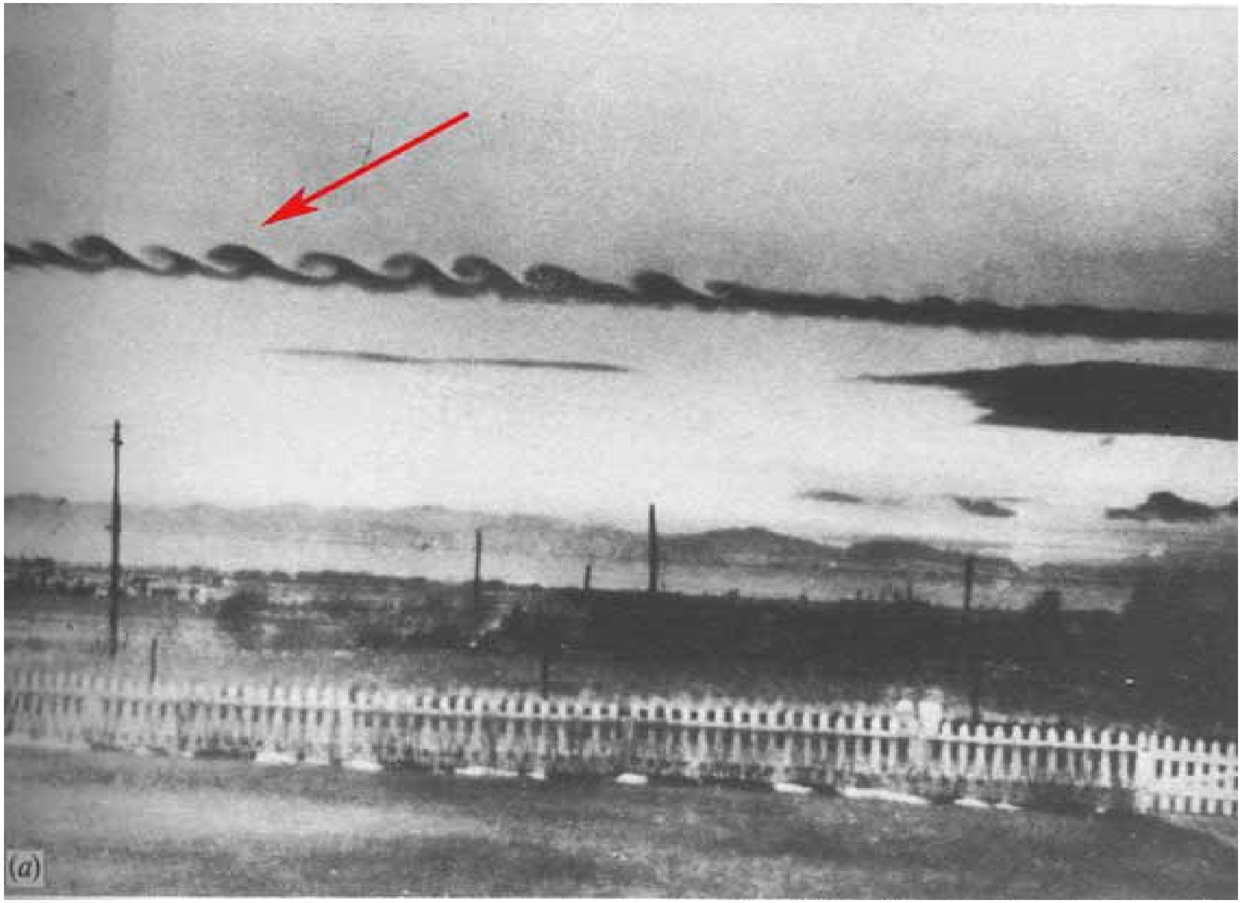
Ri > 1/4 Stable

0 < Ri < 1/4 Unstable (Dynamical Instability)

Consequences of Instability

Dynamical Instability → Kelvin-Helmholtz Billows



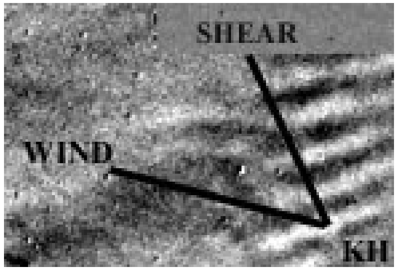


KH Billows Characteristics

Wavelength (λ_a) approx 8 times thickness of unstable layer (L)

Height (h) approx 5 times L

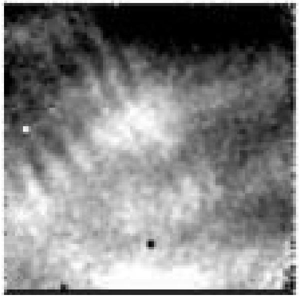
Billow Phasefronts Aligned $\perp$ to the Wind Shear Vector (Parallel to Gravity Wave Phasefronts)



Lifetime 10s of minutes   Decay- Diffusion-Turbulence

Convective Billows

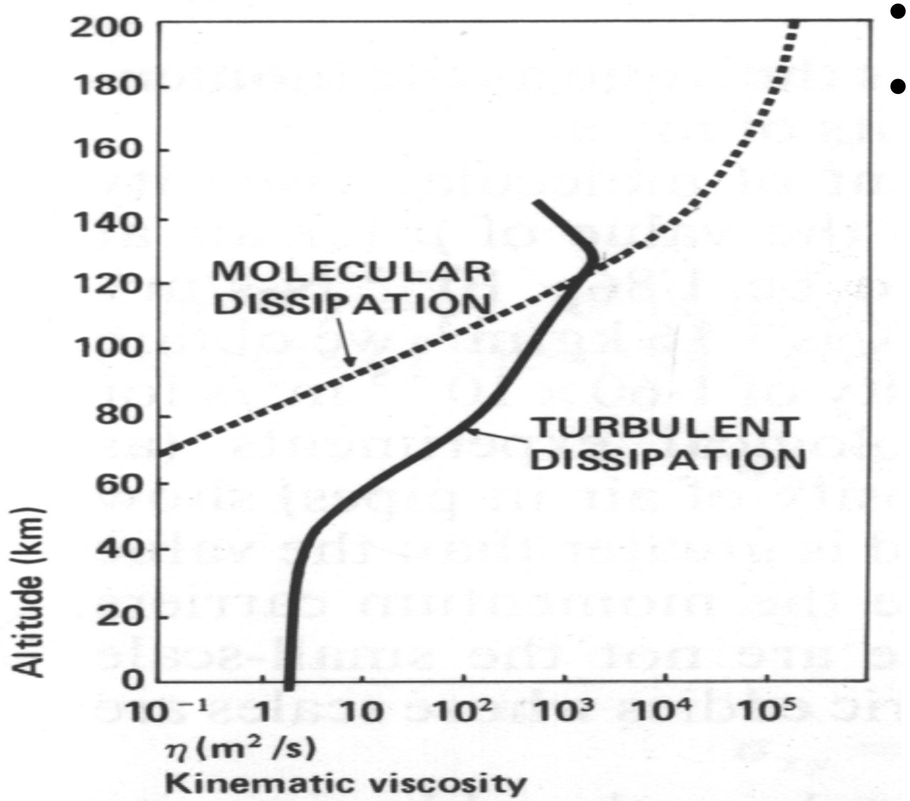
- Convective Instabilities also form billows
  - They would appear parallel to shear vector and perpendicular to Gravity Wave Phasefronts.



- Decay into Turbulence
  - KH billows can also form regions of convective instabilities

- Why do Convective Instabilities Form in the Atmosphere since Ri of 1/4 always occurs first

Motivation



- Kinematic Viscosity≈ Diffusion (D)
- Below 110 km
  - Eddy D > Molecular Diffusion
  - 83 km
    - Molecular D≈1 m^2/s
    - Eddy D ≈100 m^2/s
  - 105 km
    - Molecular D≈100 m^2/s
    - Eddy D ≈300-500 m^2/s

Gravity Waves and Eddy Diffusion

- Hodges (1967,1969)
    - Gravity Wave Amplitudes grow with height
    - Temperature Gradient Becomes Convectively Unstable
    - Turbulence
    - Enhanced Eddy Diffusion
- Lindzen (1981) and others to date
    - Enhanced Eddy Diffusion Occurs in Thin Layers (1 km)
        - Layers Separated by Nominal Low Diffusion (?)
        - Rocket Experiments (Luebken, Blix etc)
            - Ionization Gauges Support This Model

TOMEX OBJECTIVE

The **overall objective** is to investigate how the presence of small (a few km or less) unstable regions affect the composition and larger scale structure of the MALT, the coldest part of the Earth’s atmosphere.

Specific TOMEX Objectives

- **To identify whether small scale convectively or dynamically unstable regions identified by super adiabatic temperature gradients or large wind shears are associated with unusually large values of eddy diffusion. (Do these regions actually produce instability features such as KH billows).**

- **To determine how these instabilities affect the vertical structure of atomic oxygen.**

- **To determine how atmospheric gravity wave activity is related to eddy diffusion and constituent transport.**

TOMEX Experiments

- Na lidar temperatures and winds from Starfire Optical Range in Albuquerque, NM (Gardner/Liu/Papen)
  - Ri, N^2-Stability of Atmosphere
- Ground-based airglow wave imaging (Swenson)
  - Wave Field (Gravity Waves)

- Payload Included:
  1. TMA (trimethyl aluminum) release- Larsen
     - Winds, energy dissipation, eddy diffusion
  2. Ionization Gauge (pressure)-Clemmons
     - Neutral Density Fluctuations
  3. Three-Channel Photometer- Hecht
     - Oxygen Airglow (OH-85km), O2A(92km), OI(95km)
       - O density profile

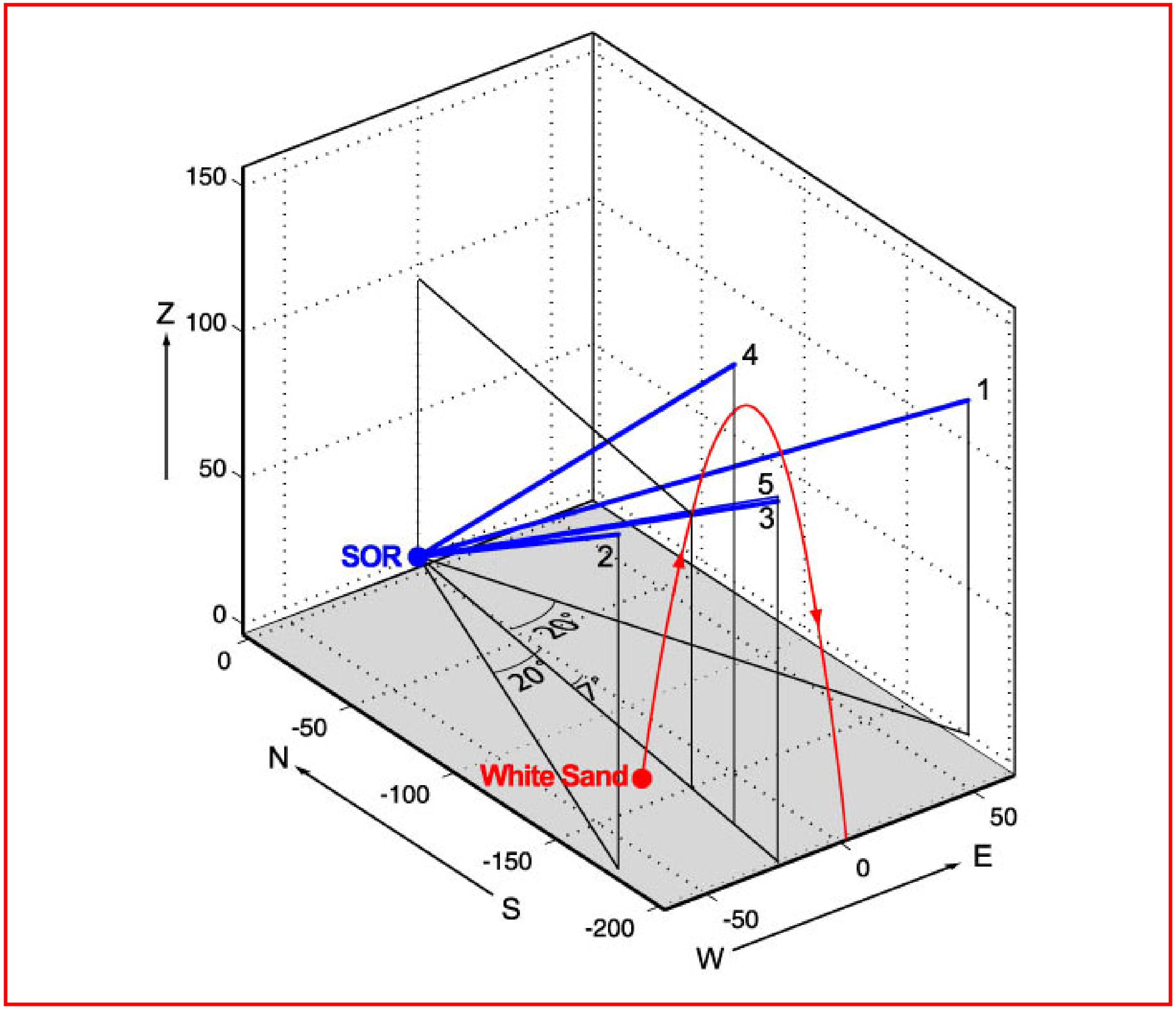
- Payload Launched From White Sands Missile Range When Lidar Data Indicated Instability
  - 2 Launches-Diff Conditions(Gravity Waves)
- Only One Launch Occurred
  - 0957 UT on October 26th 2000

TOMEX Experiment Configuration

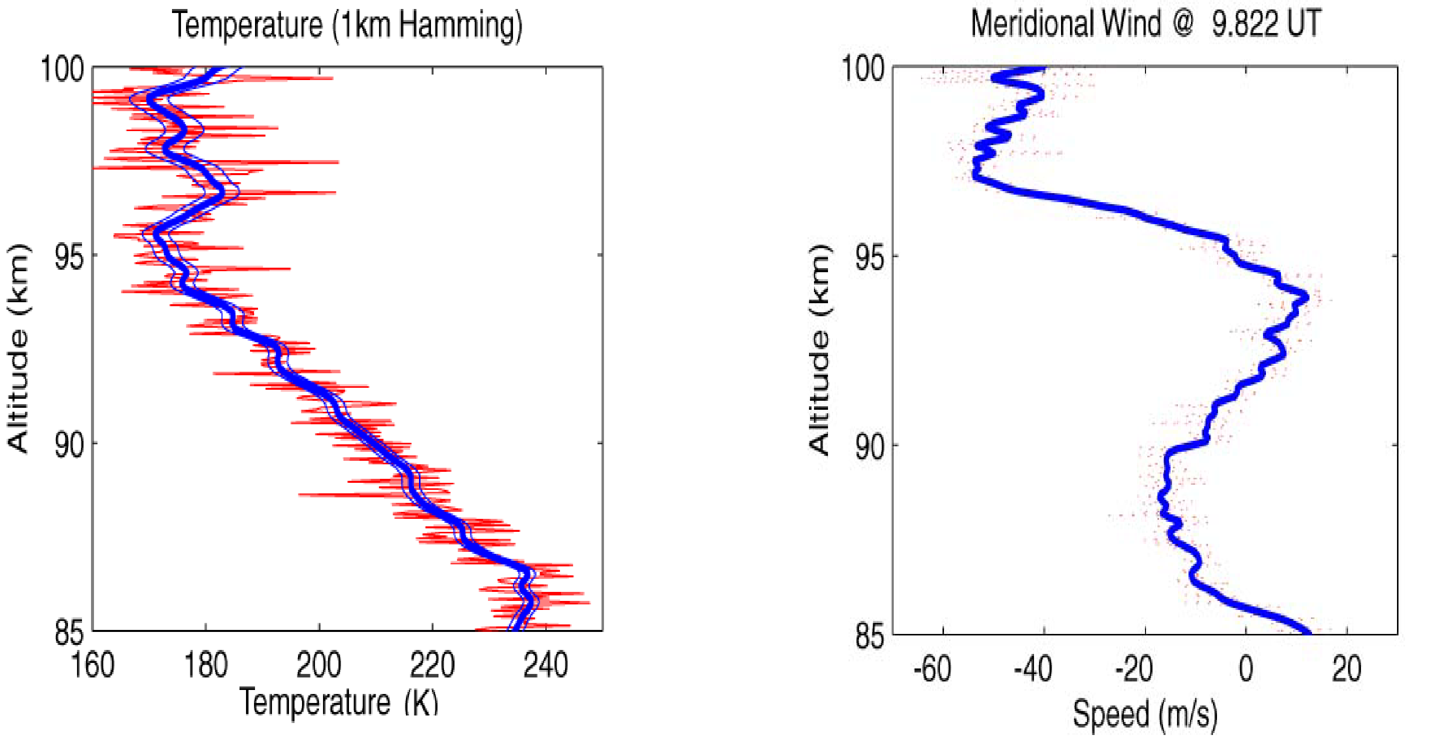
Site Separation 140 km

Lidar Elevation Angle 30Þ-40Þ

TOMEX Geometry

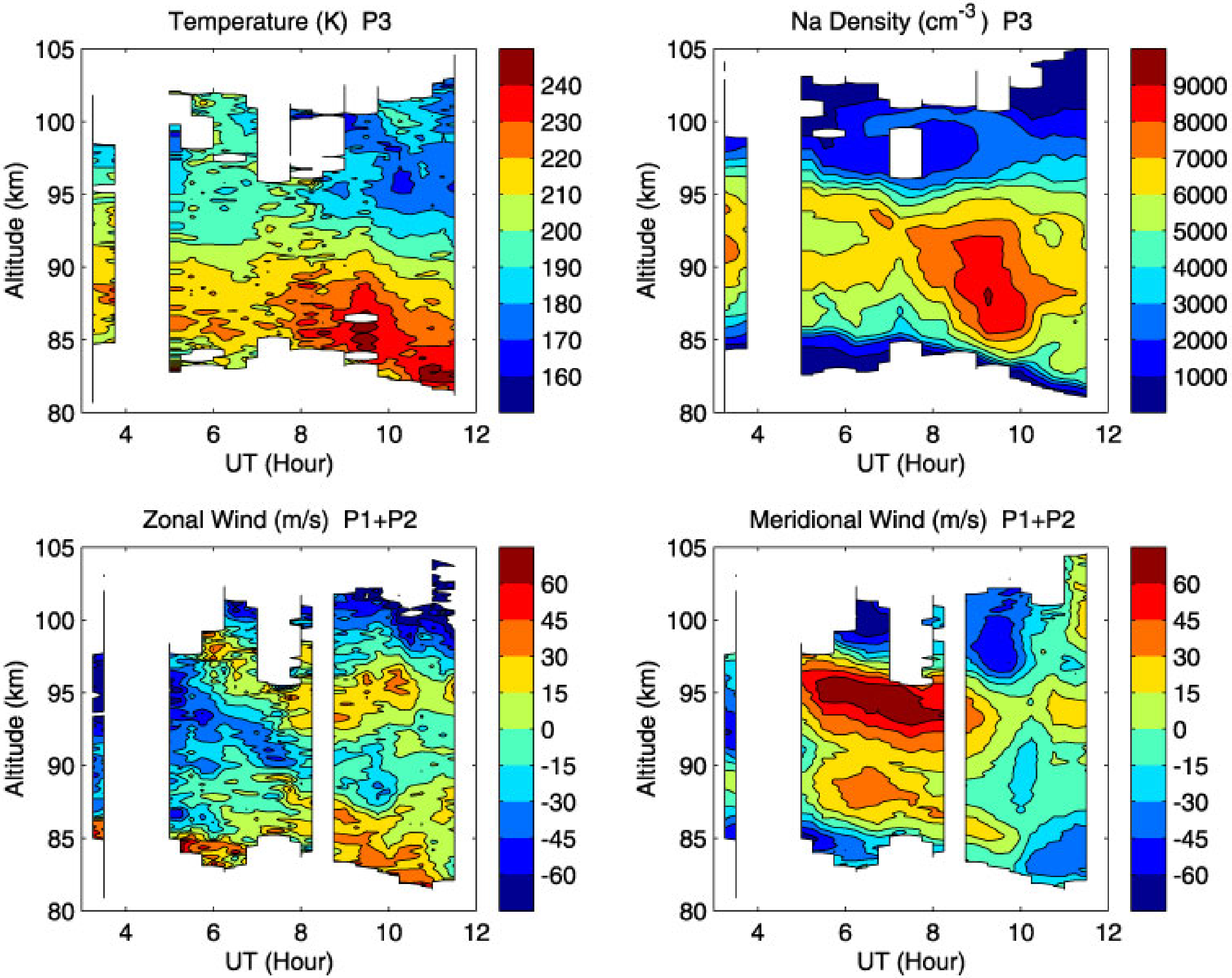


	Azimuth	Elevation
1.	160.00	30.48
2.	200.00	30.48
3.	187.02	30.48
4.	187.02	40.48
5.	187.02	30.75

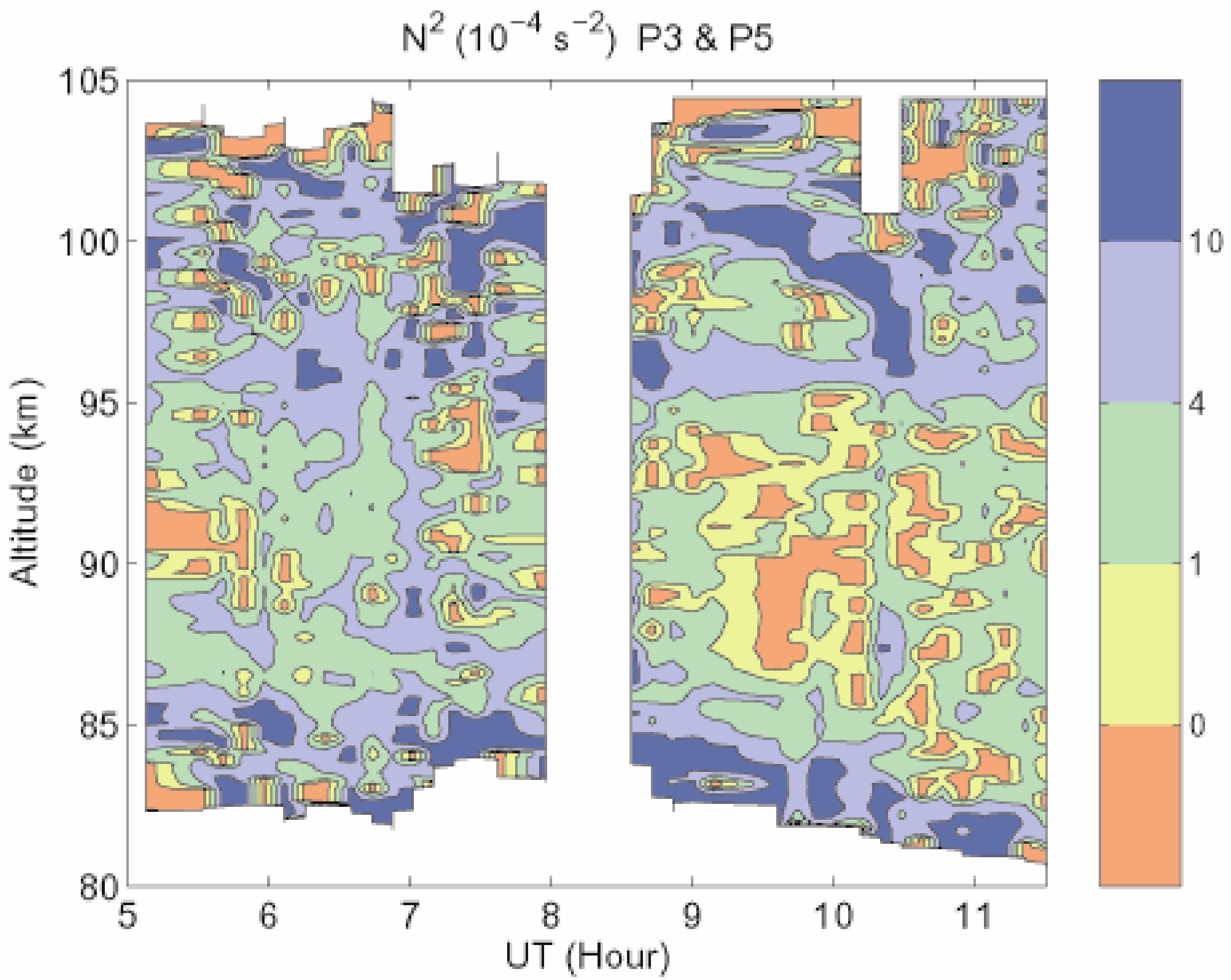

Temperature (1km Hamming)
100
95
90
85
Altitude (km)
160
180
200
220
240
Temperature (K)
Meridional Wind @ 9.822 UT
100
95
90
85
Altitude (km)
-60
-40
-20
0
20
Speed (m/s)

QuickTime™ and a
Sorenson Video 3 decompressor
are needed to see this picture.

LIDAR RESULTS

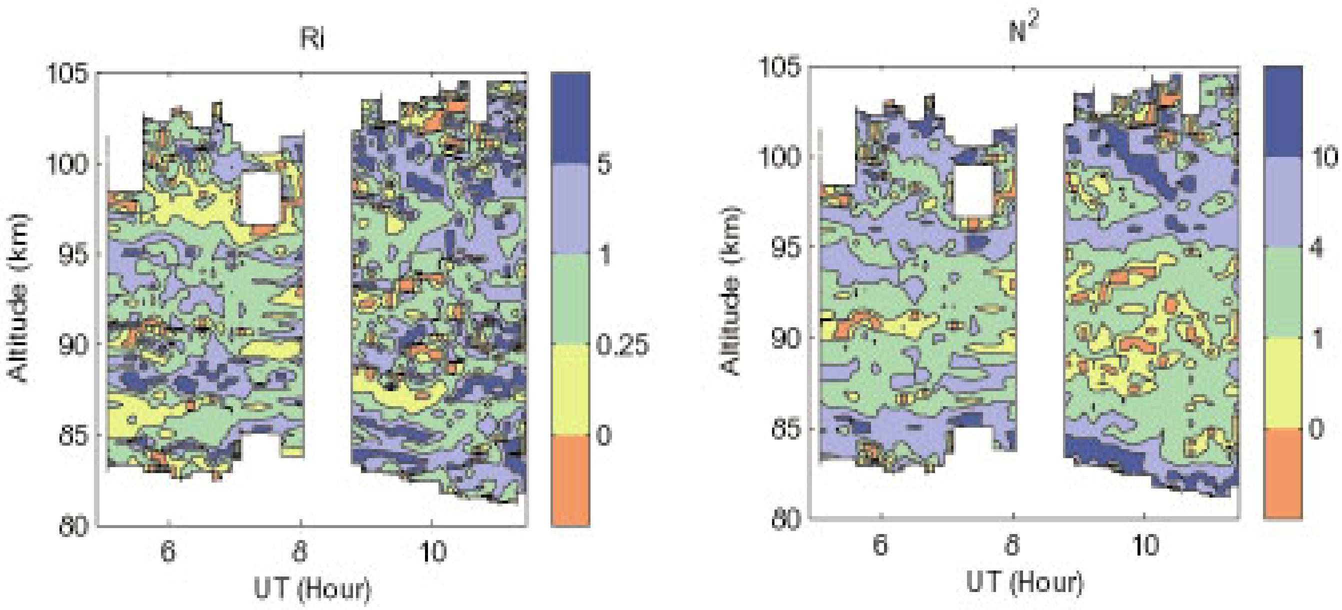


Na Wind/Temperature Lidar, SOR, NM Oct 26, 2000

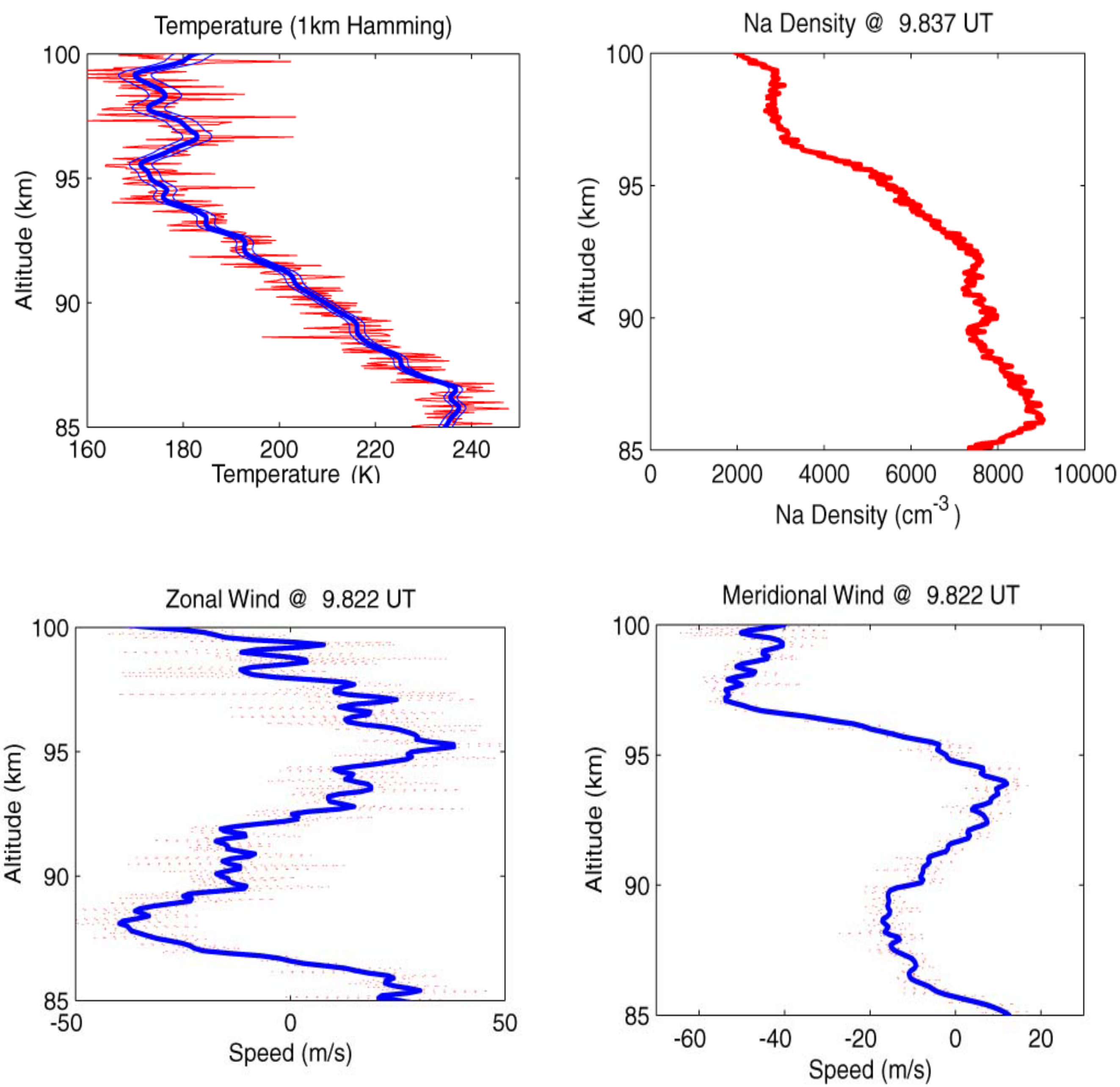


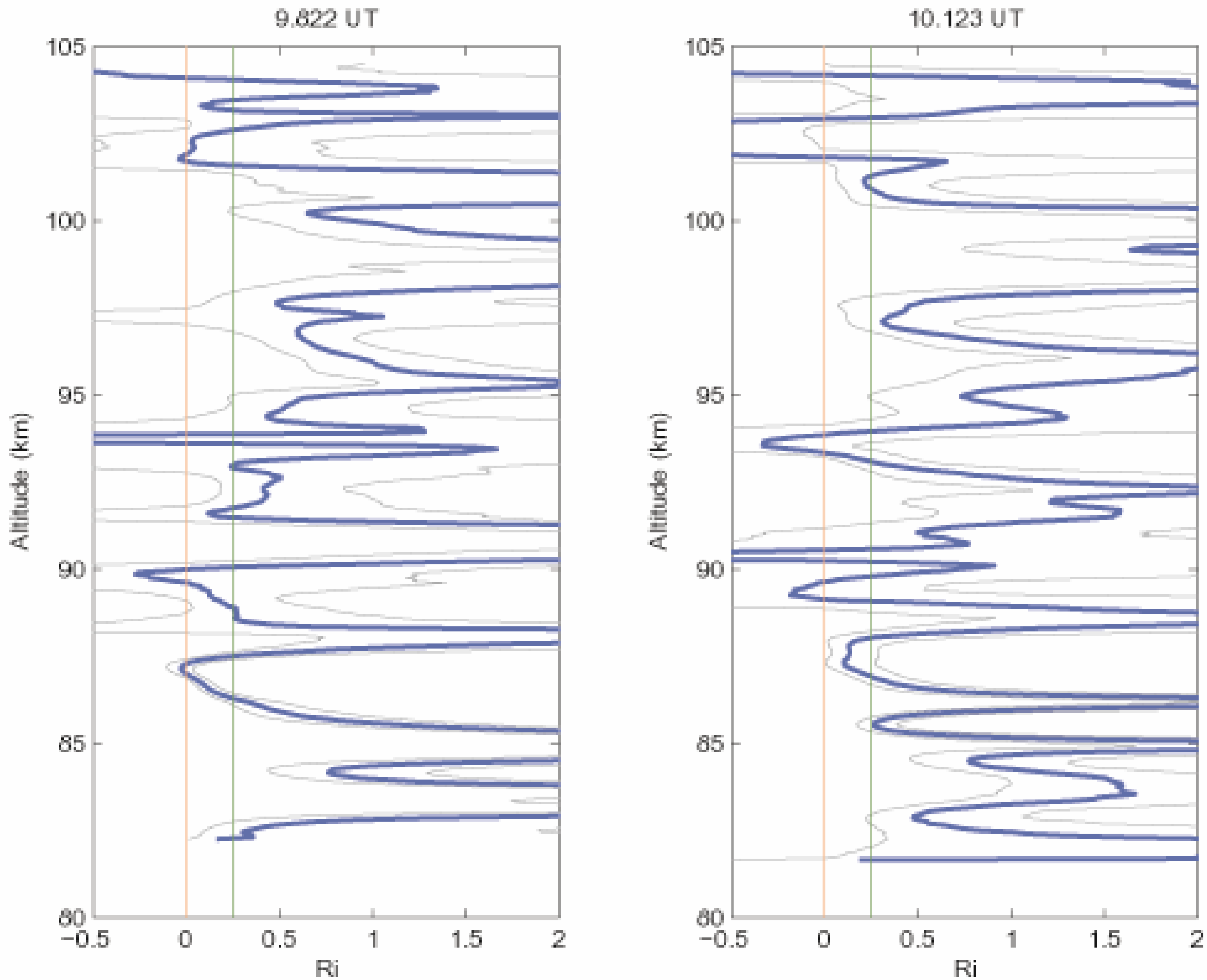
1 km Hamming

Oct 26, 2000



Ri
N^2
Altitude (km)
UT (Hour)
105
100
95
90
85
80
6
8
10
5
1
0.25
0
4

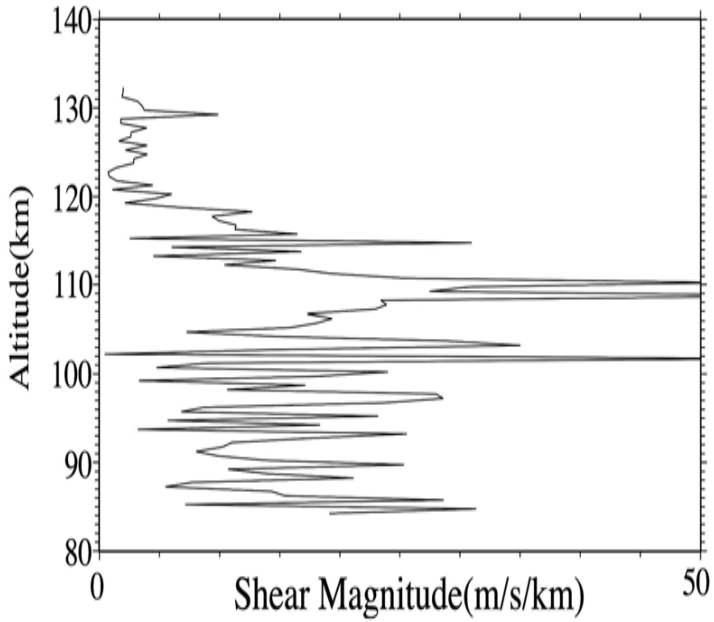

Temperature (1km Hamming)
Altitude (km)
Temperature (K)
Na Density @ 9.837 UT
Altitude (km)
Na Density (cm^{-3})
Zonal Wind @ 9.822 UT
Altitude (km)
Speed (m/s)
Meridional Wind @ 9.822 UT
Altitude (km)
Speed (m/s)



1 km Hamming Δz=1km

Oct 26, 2000

TMA Summary



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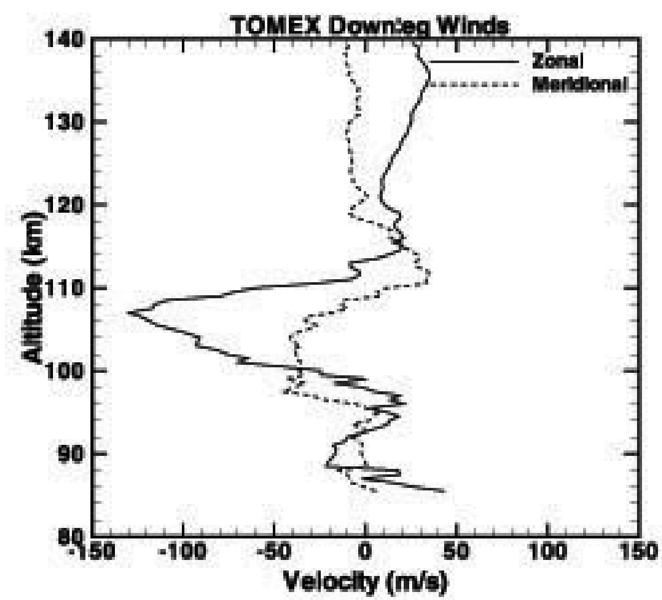
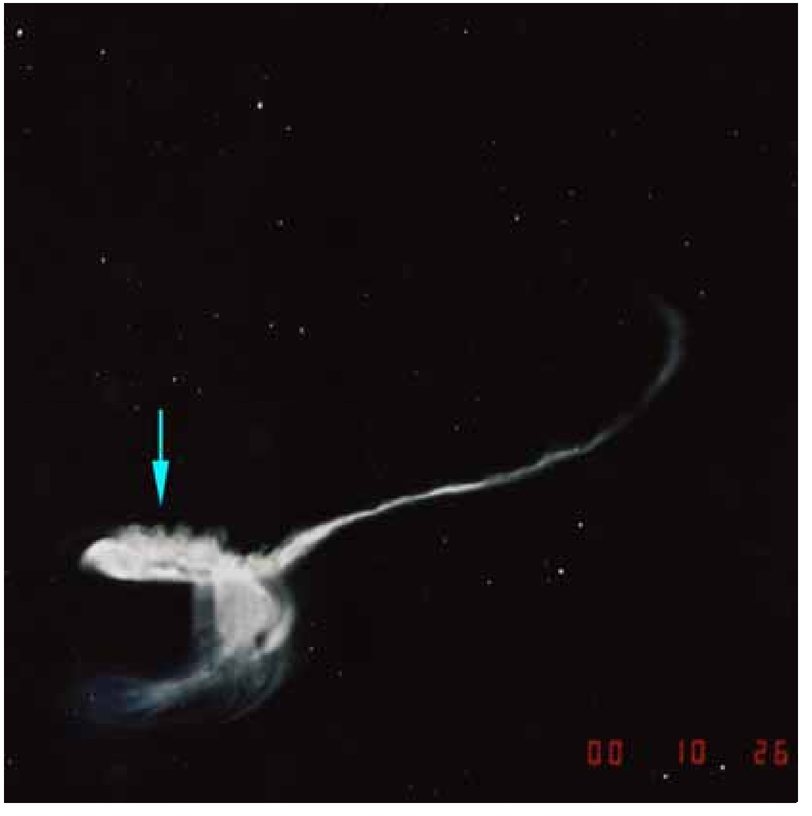
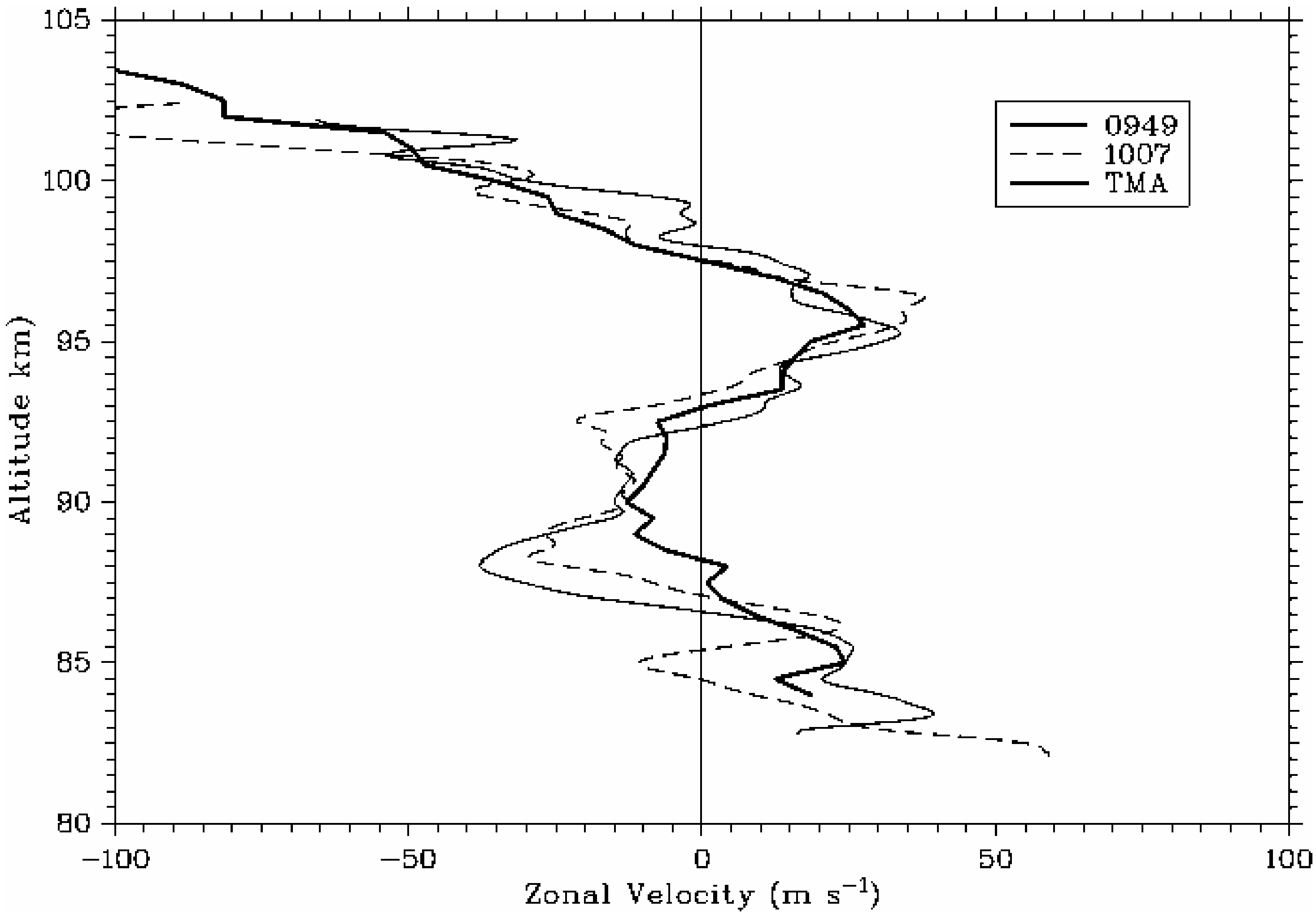
TIFF (LZW) decompressor
are needed to see this picture.



Altitude (km)	Energy Dissipation rate (W/kg)	Eddy Diffusion (m^2/s)
85	0.059 (**Nothing**)	62
87	0.14 (**Dynamical**)	1500 (Low N^2)
93	0.090 (**Convective**)	880 (Low N^2)
96	0.44 (**KH Billows**)	420
98	0.38 (**Convective Roll**)	920
100	**0.92** (**Convective Roll**)	750
102	0.41 (**Convective Roll**)	**1900**
105	0.23	270 (MSIS N^2)
110	0.75 (**Large Shear**)	820 (MSIS N^2)

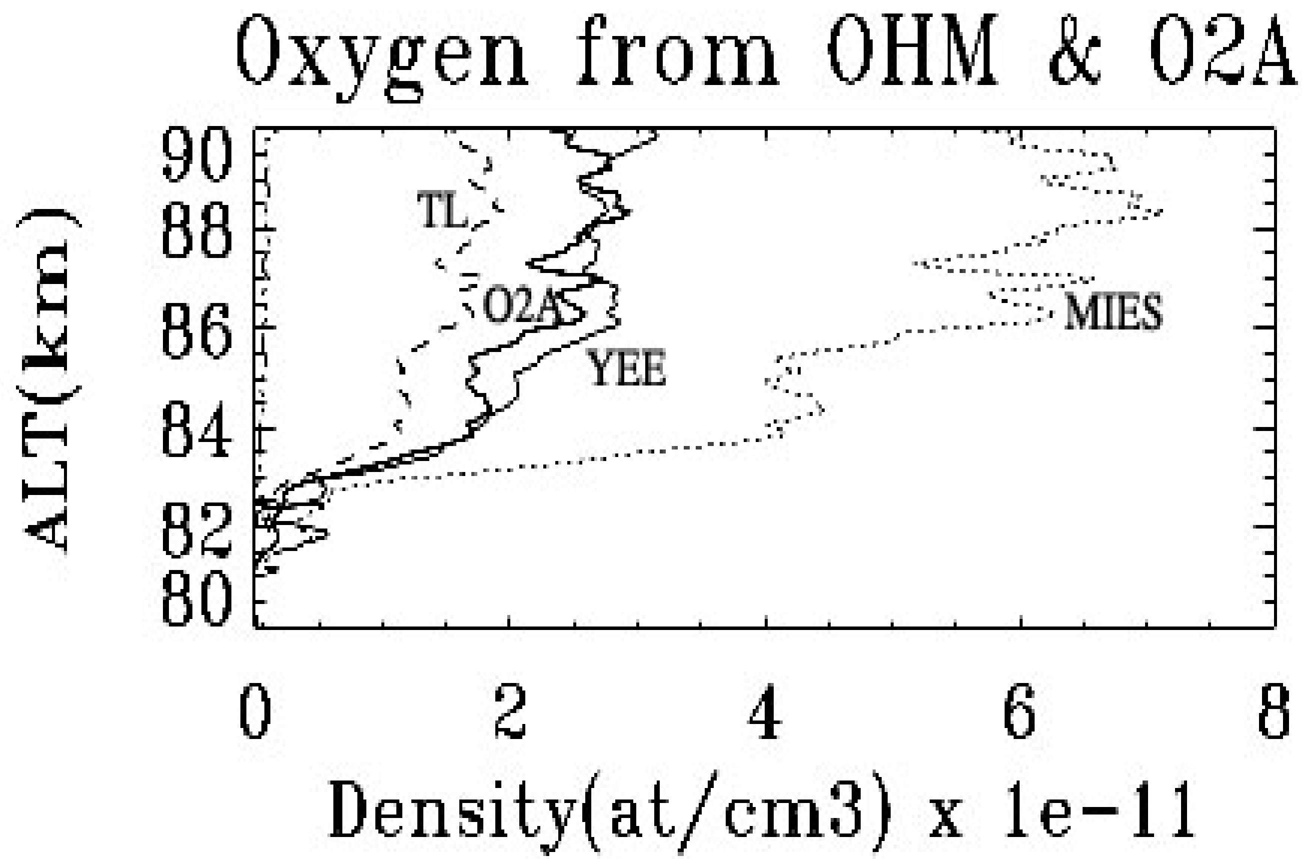
Dynamical Instability/KH Billows





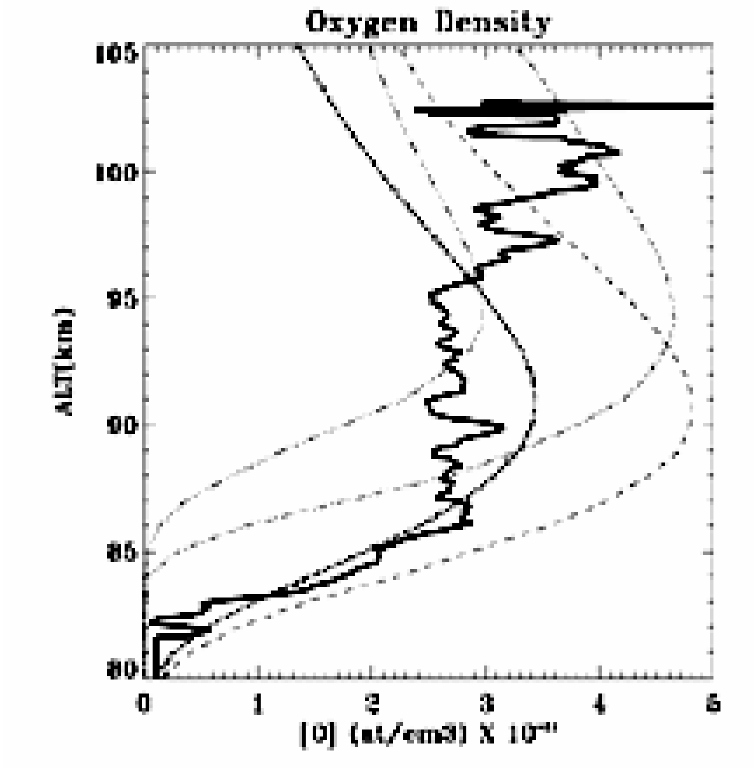
0949
1007
TMA
Altitude km
Zonal Velocity (m s^{-1})
105
100
95
90
85
80
−100
−50
0
50
100

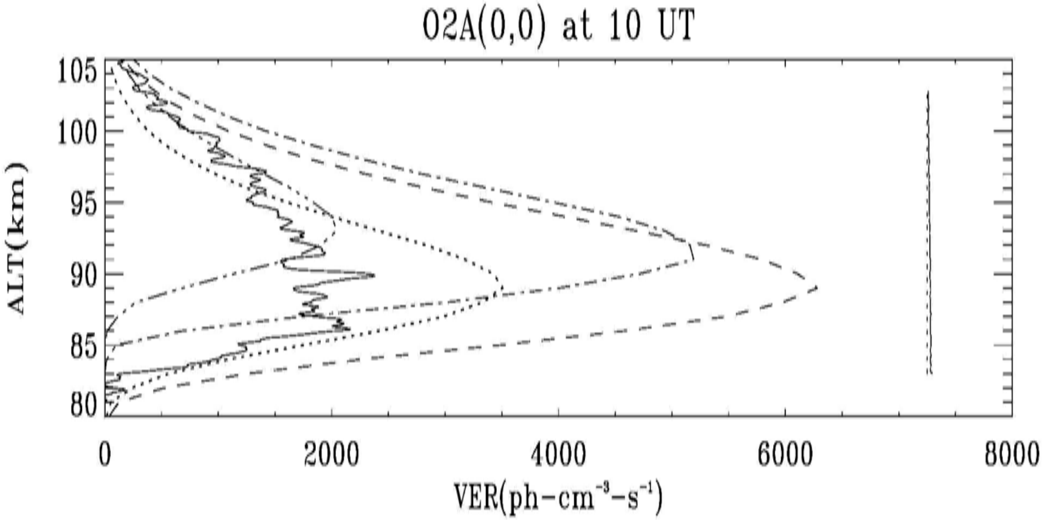
Photometer Summary

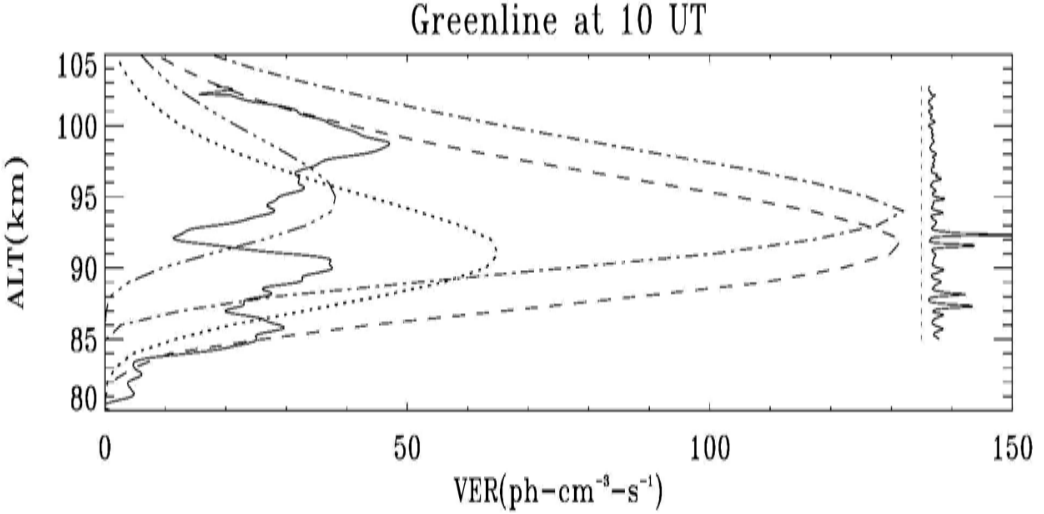


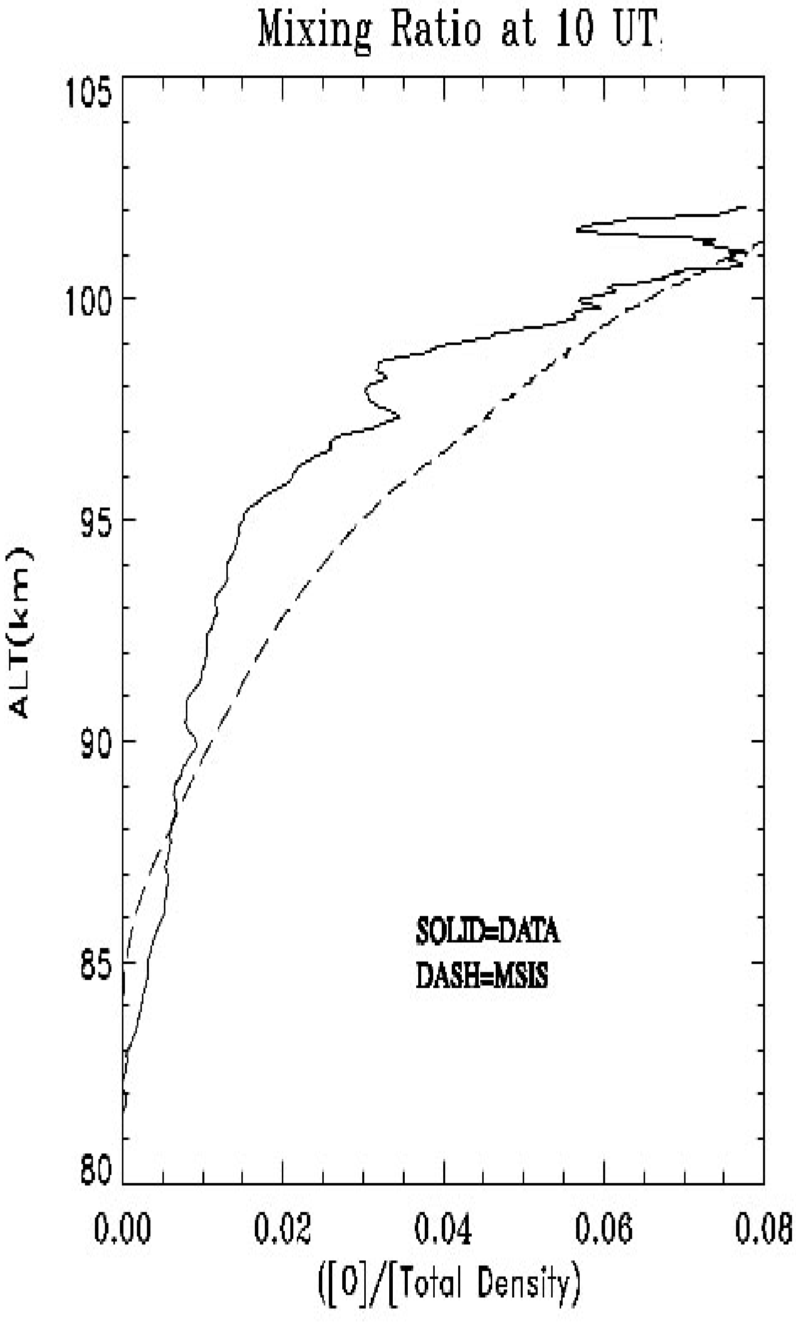
Oxygen from OHM & O2A
90
88
86
84
82
80
ALT(km)
TL
O2A
YEE
MIES
0
2
4
6
8
Density(at/cm3) x 1e-11

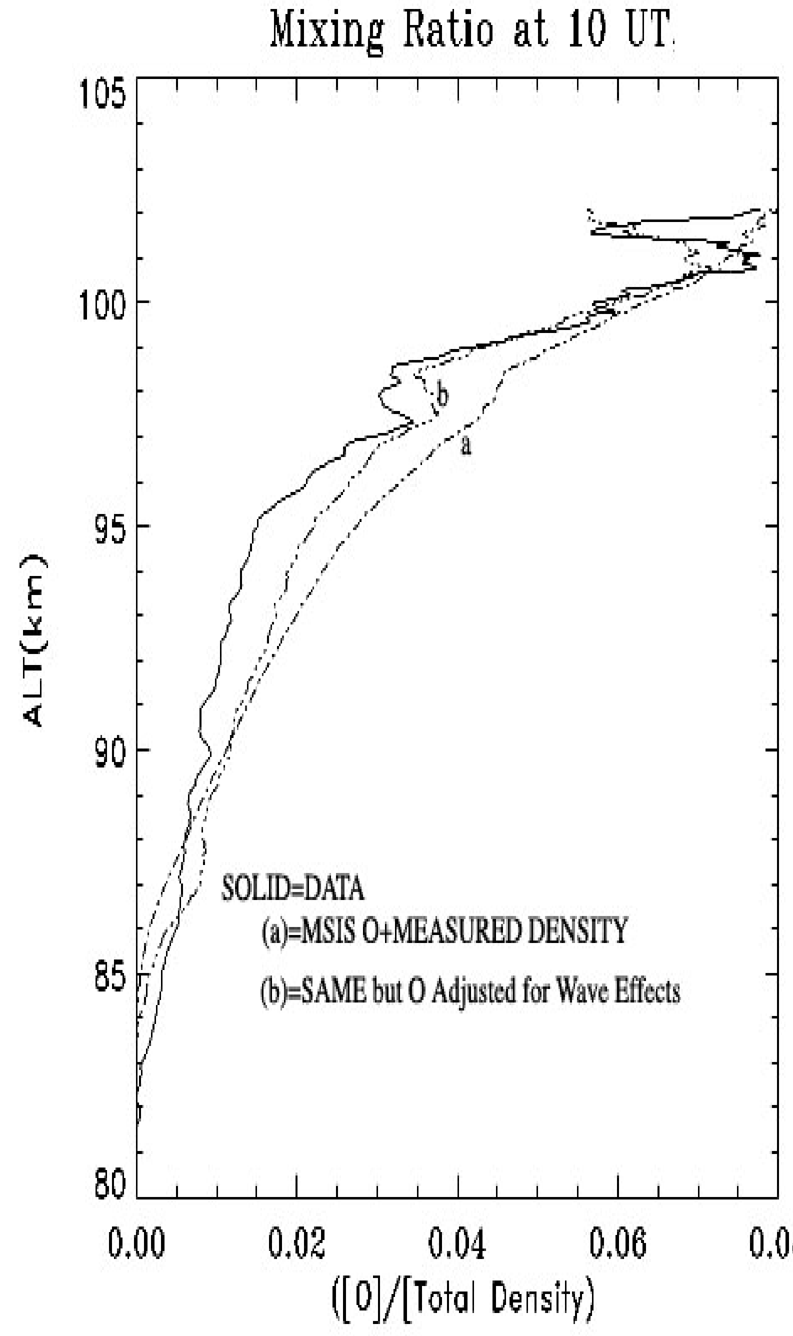
Atomic Oxygen Profile



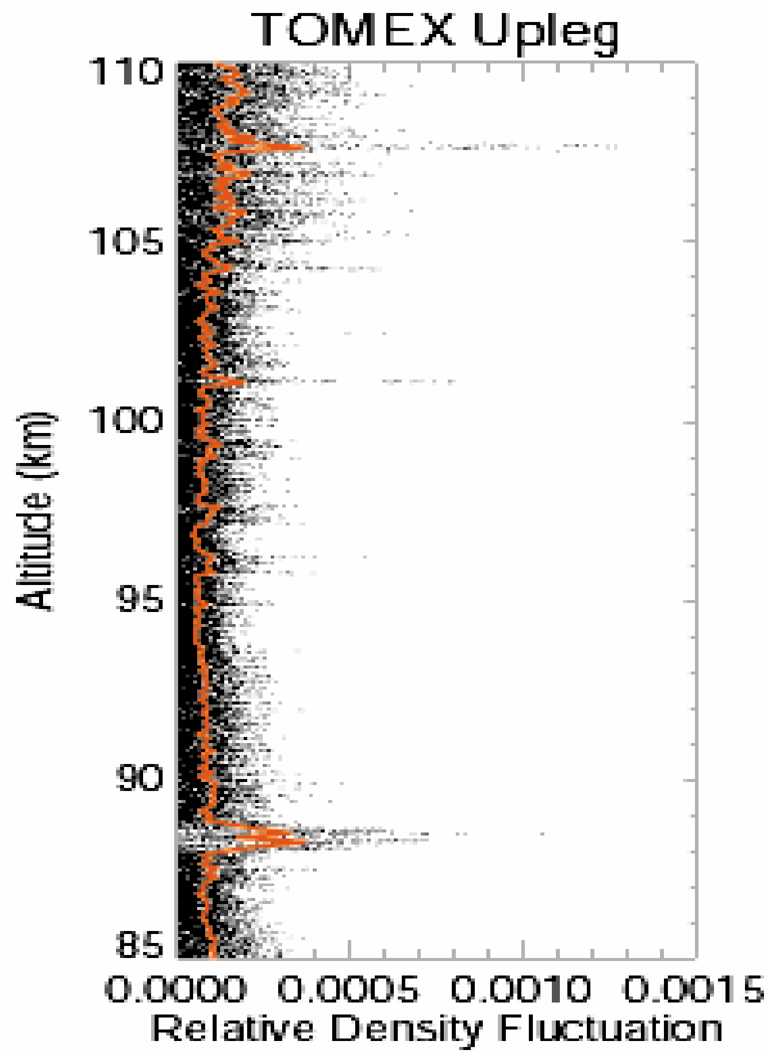




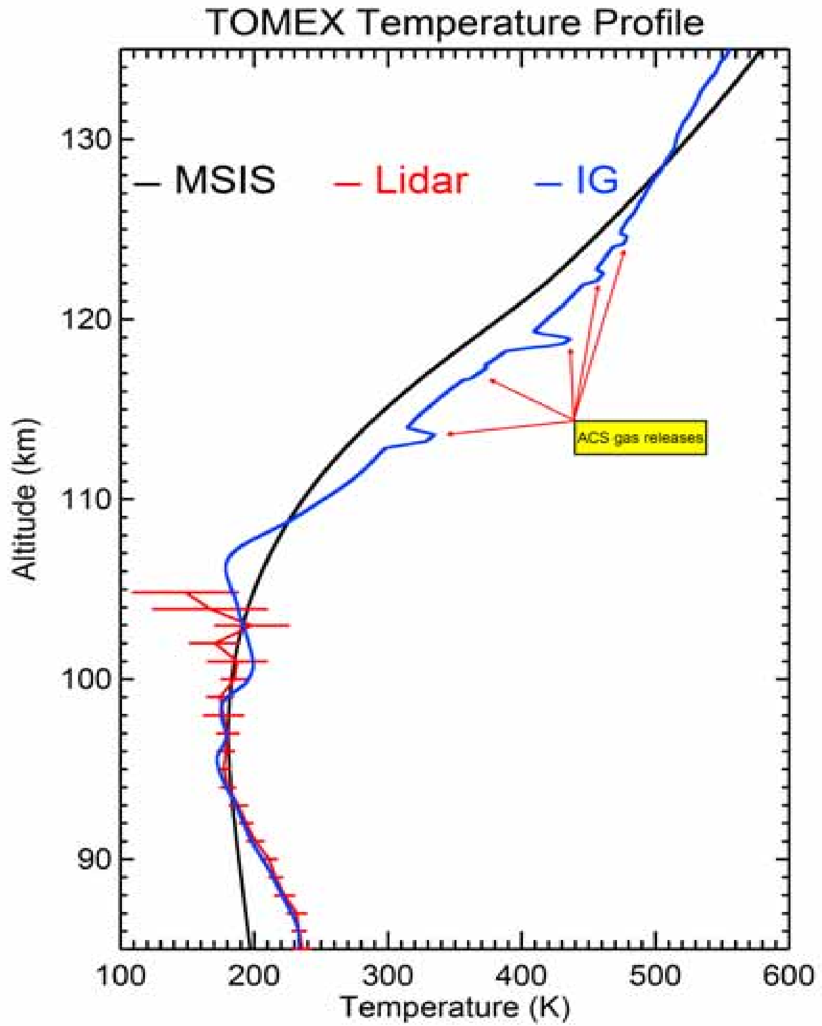

Mixing Ratio at 10 UT
ALT(km)
105
100
95
90
85
80
0.00
0.02
0.04
0.06
0.08
([O]/[Total Density)
SOLID=DATA
DASH=MSIS


Mixing Ratio at 10 UT
ALT(km)
105
100
95
90
85
80
0.00
0.02
0.04
0.06
0.08
([O]/[Total Density)
b
a
SOLID=DATA
(a)=MSIS O+MEASURED DENSITY
(b)=SAME but O Adjusted for Wave Effects

ION GAUGE Summary



TOMEX Upleg
110
105
100
95
90
85
Altitude (km)
0.0000
0.0005
0.0010
0.0015
Relative Density Fluctuation



TOMEX Temperature Profile
MSIS
Lidar
IG
ACS gas releases
130
120
110
100
90
Altitude (km)
100
200
300
400
500
600
Temperature (K)

Airglow Imager Summary

- Wave Periods- 5hrs, 1.5 hrs, 13 minutes
- Momentum Fluxes Dominated by 13 minute wave
- 13 minute, 1.5 H wave
  - Dissipation up to 92 km
  - Freely Propagating Above 95 km

Instability Summary

Alt(km)	Instability[a,b,c]	Billows[d]	Energy Dissipation[e]	ND Fluctuations[e,f]	O Mixing[e]
86-94	Convective(H)	Some	High	Low	High
87-88	Dynamical(A)	None	Peak	Peak	no Peak
90	Convective(A)	None	Very low	Low	Peak
93	Convective(A)	up	High	Low	no Peak
96-98	Dynamical(A,H),Over	up/down	High	Low	High
100-102	Dynamical?(A),Over	None	Highest	Peak	Peak
105	Largest Winds(TMA)	None	High	No Peak	No data
105-110	High Shears(TMA)	None	High	Increasing	No data

State of the Atmosphere

- Liu and Roble
- Nearly Convective Instability Region-diurnal tide and/or AGW
  - Large Altitude region nearly unstable for a long period
  - Not reproduced (in magnitude) by TIME-GCM
    - Affect dissipation
- Small amplitude AGWs then can push the atmosphere into instability
  - Instead of their being small isolated regions of enhanced diffusion those regions can be much thicker

TOMEX Conclusions

- Mesopause Region
  - Complex
  - Numerous Unstable Regions
- Mixing
  - Convective - Largest Effect (Temporal/Spatial)
  - Dynamical - Confined to Narrower Layers

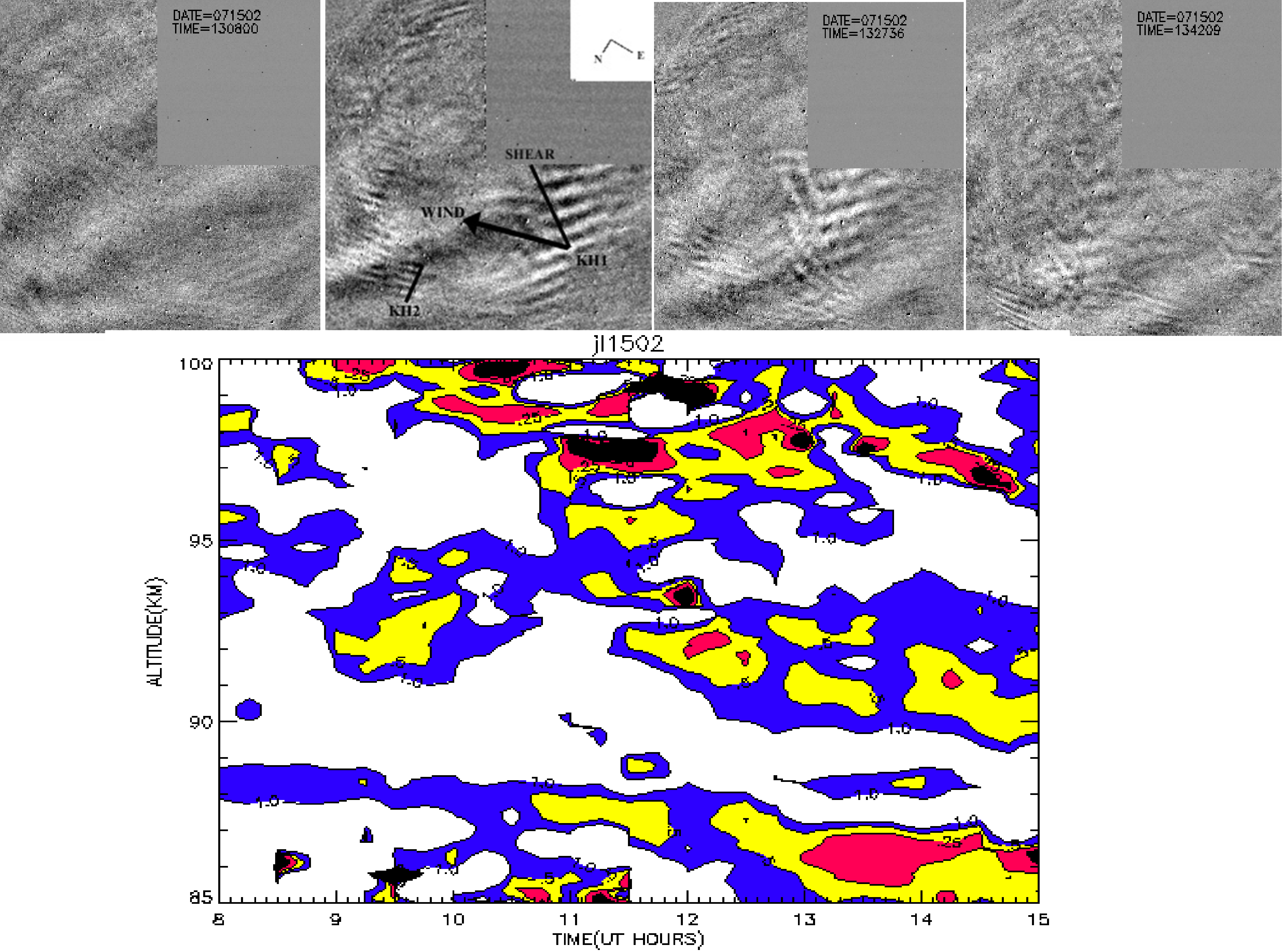
- Energy Dissipation
  - TMA- Much Higher than Ion Gauge
  - Large- Convective Instability
    - Waves Dissipate
  - Very Large -Convective Roll

- KH Billows
  - Recent Not Current Dynamical?

- Atmosphere Nearly Unstable
  - Small Scale Waves - Unstable
  - Lidar Data- Starfire, Maui

Post-TOMEX Work

- Time History - Evolution of Mixing/Dissipation
    - TRIO (Turbulent Response in Oxygen)
    - Three Rockets in One Night to study this Evolution
    - Kauai
- Instability Billows (KH and Convective)-Airglow
    - Ripples
        - Peterson-Taylor
        - CORN Campaign-OH+Lidar Temp-infer Convective
    - Maui-MALT-Airglow Imagers+Wind/Temp Lidar
        - Convective of Dynamically Unstable
            - Need 1 km or better resolution <10 minutes



DATE=071502
TIME=130800
N
E
SHEAR
WIND
KH1
KH2
DATE=071502
TIME=132736
DATE=071502
TIME=134209
jl1502
100
95
90
85
ALTITUDE(KM)
8
9
10
11
12
13
14
15
TIME(UT HOURS)

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

- TOMEX
    - Special Section of JGR-published- notes
- Maui-MALT
    - Special Section of JGR
        - University of Illinois Group-Feng Li
- Colorado State University
    - Wind/Temp Lidar + Airglow Imager
- Future Ground-Based Work
    - Temporal/Spatial Resolution All important
        - Currently 500m-1 km in 1.5 minutes
        - Improved Maui-Malt may decrease these by factor of 10