Boundary Layer Structure, Turbulence and Shallow Cumulus Observations During RICO 2005

A Thesis Defense

By

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Talk Outline

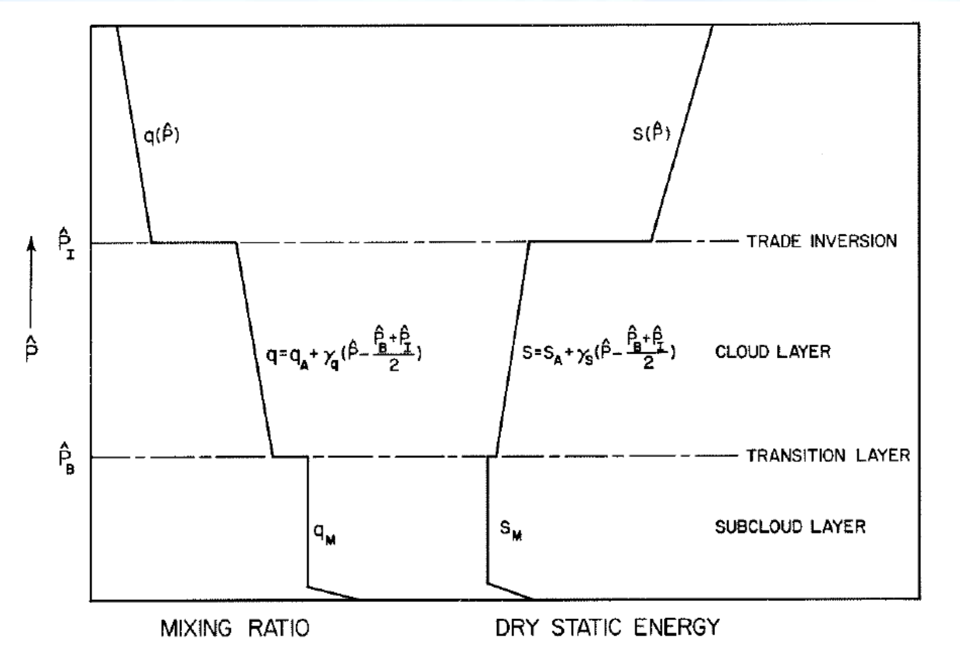
- Introduction/ Motivation
  - Previous Experiments
  - Thesis Objectives
- Field Experiment
  - Instrumentation
- Boundary Layer Structure
  - Synoptic Conditions
  - Clouds and Precipitation
- Lidar Observations
  - Turbulence statistics
  - Mass flux
- Summary/ Future work
- Acknowledgements

Trade Wind Cumulus Clouds: Focus on the Tropical North Atlantic

- The large area pure oceanic environment extends from the western coast of Africa westward to about 61.5ºW and from about 10ºN to 25ºN in latitude.
- Steady or nearly-steady winds from the east or northeast
- During the winter season, this flow is generally uninterrupted by strong convective events

Advection, convection, and radiation maintain a characteristic thermodynamic structure with a cloud layer that is often capped by an inversion of sufficient strength to inhibit deep convection

Albrecht (1993)



Previous Experiments

1946: Puerto Rico (Experiment 1)

- found no evidence of cloud-scale motions below clouds base except in precipitating downdrafts (Malkus 1958)

1969: ATEX (Atlantic Trade Wind Experiment)

1969: BOMEX (Barbados Oceanographic and Meteorological Experiment)

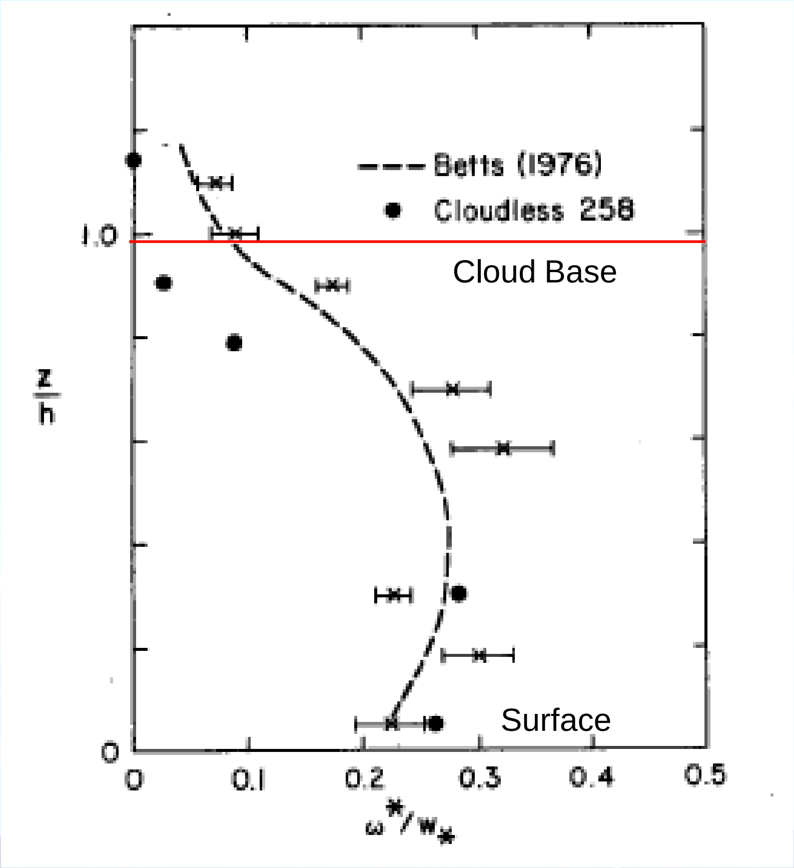
1972: Puerto Rico (Experiment 2)

- found cloud scale updrafts which were traceable to at least 100 meters below cloud base (LeMone and Pennell 1976)

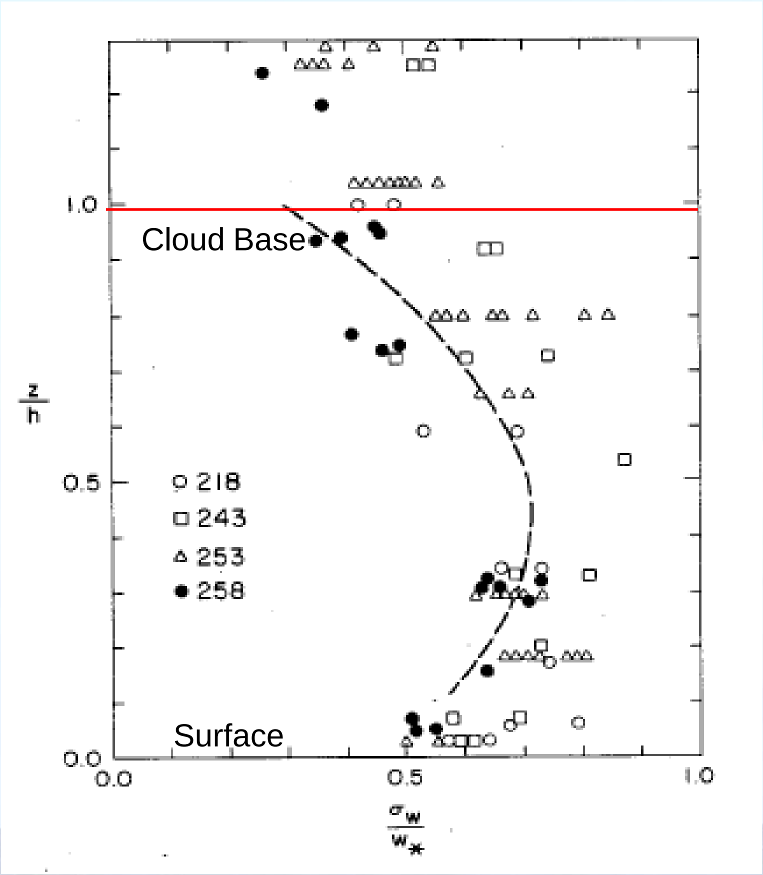
1974: GATE (GARP Atlantic Tropical Experiment)

found updrafts extending from near the ocean surface to just above cloud base (Emmitt 1978)

Nicholls and LeMone Turbulence Profiles (1980)



Mass Flux



Standard Deviation of w

Betts (1976) results from BOMEX

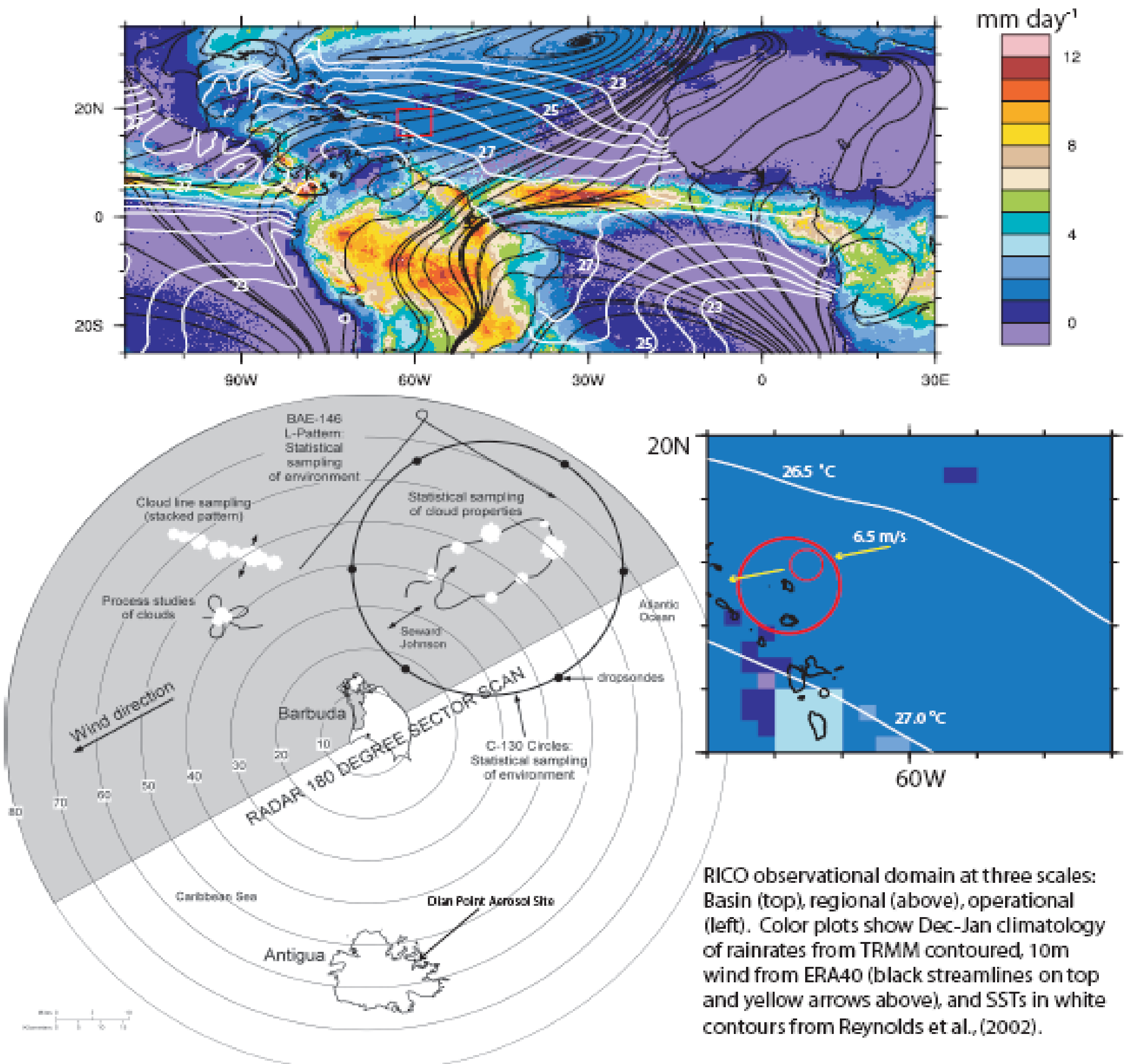
Nicholls and LeMone results from GATE

Curved line is from laboratory results of Willis and Deardorff (1974)

Thesis Objectives

- Analyze the observed variability and relationship between MABL cloud properties and surface meteorology variables and radiative fluxes.
- Study the temporal and spatial scales of variability of cloud properties and boundary layer structure during RICO.
- Investigate the coupling between the observed boundary layer cloud variability and sub-cloud turbulence.

Rain In Cumulus Over the Ocean (RICO) Field Experiment



RICO observational domain at three scales: Basin (top), regional (above), operational (left). Color plots show Dec-Jan climatology of rainrates from TRMM contoured, 10m wind from ERA40 (black streamlines on top and yellow arrows above), and SSTs in white contours from Reynolds et al., (2002).

(Rauber et al. 2007)

Objective:

To characterize and understand the properties of trade wind cumulus at all scales, with particular emphasis on determining the importance of precipitation.

Rain In Cumulus Over the Ocean (RICO) Field Experiment

1) Antigua

   Sky observations, briefings, seminars, outreach

2) Barbuda
   - Soundings
   - S-PolKa Radar

3) Aircraft
   - University of Wyoming King Air
   - BAE
   - NCAR/NSF C-130

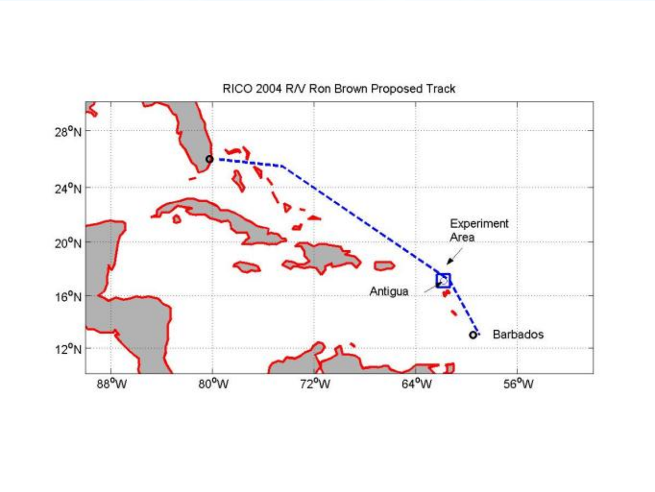
4) Puerto Rico

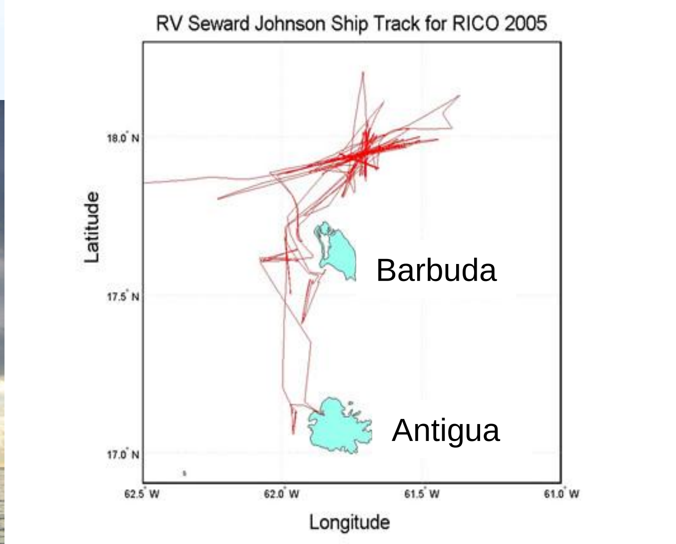
   Aerosol Measurements

5) Ship Observations

R/V Seward Johnson

1/9/05-1/23/05





Ship Instrumentation

Remote Sensor	Technical Specifications	Measurement
Ceilometer	Vertically pointing, laser diode	Cloud-base height with time
Doppler Lidar (ESRL)	scanning and staring, stabilized	High resolution Doppler spectra around and below clouds
W-Band Doppler radar (UM)	94 GHz vertically pointing, unstabilized	High resolution Doppler spectra, cloud and precipitation microphysics and dynamics
Ka-Band Doppler cloud radar (ETL)	35GHz scanning	Cloud microphysical properties
X-Band Doppler Radar (UM)	9.4 GHz vertically pointing, unstabilized	Cloud dynamics and precipitation physics
Wind Profiler (ETL)	915 MHz	PBL 3-D winds, inversion height, clouds
Microwave Radiometer (ETL)	Laser diode, 2-channel “mailbox”	Integrated cloud liquid water and integrated total water vapor

→

Lidar Technical Specifications

Line Tunable Wavelength:

9.2-11.3 μm

Pul 2 mJ

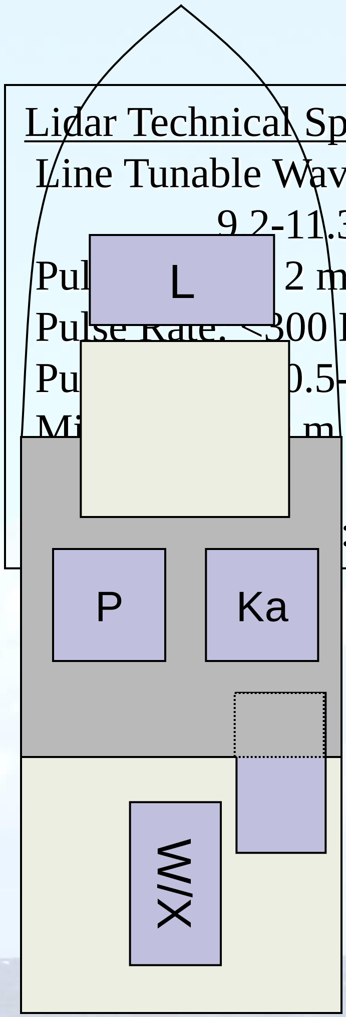
Pulse Rate: <300 Hz

Pu 0.5-10 μs

Mi m

km

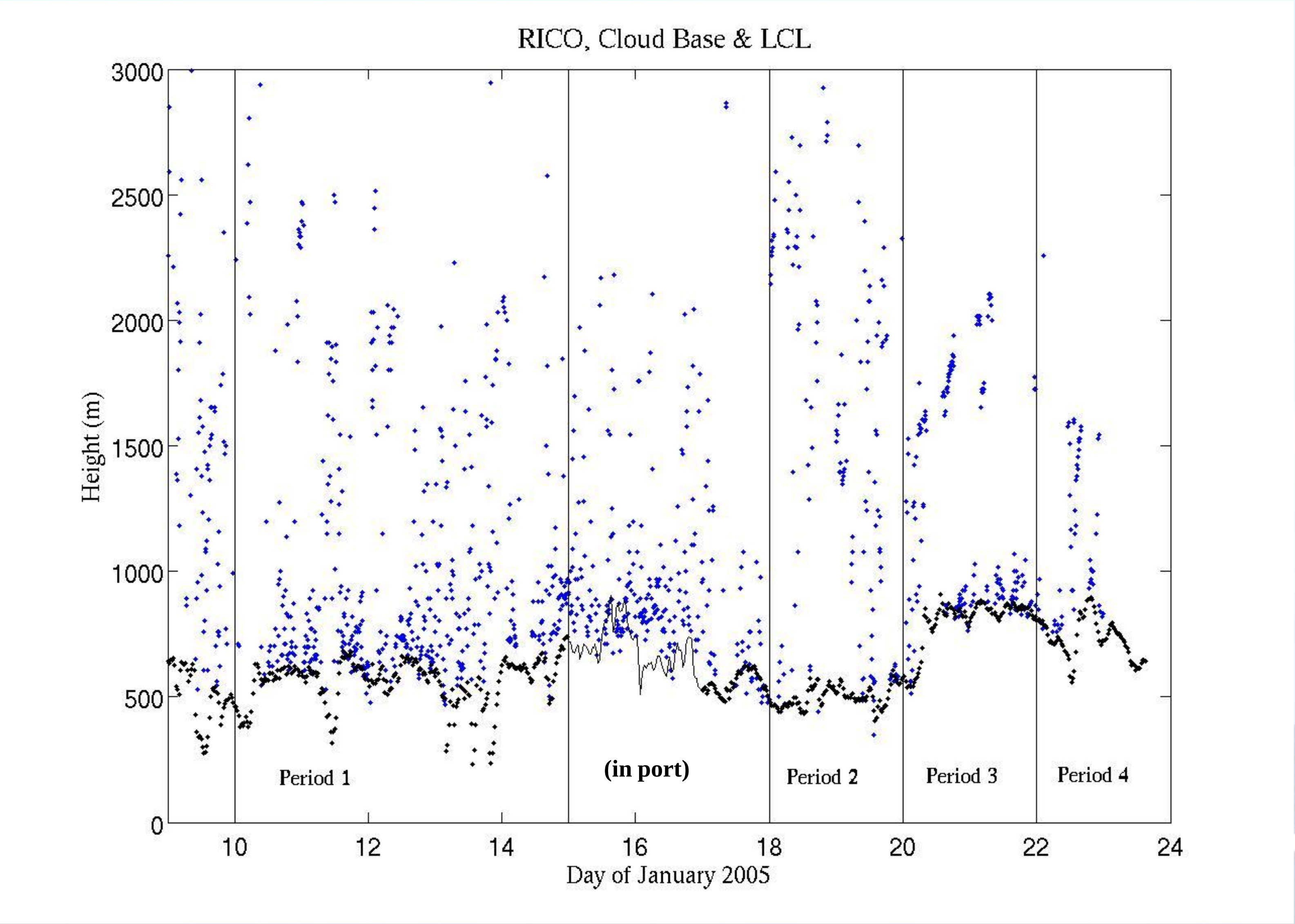
: >60m



Surface meteorology, turbulent and radiative flux measurements as well as aerosol spectrometer measurements provided a near-surface complement to these remote sensing instruments.

Rawinsondes: Soundings were launched between 4-6 times a day depending on stage of experiment.

Boundary Layer Structure: Cloud Base Height and LCL



Synoptic Periods

Period 1: January 10th-14th (SP1)

- Disturbed period. Winds strong and zonal, atmosphere moist, frequent rain showers. Clouds convective in nature.

Period 2: January 18th-20th (SP2)

- Period of transition. Increased low level moisture, very dry air aloft. Many rain showers. Winds weaker and from NE.

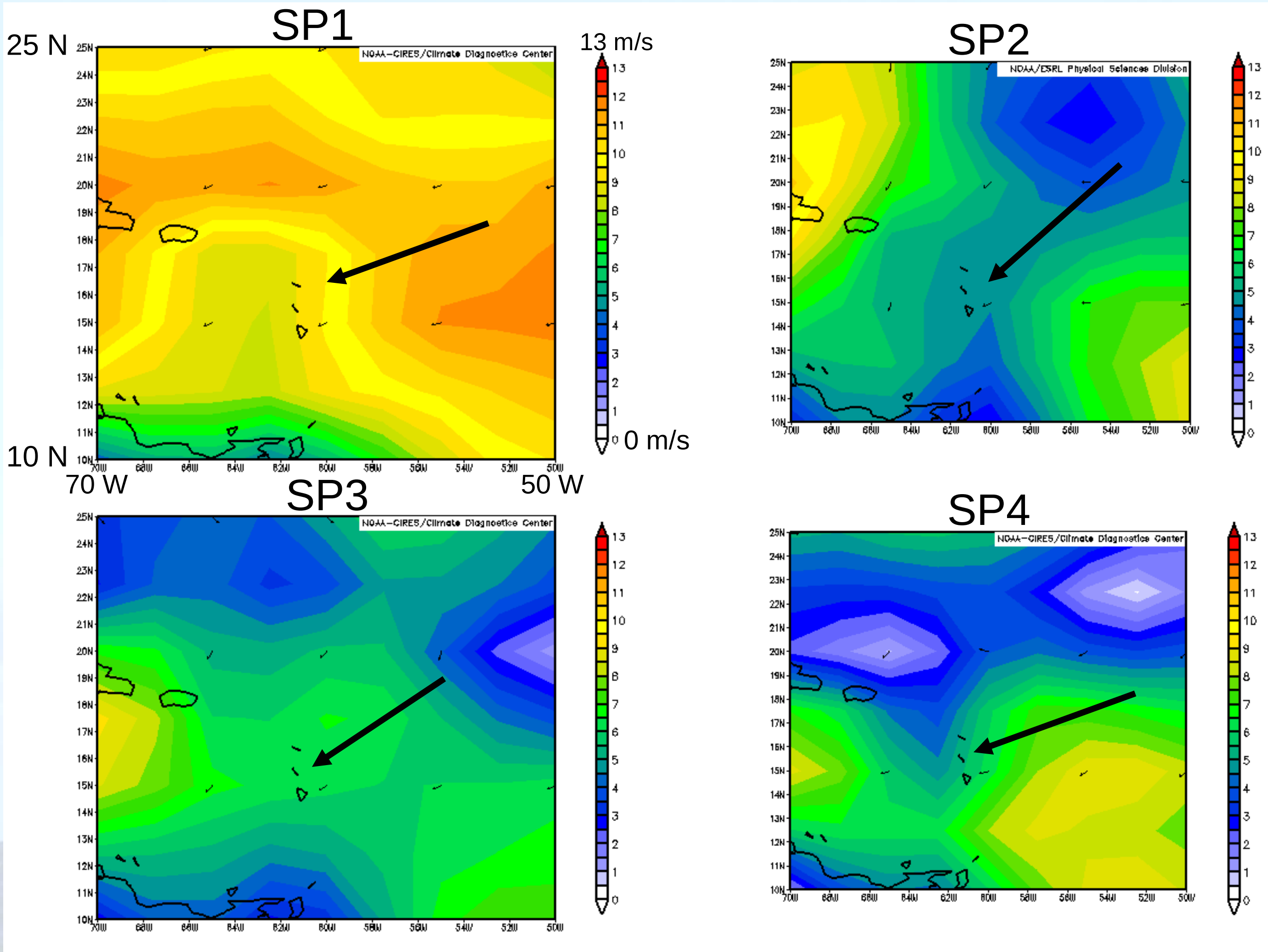
Period 3: January 20th-22nd (SP3)

- Very stable environment. “Typical” trade wind conditions- light to moderate easterly winds and very little convection or precipitation. High pressure built in from the NW, clouds were very small and shallow.

Period 4: January 22nd-24th (SP4)

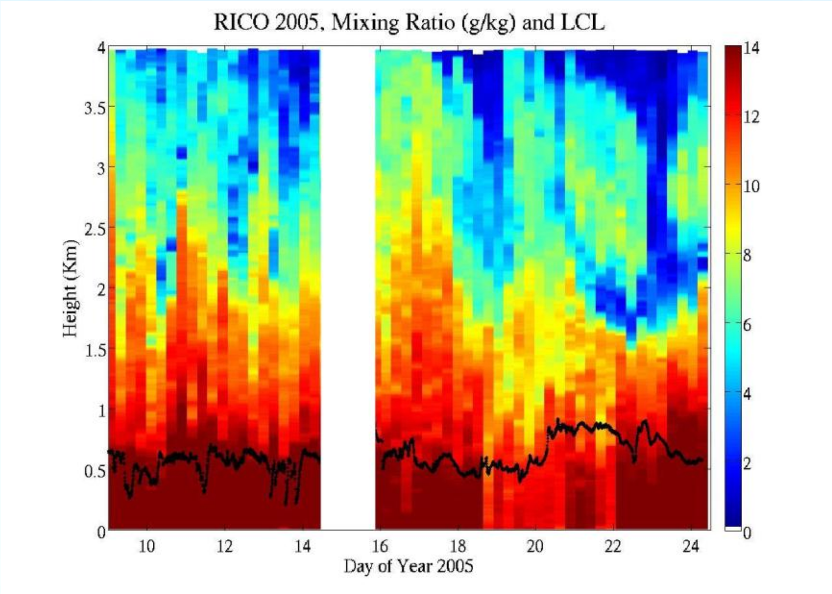
- Similar to SP3 except with increasing temp and humidity. Strong inversions existed at 850 mb and 670 mb keeping conditions stable.

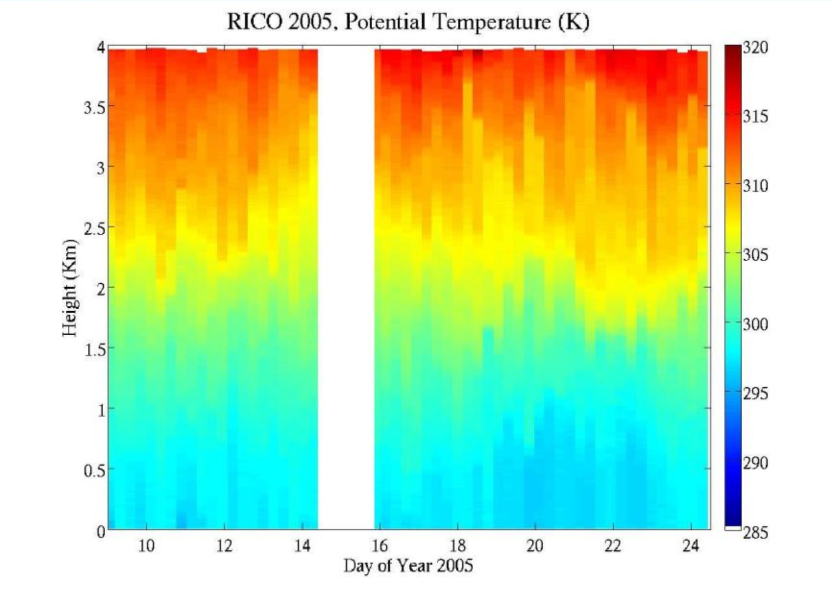
Vector Winds by Synoptic Period

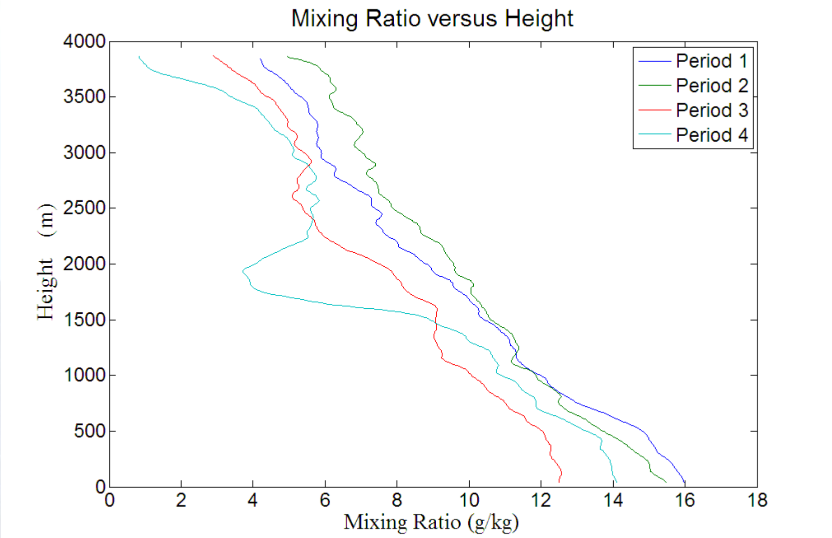


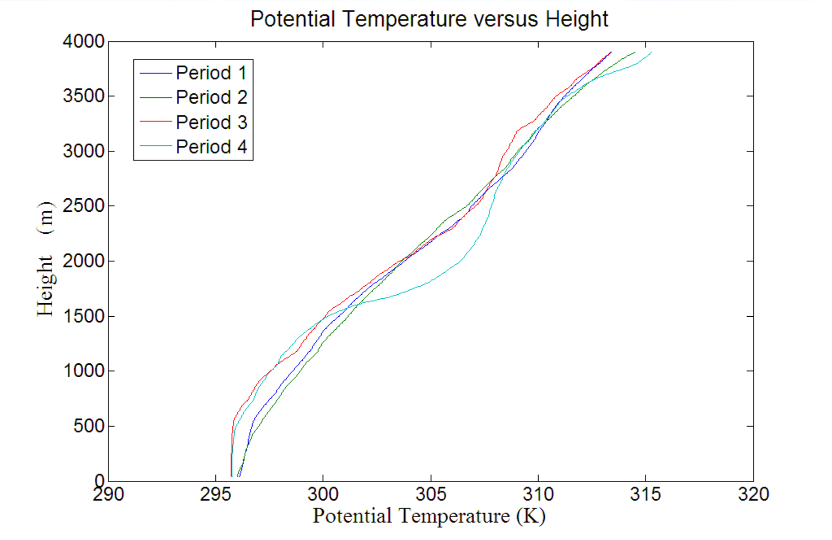
Surface Vector Wind Composites, m/s: January 10-14, 2005 (upper left), January 18-20, 2005 (upper right), January 20-22, 2005 (lower left) and January 22-24, 2005 (lower right).
Created at www.cdc.noaa.gov using NCEP Reanalysis.

Moisture and Potential Temperature Structures

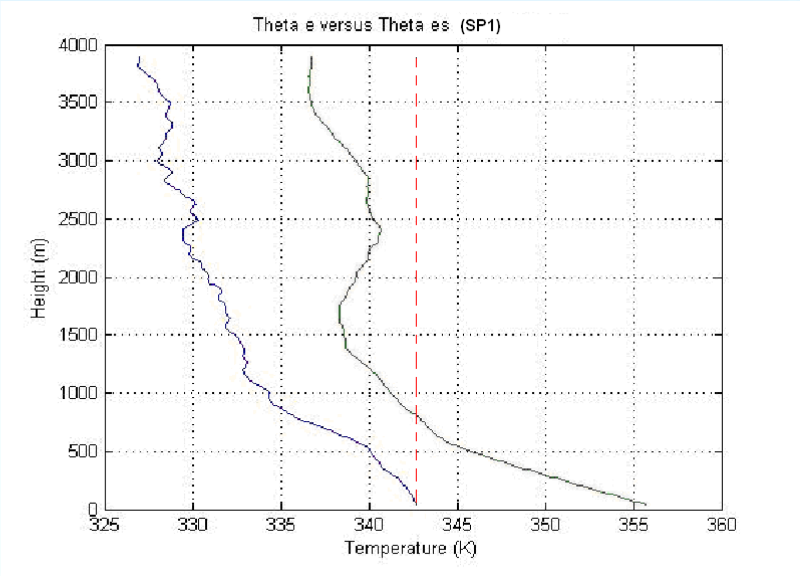


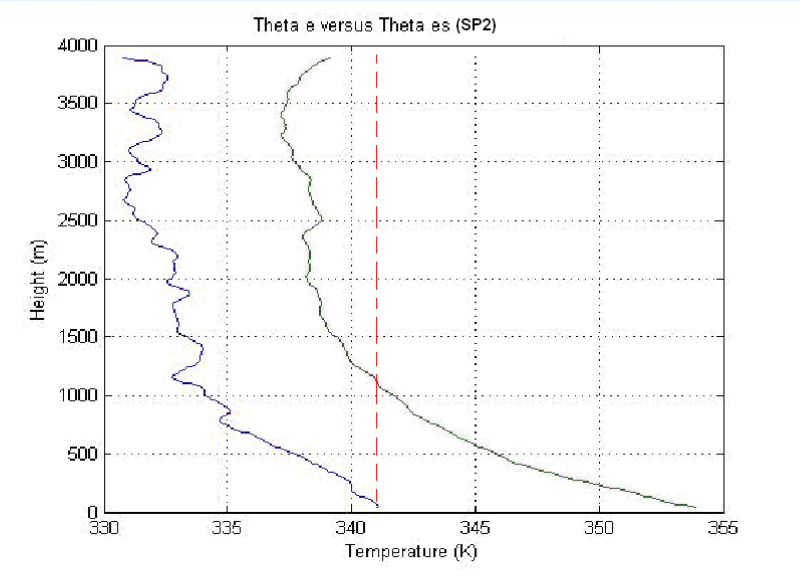


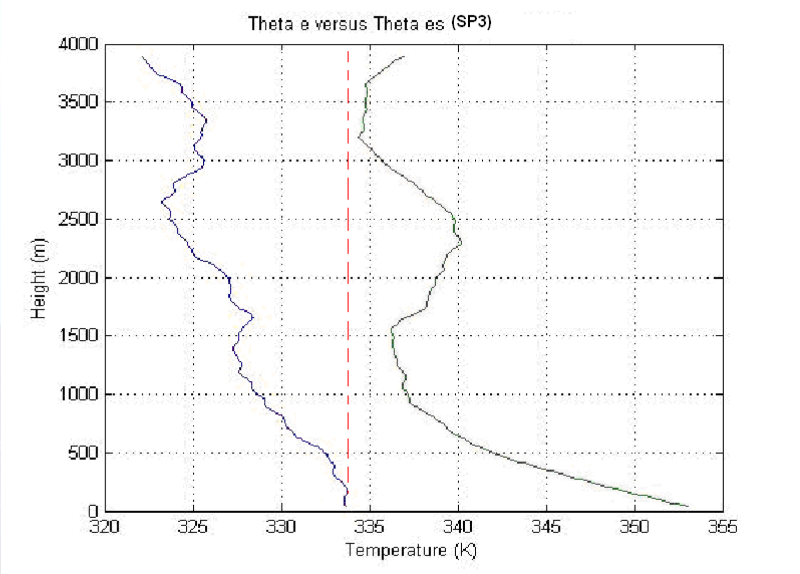


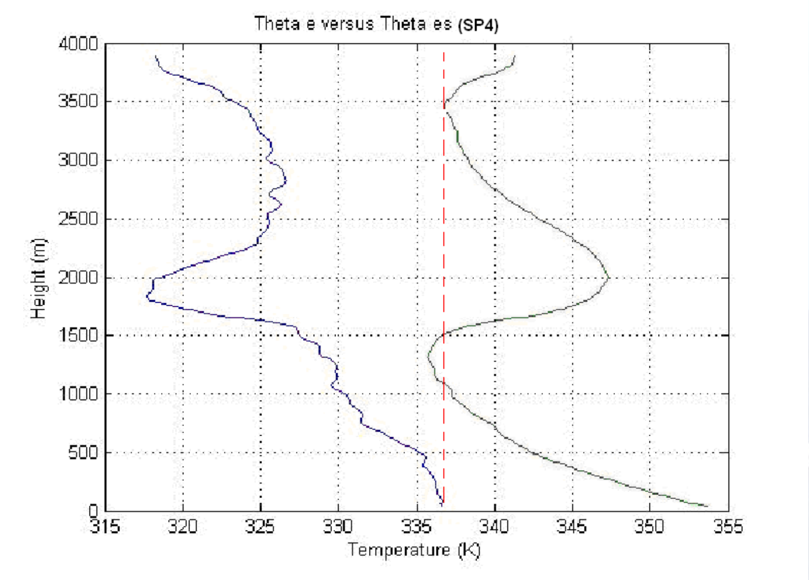


Mean Thermodynamic Profiles

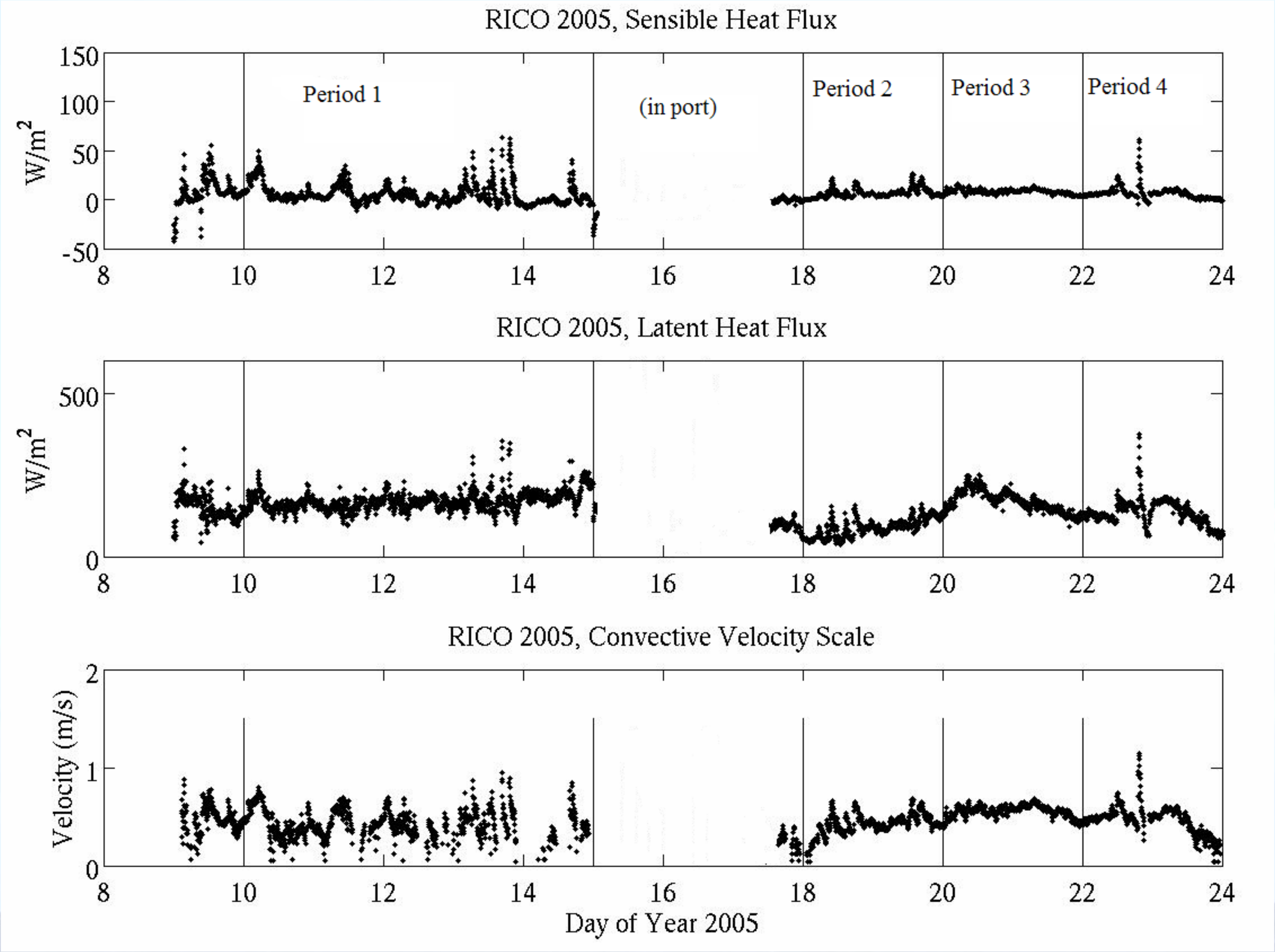








Sensible Heat (SH) and Latent Heat (LH) Fluxes

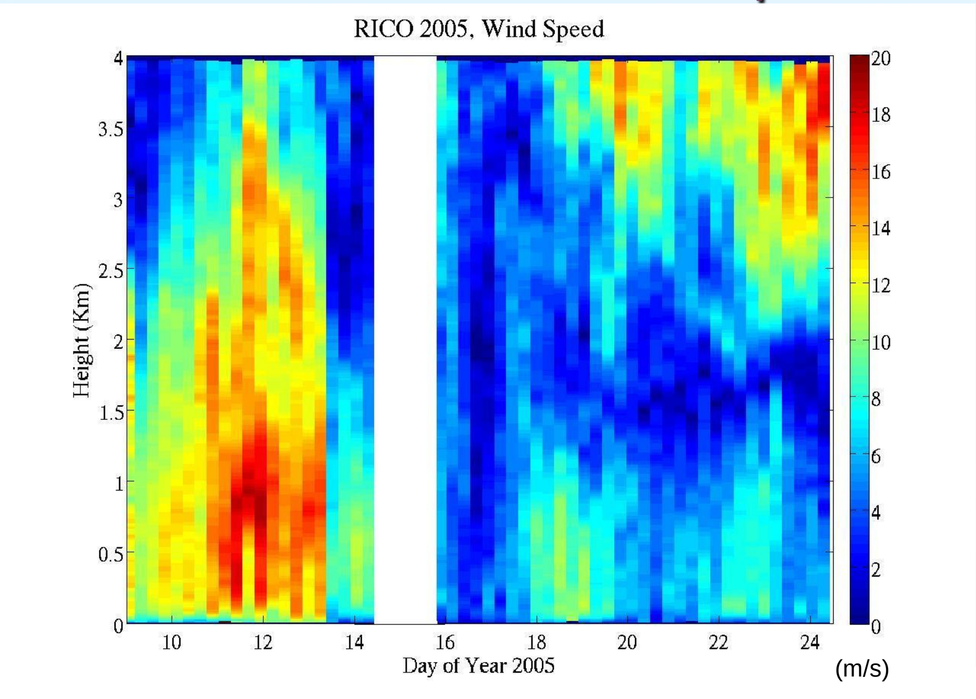


(also known as the Deardorff velocity)

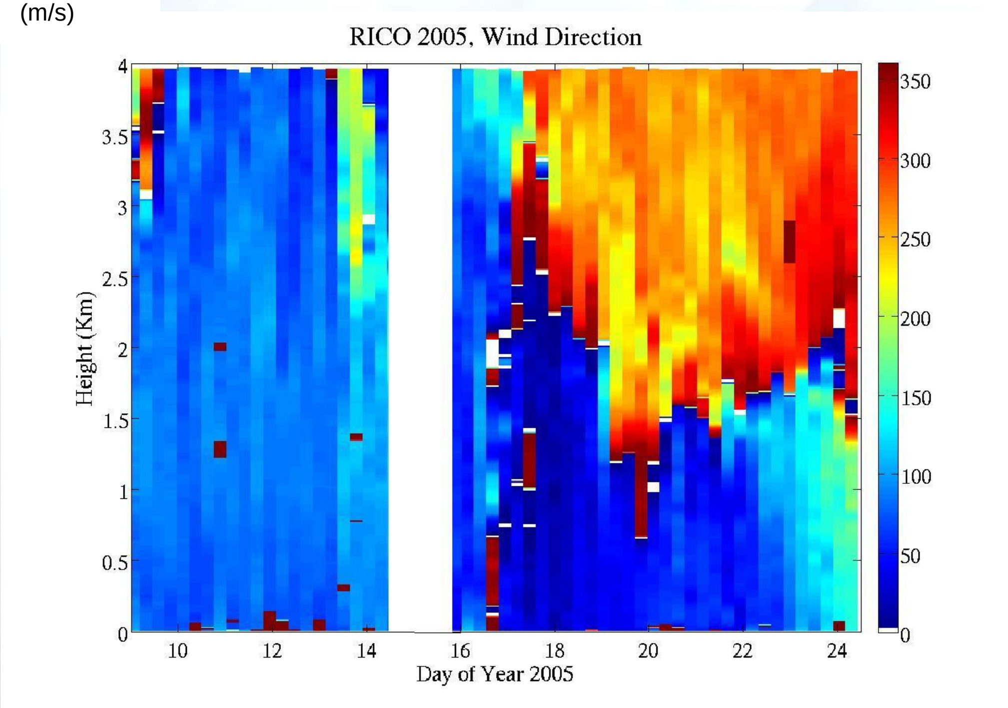
Convective Velocity Scale= $w* = [g\overline{T}^{-1}\overline{(w'T_v')}_0 h]^{1/3}$

The values of our calculated w* range from 0-1 m/s, with a cruise average of 0.48 m/s, which is similar to the average w* values of 0.54 m/s found by Nicholls and LeMone (1980) during GATE.

Wind Speed and Direction



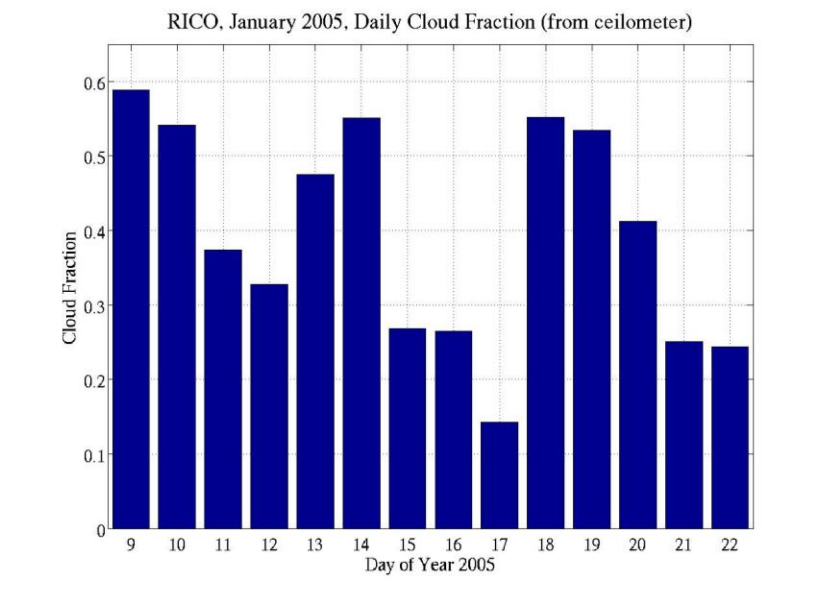
Wind speeds decrease dramatically after SP1



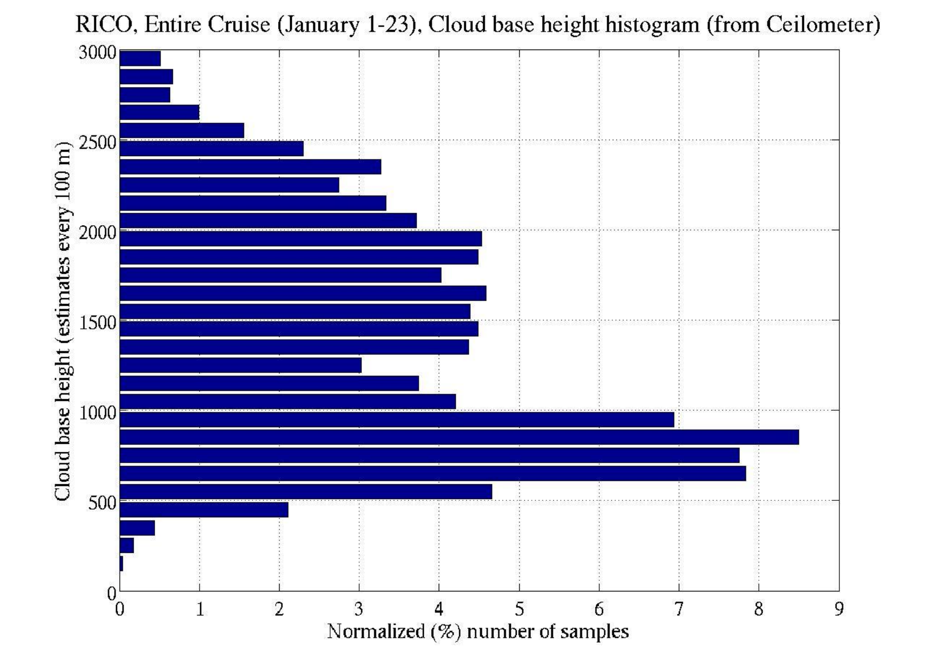
In subcloud layer, easterly winds during SP1 and 4, NE during SP2 and 3.

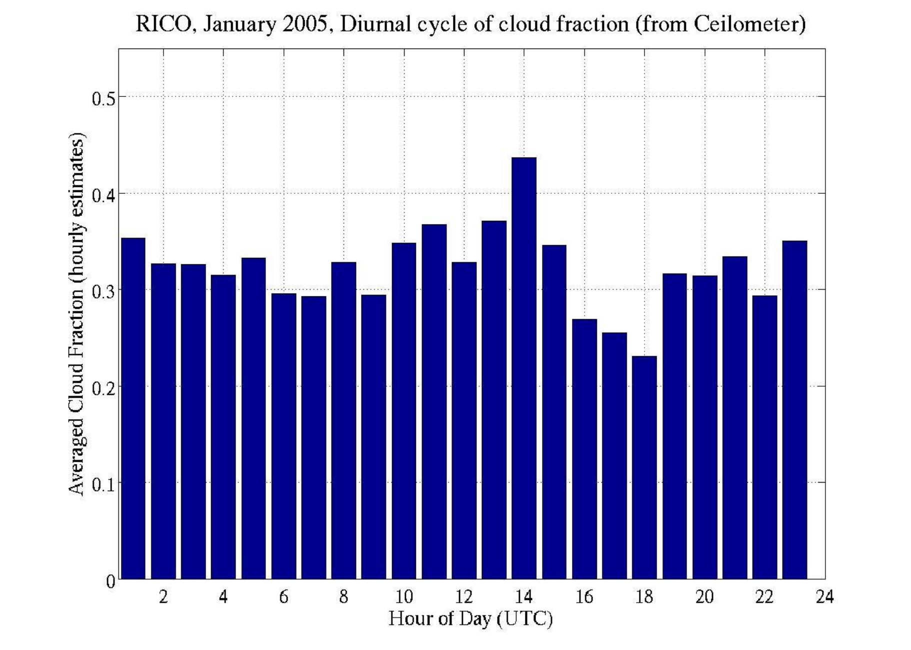
Aloft, westerlies lower to 1.5 km during SP3 and SP4

Fractional Cloudiness and Cloud Bases



RICO Cloud Fraction= 0.39

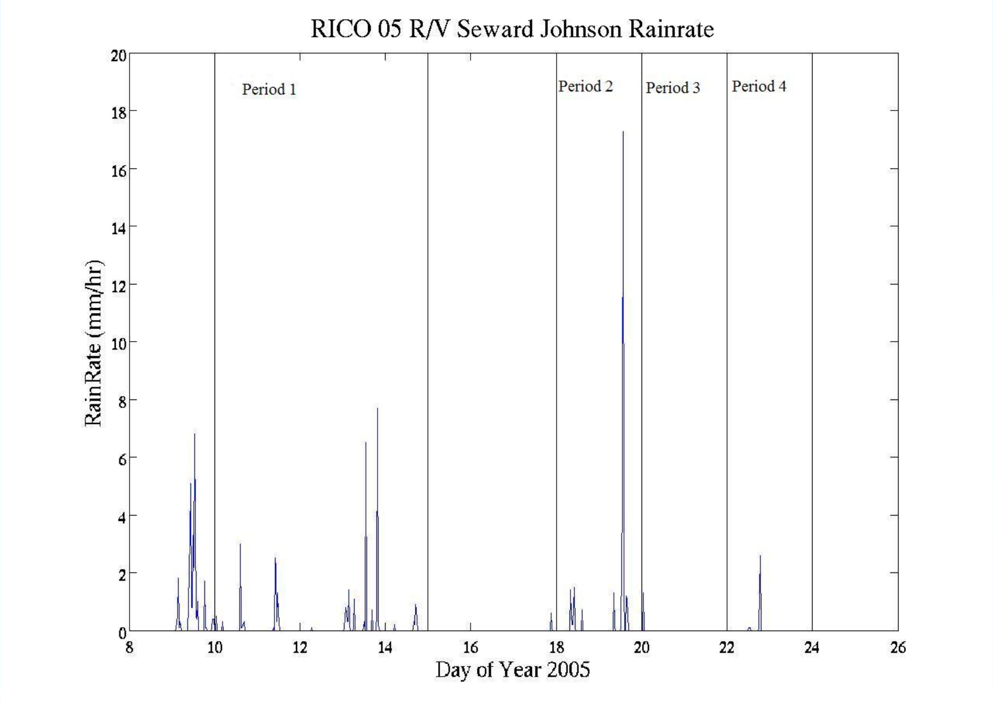




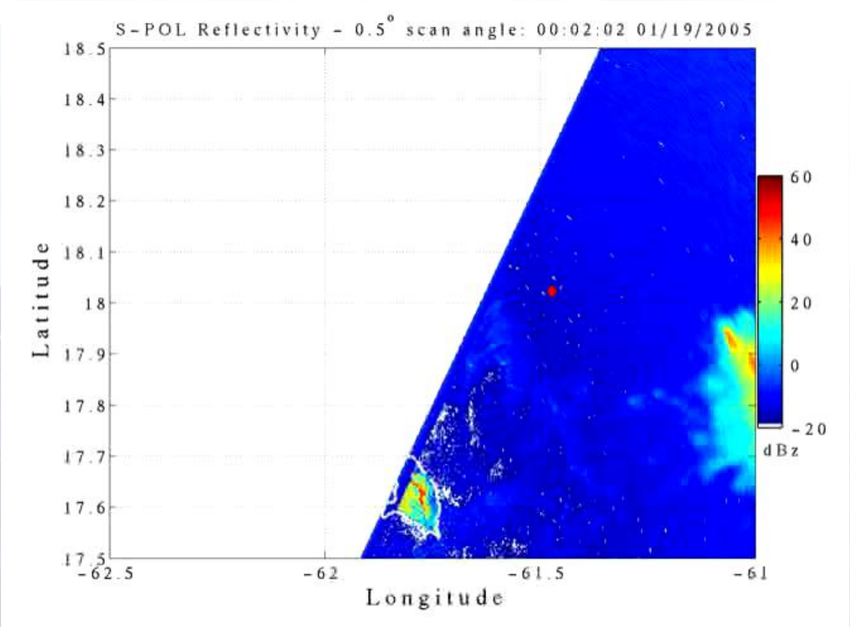
Two cloud bases:
~700 m from SP1 and SP2,
~1400-2000 is from SP3 and SP4

Highest cloud fraction occurred during morning hours

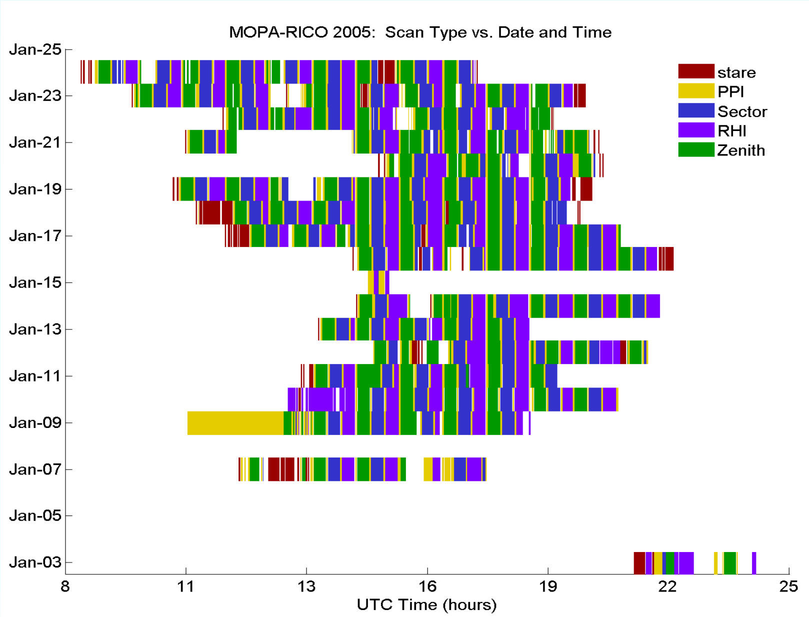
Rainfall Occurrence

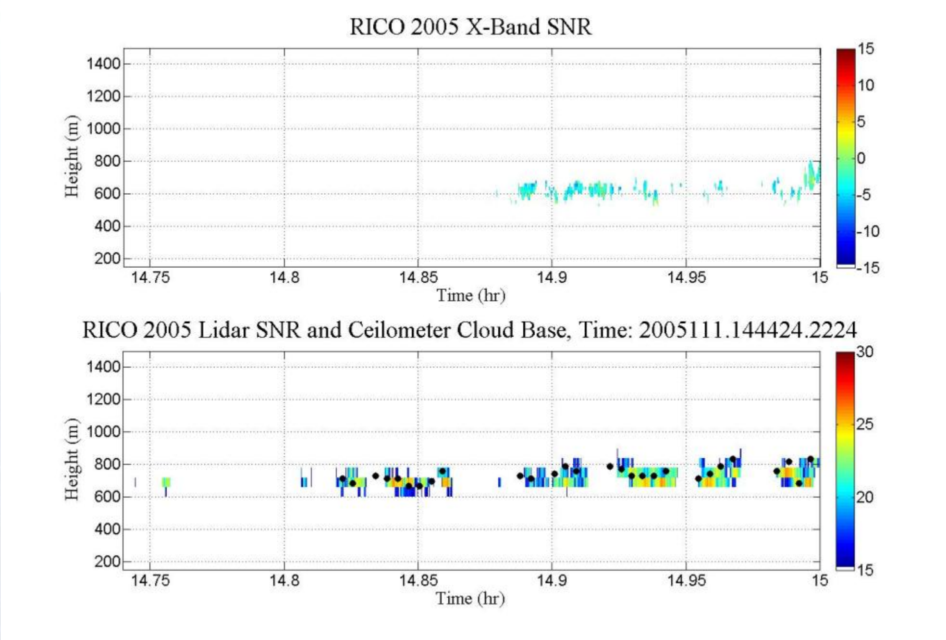


S-Pol Radar on Barbuda

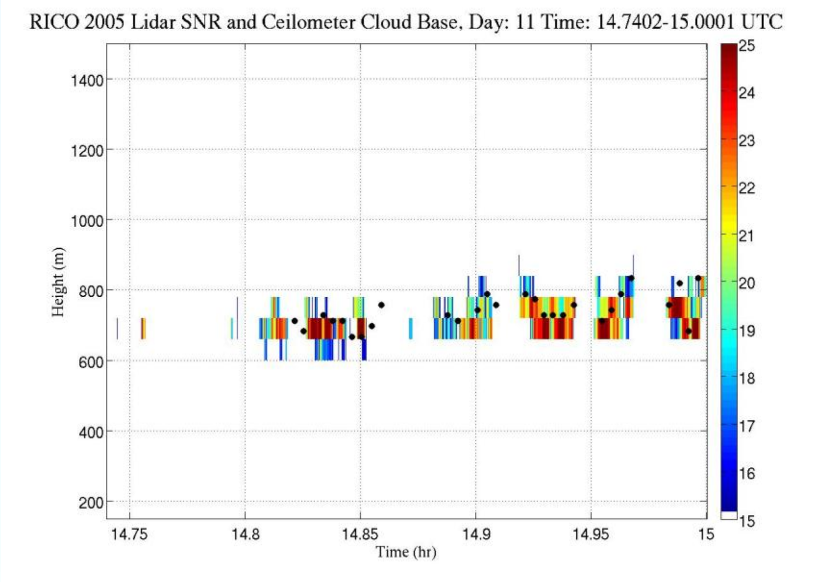


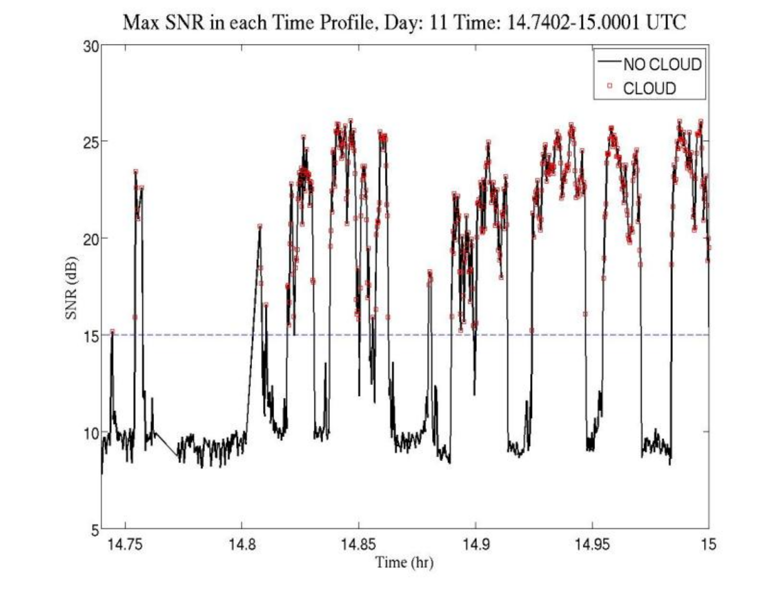
Lidar Instrumentation





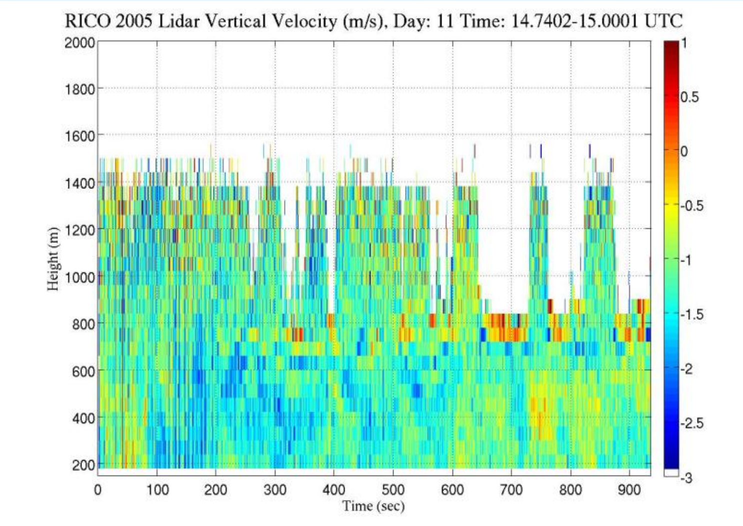
Data Processing: Finding Clouds





- SNR from lidar (only using SNR>15 dB to see where clouds are). Black dots are cloud base from ceilometer.
- Maximum SNR in each time profile with red boxes representing where clouds are.
- Same processes was done with **strong** updrafts (w>1 m/s)

Data Processing: Removing Residuals



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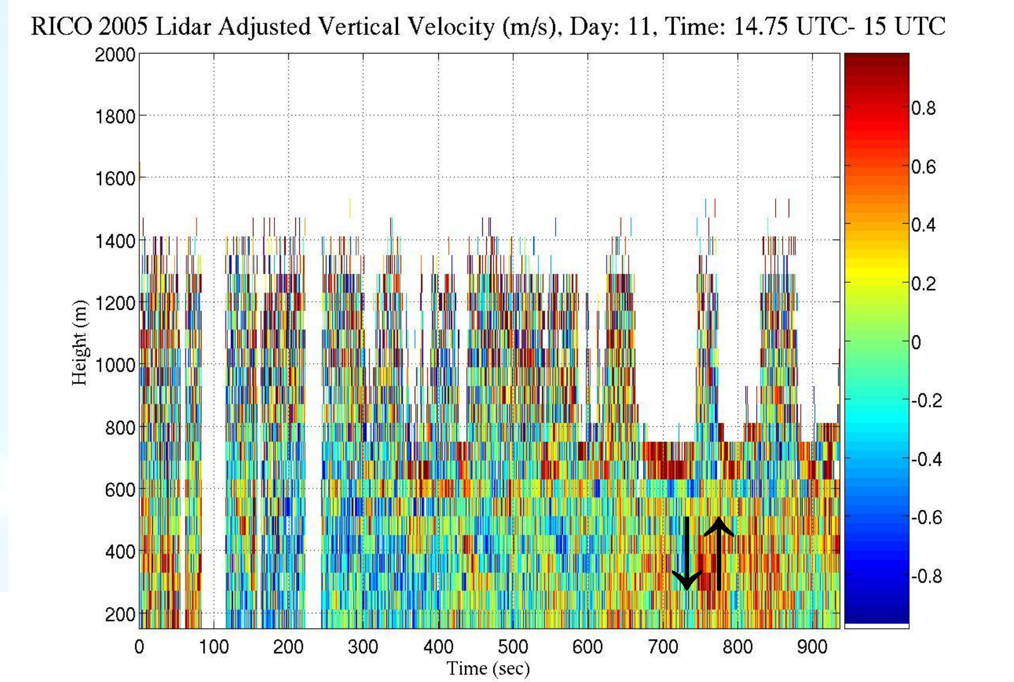
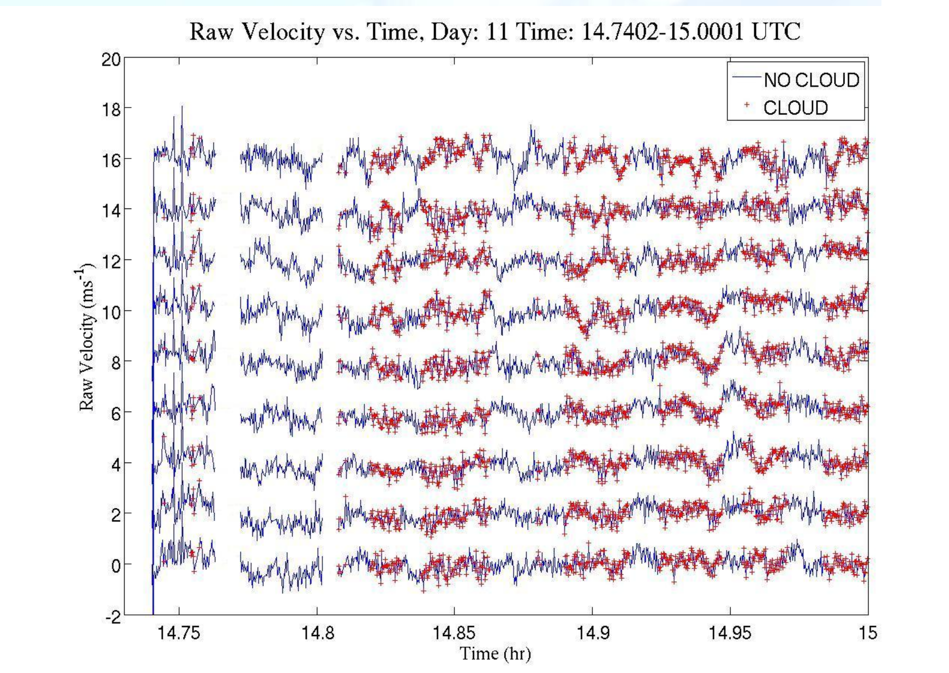
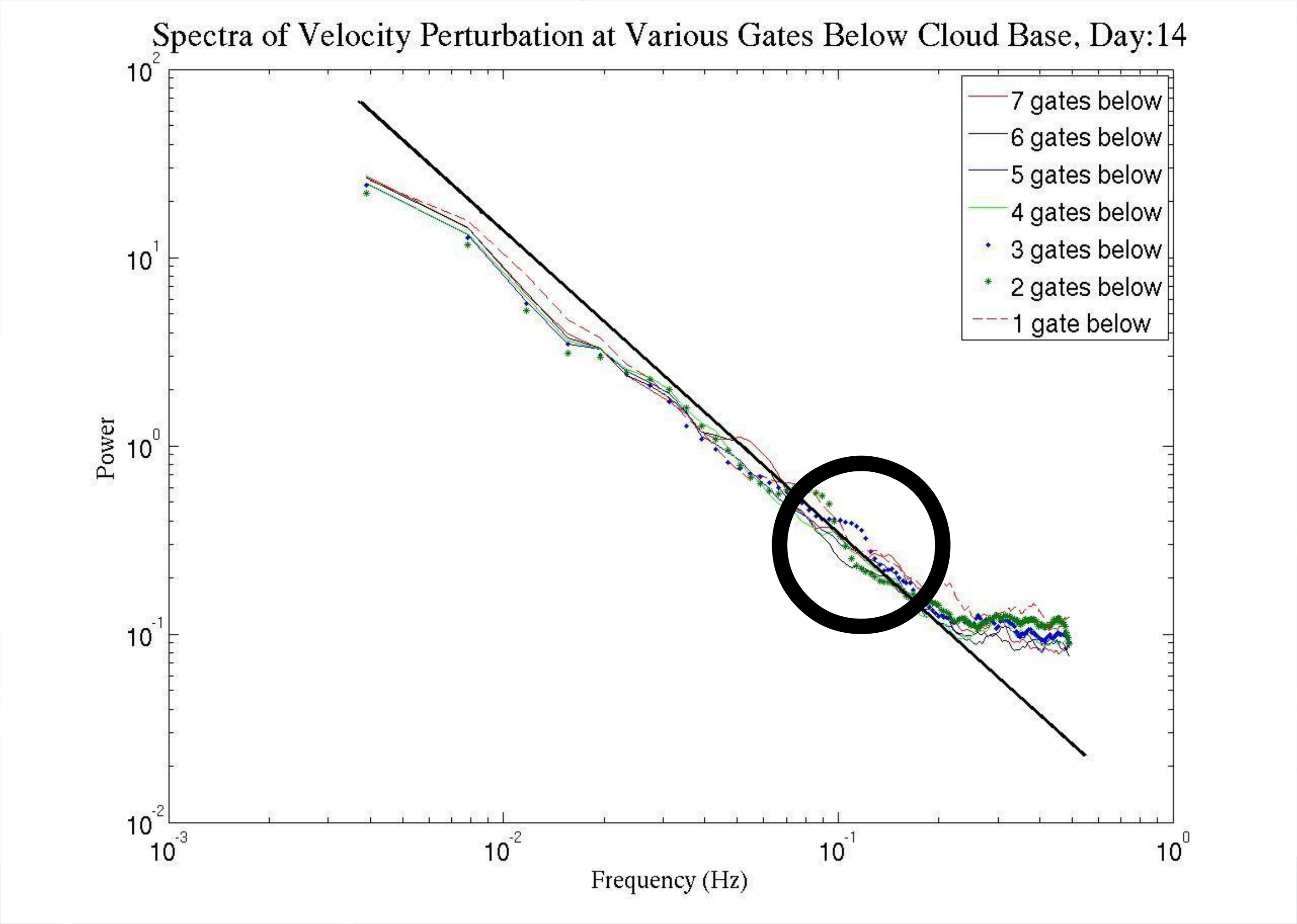




Perturbation Velocity

- Red colors represent updrafts and blue colors represent downdrafts
- Visible turbulence
- Updrafts and downdrafts extend over 400 meters

Spectra

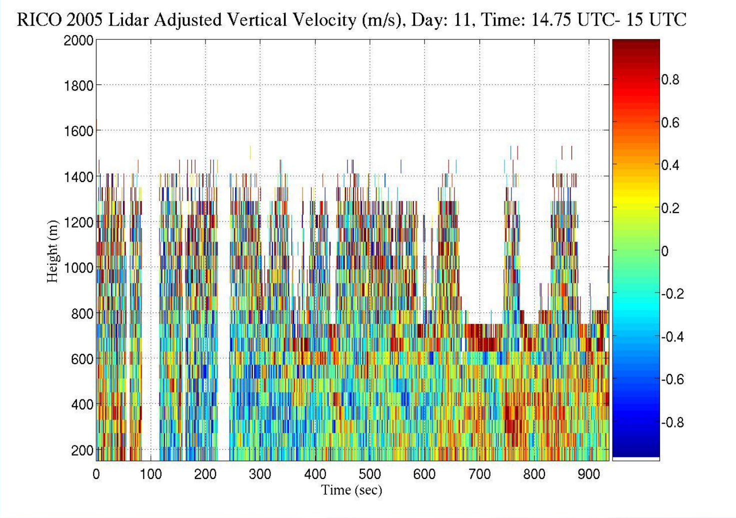


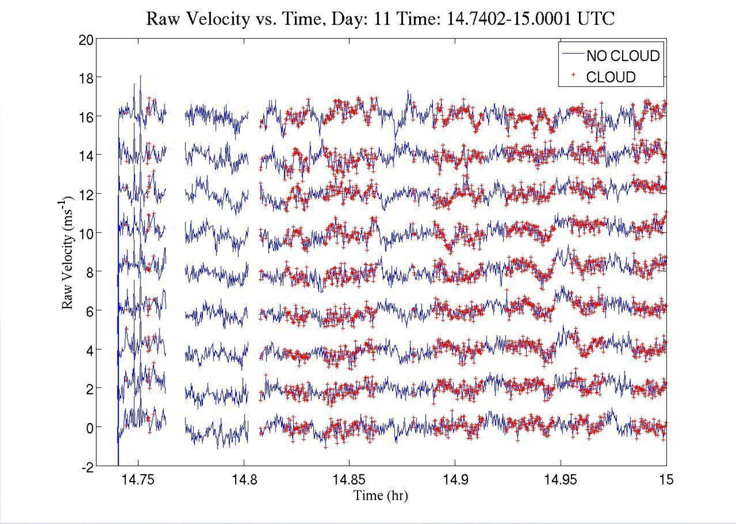
- Logarithmically smoothed, -5/3 slope line is also shown (thick black line)

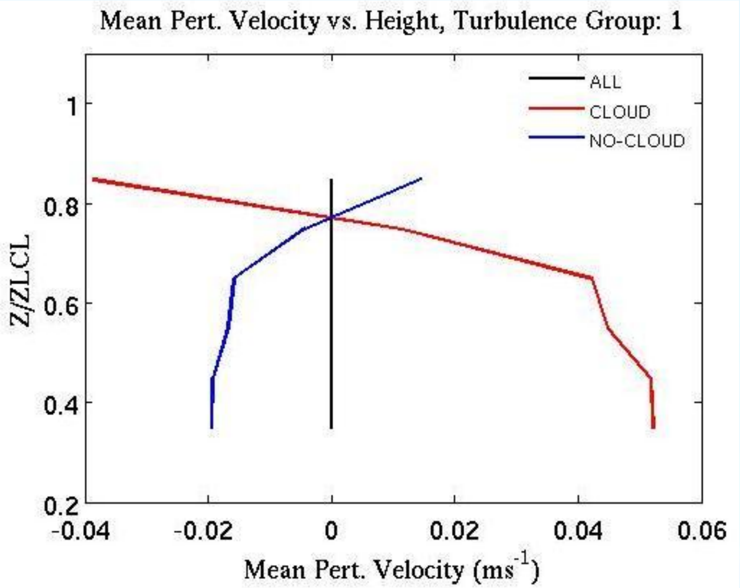
- Noise at high frequencies

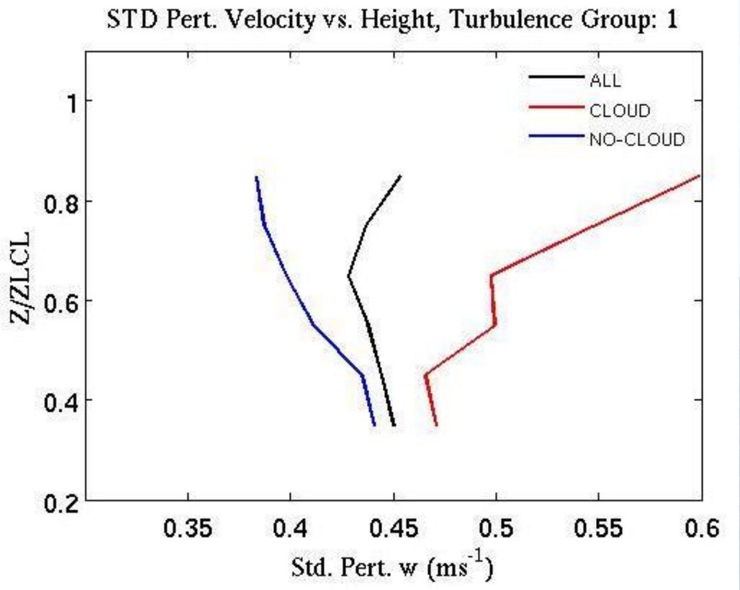
- Small peak in the spectra around 0.1 Hz due to something occurring on a time scale of 10 seconds and spatial scale of 100 m, possibly ship motion residuals

Turbulence: Cloudy vs. Clear

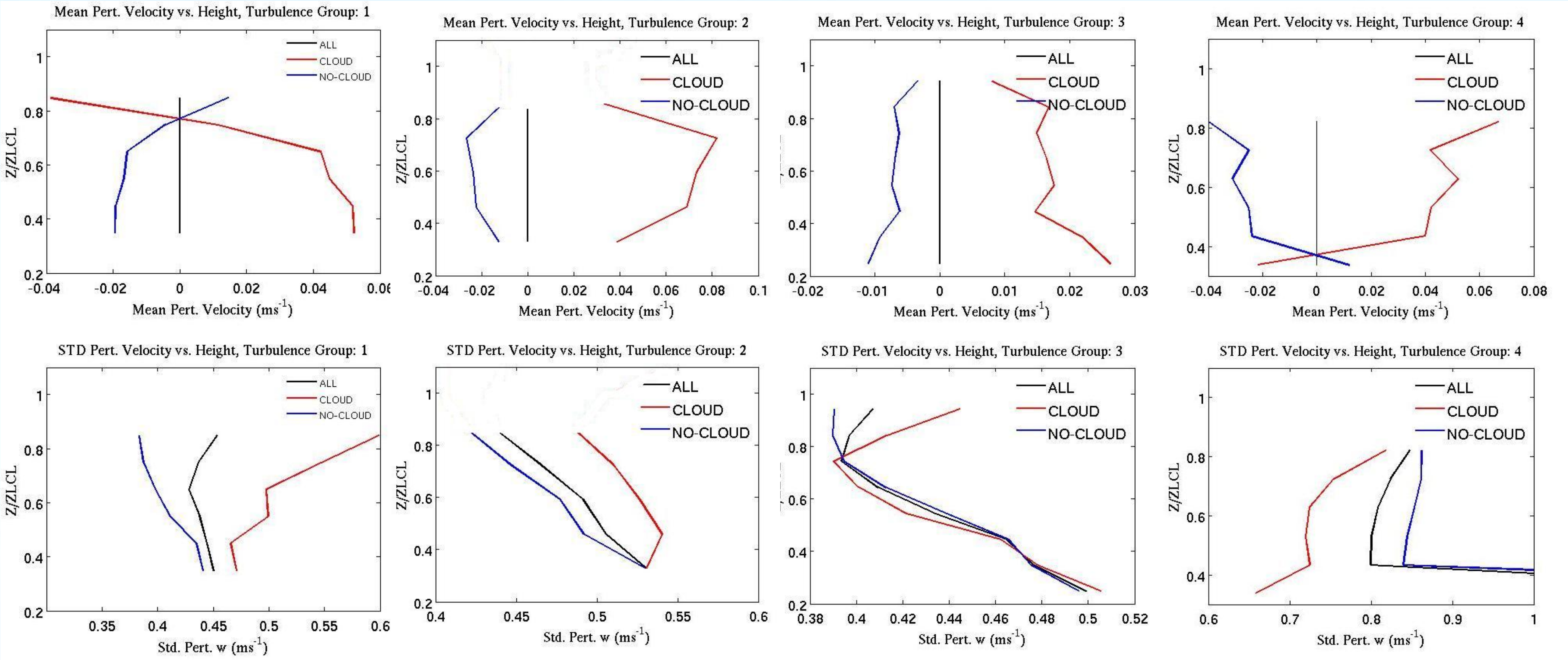








Turbulence: Cloudy vs. Clear



Group 1 Group 2 Group 3 Group 4

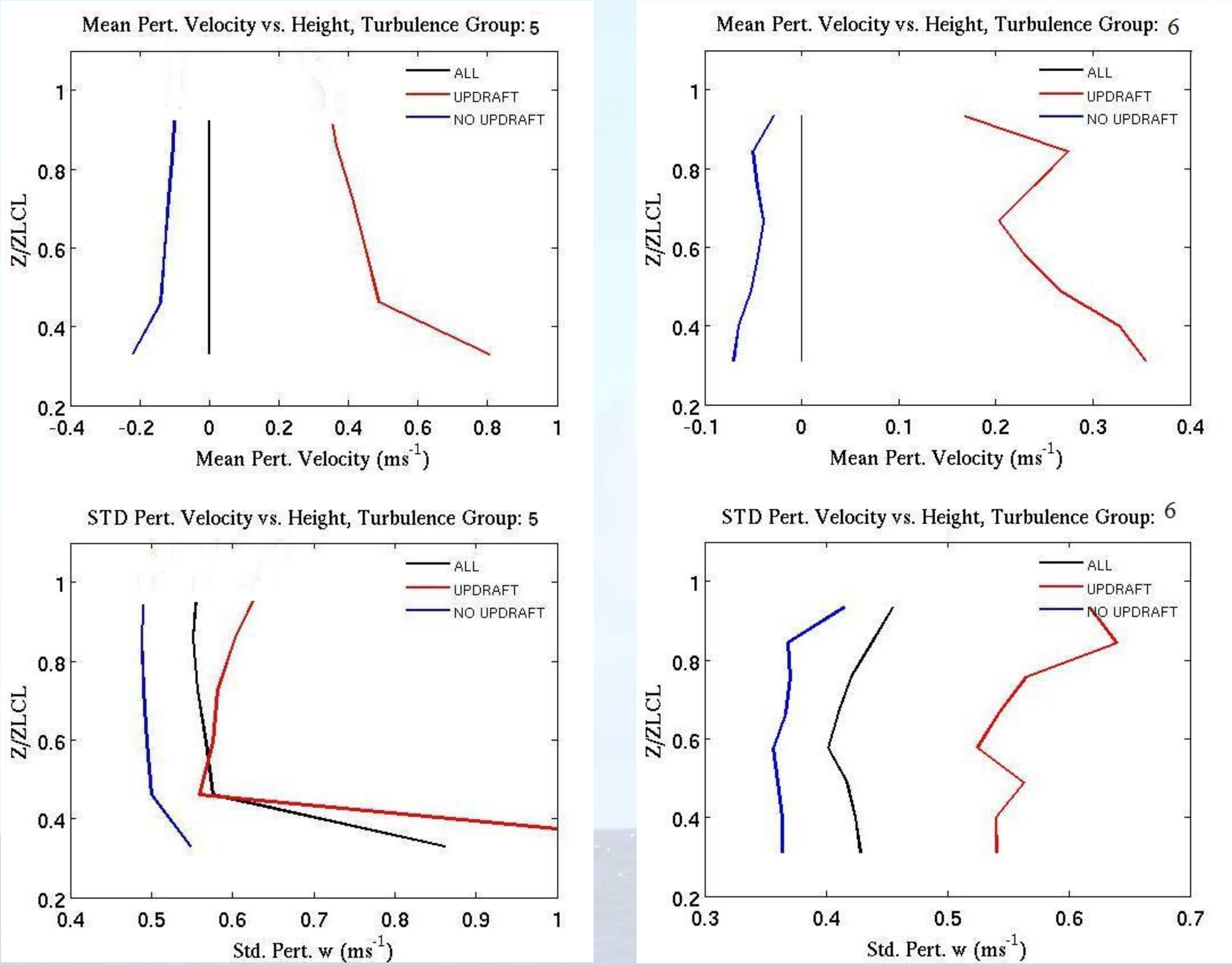
Turbulence Group 1: 14th, 16th, 17th, 18th, 19th, 23rd and 24th

Turbulence Group 2: 9th, 11th and 21st

Turbulence Group 3: 10th and 20th

Turbulence Group 4: 12th and 13th

Updrafts



Turbulence Group 5: 9th, 11th, 12th, 13th, 14th, 22nd, 23rd and 24th

Turbulence Group 6: 16th, 17th, 18th, 19th, 20th and 21st

Mass Flux

$$M_c = \rho\sigma(1-\sigma)(w_u - w_d)$$

Mass flux equation from Kollias and Albrecht (2000).

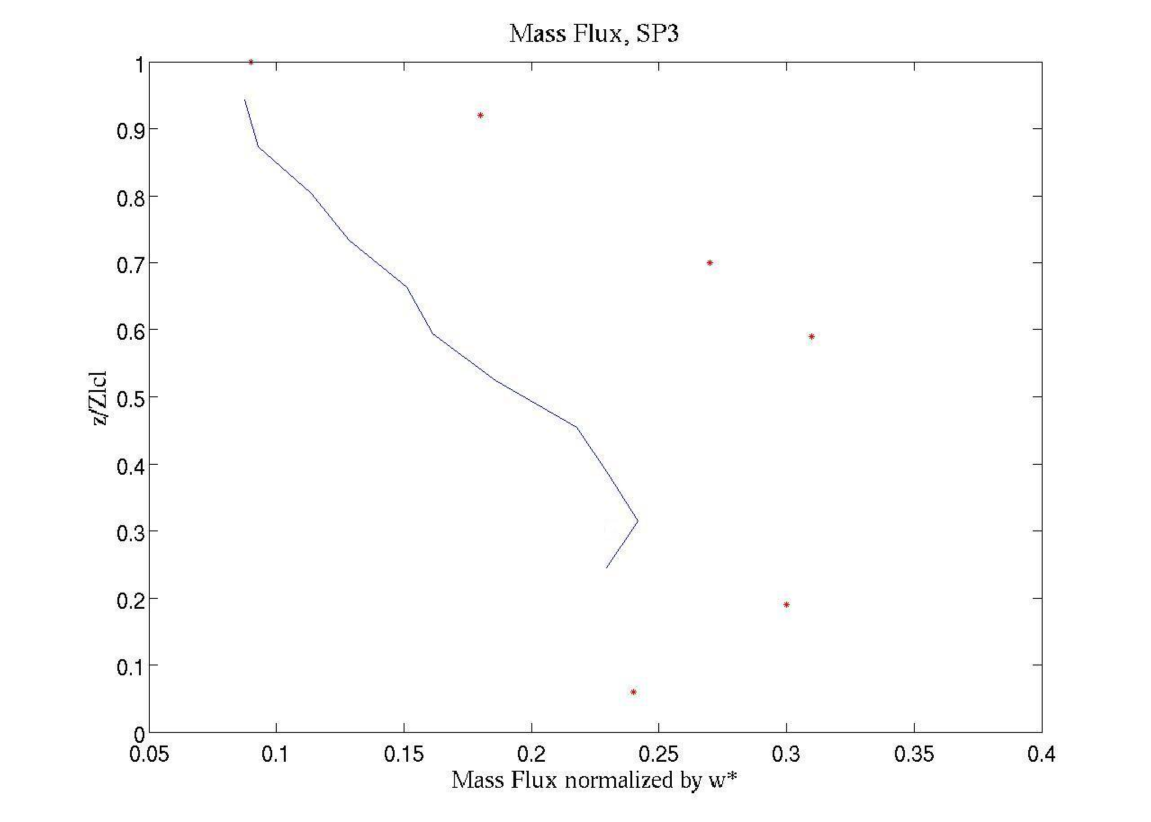
ρ=density, σ =fractional updrafts

w_u =average w of updrafts, w_d=average w of downdrafts

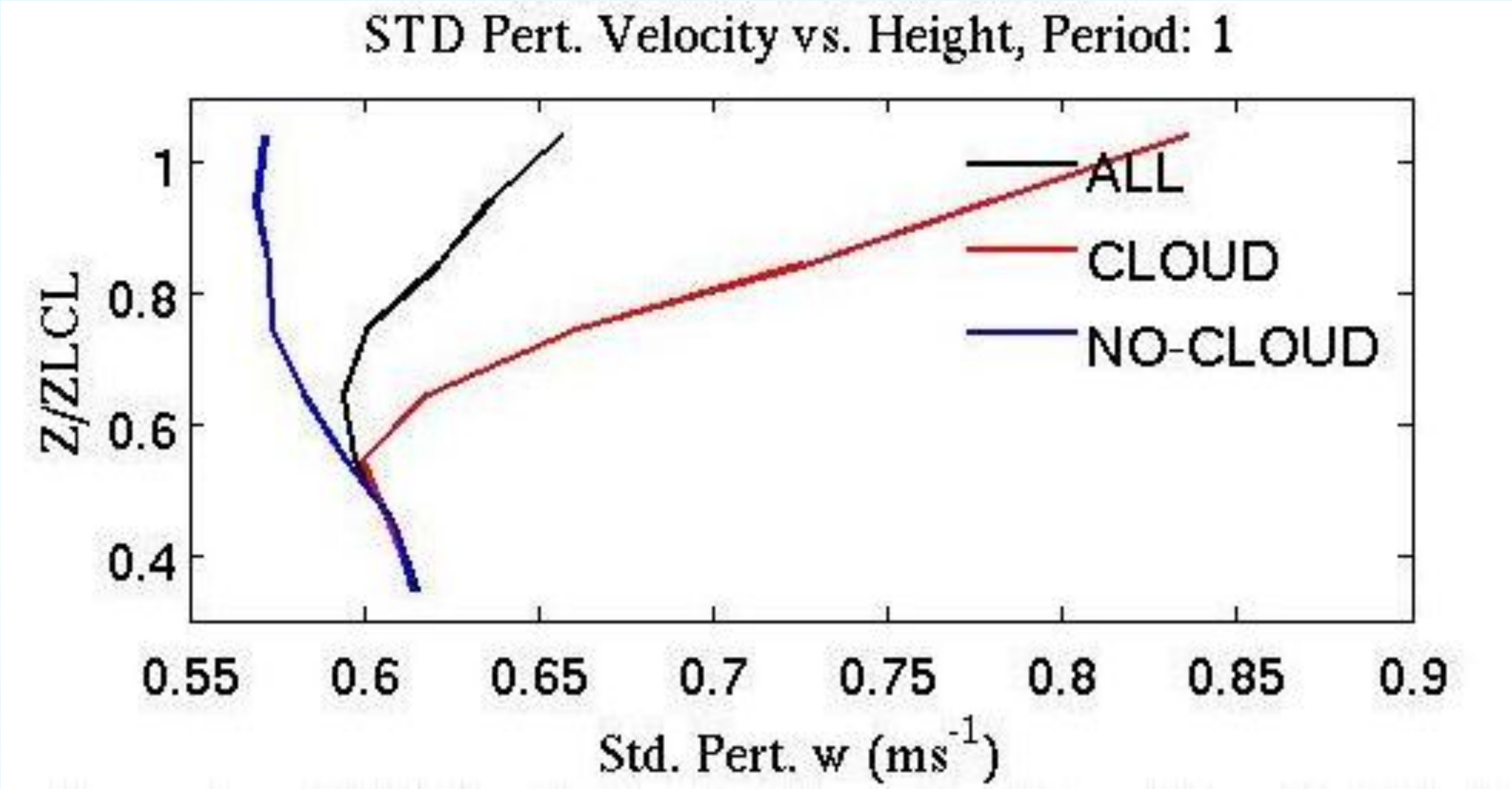
Threshold of w'>0 .5 m/s below cloud base to be considered updraft.

Normalized values are nearly doubled on days when convective conditions are present, tying in with increased convection

Red dots are results from Nicholls and LeMone



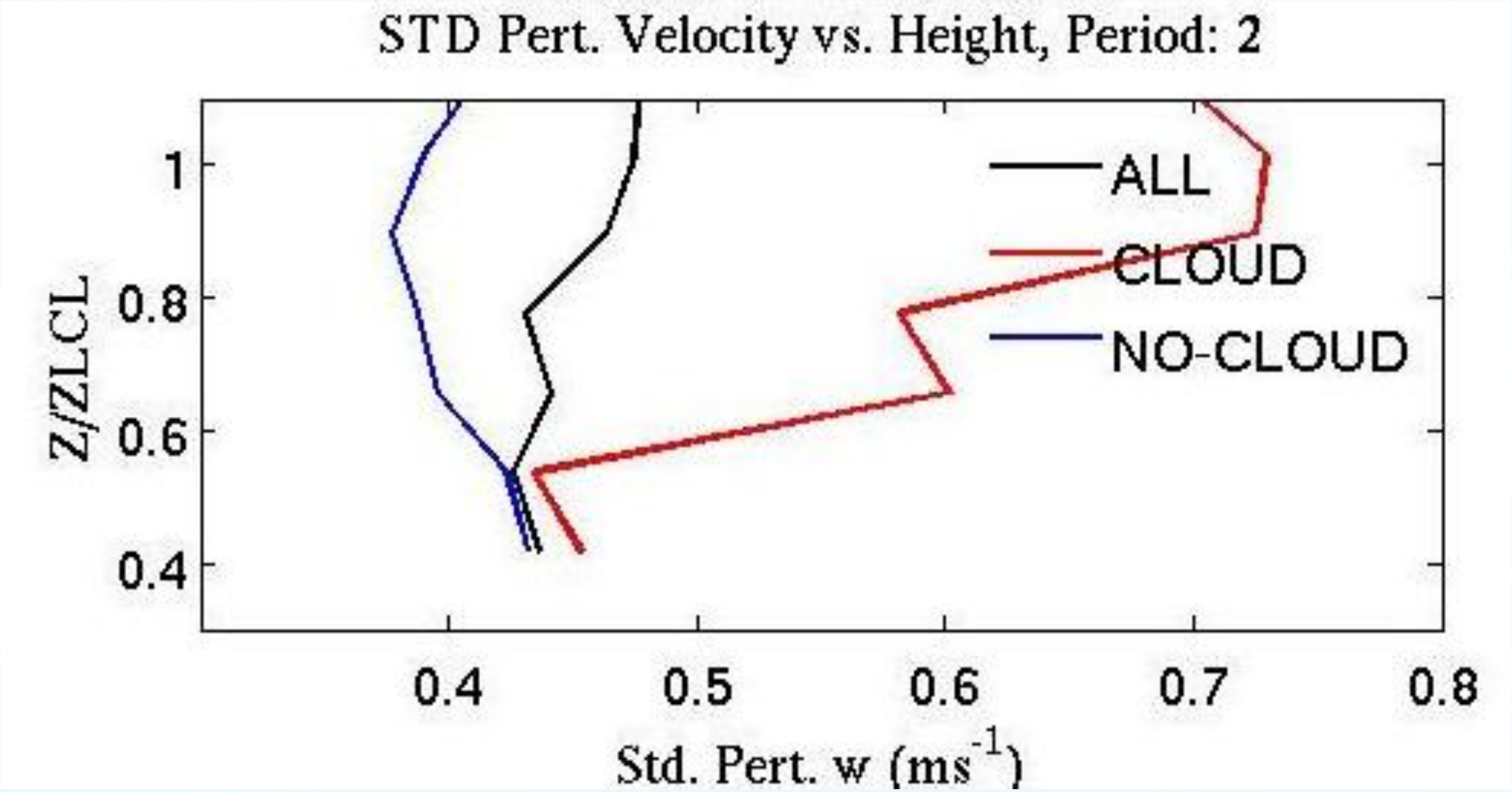
Turbulence by Period: SP1



The variance of w’ under clear sky decreases with height, while under clouds it decreases at first and then increases into cloud base. This is most likely due to the influence of both updrafts and downdrafts just under cloud base.

SP1: Convective, windy, rainy

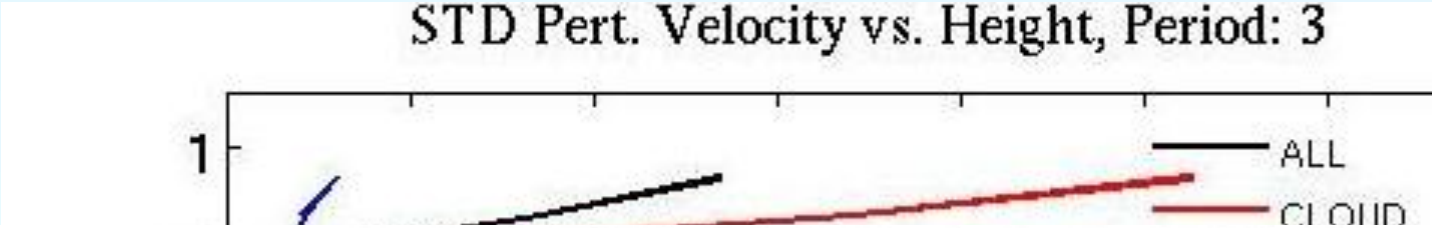
Turbulence by Period: SP2

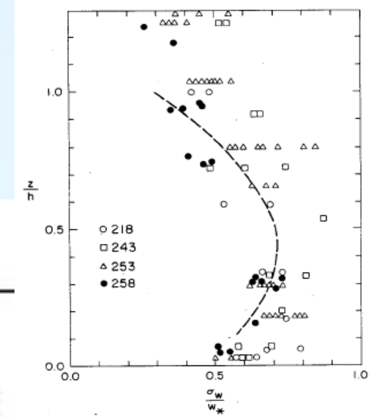


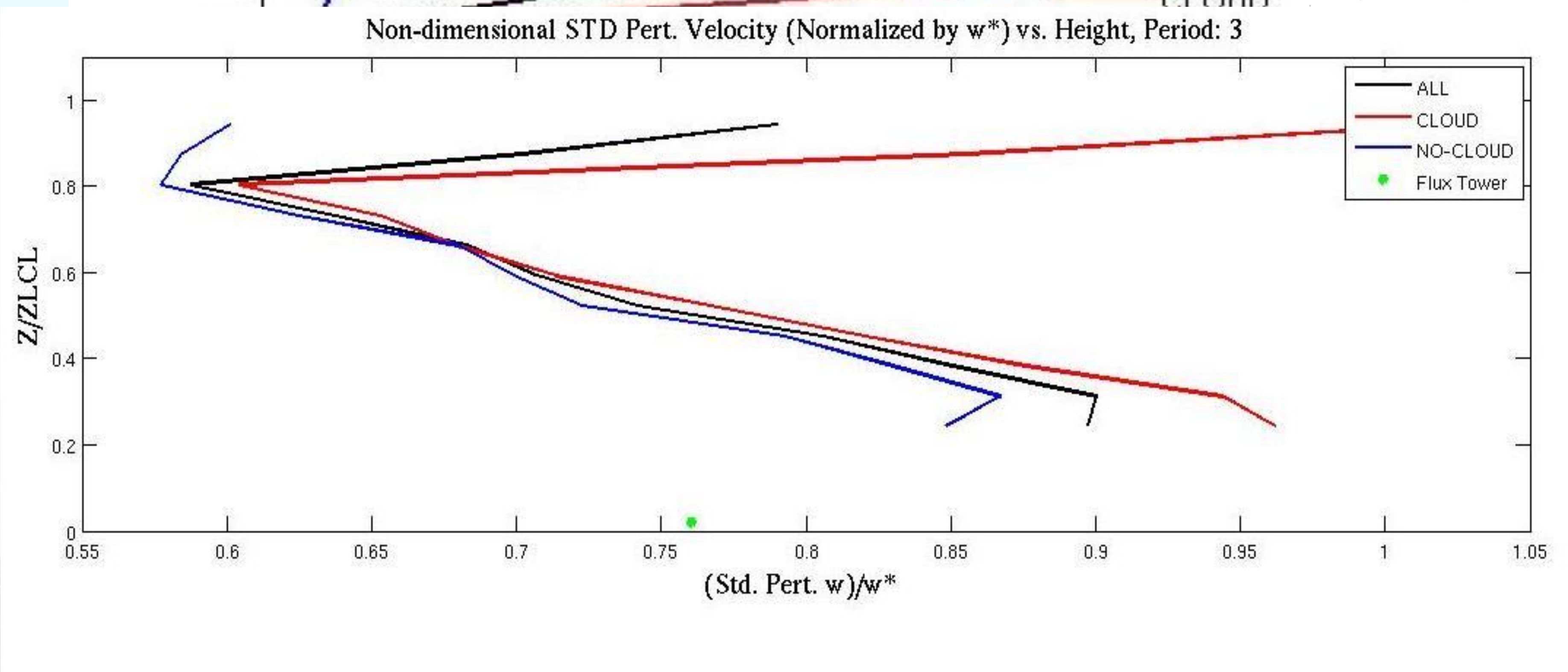
The decrease just below base is most likely caused by the increase in downdrafts just beneath the clouds.

SP2: Convective, rainy, lower wind speeds

Turbulence by Period: SP3

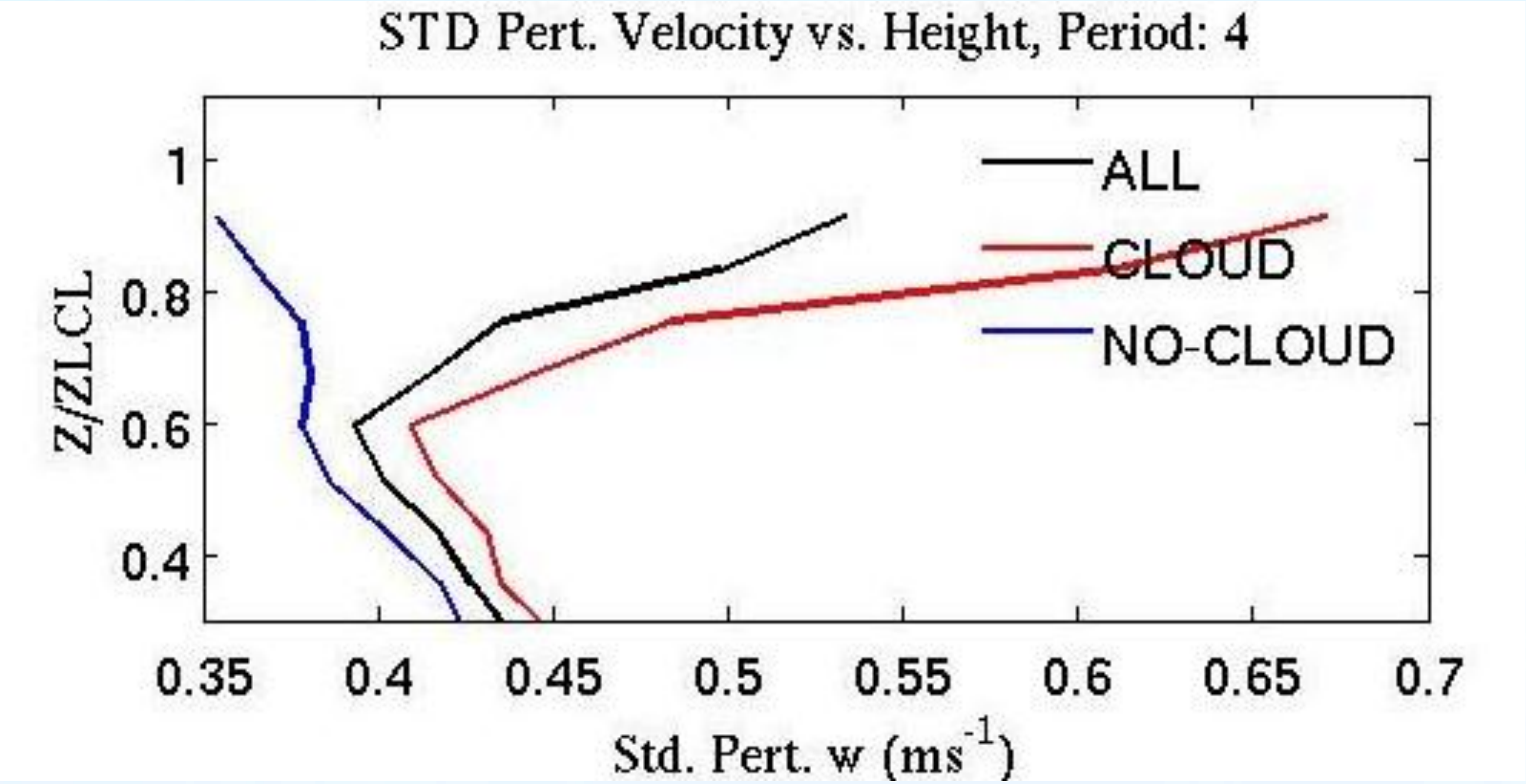






SP3: Calm, suppressed cloud conditions

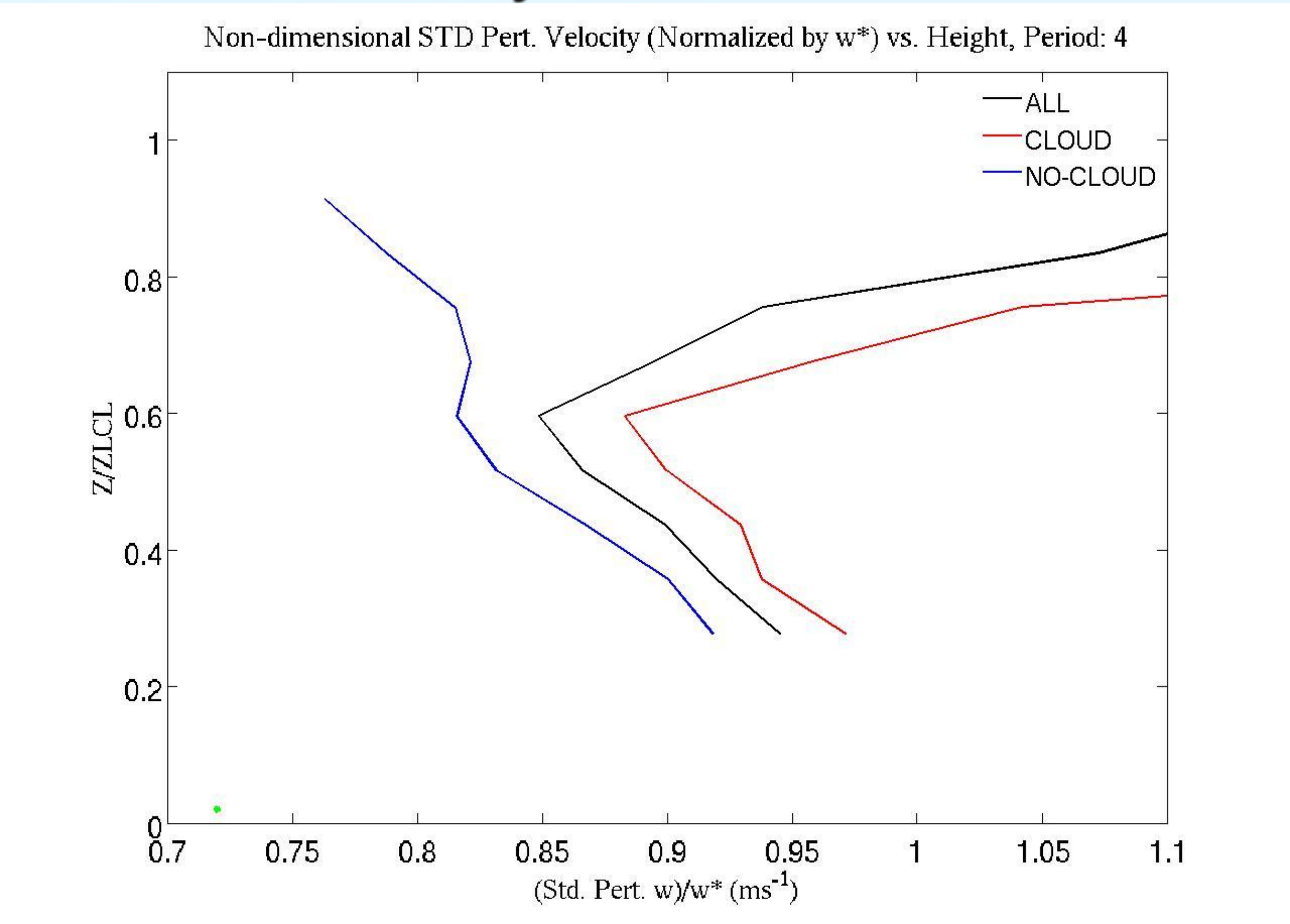
Turbulence by Period: SP4



Again the variance of w' under clear sky decreases with height, while under clouds it decreases at first and then increases just below cloud base

SP4: Suppressed cloud conditions, increasing temp and moisture

Turbulence by Period: SP4, cont.

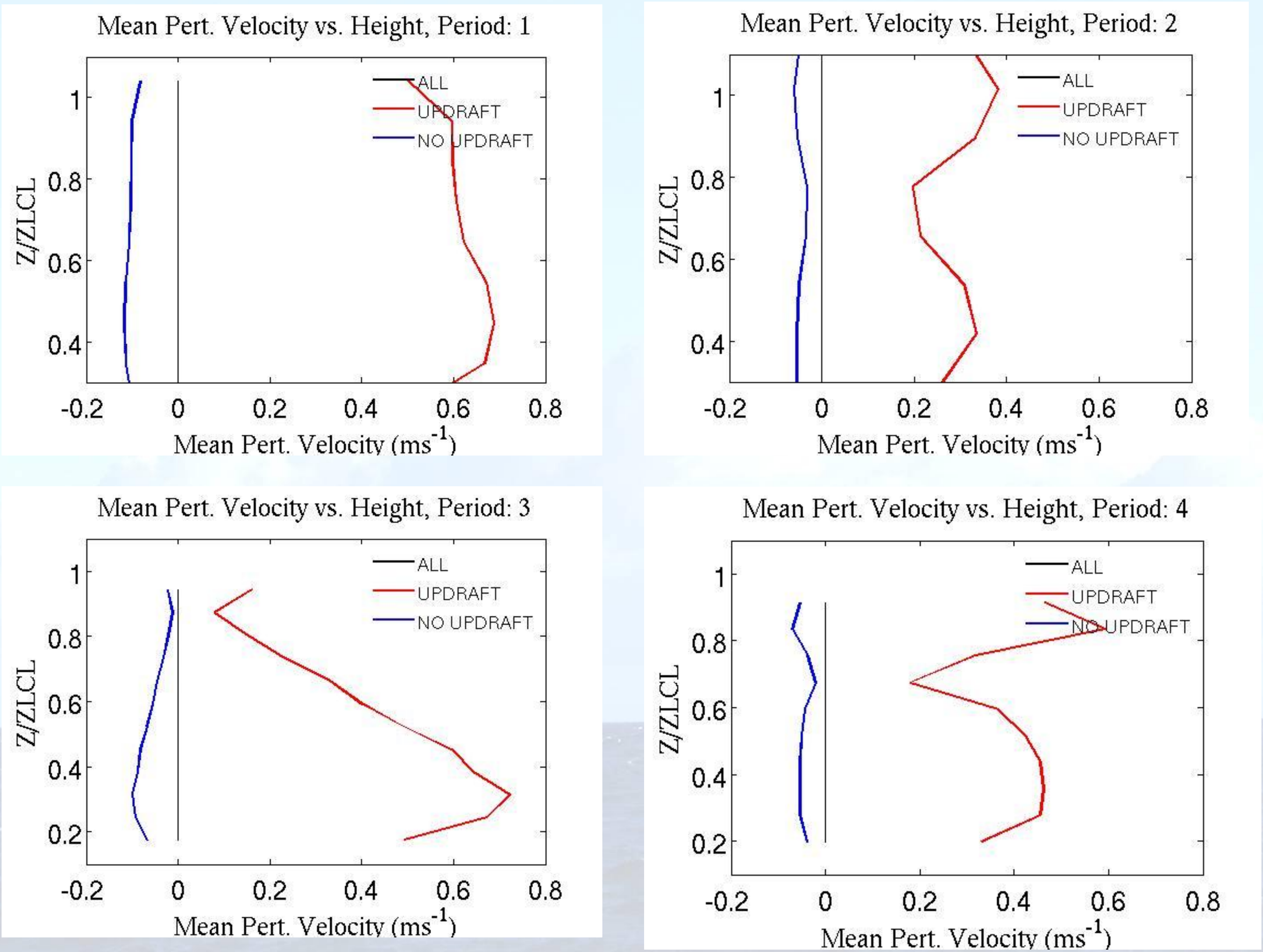


-Interpolating the lidar variance curve to the flux variance point, the clear sky curves in all synoptic periods follow that of Nicholls and LeMone (1980)

-Cloud activity/convection alters the expected turbulence curve

SP4: Suppressed cloud conditions, increasing temp and moisture

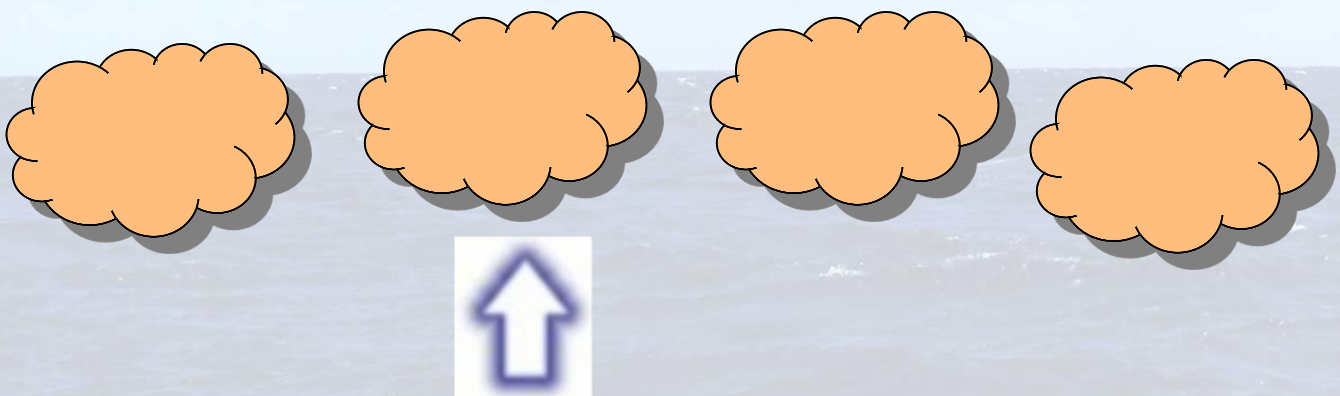
Turbulence Statistics: Updrafts



Clouds and Updrafts By Period

Synoptic Period	Dates in January 2005	% Clouds	% Strong Updrafts	% Clouds & Updrafts
1	10th-15th	28	15	6.3
2	18th-20th	18	13	5.7
3	20th-22nd	38	12	6.9
4	22nd-24th	47	10	6.7
ALL	9th-24th	30	14	7.1

1 in 4 FWC have an active updraft



Summary (1)

- 4 distinct weather conditions were experienced
- Wind speeds were high during the first leg of the cruise.
  - Winds were easterly throughout the lowest 4 km of the BL except for a lowering of westerlies down to 2 km during SP3 and SP4.
- Cloud cover during RICO was observed to be more frequent than previous experiments with a cloud fraction of .39
  - Majority of RICO saw cloud fractions between 0-0.1 (ceilometer)
  - Lidar fractional cloudiness typically significantly lower than the ceilometer
  - Lidar findings
    - clouds are present between 10-65% of the time
    - updrafts are present between 21-45% of the time
    - strong updrafts are present between 8-28%
- Spectra show that low frequency motions closely follow -5/3 slope line

Summary (2)

- Mass flux follows previous curves, but values are much higher during SP1 and SP2
- Turbulence profiles of cloudy vs. clear conditions
  - suppressed conditions: variance in w’ decreases with height from the middle of the subcloud layer up to cloud base
  - convective conditions: cloud profiles are found to increase in variance with height into cloud base
- Turbulence profiles of strong updrafts show the mean w’ in updraft columns decreasing with height up to cloud base
  - updrafts are stronger in the middle of the subcloud layer than they are just under cloud base
  - columns that have a strong updraft lower in the subcloud layer often have downdrafts just below cloud base
- Despite changing synoptic influences, the occurrence of both clouds and strong updrafts remain constant with each synoptic period

Outlook and Future Work

- While RICO was designed to study typical suppressed conditions, the first half of the cruise encountered disturbed conditions
- Data set is useful for comparisons with satellite retrievals, Reanalysis data
- Lidar results could be compared with Large Eddy Simulation (LES)
- Have longer vertical stares, use horizontal stares to study horizontal features

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Questions??