Evaluation of Cirrus Statistics Produced by General Circulation Models Using ARM Data

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METEOROLOGY

Atmospheric Radiation Measurement
Climate Research Facility
A National User Facility for the Scientific Community

Outline

- Introduction
- Data and Technique
- Results Occurrence Statistics
- Results Large-scale Meteorology
- Summary and Conclusion

Outline

- **Introduction**
  - **Introduction to Cirrus**
  - **Impact of Cirrus on Climate**
  - **Motivation for Cirrus Climate Studies in GCMs**
  - **Goals**
- Data and Technique
- Results Occurrence Statistics
- Results Large-scale Meteorology
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Introduction to Cirrus

- Predominately composed of ice crystals and found in the upper troposphere
- Globally distributed (20-40% coverage)
- Differing dynamic processes involved in cirrus generation
  - Ouflow from deep convection (tropics)
  - Synoptic lifting ahead of baroclinic waves (mid-latitudes)
- Variable microphysical and radiative properties
  - Water content
  - Particle size
  - Optical depth

images.arm.gov

www.srh.noaa.gov

Impact of Cirrus on Climate

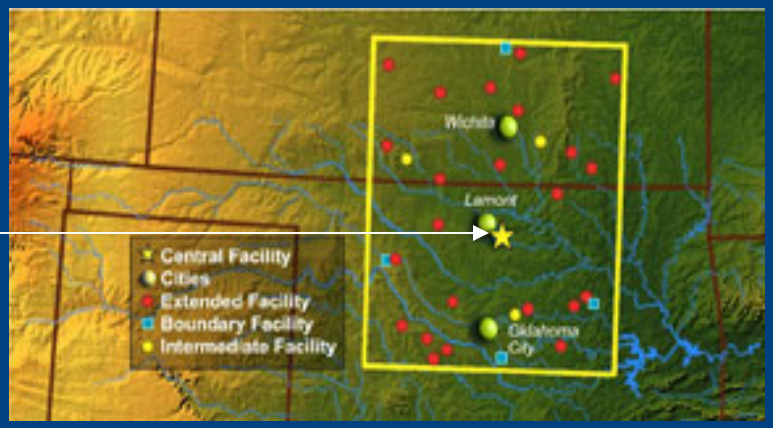
- Earth Radiation Budget: Clouds act to
  - Reflect incoming shortwave (cooling)
  - Absorb outgoing longwave (warming)
- Cloud Radiative Forcing on average has a net cooling effect
- Cirrus can have either a net warming or cooling effect depending on cloud temperature and optical thickness
- Climate sensitivity and cloud feedbacks
  - How clouds respond to climate changes

Motivation for Cirrus Climate Studies in GCMs

- Important role in climate change and reduce uncertainties in climate prediction
- Cirrus pose particular problems in model climate simulations
- Accurate representation of cirrus in models depends on realistic treatment of cloud variables
  - Clouds exist on smaller scales than GCMs resolve
  - Parameterizations needed in GCMs
- Only grid box mean values of water content and cloud fraction predicted

ARM Program

- Atmospheric Radiation Measurement (ARM) established by DOE
- Purpose to improve GCM parameterizations
- Instruments gather data continuously
- Southern Great Plains (SGP) site located in north-central Oklahoma



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Goals

- Evaluate the skill of GCMs in producing climatological cirrus cloud statistics
  - Compare cirrus occurrence statistics to compiled climatology observed at SGP ARM site
  - Differences between the large-scale meteorological state of modeled cirrus and cirrus found in real atmosphere

Outline

- Introduction
- **Data and Technique**
  - **Observational Data**
  - **Model Output**
    - **ECMWF**
    - **CAPT Program**
    - **NCAR CAM3**
    - **GFDL AM2**
  - **Analysis Technique**
    - **NCEP/NCAR Reanalysis**
    - **Case Study (Defining Cirrus)**
    - **Klein-Jakob Subgrid Approximation Technique**
- Results Occurrence Statistics
- Results Large-scale Meteorology
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Observational Data

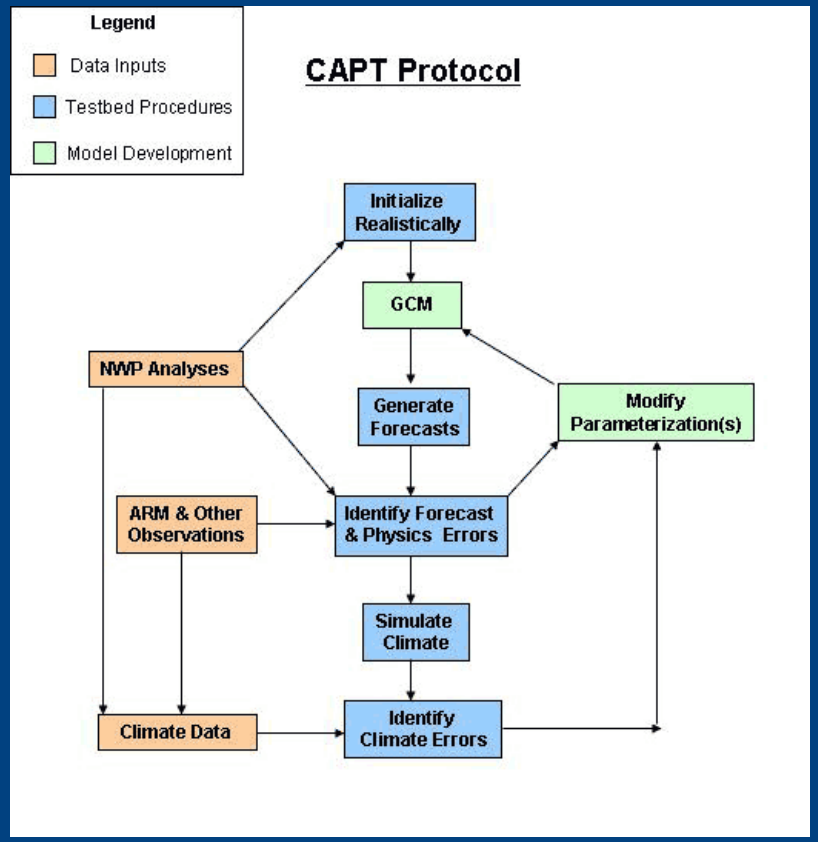
- Mace et al., 2006: Relationship between cirrus cloud properties and the large-scale meteorology
- Data from 1997-2002 compiled from ACRF ground-based sensors
- Cirrus definition based on radar reflectivity and temperature restrictions
- ZR Algorithm combines MMCR and AERI to retrieve bulk microphysical properties

Model Output

- ECMWF
  - Numerical weather prediction global model freely available from ARM
  - Resolution 0.56° (60km) horizontal, grid-point nearest SPG site, 60 vertical levels (~25 hPa in upper troposphere), hourly output
  - Cloud scheme of Tiedtke (1993)
- NCAR CAM3
  - T42 spectral resolution (2.8° horizontal), 18 vertical levels, 20 minute time-step
  - Cloud parameterization of Rasch and Kristiansson (1999)
- GFDL AM2
  - Horizontal grid 2.0°x2.5° (lat-lon), 24 vertical levels (~2km in upper troposphere)
  - Cloud schemes of Tiedtke (1993) (macro) and Rastayn (1997) (microphysics)

CAPT Program

- Climate Change Prediction Program (CCPP)-ARM Parameterization Testbed (CAPT)
- Unique: Implementing GCM in NWP framework
  - initialize with high-frequency analyses (ERA40)
  - run short term forecasts
  - model stays close to observations



- Errors then primarily in the parameterizations

CAPT-GCM Output Files

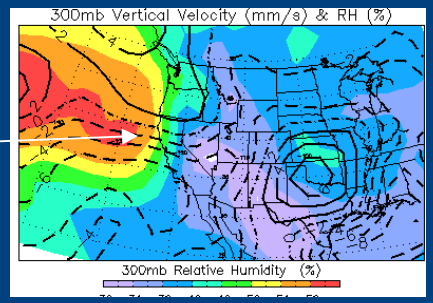
- Variables available from the CAPT-GCM output files

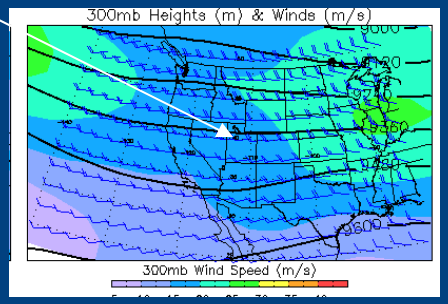
CAPT-CAM3 variables	Units	Description
time	days	Time offset
lev	hPa	Model pressure levels
cl	fraction	Cloud area fraction in atmosphere layer
cli	kg/kg	Mass fraction of cloud ice in air
clw	kg/kg	Mass fraction of cloud water in air
ta	K	Bulk temperature of air

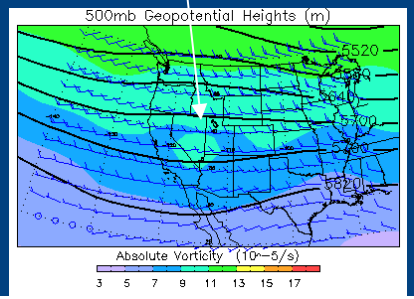
- Hourly files, 37 vertical model levels at a resolution 25-hPa
- Only the year 2000 available from CAPT

NCEP/NCAR Reanalysis

- One of main goals to statistically compare large-scale atmospheric states when models predict cirrus at ACRF with radar observed cirrus
- Use NCEP reanalysis (as in M06)
- Historical record (assimilated available observations), valid 4 times a day (00, 06, 12, 18 UTC)
- Variables examined
  - Vertical ascent and RH (300 hPa)
  - Geopotential height and winds (300 hPa)
  - Heights and absolute vorticity (500 hPa)

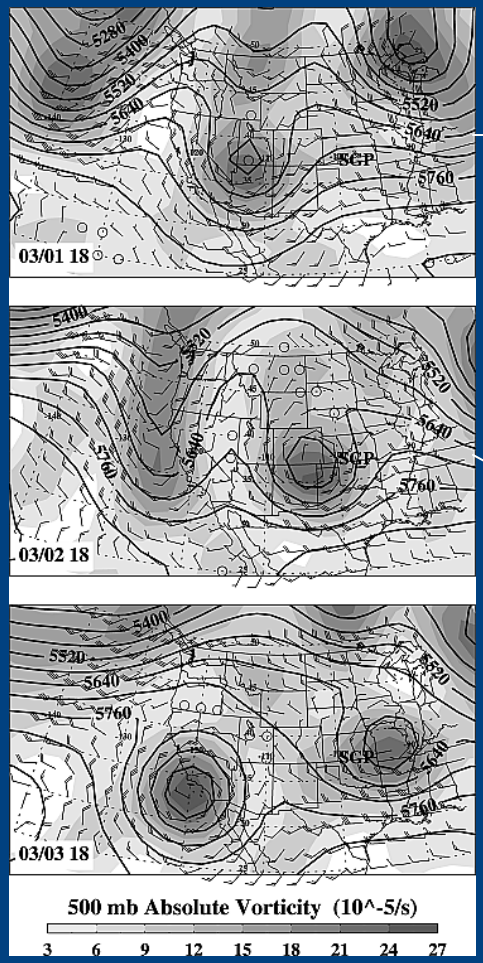




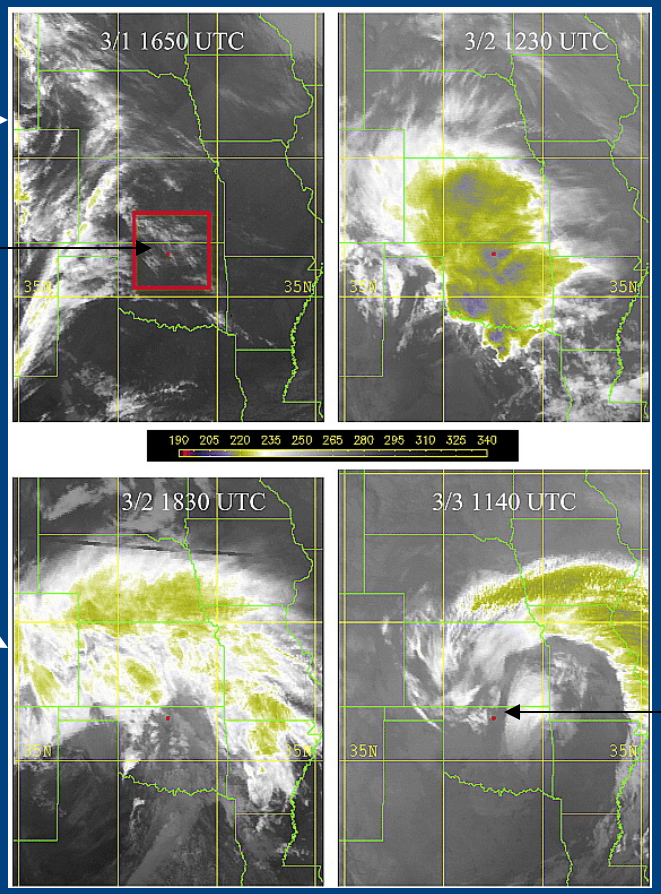


Case Study: 1-3 March 2000

Meteorology



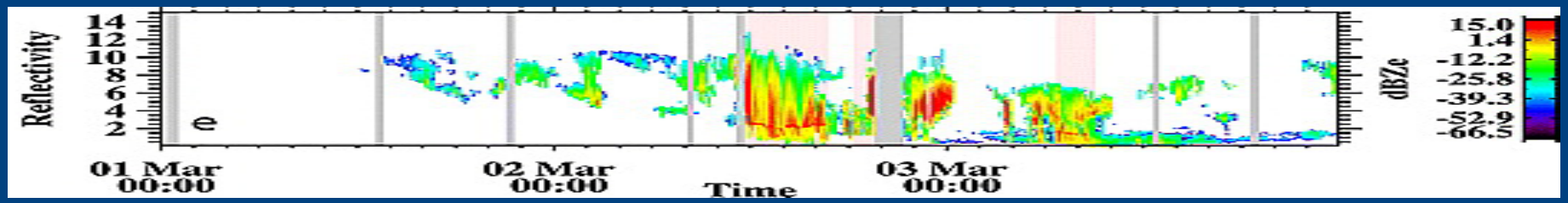
Cirrus ahead of the cyclone

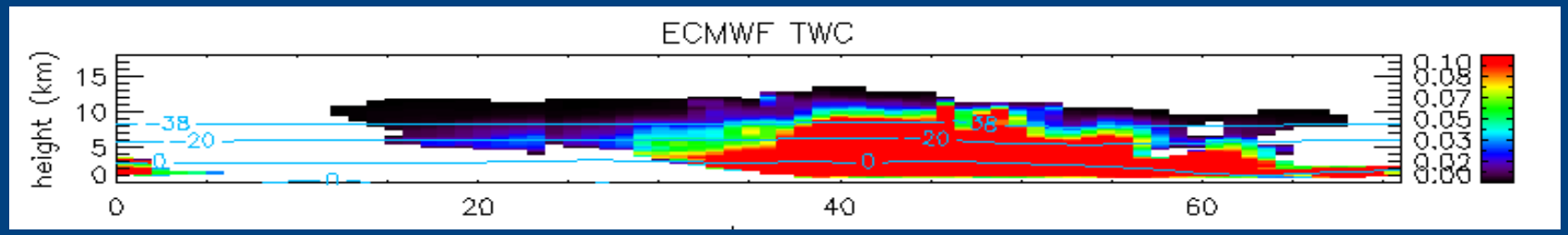


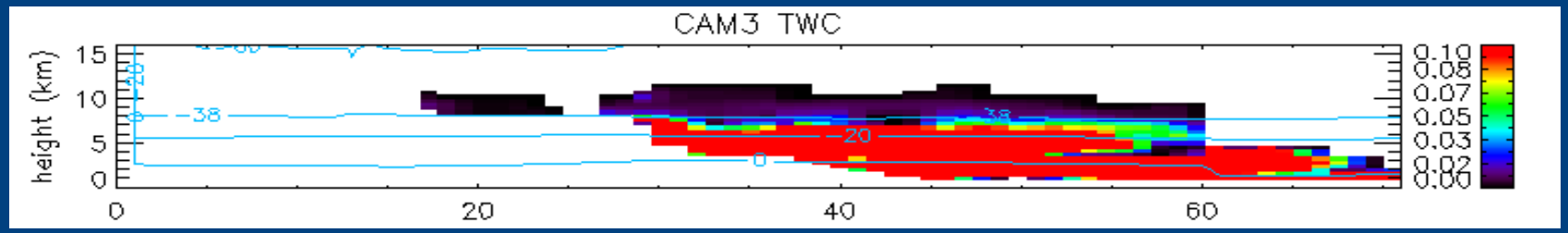
Wrap around cirrus

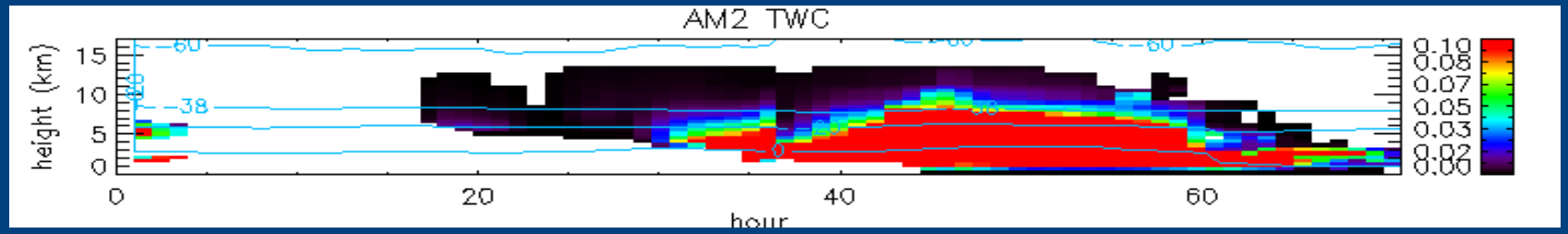
Case Study: 1-3 March 2000

Radar Reflectivity and TWC

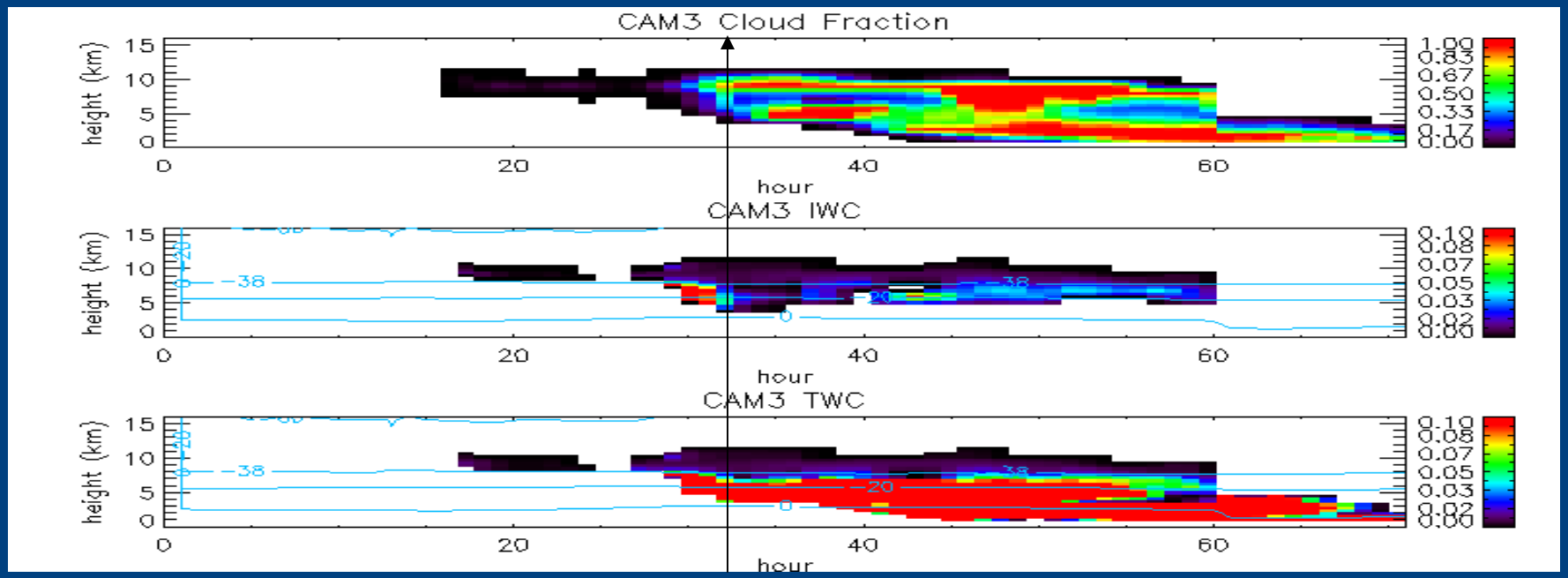








Cirrus Definition in Model



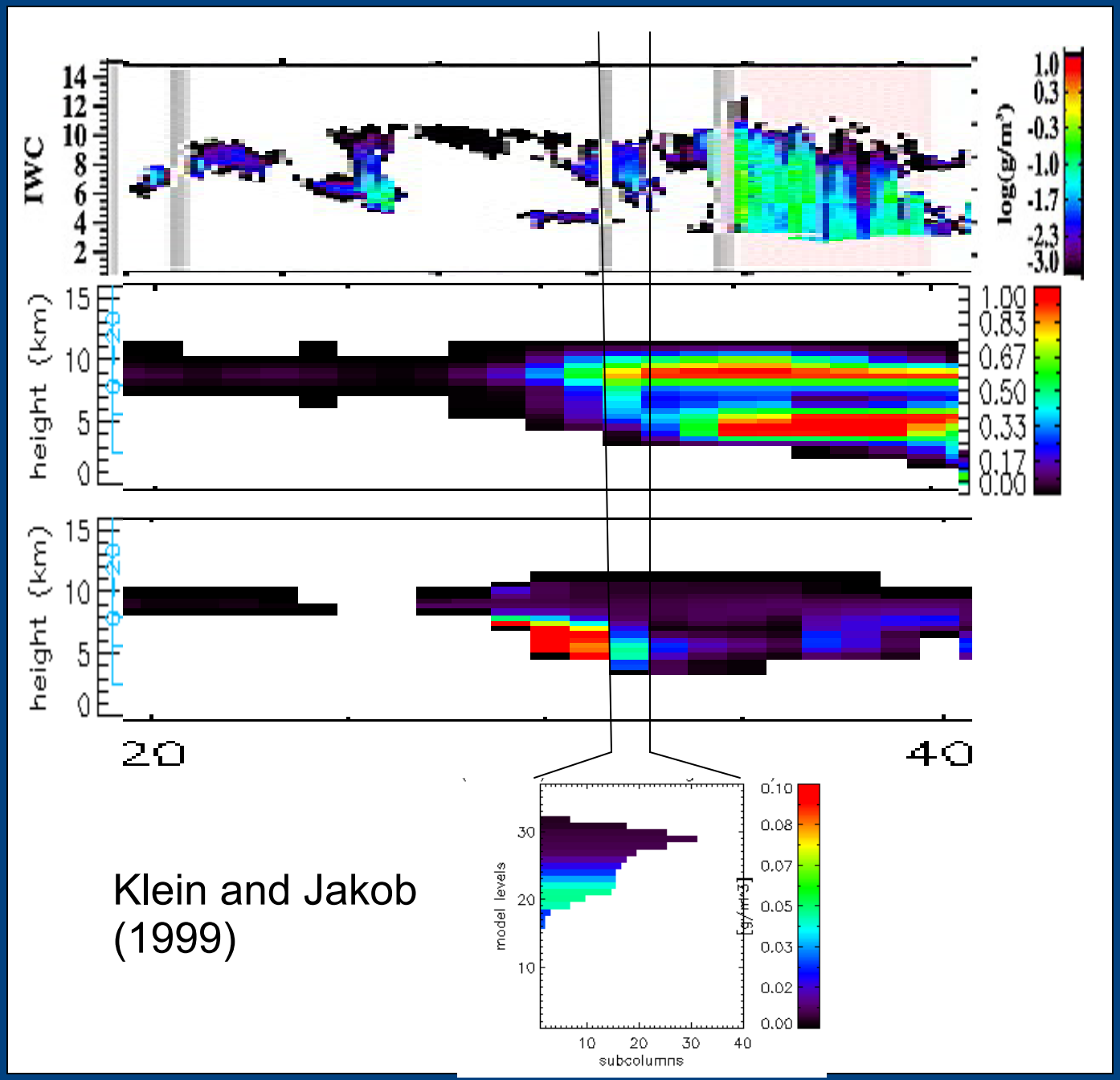
- Restrictions
  - Cloud top ≤ 235 K (-38°C)
  - Max IWC Layer ≤ 253 K (-20°C)
  - Cloud base ≤ 273 K (0°C)
  - LWC < IWC×10% in the cloud layer

*Problems exist with this definition when dealing with model output

MMCR IWC

Cloud Fraction

GCM IWC

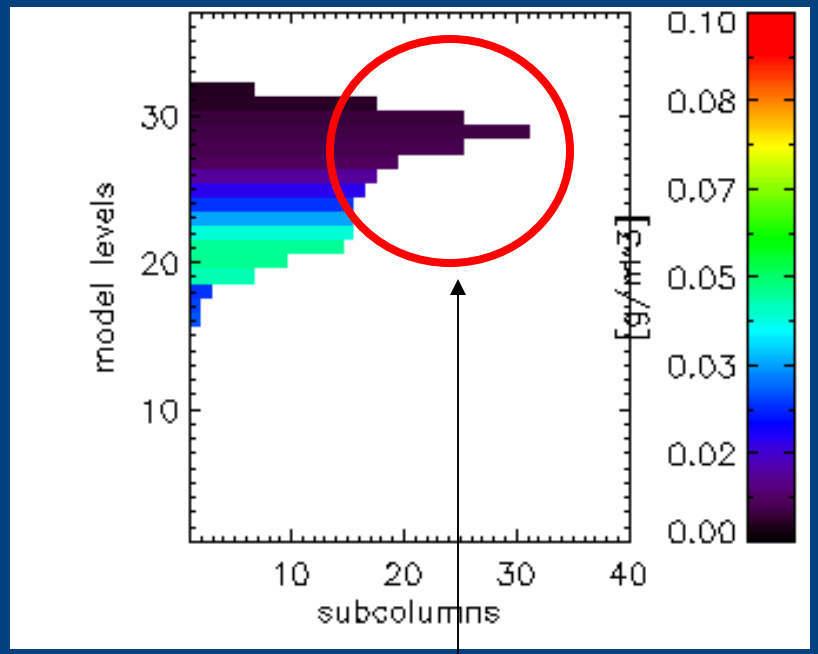


Klein and Jakob (1999)

Subgrid Technique

Klein and Jakob (1999)

- Klein-Jakob cloud overlap approximation represents sub-grid scale statistically from grid-scale
- Cloud fraction either 1 or 0 (instead of %)
- Allows for more statistically accurate cirrus retrieval from model output



Now meets cirrus definition in sub-columns 15-32

Outline

- Introduction
- Data and Technique
- **Results Occurrence Statistics**
  - **Model Cirrus Occurrence Statistics (compared to observations)**
    - **ECMWF (1997-2002)**
    - **CAPT-CAM3 (2000)**
    - **CAPT-AM2 (2000)**
  - **Bulk Microphysics and Sensitivities to Large-scale Vertical Motion**
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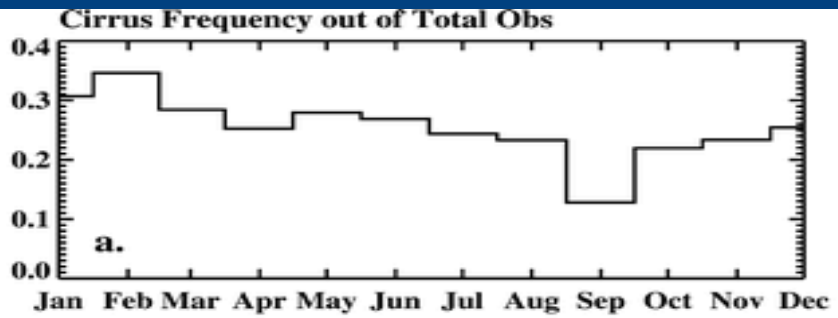
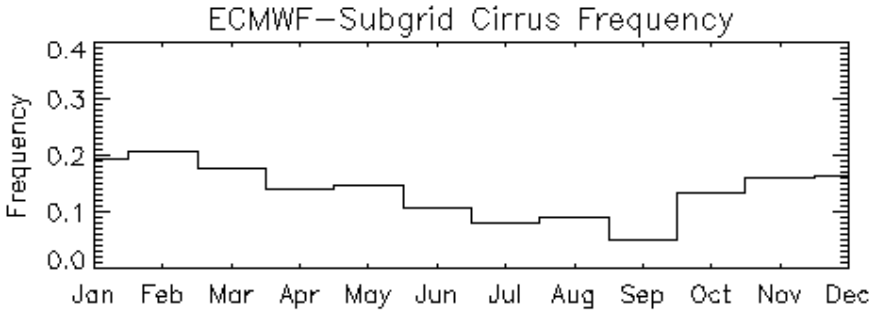
Occurrence Statistics

Cirrus Frequency

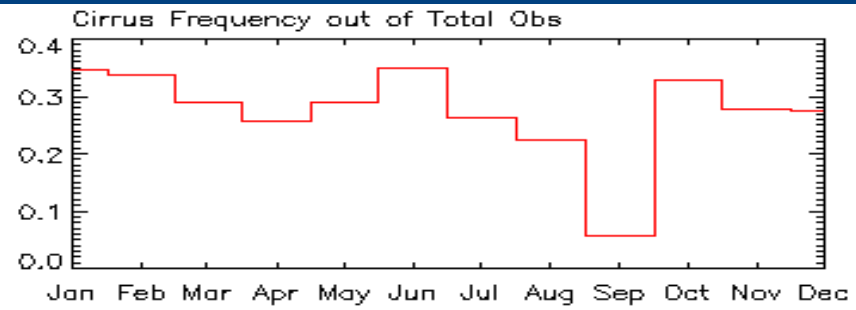
1997-2002

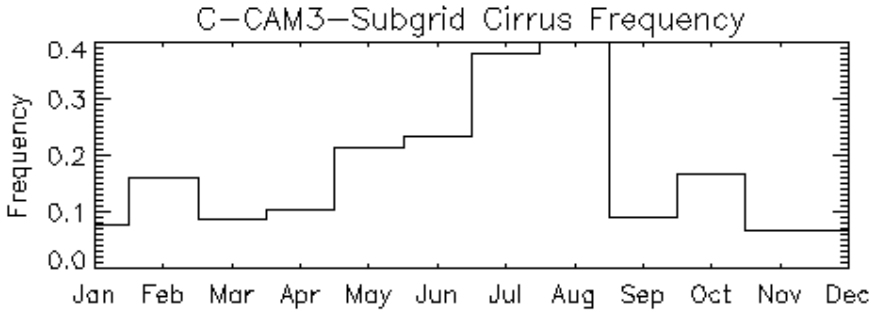


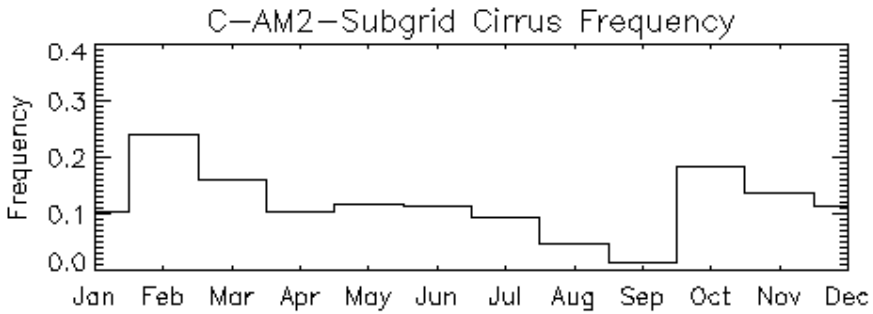


	M06 OBS	ECMWF	2000 OBS	C-CAM3	C-AM2
Annual	0.25	0.14	0.28	0.17	0.12
NDJFM	0.28	0.18	0.27	0.08	0.15
MJJAS	0.23	0.09	0.24	0.27	0.08

Year 2000



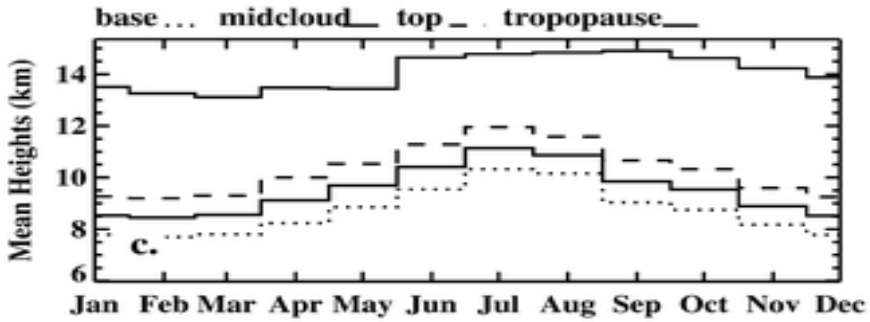


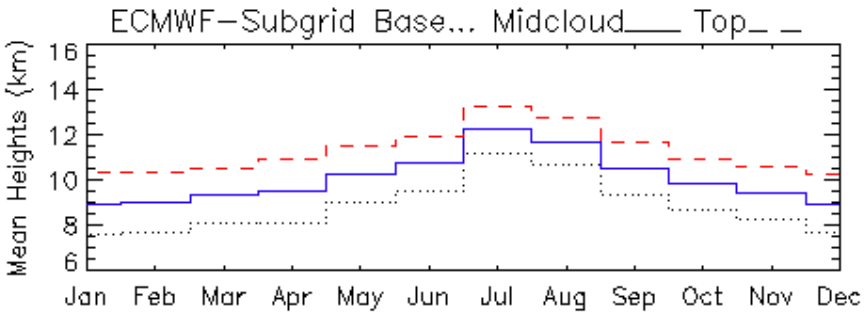


Occurrence Statistics

Cloud Heights

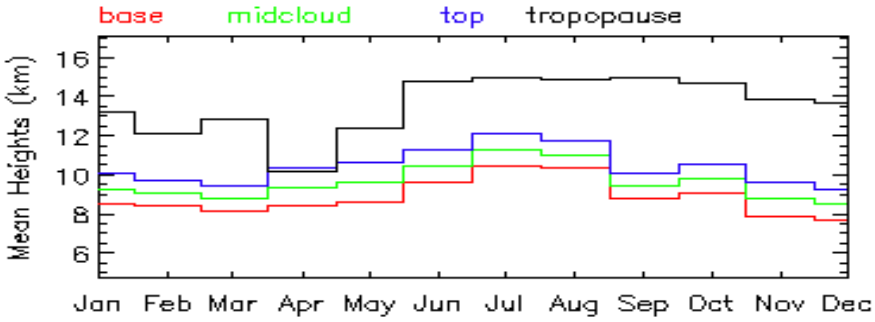
1997-2002

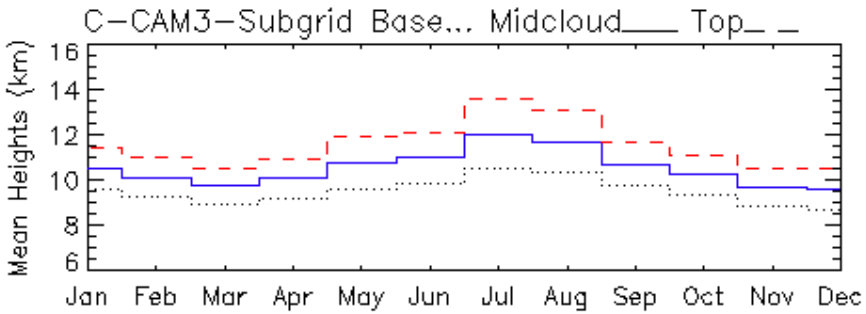


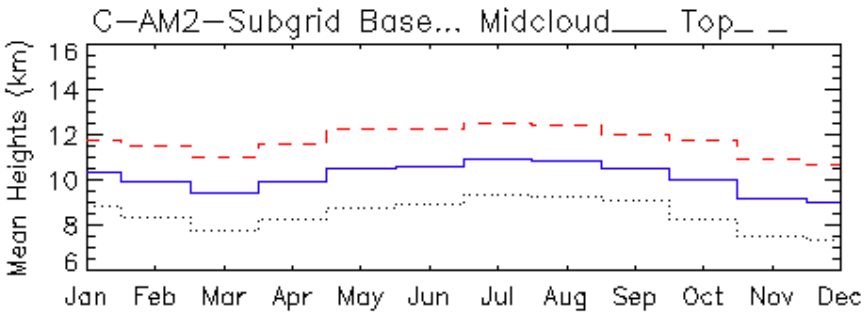


	M06 OBS	ECMWF	2000 OBS	C-CAM3	C-AM2
Base	8.60	8.55	8.76	9.82	8.30
Mid-Cloud	9.38	9.81	9.57	10.98	9.95
Top	10.17	11.07	10.39	12.14	11.60

Year 2000



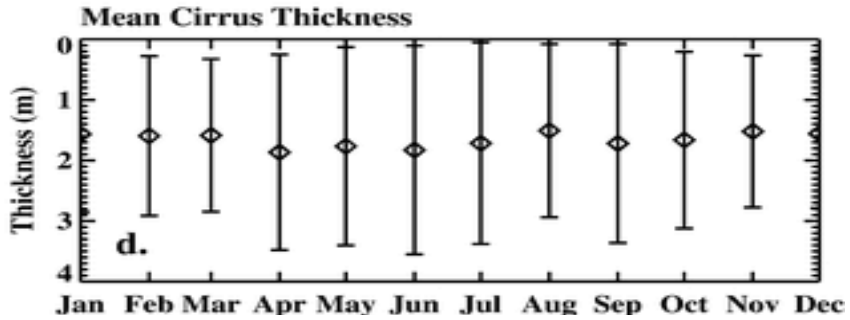


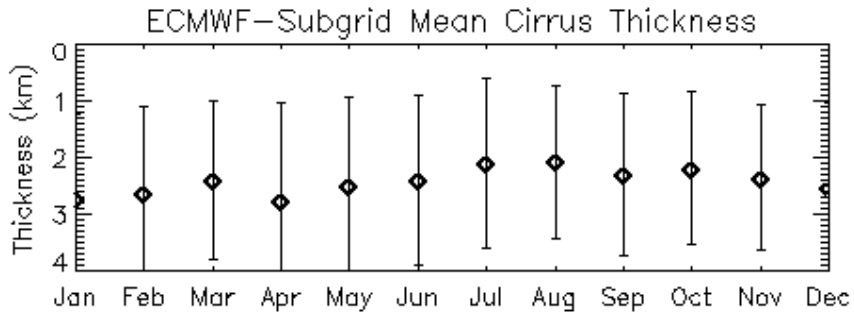


Occurrence Statistics

Thickness

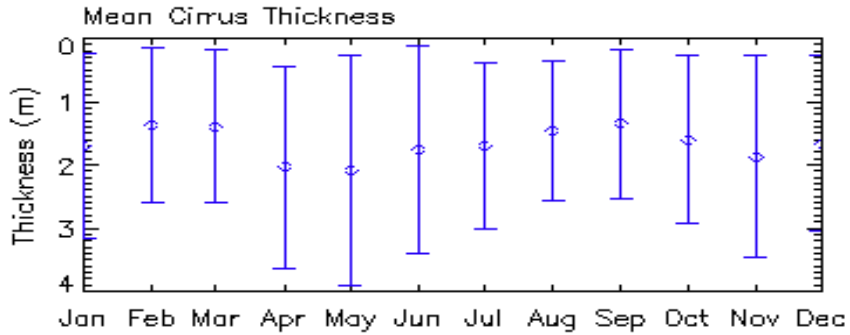
1997-2002

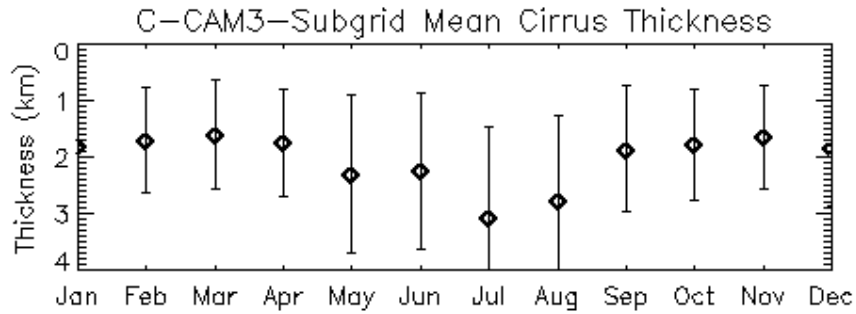


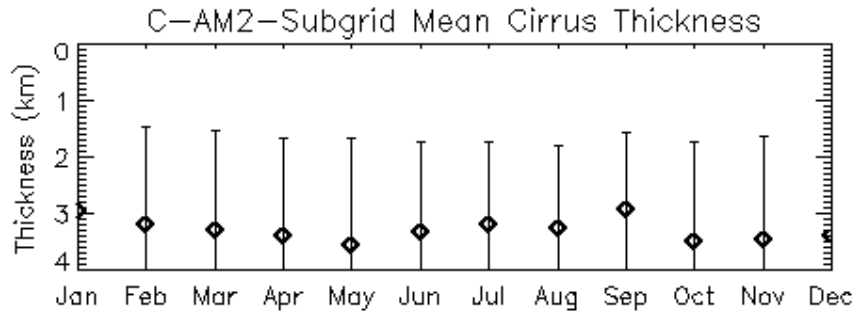


	M06 OBS	ECMWF	2000 OBS	C-CAM3	C-AM2
Annual	1.66	2.52	1.71	2.32	3.30
NDJFM	1.57	2.60	1.50	1.71	3.23
MJJAS	1.72	2.36	1.76	2.36	3.32

Year 2000







Bulk Microphysics

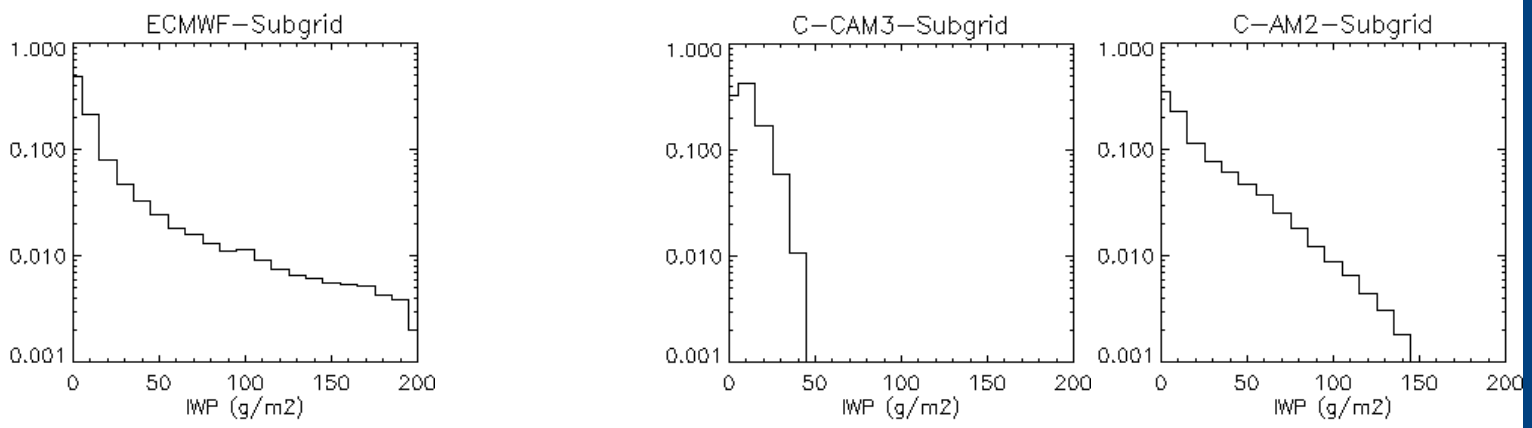
IWP

1997-2002

Annual (M06)	ECMWF
18.0 ± 24	21.6 ± 37.1

2000

Annual (Observed)	C-CAM3	C-AM2
15.1 ± 26.6	10.4 ± 8.4	21.9 ± 27.2



Cold Season

18.6 ± 23	18.9 ± 34.2

Warm Season

17.7 ± 26	26.7 ± 41.5

Cold Season

15.6 ± 23.1	6.9 ± 7.0	17.4 ± 25.6

Warm Season

15.0 ± 29.0	11.7 ± 8.7	30.9 ± 29.7

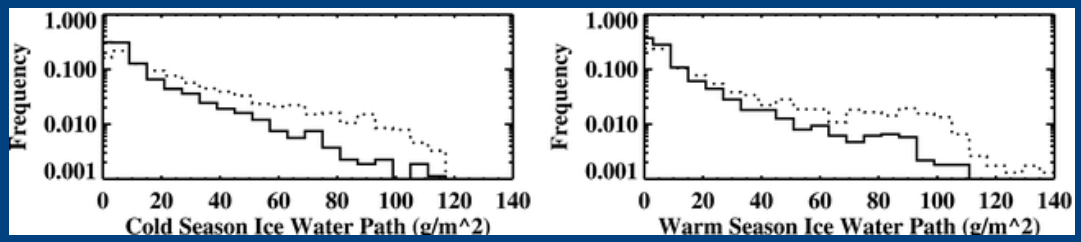
IWP calculated from layer IWC and thickness

*thin cirrus subset (IWP < 200 g m-2)

Bulk Microphysics Sensitivity

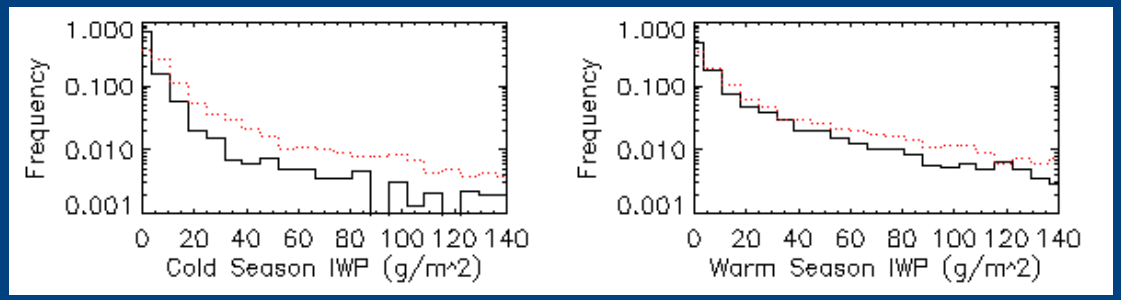
1997-2002

M06 OBS



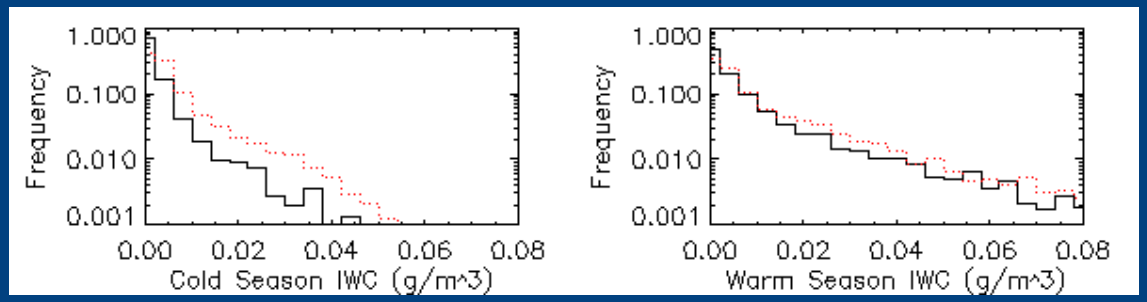
		Mean ± Std dev
Cold	Up	24.3 ± 25.8
	Down	12.7 ± 17.5
Warm	Up	24.0 ± 20.5
	Down	12.8 ± 20.4

ECMWF



Cold	Up	20.2 ± 34.7
	Down	7.8 ± 20.5
Warm	Up	29.4 ± 43.3
	Down	19.4 ± 35.1

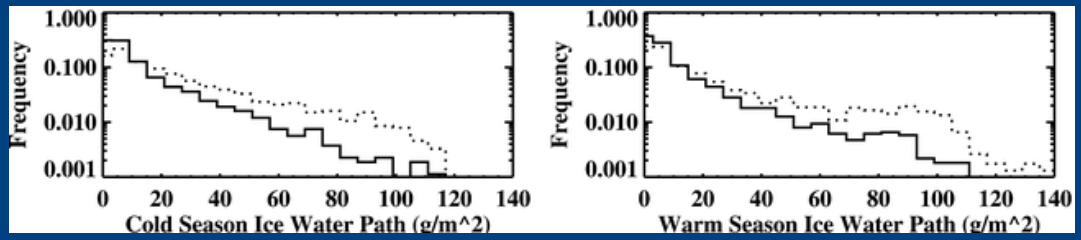
Also see the effects on the optical properties: similar results in IWC, optical depth, and emissivity.



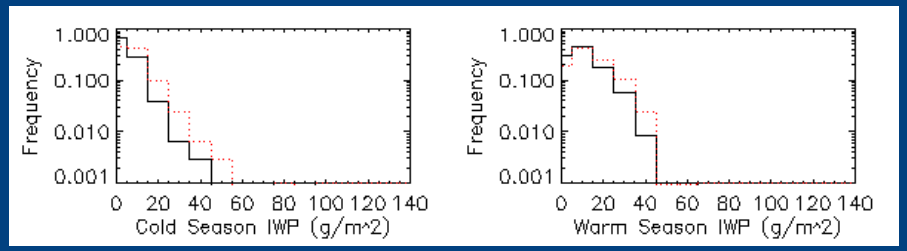
Bulk Microphysics Sensitivity

2000

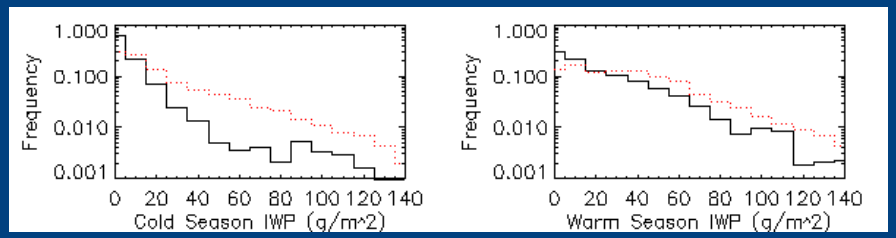
OBS



C-CAM3



C-AM2



Mean ± Std dev

Cold	Up	19.2 ± 24.5
	Down	13.9 ± 23.7
Warm	Up	21.5 ± 35.1
	Down	13.2 ± 27.0

Cold	Up	8.0 ± 7.5
	Down	5.2 ± 5.8
Warm	Up	13.5 ± 9.3
	Down	10.5 ± 8.1

Cold	Up	23.3 ± 28.8
	Down	8.2 ± 16.8
Warm	Up	36.9 ± 31.4
	Down	23.1 ± 25.8

Conclusions - Occurrence Statistics

- GCMs predict cirrus at lower occurrence frequency
- Thicker cirrus cloud layers produced by the models (higher cloud top heights)
- Smaller mean IWC values predicted in GCMs (IWP more consistent with observed values)
- Microphysics more variable between seasons in GCM predicted cirrus
- Strong sensitivity of microphysics to large-scale motions in GCMs (stronger than obs cold season)

Outline

- Introduction
- Data and Technique
- Results Occurrence Statistics
- **Results Large-scale Meteorology**
  - **Mean meteorology and anomalies during observed cirrus occurrence (2000)**
  - **Seasonal anomaly comparisons between observation and CAPT-GCMs**
  - **Agreement/Disagreement between GCM and MMCR cirrus events**
- Summary and Conclusion

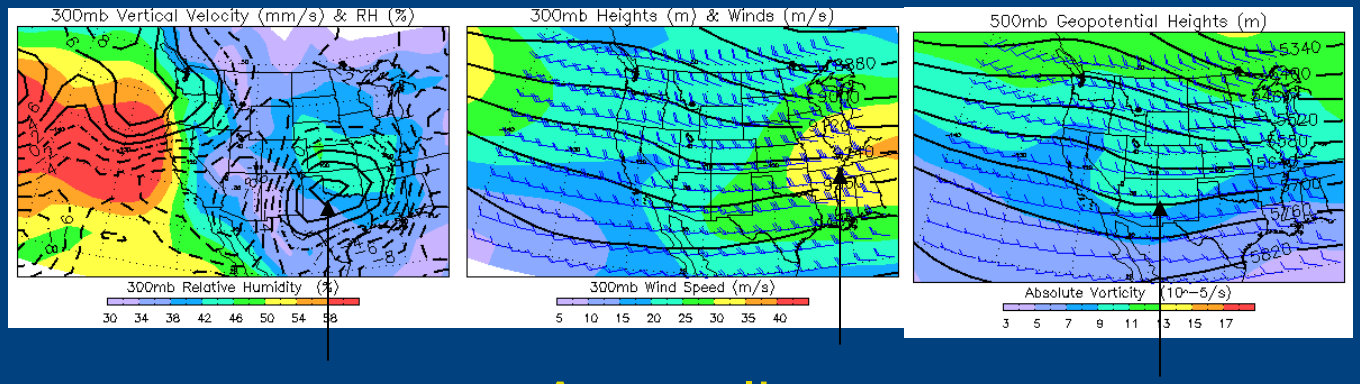
Large-Scale Meteorology

- Mean meteorology produced by averaging cirrus NCEP times
- Seasonal Anomalies
  - How: Take the seasonal (warm/cold) mean and subtract it from the 30-year respective seasonal average
  - Why: Anomalies provide more detail, showing differences more clearly
- We want to focus on the seasonal anomalies because cirrus produced differently in cold/warm season

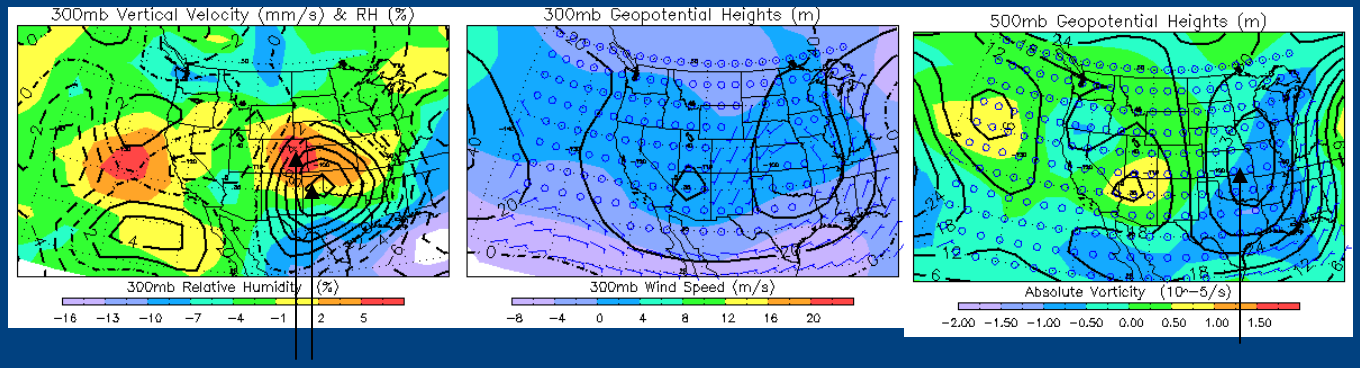
Meteorology of Observations

Cold Season

Mean Meteorology



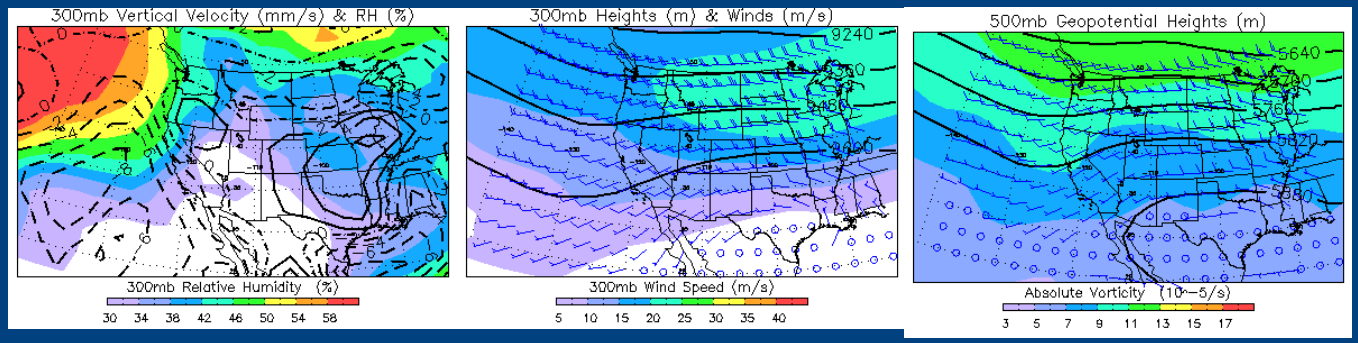
Anomalies



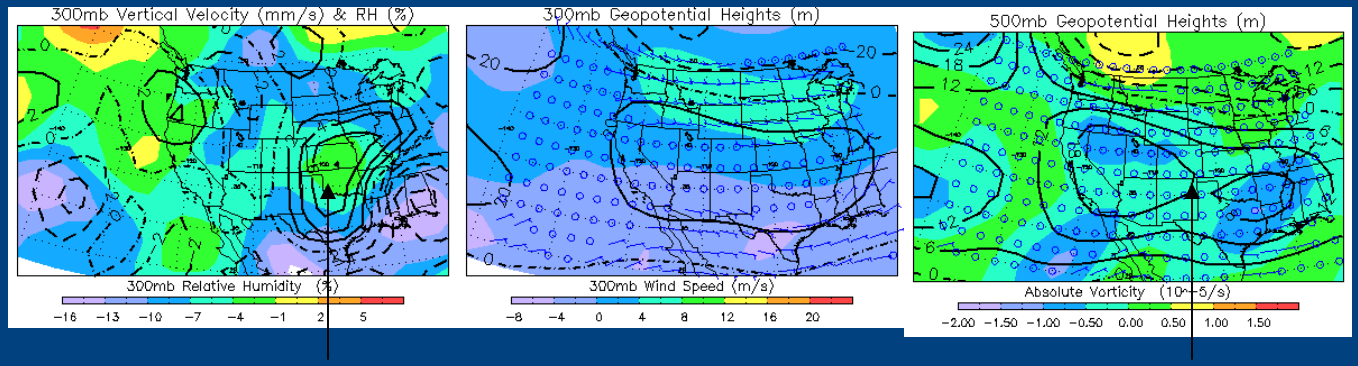
Meteorology of Observations

Warm Season

Mean Meteorology

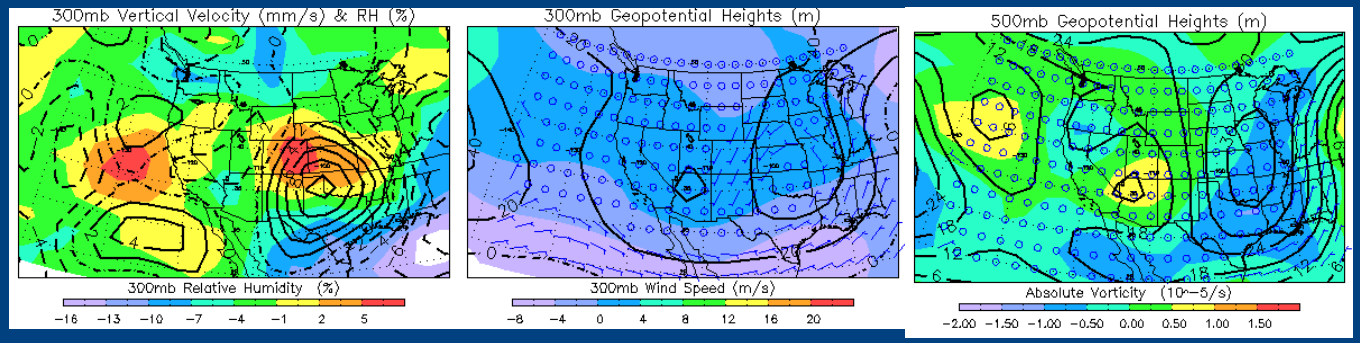


Anomalies

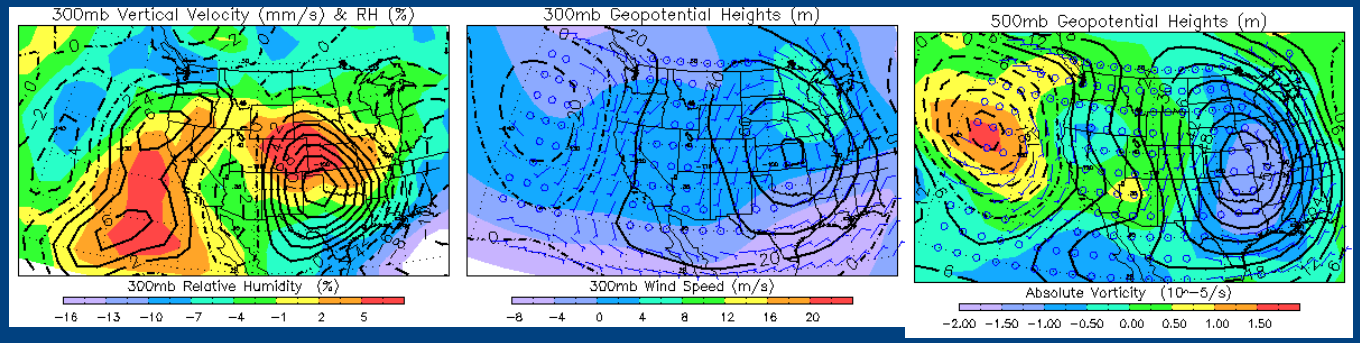


Cold Season Anomalies

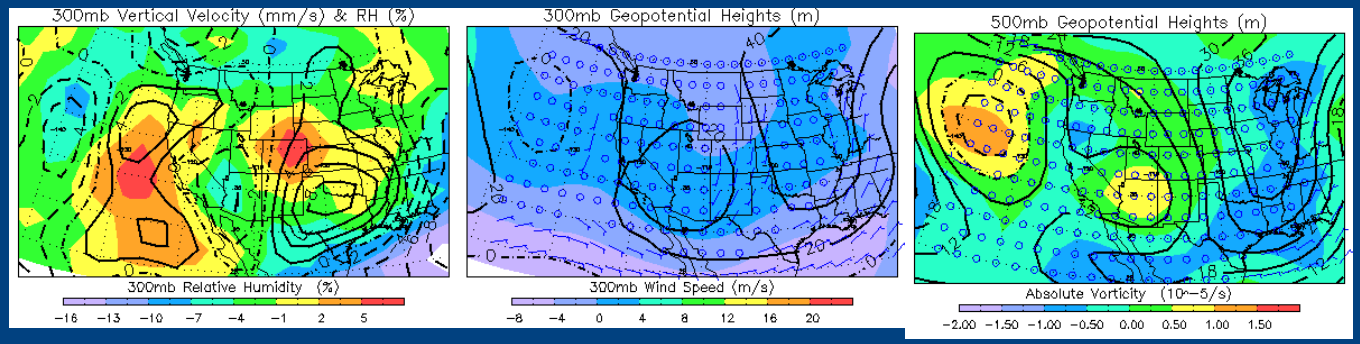
OBS



CAM3

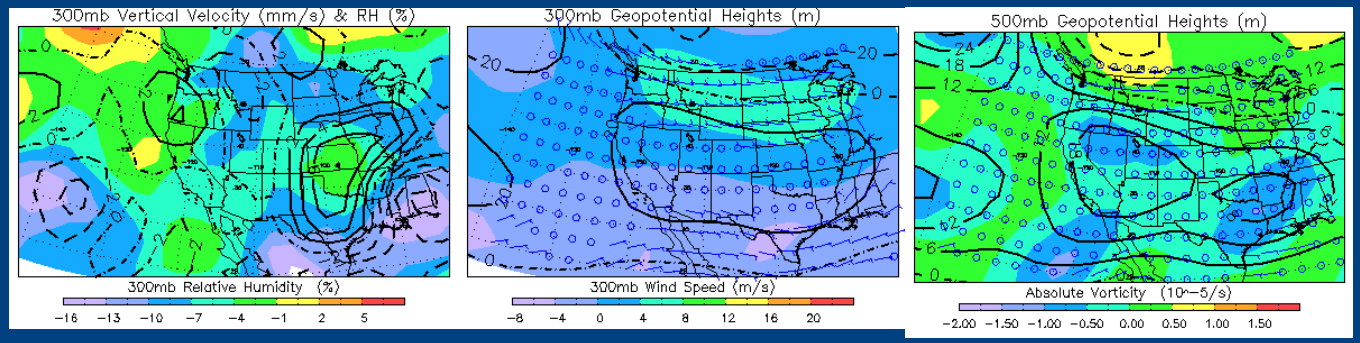


AM2

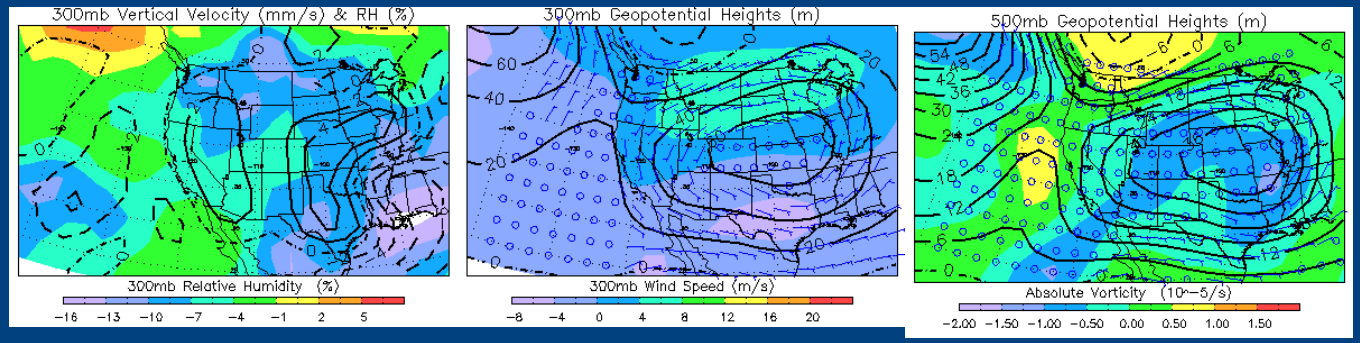


Warm Season Anomalies

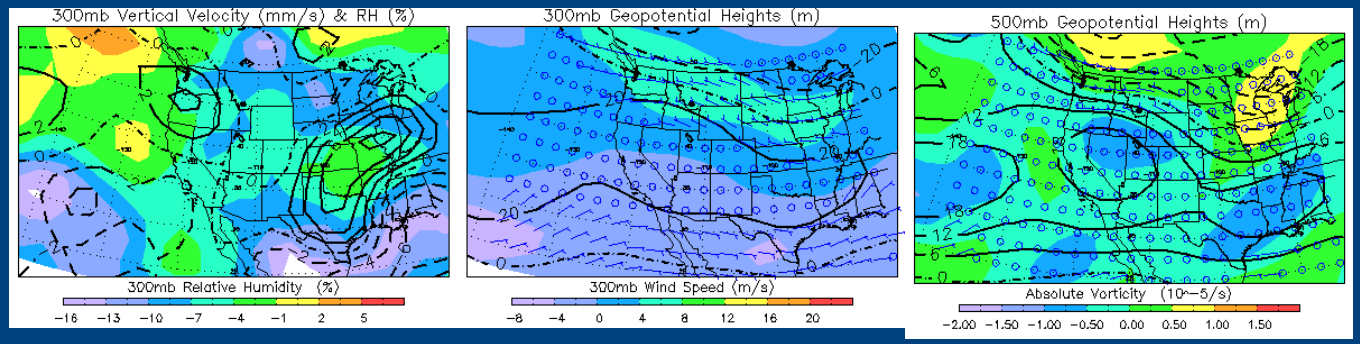
OBS



CAM3



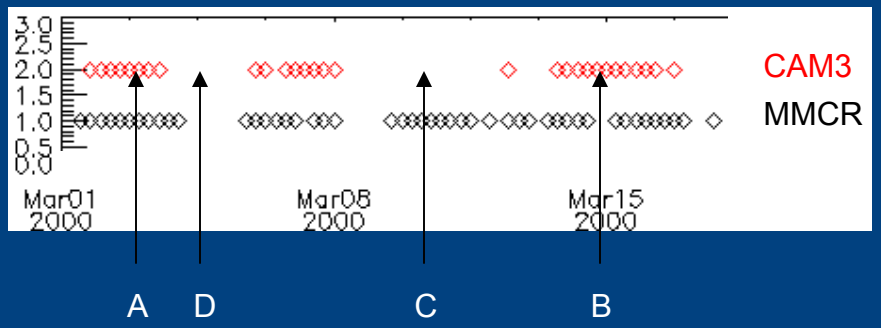
AM2



Agree/Disagree Definitions

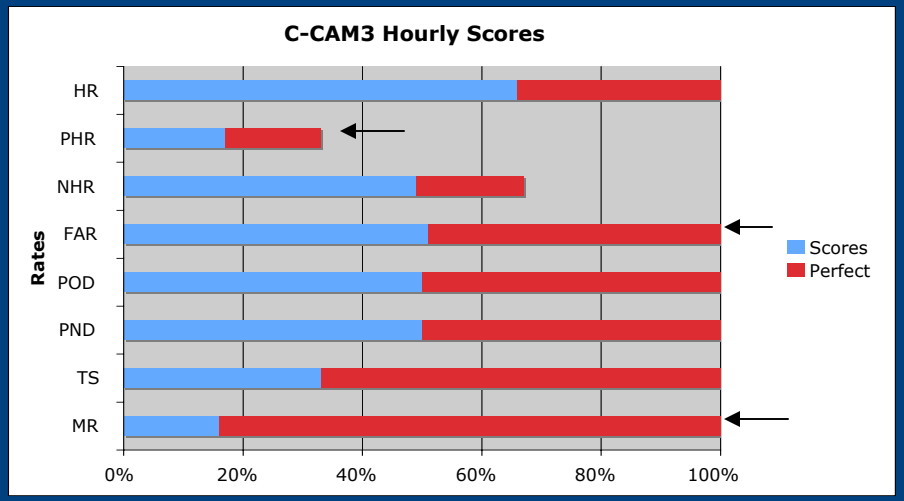
	Yes (Radar)	No (Radar)
Yes (Model)	A, Hit	B, False Alarm
No (Model)	C, Miss	D, Hit

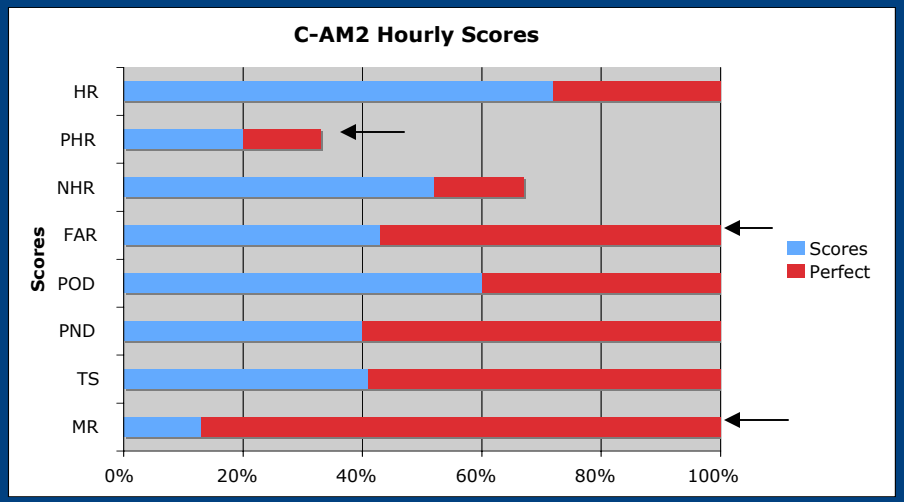
Example NCEP Time Series



Name of rate	Equation
Hit Rate (HR)	(A+D)/ (A+B+C+D)
Positive Hit Rate (PHR)	A/ (A+B+C+D)
Negative Hit Rate (NHR)	D/ (A+B+C+D)
False Alarm Rate (FAR)	B/ (A+B)
Probability of Detection (POD)	A/ (A+C)
Probability of Non-Detection (PND)	C/ (A+C)
Threat Score (TS)	A/ (A+B+C)
Miss Rate (MR)	C/ (A+B+C+D)

Scores

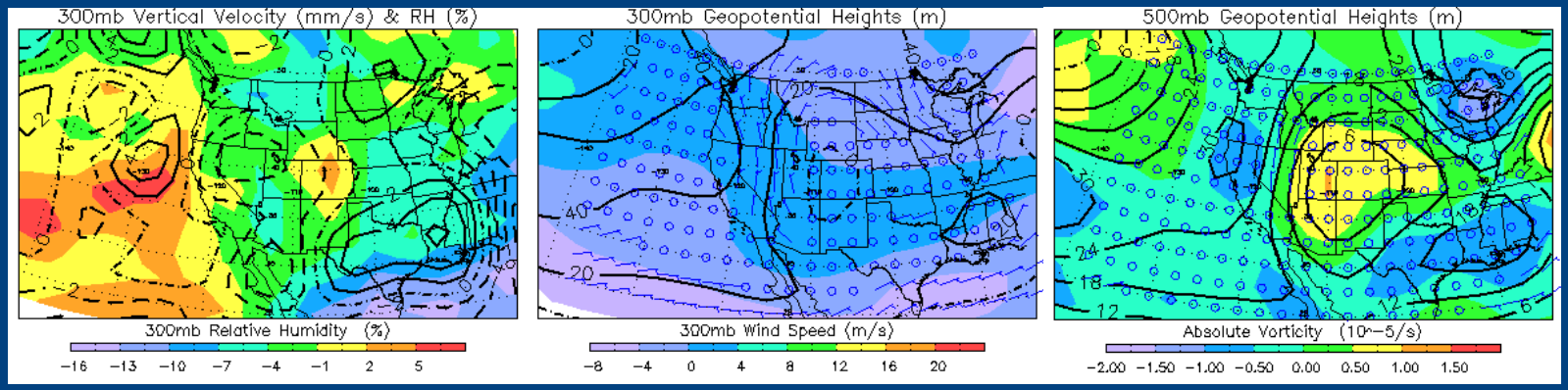




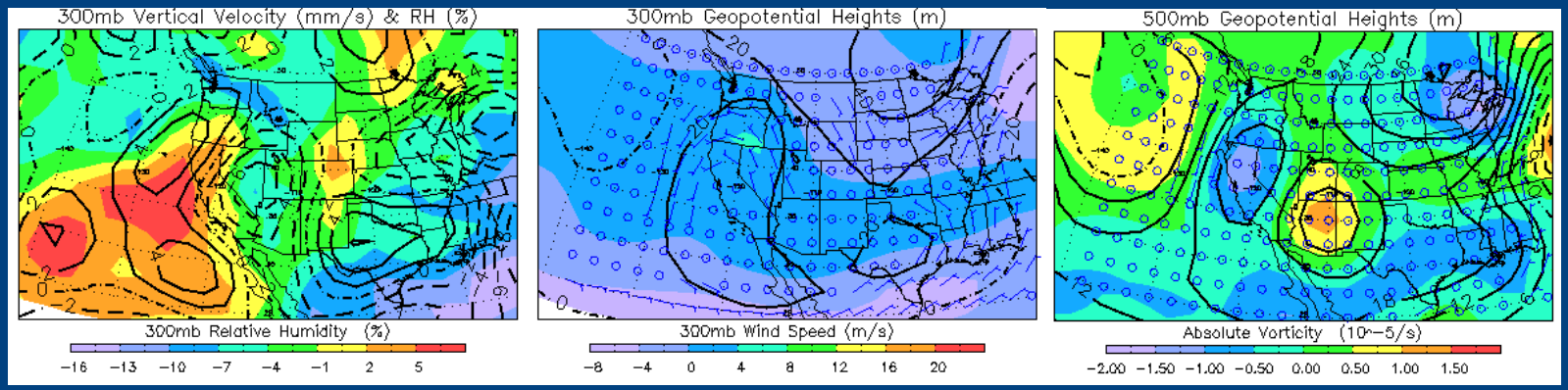
Hourly Metrics	Equation	Rate CAM3	Perfect Score	Rate AM2
Hit Rate (HR)	(A+D)/ (A+B+C+D)	0.66	1.00	0.72
Positive Hit Rate (PHR)	A/ (A+B+C+D)	0.17	0.33	0.20
Negative Hit Rate (NHR)	D/ (A+B+C+D)	0.49	0.67	0.52
False Alarm Rate (FAR)	B/ (A+B)	0.51	0.00	0.43
Probability of Detection (POD)	A/ (A+C)	0.50	1.00	0.60
Probability of Non-Detection (PND)	C/ (A+C)	0.50	0.00	0.40
Threat Score (TS)	A/ (A+B+C)	0.33	1.00	0.41
Miss Rate (MR)	C/ (A+B+C+D)	0.16	0.00	0.13

MMCR Only (MR)
Cold Season Anomalies

CAM3

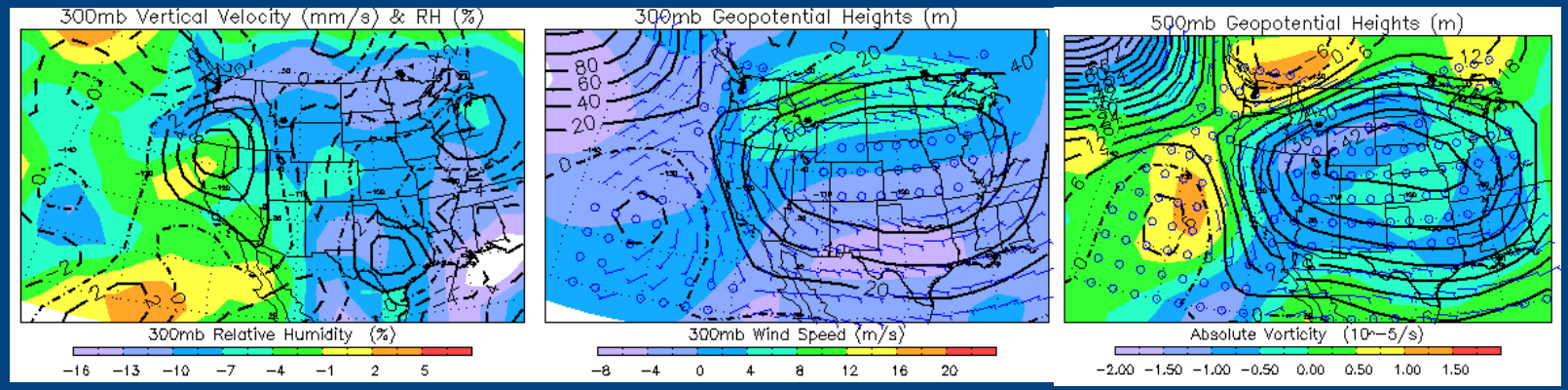


AM2

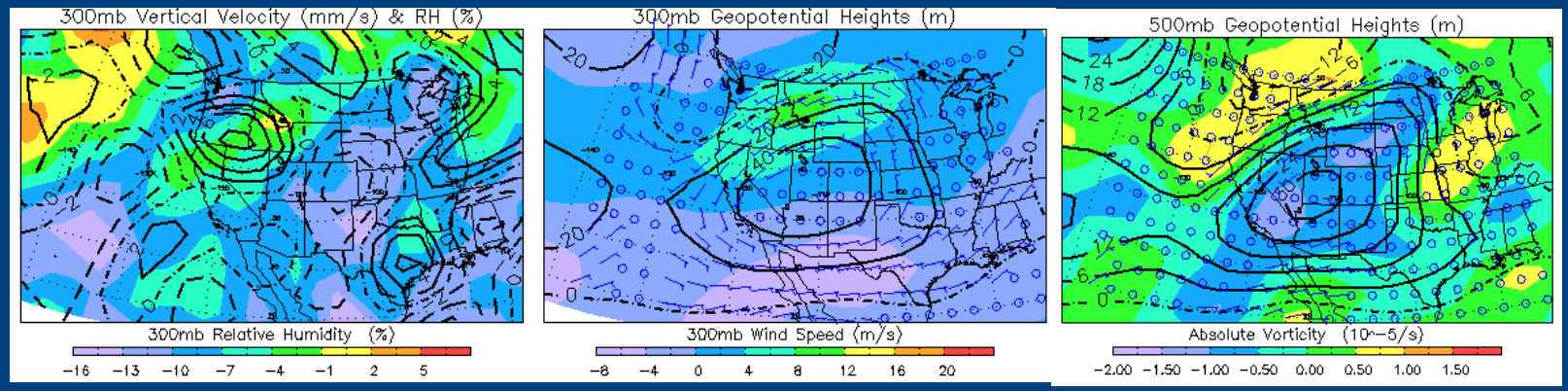


GCM Only (FAR)
Warm Season Anomalies

CAM3



AM2



Conclusions - Large-Scale Meteorology

- Similar cold and warm season patterns to observations, but important deviations in GCMs
- AM2 does marginally better than CAM3 in timing of cirrus placement with what is observed (scores)
- Warm season false produced cirrus under amplified anomalous high pressure when convection typically suppressed in real atmosphere
- Cold season missed cirrus found in more climatological flow, most likely generated on scales smaller than can be resolved by GCM

Summary

- ECMWF performs best overall in both cirrus occurrence and microphysical statistics
- AM2 scores better quantitatively than the CAM3 in cirrus occurrence
- IWP of AM2 does well in cold season but extremely high in the warm season
- CAM3 IWP values are low but more consistent

Future Work

- Derive the large-scale meteorology from the ERA40
- Compile a longer climatology for the CAPT GCMs (more comparable to M06) when more years are available
- Understand reasons why problems exist in models and eventually improve them

Acknowledgments

- My advisor Jay Mace and other committee members Tim Garrett and Steve Krueger.
- Sally Benson, U-Meteo faculty and staff, Steve Klein, and others in the ARM program.
- The support of God, my family back home and abroad, and my friends here in Utah.

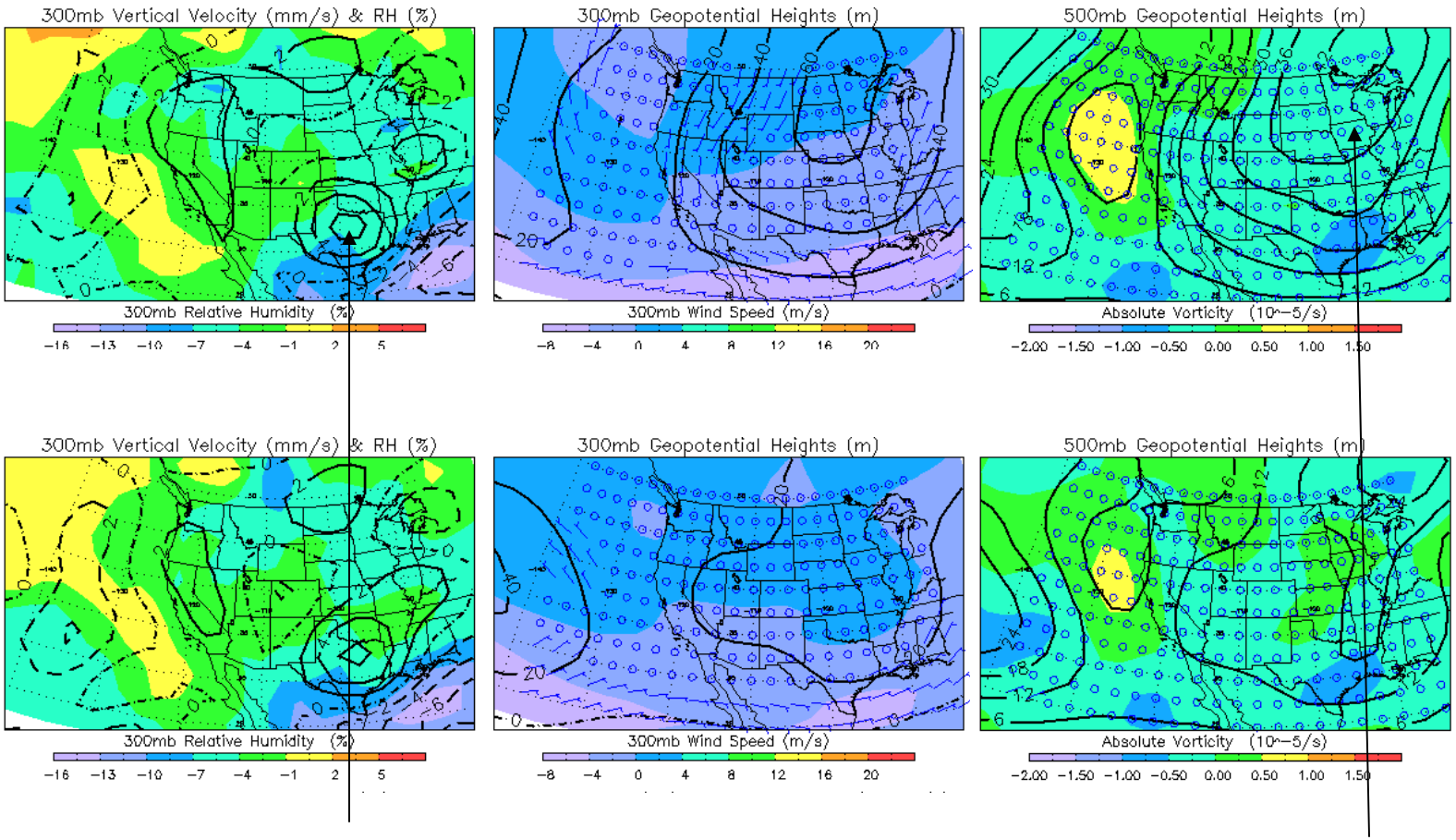
La Fin

MMCR/GCM See Cirrus

Annual Anomalies

CAM3

AM2

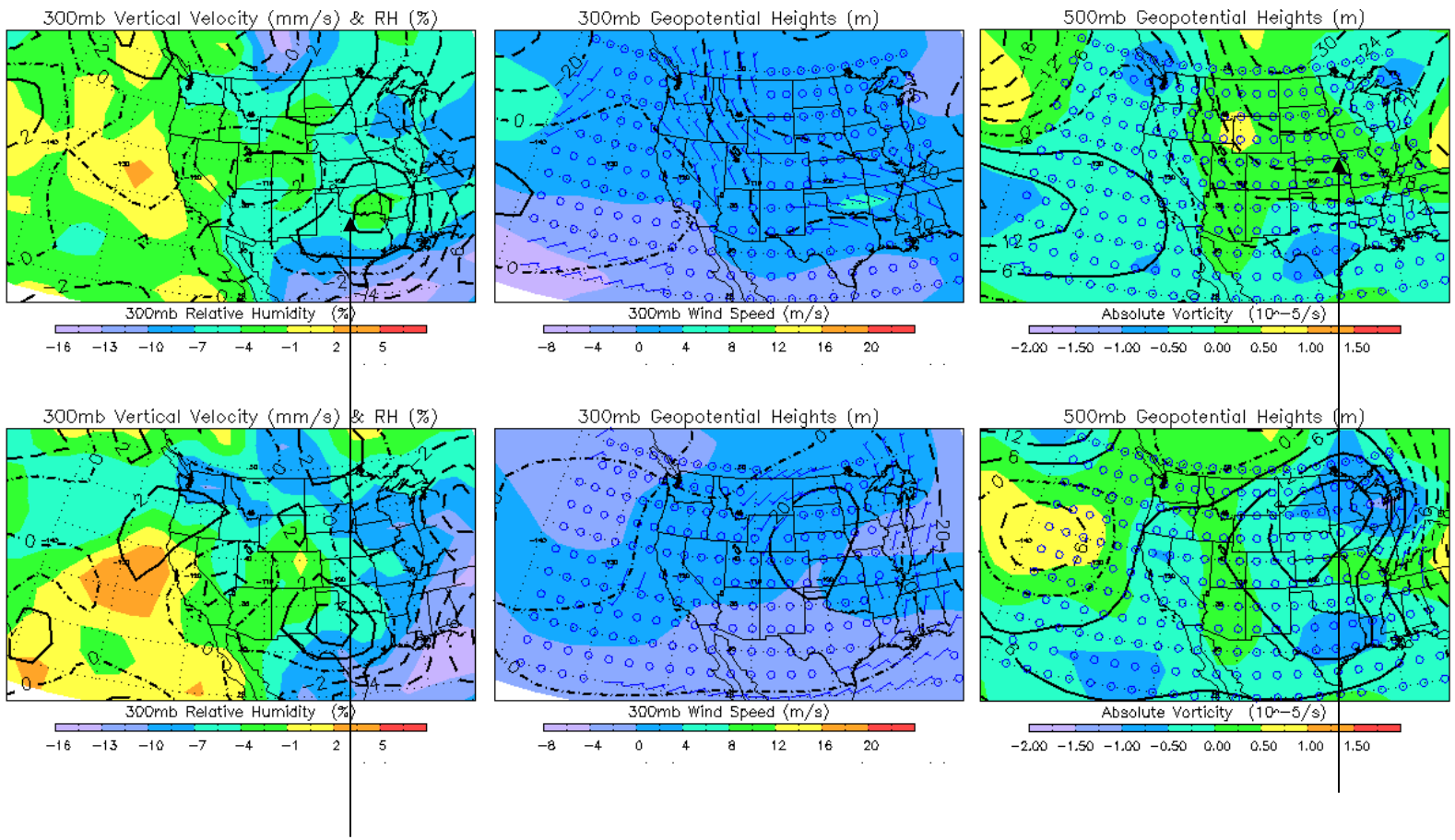


MMCR Only

Annual Anomalies

CAM3

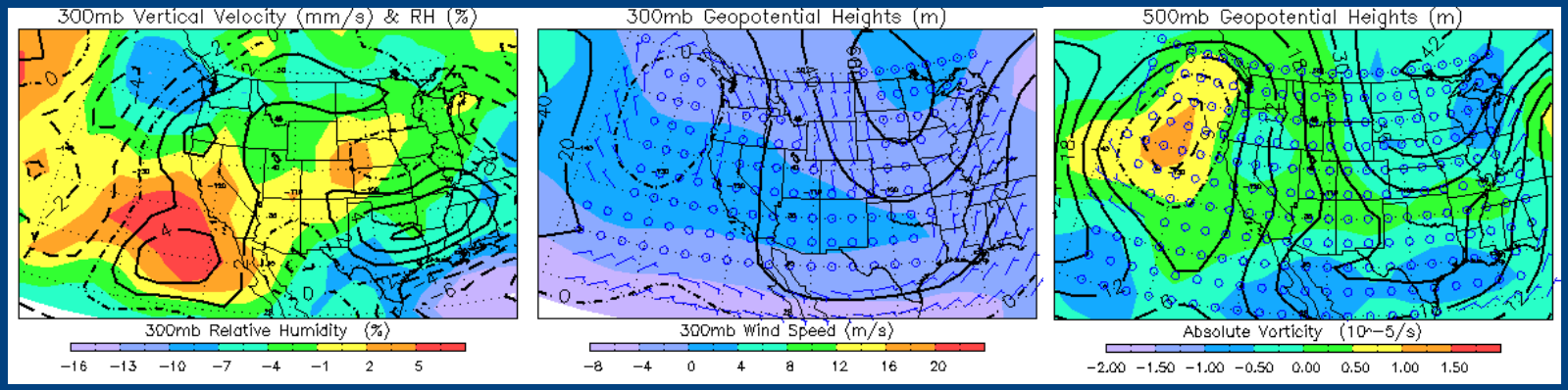
AM2



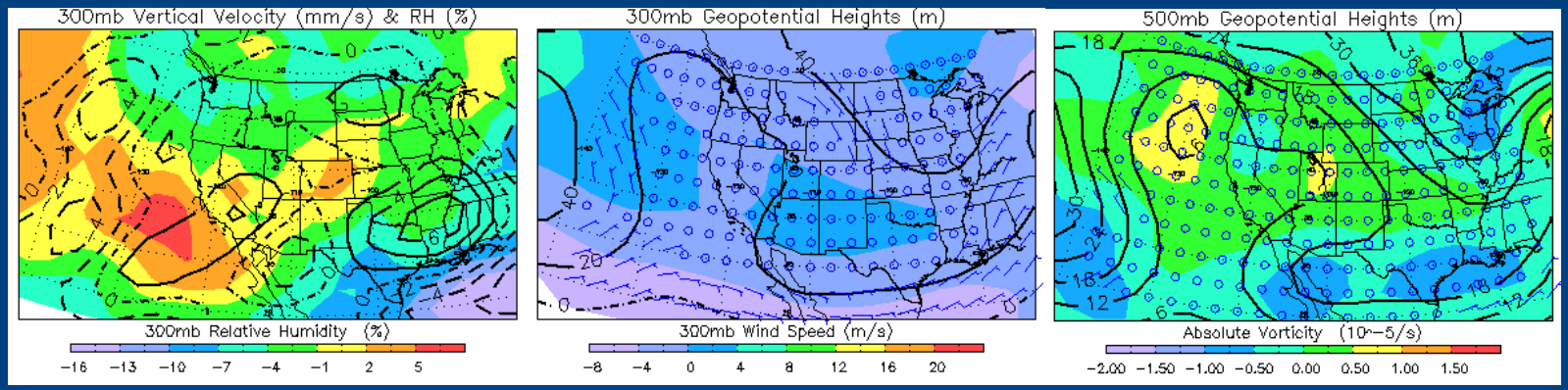
MMCR/GCM See Cirrus (PHR)

Cold Season Anomalies

CAM3



AM2

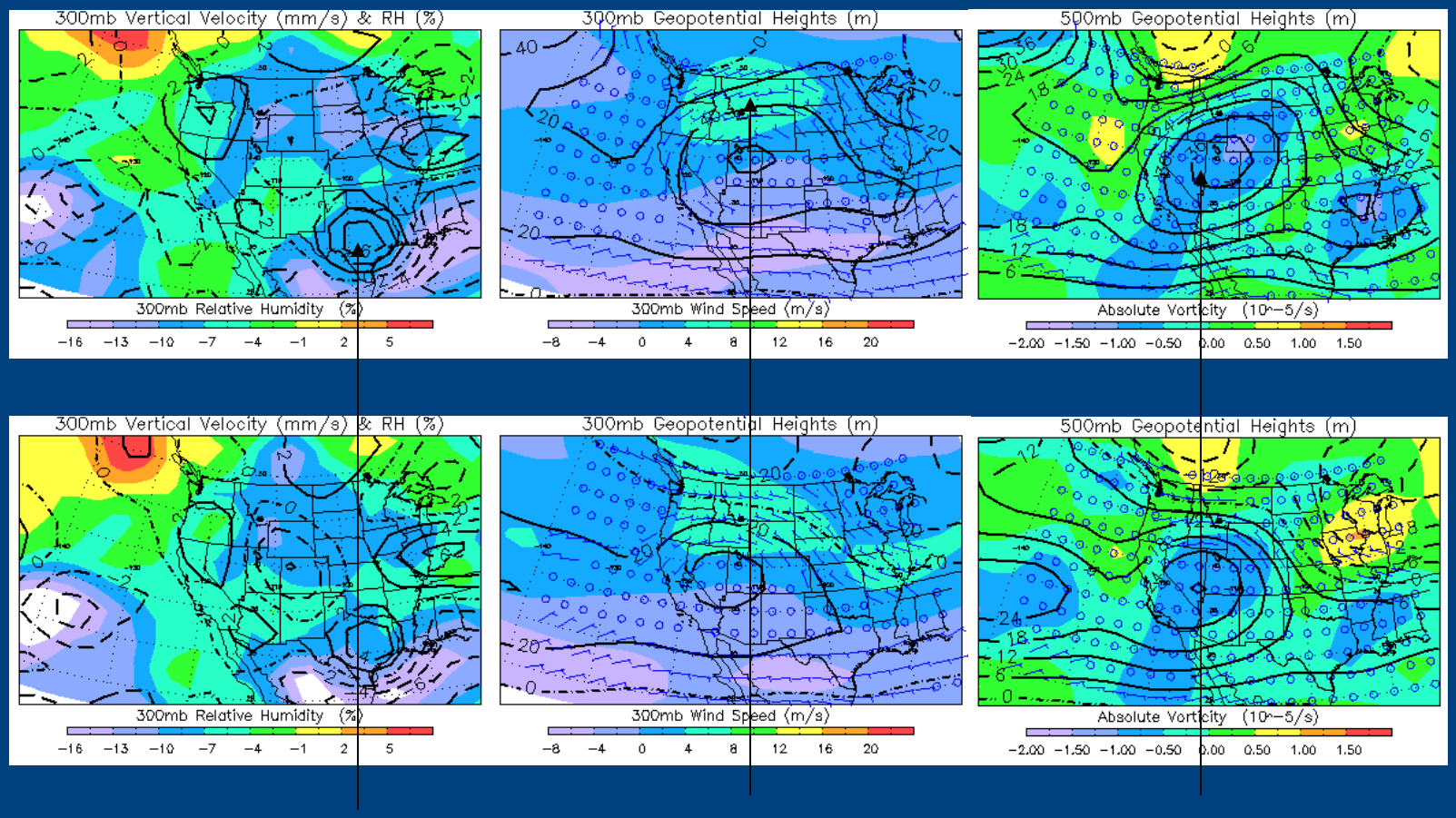


MMCR/GCM See Cirrus

Warm Season Anomalies

CAM3

AM2

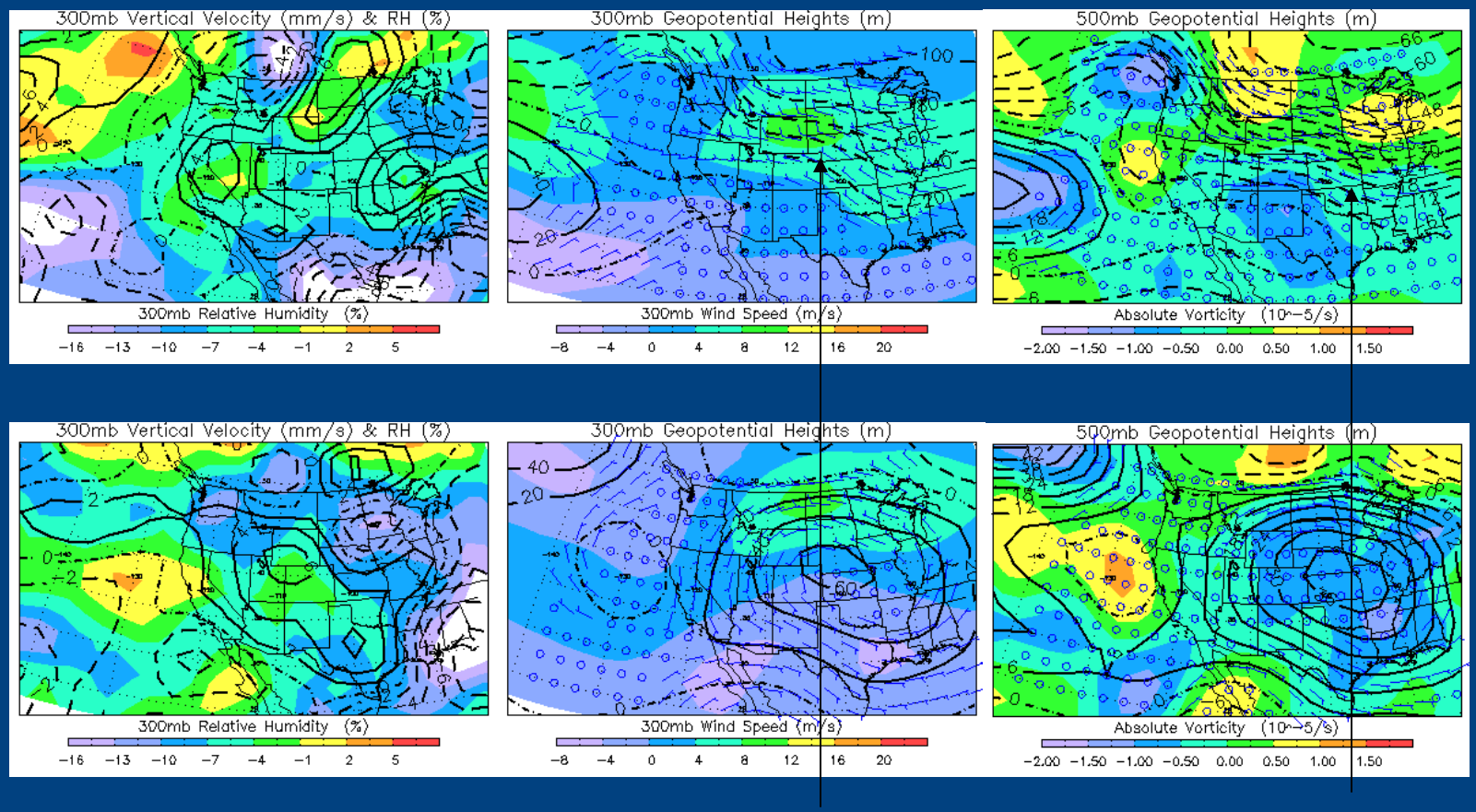


MMCR Only

Warm Season Anomalies

CAM3

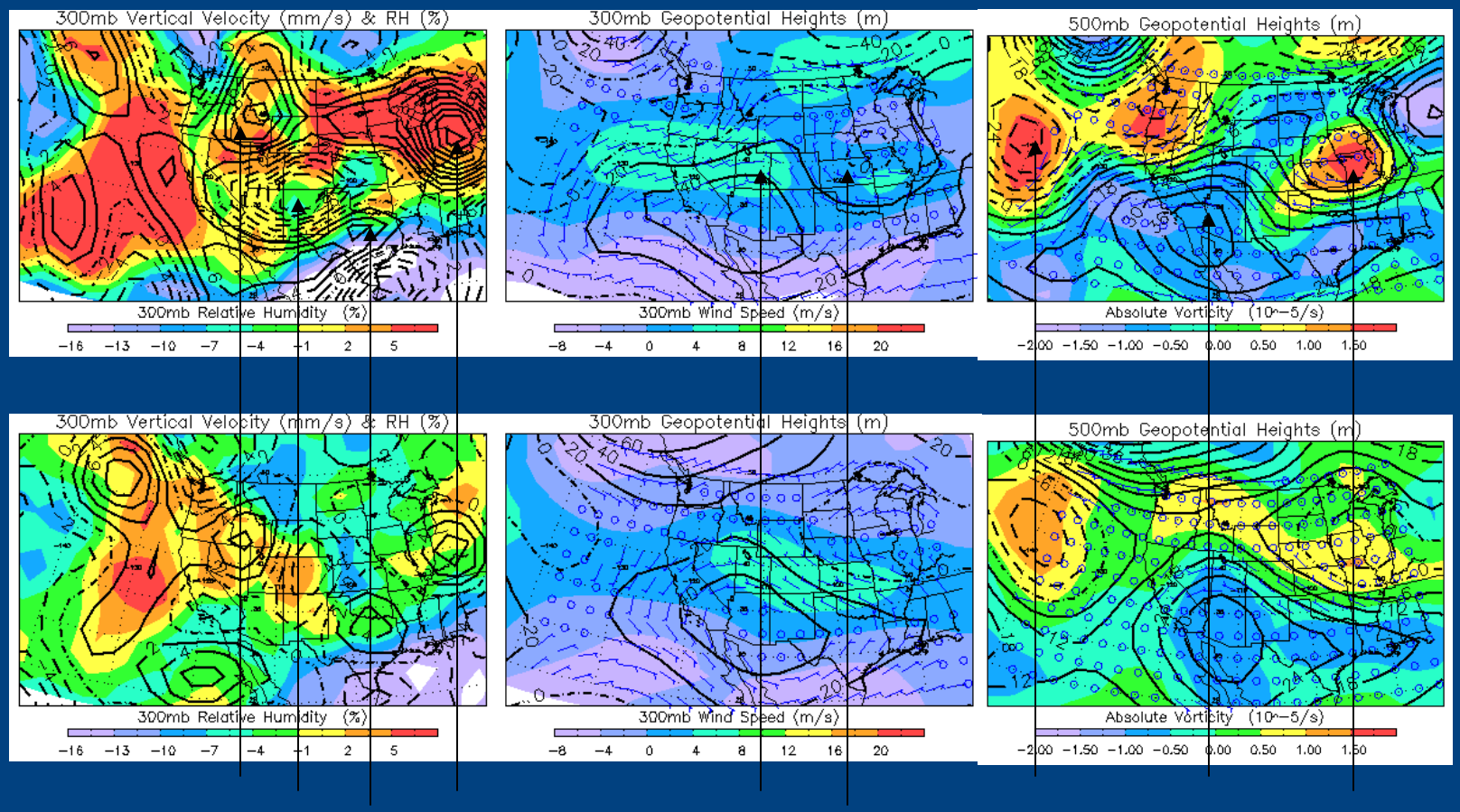
AM2

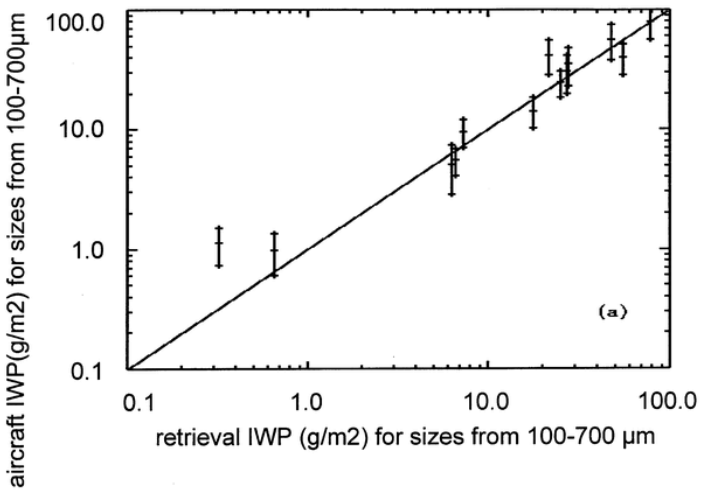
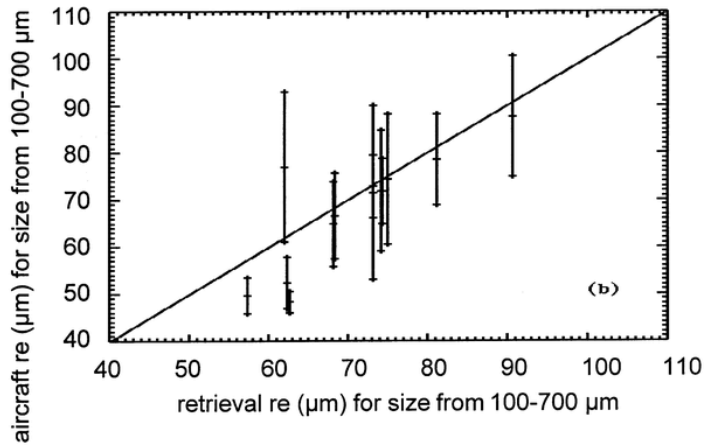


GCM Only (FAR)
Cold Season Anomalies

CAM3

AM2



ZR Algorithm

- High degree of linear correspondence found between retrievals of ZR-algorithm and in situ observations (Mace et al., 2005; Zhang 2002)