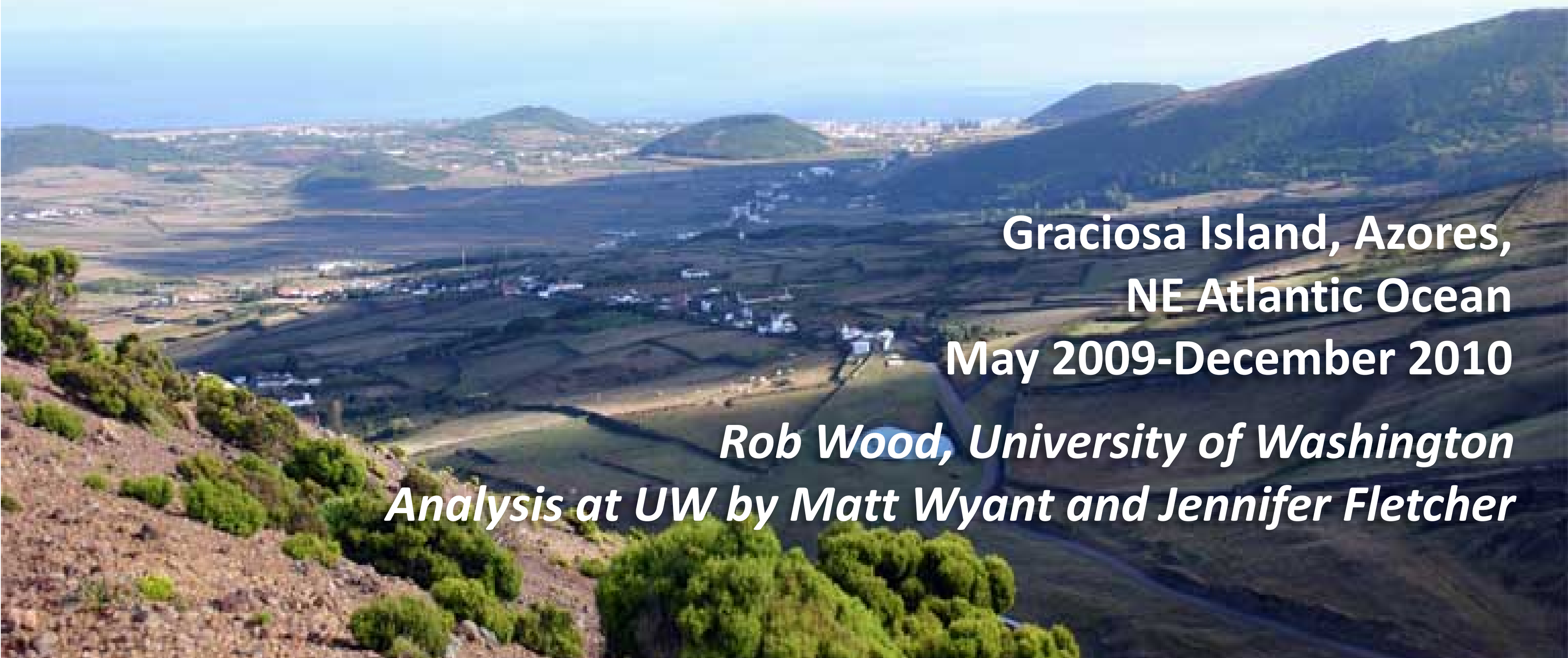
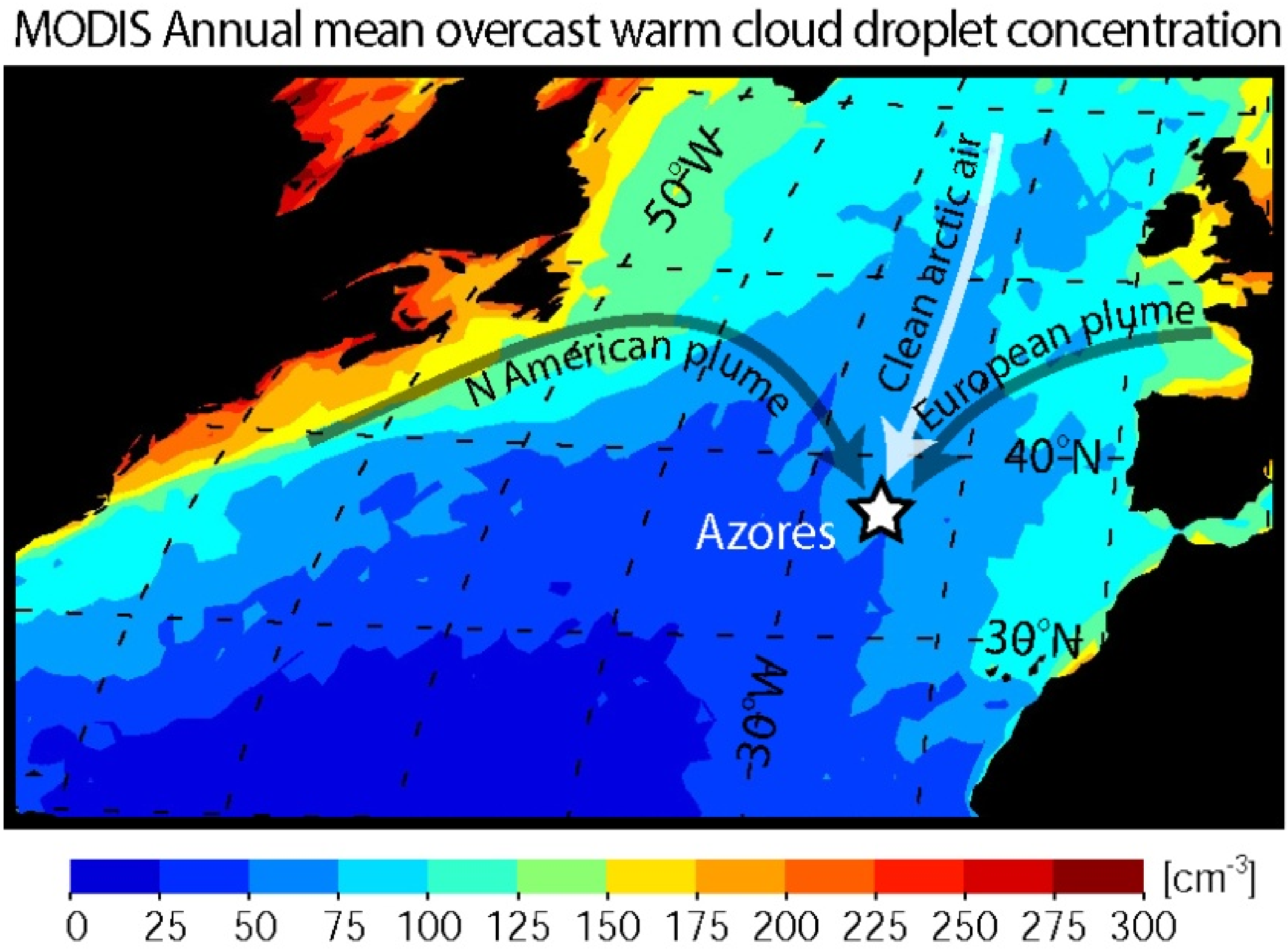
Clouds, Aerosols and Precipitation in the Marine Boundary Layer (CAP-MBL)



Graciosa Island, Azores,
NE Atlantic Ocean
May 2009-December 2010

Rob Wood, University of Washington
Analysis at UW by Matt Wyant and Jennifer Fletcher

Azores: location



Scientific Goals of CAP-MBL

- Which synoptic-scale features dominate the variability in subtropical low clouds on diurnal to seasonal timescales over the NEA? Do physical, optical, and cloud-forming properties of aerosols vary with these synoptic features? How well can state-of-the-art weather forecast and climate models (run in forecast mode) predict the day-to-day variability of NEA cloud cover and its radiative impacts?

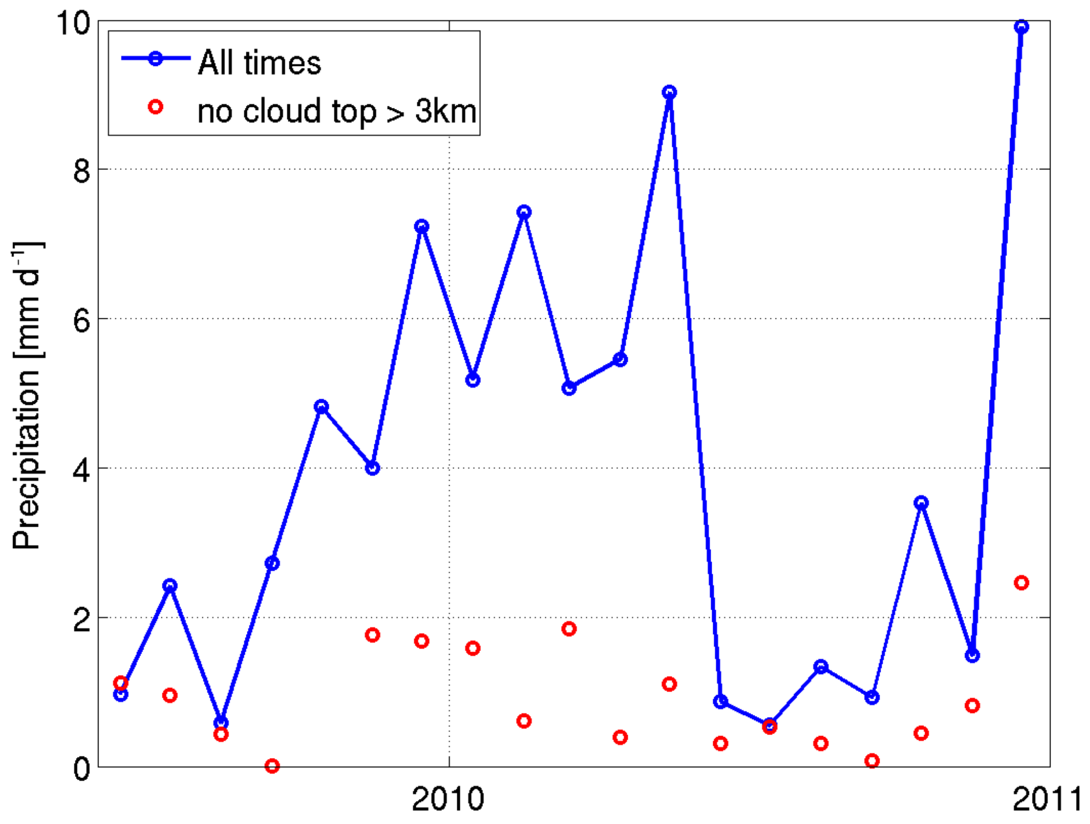
- Can we find observational support for the Twomey effect in clouds over the NEA?

- What is the variability in precipitation frequency and strength in the subtropical cloud-topped MBL on diurnal to seasonal timescales, and is this variability correlated with variability in aerosol properties?

- Are observed transitions in cloud mesoscale structure (e. g. from closed cellular to open cellular convection) influenced by the formation of precipitation?

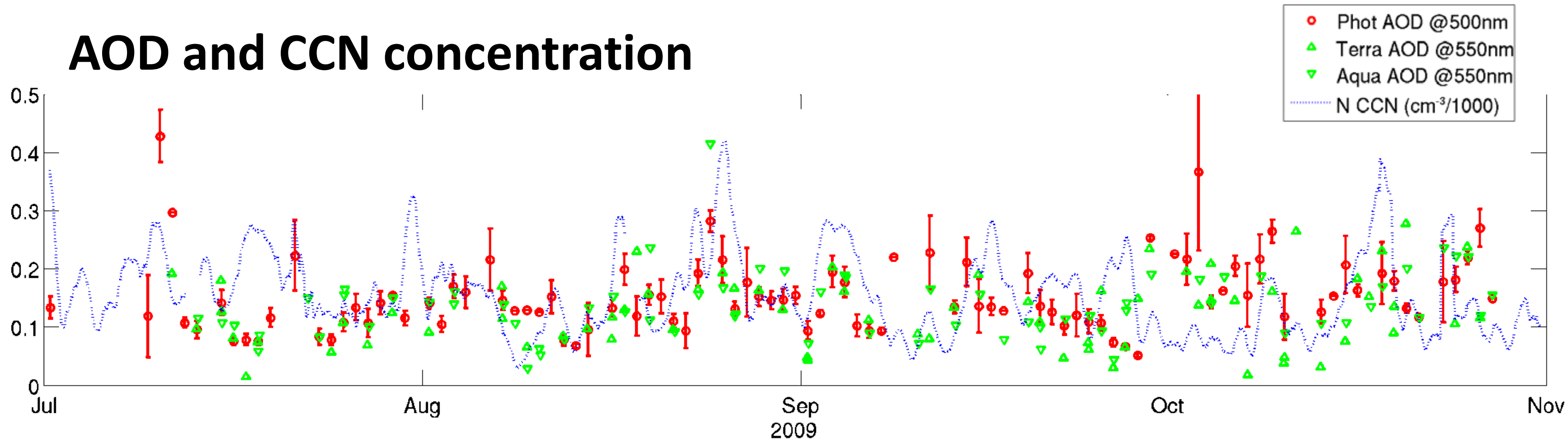
Nature of the precipitation at Graciosa

- Strong seasonal cycle with late winter maximum and summer/fall minima
- Roughly a quarter of the precipitation is from clouds with tops below 3 km

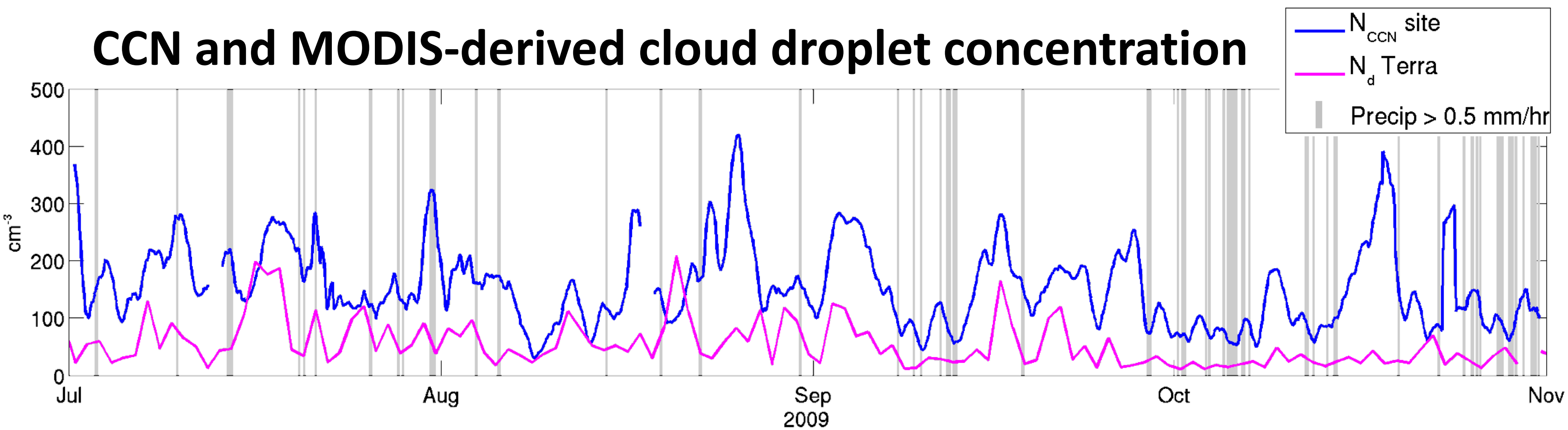


Microphysical variability at Graciosa

AOD and CCN concentration

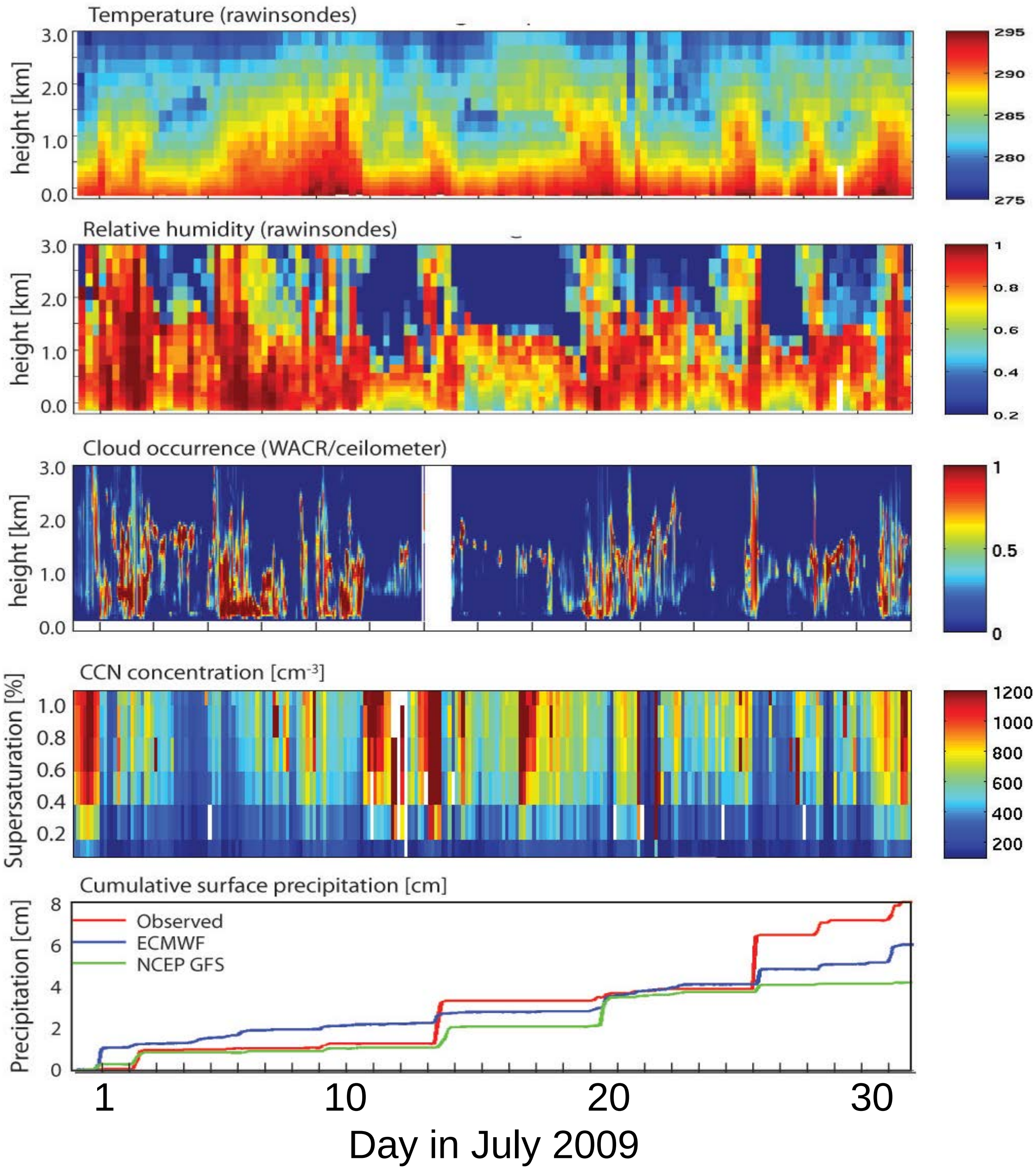


CCN and MODIS-derived cloud droplet concentration

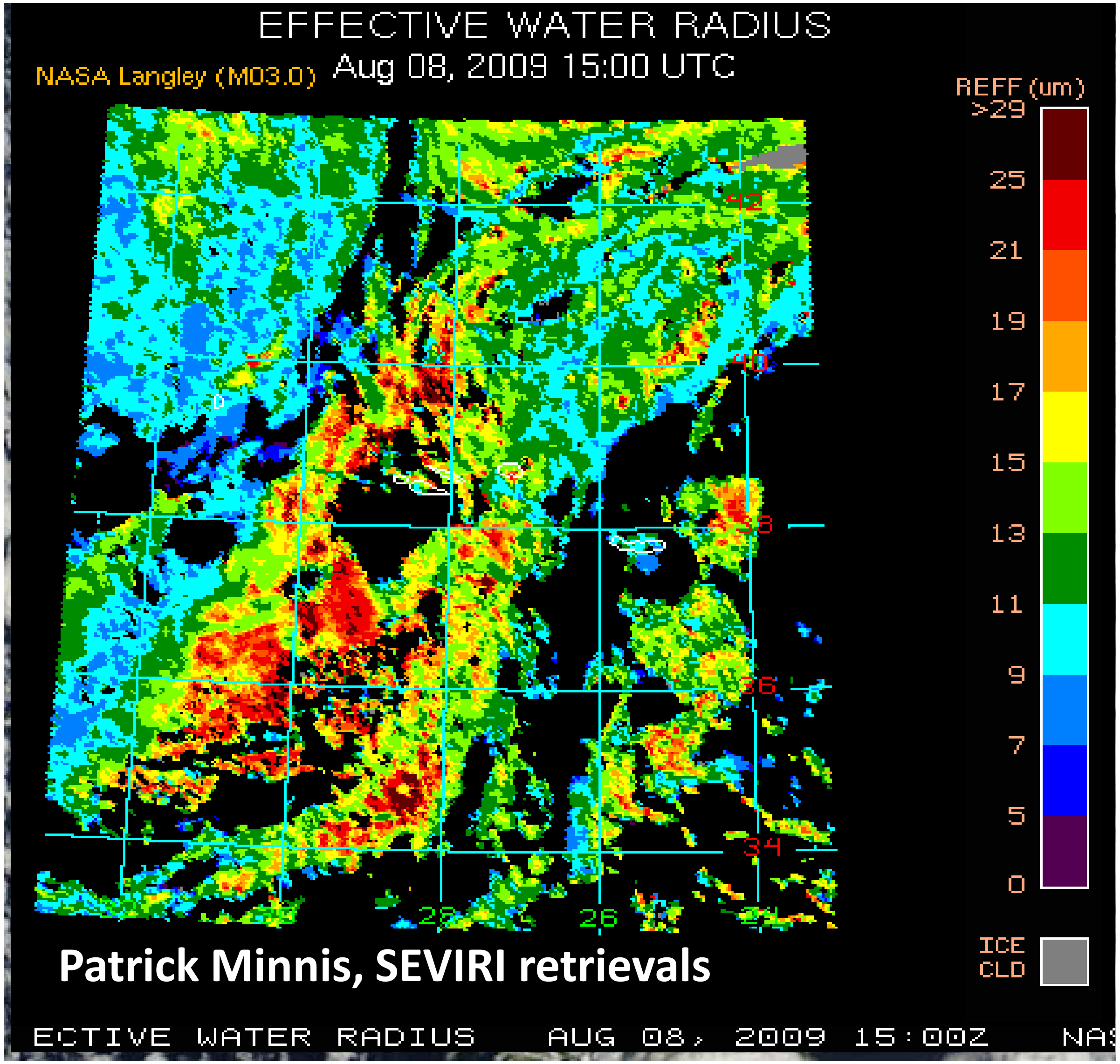


Variability

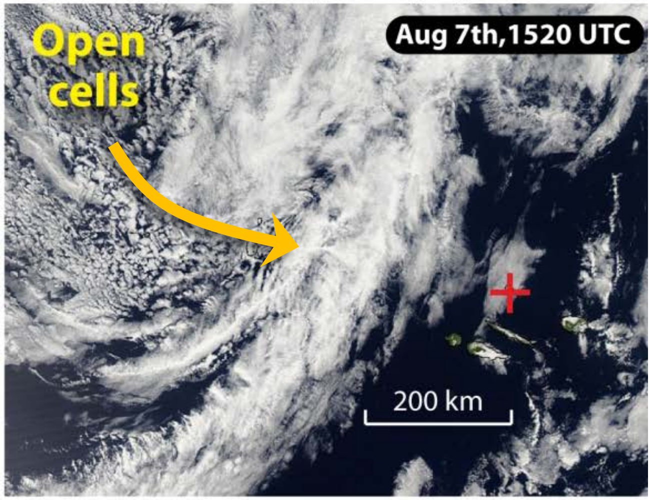
- Disturbed and quiescent periods
- Broad range of cloud types and properties, aerosol loadings, and controlling meteorology

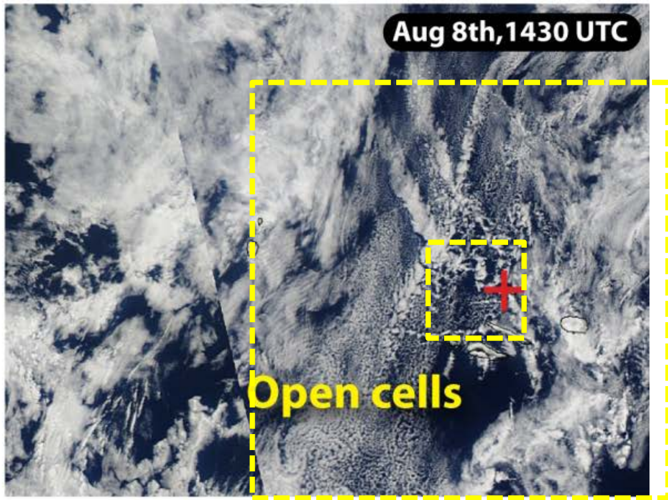


Ultra-clean marine boundary layers



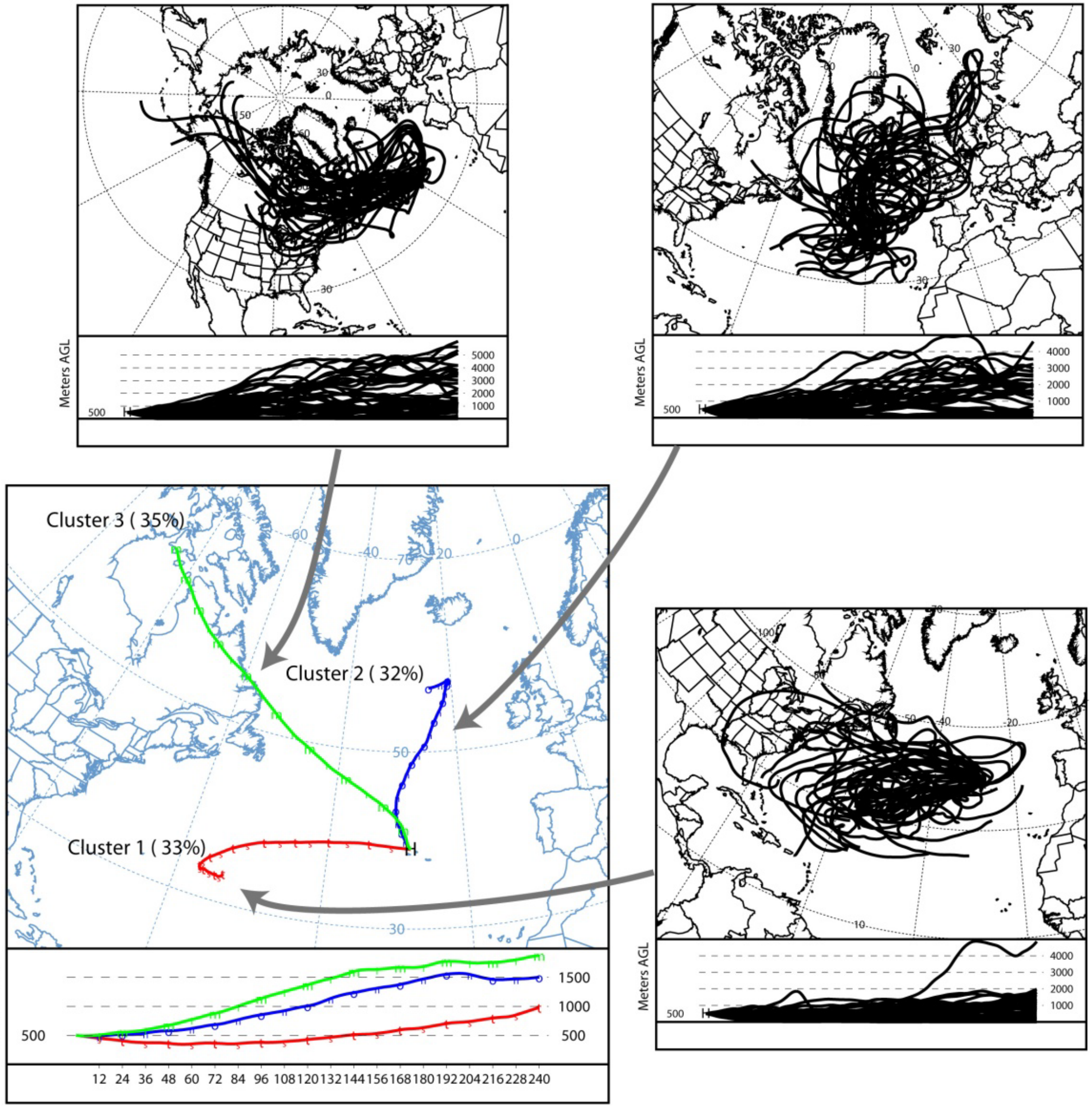
MODIS Aqua Imagery



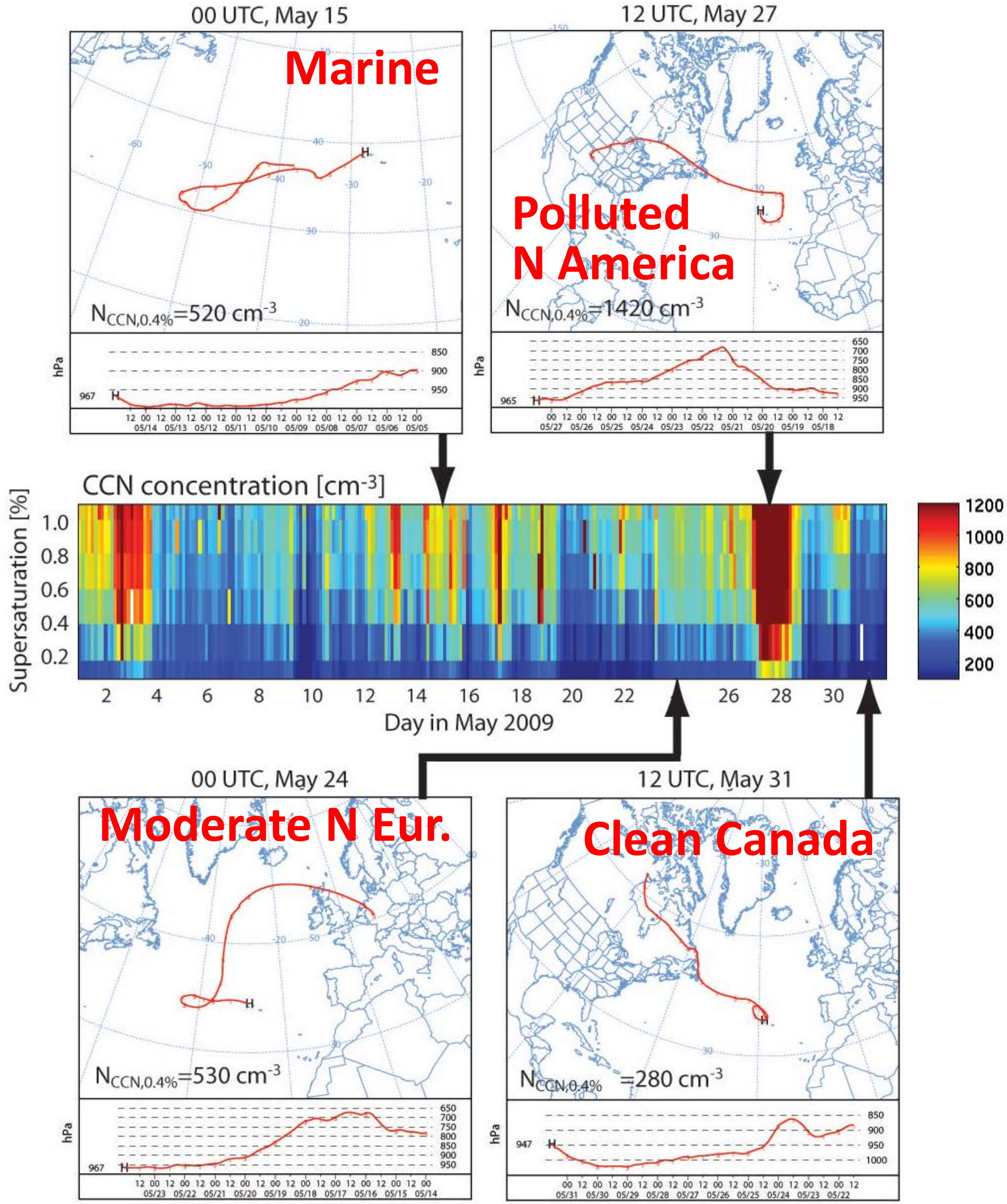


Airmasses at Graciosa

- Trajectories calculated using NOAA HYSPLIT with global model
- Diverse array of airmass origins



Diverse airmasses and aerosol signatures



VAPs/PI products needed to maximize productivity and use of AMF Azores data

VAP	***Key derived parameters***[input variables, instruments](references)
(i) Quantitative drizzle precipitation	**Cloud base and sub cloud precipitation profiles** [reflectivity statistics from WACR, lidar backscatter from ceilometer/lidar] (O'Connor et al. 2003, Kollias et al. 2010)
(ii) Cloud microphysical properties	(i) **Surface-derived cloud effective radius and droplet concentration** [LWP from MWR and downwelling shortwave radiance from broad band radiometer] (Dong et al. 1997, Dong and Mace 2003) (ii) **Satellite-derived cloud effective radius and droplet concentration** from MODIS and SEVIRI (King et al. 1992, Bennartz 2007)
(iii) Aerosol/CCN	(i) **Surface CCN spectra** (AOS) (ii) **Aerosol scattering coefficient** (nephelometer) (iii) **Vertical lidar backscatter profile** below cloud base (lidar)
(iv) Combined synthesis/modeler-friendly	(i) Combination of VAPs (i)-(iii) into a continuous **three-hourly averaged dataset** for data analysis/synthesis and model initialization/evaluation (ii) **Cloud occurrence** (ARSCL), **drizzle occurrence** (Reading), **cloud boundaries** (ARSCL), **LWP** (MWR) (iii) **Vertical thermodynamic profiles** (soundings and models) (iv) **Forcing tendencies** from model analysis datasets

Clouds, Aerosol, and Precipitation in the Marine Boundary Layer: The ARM Mobile Facility deployment at Graciosa

Collaborative paper for submission to BAMS

- **Clouds and cloud variability at Graciosa**
  1) Different cloud types (climatology e.g. from Warren cloud atlas)
  2) Statistics of variability in cloud types (e.g. frequency of fair weather Cu, cloud fraction by cloud height and season from AMF data)
  3) Island effects?
- **Aerosol variability and airmass origins at Graciosa**
  1) Highlighing seasonal and synoptic variability
  2) Air mass origins (back trajectory analysis)
  3) Comparisons of approaches to detect and quantify aerosols (spaceborne remote sensing, vs in-situ, CCN vs scattering etc.)
- **Precipitation at Graciosa**
  1) How prevalent? How much is drizzle from low clouds? How frequent?
  2) Process studies on drizzle formation
- **Interactions between clouds, aerosols, and precipitation**
  1) Case studies, e.g. open cells
  2) Effect of precipitation on aerosols by examining aerosol properties
- **Testing large scale numerical models using data from CAP-MBL**
  1) Preliminary work comparing ECMWF and NCEP forecast models: skill in predicting meteorology, skill in clouds (ECMWF), less with NCEP particularly in low cloud conditions
  2) Comparisons with climate models run in forecast mode (in progress)

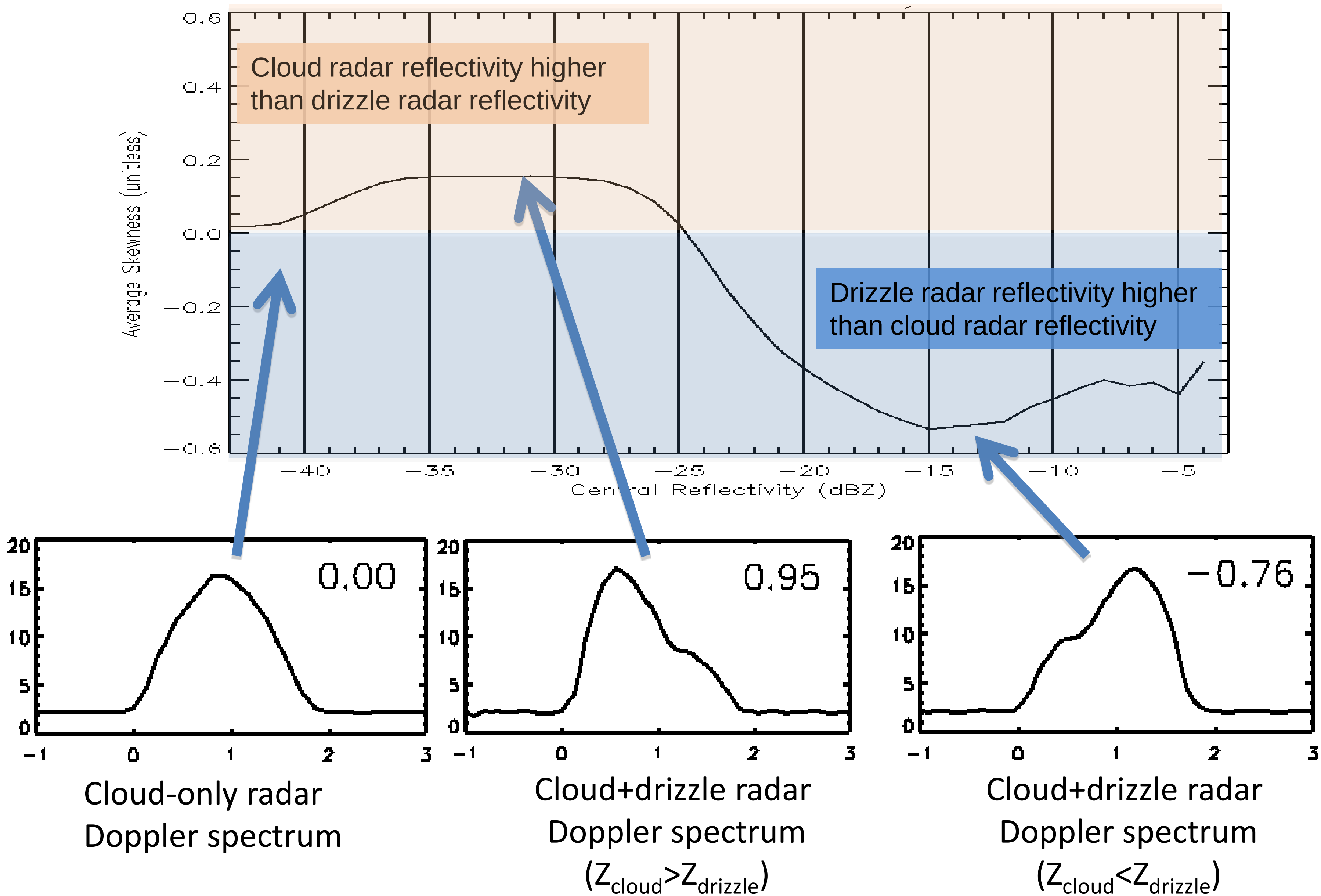
Summary

- First ARM deployment in marine low cloud environment

- AMF Azores deployment providing a rich dataset for investigating links between aerosols, clouds and precipitation processes in (mainly) shallow marine clouds

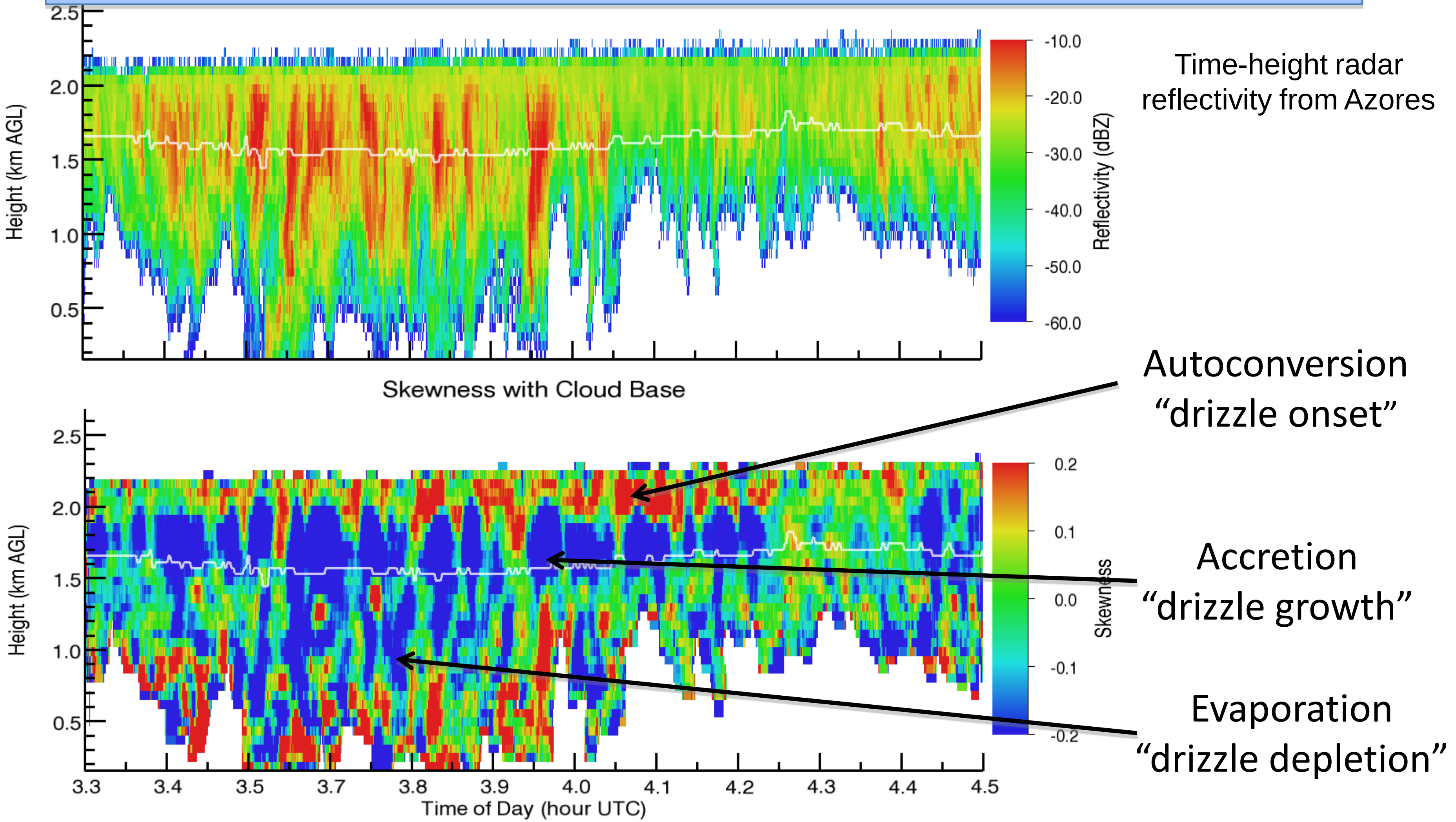
- Large variability in both aerosol and cloud properties $\Rightarrow$ potential for isolating aerosol effects on precipitation and vice versa

- Plans for overview paper in BAMS to highlight the above



Cloud radar Doppler spectra in drizzling stratiform clouds**. Part I**: Forward Modeling and Applications
Kollias P., J. Remillard, E. Luke and W. Szyrmer, 2010. Submitted to JGR-Atmospheres

Use Doppler spectra skewness as a new observable to follow particle growth (Pavlos Kollias)

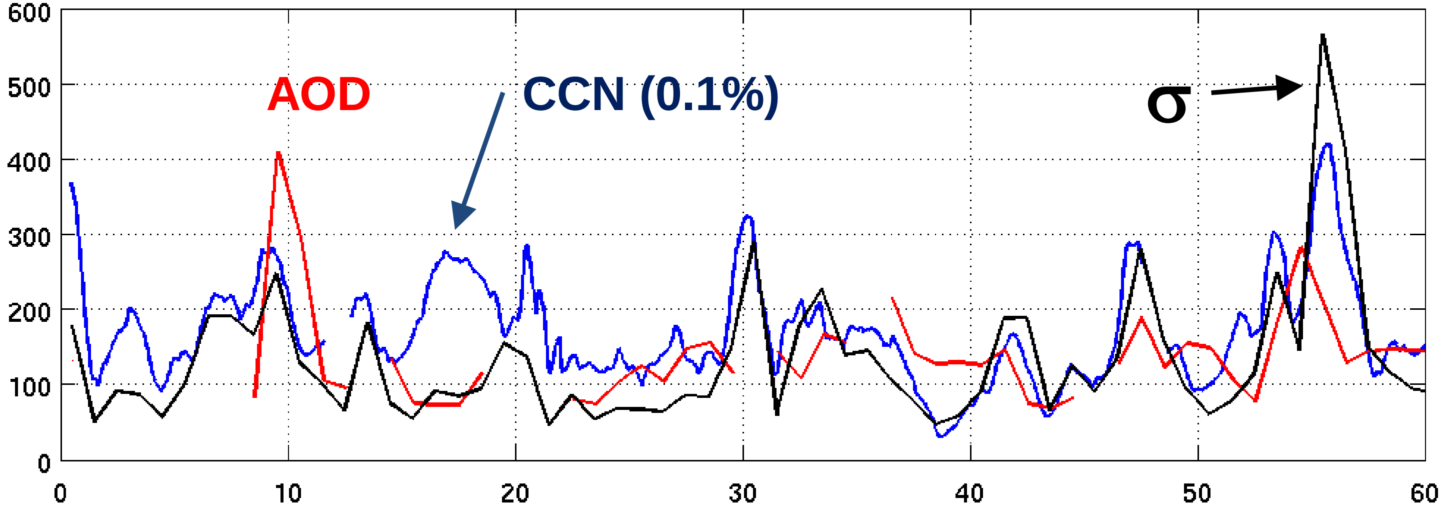


Cloud radar Doppler spectra in drizzling stratiform clouds**. Part II:** Observations and modeling of drizzle evolution processes. Kollias, P. W. Szurmer, J. Remillard and E. Luke, 2010. Submitted to JGR-Atmospheres

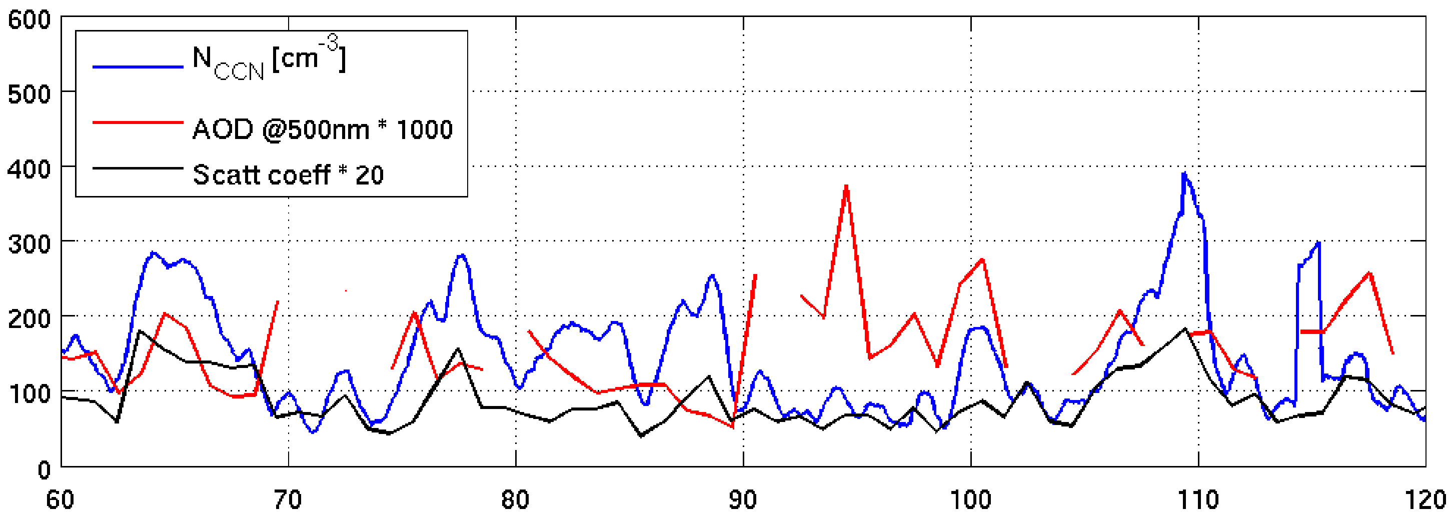
Aerosol scattering, AOD and CCN (0.1%)

- Good correlation between CCN and scattering

- AOD not so well correlated

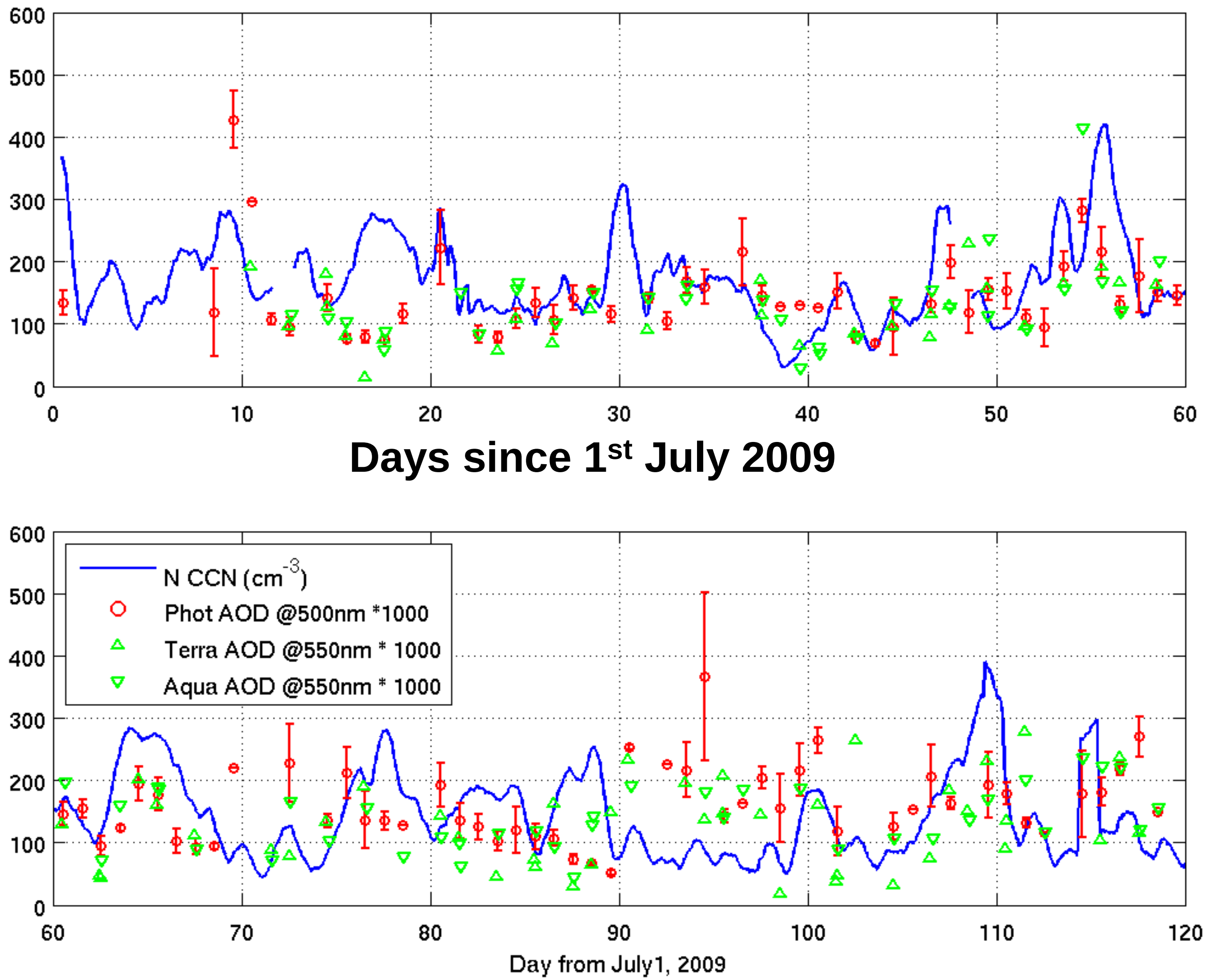


Days since 1st July 2009



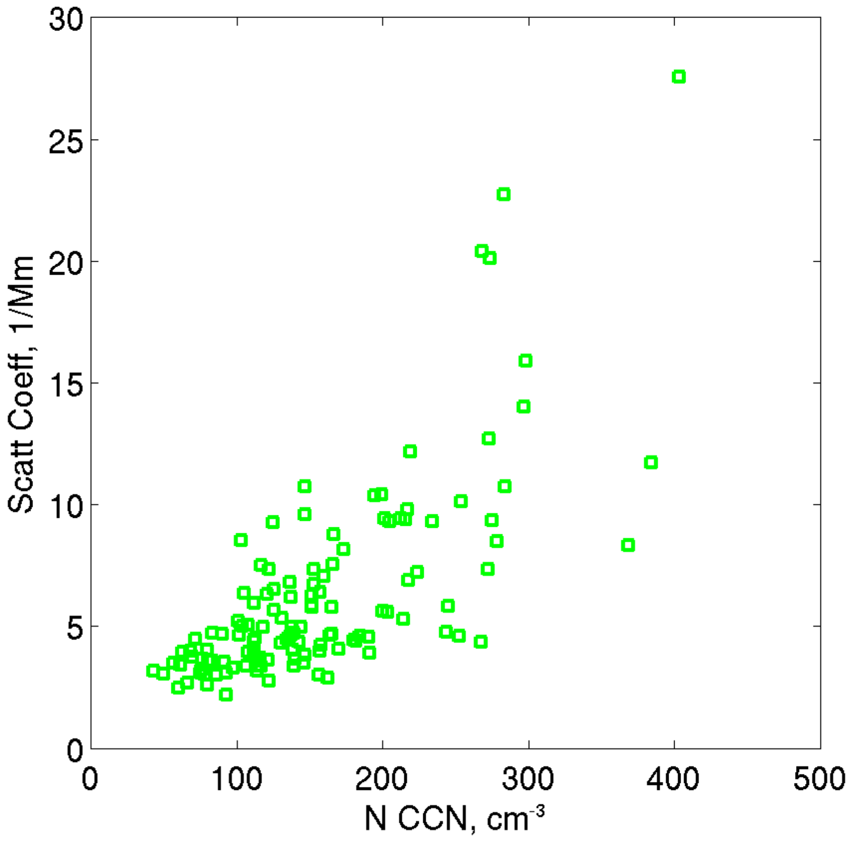
Different AOD estimates and CCN

- Sunphotometer AOD estimates mostly in good agreement with those from MODIS (Terra+Aqua)

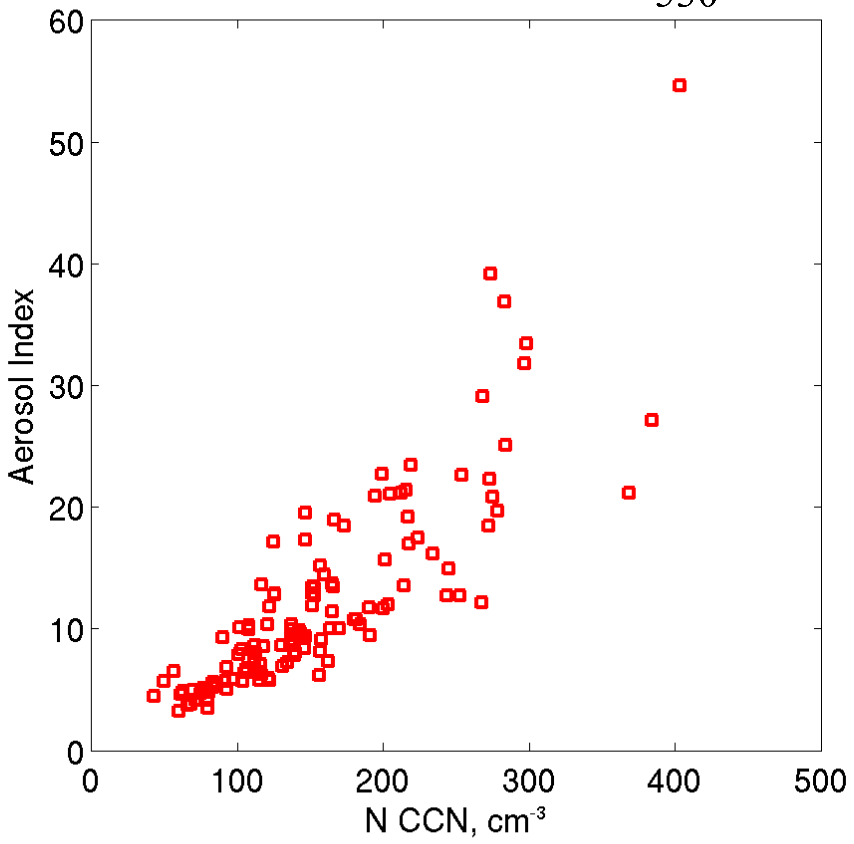


How well can we predict CCN from scattering at Graciosa?

Scattering = $\sigma_{530} \times å_{467\text{-}660}$

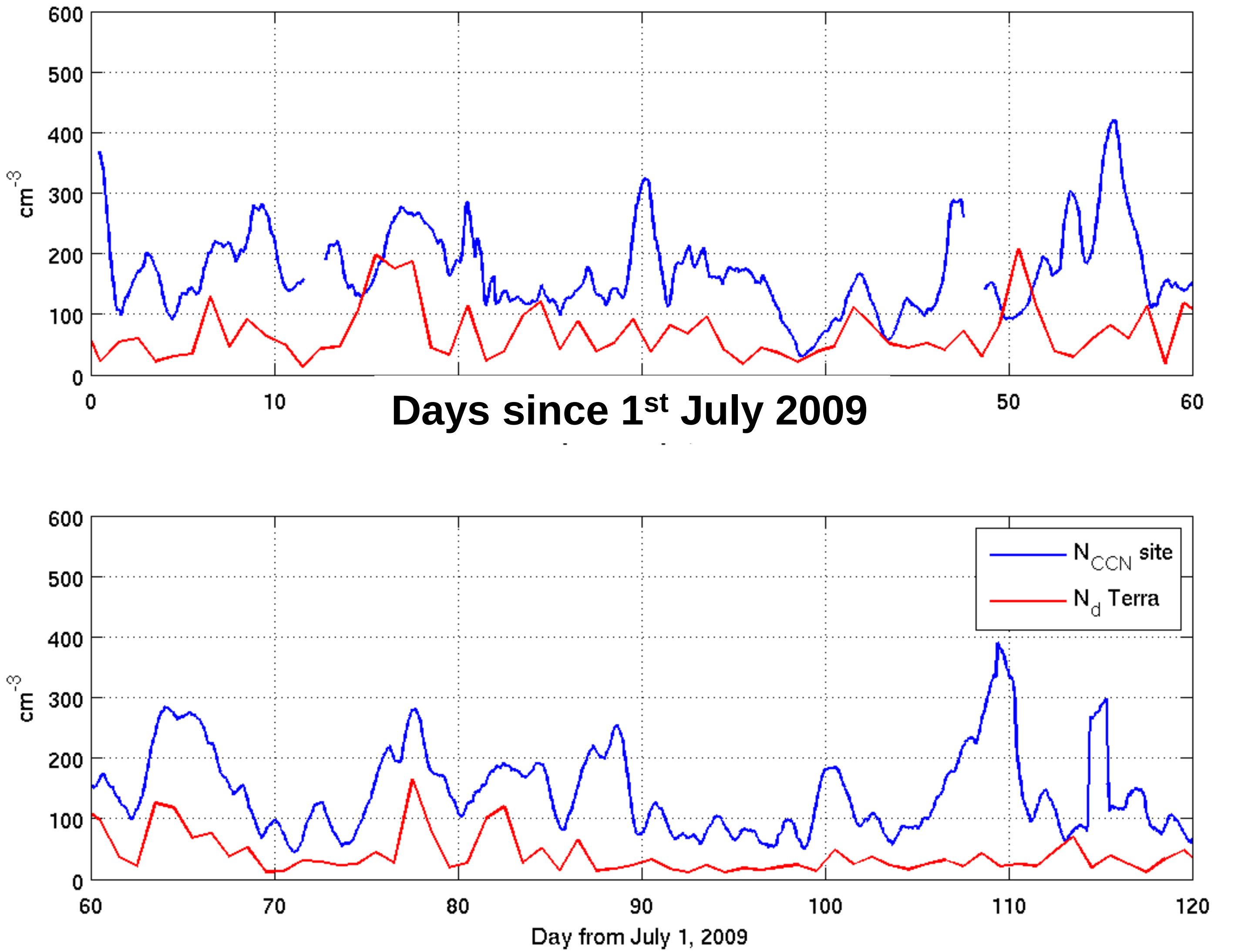


Aerosol index = $\sigma_{530} \times å$



In-situ CCN and MODIS cloud droplet concentration N_d

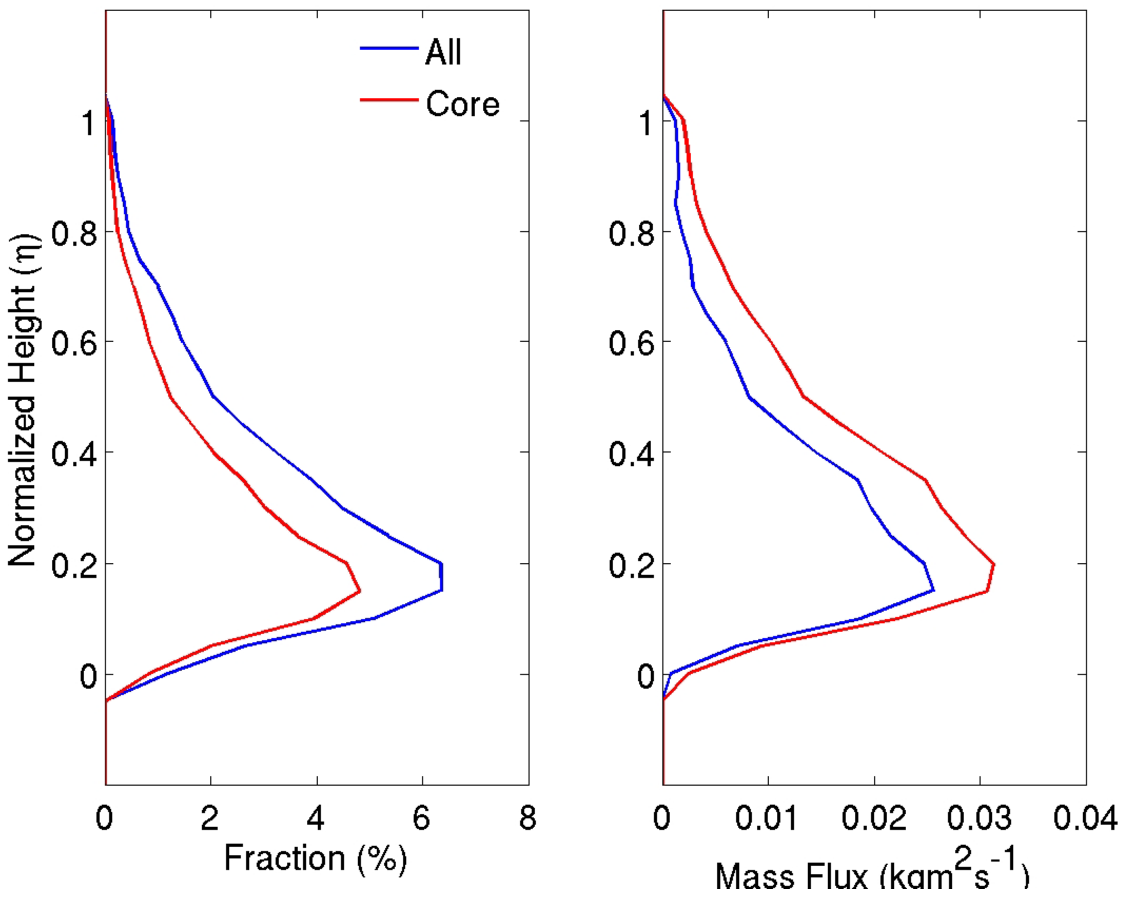
- Some correlation between CCN and MODIS-derived cloud droplet concentration, but not universal.



- Surface remote sensing-derived N_d and vertical velocity can provide important constraints for closure studies

Cloud mass flux profiles for trade cumulus clouds (Virendra Ghate)

- Selected cases with trade cumulus clouds
- Derived from 114 hours of data (557 individual cloud elements sampled)
- Core: updrafts only
- All: updrafts+downdrafts

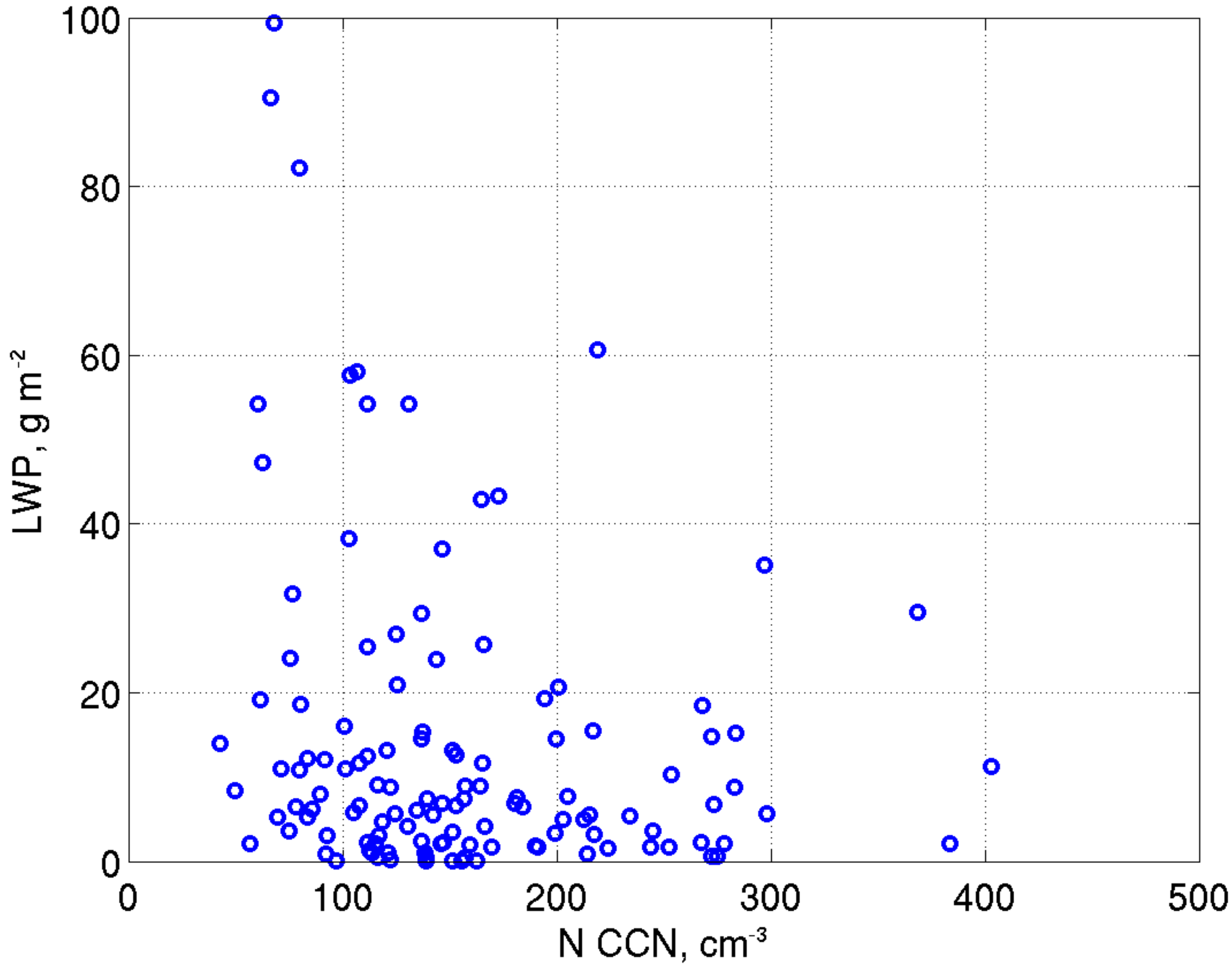


Meteorological and aerosol correlations

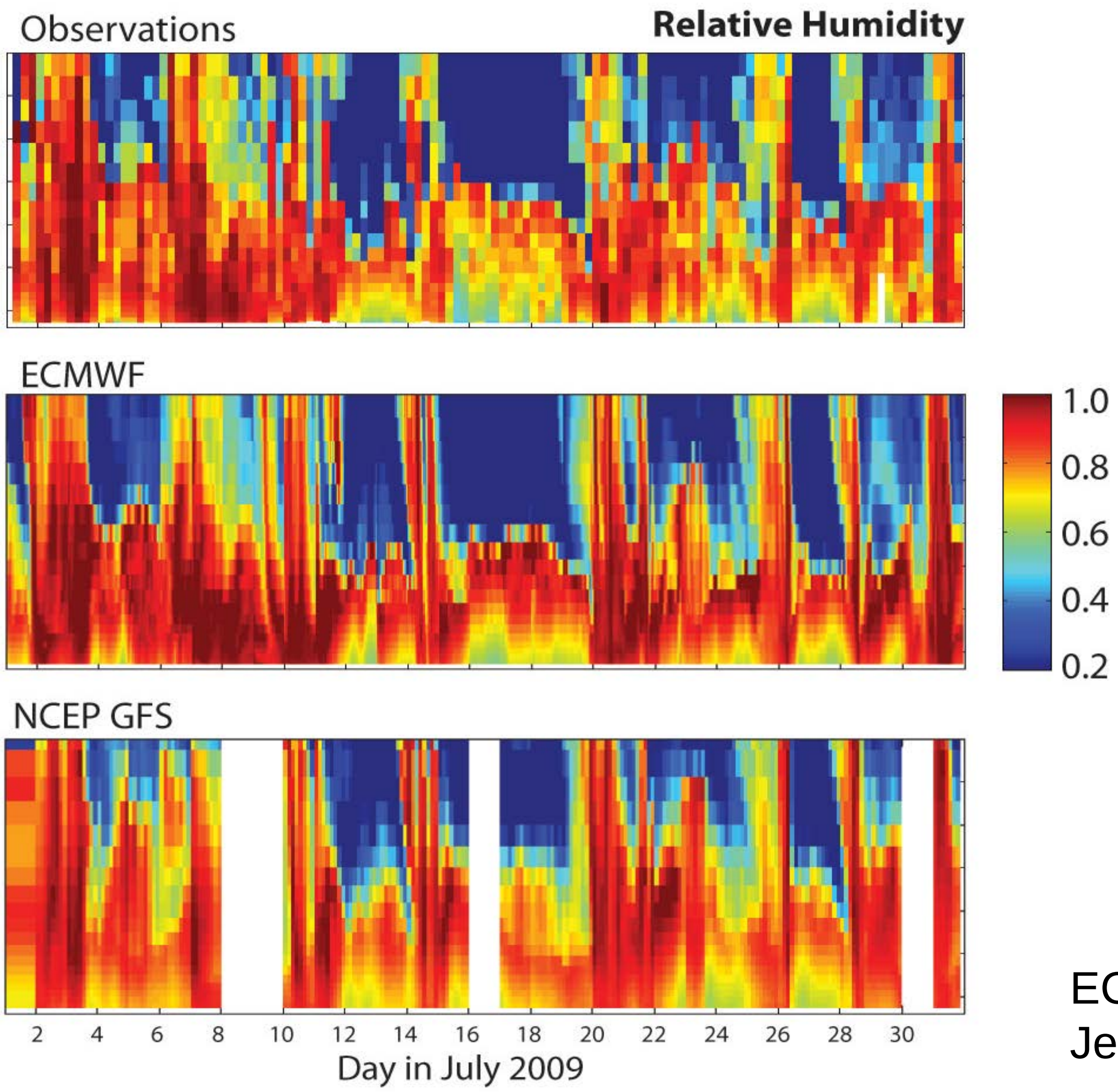
• Daily mean LWP correlated with CCN

•High CCN cases tend to occur with lower LWP clouds

• Possibly indicative of cloud effects on aerosol



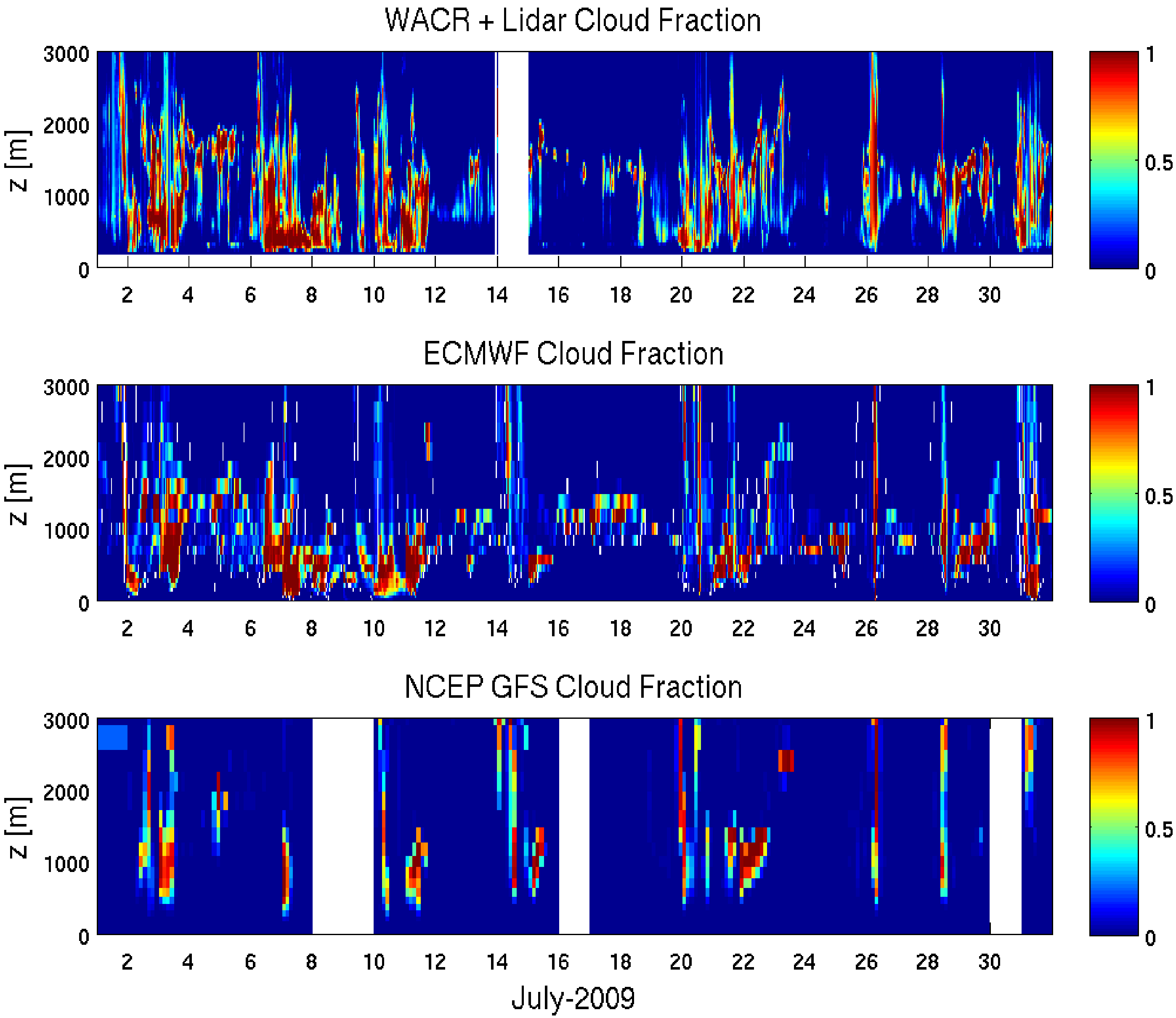
How well do forecast models do?



Meteorology:
good skill

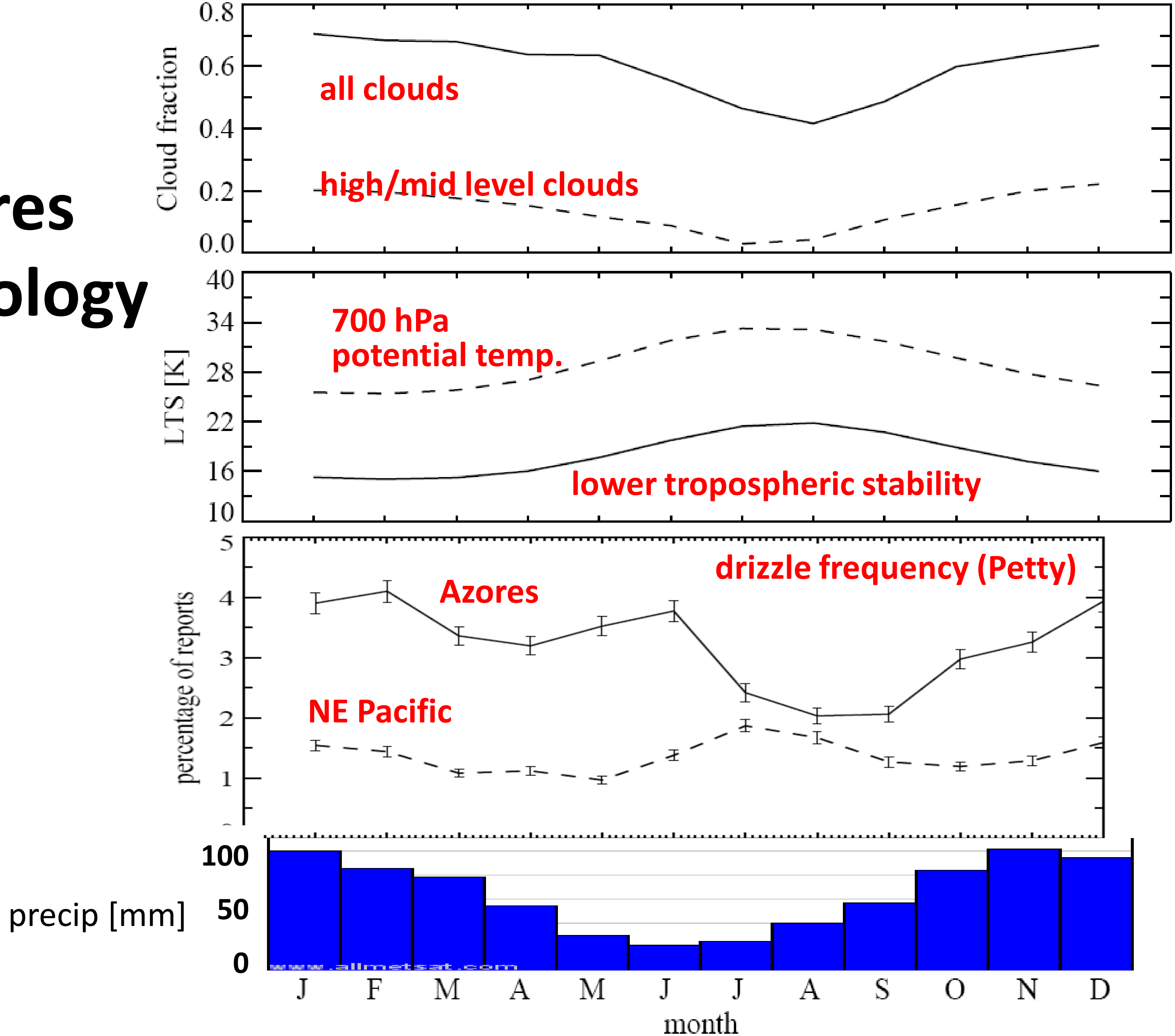
ECMWF data courtesy
Jean-Jacques Morcrette

How well do forecast models do?

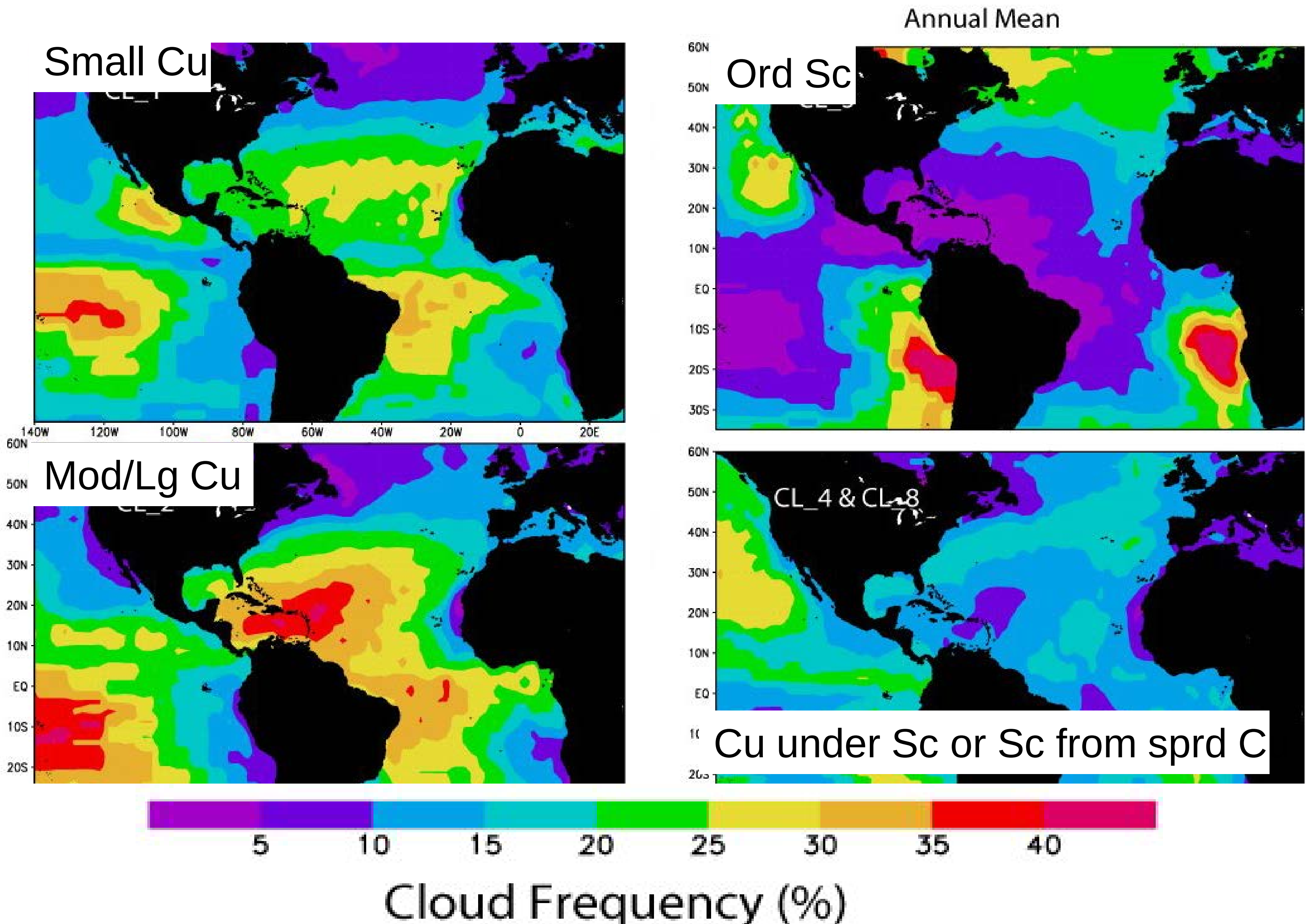


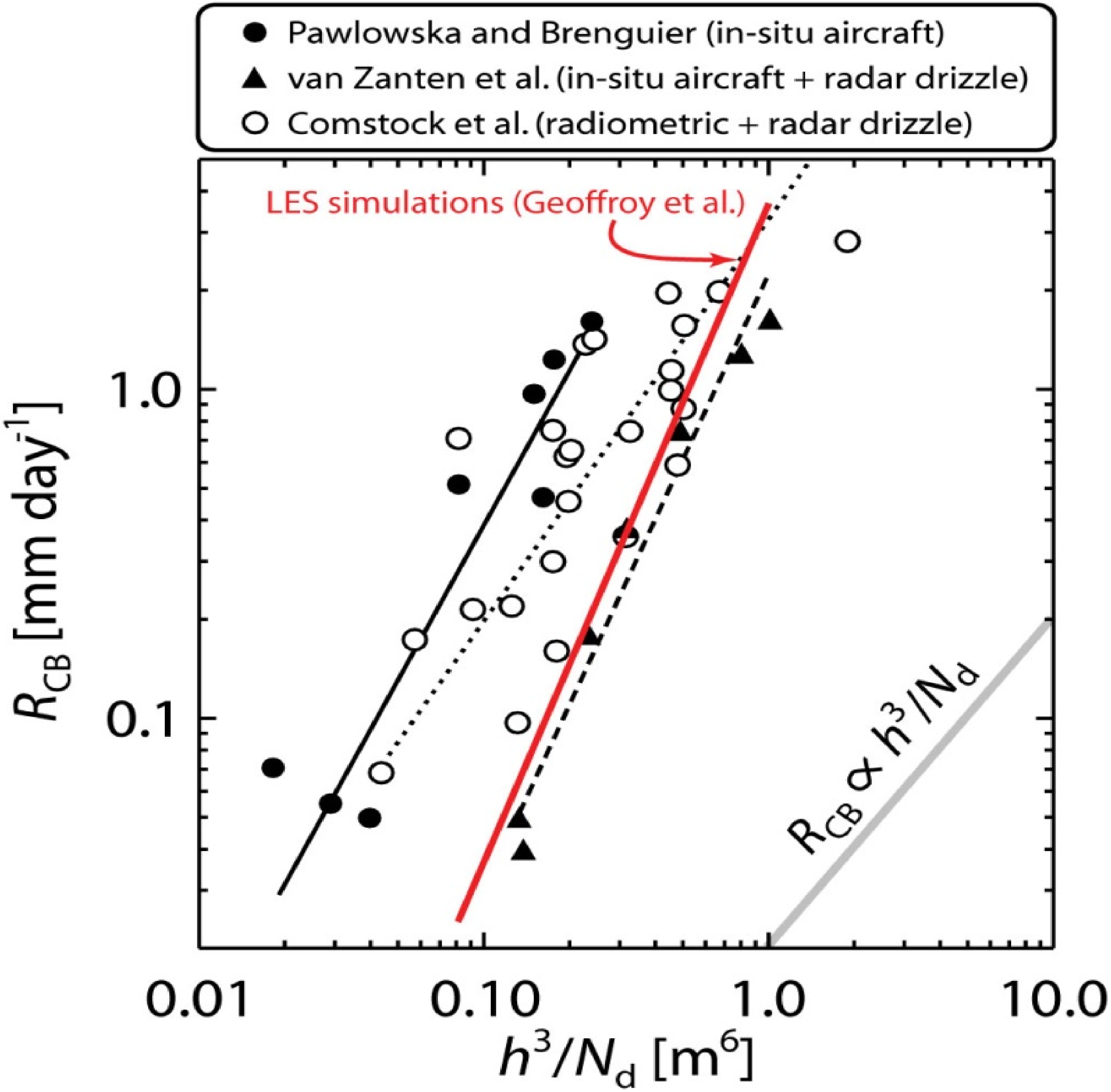
Clouds:
ECMWF quite good
NCEP bad

Azores climatology

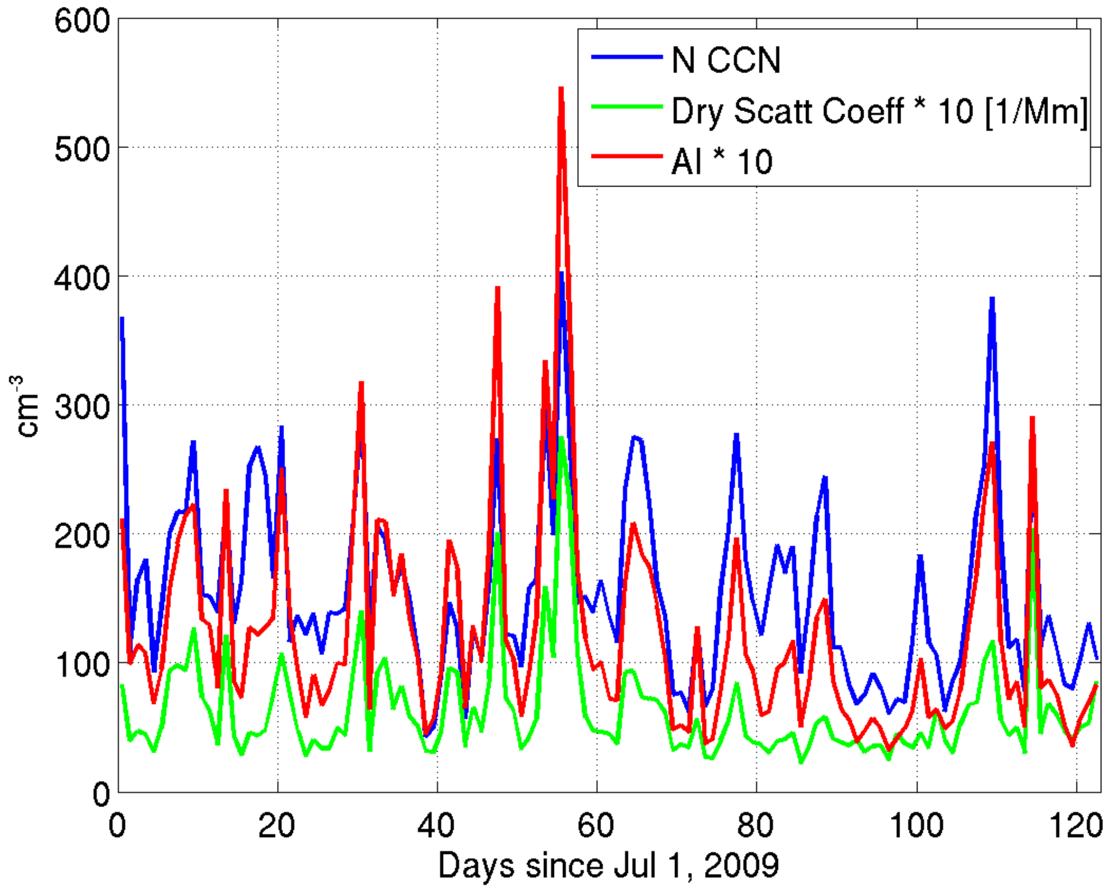


Low clouds - frequency

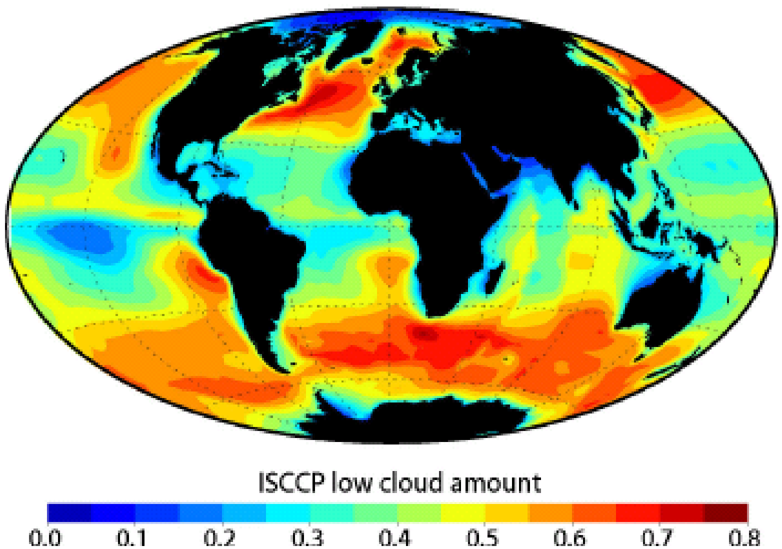


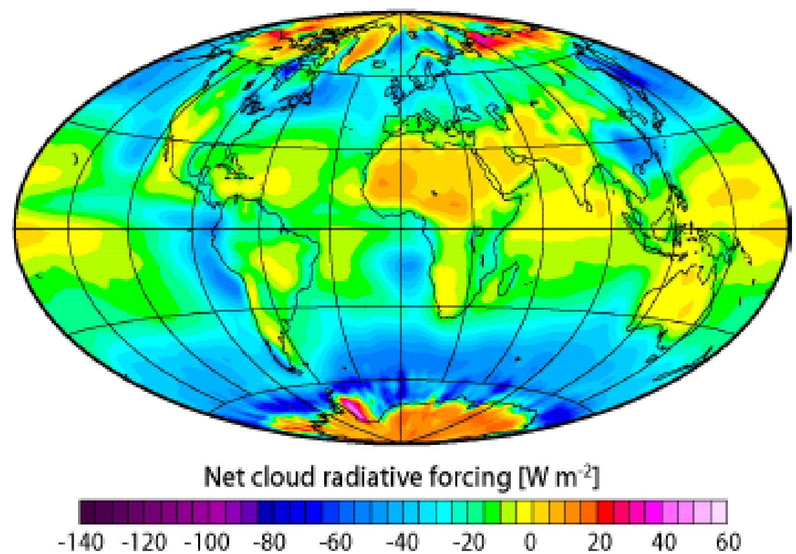


Pawlowska and Brenguier (in-situ aircraft)
van Zanten et al. (in-situ aircraft + radar drizzle)
Comstock et al. (radiometric + radar drizzle)
LES simulations (Geoffroy et al.)
$R_{CB} \propto h^3/N_d$
R_{CB} [mm day^{-1}]
1.0
0.1
0.01
0.10
1.0
10.0
h^3/N_d [m^6]



N CCN
Dry Scatt Coeff * 10 [1/Mm]
AI * 10
cm^{-3}
Days since Jul 1, 2009
0
100
200
300
400
500
600
0
20
40
60
80
100
120





Importance of Low-Clouds for Climate

Imperative that we understand the processes controlling the formation, maintenance and dissipation of low clouds in order to improve their representation in climate models.

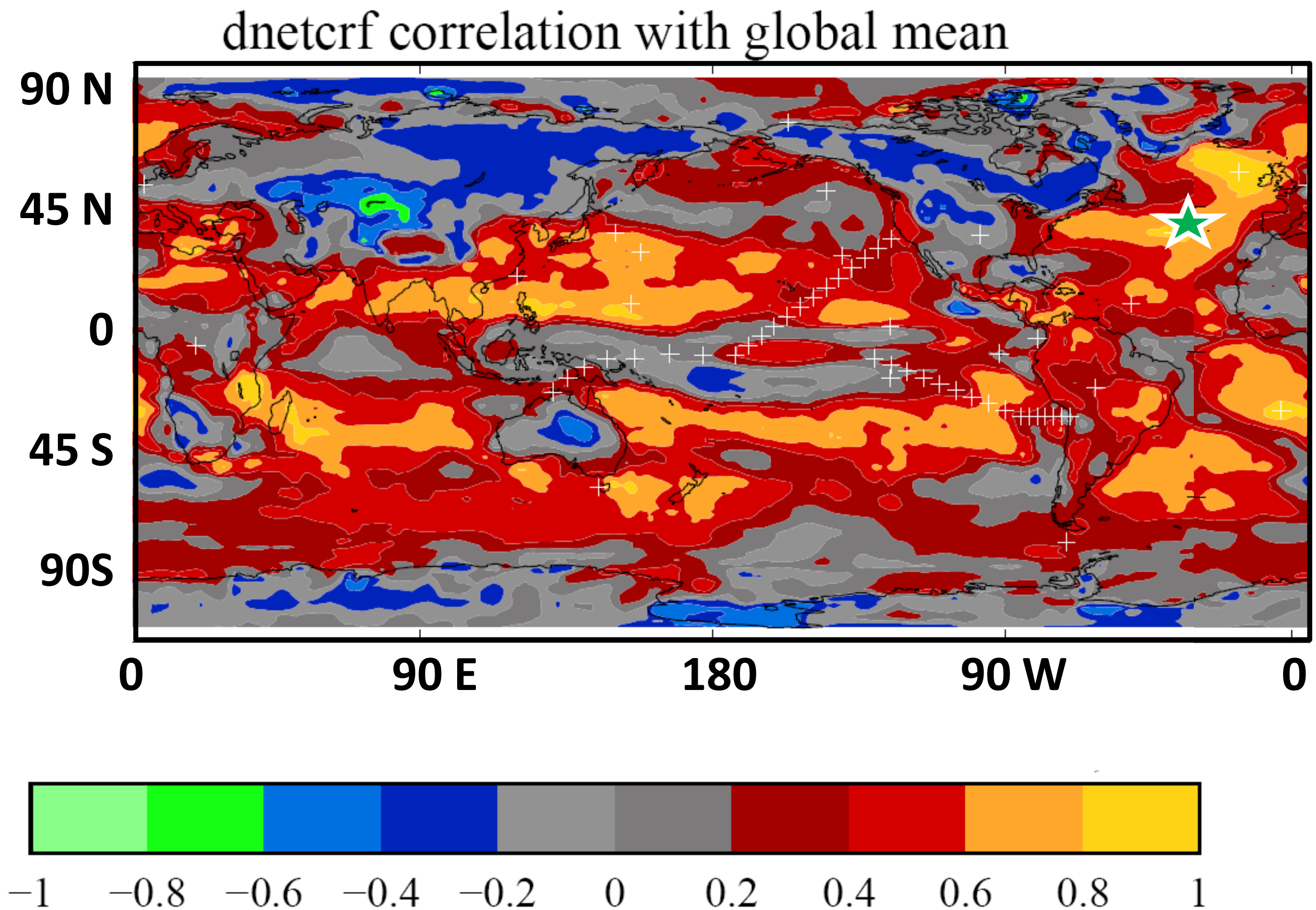
Which clouds matter for climate sensitivity?

Climate Feedbacks Model Intercomparison Project (CFMIP)

12 slab ocean models

$2xCO_2$ – control

Correlation of global mean ΔCRF with local values



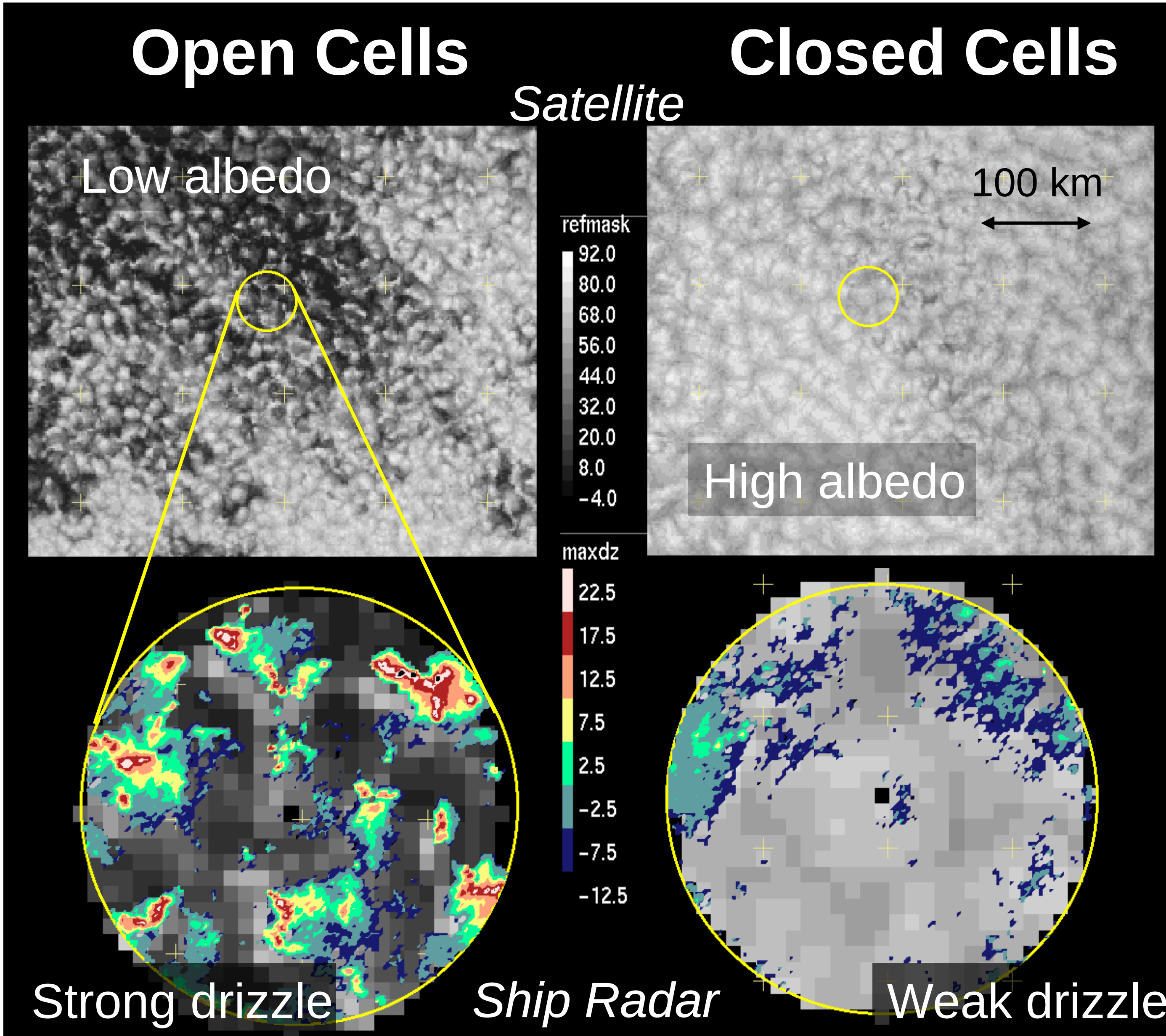
Mark Webb, Hadley Center

Precipitation and its effects on albedo

- Cloud albedo strongly dependent upon open/closed cells

- Strong precipitation associated with open cell structure

- Open cells form in clear marine environment – potential anthropogenic impacts



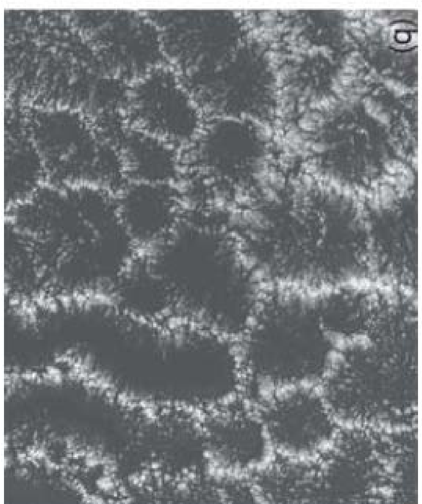
LES Models: Aerosol Effects on Cloud Morphology via Drizzle

Albedo

Closed-cell
Albedo ~ 0.6
(non-precipitating)

→ **high aerosol**

Onset of ***drizzle*** *results in transition to open-cell convection*



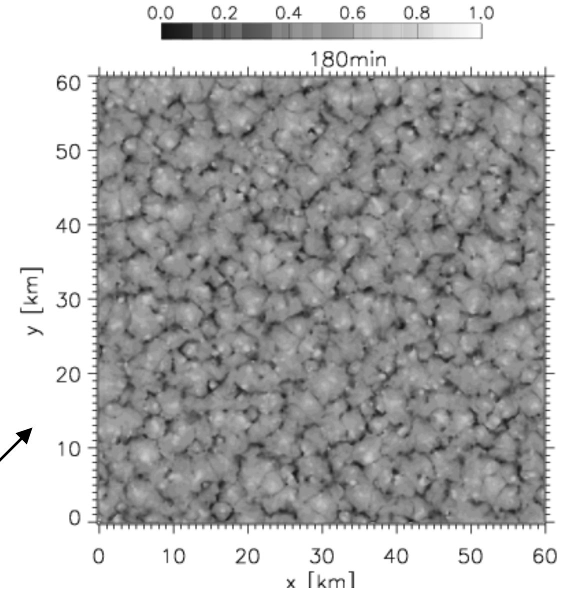
Open-cell
Albedo ~ 0.2
(precipitating)

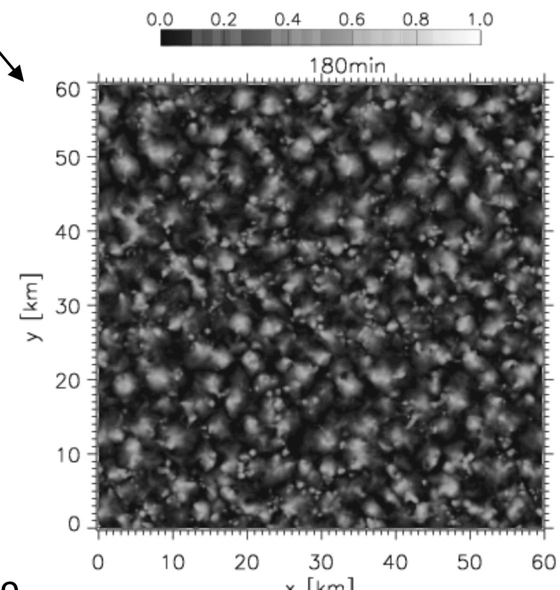
→ **low aerosol**

Garay et al. 2004, MISR

WRF Model
+ 2-moment
μphysics;
60 km domain;
$\Delta x = \Delta y = 300$ m
$\Delta z = 30$ m

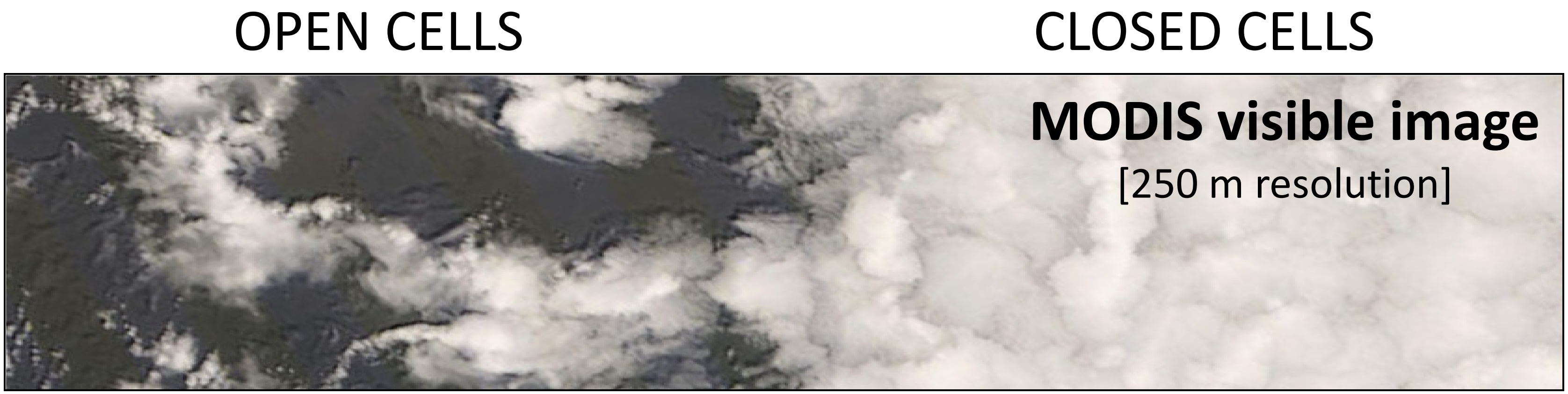
Albedo

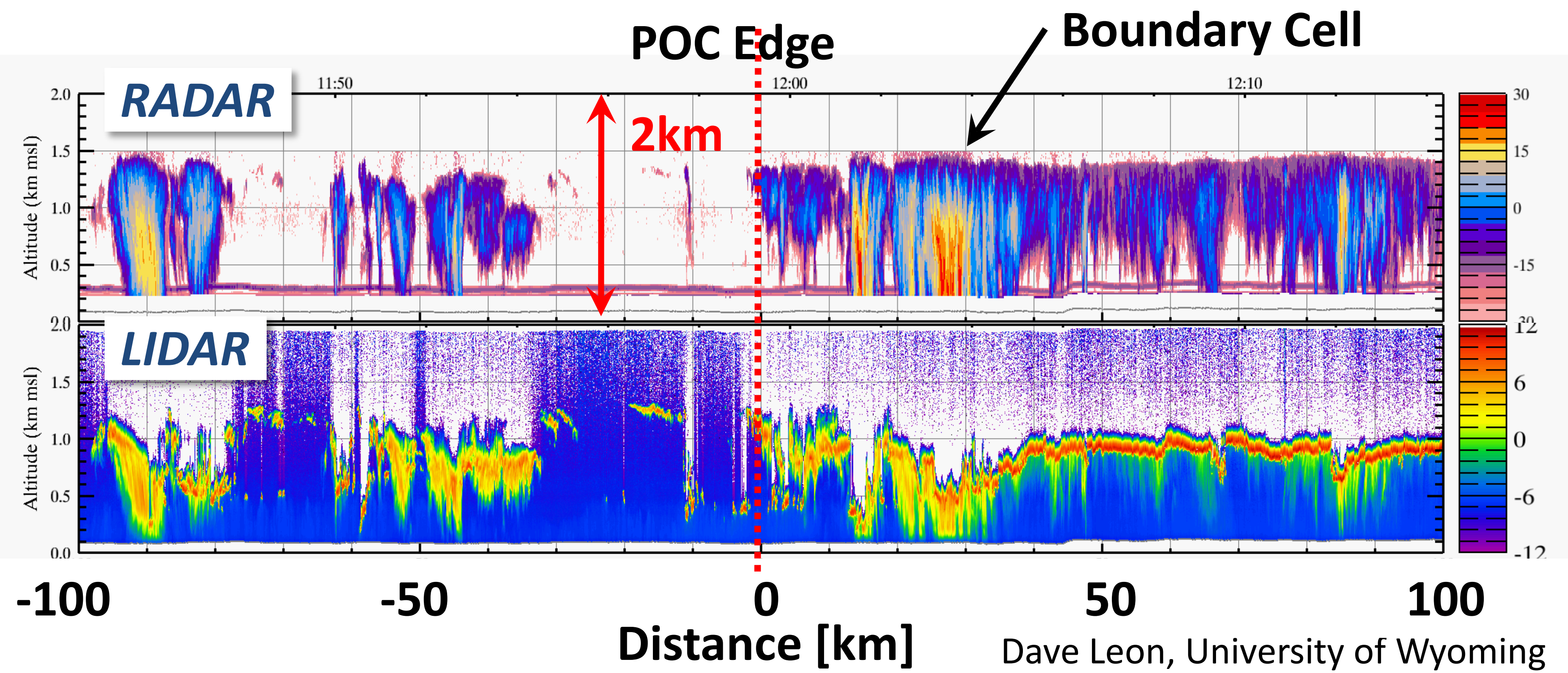




Wang and Feingold, 2009

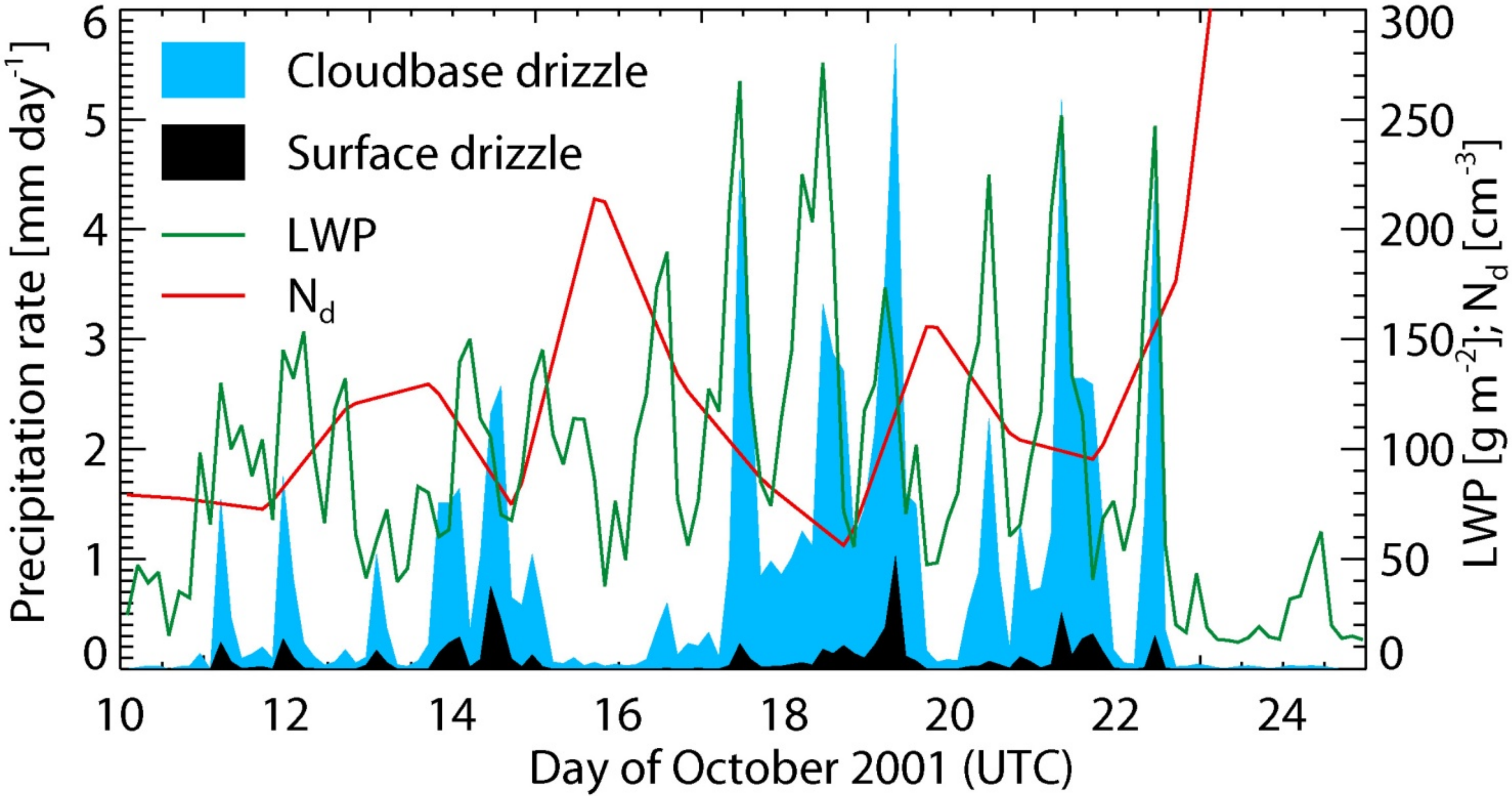
VOCALS: Observations of Cloud and Precipitation





Dave Leon, University of Wyoming

Aerosols, clouds, and precipitation



AMF-like suite on NOAA R/V Ronald H Brown
during EPIC 2001
(Bretherton et al. 2004)

No long-term records exist that can be used to link cloud, precipitation, and aerosol microphysical variability in the remote-capped MBL.

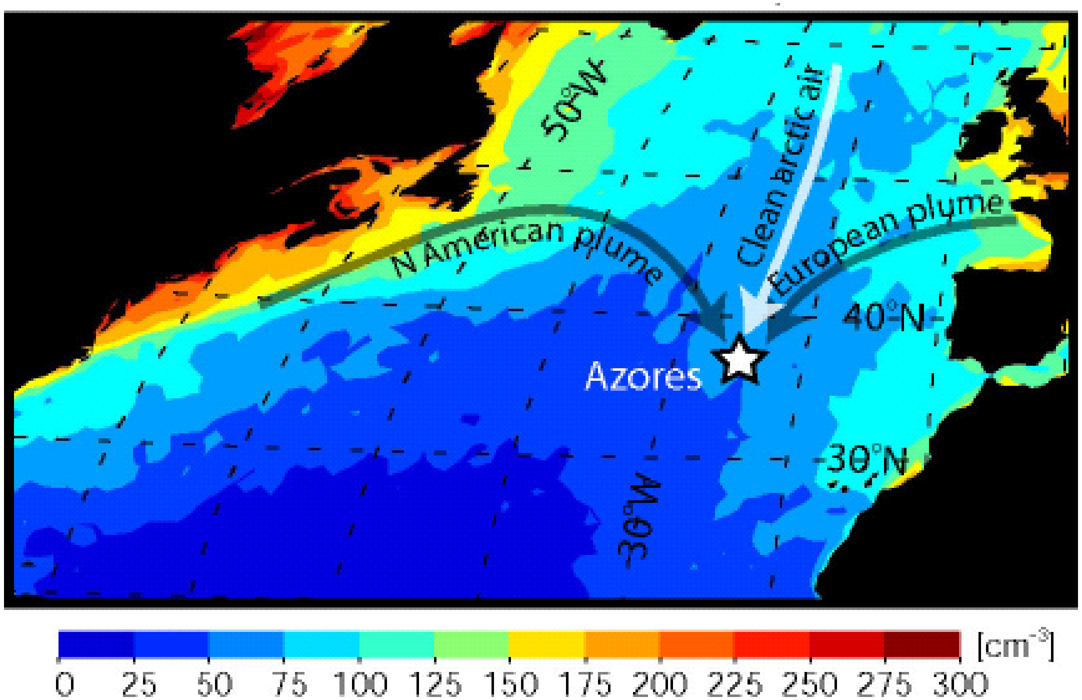
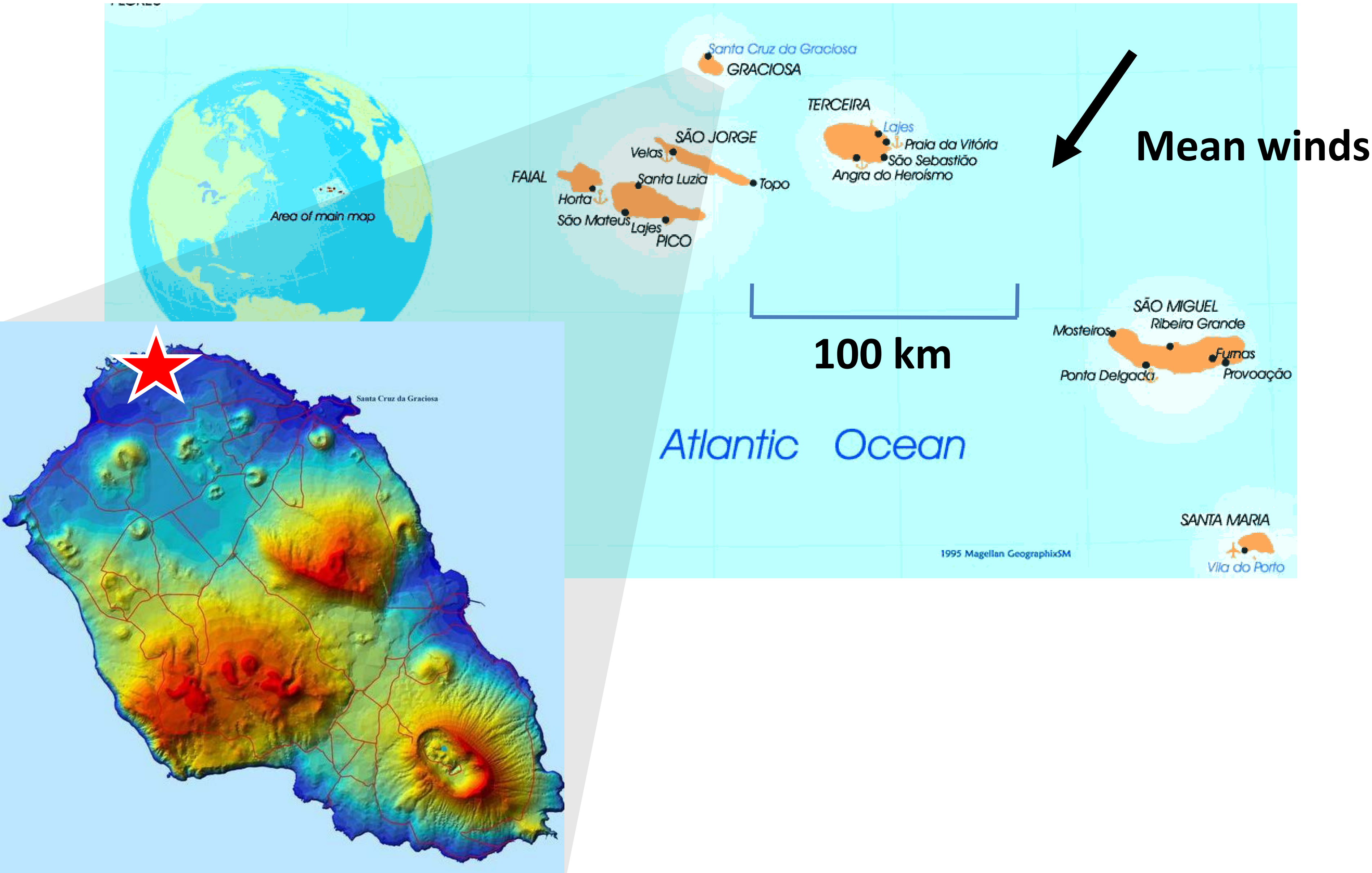


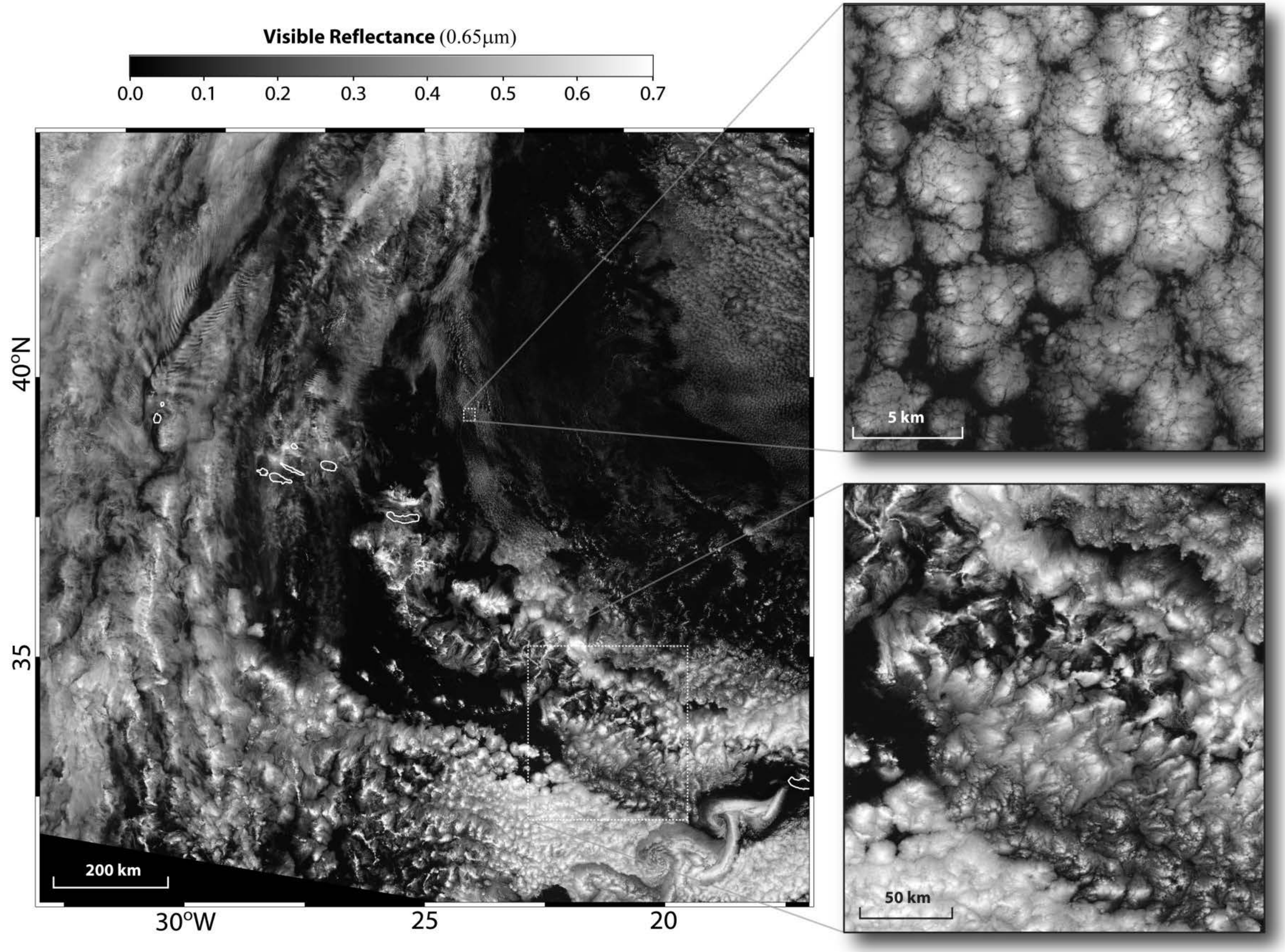
Figure 2: MODIS annual mean cloud droplet concentration for overcast warm clouds over the North Atlantic. The Azores typically experiences relatively clean conditions with northerly flow, but with periodic episodes of continentally-influenced polluted airmasses. The location is therefore ideal for capturing a wide range of aerosol conditions.

AMF Site: Graciosa Island in the Azores (28 °W 39 °N)

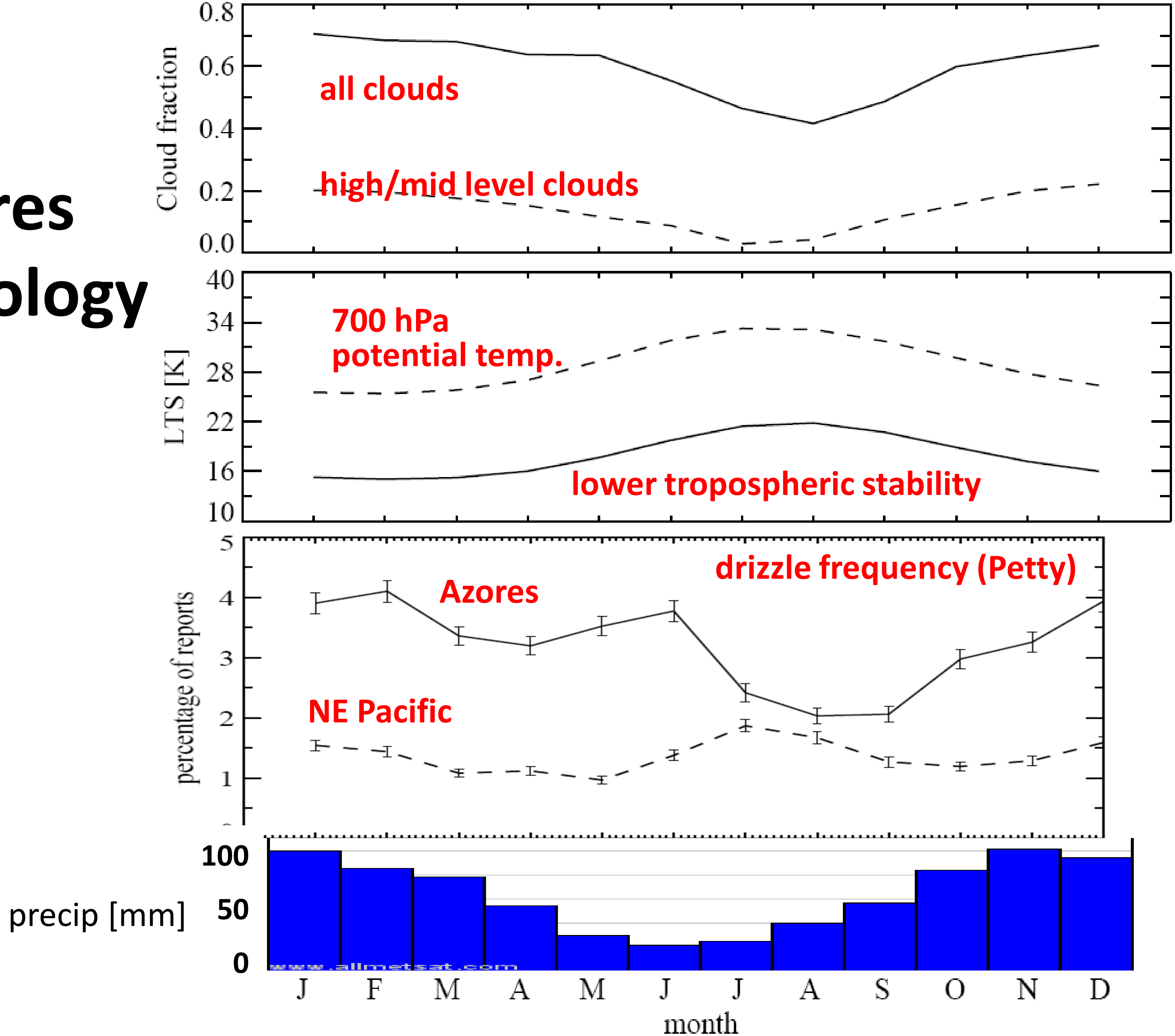
Small Low Island - No Direct Continental Influence - MBL Depths 1-2 km



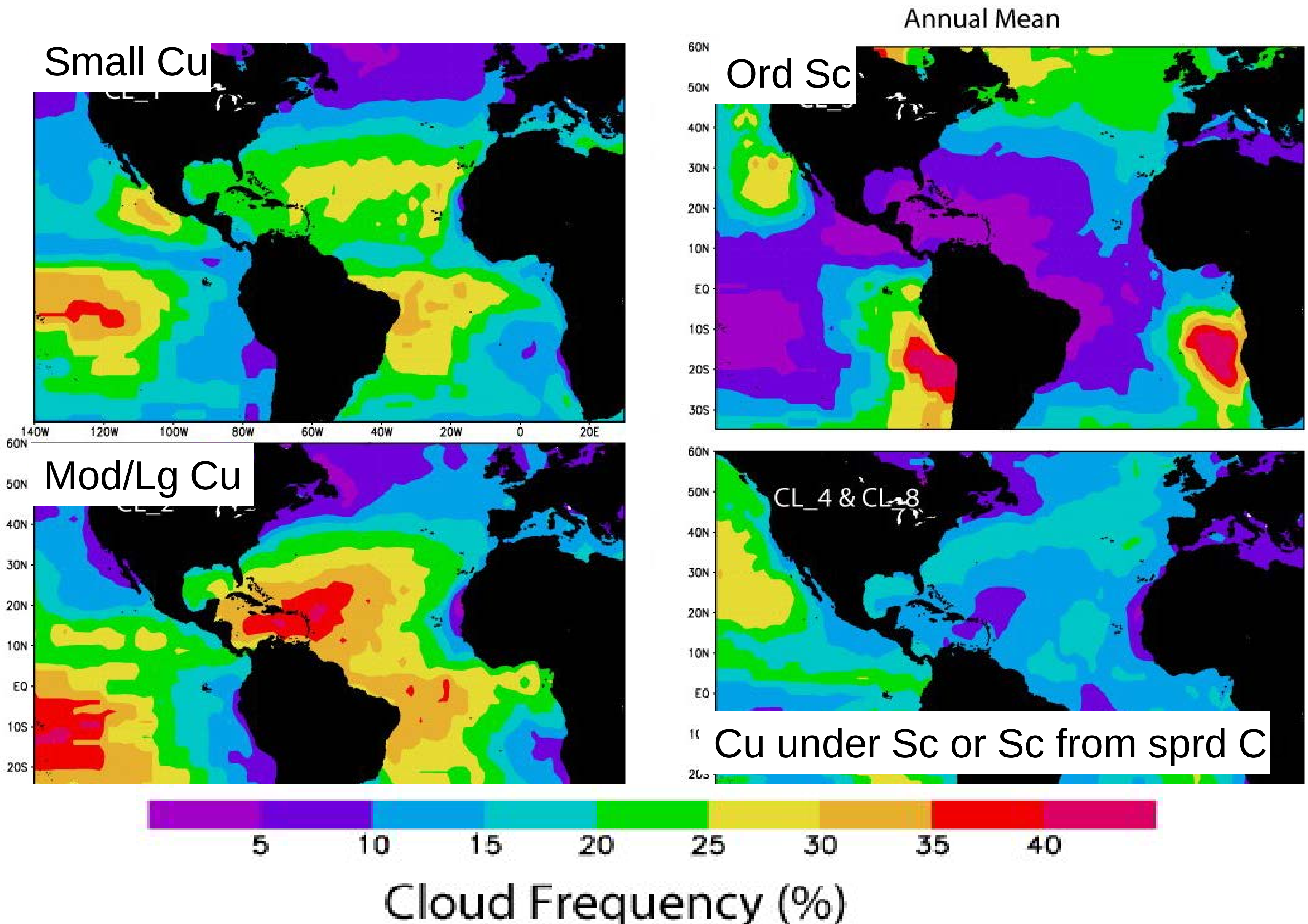
Marine boundary layer cloud in the Azores



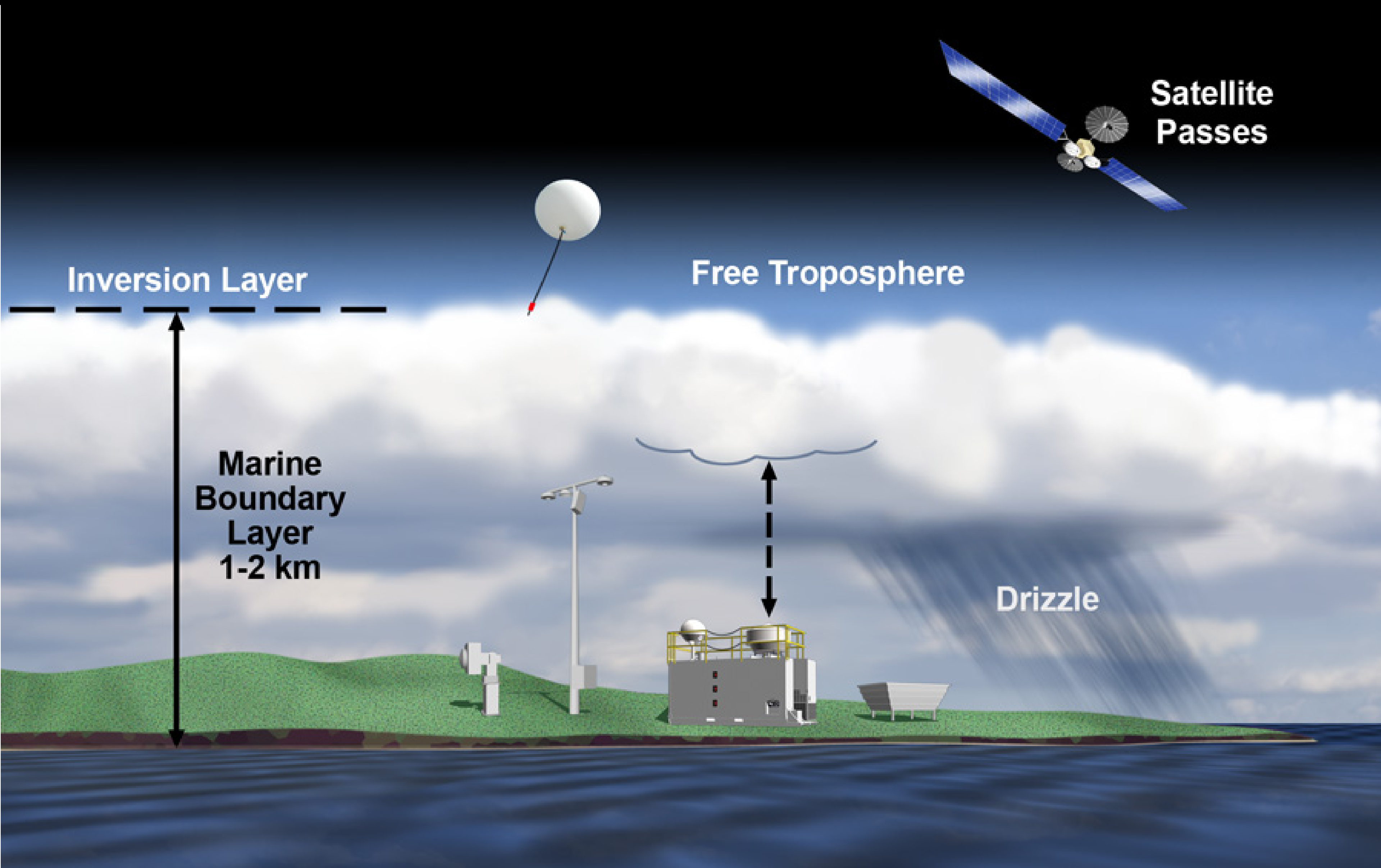
Azores climatology

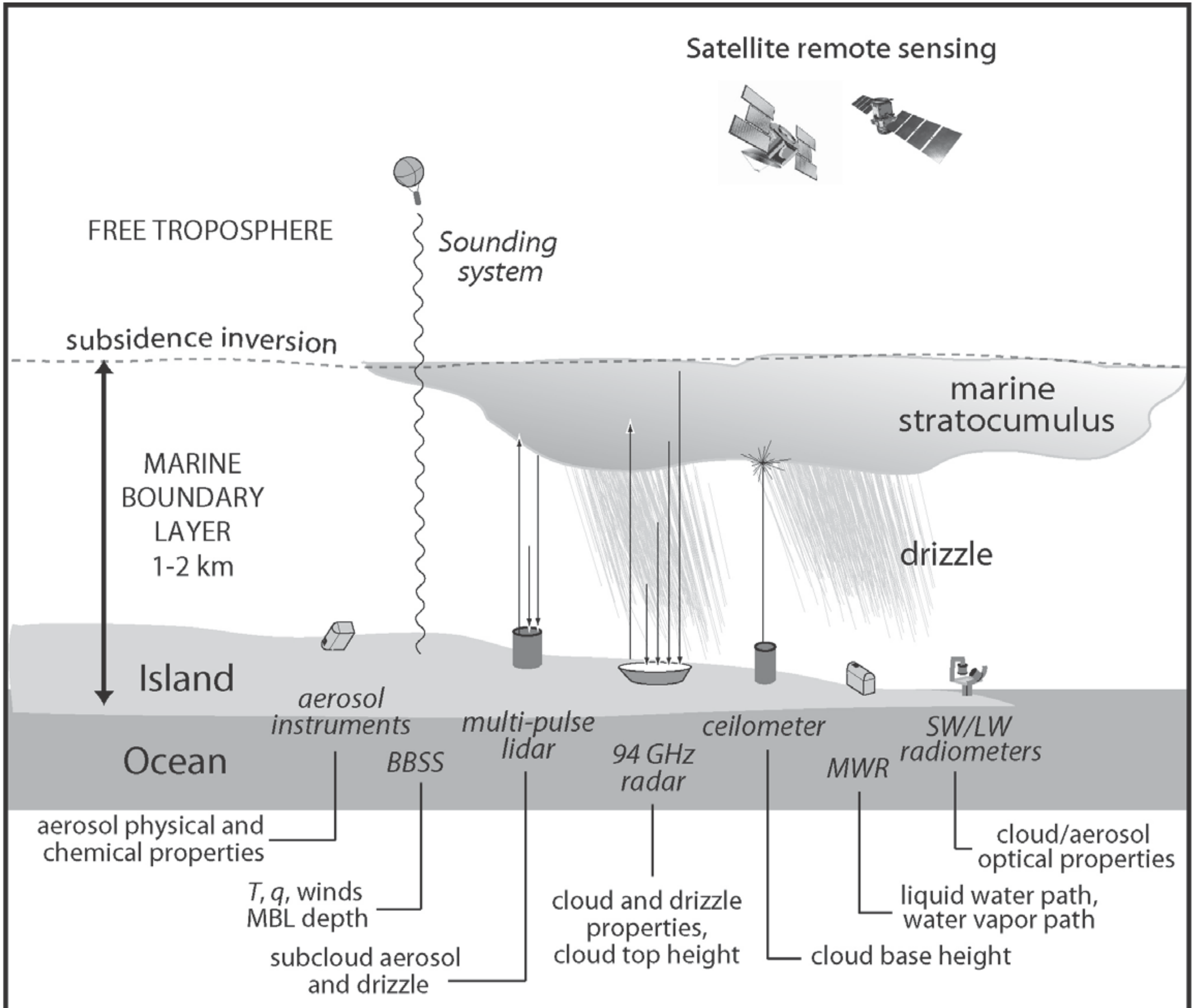


Low clouds - frequency

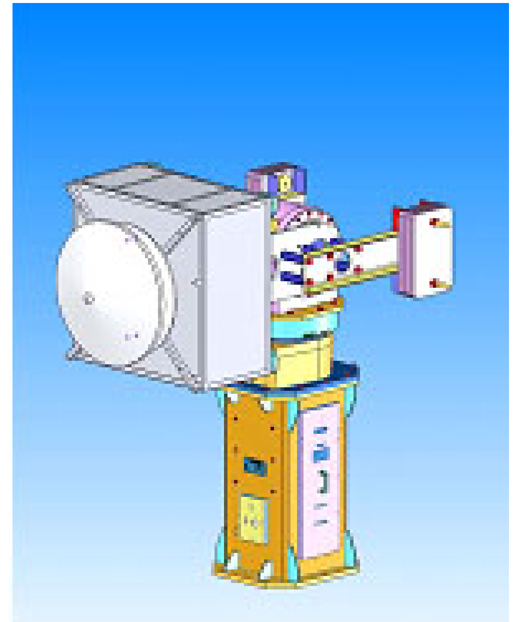


AMF configuration for CAP-MBL




Satellite remote sensing
FREE TROPOSPHERE
Sounding system
subsidence inversion
marine stratocumulus
MARINE BOUNDARY LAYER 1-2 km
drizzle
Island
Ocean
aerosol instruments
BBSS
multi-pulse lidar
94 GHz radar
ceilometer
MWR
SW/LW radiometers
aerosol physical and chemical properties
T, q, winds MBL depth
subcloud aerosol and drizzle
cloud and drizzle properties, cloud top height
cloud base height
liquid water path, water vapor path
cloud/aerosol optical properties

Scanning W-band ARM Cloud Radar



Same radar frequency as NASA's CloudSat

Capable of detecting all radiatively significant clouds in a radius of 5-10* km

Scanning capabilities:

1. Horizon to Horizon (fixed azimuth)
2. 360° revolution (fixed elevation)
3. Sector scan (for cloud tracking)
4. Staring mode

Discussion of scanning strategies in afternoon breakout session

Pavlos Kollias

Scientific Goals of CAP-MBL

- Which synoptic-scale features dominate the variability in subtropical low clouds on diurnal to seasonal timescales over the NEA? Do physical, optical, and cloud-forming properties of aerosols vary with these synoptic features? How well can state-of-the-art weather forecast and climate models (run in forecast mode) predict the day-to-day variability of NEA cloud cover and its radiative impacts?

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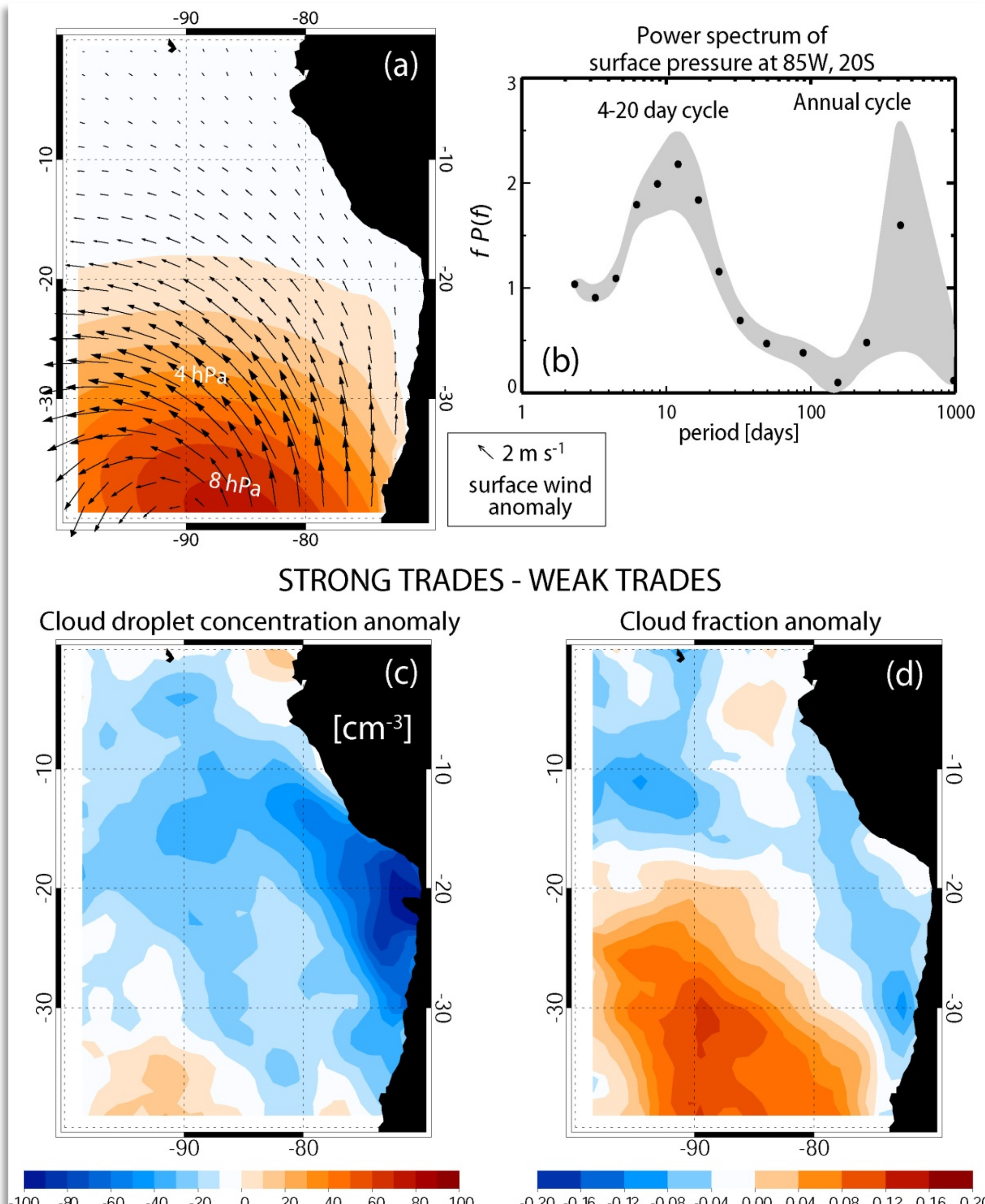
- Are observed transitions in cloud mesoscale structure (e. g. from closed cellular to open cellular convection) influenced by the formation of precipitation?

Addressing the goals of CAP-MBL

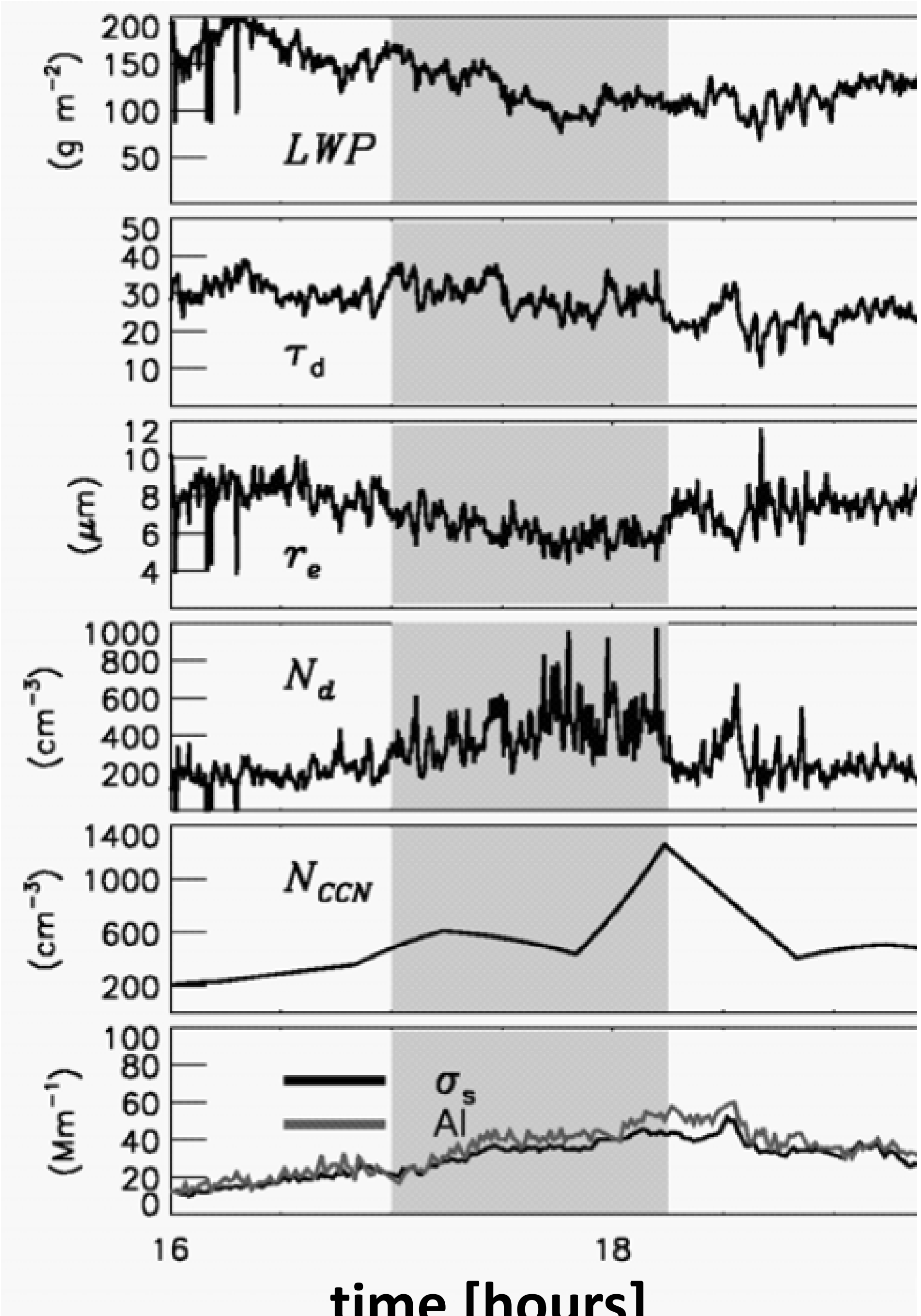
Microphysical synoptic (subseasonal) variability

Composite strong - weak SE Pacific high pressure



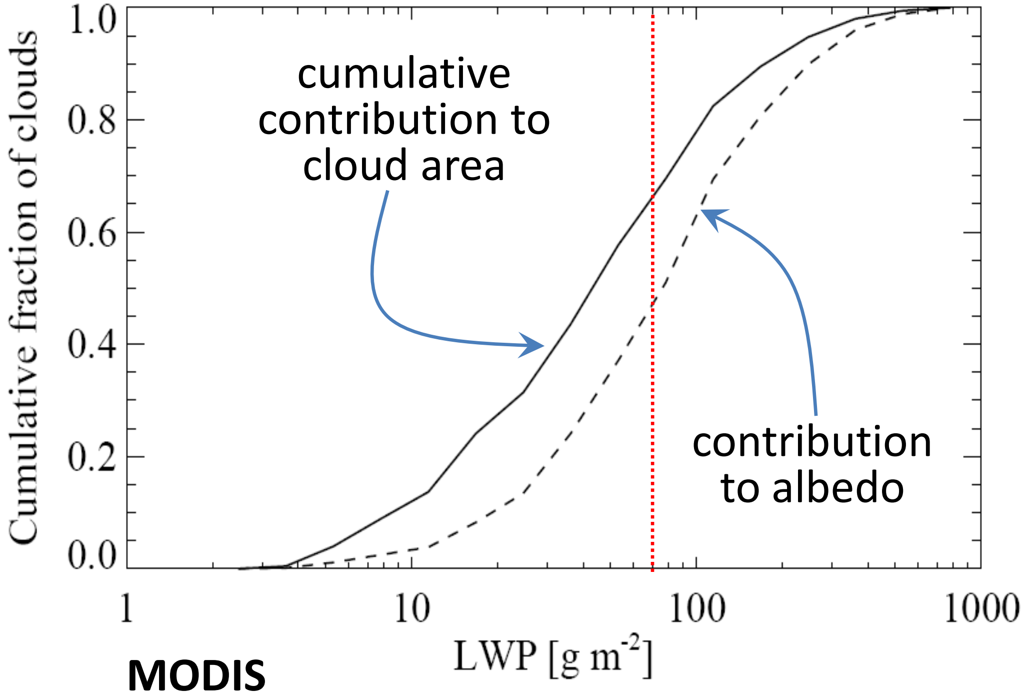
Rhea George

Can we find observational support for the Twomey effect in clouds over the NE Atlantic?

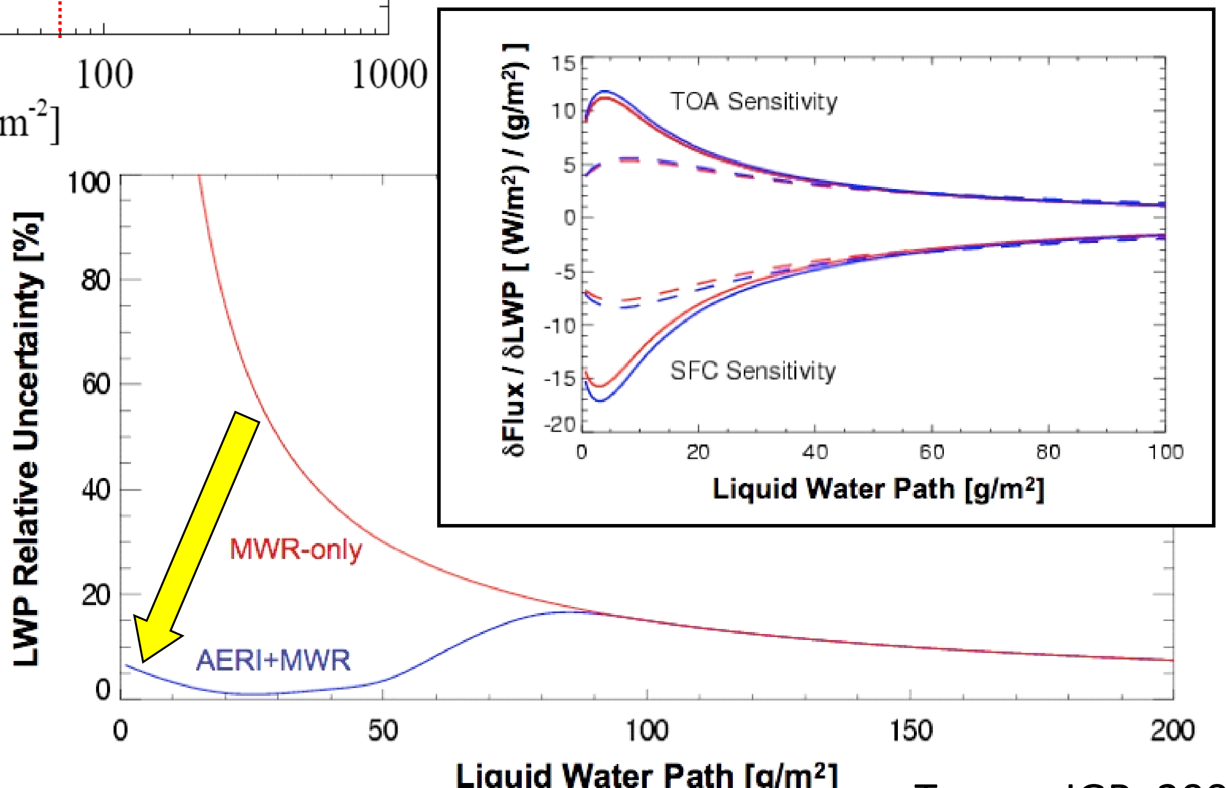


McComiskey et al. (2009)

The importance of thin clouds to albedo

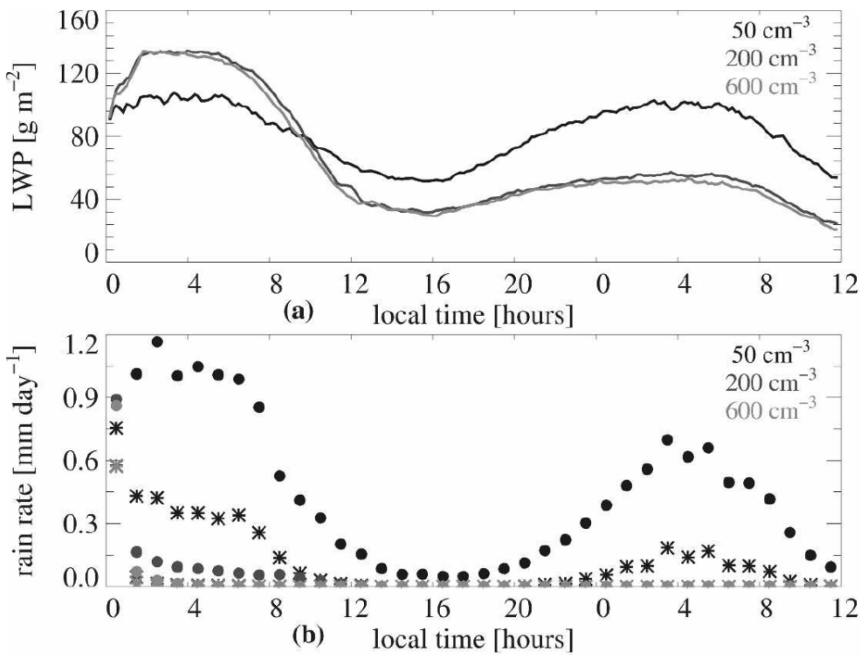


MODIS
Azores, Jun-Aug



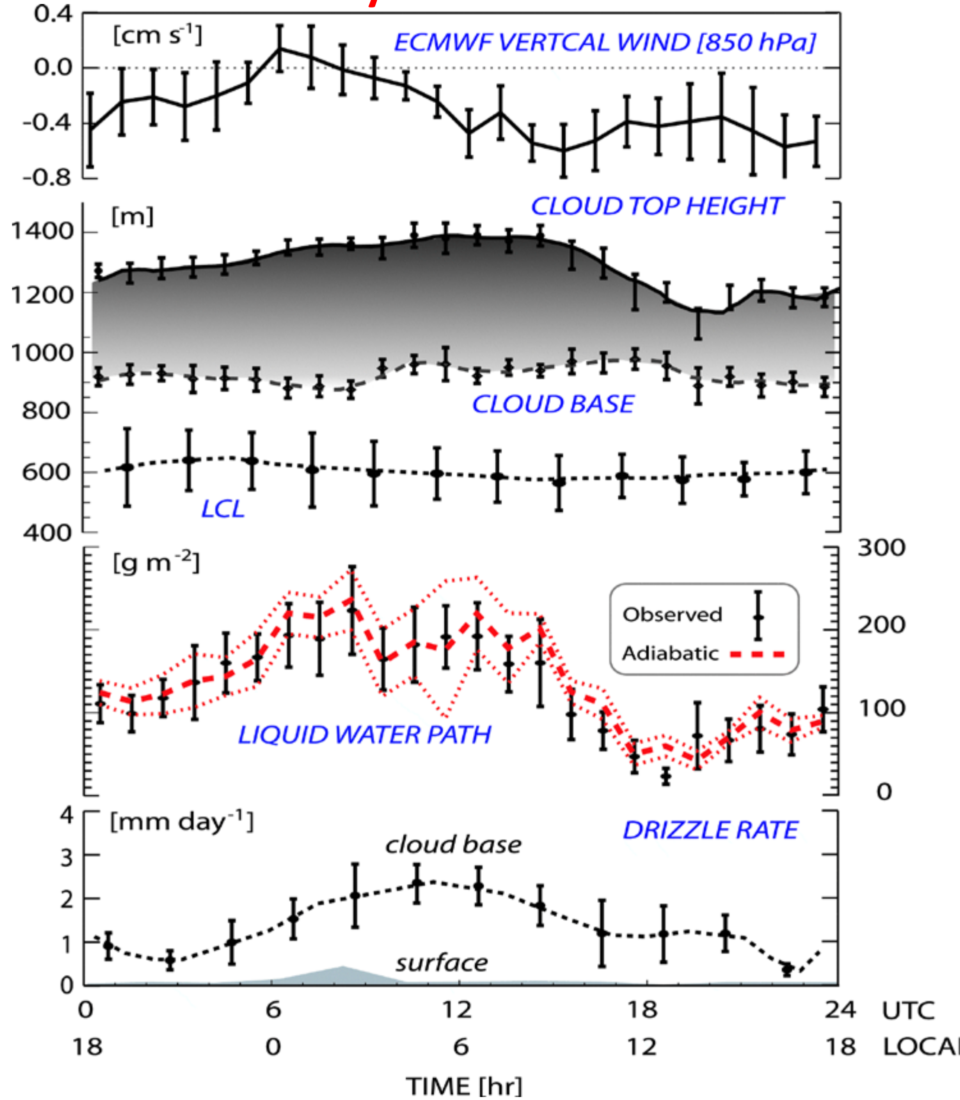
Turner, JGR, 2007

What is the variability in precipitation frequency and strength in the subtropical cloud-topped MBL on diurnal to seasonal timescales, and is this variability correlated with variability in aerosol properties?



LES simulations of the diurnal cycle of marine stratocumulus (Sandu et al. 2008)

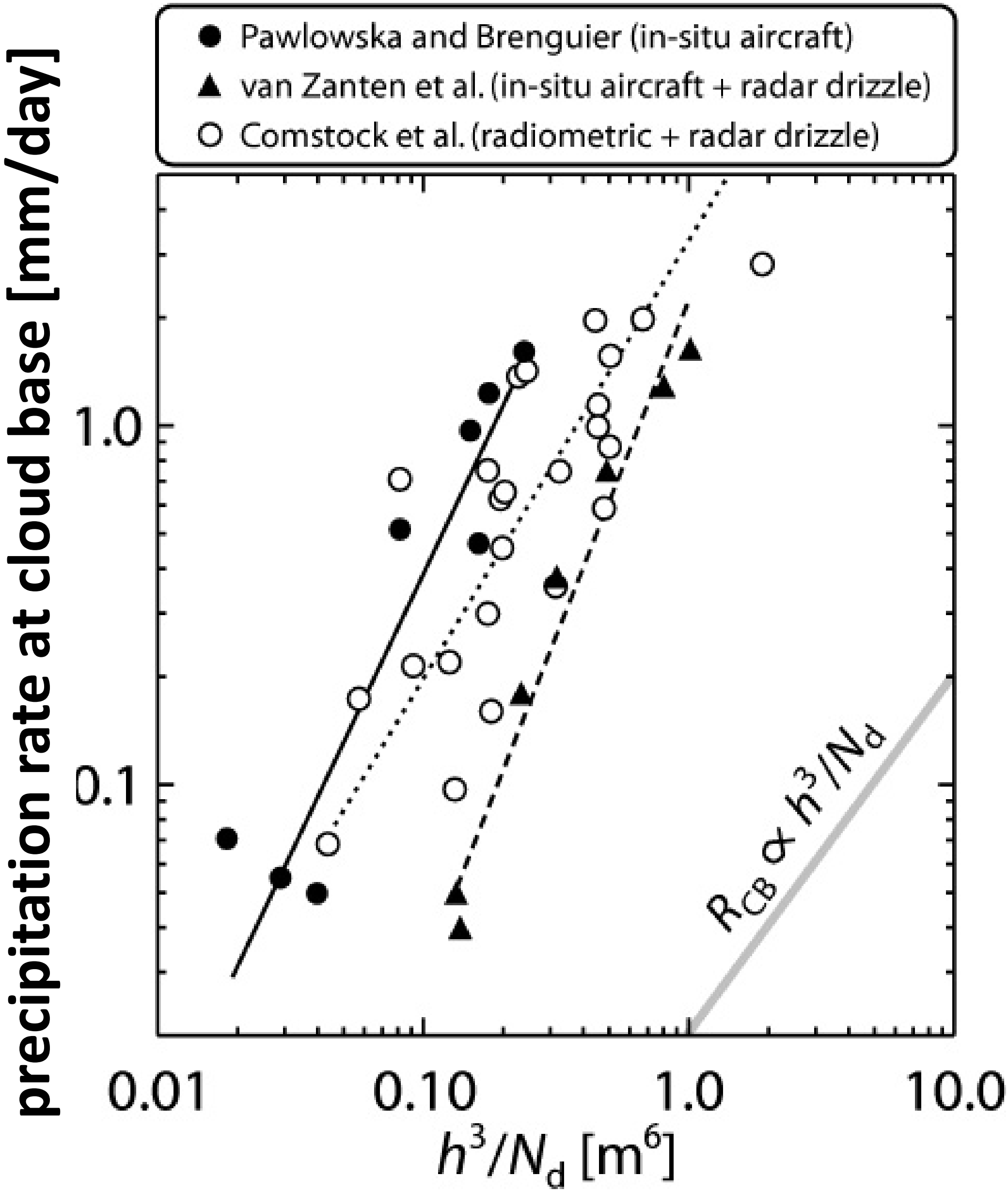
6 days from EPIC



Precipitation closure

- Precipitation rate dependent upon:
    - cloud **macrophysical** properties (e.g. thickness, LWP);
    - **microphysical** properties (e.g. droplet conc., CCN)

- Dependencies critical for constraining 2nd aerosol indirect effect in models



from Brenguier and Wood (2009)

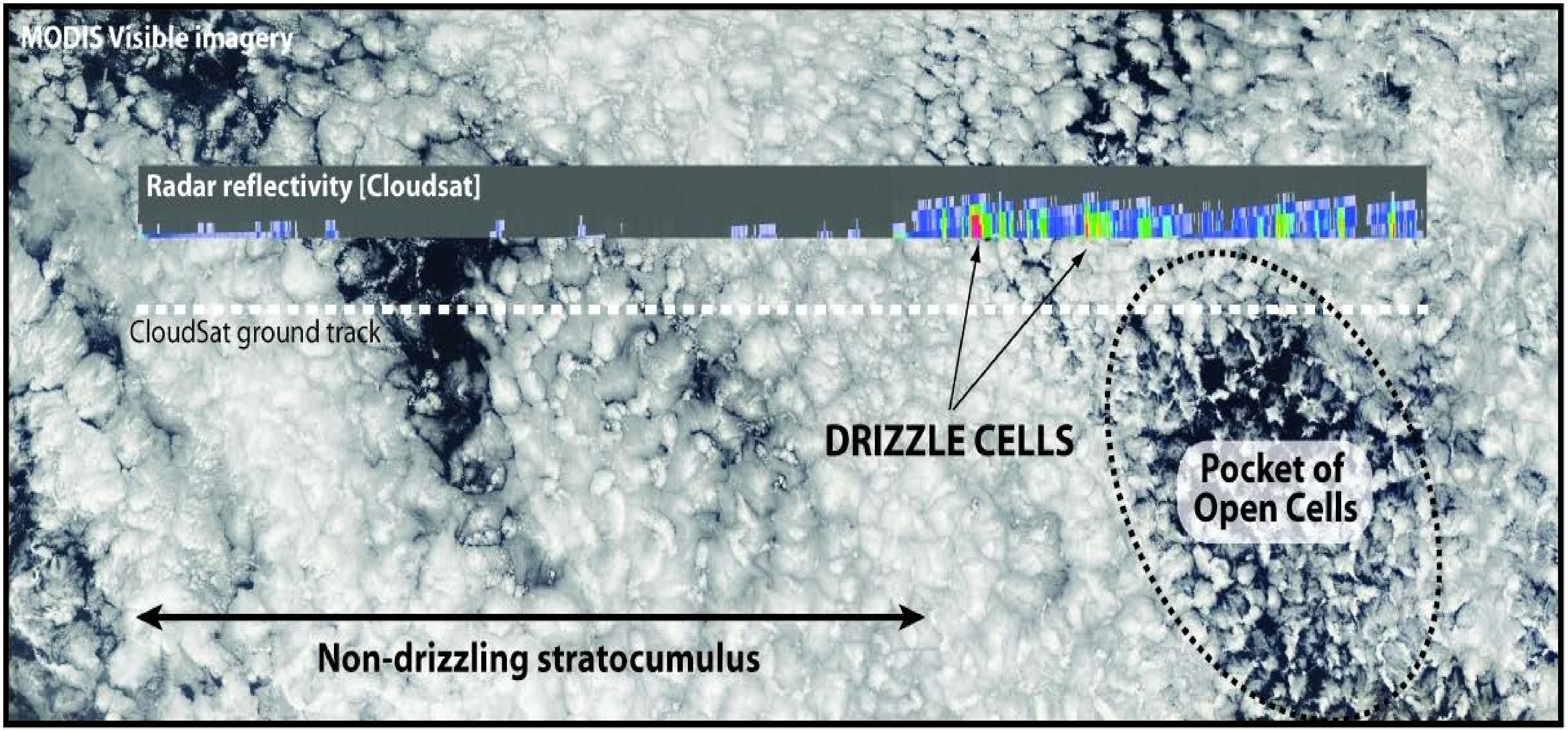
Synergistic Activities

- PICO international Chemical Observatory, a component of the North Atlantic Regional Experiment (PICO-NARE)
- Azores AERONET Site
- Modeling
- Satellite and Reanalysis Data Sets

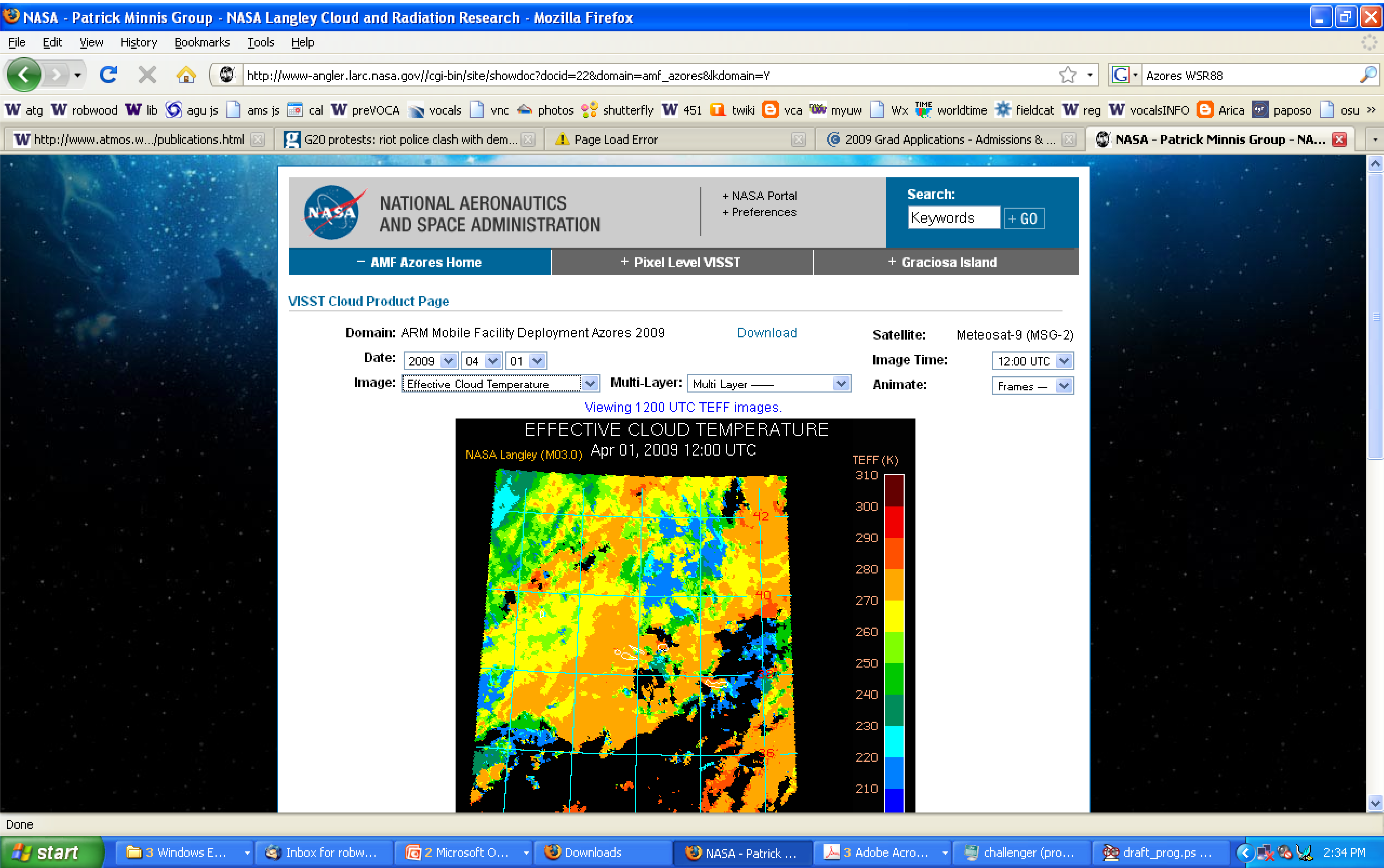
Modeling activities with CAP-MBL

- Forcing datasets for model initialization
- Process models (LES, mixed layer)
  - Run for entire campaign
- Regional mesoscale models
- Global models
  - CAPT Framework, extend to investigation of aerosol-cloud interactions in models
  - Ensemble Kalman Filter (DART)

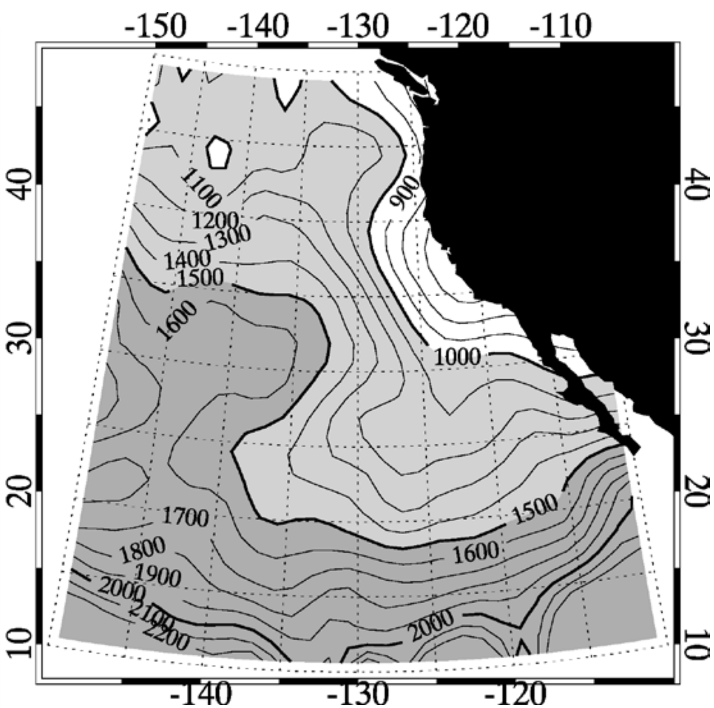
Satellite activities with CAP-MBL



Minnis: CAP-MBL subset

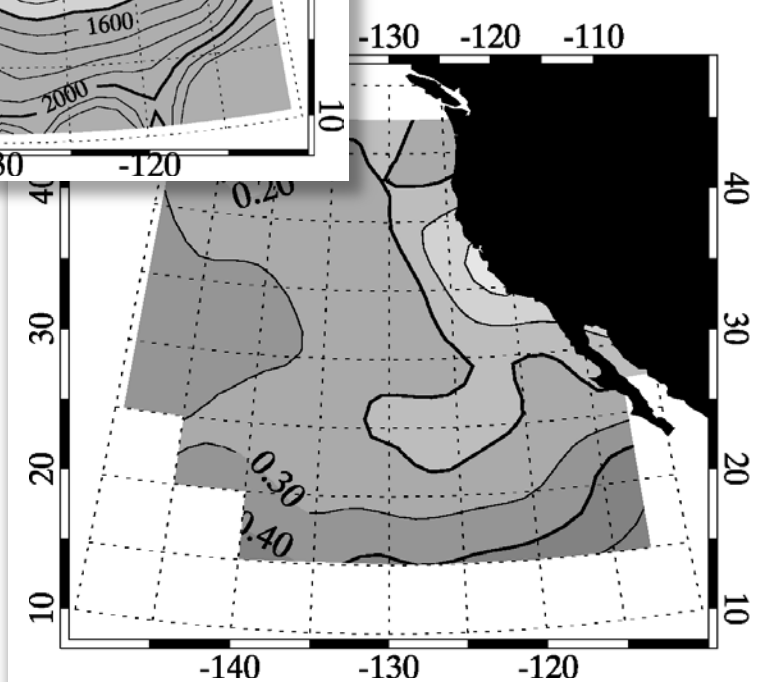


MBL depth, decoupling and entrainment rate using MODIS

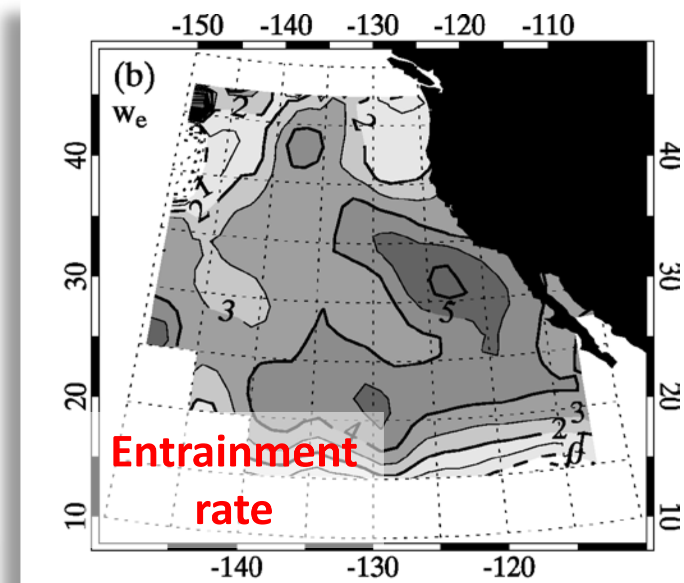


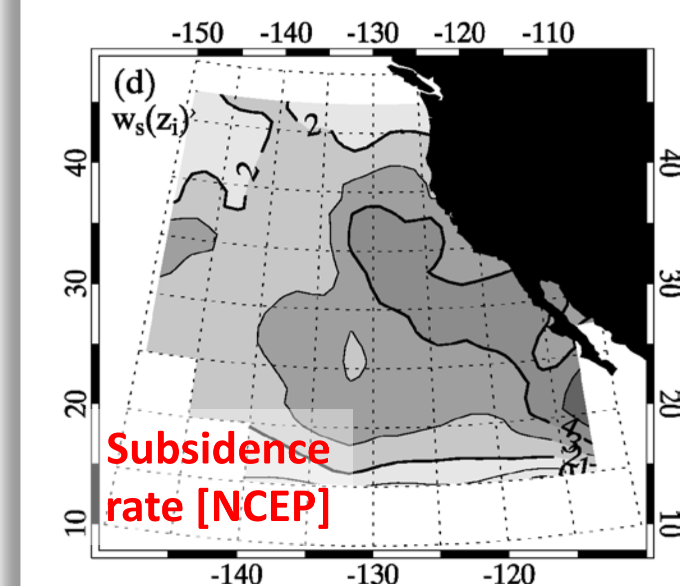
MBL Depth

Wood and Bretherton (2004)



Decoupling parameter





Afternoon breakout session, 1-3 pm

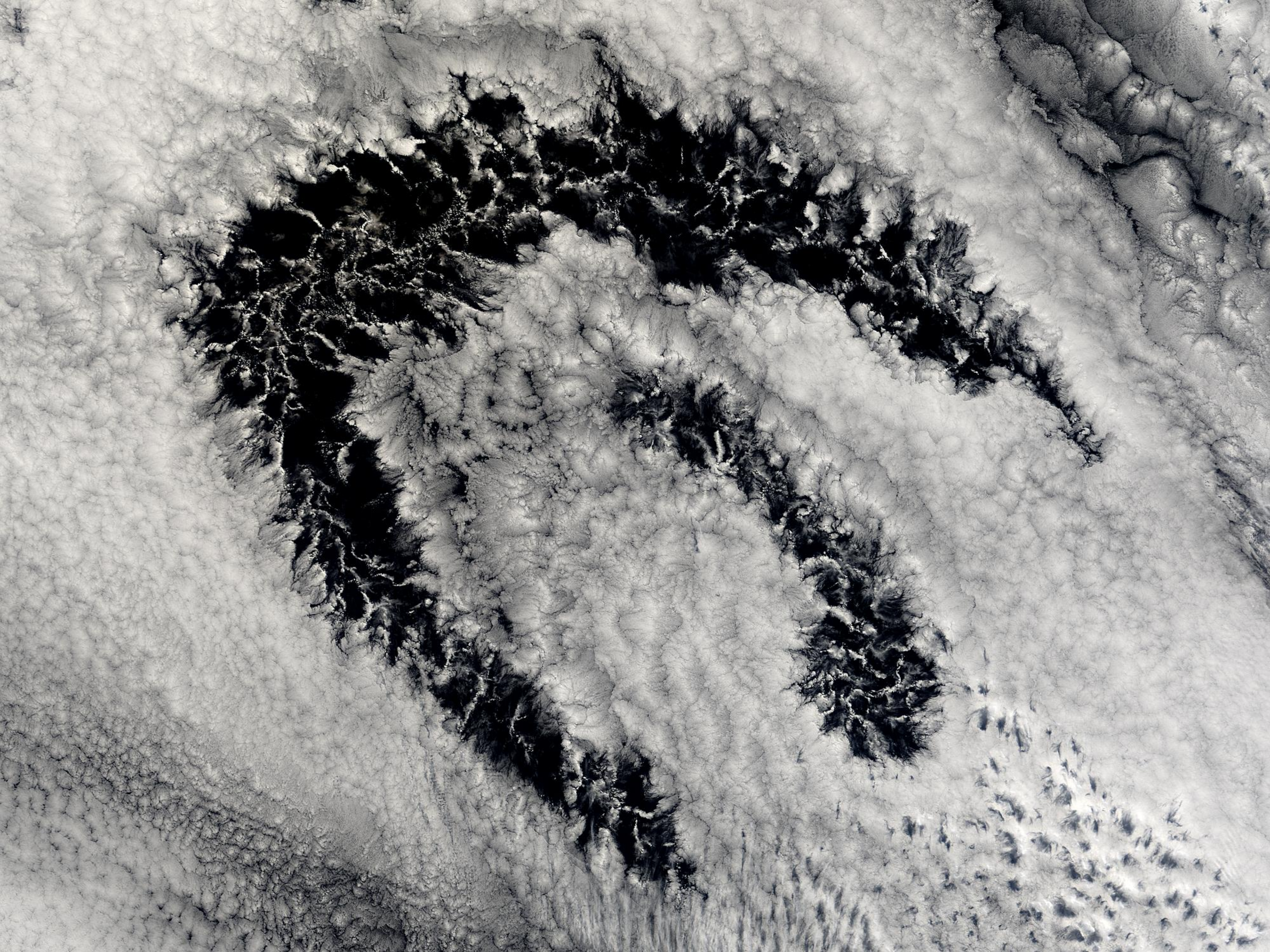
Short (nominally 15 minutes) presentations:

Rob Wood: Introductions, brief recap of deployment science, notes on climatology, and planned modeling activities.

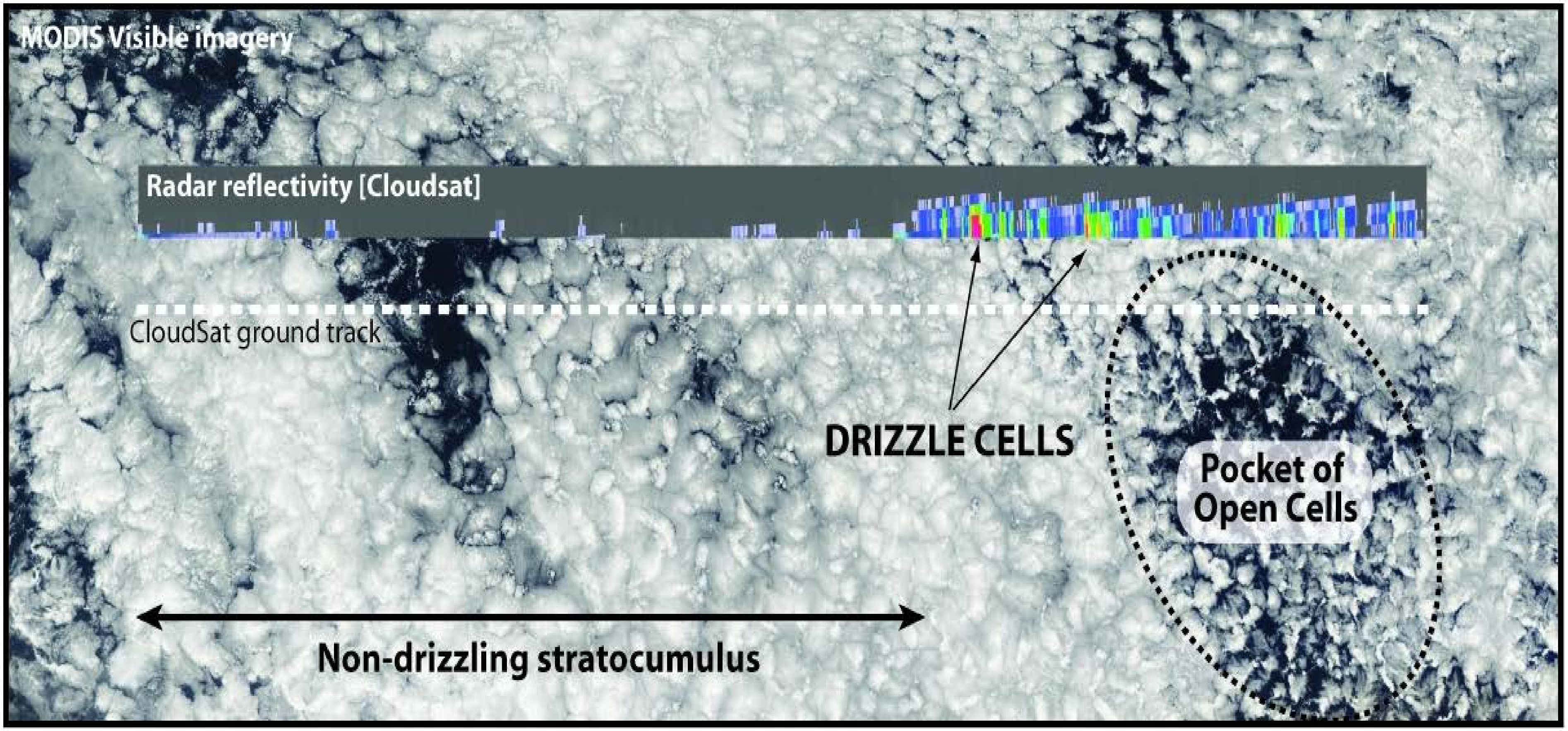
Mark Miller: AMF Graciosa site, free-tropospheric measurements

Bruce Albrecht/Pavlos Kollias: SWACR Scanning Radar deployment in the Azores

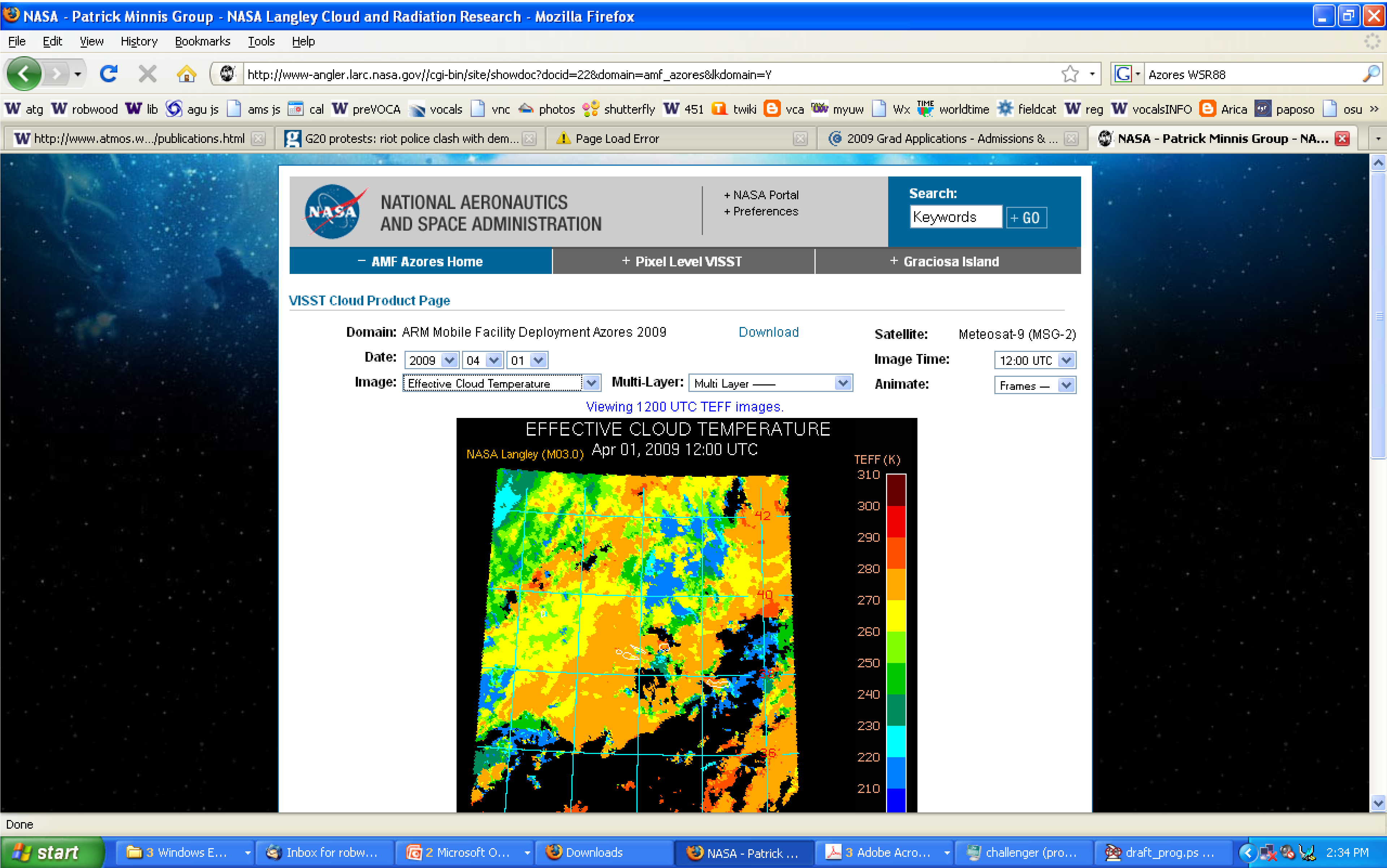
General discussion.



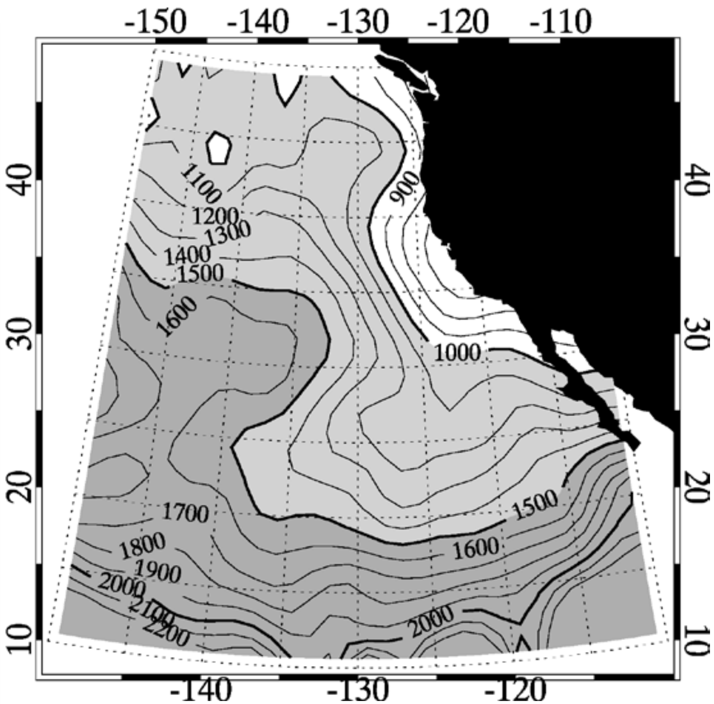
Satellite activities with CAP-MBL



Minnis: CAP-MBL subset

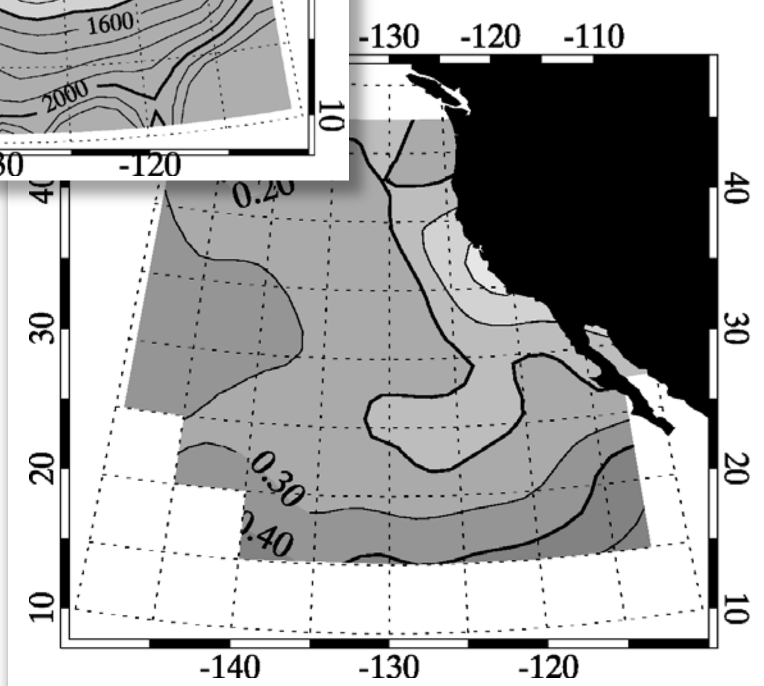


MBL depth, decoupling and entrainment rate using MODIS

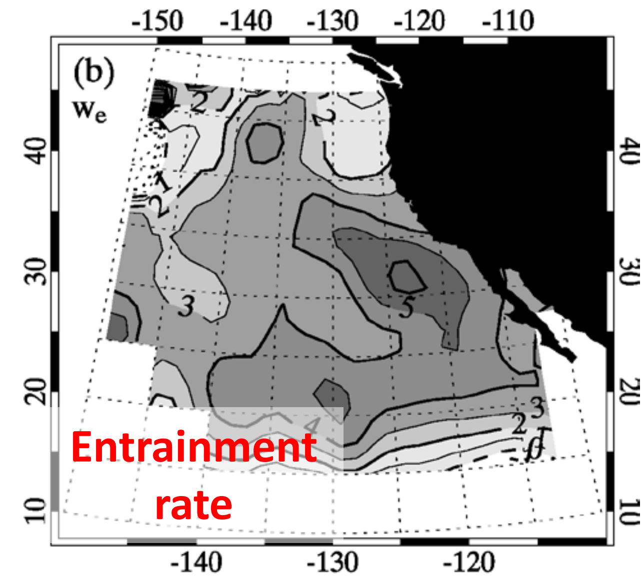


MBL Depth

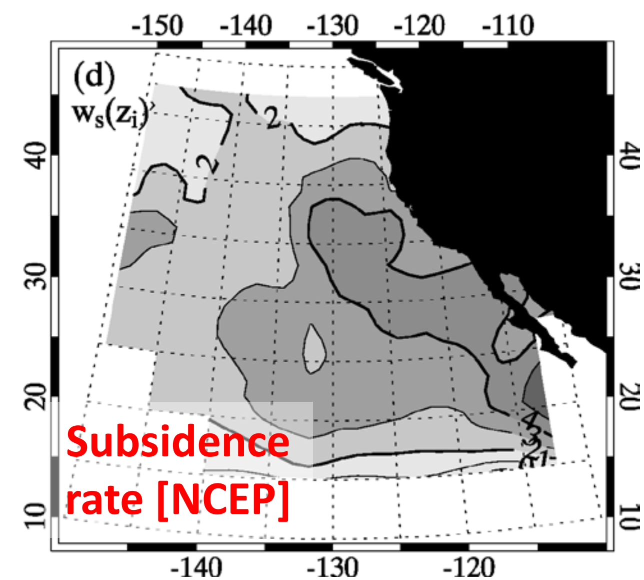
Wood and Bretherton (2004)



Decoupling parameter

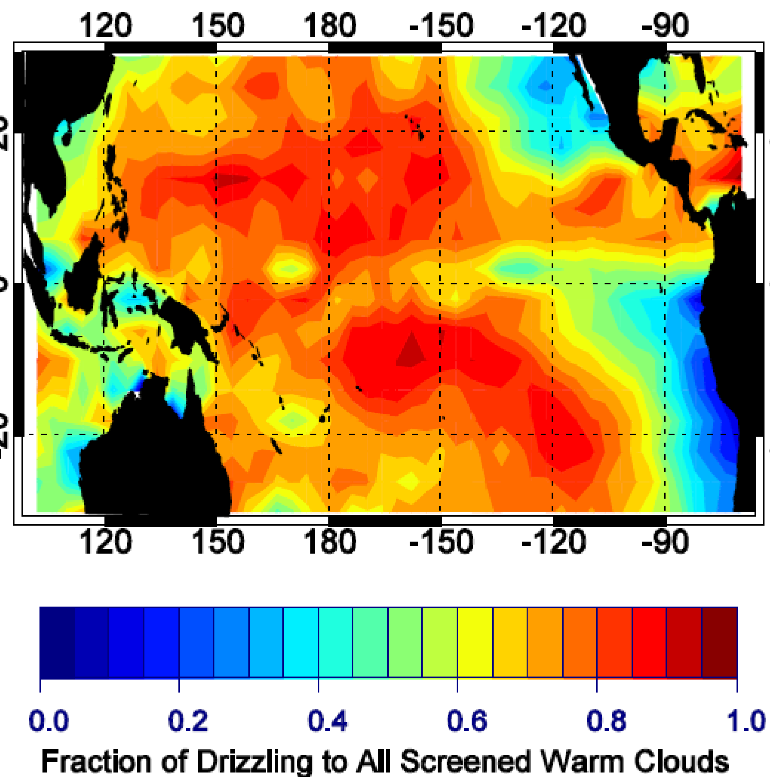


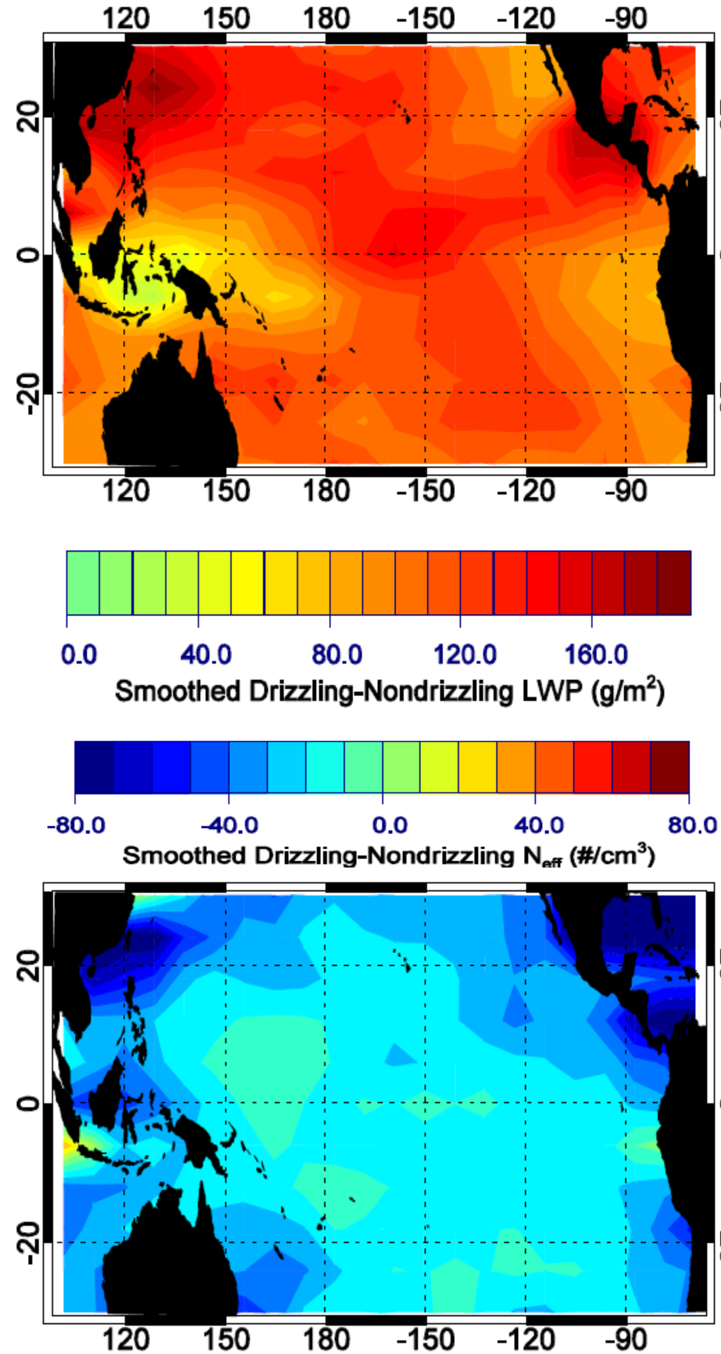
Entrainment rate



Subsidence rate [NCEP]

A-Train
(CloudSat, CALIPSO, AMSR, MODIS)





Kubar et al., in review

Modeling activities with CAP-MBL

- Forcing datasets for model initialization
- Process models (LES, mixed layer)
  - Run for entire campaign
- Regional mesoscale models
- Global models
  - CAPT Framework, extend to investigation of aerosol-cloud interactions in models
  - Ensemble Kalman Filter (DART)

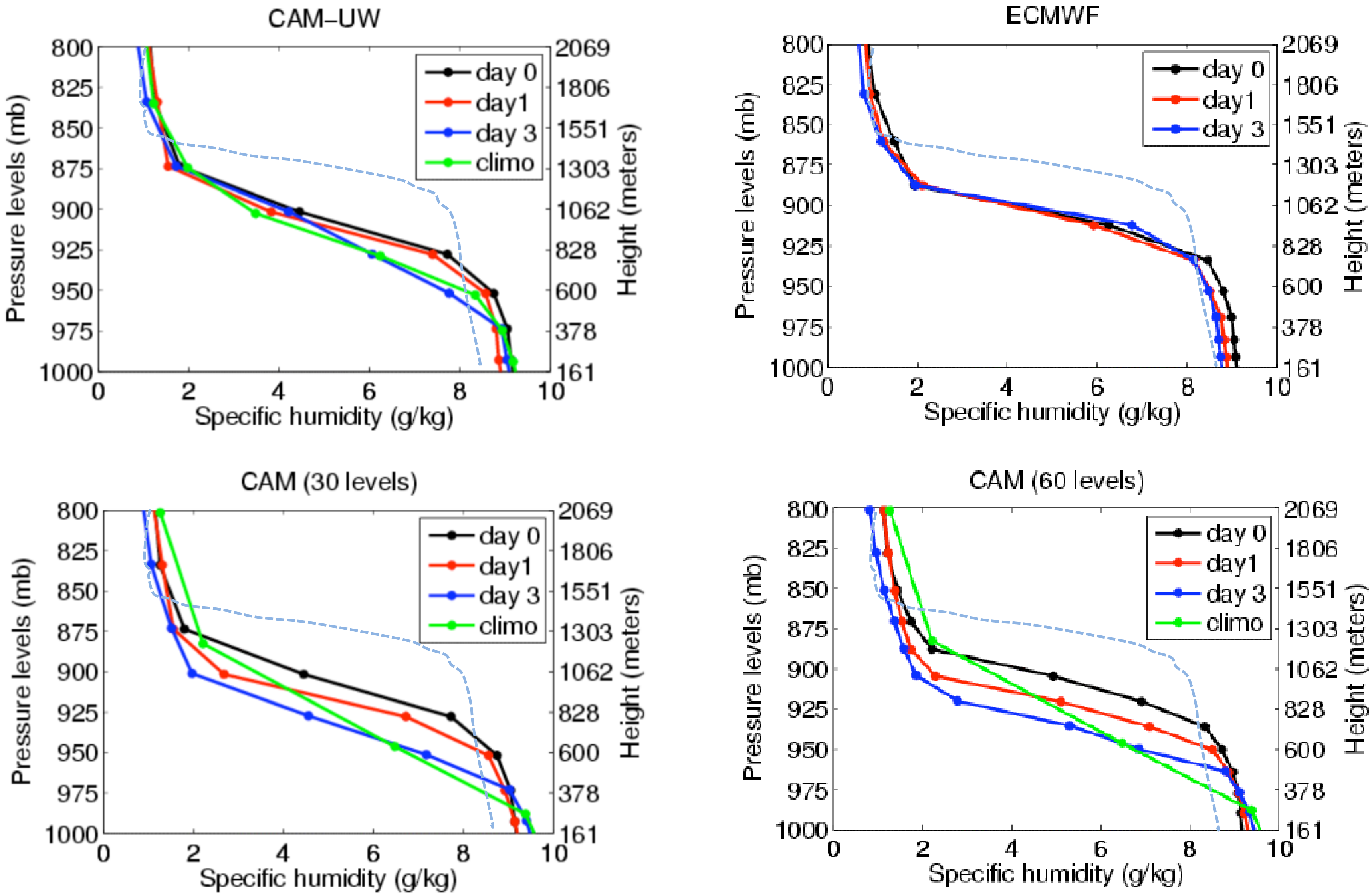
Large eddy simulations

- Run LES for entire campaign nudged to observed large-scale forcings

Climate models in forecast mode

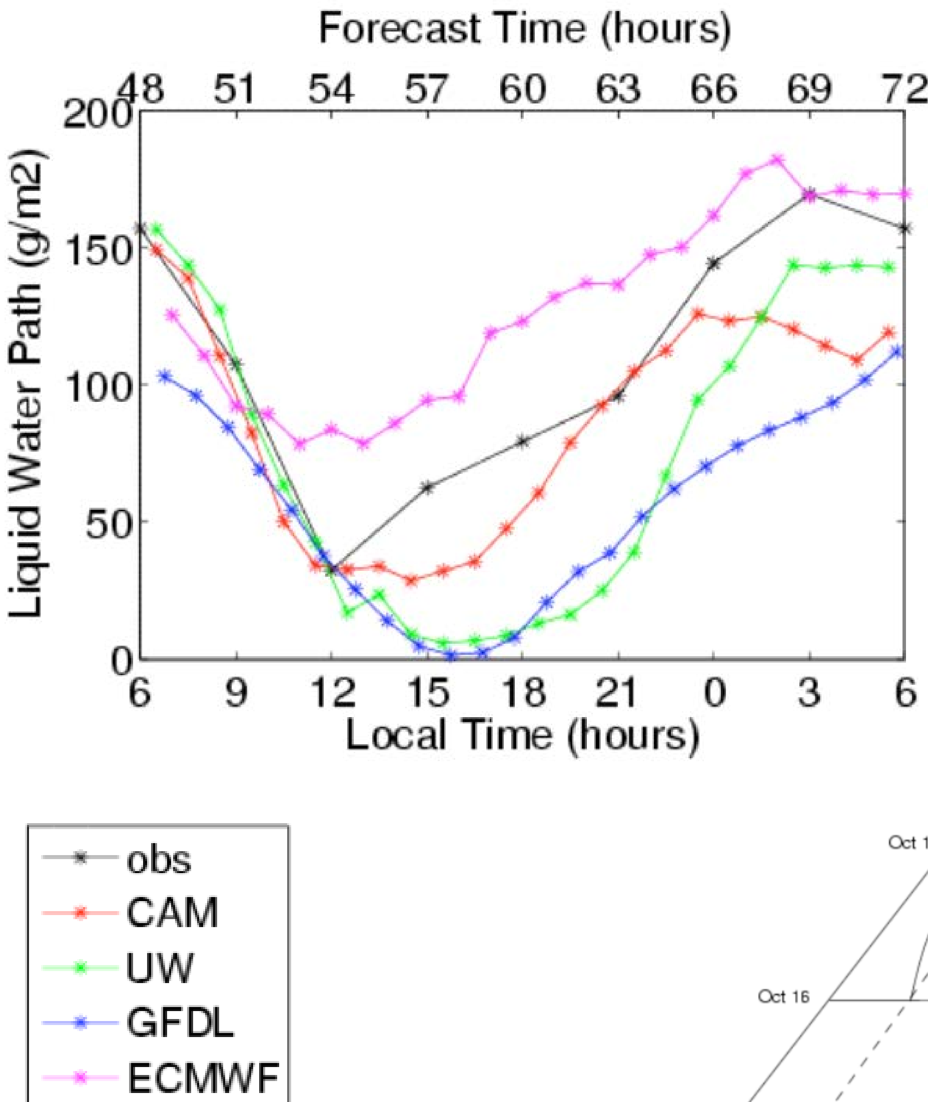
(in collaboration with PCMDI/NCAR)

Obs.
SE Pacific

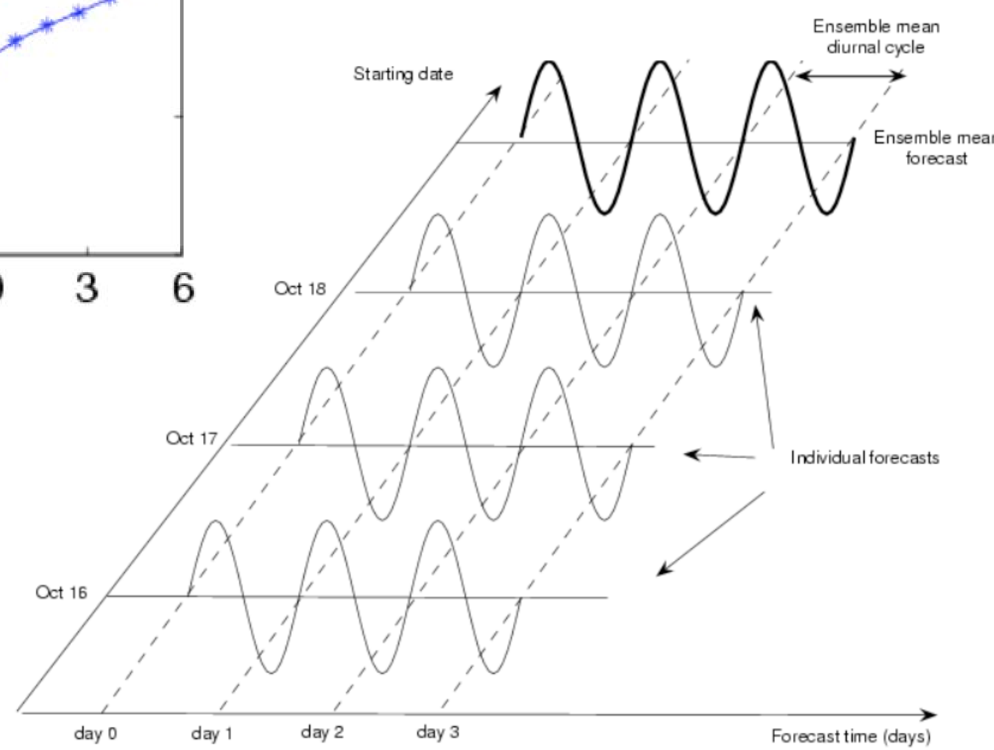


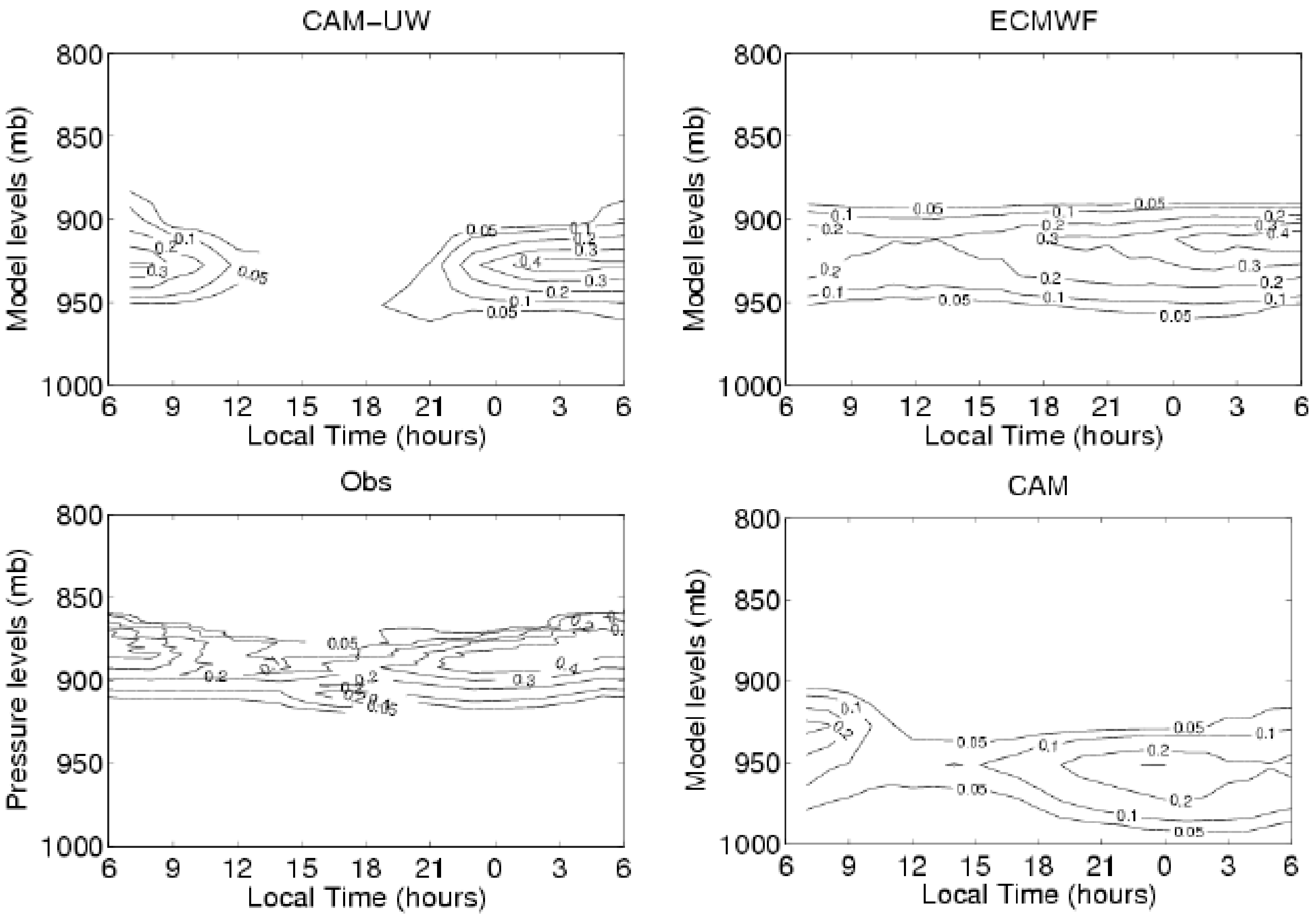
from Hannay et al. (2009)

Climate models in forecast mode: diurnal cycle



from Hannay et al. (2009)



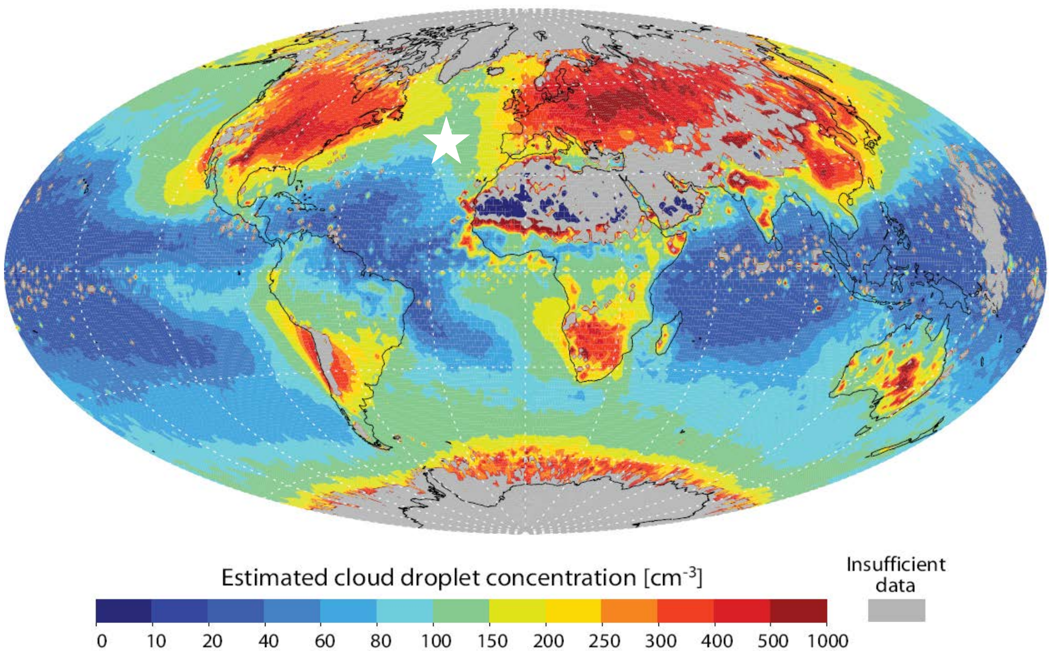


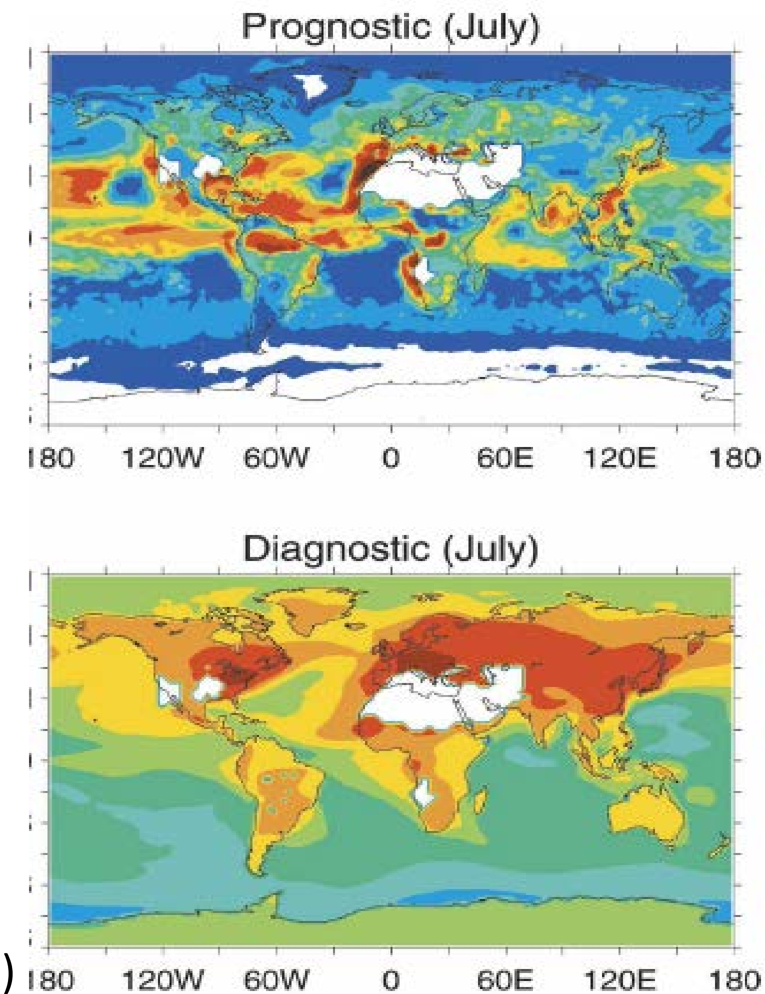
from Hannay et al. (2009)

Cloud microphysics/aerosol transport

- Long term aerosol physical measurements at a remote marine boundary layer site, cloud number measurements from surface remote sensing (Dong and Mace)

MODIS cloud droplet conc., Wood (2009)





GFDL Model, Ming et al. (2007)

DART/Ensemble Kalman filter (EnKF)

- Run 50-100 single column versions of CAM
  - vary large-scale forcings (based on ECMWF or NCEP)
  - perturbed physics experiments (a la *climateprediction.net*)
- Nudge ensemble towards AMF Azores measurements and local satellite measurements
- Useful for exploring sensitivity of model simulations to both large scale forcings and model physics

Modeling center collaborators

- ECMWF (Martin Koehler) and NCEP (Hualu Pan) will provide column data from operational models for Graciosa for entire deployment
- CAM (Cecile Hannay); GFDL (Yanluan Lin)
- Involvement of CAPT (Klein)

AMF Site: Graciosa Island in the Azores (28 ºW 39 ºN)

- Small Low Island
- No Direct Continental Influence
- MBL Depths 1-2 km

Cloud Climatology for Azores

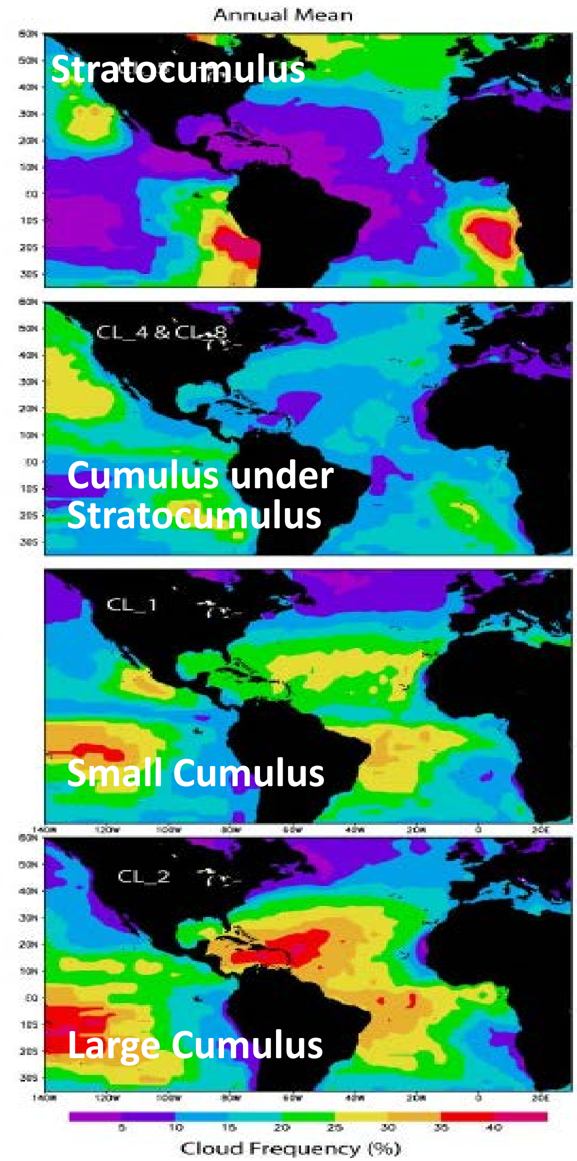
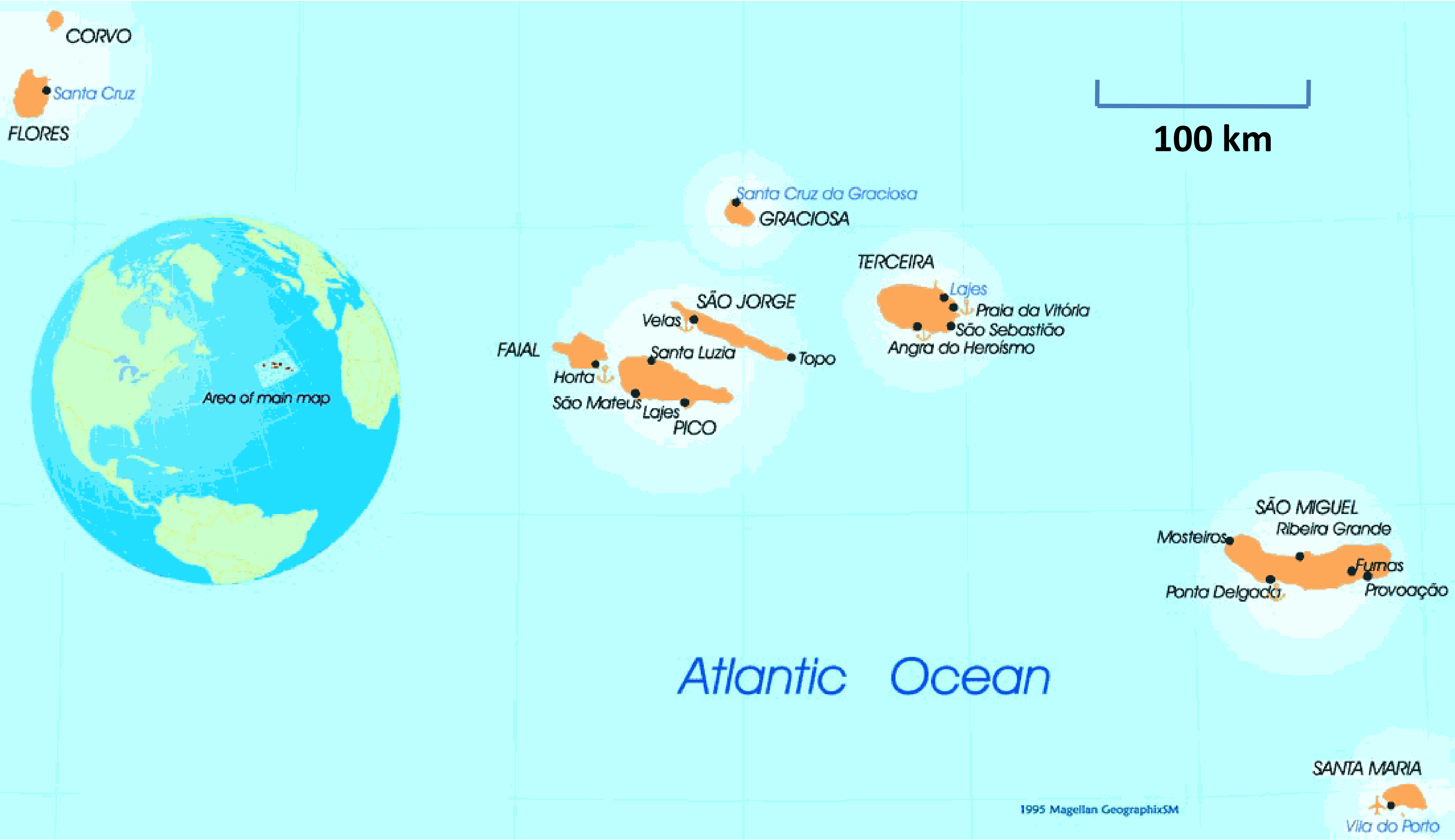
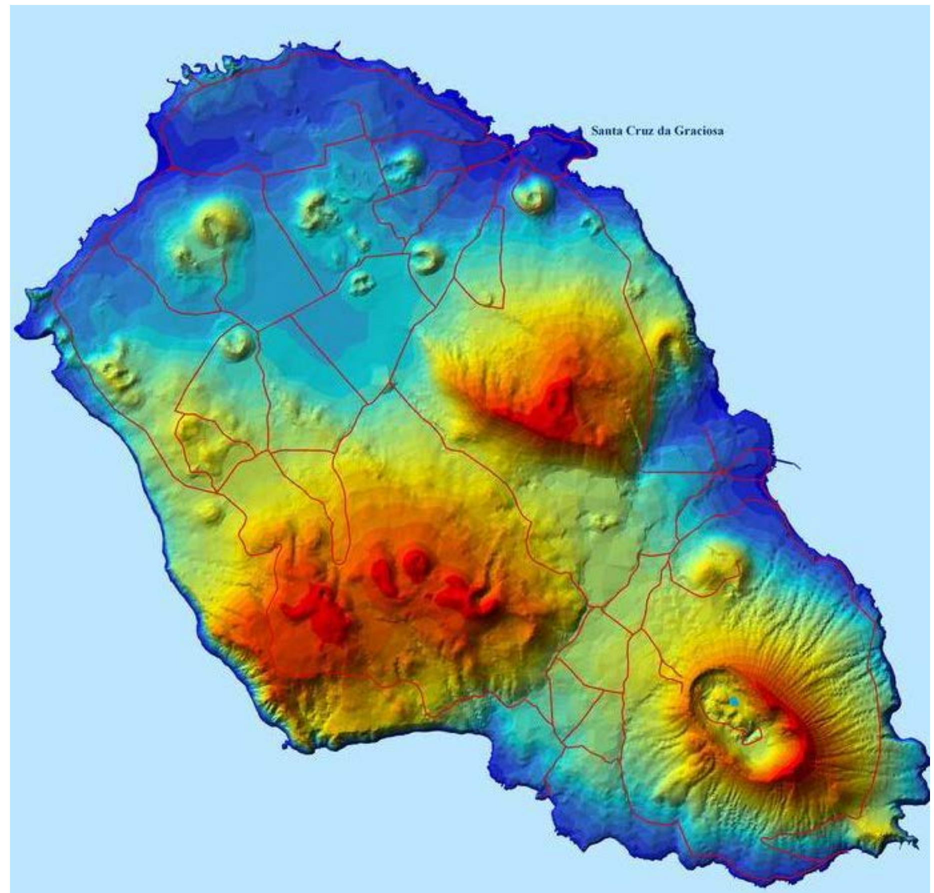


Figure 6: Annual mean frequency of occurrence of (from top) stratocumulus, stratocumulus with cumulus beneath or formed from spreading cumulus, small cumulus, and large cumulus

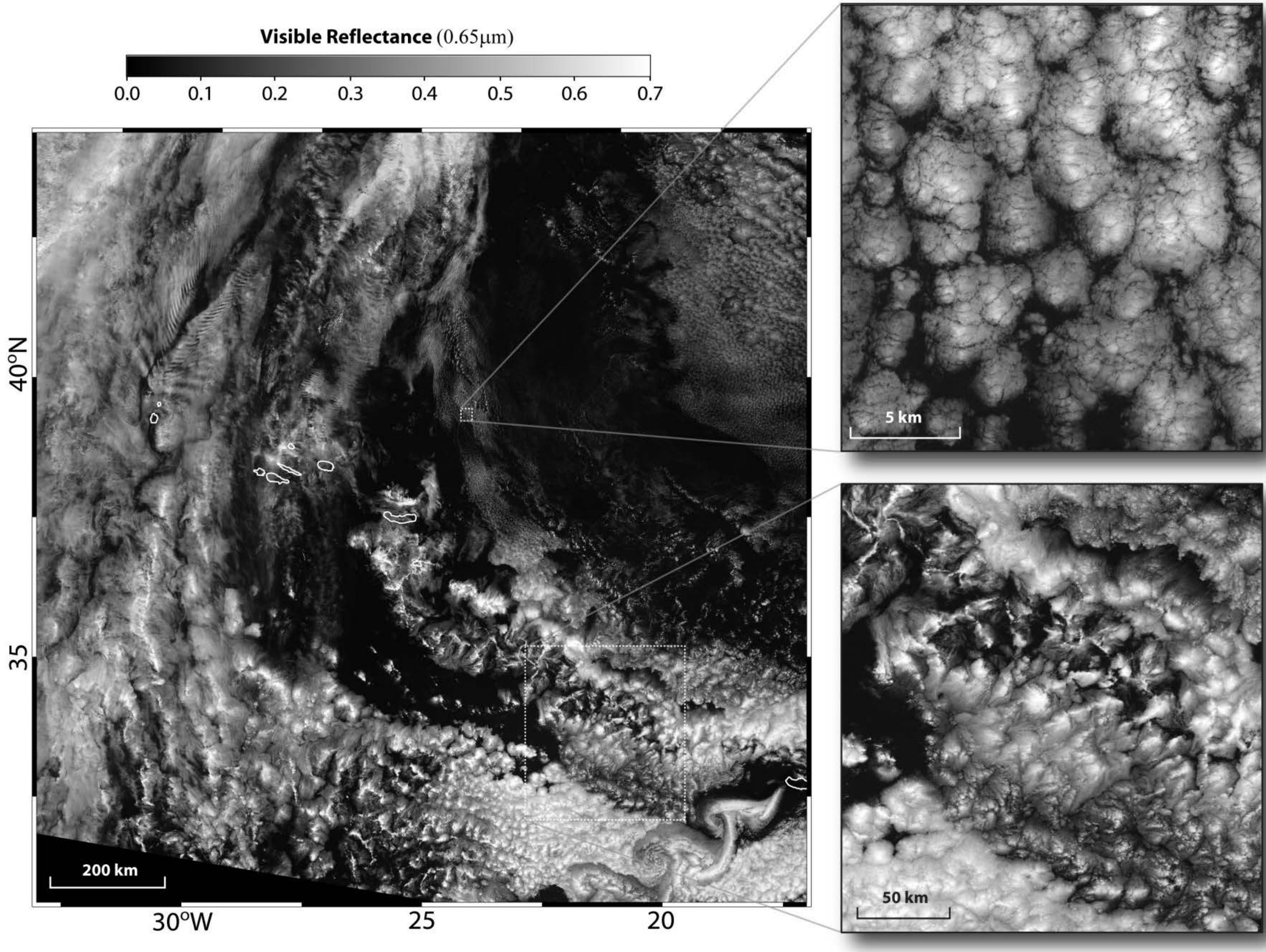
The Azores and Graciosa



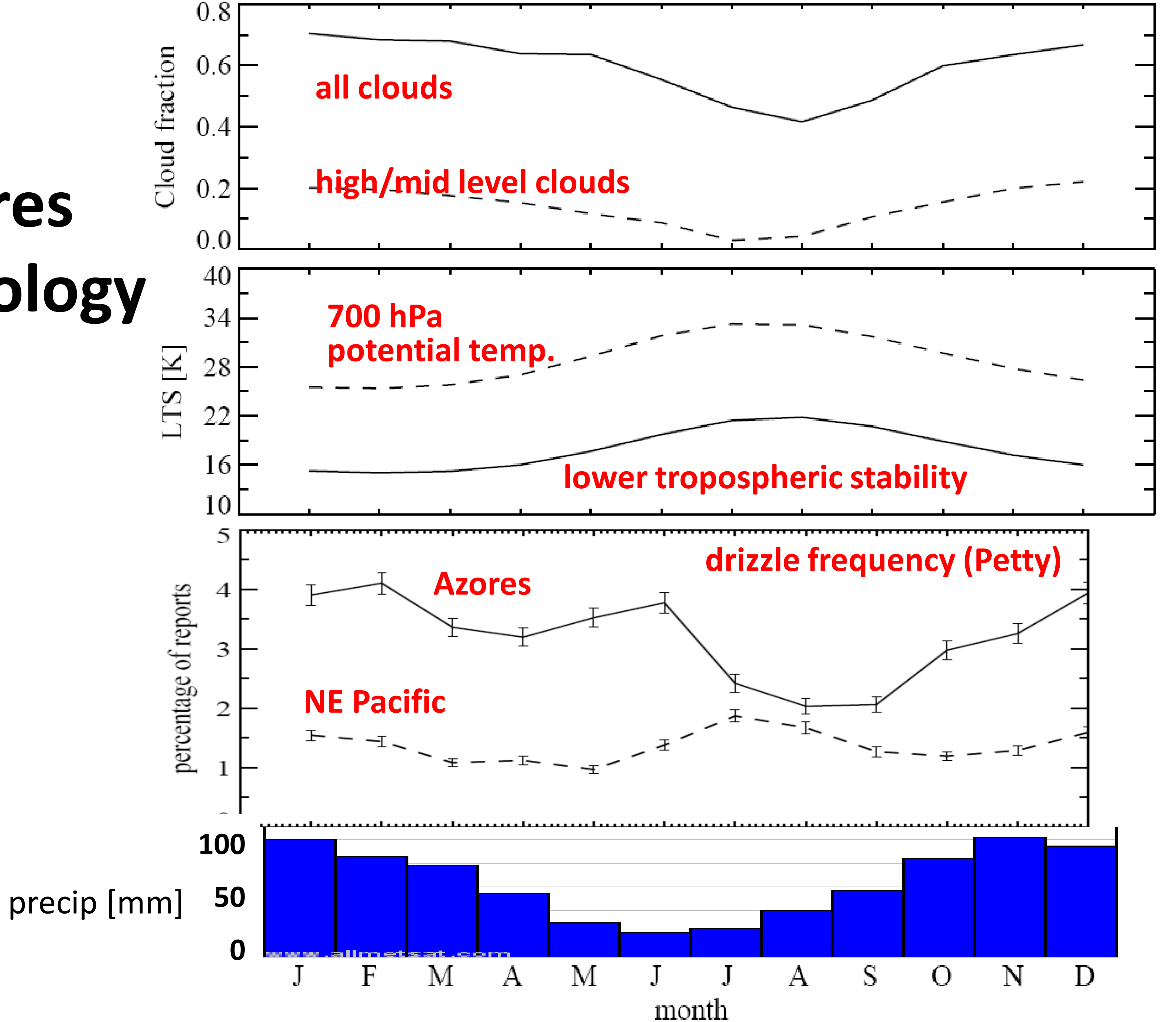

Flores
Fajazinha
Santa Cruz


Santa Cruz da Graciosa

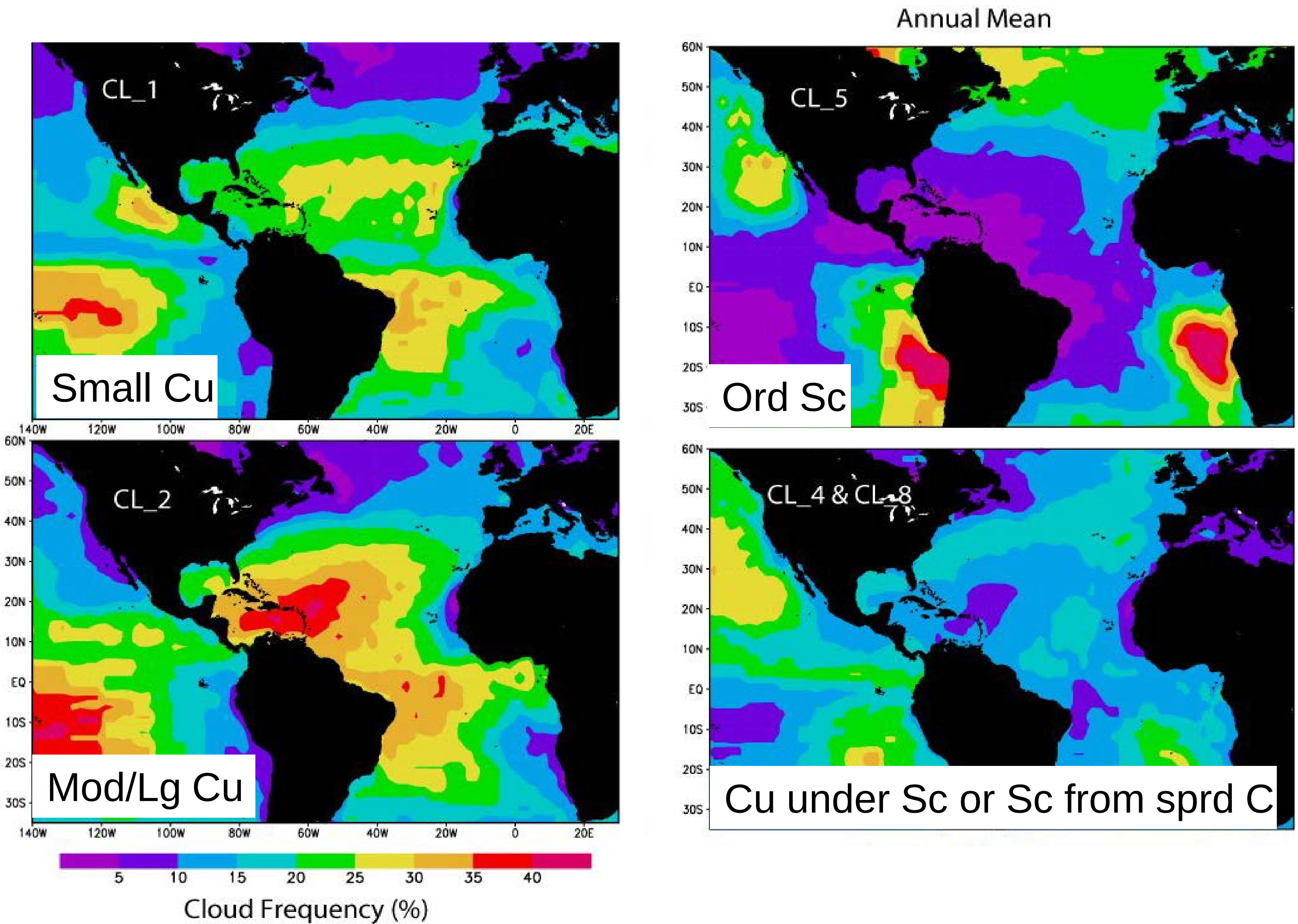
Marine boundary layer cloud in the Azores

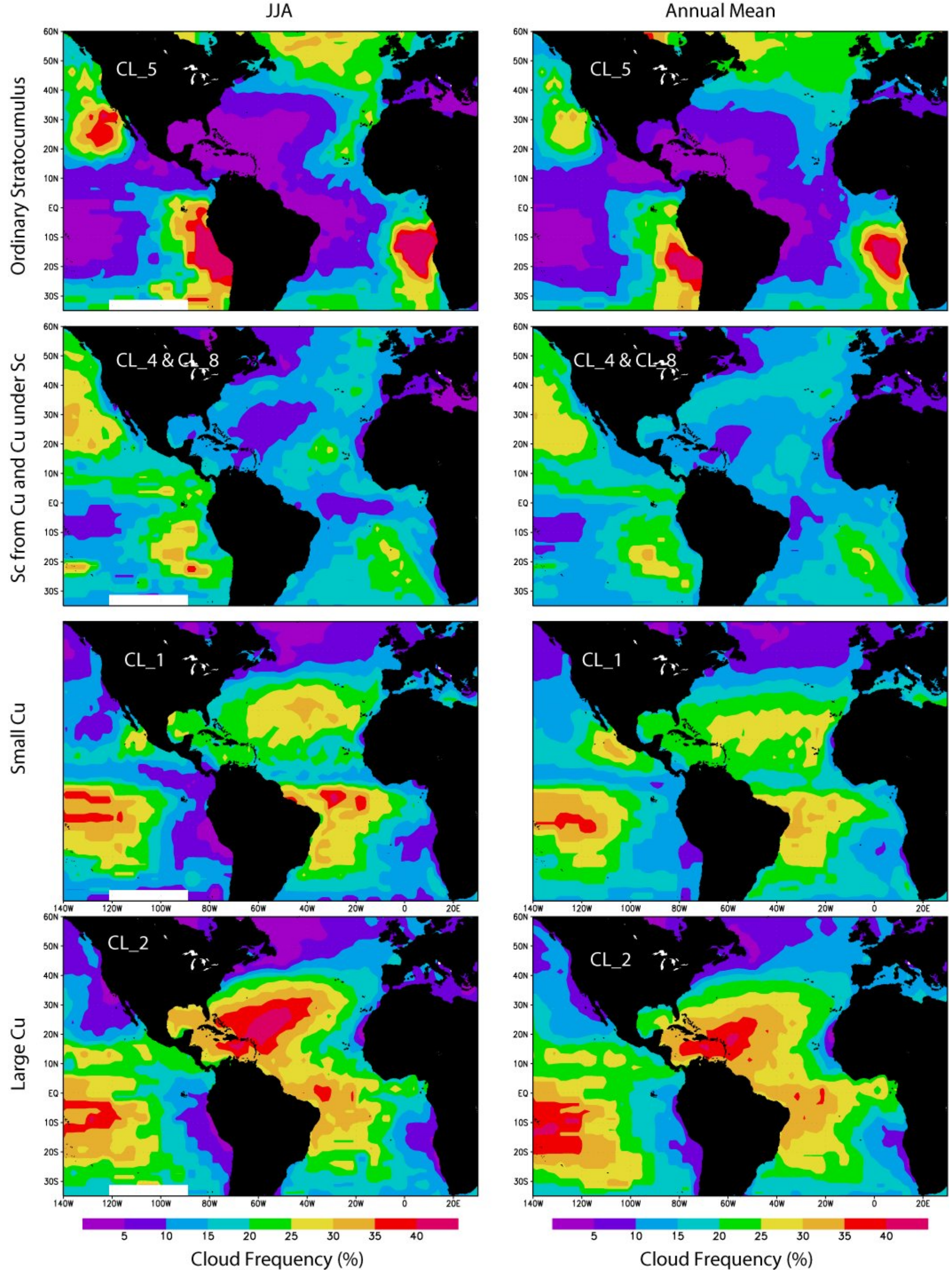


Azores climatology



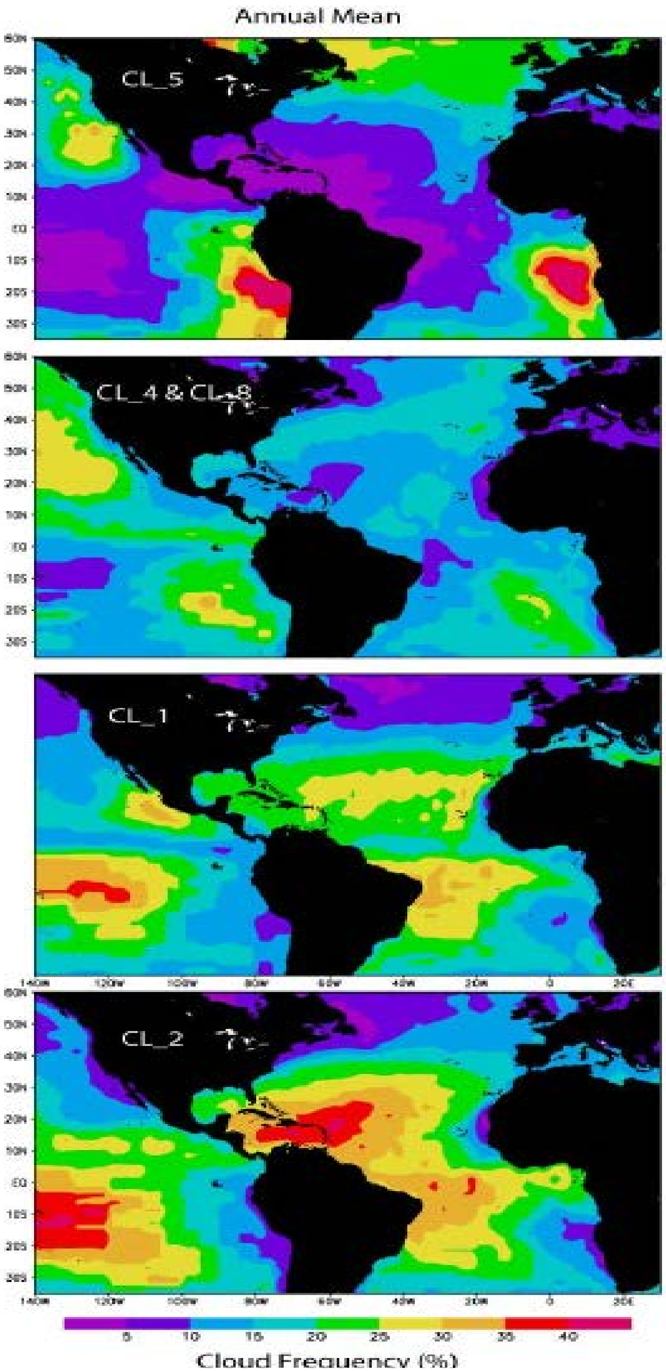
Low clouds - frequency

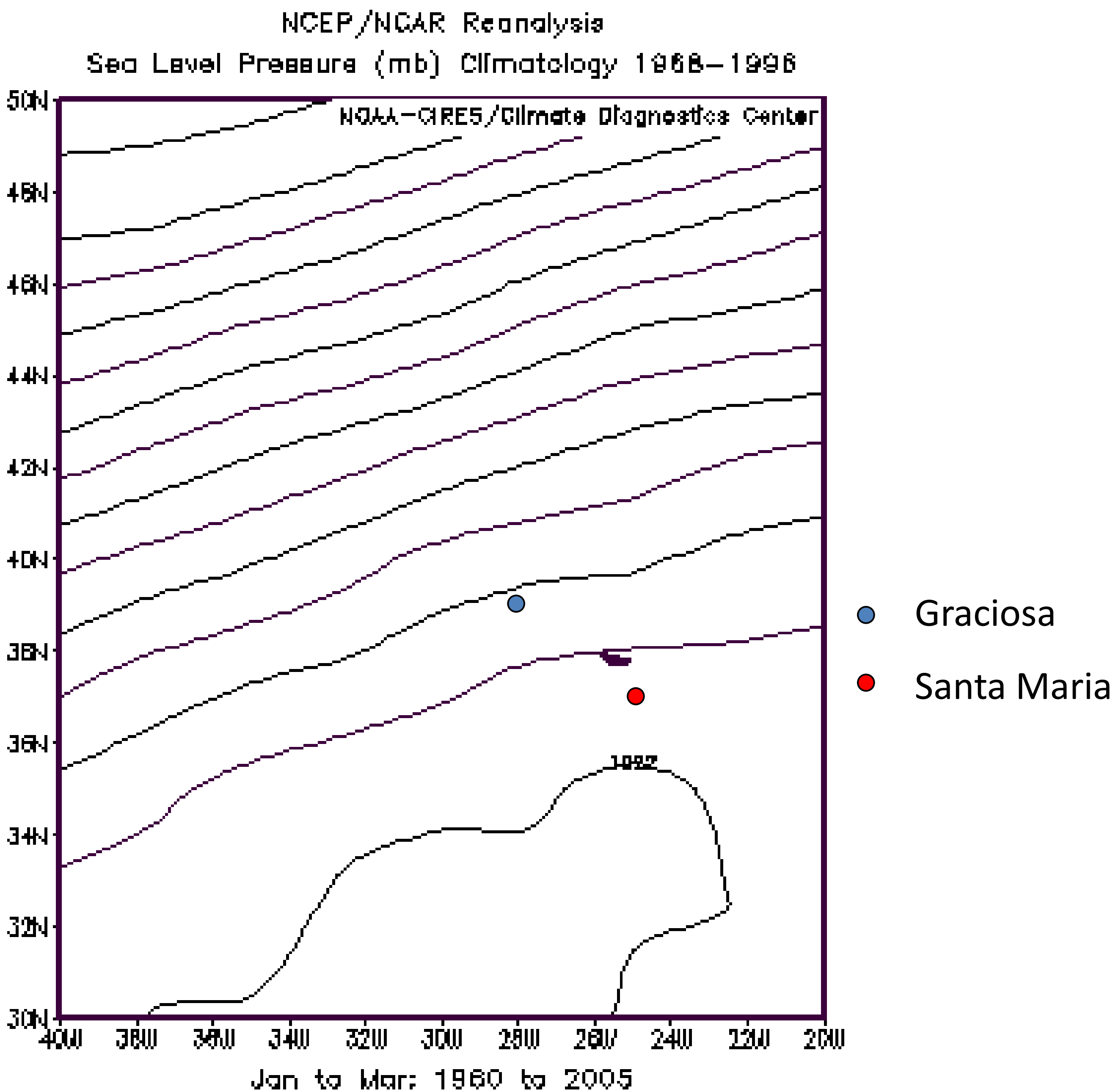


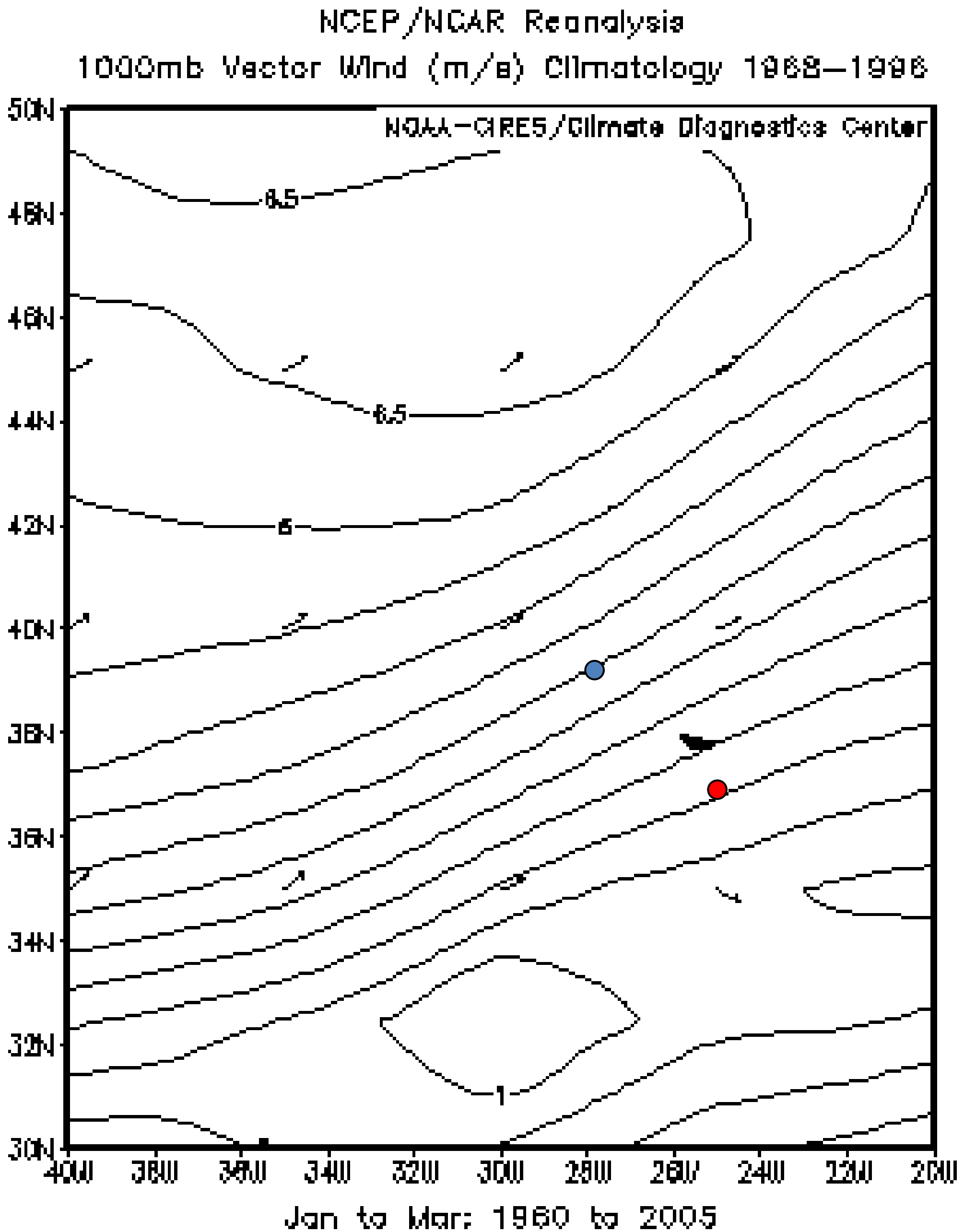


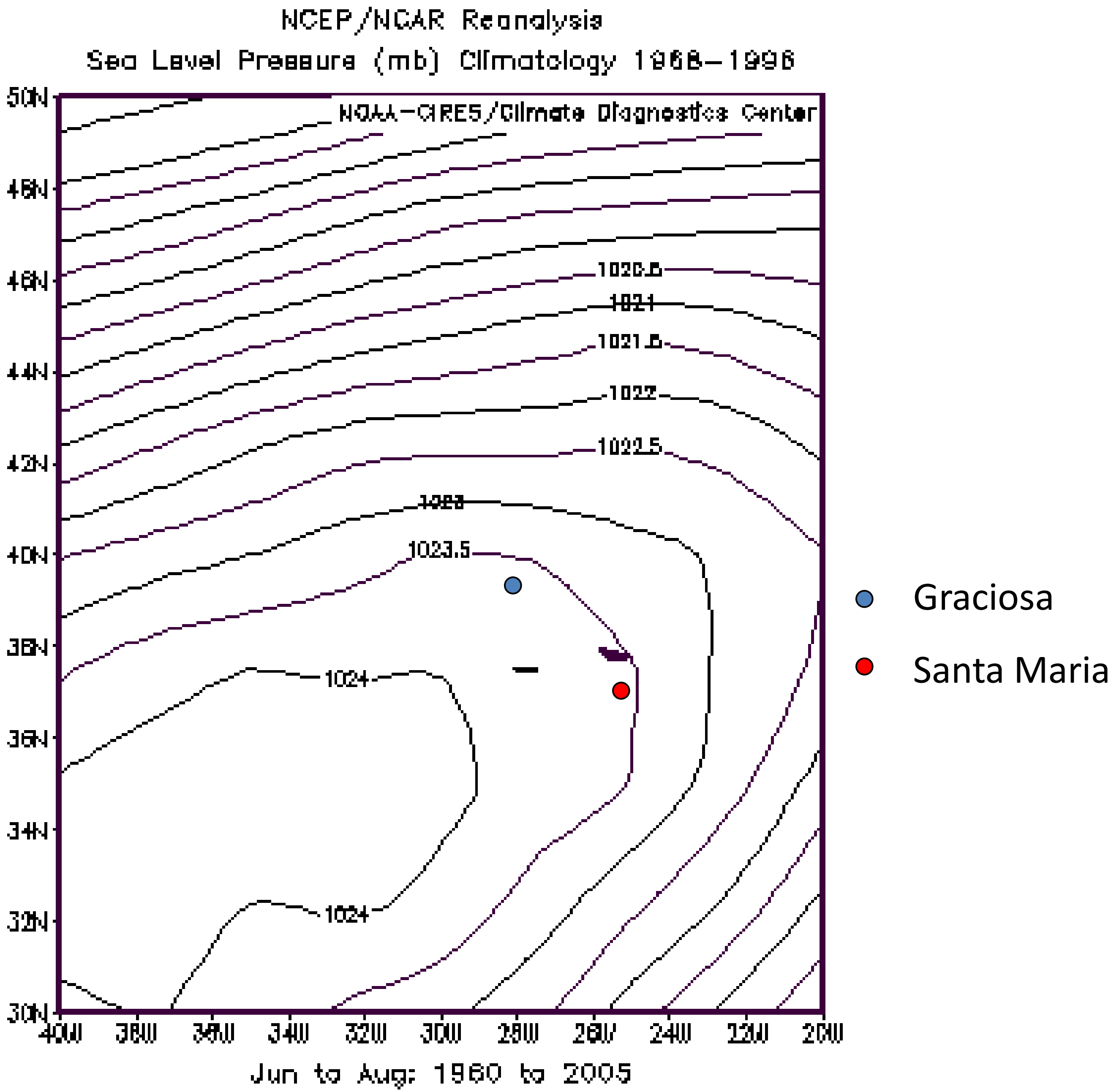
JJA
Annual Mean
Ordinary Stratocumulus
Sc from Cu and Cu under Sc
Small Cu
Large Cu
CL_5
CL_4 & CL_8
CL_1
CL_2
60N
50N
40N
30N
20N
10N
EQ
10S
20S
30S
140W
120W
100W
80W
60W
40W
20W
0
20E
5
10
15
20
25
30
35
40
Cloud Frequency (%)

Cloud Climatology for Azores




NCEP/NCAR Reanalysis
Sea Level Pressure (mb) Climatology 1968–1996
NOAA-CIRES/Climate Diagnostics Center
50N
48N
46N
44N
42N
40N
38N
36N
34N
32N
30N
40W
38W
36W
34W
32W
30W
28W
26W
24W
22W
20W
Jan to Mar: 1960 to 2005
Graciosa
Santa Maria


NCEP/NCAR Reanalysis
1000mb Vector Wind (m/s) Climatology 1968–1996
NOAA-CIRES/Climate Diagnostics Center
6.5
6.5
6
1
50N
48N
46N
44N
42N
40N
38N
36N
34N
32N
30N
40W
38W
36W
34W
32W
30W
28W
26W
24W
22W
20W
Jan to Mar: 1960 to 2005


NCEP/NCAR Reanalysis
Sea Level Pressure (mb) Climatology 1968-1996
NOAA-CIRES/Climate Diagnostics Center
1020.5
1021
1021.5
1022
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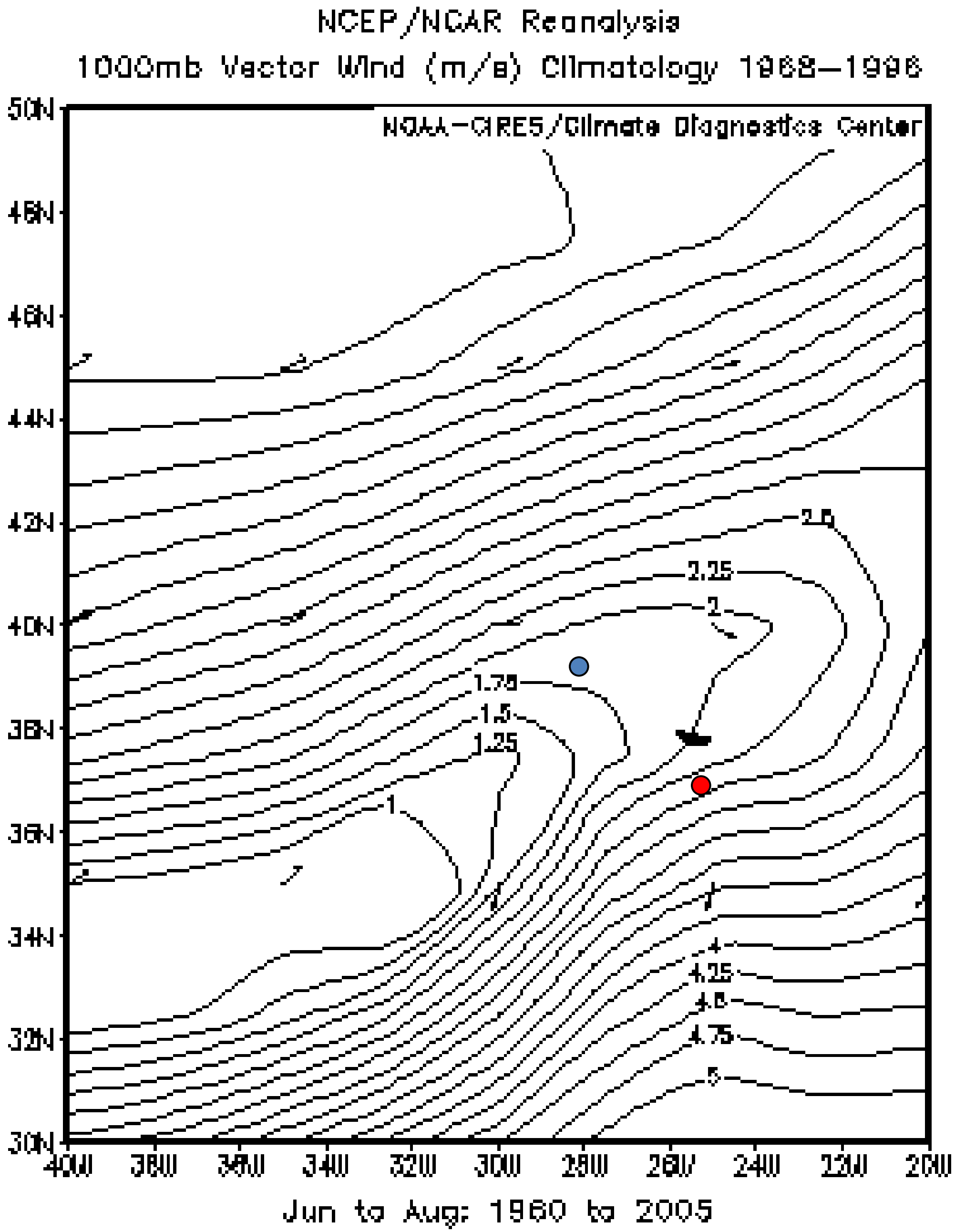
1023
1023.5
1024
1024
50N
48N
46N
44N
42N
40N
38N
36N
34N
32N
30N
40W
38W
36W
34W
32W
30W
28W
26W
24W
22W
20W
Jun to Aug: 1960 to 2005
Graciosa
Santa Maria


NCEP/NCAR Reanalysis
1000mb Vector Wind (m/s) Climatology 1968–1996
NOAA-CIRES/Climate Diagnostics Center
50N
48N
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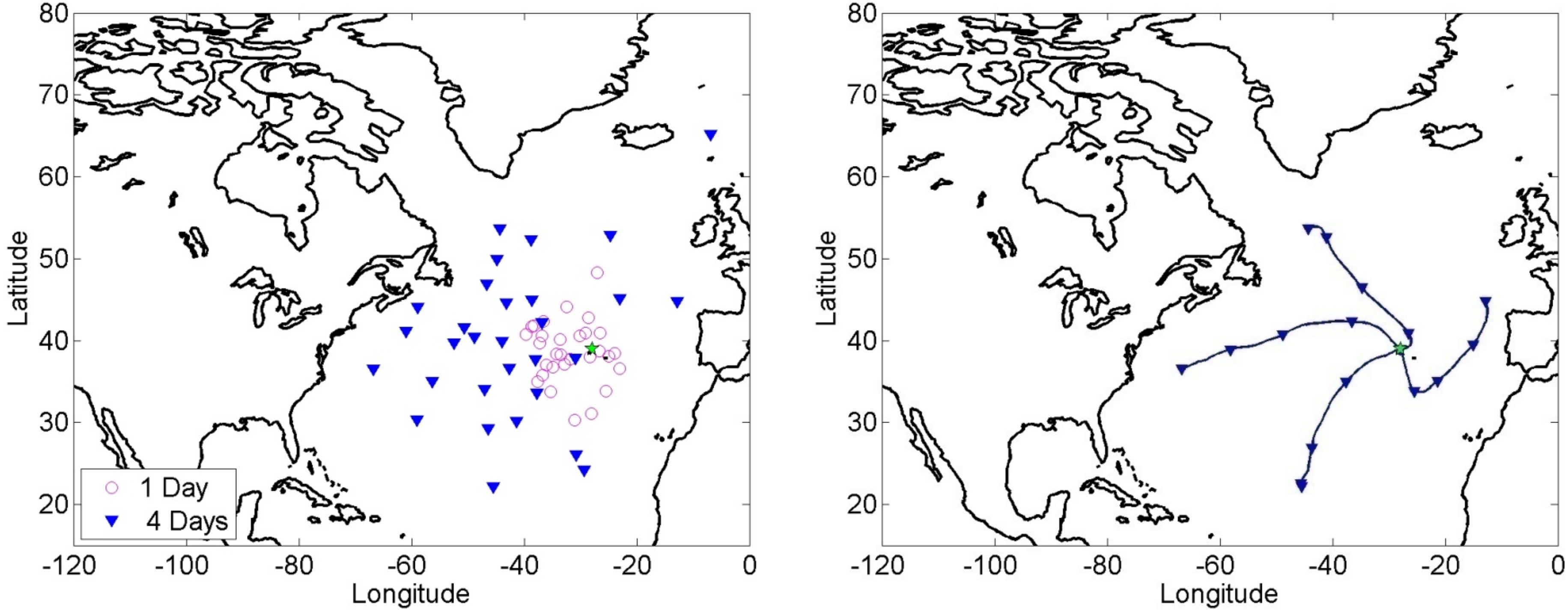
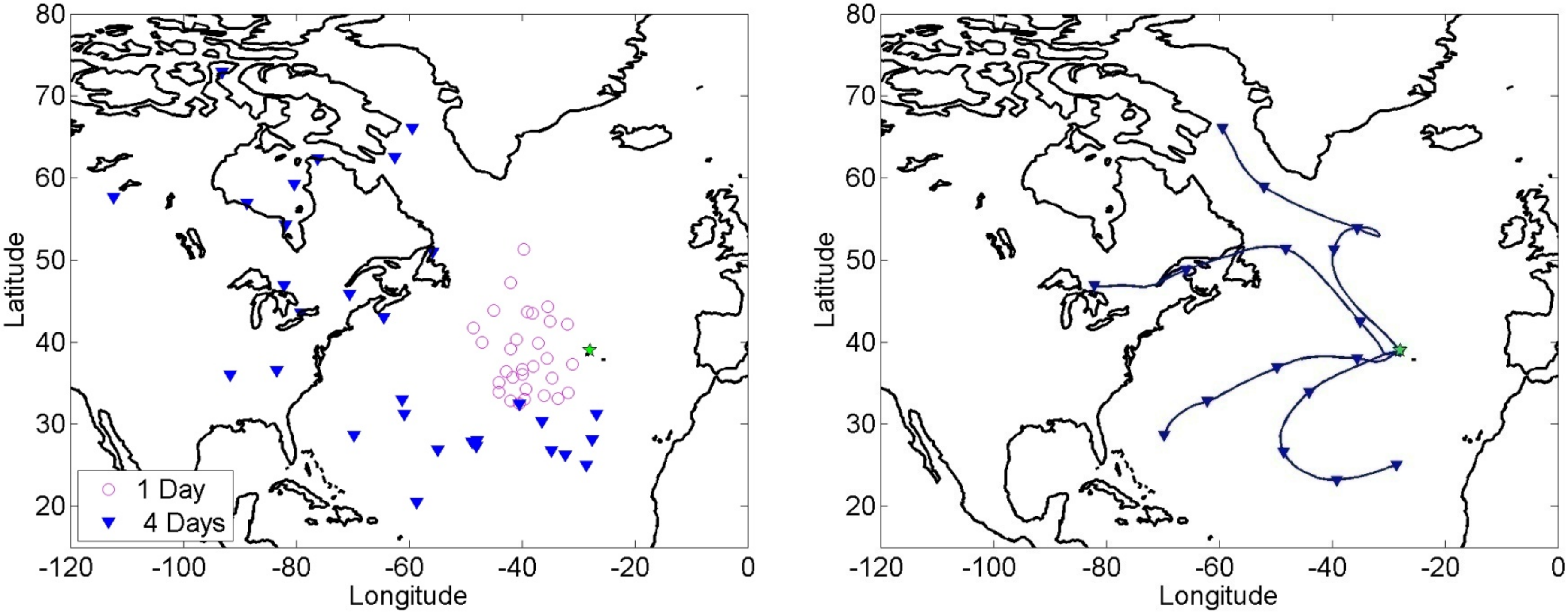
42N
40N
38N
36N
34N
32N
30N
40W
38W
36W
34W
32W
30W
28W
26W
24W
22W
20W
2.5
2.25
2
1.75
1.5
1.25
1
4
4.25
4.5
4.75
5
Jun to Aug: 1960 to 2005

NCEP July 2008 (500m) Back Trajectories

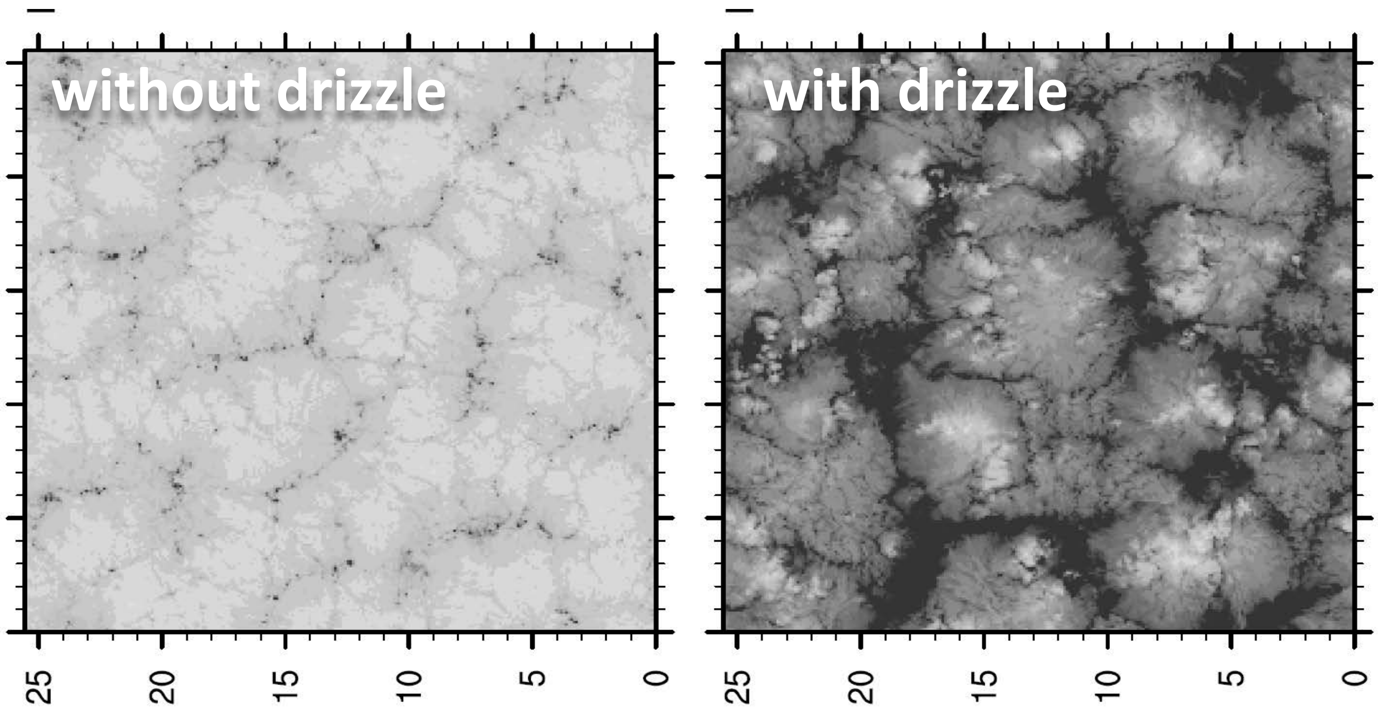


Bruce Albrecht

NCEP January 2009 (500m) Back Trajectories



Drizzle



Large eddy simulations by Savic-Jovcic and Stevens (2007)

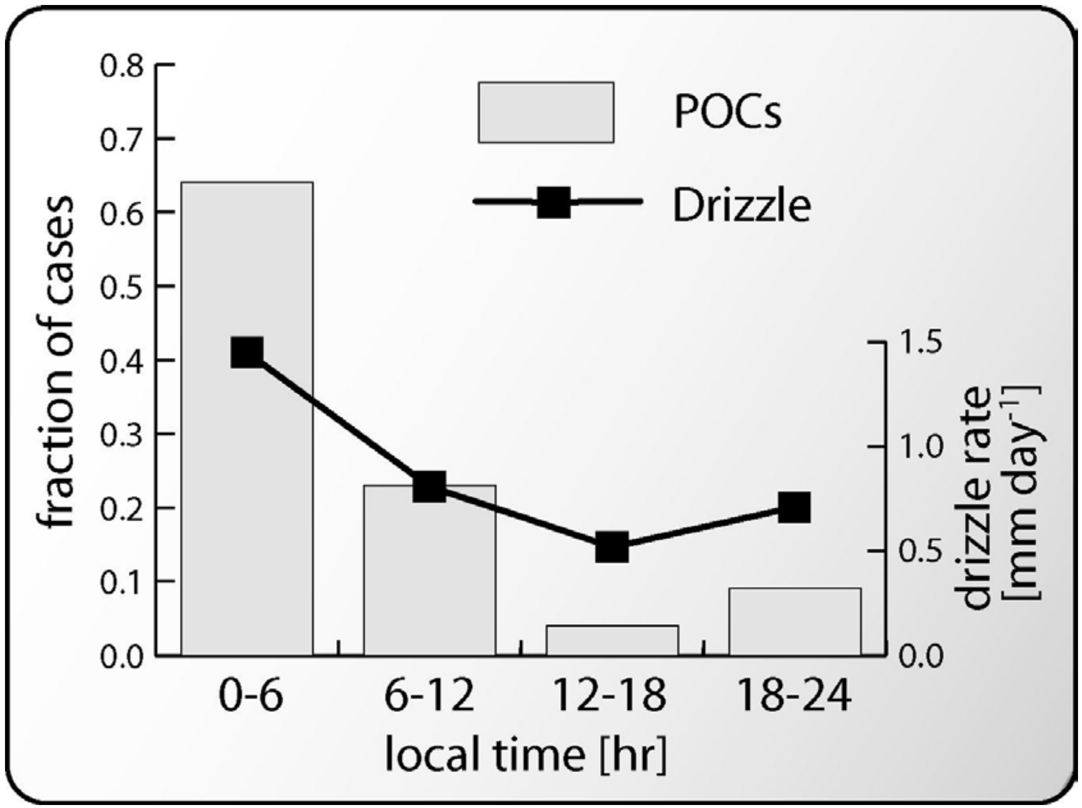
Table 2: Key additional instrumentation and observational datasets

Instrument [Provider]	*Important derived parameters*
Scanning X-band radar [Bruce Albrecht, University of Miami]	Light precipitation horizontal and vertical structure
High Resolution Doppler Lidar (HRDL) [NOAA ESRL]	(i) MBL winds below cloud base, (ii) Vertical turbulent wind estimates (iii) Vertical aerosol stratification/homgeneity
Ground-based chemistry [Hugh Coe, University of Manchester, UK]	(i) Aerosol size resolved chemistry (inorganic, organic) (ii) Aerosol hygroscopic growth
BAe-146 aircraft deployment [coordinator Hugh Coe, University of Manchester]	(i) Cloud and drizzle microphysical properties (ii) Turbulence and meteorology measurements (iii) Aerosol and gas phase chemistry suite, CCN, aerosol mass spectrometry

Table 1: Key instrumentation requirments for the AMF deployment

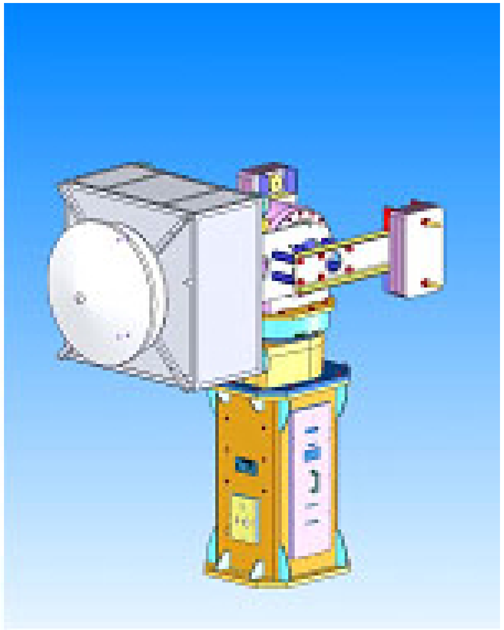
Instrument	*Important derived parameters*
94 GHz Profiling Radar	(i) Cloud and precipitation vertical structure (ii) Cloud top height (iii) Drizzle drop size distribution using both Doppler spectral measurements (Frisch et al. 1995) and with MPL below cloud base (O'Connor et al. 2005)
Micropulse Lidar (MPL)	(i) Cloud occurrence, (ii) Precipitation profiling below cloud base (with radar) (iii) Aerosol properties in MBL and above MBL (clear skies)
Microwave Radiometer (MWR)	(i) Cloud liquid water path (ii) Column water vapor path
MultiFilter Rotating Shadowband Radiometer (MFRSR) and Narrow Field of View Radiometer (NFOV)	(i) Cloud visible optical thickness. Will be used to infer cloud microphysical properties (droplet concentration, effective radius) in combination with MWR (ii) Aerosol optical properties in clear skies
Marine Atmospheric Emitted Radiance Interferometer (MAERI).	Cloud liquid water path estimates for thin clouds (combined with MWR, following Turner 2007)
Total Sky Imager (TSI)	Cloud coverage and type
Ceilometer (VCEIL)	(i) Cloud base height (ii) Cloud cover
Balloon-borne Sounding System (BBSS)	(i) Atmospheric profile structure (ii) MBL depth (iii) Inversion strength
Eddy Correlation Systems (ECOR)	Surface turbulent fluxes of latent and sensible heat
Surface Meteorological Instruments	Surface temperature, humidity, pressure, winds
Sky Radiometers	Downwelling shortwave and longwave radiative fluxes used to constrain the surface energy budget
Surface aerosol observing system	Aerosol physical properties (total concentration, scattering and absorption), CCN characteristics

Are observed transitions in cloud mesoscale structure (e.g. from closed cellular to open cellular convection) influenced by the formation of precipitation?



ARM Scanning Radar

Scanning W-band ARM Cloud Radar



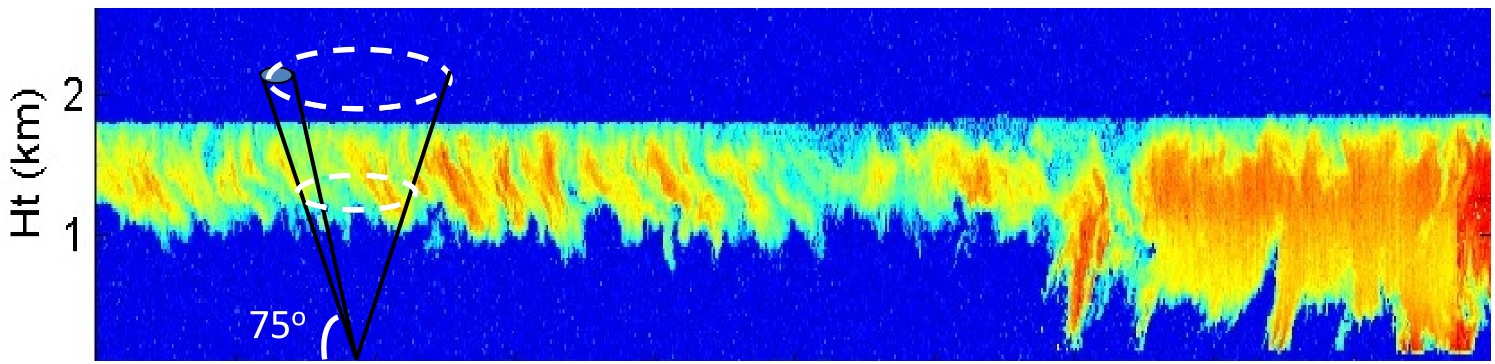
Same radar frequency as NASA's CloudSat

Capable of detecting all radiatively significant clouds in a radius of 5-10* km

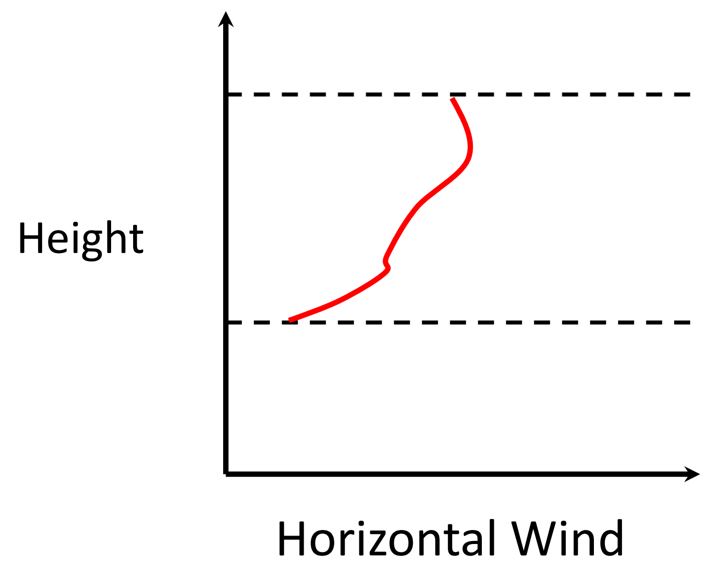
Scanning capabilities:

1. Horizon to Horizon (fixed azimuth)
2. 360° revolution (fixed elevation)
3. Sector scan (for cloud tracking)
4. Staring mode

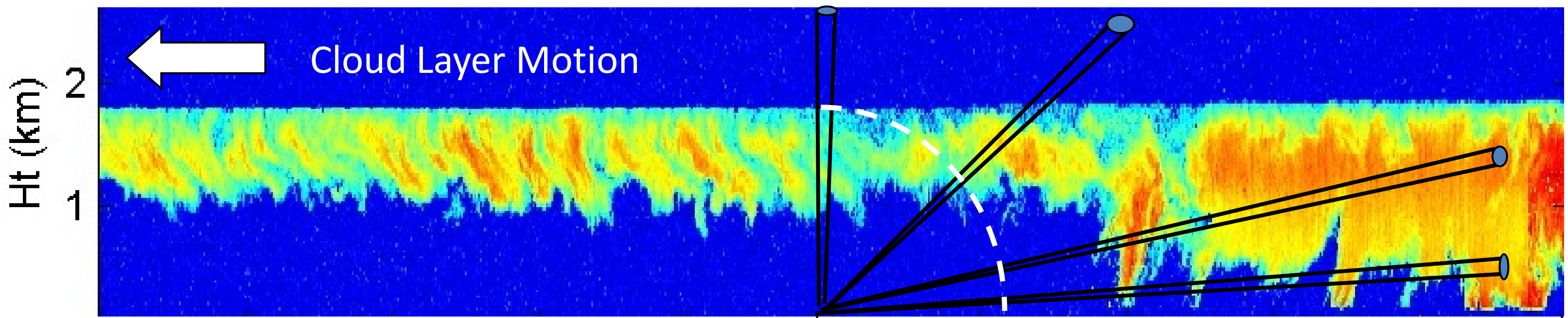
3D-Cloud Products
Case Study - Marine Stratocumulus



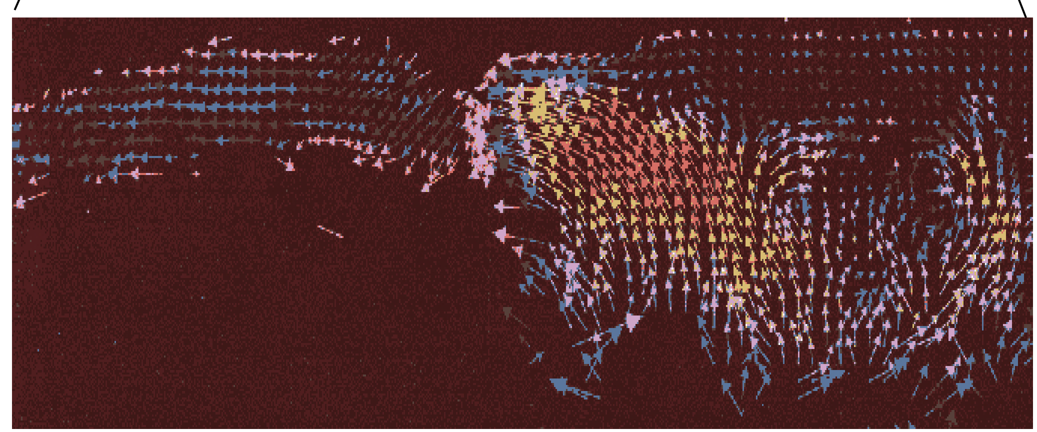
In-cloud horizontal wind
direction and magnitude



3D-Cloud Products
Case Study - Marine BL Clouds

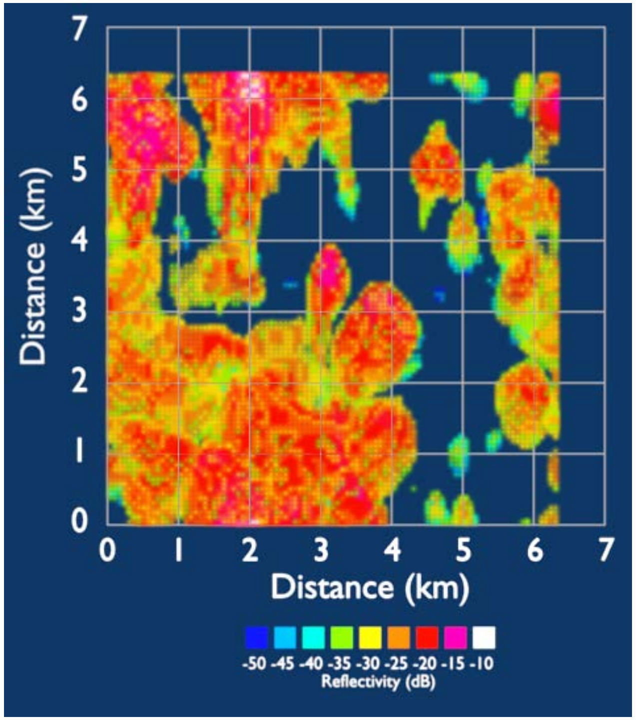


Scan into the direction the cloud layer comes from

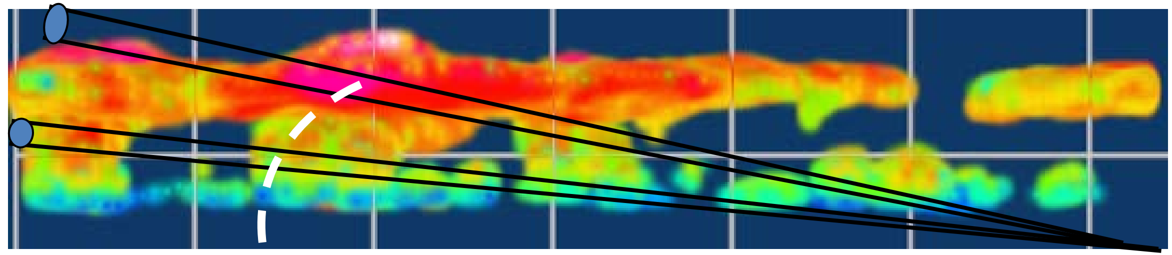


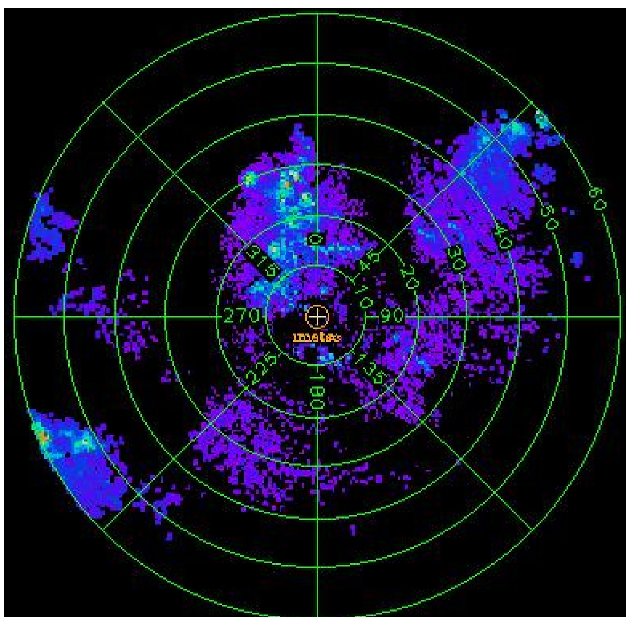
Follow the lifecycle of cloud elements

Retrieve the 2D kinematic structure of the cloud



3D-Cloud Products
Case Study - Marine BL clouds

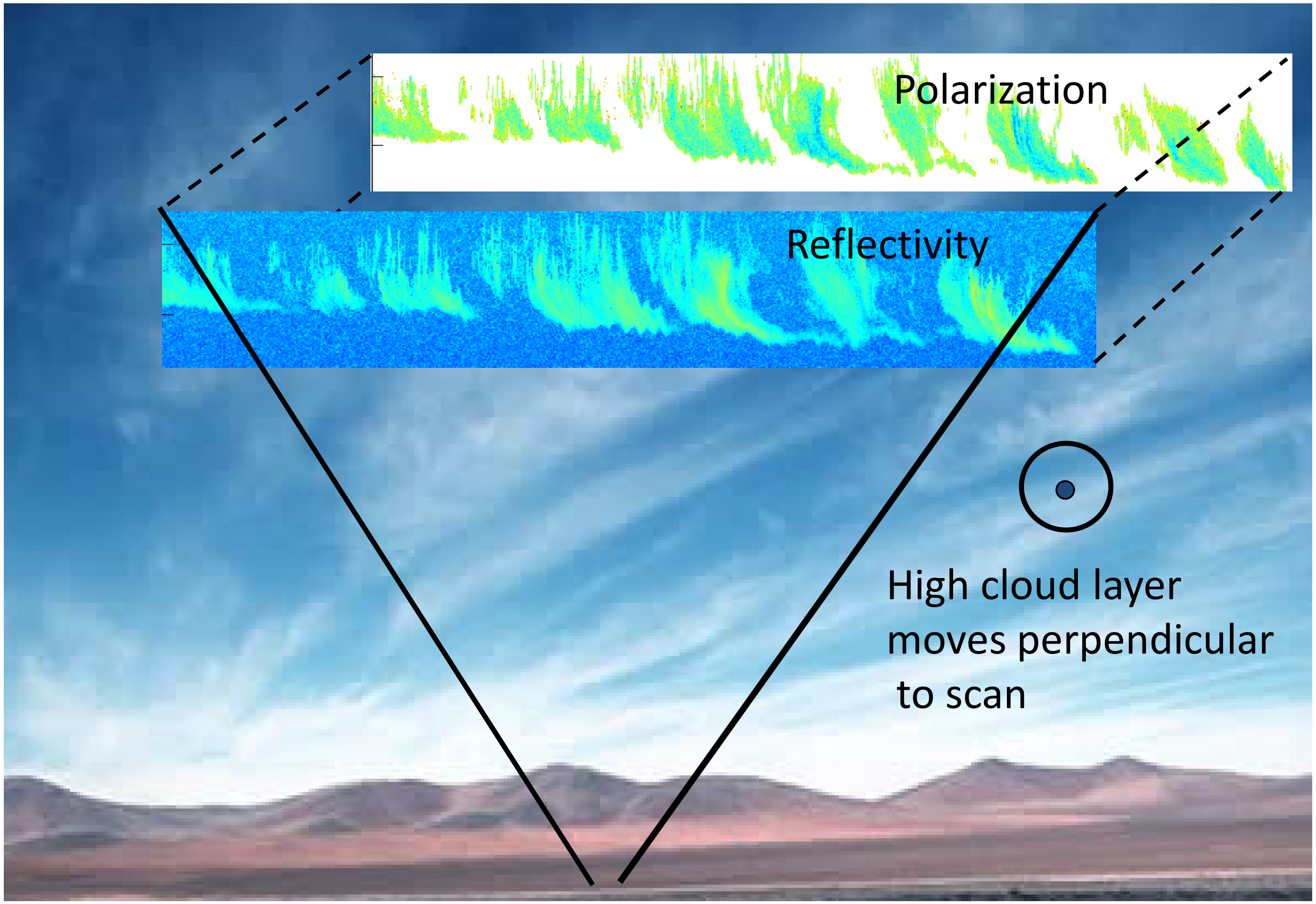




Low Elevation 360° revolution

Product: 3D cloud fraction

3D-Cloud Products
Case Study - Cirrus Clouds



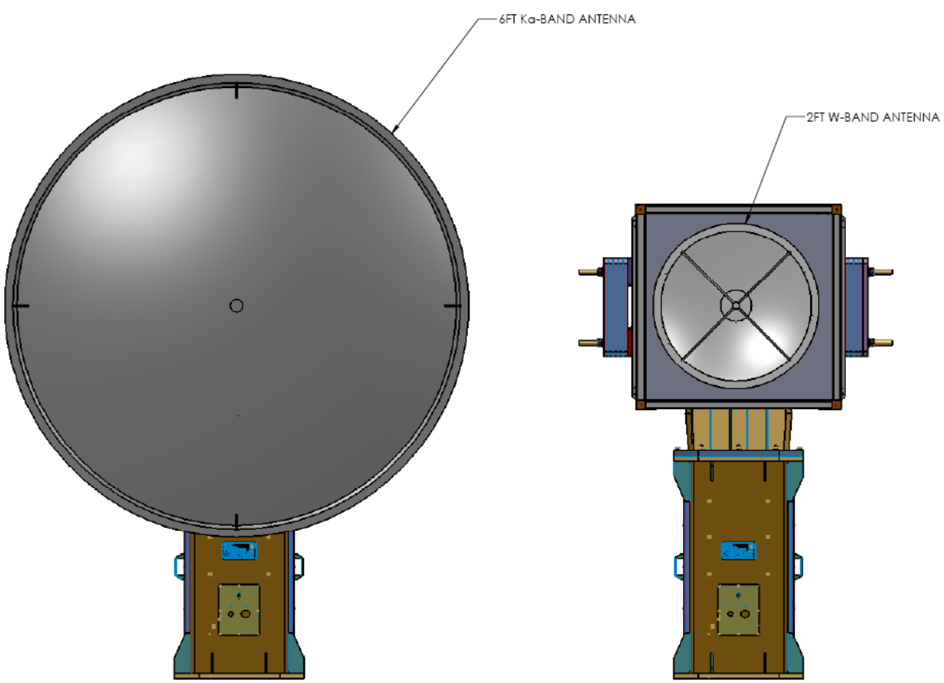
Particle size

Cloud Structure

Scanning Dual-Frequency Radar

- Scanning dual frequency, dual polarization millimeter-wave cloud radar (35/95 GHz)
- Auxiliary radiometer channels at 35 and 95 GHz
- Matched beamwidths
- Implementation will be similar to SWACR

- Two independent radars mounted on separate pedestals
- Allows re-use of SWACR
  - RF unit could be slightly modified to add radiometer channel
- Phase II SBIR funds sufficient to build Ka-band system



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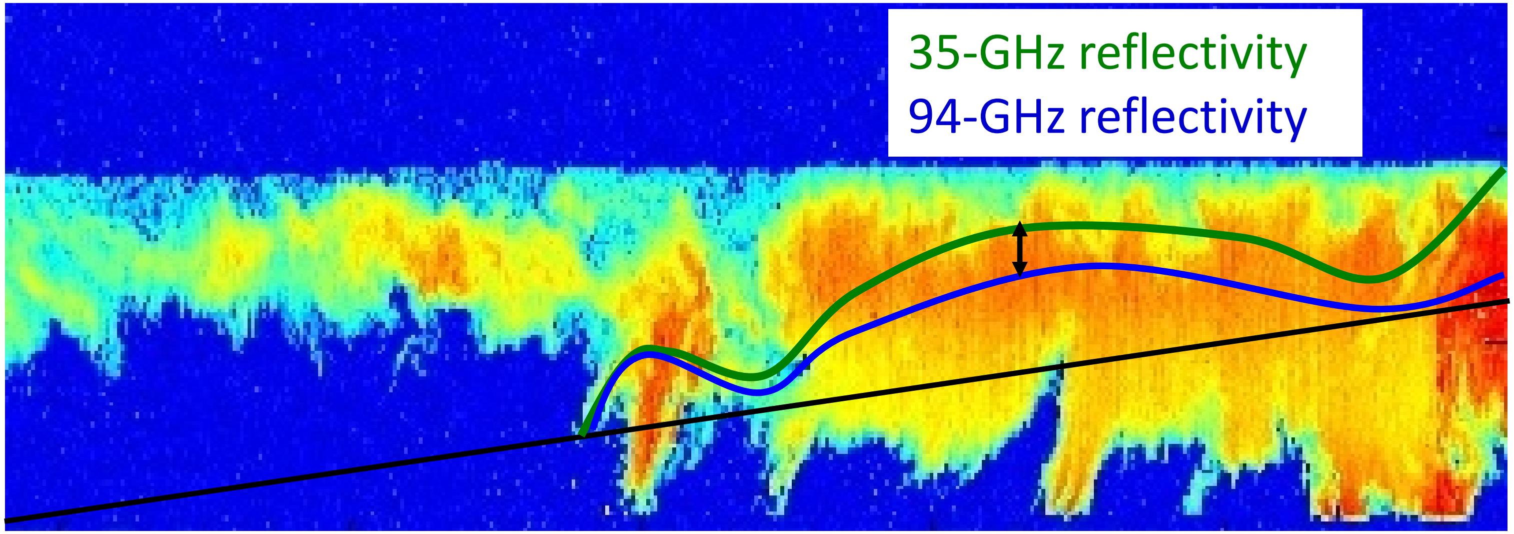

The second frequency extends the range of the system into drizzle and shallow precipitation.

The second frequency allow the retrieval of LWC and particle size using the differential reflectivity that is proportional to cloud LWC