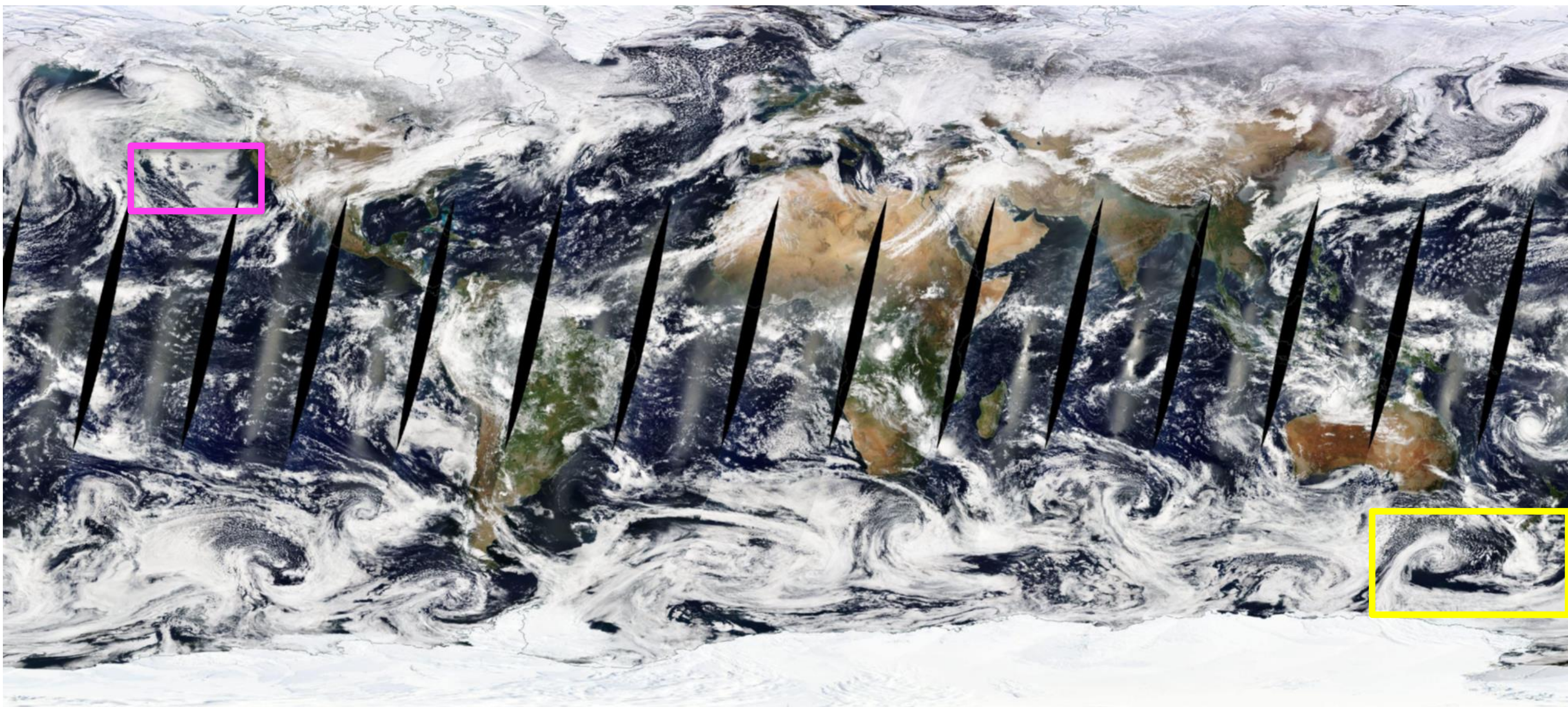
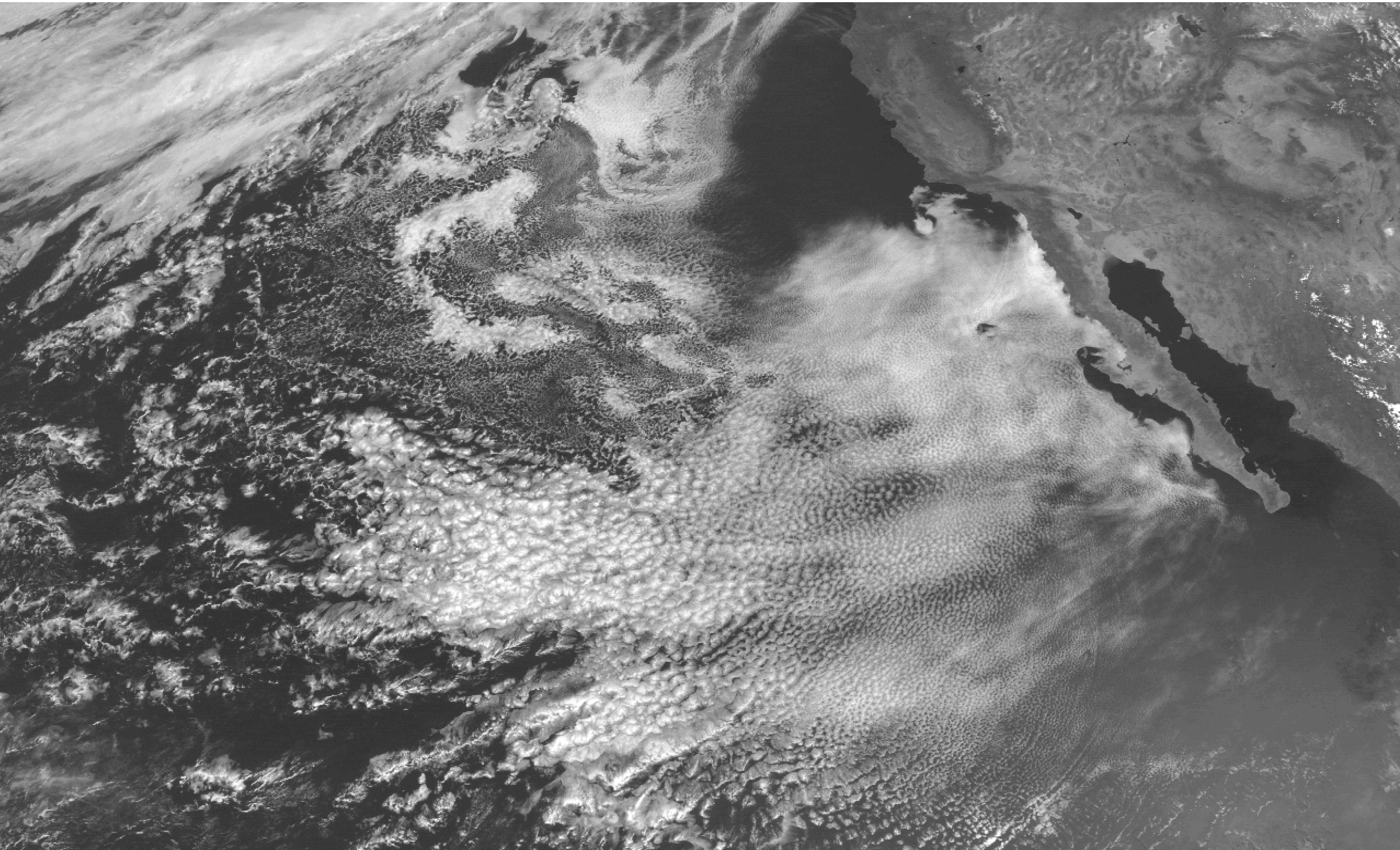
Cloudy boundary layers over the Northeast Pacific and Southern Ocean: Field observations, ERA5 and GCMs

Christopher S. Bretherton, Univ. of Washington

(plus many collaborators acknowledged during the talk)



- Clouds are a creature of weather that also are central to climate
- Fully exploiting this connection is the 21C way.



Forecast models and field studies: a synergy

- Field studies rely on forecast models and reanalyses
  - Mission planning
  - Data interpretation/context; trajectories
  - Ancillary information for process modeling
- Field studies can improve forecast models
  - Often motivated by global model biases
  - Unique measurements with specific scientific goals
  - Diversifies the community looking at forecast products
- Representativeness issues
  - How to make the most of localized measurements?

Southern Ocean (SO) and Northeast Pacific (NEP) field studies

Science motivations

- In-situ documentation of Sc and Cu in the subtropical transitions and midlatitude cold-sector clouds, both causes of GCM biases
- Role of mesoscale organization of MBL clouds
- Aerosol-cloud interactions in these regimes and RF_{aci}
- Liquid/ice partitioning in SO marine boundary layer clouds

Both field campaigns were designed to take advantage of and to complement the rich context of modern global weather forecast models, and to inform climate and weather model improvement.

Nudged-hindcast climate model testing

Strategy for testing/improving cloud/aerosol/PBL processes in a GCM

- GCM is run with its customary resolution, but as a ‘forecast’ model
- Relax GCM 3D u, v, T fields to time-varying interpolated reanalysis (GCM humidity, clouds, aerosols are freely evolving)
- Sample GCM output at lat/lon/times of field observations

Shown: NCAR CAM6: 1°x1° L32, MG2+MAM3, 24 hr nudging to MERRA-2

In process: ERA-5 nudged hindcasts with CAM6 and AM4 for SO studies.

Partners: A. Gettelman (NCAR), Y. Ming (GFDL)

ECMWF role

IFS/ERA5 are the state-of-the-art global model and reanalysis.

- How good are they in remote marine cloudy boundary layers?
- Does ERA5 get details of clouds and precipitation right?
- Is a hindcast nudged to ERA5 meteorology a good test of a climate model?
- How can field observations make models like IFS even better?

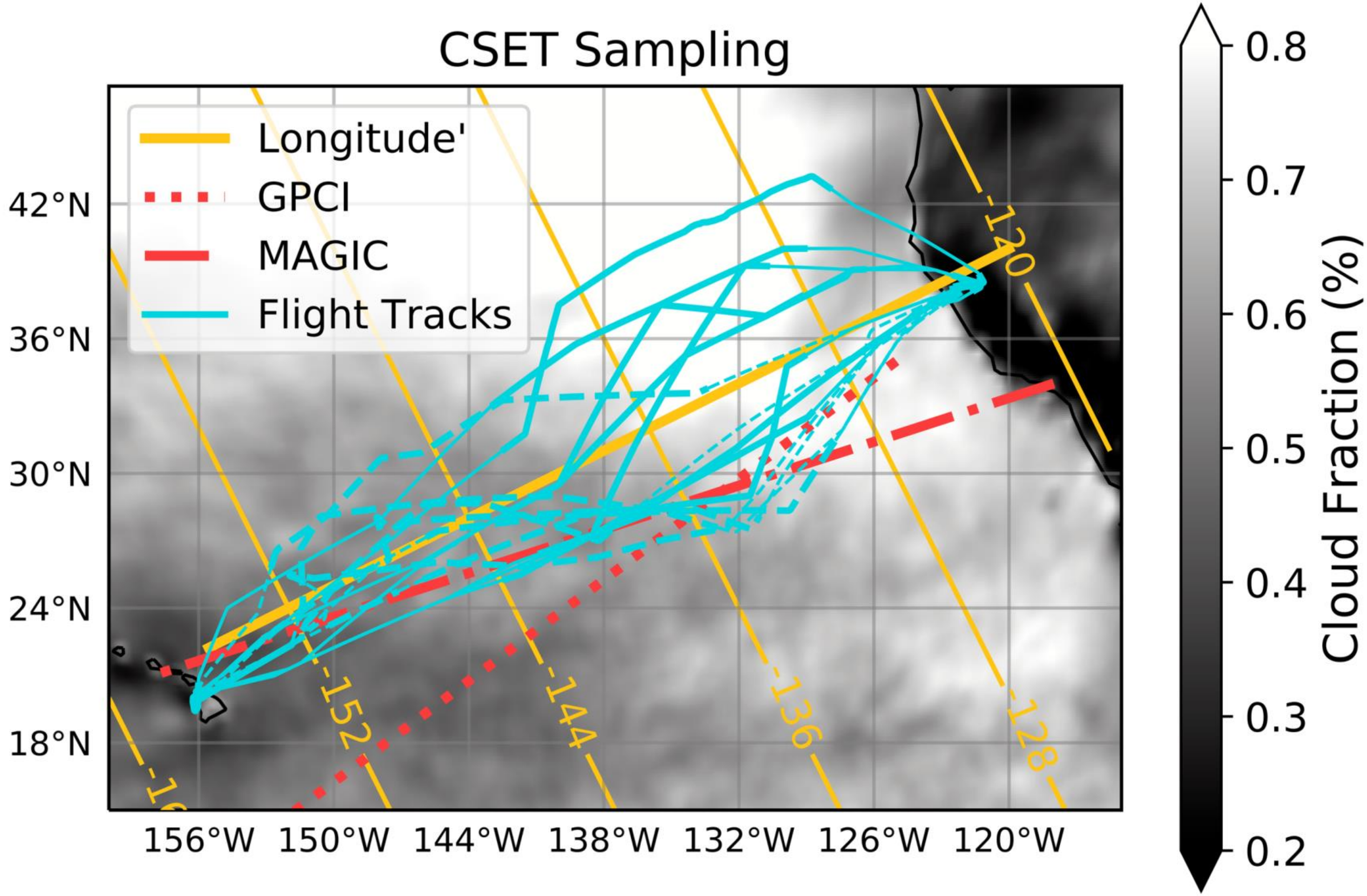
Cloud System Evolution in the Trades
(CSET, Jul 1-Aug 15 2015)

Bruce Albrecht and Paquita Zuidema, U. Miami
Virendra Ghate, Argonne Natl. Labs
Chris Bretherton, Rob Wood, Hans Mohrmann, U. Washington
NCAR RAF CSET team

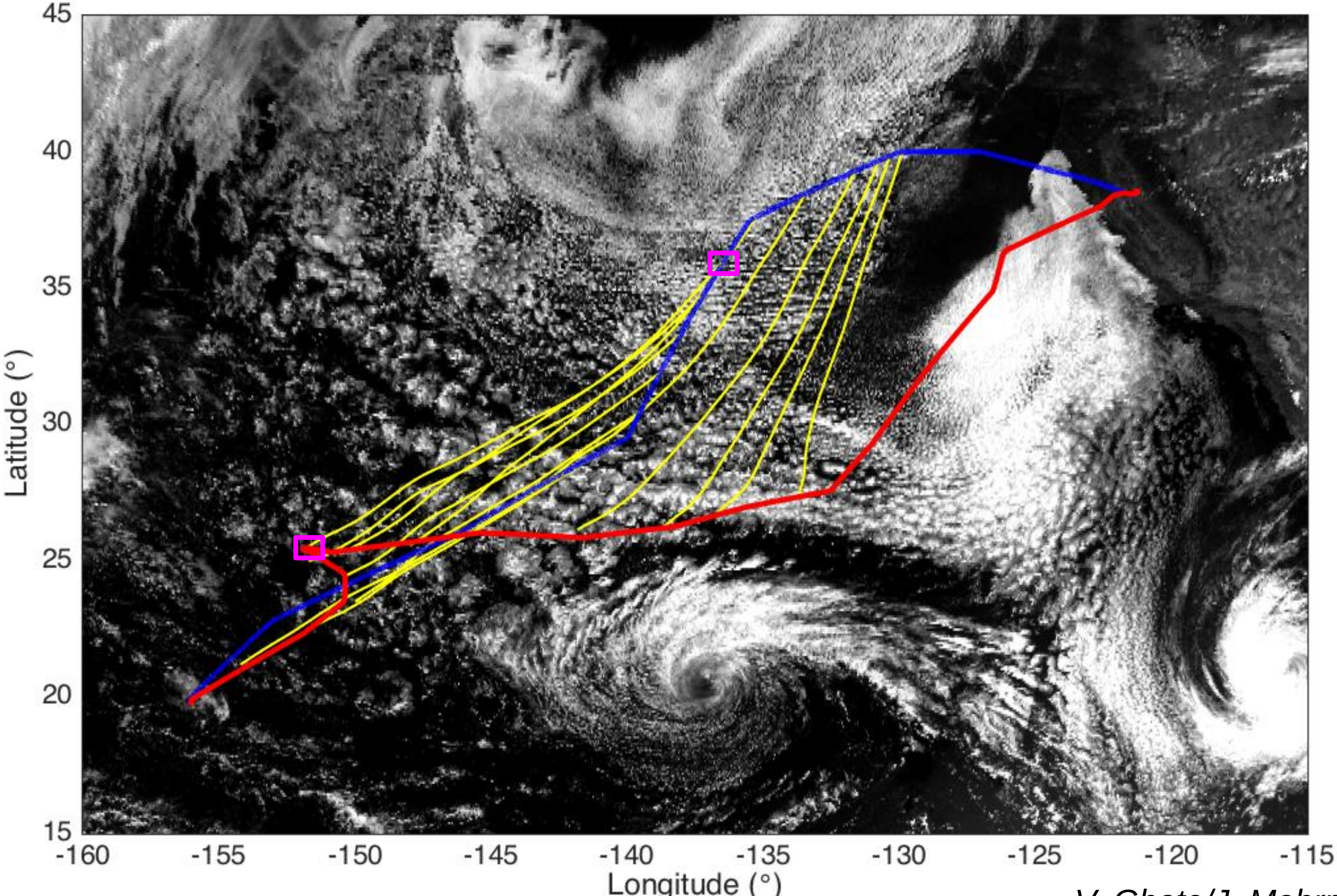
Albrecht et al. (2018, *BAMS*)

Wood et al. (2018); O et al. (2018)

Bretherton et al. (2019, MWR); Mohrmann et al. (2019, MWR)

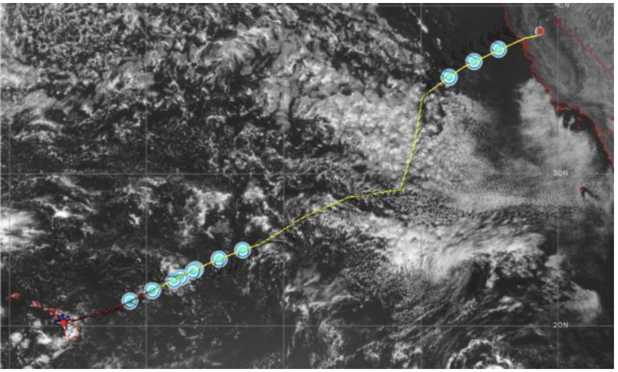

CSET Sampling
Longitude'
GPCI
MAGIC
Flight Tracks
42°N
36°N
30°N
24°N
18°N
156°W
150°W
144°W
138°W
132°W
126°W
120°W
-152
-144
-136
-128
-120
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Cloud Fraction (%)

CSET RF06-07 950 hPa
2 day GFS trajectories



V. Ghate/J. Mohrmann

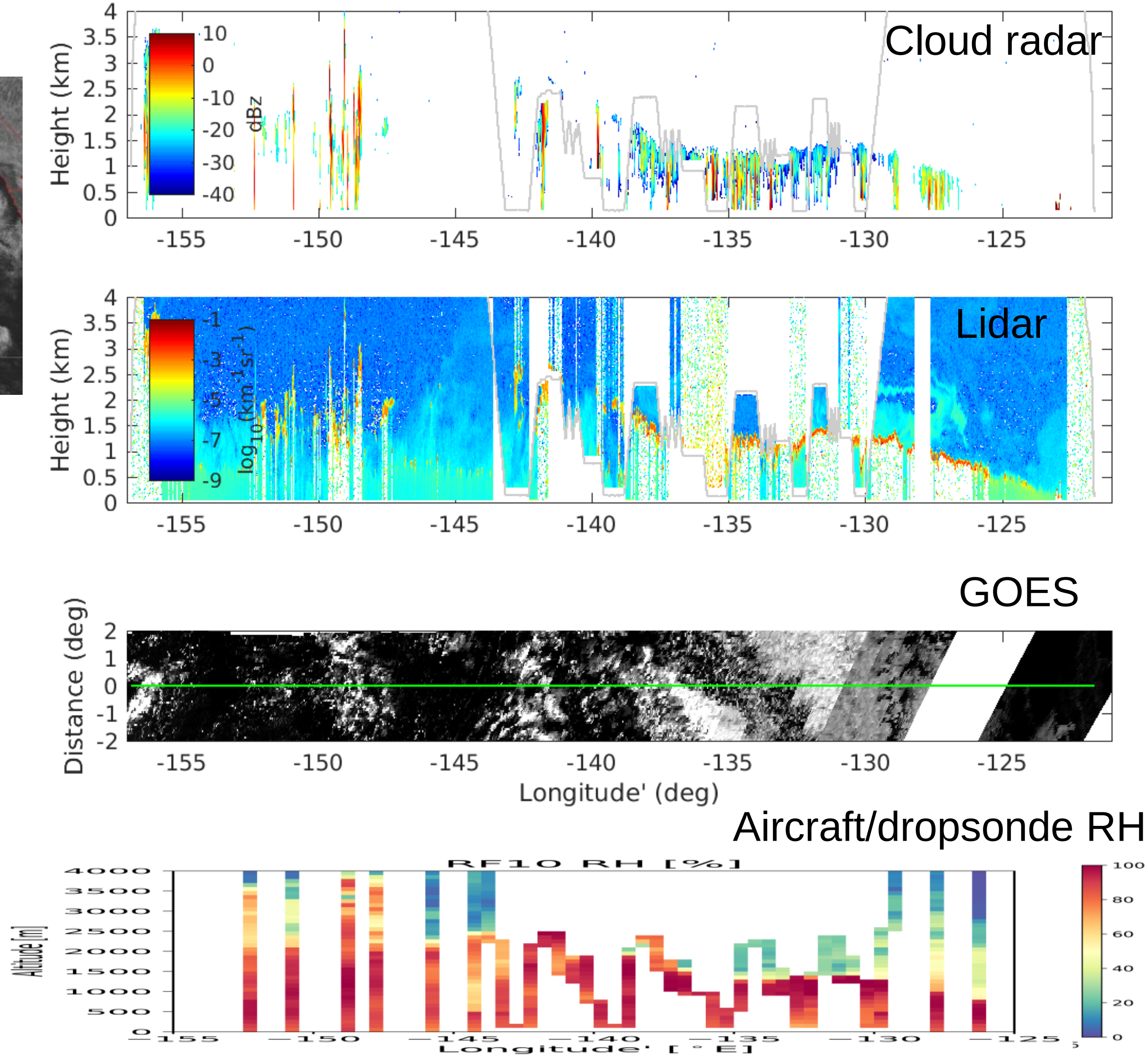
CSET RF10



Multiscale variability

On the NCAR G-V:

- Cloud radar
- Lidar
- Dropsondes
- In-situ meteorology
- Cloud probes
- Aerosol sizing
- Ozone, CO
- Turbulence

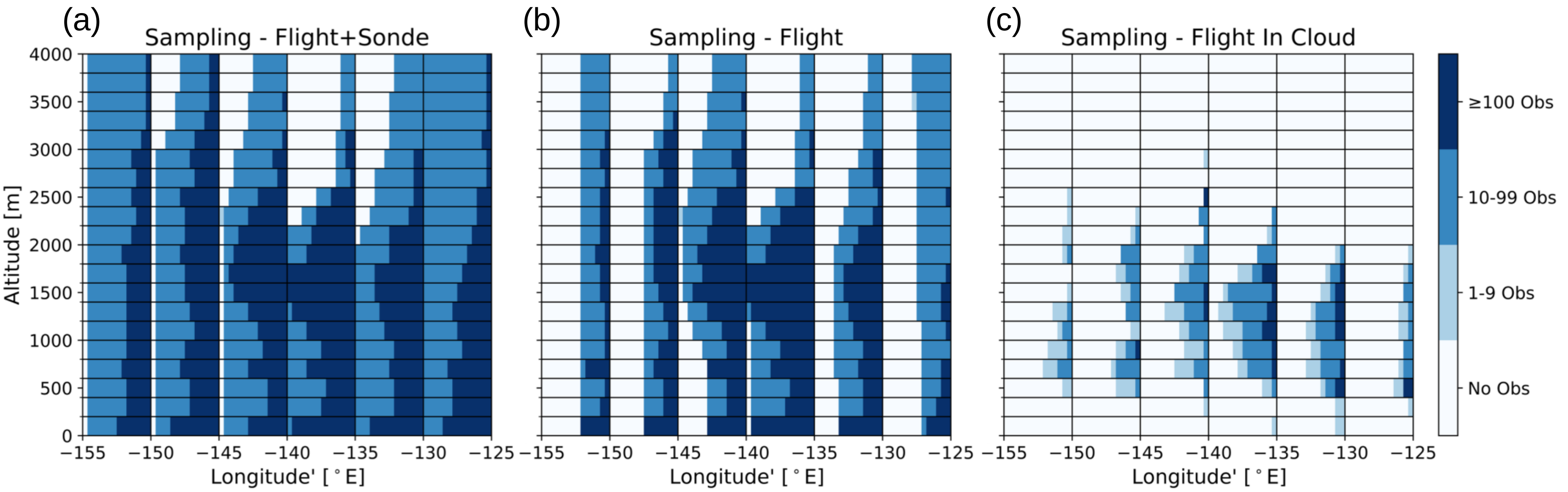


Representativeness issues and binning

Sparse sampling is a challenge

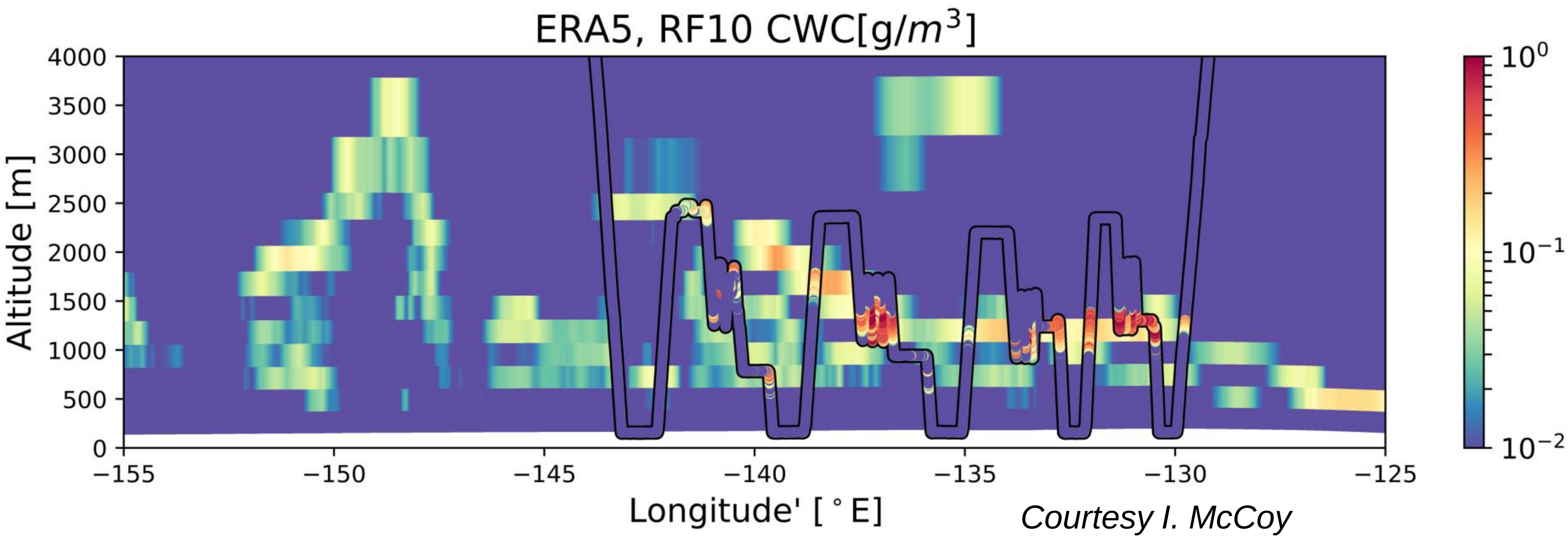
To compare complex CSET flights with models use:

- direct comparison along flight tracks (if not too noisy)
- 200 m x 5º longitude binning for a poor-man's climatology

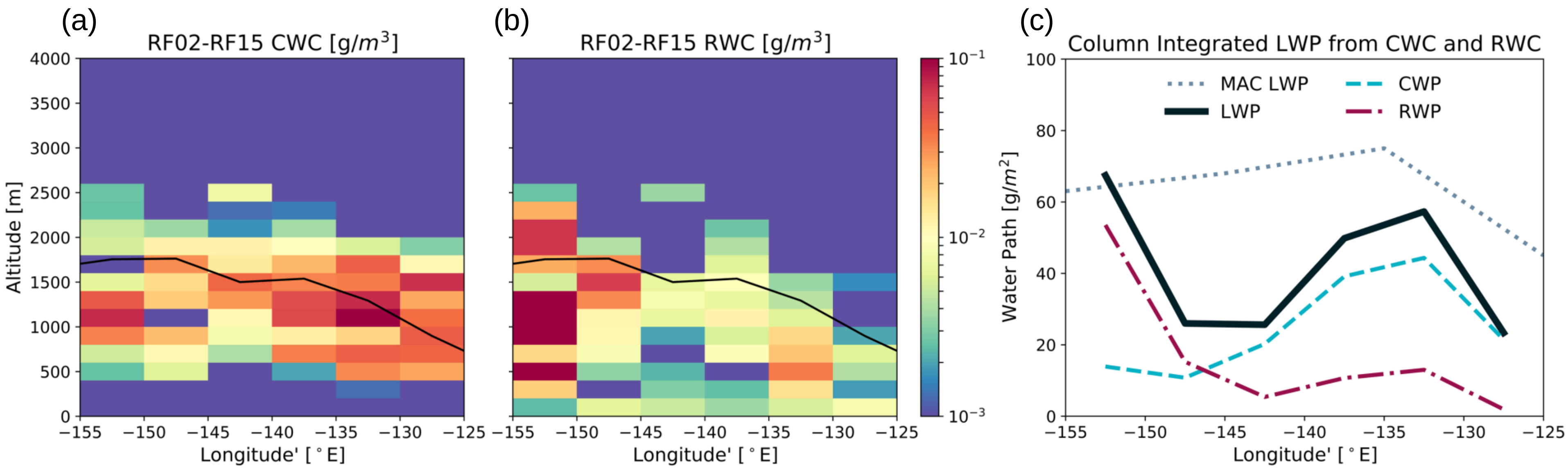


Bretherton et al. 2019

Liquid water content

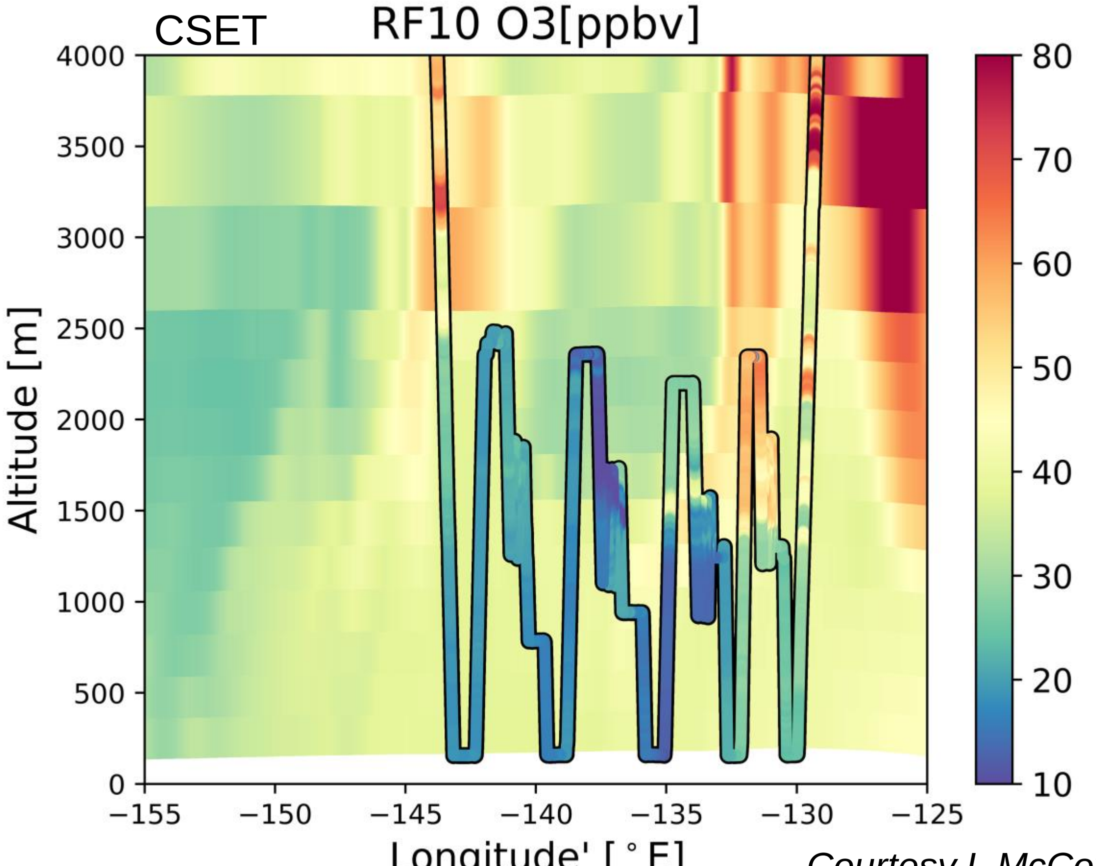


Courtesy I. McCoy



Bretherton et al. 2019

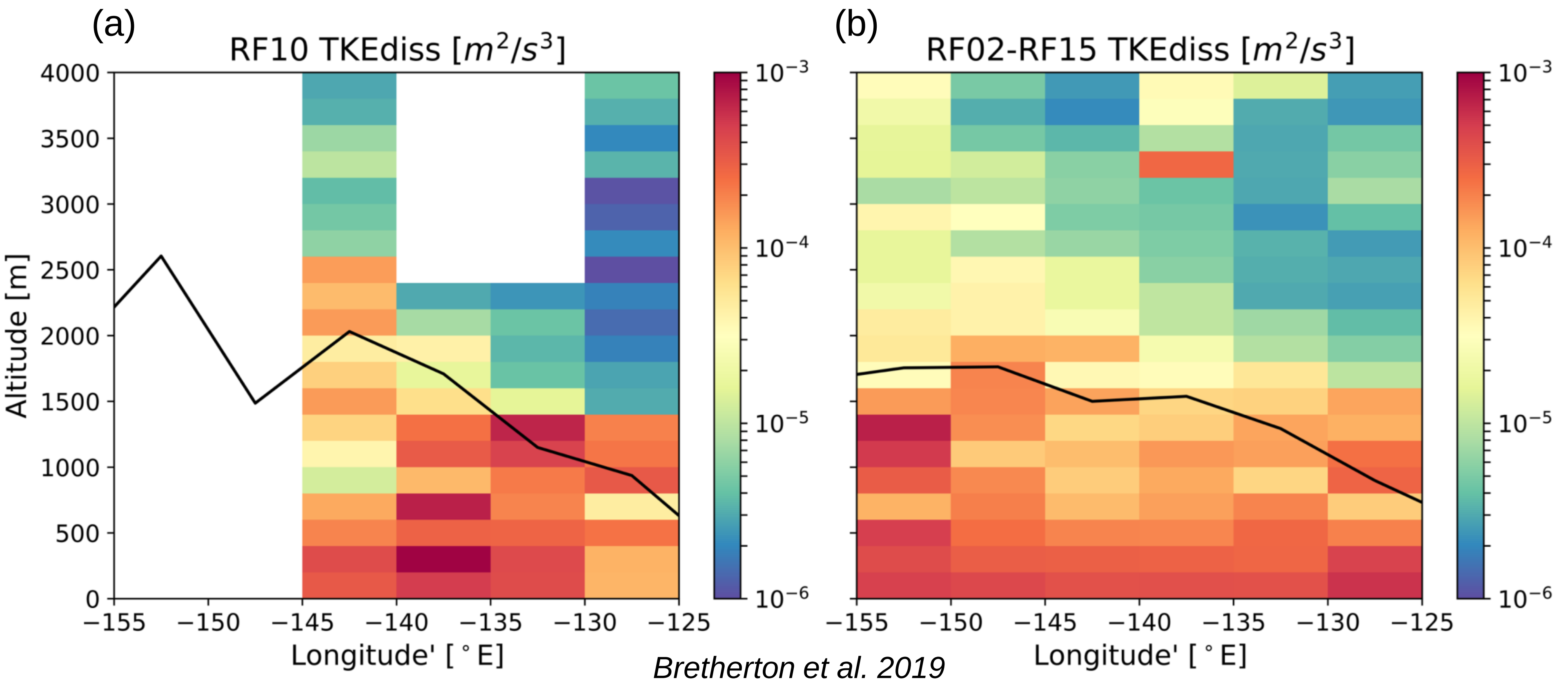
ERA5



Courtesy I. McCoy

ERA5 ozone good above PBL, too high in the PBL

Turbulence (TKE dissipation rate)

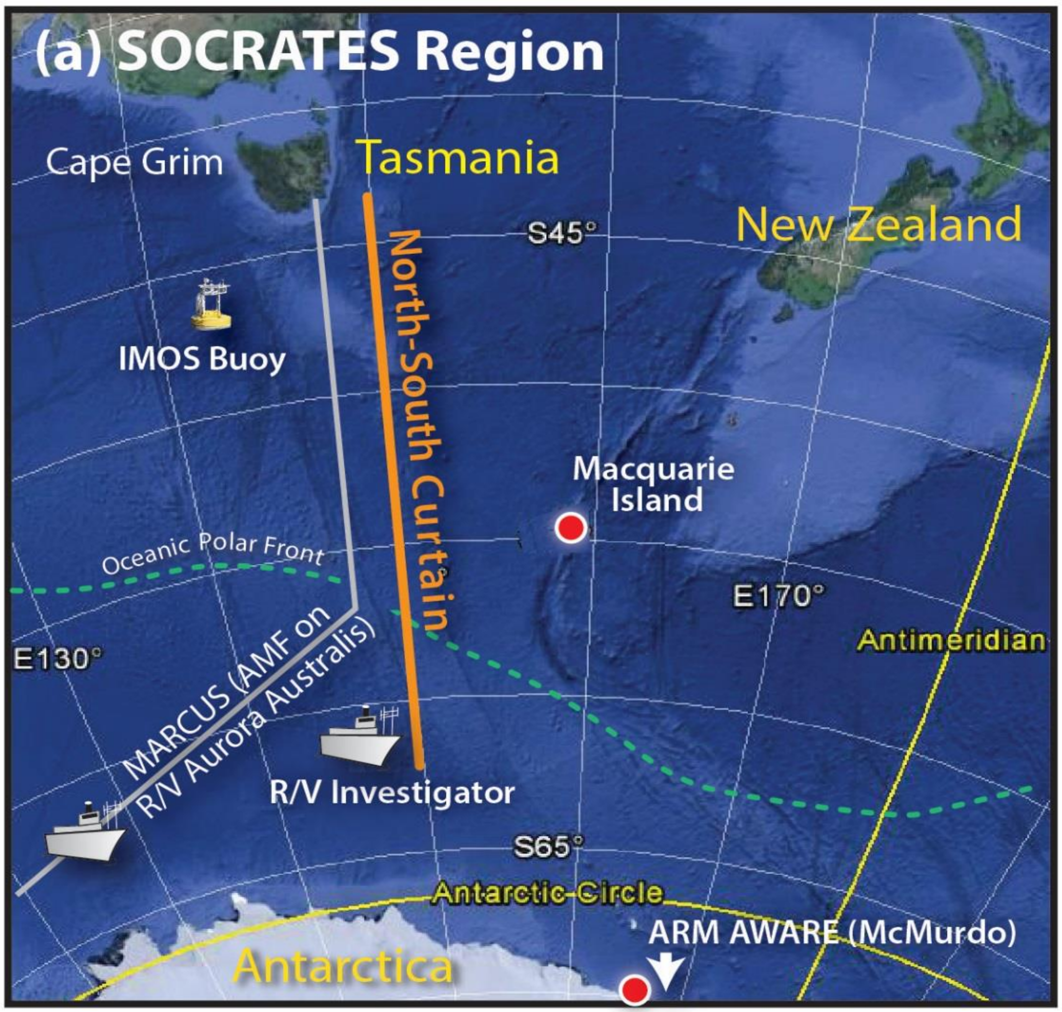


Bretherton et al. 2019

Another measurement with substantial small-scale variability

Southern Ocean Atmosphere Research (SOAR) 2016-2018

G. McFarquhar, U. Illinois
C. Bretherton, R. Wood & R. Marchand, U. Washington
A. Protat, Australian BoM
S. Alexander, AAD
… **and SOAR Science Teams**



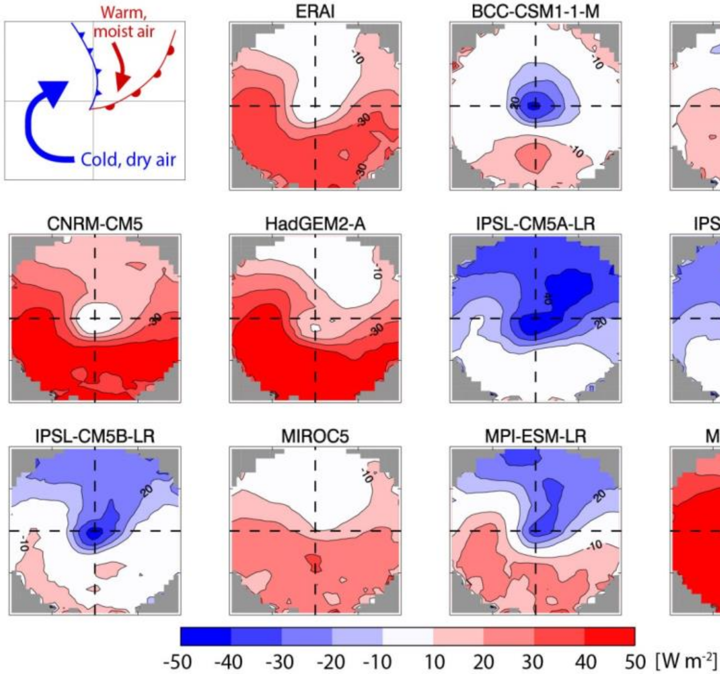
SOCRATES (Jan 15-Feb 26 2018):
NSF G-V deployment
CAPRICORN (2016-2018):
Australian R/V Investigator
MICRE (2017-2018):
Macquarie Island (DOE, AUS)
MARCUS (2017-2018):
AMF-2 on Aurora Australis:

Complementary space/time sampling:
All: mm radar, lidar, sondes, met, aerosols + specialized

Other recent SO/Antarctic campaigns have gathered data in other regions: ORCAS & ARM-AWARE (2016), ACE (2017)

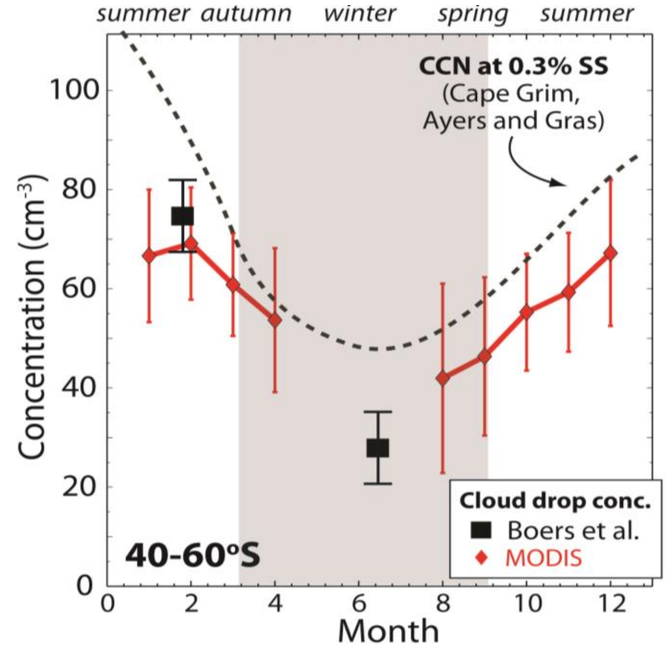
The SOAR campaigns…complementary sampling strategies

Southern Ocean clouds are interesting and challenging to model



Cyclone compositing indicates consistent patterns of insufficient reflected shortwave in the cold, dry regions of the cyclones (Williams et al. 2013)

Courtesy R. Wood



Large seasonal cycles of cloud droplet and CCN concentrations exist over the SO. *Biogenic sources are believed responsible, but much unknown about aerosol composition and the underlying physical processes, especially at more southerly latitudes.*

Cold sector mixed-phase boundary-layer clouds are particularly problematic for models

In SO ocean summer, biogenic gas/particle sources seem microphysically important

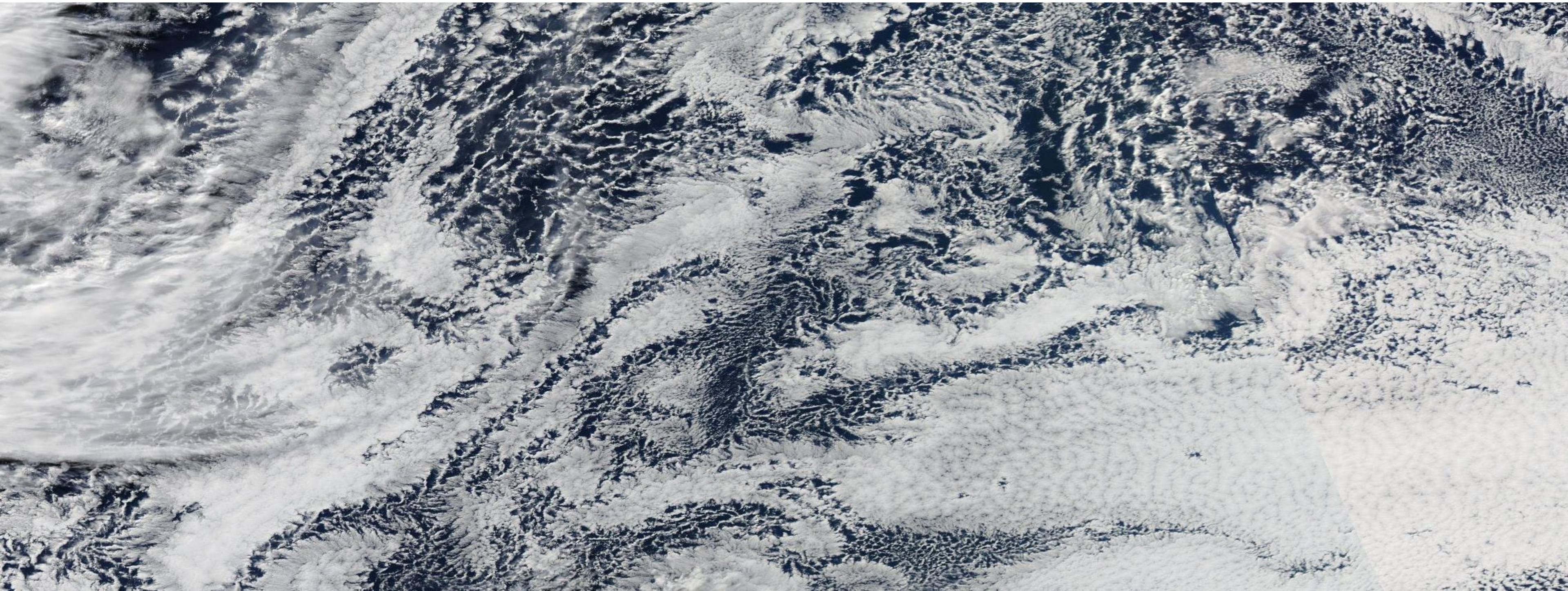
SOAR Themes

Theme 1: Documenting the **synoptically-varying vertical structure** of Southern Ocean boundary layers and clouds

Theme 2: Variability of **sources and sinks of SO CCN and INPs** and seasonally-varying role of local biogenic sources.

Theme 3: Supercooled liquid clouds over the SO

Theme 4: Retrieving the properties of mixed-phase clouds



CAPRICORN: Clouds, Aerosols, Precipitation, Radiation, and atmospherIc Composition Over the southeRn ocean

Lead PI: Alain Protat

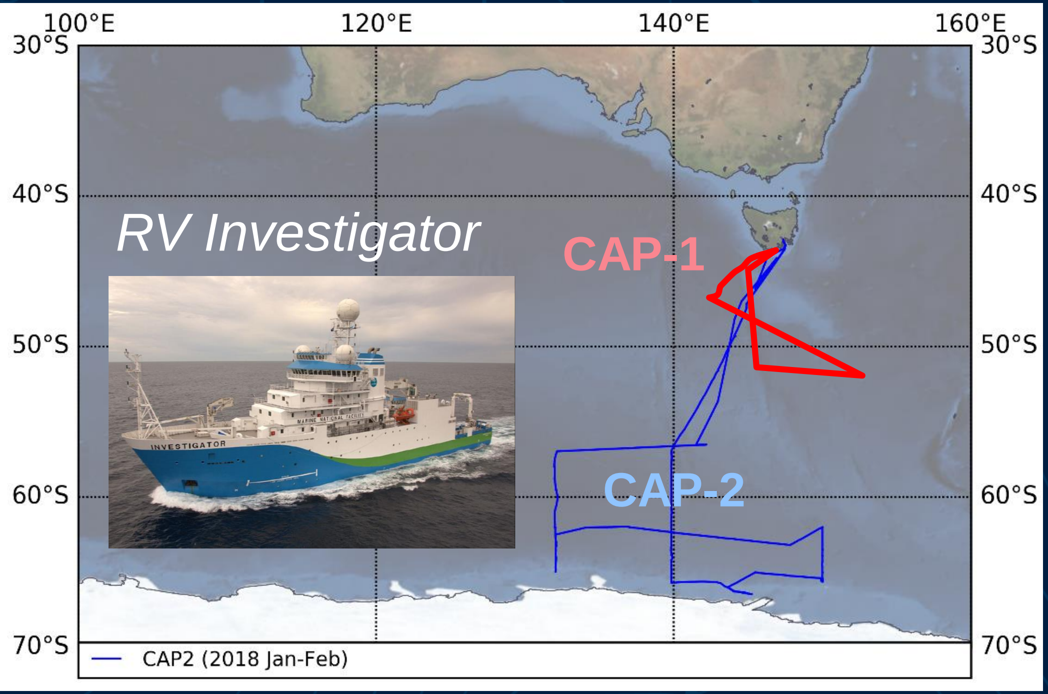
- **2016 (March – April, 35 days): CAP-1**
- **2018 (Jan – Feb, 45 days): CAP-2** Coordinated with **SOCRATES** flights.

CAPRICORN goals:

- MBL-cloud-aerosol-precip vs. latitude and weather
- A-Train and Himiwari evaluation
- ACCESS model, mixed-phase cld

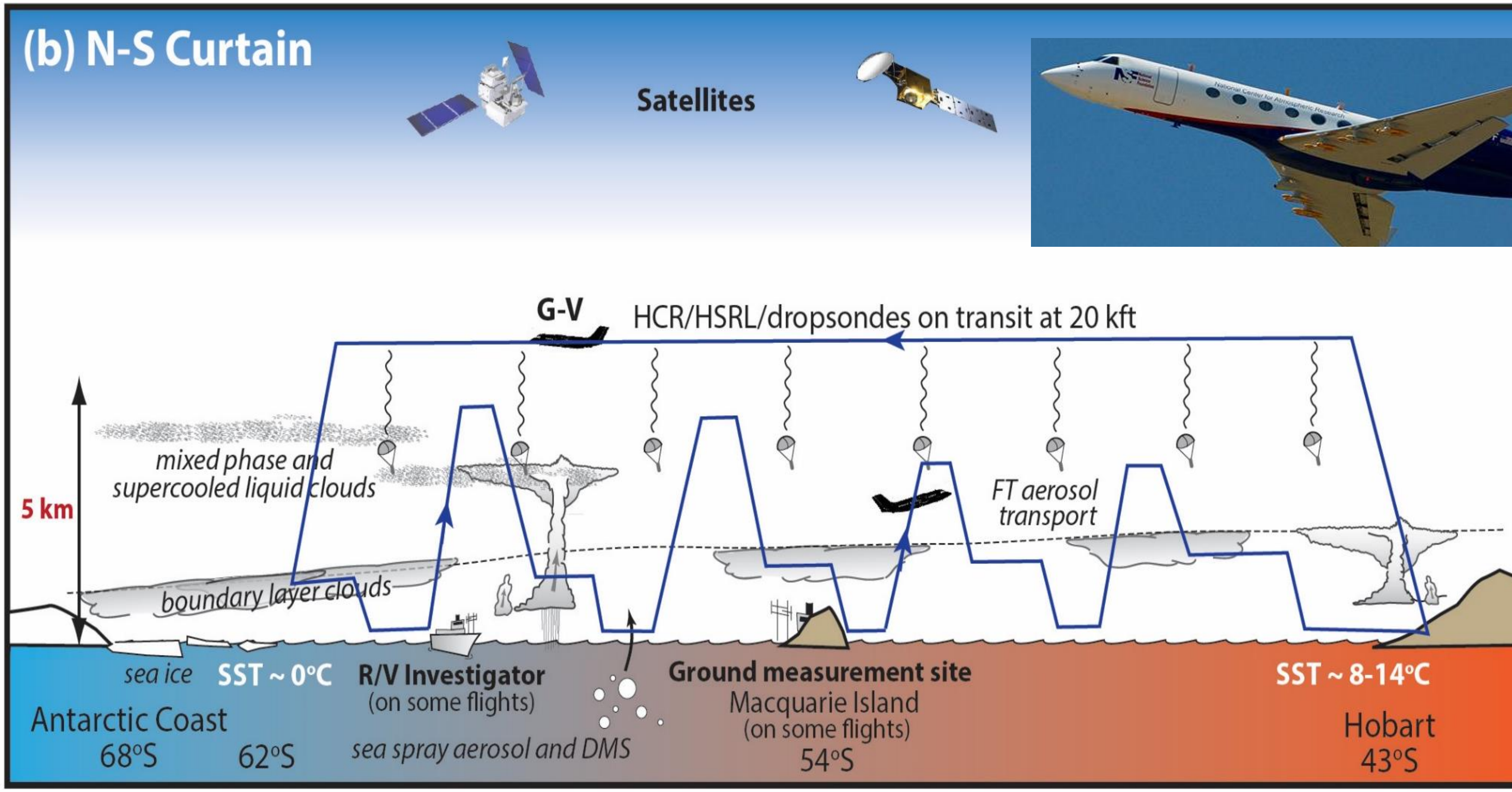
Key CAPRICORN Measurements:

Cloud radar-Polarized lidar (Protat)
Microwave Radiometer (Mace)
Disdrometer (Klepp/Protat)
In-situ aerosol/sulfur chemistry (Moore)
IFN (DeMott)
Trace gases (CAP-1, Humphries)
Ocean water (CAP-1, Strutton)
Wind profiler (CAP-2, NCAR)
Sondes (BOM/NCAR)



SOCRATES: Southern Ocean Clouds Radiation Aerosol Transport Experimental Study

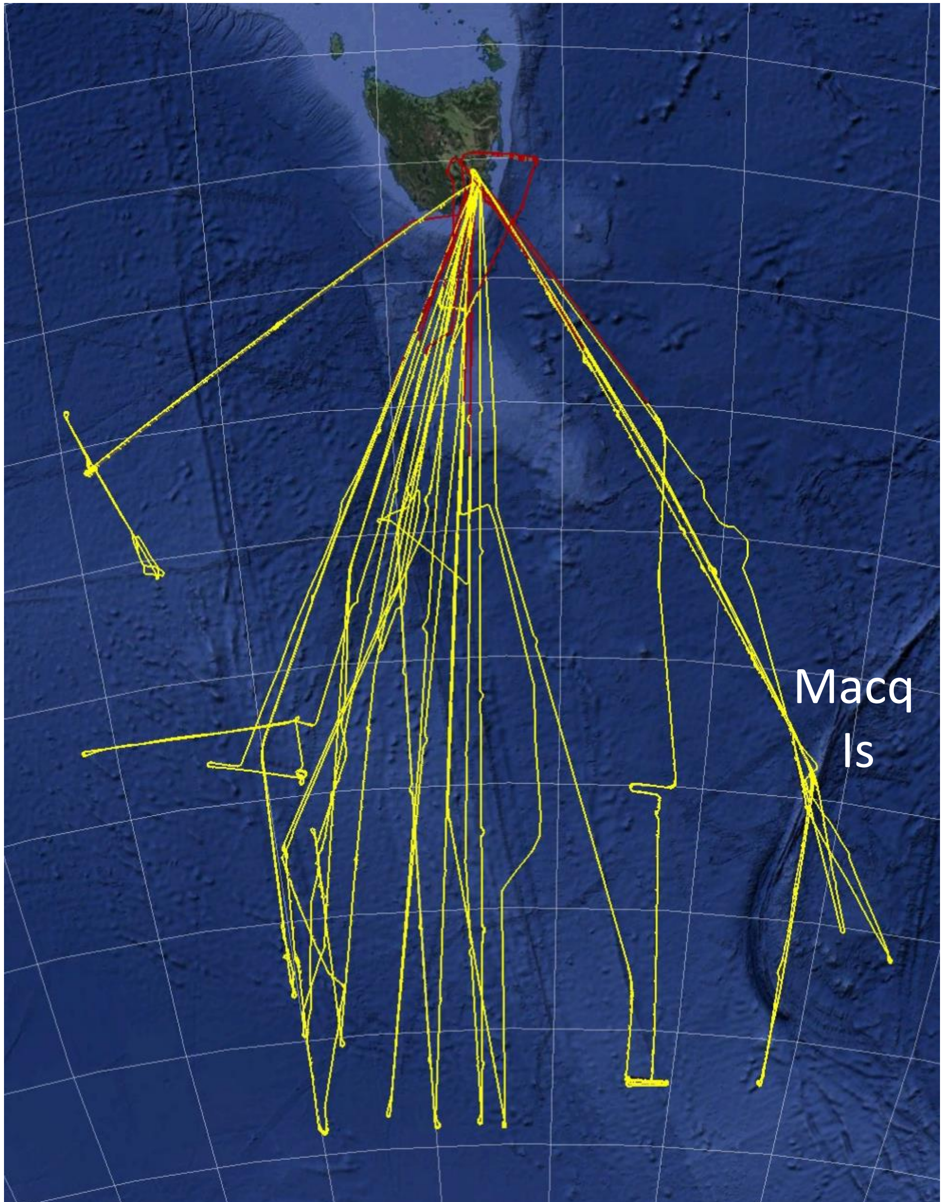
Lead PIs: Greg McFarquhar and Chris Bretherton



G-V Goal:

- ***Characterize SO clouds, radiation, aerosols, and precipitation using both cloud remote sensing and in-situ instrumentation on both NSF/NCAR G-V and R/V Investigator***

SOCRATES flights (Jan-Feb 2018)

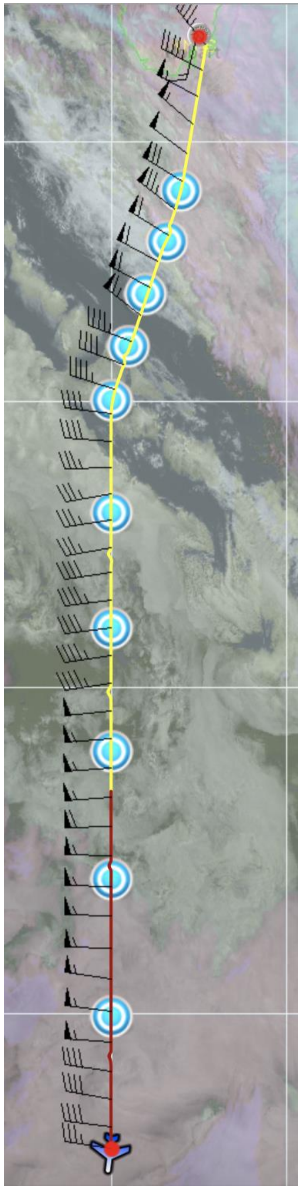


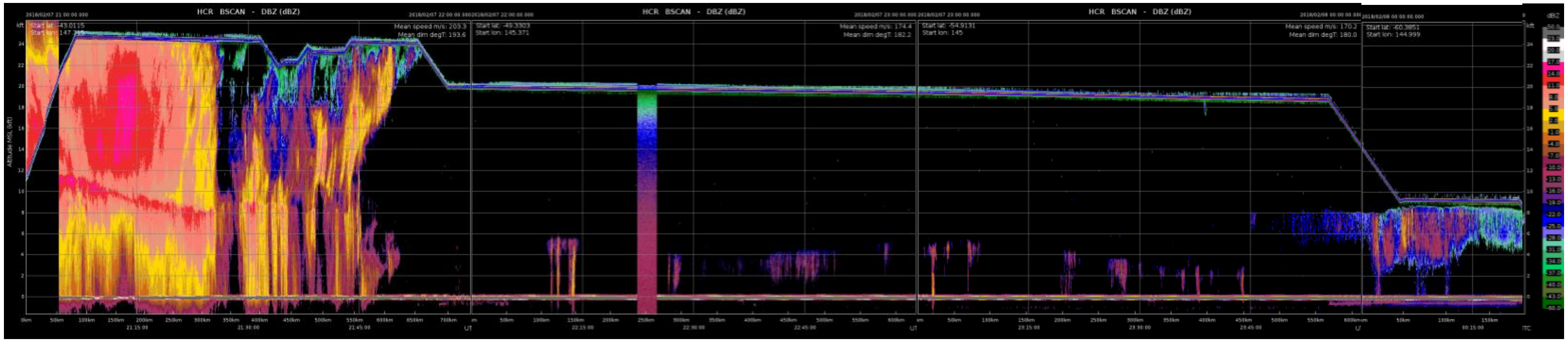
- Cloud probes
- Aerosol/CCN/IFN
- W-band Doppler radar, lidar
- Dropsondes
- Turbulence

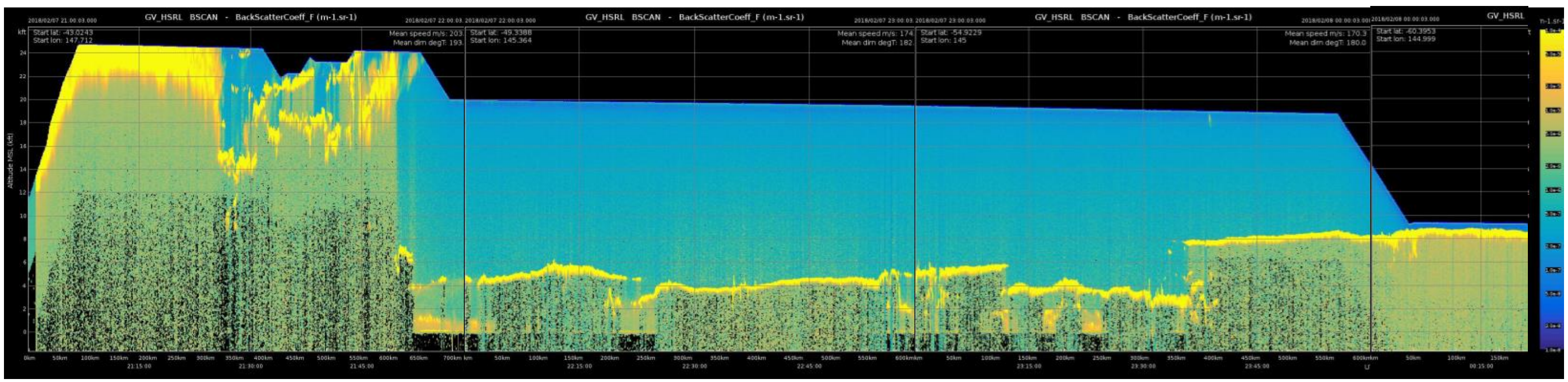
Investigator overflights

Macquarie Island overflights

A typical SOCRATES flight: RF10   8 Feb 2018

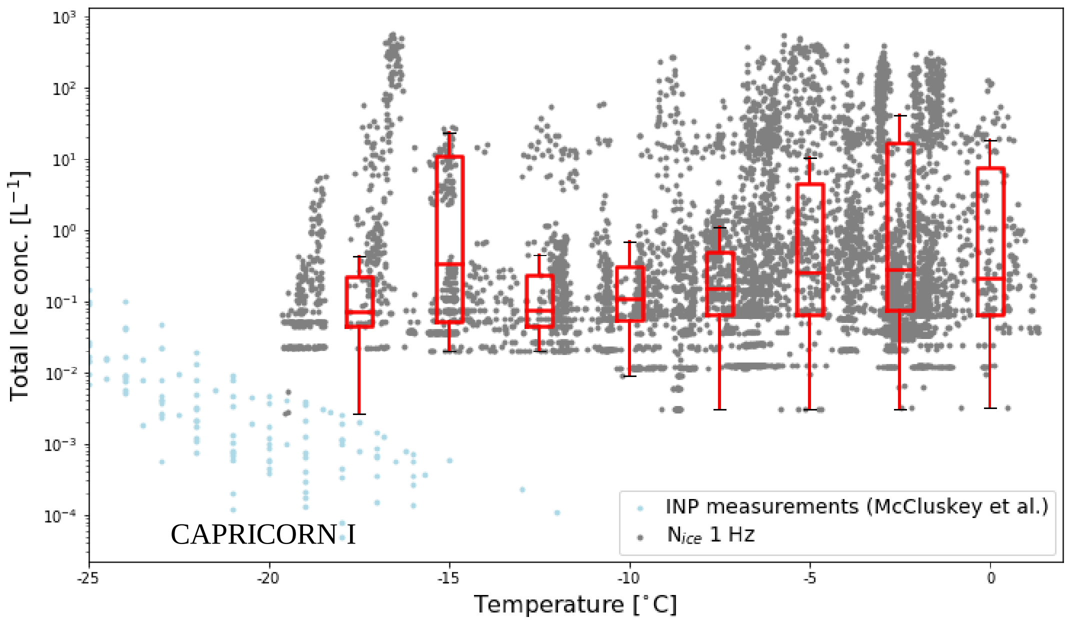


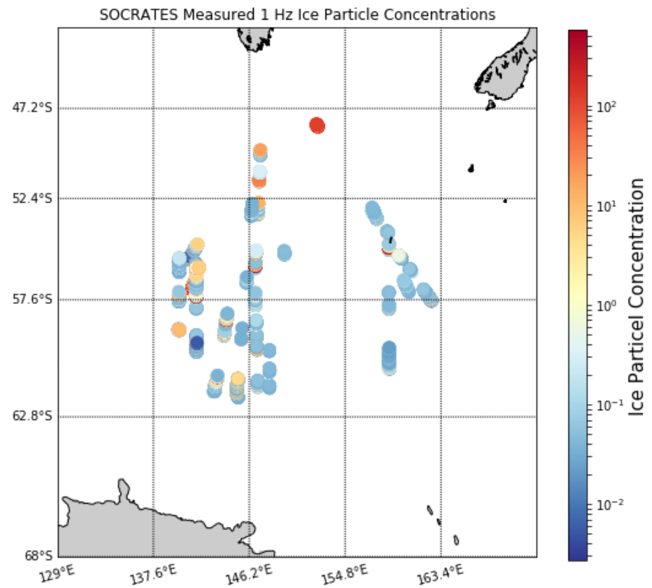




Mixed-phase: Secondary ice production dominant at 0 to -20 C

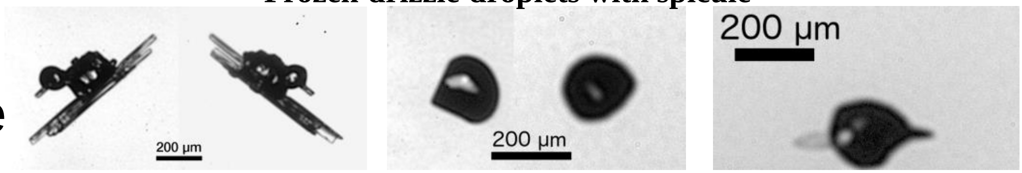
E. Jarvinen/C. McCluskey (NCAR)





- INP concs. 0.1% of typical NH
- Lots of SLW but mixed with some ice over broad temperature range, especially 0 to -5℃
- Observed ice concentrations are several orders of magnitude above INP concentrations -> secondary ice production

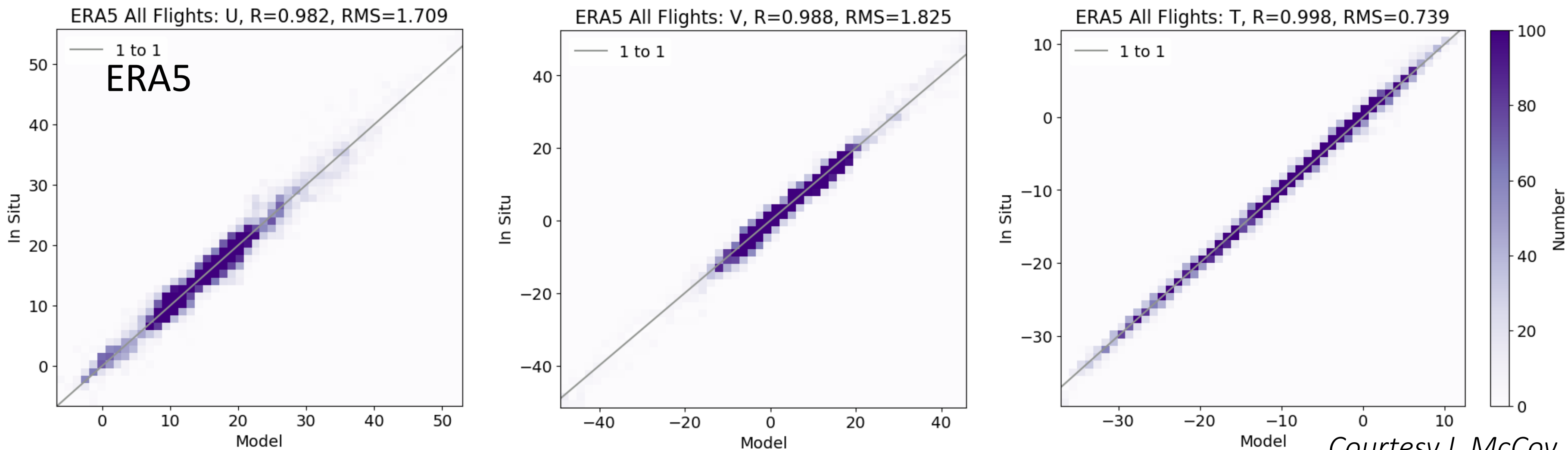
Frozen drizzle droplets with spicule



Frozen drizzle droplets

PHIPS images

Reanalysis, nudged forecast skillful vs. in-situ u, v, T



Courtesy I. McCoy

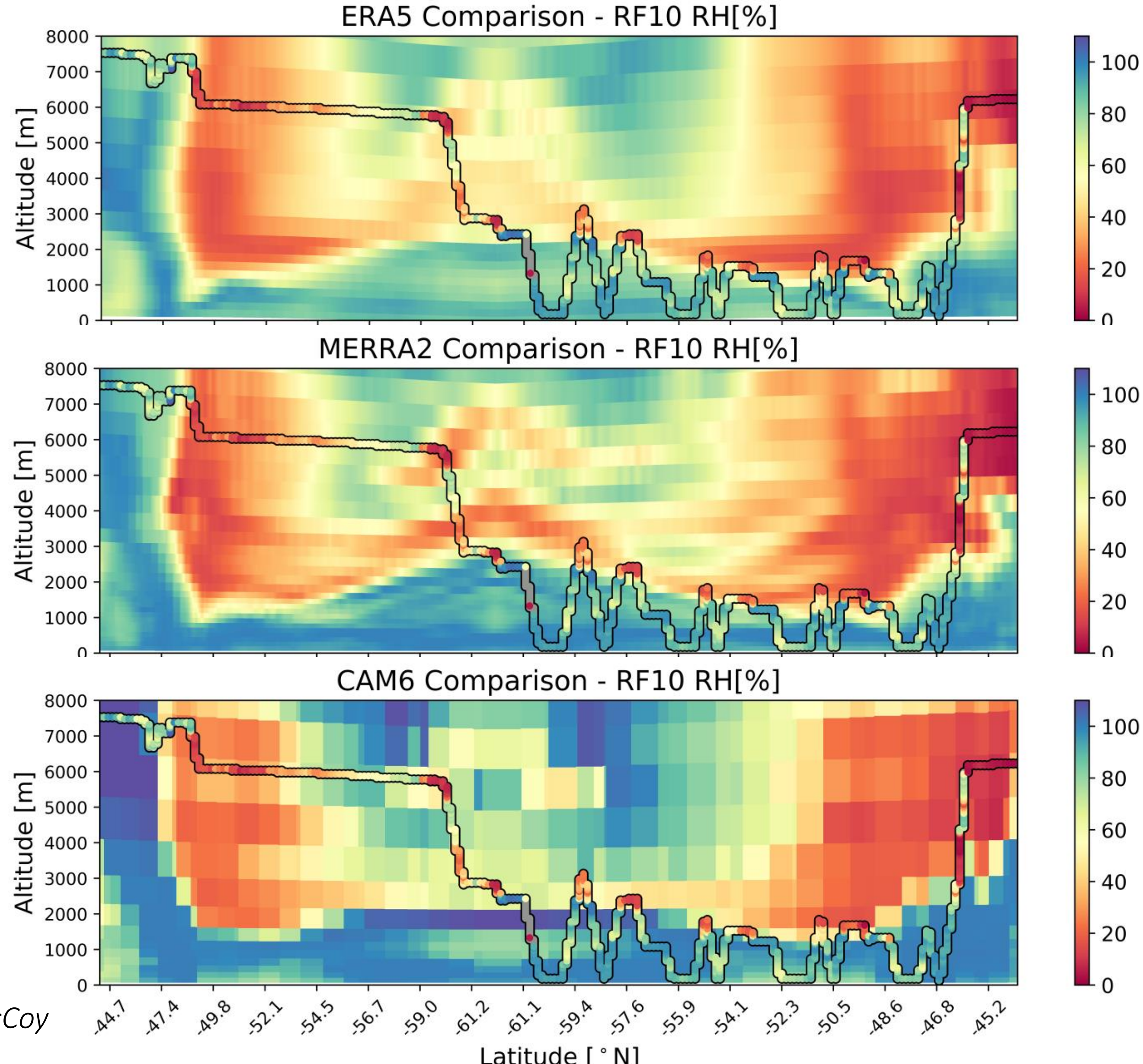
SOCRATES-wide statistics vs. 1 min in-situ binned observations

RMSE	ERA5	MERRA2	CAM6
U (m/s)	1.7	2.0	2.5
V (m/s)	1.8	2.0	2.6
T (K)	0.7	1.0	1.3
RH (%)	17	19	27 (unnudged)

ERA5 RMS u, v, T errors in remote SO remarkably small!
24-hr CAM6 nudging to MERRA-2 maintains small errors – good!
How about the hard stuff (clouds, precip, turbulence, aerosols, etc.)?

Relative humidity

RMSE



17%

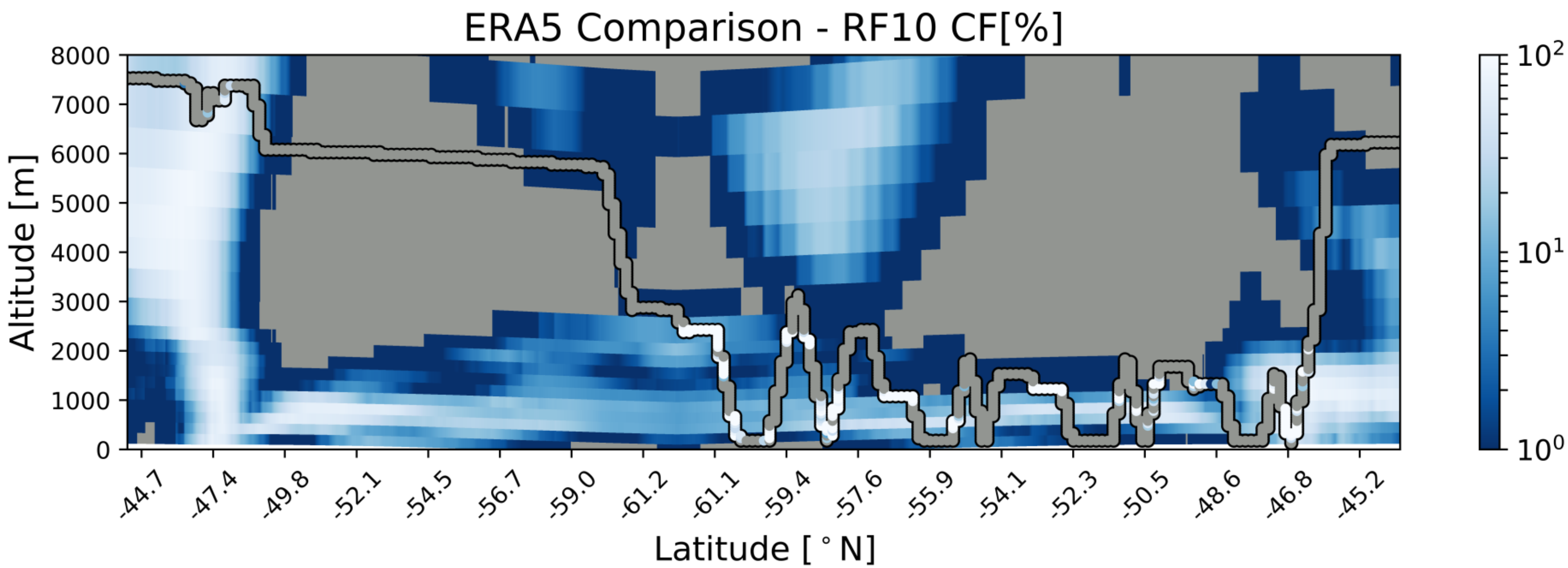
19%

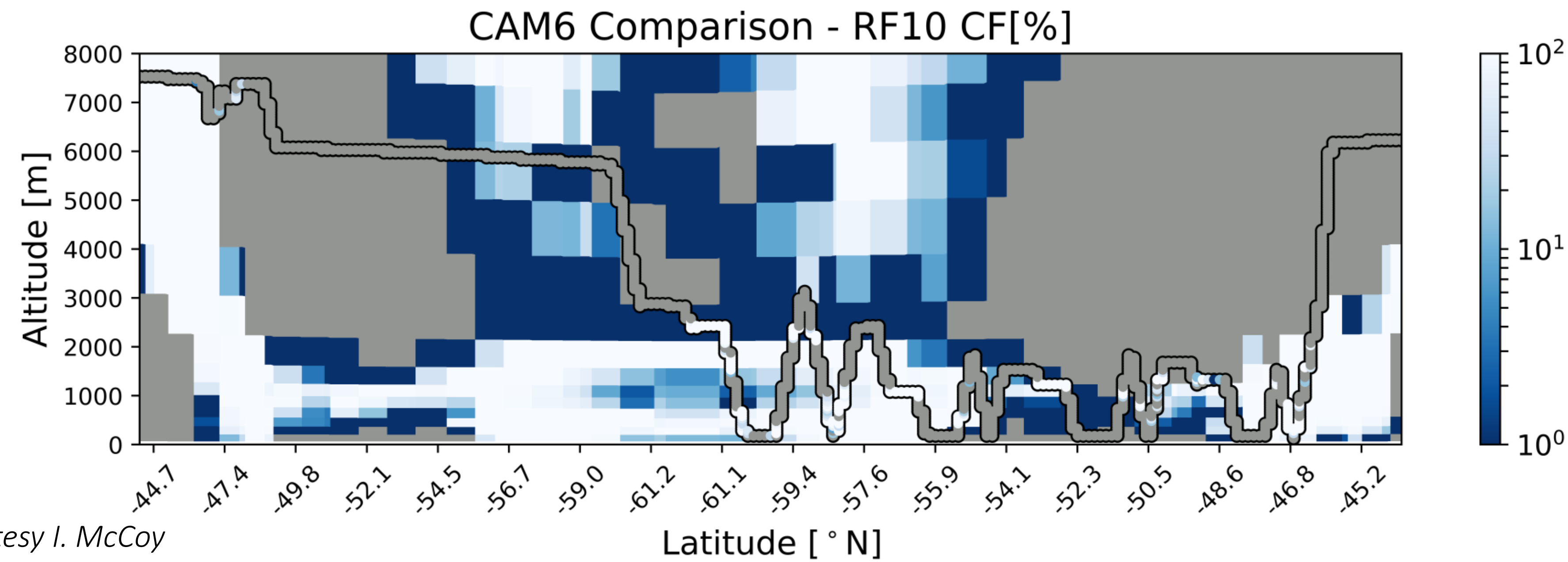
27%

Courtesy I. McCoy

CAM6 RH un-nudged, but still good

Cloud fraction

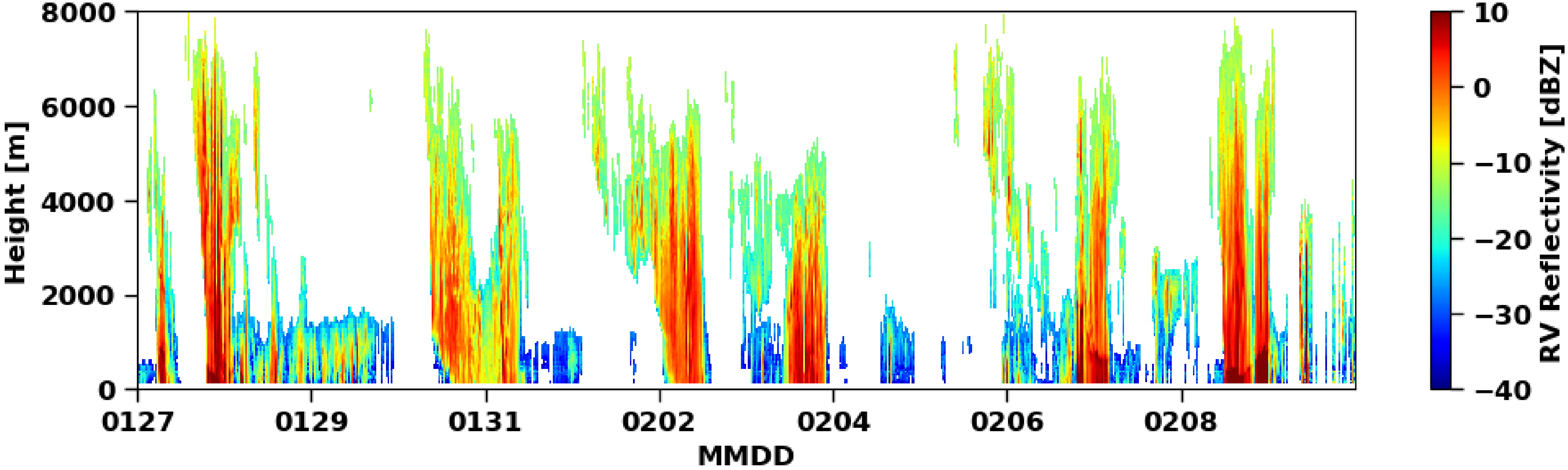




Courtesy I. McCoy

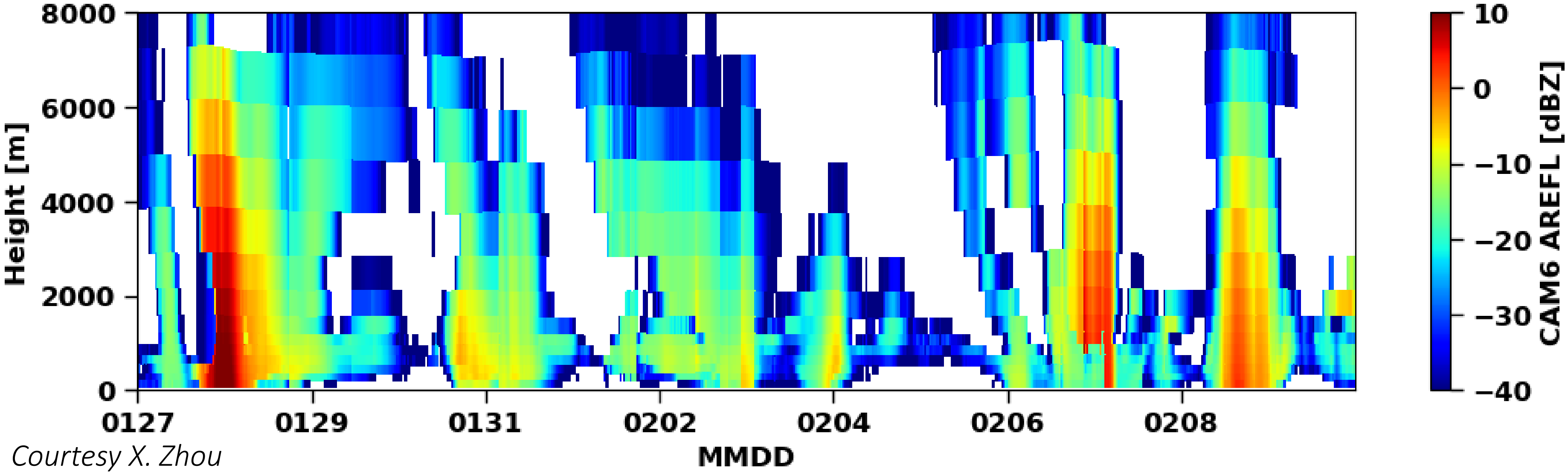
CAM6 precipitation bias suggested by nudged hindcast

Investigator cloud radar reflectivity



Nudged CAM6

X. Zhou, UW



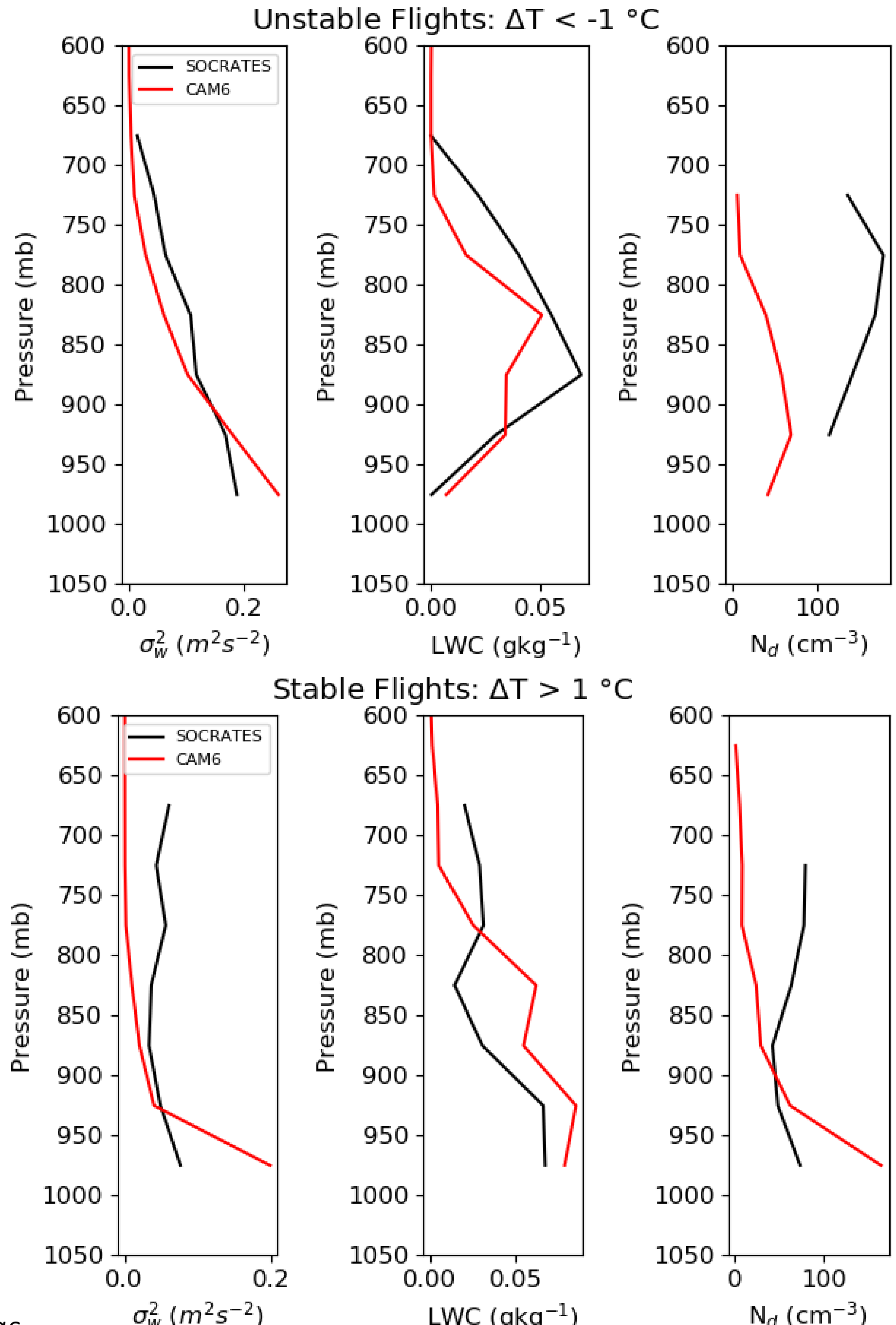
Courtesy X. Zhou

Turbulence, LWC, N_d

Vertical velocity variance can be noisily estimated from 20 s samples. CAM6 overintensifies surface vs. cloud-driven turbulence.

CAM6 has decent liquid water profiles

CAM6 has low N_d in unstable BLs.



Courtesy R. Atlas

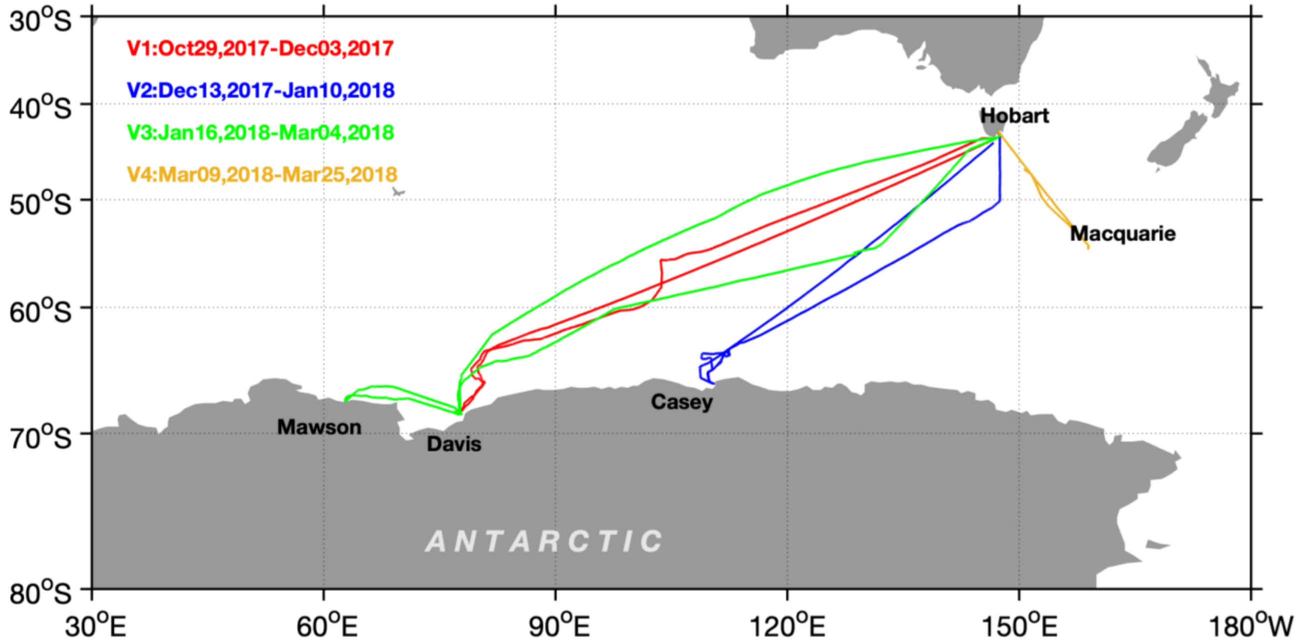
Conclusions

- High-quality forecasts greatly extend the reach of modern field campaigns, from planning to execution to context.
- CSET and the SOAR studies provide a wealth of comparison data for ECMWF models and reanalysis as well as for science.
- Reanalysis-nudged forecasts: a good test of GCM clouds/aerosols that makes use of the high quality of ERA5 and other modern reanalyses.
- Some fields (e. g. humidity) are good for direct comparison along flight tracks; others (e. g. cloud condensate) have small-scale structure that requires compositing to reveal meaningful observational signals.

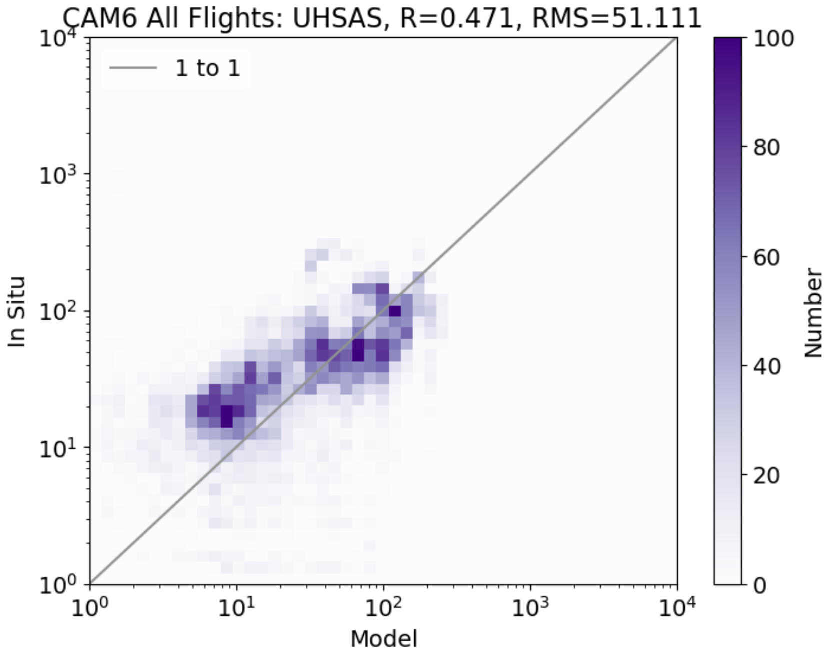
MARCUS (Lead PI: Greg McFarquhar)

- Observations of SO clouds, aerosols, precipitation and radiation from AMF2 on an AAD icebreaker **including near Antarctica.**
- 29 October 2017 to 25 March 2018 (Austral spring-autumn)

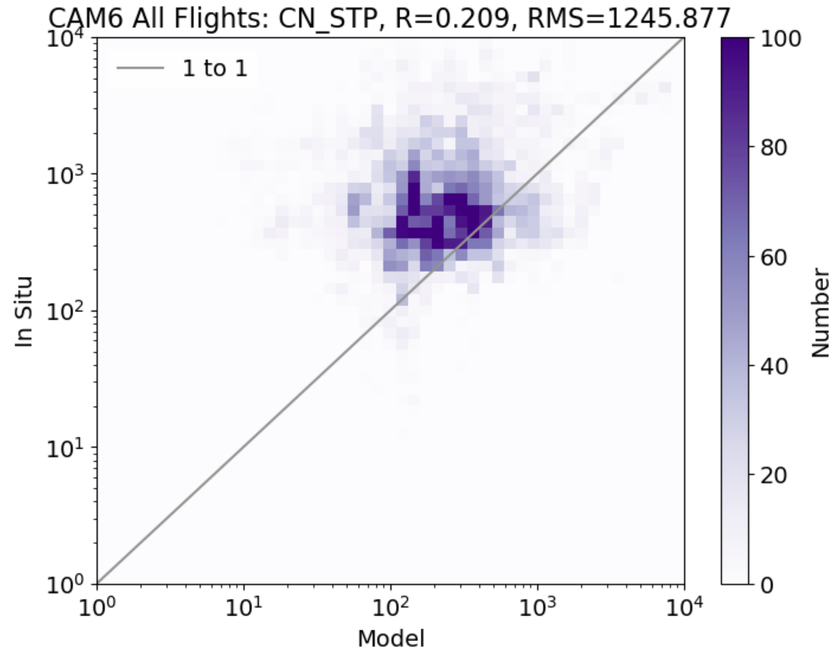
Active remote sensing: 95-GHz radar & stabilized platform, lidar, ceilometer, radar wind profiler
Passive remote sensing: AERI, Radiometers, Infrared thermometer, total sky imager
In-situ aerosols: Size distributions, optical properties, absorption
Gases: CO, O_3
Meteorology: Wind speeds, rain gauges, disdrometers & soundings 4 times per day



CAM6 Accum/Aitken aerosol vs. UHSAS100, CN



Some skill for CCN-size aerosol



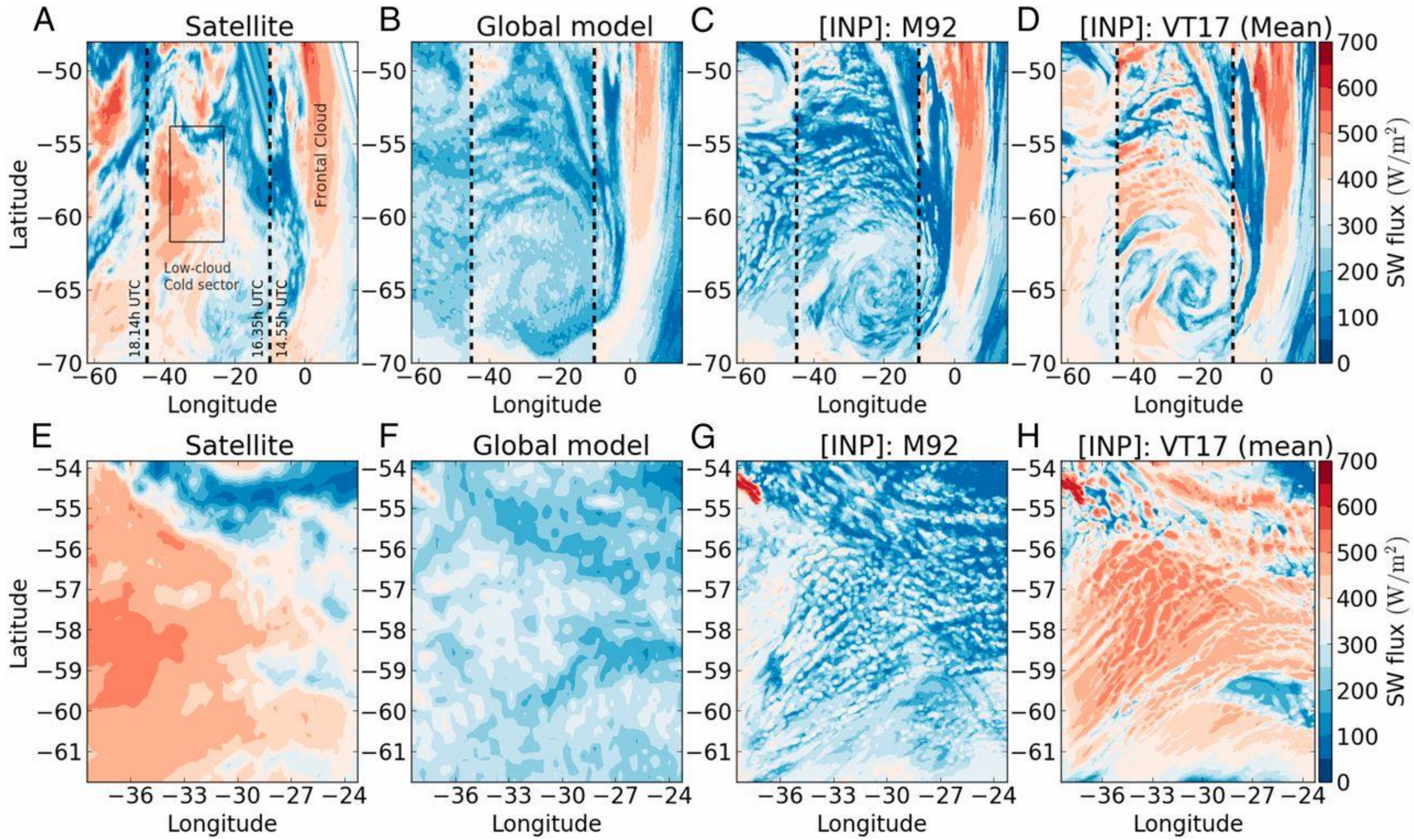
CAM6 underestimates small aerosol

…room for improvement, especially when model predicts low CCN

High-resolution and LES modeling of SO clouds and aerosols

Vergara-Temprado et al. (2018) simulated a SE Atlantic cold-air outbreak with regional UK Unified Model at 2 km resolution.

They showed strong increase of simulated cloud cover with realistic ice nucleating particle concentrations 10^{-4}-10^{-6} of previously assumed.



At UW, we are doing large-eddy simulation of SOCRATES cases.