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Cloud System Evolution in the Trades—CSET

Following the Evolution of Boundary Layer Cloud Systems with the NSF/NCAR GV

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1 **Abstract**

2

3 The Cloud System Evolution in the Trades (CSET) study was designed to describe and

4 explain the evolution of the boundary layer aerosol, cloud, and thermodynamic structures along

5 trajectories within the north-Pacific trade-winds. The study centered on 7 round-trips of the NSF

6 NCAR Gulfstream V (GV) between Sacramento, CA and Kona, Hawaii between 1 July and 15

7 August 2015. The CSET observing strategy was to sample aerosol, cloud, and boundary layer

8 properties upwind from the transition zone over the North Pacific and to resample these areas

9 two days later. GFS forecast trajectories were used to plan the outbound flight to Hawaii with

10 updated forecast trajectories setting the return flight plan two days later. Two key elements of the

11 CSET observing system were the newly developed HIAPER Cloud Radar (HCR) and the High

12 Spectral Resolution Lidar (HSRL). Together they provided unprecedented characterizations of

13 aerosol, cloud and precipitation structures that were combined with *in situ* measurements of

14 aerosol, cloud, precipitation, and turbulence properties. The cloud systems sampled included

15 solid stratocumulus infused with smoke from Canadian wildfires, mesoscale cloud-precipitation

16 complexes, and patches of shallow cumuli in very clean environments. Ultra-clean layers

17 observed frequently near the top of the boundary layer were often associated with shallow,

18 optically thin, layered veil clouds. The extensive aerosol, cloud, drizzle and boundary layer

19 sampling made over open areas of the Northeast Pacific along 2-day trajectories during CSET is

20 unprecedented and will enable modeling studies of boundary layer cloud system evolution and

21 the role of different processes in that evolution.

1 **1) Introduction and Motivation**

2 Boundary-layer clouds in the form of stratocumulus and small marine cumulus are the
3 most frequently observed cloud types over the Earth's oceans, are the most abundant types
4 globally (Norris, 1998) and have an important impact on the Earth's radiation budget (Hartmann
5 and Short 1980). The energy and moisture fluxes associated with these clouds are critical in
6 maintaining the thermodynamic structure of the lower troposphere. Thus, both the turbulent
7 mixing and the radiative impact on the surface associated with marine boundary layer (MBL)
8 clouds need to be adequately parameterized in large-scale models (Bony and Dufrense, 2005).
9 The inadequate representation of MBL cloud processes in large-scale models continues to be a
10 major contributor to model uncertainties in cloud feedback representations-- particularly in
11 subtropical anticyclone regions (Zhang et al. 2005, Wyant et al. 2010, Teixeira et al. 2011, Soden
12 and Vecchi, 2011).

13 The stratocumulus (Sc) regimes associated with the eastern flank of the subtropical
14 anticyclones evolve into fair-weather cumulus (Cu) regimes in the persistent trade winds
15 associated with the anticyclones. The high albedo and large areal extent of Sc corresponds to a
16 significant reduction in surface solar heating (e.g., Hartmann et al, 1992; Klein and Hartmann
17 1993). Cu, on the other hand, play a fundamental role in the regulation of ocean surface
18 evaporation and convergence of moisture into deep convective regions (e.g., Tiedtke 1989,
19 Neggers et al. 2007), and therefore the global hydrological cycle. The transition from shallow,
20 cloud-topped MBLs in the cool subtropics to broken trade cumulus over the warm tropics
21 (Bretherton and Wyant 1997, Bretherton et al. 1999, Sandu and Stevens 2011) occurs over all
22 subtropical ocean basins and sets the climatological distribution of cloud cover (Albrecht et al.
23 1995). In the Sc-Cu transition, the MBL evolves from a well-mixed, single layer topped with

1 extensive clouds under a sharp inversion, into a deeper, vertically-stratified structure containing
2 cumulus clouds with greatly reduced cover capped by a weaker and more diffuse inversion.

3 Cloud top entrainment is one of the key processes driving the stratocumulus-to-cumulus
4 transition. The MBL deepening associated with entrainment causes decoupling: the separation of
5 the MBL into two distinct layers with limited exchange between them. Decoupling that starves the
6 Sc of their surface moisture source and increased entrainment of dry air into the MBL due to more
7 energetic cumulus plumes lead to their breakup. They are replaced by broken Cu whose tops are
8 more variable, with a greater spread of cloud top height and fewer reaching the inversion. Cloud
9 top entrainment profoundly impacts the type and coverage of clouds within the MBL because it
10 plays such an important role in the MBL moisture, heat and momentum budgets (Lilly 1968,
11 Bretherton and Wyant 1997, Wyant et al. 1997, Stevens 2002, Stevens et al. 2002). In addition,
12 cloud top entrainment controls how MBL clouds respond to increased greenhouse gases (Caldwell
13 and Bretherton 2009) and atmospheric aerosols (Ackerman et al. 2004, Wood 2007, Bretherton et
14 al. 2007).

15 Cloud System Evolution in the Trades (CSET) was developed to describe and explain the
16 evolution of the MBL aerosol, cloud, and thermodynamic structures along trajectories within the
17 north-Pacific trade-winds using the NSF/NCAR Gulfstream V (GV, formerly known as HIAPER
18 (High Performance Instrumented Airborne Platform for Environmental Research)) on flights
19 between California and Hawaii. The long range of the NSF GV allowed for the sampling of air
20 masses on low-level trajectories extending from California to Hawaii and then a re-sampling of
21 these same air masses on the return flight two days later.

22 The stratocumulus-trade cumulus transition is often sharply defined as shown in Fig. 1.
23 The upstream part of the transition was arguably first examined with five NCAR Electra flights

1 undertaken in 1975 and documented in Brost et al. (1982a; 1982b) and Albrecht et al. (1985). The
2 Atlantic Stratocumulus Transition Experiment (ASTEX; Albrecht et al., 1995a) brought new cloud
3 remote sensors to the field, as well as an explicit Lagrangian sampling approach. Two Lagrangian
4 experiments each tracked air masses for 36-48 hours using instrumented aircraft (Bretherton and
5 Pincus, 1995; Bretherton et al., 1995). The ASTEX Lagrangian studies, however, were not made
6 in classic trade-wind flow and lacked aircraft-based lidar and radar observations needed to provide
7 a detailed mapping of cloud and precipitation structures.

8 More recent regional observational and modeling studies have also focused on the MBL
9 cloud, aerosol, and precipitation structures within the MBL in the cloud regimes associated with
10 the transition. During the VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment
11 (VOCALS-REx, 2008) a comprehensive study was made of the aerosol-cloud-and precipitation
12 properties of stratocumulus clouds in the southeastern Pacific (Wood et al., 2011a; Mechoso et
13 al., 2014). The observational and modeling studies focused on the stratocumulus structures
14 extending westward from the west coast of Chile. The VOCALS studies have brought important
15 new insight into the extreme aerosol-cloud interactions associated with Pockets of Open Cells
16 (POCs) and the role of mesoscale organizations in those interactions (Wood et al, 2011b; Berner
17 et al., 2011; Kazil et al., 2012; Wang et al., 2010; Berner et al., 2013) In addition, VOCALS
18 provided a comprehensive description of the aerosol, cloud, precipitation and MBL structures as
19 the MBL deepens along 20 °S for ~1500 km westwards from the Chilean coast (Bretherton et al.,
20 2010a). The VOCALS results provide an important baseline for comparing the microphysical
21 and macrophysical structure of the stratocumulus clouds sampled during CSET.

22 VOCALS did not extend into the trade-wind cumulus regime downwind of the main Sc
23 deck. Much of the early observational work on small cumuli in the trade wind boundary layer

1 was conducted using *in situ* aircraft observations. But there are inherent limitations to this
2 approach since the volume sampled during an aircraft penetration is relatively small and it is
3 difficult to study the time evolution of the vertical structure. Furthermore, it is difficult to
4 determine exactly where in the cloud the measurements are being made and at what stage of the
5 life cycle the cloud is being sampled. During the Rain in Cumulus over the Ocean (RICO;
6 Rauber et al., 2007) field campaign some important issues were addressed concerning aerosol
7 cloud interactions (e.g. Gerber et al. 2008); but the RICO aircraft measurements did not benefit
8 from good cloud radar observations. During the Barbados Aerosol Cloud Experiment (BACEX,
9 2010) *in-situ* cloud observations in fair weather cumulus clouds were made with the CIRPAS
10 Twin Otter research aircraft (Jung et al.,2012) and with an upward-pointing Frequency
11 Modulated Continuous Wave (FMCW) cloud radar. The RICO and BACEX observations
12 provided insight into entrainment and precipitation processes in small cumulus clouds (e.g.,
13 Nuijens et al., 2009; Minor et al., 2012; Zuidema et al., 2012a) and provide a background for the
14 CSET observations in the fair weather cumulus regions sampled.

15 Although recent field programs have advanced our understanding of processes operating
16 in the two cloud regimes central to CSET, they have not directly addressed the stratocumulus to
17 trade cumulus transition. A recent study, DOE MAGIC (the Marine ARM GPCI Investigation of
18 Clouds), involved ship-borne measurements from a container ship that made regular transects
19 between Los Angeles and Hawaii from October 2012 to September 2013 using the ARM Mobile
20 Facility (Zhou et al., 2015). In addition to *in situ* observations, the clouds above the ship were
21 sampled using lidar and radar observations in both the stratocumulus and the trade cumulus
22 regime. Although the cloud transition is well defined in some of the transects, the slow
23 movement of the ship limits the usefulness of these observations for Lagrangian studies. The

1 long range of the GV uniquely positions it to provide in-situ measurements of aerosols and cloud
2 microphysics, including interactions with the free troposphere across the entire transition and to
3 track the evolutions of cloud systems.

4 The subtropical NE Pacific stratocumulus to cumulus transition sampled during CSET
5 flights has long been a canonical modeling challenge. Two benchmark cases of Sc-Cu transition
6 have been used for international modeling inter-comparison efforts as part of the Global
7 Atmospheric System Study (GASS) and its predecessor, GCSS. The first of these was from the
8 1992 NE Atlantic ASTEX project described previously (Bretherton et al. 1995,1999; van der
9 Dussen et al. 2013). The second was a satellite derived composite (Sandu et al. 2010) of several
10 thousand Lagrangian trajectories based on MODIS cloud observations with trajectories based on
11 ECMWF reanalyses. Neither case includes a good accompanying set of aerosol observations in
12 or above the boundary layer or the robust statistics on horizontal cloud and precipitation
13 inhomogeneity that a cloud radar and lidar combination can provide (e. g. Bretherton et al.
14 2010b; Wood et al. 2011b).

15 LES models have become a robust tool for Lagrangian simulations of subtropical
16 cloudiness transitions, but there are few good datasets for comprehensively testing these
17 simulations. In particular, we lack adequate observations of the coupled evolution of aerosol,
18 cloud droplet number concentration and precipitation during such transitions. The MAGIC AMF
19 deployment provided a ship-based perspective on this problem (McGibbon and Bretherton, 2017;
20 Zhou et al., 2015), but the long range of the GV allows *in situ* measurements of aerosols and
21 cloud microphysics, including interactions with the free troposphere, across the entire transition.
22 By resampling the same boundary-layer air masses on the return flights as the outbound flights,
23 the measurements can naturally be compared with the Lagrangian LES and SCM simulations

1 that have proved to be valuable for constructing and analyzing better models of MBL cloud and
2 its sensitivity to environmental conditions.

3 Based on this background, the following scientific goals were set for CSET:

4

5 • *Define the evolution of the cloud, precipitation and aerosol fields in stratocumulus clouds*
6 *as they transition into the fair-weather cumulus regimes within the subtropical easterlies*
7 *over the northern Pacific.*

8

9 • *Examine the cloud microphysical properties and processes as a function of boundary-*
10 *layer depth, towards assessing the relative contributions of internal and external*
11 *processes to boundary-layer cloud-system evolution.*

12

13 • *Evaluate the relative importance of boundary layer deepening and precipitation*
14 *processes in driving boundary layer decoupling and cloud breakup.*

15

16 • *Provide comprehensive case studies and integrated data sets to evaluate and improve*
17 *process models, LES, and GCMs to describe and explain describe and explain cloud*
18 *system evolution in the trades.*

19

20 CSET was designed to describe and explain the evolution of the MBL aerosol, cloud, and

21 thermodynamic structures along trajectories within the north-Pacific trade-winds. The

22 NSF/NCAR GV supported by the NCAR Earth Observing Laboratory (EOL) served as the

23 principal source of the observations used in this study. The observational effort included

24 characterization of the cloud, precipitation and aerosol fields in the stratocumulus and the fair-

1 weather cumulus regimes within the subtropical easterlies over the northern Pacific. These
2 characterizations along trajectories were designed to aid in our understanding and simulation of
3 the transition between the two convective regimes. The Lagrangian approach allowed us to track
4 air masses as they flowed from colder to warmer sea surface temperatures and thus minimize
5 uncertainties in the large-scale forcing due to horizontal advection in the lower troposphere. This
6 approach facilitates comparison with Lagrangian model simulations and the isolation of critical
7 physical processes operating in the cloud evolution.

8

9 **2. Experiment Design**

10

11 . The NSF/NCAR GV was selected for CSET because of its range and endurance in
12 addition to its observational capabilities. Two modes of operations were implemented for the
13 GV flights between the west coast of California and Hawaii. The first—a surveying mode—
14 included radar and lidar remote sensing of the clouds and MBL from an altitude of about 6 km
15 (20 kft) altitude along transects. In this mode, dropsondes were deployed to obtain the
16 thermodynamic and wind structure in and above the MBL upstream and downstream from the
17 StCu to Cu transition zone. The second—*in situ* mode—involved detailed profiling in the sub-
18 cloud, cloud layer, and across the top of the boundary layer in three to four selected areas
19 upstream and downstream of the transition zone. The lidar and cloud radar remained critical
20 components of the low-level sampling. These two sampling modes were necessary, since the
21 GV would not have the range to do all the sampling at low levels. With about half of the flight
22 flown at a higher altitude, the GV flights from California to Hawaii were possible.

23

1 a. *Instrumentation*

2 A full suite of probes on the GV were used for *in situ* measurements of aerosol, cloud,
3 precipitation, and turbulence properties. The instrumentation is listed in Table 1 and described in
4 detail on the EOL website (<http://www.eol.ucar.edu/raf/instruments/doc/>). The GV was well-
5 instrumented for making *in situ* characterizations of the mean and turbulent wind and
6 thermodynamic structures below, in and above the cloud layer. Further, aerosol, cloud and
7 precipitation observations were made from the G-V using several probes. The GV aerosol
8 measurements were made using a Ultra-High Sensitivity Aerosol Spectrometer (UHSAS) that
9 samples particles in the nominal range of 0.06-1.0 microns (but reduced to 0.075-1.0 microns for
10 CSET). A Condensation Nuclei (CN) counter gives the total aerosol concentrations greater than a
11 threshold of about 10 nanometers. The cloud particle distributions were measured with a cloud
12 droplet probe (CDP) and the precipitation sized water droplets were obtained using an optical
13 array probe (OAP 2-D Precipitation Probe and a 3-D CPI). The second generation Holographic
14 Detector for Clouds (HOLODEC: Fugal and Shaw, 2009; Spuler and Fugal, 2011) was a new
15 instrument used on the GV to size cloud and drizzle droplets (in the range of about 6 μm to 1
16 mm) and to determine the three-dimensional position of hydrometeors using digital in-line
17 holography. The unique aspects of HOLODEC are that the sample volume measured per second
18 (about 43 cm^3) is not speed dependent and the effects produced by shattering from the aperture
19 edges can be identified and eliminated. Most significantly, it is possible to measure cloud
20 droplet size distributions from individual localized sample volumes with the largest dimension
21 being 130 mm, instead of an average over more than 10 m (e.g. for a measurement from CDP at
22 10 Hz), as well as determine the positions of the droplets within that volume. Post-flight analyses

1 of the holograms recorded at 3.3 Hz produce size distributions for all samples in cloud and
2 precipitation areas sampled during CSET by HOLODEC (Glienke et al, 2017).

3 Ozone and carbon monoxide measurements were made using the Fast Response Ozone
4 (F03_AD) and the Carbon Monoxide (Aero-Laser VUV) instruments supported by the
5 Community Airborne Research Instrumentation (CARI) group in Atmospheric Chemistry
6 Observations and Modeling (ACOM). Upward and downward longwave and short wave
7 radiative fluxes were measured from broadband sensors (Kipp & Zonen broadband radiometers)
8 and the HIAPER Airborne Radiation Package (HARP) provided downward spectral irradiances.

9 Two key remote sensing systems used on the GV during CSET were the HIAPER Cloud
10 Radar (HCR) developed by NCAR EOL and the High Spectral Resolution Lidar (HSRL)
11 developed under the NSF HIAPER Aircraft Instrumentation Solicitation (HIAS; ref). These
12 remote sensing instruments were used to define macroscopic and microscopic cloud properties as
13 the GV flew above, below, and in the clouds. The HCR characteristics are described in Rauber et
14 al, (2017) and in Schwartz et al. (2018). It is a pulsed Doppler radar that operates at a 95 GHz
15 frequency (3 mm wavelength) and has a sensitivity of -39.6 dBZ at 1 km range. The HCR in
16 CSET was operated with a temporal resolution of 0.5 sec, which for air speeds of the GV gives a
17 horizontal resolution of 50-100 m. The vertical range resolution of 20 m makes the HCR ideal
18 for observing stratocumulus and cumulus clouds and their associated precipitation structures.
19 The first three Doppler spectra moments (reflectivity, mean Doppler velocity and spectral width)
20 calculated using the pulse-pair technique were displayed in real-time on the aircraft and recorded
21 and archived for processing. In addition, the raw data that give phase and amplitude from the in-
22 phase (I) and quadrature-phase (Q) signals for each pulse were recorded and archived for each

1 flight. These raw I and Q data were used in post processing to calculate the full radar Doppler
2 spectrum and its first four moments (Schwartz et al. 2018).

3 A special wing pod was developed for mounting the HCR on the GV (Fig. 2). The pod
4 design allowed a steerable reflector to extend ahead of the wing to allow for sampling both
5 below and above the aircraft. The reflector was also actively controlled to remove pointing errors
6 due to pitch variations on the GV (Vivekanandan et al. 2014). Operating at 95 GHz frequency,
7 the HCR suffers from signal attenuation due to absorption by water vapor and oxygen.
8 Corrections were made using dropsonde data obtained on CSET and applying a method
9 described by Ulaby (1981) when the radar is looking downward from above the clouds.

10 The HCR characterized the cloud and precipitation structures and provided a measure of
11 cloud-top heights during both pointing directions. Its volume sampling is particularly suited for
12 characterizing light precipitation--a highly-localized and variable quantity (see, e.g., Wood,
13 2005). Aircraft-based 95-GHz radar measurements have a proven track record for advancing our
14 understanding of the role of precipitation in MBL clouds (Vali et al., 1998; Stevens et al., 2003;
15 Wood et al., 2011a). Ground-based and airborne cloud radars have been used to characterize the
16 vertical velocity structure of stratocumulus clouds (e.g. Lothon et al. 2004; Ghate et al. 2010)
17 and of shallow cumulus clouds (e.g, Geerts and Miao, 2005; Ghate et al., 2011; Wang and Geerts,
18 2012). During non-precipitating conditions (reflectivity < -15 dBZ) when the cloud droplets have
19 negligible fall velocity, the measured Doppler velocity corrected for the aircraft motion can be
20 used as a proxy for the vertical air motion (Lothon et al. 2004). During precipitating conditions,
21 either (a) the fall velocity of precipitating drops can be removed from the measured Doppler
22 velocity corrected for the aircraft motion to retrieve the vertical air motion or (b) the method
23 proposed by Luke and Kollias (2013) that uses the higher order moments of radar Doppler

1 spectrum to distinguish between the echoes due to cloud droplets and drizzle drops and can be
2 used to calculate the vertical air motion. Also, when drops larger than 1.6 mm in diameter exist
3 in the radar sample volume, a “notch” in the Doppler spectrum can be observed (Kollias et al.
4 2000) due to scattering by the drops in the Mie regime. The presence of the Mie notch allows the
5 retrieval of air vertical velocity (e.g. Kollias et al, 2000; Giangrande et al 2012; Ming et al,
6 2017). Mie notches were observed frequently during CSET and will be used to deduce vertical
7 air motions in more heavily precipitating clouds using the HCR.

8 The HSRL used in CSET is an eye-safe calibrated lidar system that measures backscatter
9 cross section, extinction and depolarization properties of atmospheric aerosols and clouds
10 (Razenkov et al.2002 and 2008). The HSRL provides estimates of cloud base heights while
11 pointing up and cloud top heights while pointing down, together with aerosol properties, derived
12 from profiles of backscatter cross-section, extinction cross-section and depolarization ratio at 532
13 nm at a temporal resolution of ~0.5 sec. The range resolution of the retrieved backscatter cross-
14 section profiles is ~30 m while that of extinction profile is ~300 m (Morley et al., 2012). The
15 circular depolarization ratio observed by the HSRL can distinguish between different aerosol
16 types (Burton et al. 2011). On the GV the laser transmitter and telescope can be manually
17 oriented to face either upward or downward (see Fig. 2) through windows on the top and bottom
18 of the fuselage.

19 The first three Doppler spectral moments from the HCR, and the backscatter and
20 extinction cross-section from the HSRL were combined to retrieve drizzle drop size distributions
21 while pointing up using the technique proposed by O’Connor et al. (2005). For optically thin
22 clouds that were detected by both the HCR and the HSRL, the cloud drop size distributions were
23 also retrieved (see Wood et al, 2018 for an example from a CSET flight).

1 When the aircraft was flying above the MBL in surveying mode (at a flight level of ~6
2 km), the HCR and HSRL were operated pointing downwards to observe MBL cloud and aerosol
3 fields from the flight level to the surface. For clouds that are 5 km below the aircraft, the HCR
4 minimum detectable reflectivity is about -23 dBz. On flight legs below the cloud base (near
5 surface), the HCR and HSRL were facing upwards to sample clouds and aerosols above the
6 flight level. During the flight legs in the clouds, the HCR and HSRL were pointing downwards to
7 characterize the sub-cloud layer aerosol and precipitating fields. The combined HCR and HSRL
8 retrievals were used to estimate cloud boundaries for the flights flown (Schwartz et al., 2018).

9 To further complement the HCR and HSRL measurements, a 4-channel zenith-pointing
10 183 GHz radiometer was flown to provide liquid water path (LWP) and water vapor
11 estimates. This radiometer is similar to one used during the VOCALS project (Zuidema et al.,
12 2012b). Such radiometers have the potential to provide an additional fundamental cloud
13 observation that can help connect the observations to models and quantify the cloud albedo and
14 rain susceptibilities, or how much the cloud albedo and rain vary as a function of droplet number
15 and LWP (Terai et al., 2012; Painemal and Zuidema, 2013). Further, they can provide a
16 geophysical constraint on lidar and radar-specific retrievals, such as a combination with the
17 attenuation-corrected HCR reflectivity data to develop a simple Z-LWC relationship for non-
18 precipitating clouds (dBz < -15). The 183 GHz channels are also fully attenuated in moist
19 environments, limiting their application to the drier northern stratocumulus clouds.

20 Dropsondes were launched from the GV during CSET using an AVAPSTM (Airborne
21 Vertical Atmospheric Profiling System ([https://www.eol.ucar.edu/observing_facilities/avaps-](https://www.eol.ucar.edu/observing_facilities/avaps-dropsonde-system)
22 [dropsonde-system](https://www.eol.ucar.edu/observing_facilities/avaps-dropsonde-system)). *In-situ* data collected from the sondes' sensors were transmitted back in
23 real time to an onboard aircraft data system via radio link. Input for times and locations of the

1 drop releases were sent from the flight scientist on the GV to the CSET home base in
2 Sacramento where an operator these would send instructions to the GV to trigger the sonde
3 launches at the designated points.

4 *b. Supporting tools and observations*

5 A key element of CSET was the EOL Field Catalog II (<http://catalog.eol.ucar.edu/cset>).
6 The Field Catalog was used extensively for mission planning, real-time access to aircraft
7 observations and satellite products during the missions, and for posting reports of mission
8 planning, operations, and summaries. The catalog was used for documentation of the mission
9 operations and serves as an archive reference for data collected during CSET. After the mission
10 the catalog is being used extensively in playback mode of all the aircraft observations and
11 ancillary products collected during each mission. The Field Catalog is developed and maintained
12 by EOL's Data Management and Services Facility (DMS) and catalogs for past field projects are
13 available at: <http://catalog.eol.ucar.edu/>. (The field catalog is identified
14 as <https://doi.org/10.5065/D6SQ8XFB> . EOL Field Catalog; UCAR/NCAR - Earth Observing
15 Laboratory, 1995-present).

16 Imagery from the 15th Geostationary Operational Environmental Satellite (GOES 15)
17 satellite observations (centered over 135 °W longitude) was used to define the larger-scale
18 (greater than 100 km x100 km) cloud fields using near-real-time visible and infrared images
19 (Ch1-Ch4; and high resolution; 1km x 1km visible at nadir). Cloud property fields derived from
20 the GOES observations were provided by the NASA Langley Satellite Cloud and Radiation
21 Property retrieval System (SatCORPS; <https://satcorps.larc.nasa.gov>) estimated using the methods
22 outlined by Minnis et al. (2008) and Sun-Mack et al. (2014) and included broadband albedo,
23 cloud-top height, cloud droplet concentrations, cloud droplet effective radius, liquid water path,

1 and other cloud properties (see the Field Catalog Maps app for a full list). The satellite products
2 were available in near real time from the Field Catalog and were instrumental for flight planning
3 and for in-flight updates during the missions. All satellite product images produced during
4 CSET are available in the playback mode with the Field Catalog Maps application.

5 3. Observing Strategy and Mission Operations

6 The general sampling strategy employed in CSET was to use the GV to sample clouds
7 and MBL structures within trajectories extending westward along the southern periphery of the
8 North East Pacific. This Lagrangian approach is designed to minimize uncertainties in the large-
9 scale forcing due to horizontal advection in the lower troposphere as air masses move from cold
10 to warm SSTs. Thus, the observing strategy was to sample aerosol, cloud, and MBL properties in
11 areas upwind from the transition zone over the North East on GV flights originating from
12 Sacramento and ending in Kona Hawaii. The GV and crew would then spend one day in Kona
13 with a return flight to Sacramento two days after the outbound flight. The return (inbound) flight
14 was planned so that GV could do low-level sampling in the same air masses that were sampled
15 two days earlier during the outbound flights.

16 Since the GV range is substantially reduced when flown at lower levels, the amount of
17 time that could be flown for low-level boundary sampling was limited to about 50% of the flight
18 time between California and Hawaii. Thus a strategy was developed that allowed for two types
19 of sampling—1) surveying and 2) *in situ*. In the surveying mode, the MBL structures, cloud
20 properties, and aerosol distributions were sampled using the HCR and HSRL operating in a
21 downward facing mode to sample from the flight level to the surface. This leg was typically
22 flown at about 6 km (20 kft). Generally, *in situ* cloud and MBL observations were made in three
23 targeted areas along these transects on profiling flight legs flown in and just above the BL over a

1 distance of 1500 to 1800 km). For the return flights from Hawaii, trajectory analyses were used
2 to identify air masses sampled two days earlier on the flight outbound from California. The
3 flights between Sacramento California and Kona Hawaii were over a distance of about 4000 km.

4 Flight plans for the outbound flights originating from Sacramento were based on 500 m
5 trajectory forecasts that were made using HYSPLIT (Hybrid Single Particle Lagrangian
6 Integrated Trajectory Model) with NCEP GFS forecasts and GDAS analyses. The trajectory
7 forecasts used for the outbound planning comprised a swarm of 28 forward planetary boundary
8 layer constant height trajectories made using the 12 UTC 0.25° forecast from the day before
9 flight. The initial points for the 28 trajectories were chosen using the current GOES satellite
10 visible imagery to identify areas of cloud transition and were prepared for the mission planning
11 meetings that were held afternoon before an outgoing flight from Sacramento the next day. An
12 example of a trajectory swarm forecast is shown in Fig. 6 with trajectories overlain on the GOES
13 visible satellite imagery with the trajectory starting points for a flight planned for July 27. These
14 trajectories show the starting points (stars) and the 48-hour end points (squares) for the 28
15 trajectories. During the mission planning meetings, the science team examined the trajectory
16 swarms and estimated which of the endpoints of these trajectories would be in the range of the
17 GV on the return flight two days later. On the basis of this process, the initial points to be
18 sampled were selected and the endpoints were set as tentative sampling areas for the return
19 flight. These flight plans were then shared with the GV pilots who would assess the feasibility
20 of the proposed flights and would suggest any modifications needed to make the planned flights
21 achievable.

22 Once in Kona, there would be another mission planning meeting the afternoon between
23 flight days. During this meeting, updated trajectory end points were used to set the flight track

1 back to Sacramento, using 12 UTC day-before-return-flight analysis and forecasts and the
2 outbound flight path. For the RF10 July 27 example shown in Fig 3, the beginning and end
3 points of the 9 trajectories selected for the sampling sequence are shown in Fig. 3b. These
4 trajectories are overlaid on the satellite image from 28 July to show (after the fact) how the
5 selected trajectories lined up with the clouds observed one day after the outgoing flight. Any
6 minor updates to the flight plan based on subsequent forecast changes were relayed to the pilots
7 4 hours before TO, based on 06 UTC day-of-flight forecasts. For the RF10 and RF 11 example
8 sequence, the actual flight paths flown are shown in Figs 3c and 3d along with the satellite
9 images at the different days of the aircraft operation. This same mission planning procedure was
10 used for all of the 7 flight pairs (dates tabulated in Table 2) that were made during CSET. The
11 detailed flight paths and field reports for each of the mission can be found in the CSET Field
12 Catalog.

13 The basic flight pattern planned for the low-level sampling segments for all of the flights
14 is shown in Fig. 4. The first segment starts with a descent from the surveying leg at 6 km to
15 about 500 ft. This descent provides a pseudo sounding (aircraft moves horizontally during the 20
16 k ft descent). Then a level leg is flown at 150 m (500 ft) for about 10 minutes. After this low-
17 level leg the aircraft ascends to about 100 m above the cloud base for another 10 minute leg.
18 During this leg and the 150 m leg, the HCR and the HSRL beams were pointed upward. After
19 the in-cloud leg, the aircraft would do an alternating ascent-descent sequence with a vertical
20 range of about 500 m (1500 ft) to sample cloud top and the stable layer that often caps the cloud.
21 The plan was flexible so that modifications could be made during the aircraft sampling as
22 dictated by local cloud and meteorology conditions.

1 Mission planning and mission control were done from the Department of Atmospheric
2 Science Department at the University of Washington and the aircraft home base was in
3 Sacramento CA where the EOL flight crew and technicians were located with the airborne
4 mission scientists. Daily mission briefing and planning meetings were held at the University of
5 Washington and networked to facilities at the Sacramento location and to Kona when the aircraft
6 was there.

7 Flight operations of each mission started with preparation of the aircraft and scientific
8 equipment about 4 hours before TO. The flight crew consisted of two pilots, three technicians
9 onboard the aircraft, the mission scientist and at least one additional scientist/observer. Once
10 airborne, the mission scientist would direct the aircraft sampling sequence during the low-level
11 profile flights and would set the dropsonde points along the surveying parts of the flight.
12 Scientists on the ground could monitor the aircraft operations and view data in near real-time
13 along with GOES satellite products using the satellite-linked Field Catalog and x-chat
14 capabilities. An example of the display from the Field Catalog work space for the midpoint of
15 the RF10 flight on 27 July is shown in Fig. 4b. In this depiction the GV flight path is plotted on
16 the high resolution visible GOES image. Any of the satellite cloud products can be displayed in
17 this same format and selected using a menu that appears on the Field Catalog display. The
18 images from the cameras onboard the G-V can also be viewed at the same time through the web
19 portal to the Field Catalog. The dropsonde points can be plotted on the flight display. During the
20 flight, these Field Catalog near-real time displays can be made using the menu to select the fields
21 to be displayed with the flight tack information. In addition the Field Catalog can be to show
22 near-real time displays of time-height plots of the HCR and HSRL returns. Other data collected
23 can be plotted and displayed in real time or after flights using EOL Aeros visualization software.

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The playback mode of the Field Catalog allows review of the observations made earlier in the flight or after flight completion. The flight path can be superimposed on the satellite product images. The Field Catalog displays are available to scientists and technicians on the GV and to anyone on the ground through a standard web connection. Scientists on the ground communicated directly with the mission scientists using x-chat. These real-time exchanges facilitated any modification of the aircraft sampling areas and procedures and made full use of the many eyes that were monitoring the flights and the associated cloud conditions seen from satellite.

4. Observational Highlights

A wide range of boundary layer structures and aerosol, cloud, and precipitation conditions were observed during the CSET missions that captured the cloud system evolution in the Pacific trades. The cloud systems sampled included solid stratocumulus infused with smoke from Canadian wildfires, mesoscale (100-200 km) cloud-precipitation complexes, and patches of shallow cumuli in very clean environments. Ultra clean layers were observed frequently near the top of the boundary layer and were often associated with shallow, veil (optically thin) layered clouds. The extent of aerosol, cloud, drizzle and boundary layer sampling that was made over open areas of the North Pacific along 2-day trajectories during CSET is unprecedented and will enable focused modeling and process studies of cloud system evolution and the role of aerosol-cloud-precipitation interactions in that evolution.

Synoptic conditions during CSET were consistent with normal summertime conditions over the North East Pacific, although sea surface temperatures were above normal. On average the center of the subtropical anticyclone was at about 43 N and 148 E during the observing

1 period (Fig. 5), which is slightly north of the climatological position. Some variations in the
2 strength and location of the anticyclone were observed during the 4 weeks of observations. The
3 sea surface temperatures (Fig. 5) in the study area were about 0.5 °C above 1981-2010 base
4 values. The mean low-level cloudiness from the GOES estimates is shown in Fig. 6. The winds
5 and clouds in the southern parts of the observing areas were occasionally perturbed by tropical
6 storms and cyclones moving through or near this area. But these perturbations had limited
7 impact on the CSET observations.

8 During CSET a total of 7 two-flight sequences (14 research flights; RF-02 to RF-15; see
9 Table 2) were flown between Sacramento and Kona. Each flight took about 8 hours with about
10 half of this time flown at the beginning and the end of each flight in survey mode at a nominal
11 height of 6 km. The middle of the flight was devoted to the level-leg sampling at low levels and
12 the profiling described previously. Rough estimates of the mean trajectories flown during these
13 14 flights are shown in Fig. 5 and are overlaid on the mean SST and wind vectors from NCEP
14 reanalyzes. The mean trajectories go from higher lower to higher SSTs with downstream and
15 upstream differences of 4- 8 °C and the mean near-surface winds decreasing in speed and the
16 cloudiness decreases (roughly 80-90% to 40-50 %; Fig. 6).

17 Sampling areas at the beginning and the ends of individual trajectories for the 14 flights
18 are overlain over the mean cloudiness from the GOES analyses shown in Fig. 6. Most of the
19 initial sampling (blue) areas are in high cloudiness areas relative to the areas at the end points of
20 the trajectories 48-52 hours later. The average cloudiness decreases about 30 % to 50% along
21 each of the couplets. Thus the transition was well sampled on the 14 flights. The locations of
22 the trajectory mapping areas shown in Fig. 6 are listed in Table 2. On the first 6 flights (RF02-
23 RF07) at the beginning of observational period, the low-level sampling time was less than on the

1 flights made after that. Thus, the two sampling areas are specified in Table 2 for RF02-RF07
2 and three sampling areas are listed for RF08-RF 15 when more time was used for low-level
3 sampling.

4 *a. Lagrangian Evolution Sample*

5 A sample of the Lagrangian tracking of clouds and aerosols with the HCR and HSRL
6 during the outbound RF10 (27 July 2015) and the inbound RF11 (29 July 2011) flight sequences
7 discussed earlier (Fig. 3) are shown in Figs. 7a and 7b. The changes in the boundary layer depth
8 with longitude are shown clearly by the HCR and HSRL returns along the outbound flight in Fig.
9 7a where the depth increases from about 0.5 km to 1.2 km from 124° to 130° W. From 130° to
10 137° W the boundary layer depth is nearly constant at a height of about 1.2 km and then
11 increases to about 2.5 km at 140° W. The cloudiness is substantially reduced west of 140° W.

12 The boundary layer is more distinctly defined by the lidar than the radar in some cases,
13 since the survey portions of the flight were flown at a height where the radar sensitivity is
14 insufficient to detect low non-precipitating thin clouds. But when flying below the cloud, the
15 lidar is facing upward and does not detect cloud top in optically thick clouds. On the RF11 return
16 flight two days later the boundary layer depth is about 1.8 km from 145 to 135° W and then
17 decrease from this height to about 300 m at 140° W.

18 The low-level sampling legs shown in Fig. 7a and 7b are segmented into the areas
19 labeled by capital letters. The segments labeled on the outbound flight sample the beginning of
20 the trajectories selected for the mission and the corresponding letters on the inbound flight
21 correspond to the equivalent end points of the 48-52 hour trajectories. A blowup of the lidar and
22 the radar sampling made on the BC segments for RF10 and RF11 are shown in Fig. 8. These
23 segments clearly show a strong change in the cloud type and amount between the beginning and

1 the end of the trajectories. After two days there is substantially less low cloud in the end of the
2 trajectory sampling than in the beginning. There is also a notable deepening of the boundary
3 layer from the beginning to the end of the segments. At the beginning of the trajectory sample
4 area BC the radar indicates relative solid cloud cover with drizzle and rain falling from the
5 clouds. The cloud fraction from the remote sensing measurements is about 80%. On the return
6 flight sampling at the end of the BC trajectories, there are relatively few clouds with a few weak
7 echoes from small cumuli. The lidar returns in this area show mesoscale variability in the time-
8 height aerosol structure in the PBL from 0.5 to 1.8 km altitude. This mesoscale variability may
9 be due to processing of the aerosols by previous mesoscale convective activity.

10 Potential temperature, mixing ratio, and wind profiles at the beginning and the end of the
11 BC trajectory (Fig. 9) show the evolution of the boundary layer structure over the two-day
12 period. As expected, there is substantial warming (about a 4 K increase) and moistening (about 3
13 g/kg) over the period that are consistent with the increase in SST along the trajectory. The
14 capping inversion defined from the soundings increases from about 1.4 km at the beginning of
15 the trajectory to about 2.3 km at the end. The potential temperature and mixing ratio profiles
16 show some decoupling at the beginning of the trajectory that becomes more pronounced at the
17 end. Since these profiles represent a combination of vertical and horizontal variability,
18 interpretation of features like the moist layer observed at the top of the boundary layer may be
19 difficult and may reflect mesoscale horizontal variability in the moisture structure as well as the
20 vertical structure.

21 In total 7 Lagrangian pairs were obtained during CSET and provided an unprecedented
22 description of the evolution of the clouds and boundary layer structures in the North Pacific
23 Trades. Although there was variability on the different days, a common feature was that on the

1 outbound flights the boundary layer was already showing signs of decoupling in the initial
2 sampling areas associated with stratocumulus clouds around 140W . These decoupled
3 stratocumulus areas were followed by areas that were dominated by mesoscale cloud systems.
4 The classic broken fair-weather cumulus fields were not generally sampled on the outbound
5 flights, but were more prevalent on the beginning of the inbound flights originating from Hawaii.

6 *b. Process Studies*

7 The CSET observations also provide an observational basis for underlying processes
8 involved in the evolution of the boundary layer clouds. This included illumination of the role of
9 aerosol-cloud-precipitation interactions and the role of mesoscale cloud systems in the evolution
10 of clouds along the trajectories sampled.

11 The environments sampled during some of the CSET cases showed substantial variability
12 in the aerosols and associated cloud characteristics. An example of this variability in the extreme
13 is shown for the RF02 (7 July 2015) and RF03(9 July 2015) cases when fires in Canada
14 produced smoke plumes that were advected into the CSET sampling area and impacted clouds in
15 Fig. 10. The effective cloud radius estimates from the GOES satellite products indicate that the
16 boundary layer clouds in the areas are affected by the smoke and showed lower effective radius
17 values compared with those obtained in the cleaner areas to the west of the smoke affected areas.
18 The HSRL returns on the outbound flight RF02 also show substantial aerosol structures above
19 the boundary layer. The *in situ* GV aerosol concentrations (labeled UHSAS in Fig. 10) and mean
20 cloud droplet concentrations sizes (labeled N_D in Fig. 10) obtained on RF02 show much higher
21 aerosol and cloud droplet number concentrations in the eastern part of the low-level sampling
22 areas than those to the west. For a trajectory starting area sampled on the first part of the
23 outbound RF02 flight, the boundary layer UHSAS aerosol concentrations are about 760 cm^{-3} and

1 the concentrations above the boundary layer are about 450 cm^{-3} . In the same air mass sampled
2 on the return flight the boundary layer concentrations are reduced to about 410 cm^{-3} and the
3 above inversion concentrations are about 70 cm^{-3} . But while the boundary layer values are
4 measured in the same air mass, there is no guarantee that the air above the inversion will follow
5 the same trajectory. Regardless, the CSET trajectory analyses are a rich source of information
6 for studying the evolution of aerosols and cloud and precipitation properties in the transition
7 process.

8 Mesoscale cloud systems in the transition area were common features observed on the
9 CSET flights. An example of the types of systems sampled is shown in Fig. 11. These systems
10 generally have heavy precipitation near the core of the systems with outflow clouds at the top of
11 the system. The two mesoscale systems sampled with the HSRL and the HCR on the RF07 (19
12 July 2015) flight have horizontal dimensions of about 20 km and are about 60 km apart. The
13 GOES visible image for the time period when these observations were made is shown in the Fig.
14 11. Overall the cloud pattern shown in the satellite image can be characterized as open cells like
15 those studied in VOCALS (Wood et al., 2011b). The core of the two systems is characterized
16 by precipitation shafts with relatively high radar reflectivity and downward motions of about 4
17 ms^{-1} . Clearly defined outflow areas extend from these cores near cloud top. Although the cloud
18 tops in the cores are at a height of about 2 km, the precipitation from these areas can be relatively
19 heavy and of sufficient intensity to give rainbows that were observed from the GV when flying at
20 low levels (example shown in Fig. 11). The precipitation cores of the systems shown in Fig. 11
21 have a horizontal extent of about 5-10 km horizontally. The out-flow areas in these mesoscale
22 systems by the radar are about double that of the precipitating cloud areas.

1 The lidar and radar observations made in this case were taken while the GV was flying
2 above the boundary layer. On the edges of the cloud away from the heavily precipitating cloud,
3 the clouds are sufficiently optically thin that aerosols below the cloud can be observed with the
4 HSRL. On the west side of the eastern cloud system two out-flow clouds at different heights are
5 present. Both are sufficiently optically thin that the lidar is able to penetrate both layers in some
6 areas. These types of mesoscale cloud systems were observed on nearly all the CSET flights and
7 clearly indicate that these systems are fundamental to the cloudiness transition observed in the
8 CSET study area. The CSET observations provide a unique data set for studying the heavy
9 precipitation events observed in these clouds and the aerosol-cloud-precipitation interactions
10 involved in these mesoscale complexes.

11 The mesoscale systems sampled are also rich in different types of aerosol cloud
12 interactions. A feature that was frequently observed during CSET was optically thin veil clouds
13 that were associated with layers of very low aerosol concentrations (UHSAS concentrations <10
14 $\# \text{ cm}^{-3}$) near the top of the boundary layer. An example of these veil cloud layers and ultra clean
15 layer is shown in Fig. 12 with the HSRL observations made on RF07. A full study of the veil
16 clouds and the clean layers observed during CSET is given in Wood et al. (2018). They estimate
17 that cloud cover associated with the veil clouds to be about 50% within the transition areas
18 sampled during CSET. These clouds are both physically and optically thin. In addition, to the
19 extensive lidar and radar observations during CSET, the GV made several direct penetrations of
20 the veil clouds during CSET that allowed for a characterization of the properties of the clouds
21 and the aerosols in the vicinity of the clouds.

22 The clean layers near cloud top are clearly shown on several of the flights (Wood et al,
23 2018). For example, the UHSAS aerosol concentrations measured on the outbound RF 06 (7

1 July) and inbound RF 07 (9 July) are shown in Fig. 13. On the inbound flight there is a well-
2 defined area of very low aerosol concentrations near the mean tops of clouds. The veil clouds
3 and clean layers observed appear to be closely coupled to the mesoscale cloud systems like those
4 shown in Fig. 11. A challenge will be to fully understand how the gray clouds form and their
5 connection to the clean layers. Modeling studies in progress are working to address these
6 questions.

7 This section is intended to give a snapshot of some of the observations made during
8 CSET. The CSET observations and the flights that were flown can be explored further by
9 visiting the CEST Field Catalog.

10 5. Summary

11 CSET made substantial advancement in our characterization of the evolution of cloud
12 systems along the southeast extent of the Pacific anticyclone further CET and demonstrated the
13 utility of a Lagrangian sampling strategy. The observations provide a unique opportunity to
14 study of the processes involved in the cloud system evolution in the Pacific trades and to
15 characterize that evolution in a way that can be used to evaluate model simulations of the
16 evolutions. CSET demonstrated the feasibility of a Lagrangian sampling strategy with
17 NSF/NCAR GV aircraft to study cloud system evolution. The range, endurance, and
18 observational capabilities of the GV make it an ideal tool for studying shallow boundary layer
19 clouds and mesoscale cloud systems over large domains. The HCR and HSRL remote sensing
20 capabilities on the GV were critical to the success of CSET. They provided a detailed
21 characterization of the structure of both precipitating and non-precipitating clouds and the
22 aerosol distributions above, below and around clouds. CSET provided unprecedented
23 observations of the evolution of boundary layer structure and cloud and aerosol fields that will

1 provide several cases for model evaluation and development. Extensive cloud areas were
2 sampled and then resampled 48 hrs later along trajectories between California and Hawaii on 7
3 round-trip missions involving low-level flights. These observations and subsequent
4 characterizations of cloud and boundary layer evolution along the trajectories provide an
5 unprecedented data set for evaluating cloud system evolution in several classes of models.

6 The observing strategy employed allowed for a low-level sampling of clouds over a total
7 flight distance of about 20,000 km and another 20,000 km of sampling made in survey mode
8 where the radar and lidar were used to characterize clouds in the boundary layer and dropsondes
9 were used to define boundary layer structure. Extensive observations of key features of cloud
10 system evolution were made—mesoscale precipitating cloud complexes, gray cloud layers, and
11 ultra clean layers at boundary layer top in areas far removed from areas sampled on past aircraft
12 missions.

13 This project demonstrated the power of EOL Field Catalog II for mission planning, flight
14 operations, and data archiving. Further, the Catalog provided enhanced learning and teaching
15 experiences for the undergraduate and graduate students involved directly in CSET. Although
16 the restricted passenger space on the GV limited the number of students who could actually fly
17 on missions, the Field Catalog allowed students to follow the progress of the CSET flights in real
18 time and examine the data as they were downloaded from the aircraft. The CSET Field Catalog
19 continues to contribute to classroom teaching and learning activities for both undergraduate and
20 graduate world-wide. A CSET teaching module was developed
21 (<https://www.eol.ucar.edu/content/cset-educational-module>;<http://cseteducation.weebly.com/>)
22 that allows students to experience the activities involved in carrying out a major aircraft field
23 deployment like CSET. This module makes heavy use of EOL's CSET Field Catalog

1 (<http://catalog.eol.ucar.edu/cset>) in playback mode (using the EOL Field Catalog Maps
2 application) and uses GV observations for analysis exercises that can be completed by the
3 students. The module endeavors to have students experience the types of activities involved in
4 the field program and includes mission planning exercises. This module can also serve as a
5 model for future EOL related aircraft field missions.

6 In summary, CSET made substantial advancement in our characterization of the
7 evolution of cloud systems along the southeast extent of the North Pacific anticyclone. The
8 observations will serve as a unique source of information for many future process and modeling
9 studies that will lead ultimately to improved simulations of low-level clouds in global models.
10 The observational techniques developed and demonstrated using the NSF/NCAR GV as an
11 observing platform provides a firm basis for future studies of boundary layer cloud regimes using
12 the GV.

13

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TABLES

Table 1: GV Instrumentation for CSET

Instrument or Observing System	Parameters Measured and Range
Thermometer (102AL TAT)	temp
Dewpoint Hygrometer (BUCK 1011C)	dewpoint temperature
Vertical Cavity Surface Emitting LASER Hygrometer (VCSEL)	water vapor concentration
Winds (gust measurements; aircraft motion and position)	3-D wind components
Cloud Droplet Probe (CDP)	cloud droplet spectra (2-50 μm)
Three-view Cloud Particle Imager (3V-CPI)	cloud droplet spectra (15-250 μm)
Two-Dimensional Optical Array Probe (2D-C)	cloud and drizzle droplet spectra (60-3200 μm)
HOLODEC	cloud and drizzle ((6 μm – 1 mm)
Ultra-High Sensitivity Aerosol Spectrometer (UHSAS)	aerosol spectra (60-1000 nm)
Cloud Nuclei Counter (CN)	aerosol concentrations (>11 nm)
King probe	cloud liquid water content
Heinmann Infrared Radiation Pyrometer	sea surface temperature
Microwave Temperature Profiler (MTP)	vertical temperature profile
Broadband SW and LW Radiometers (Kipp & Zonnen)	upward and downward irradiances
HIAPER Airborne Radiation (HARP)	downward spectral radiances
Digital Cameras (on right and left Wing)	forward looking images
Airborne Vertical Atmospheric Profiling System (AVAPS)	dropsonde signal processor
HIAPER Cloud Radar (HCR; 95 GHz)	reflectivity, spectral width, Doppler velocity, raw I and Q
G-Band Microwave Radiometer (183 GHz)	liquid water path
High Spectral Resolution LIDAR (HSRL)	backscatter and linear depolarization
Fast Response Ozone (FO3_AD)	Ozone mixing ratio
Carbon Monoxide (Aereo-Laser VUV)	carbon monoxide
Dropsondes	temp, humidity, and wind profiles

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1 Table 2: Dates for research flight couplets with latitude and longitude positions of
 2 trajectory start areas (blue circles) and end areas (red circles) 2 days later plotted in Fig 5.
 3 Two sampling areas were identified on RF02-RF07. Three were identified on RF08-RF15.
 4

Flight	West Bound: WB East Bound: (EB)	Dates	Lat 1 (°N)	Lon 1 (°E)	Lat 2 (°N)	Lon 2 (°E)	Lat 3 (°N)	Lon 3 (°E)
RF02	WB	7/7/2015	36.6	-136.7	34.0	-141.6		
RF03	EB	7/9/2015	28.6	-133.9	27.5	-142.6		
RF04	WB	7/12/2015	31.8	-130.6	28.4	-137.1		
RF05	EB	7/14/2015	27.9	-136.4	25.0	-146.4		
RF06	WB	7/17/2015	39.0	-131.5	34.49	-137.0		
RF07	EB	7/19/2015	27.2	-140.2	25.23	-149.5		
RF08	WB	7/22/2015	38.1	-128.4	35.9	-132.9	31.7	-138.4
RF09	EB	7/24/2015	28.3	-138.0	28.1	-147.4	25.1	-151.4
RF10	WB	7/27/2015	33.5	-129.6	29.7	-133.9	26.5	-140.0
RF11	EB	7/29/2015	28.5	-140.4	27.0	-146.8	23.7	-151.5
RF12	WB	8/01/2015	42.0	-130.0	40.8	-134.3	38.74	-138.1
RF13	EB	8/03/2015	33.5	-136.3	32.2	-142.6	30.02	-147.8
RF14	WB	8/07/2015	37.9	-131.9	34.7	-134.7	29.8	-137.8
RF15	EB	8/09/2015	28.5	-141.0	26.5	-148.3	23.4	-151.5

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FIGURE CAPTIONS

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Figure 1: NSF/NCAR G-V and visible GOES satellite image with aircraft path and winds on flight made on 27 July 2015 (RF07) during CSET. The blue points indicate where dropsonde launches made. Photos were taken during CSET GV flights and show clouds observed along CSET varying in the downstream direction (east to west) from solid stratus (right bottom photo) to mesoscale complexes to fair-weather cumuli (left bottom photo).

Figure 2: Photos of HCR on wing of GV and HSRL pointing up and down inside the GV.

Figure 3: Visible satellite images with trajectories used for mission planning and flight operations. White dotted line indicates great circle from Sacramento, CA to Kona, HI. a) Trajectory swarm used on 26 June 2015 for RF-10 flight planning, with GOES visible imagery from the morning of June 26; b) RF-10 flight path with dropsonde locations marked by closed circles, GOES visible imagery from morning of June 27 (day of flight); c) RF10 flight path and RF11 planning trajectories (return flight planned through squares at trajectory ends), GOES visible imagery from morning of June 28 (day between flights); d) return flight path flown for RF-11 with dropsonde locations, GOES visible imagery for June 29 (day of return flight).

Figure 4: a) Flight pattern plan for low-level sampling legs. Level legs are typically 8-10 minutes in duration. b) Screen shot of display from EOL Field Catalog II during RF 10; 27 July 2015 at 1042 UTC. Yellow line shows flight path with wind barbs overlain on high resolution visible GOES image and real-time photo from camera mounted on starboard (right) wing of GV.

1 **Figure 5:** Mean surface pressure, SST, and surface wind vectors for CSET (July 6-August 12)
2 from NCAR/NCEP Reanalysis (Kalany et al. 1996). Study area is indicated by shaded areas
3 and trajectories represent rough means of all trajectories flown.

4 **Figure 6:** Cloud fraction from GOES analyses (using Minnis et al, 2008). Blue points are
5 starting points of trajectory sampling areas on outbound flights from Sacramento. Red points are
6 areas sampled at end points of 48-52 hr. trajectories.

7 **Figure 7:** HSRL and HCR returns for RF 10 (27 July 2010) shown as a function of longitude
8 with corresponding high resolution visible GOES images ($4^{\circ} \times 4^{\circ}$ sample areas) stitched together.
9 The lettered areas indicate the box areas analyzed at the trajectory starting points. Since flights
10 were not made in a strictly east-west orientation, the data plotted on the longitudinal axes can be
11 relatively compressed during parts of the flight where there might be a strong north-south
12 component to the flight path. b) for inbound RF-11 (July 29 2010). b)

13 **Figure 8:** HSRL backscatter with HCR reflectivity and Doppler velocity for a) RF-10 segments
14 BC at beginning of trajectories and b) RF-11 segments BC at trajectory end points.

15 **Figure 9:** Soundings from G-V ascents and descents comparing the thermodynamic and wind
16 structure differences between equivalent air masses sampled on outbound RF-10 on segments
17 BC in Fig. 7a and on inbound RF-11 BC segments shown in Fig. 7b.

18 **Figure 10:** Effective droplet radius from GOES analyses for the outbound RF02 on July 7 at
19 1600 and 1800 UTC. The path of the G-V is indicated by a yellow line where the red marker at
20 the end of the line is the location of the G-V. Photos from camera on G-V and the GOES images
21 are from screenshots of the Field Catalog. The HSRL scattering returns are for the hour starting at
22 1700 UTC. The GV flight path is shown by yellow line and aircraft location by red dot. The
23 UHAS particle concentrations and the median cloud droplet sizes from the cloud probe are

1 shown as functions of longitude and altitude on both the RF02 outbound and RF03 inbound
2 flights.

3 **Figure 11:** HCR and HSRL returns from mesoscale cloud and precipitation complexes observed
4 on RF-07 (July 19 2015) at 1910-1920 UTC. GOES high-definition visible image for this time
5 period showing location of the aircraft near the time of the measurements. The photo of rainbow
6 was taken on a 500' leg at 1802 UTC (courtesy of Jonathan Emmett).

7 **Figure 12:** Optically thin clouds and ultra clean layers sampled from GV on 19 July 2015 by
8 HSRL starting at 1900 UTC. Path of aircraft during these measurements is overlaid (red line) on
9 high resolution visible GOES image at same time. Photo was taken at 1905 UTC from GV.

10 **Figure 13:** UHSAS aerosol concentrations observed on outbound July 7 (RF06) and inbound
11 July 9 (RF07) flight showing dominance of ultra clean layer (UHSAS concentration of $<10 \text{ cm}^{-3}$)
12 near cloud top on return flight RF07. The dashed black line is the cloud top height from
13 (Schwartz, 2018). Some of the UHSAS points missing below the top are from samples made
14 within the cloud where aerosol measurements tend to be unreliable.

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4 Figure 1: NSF/NCAR G-V and visible GOES satellite image with aircraft path and winds on
 5 flight made on 27 July 2015 (RF07) during CSET. The blue points indicate where dropsonde
 6 launches made. Photos were taken during CSET GV flights and show clouds observed along
 7 CSET varying in the downstream direction (east to west) from solid stratus (right bottom photo)
 8 to mesoscale complexes to fair-weather cumuli (left bottom photo).

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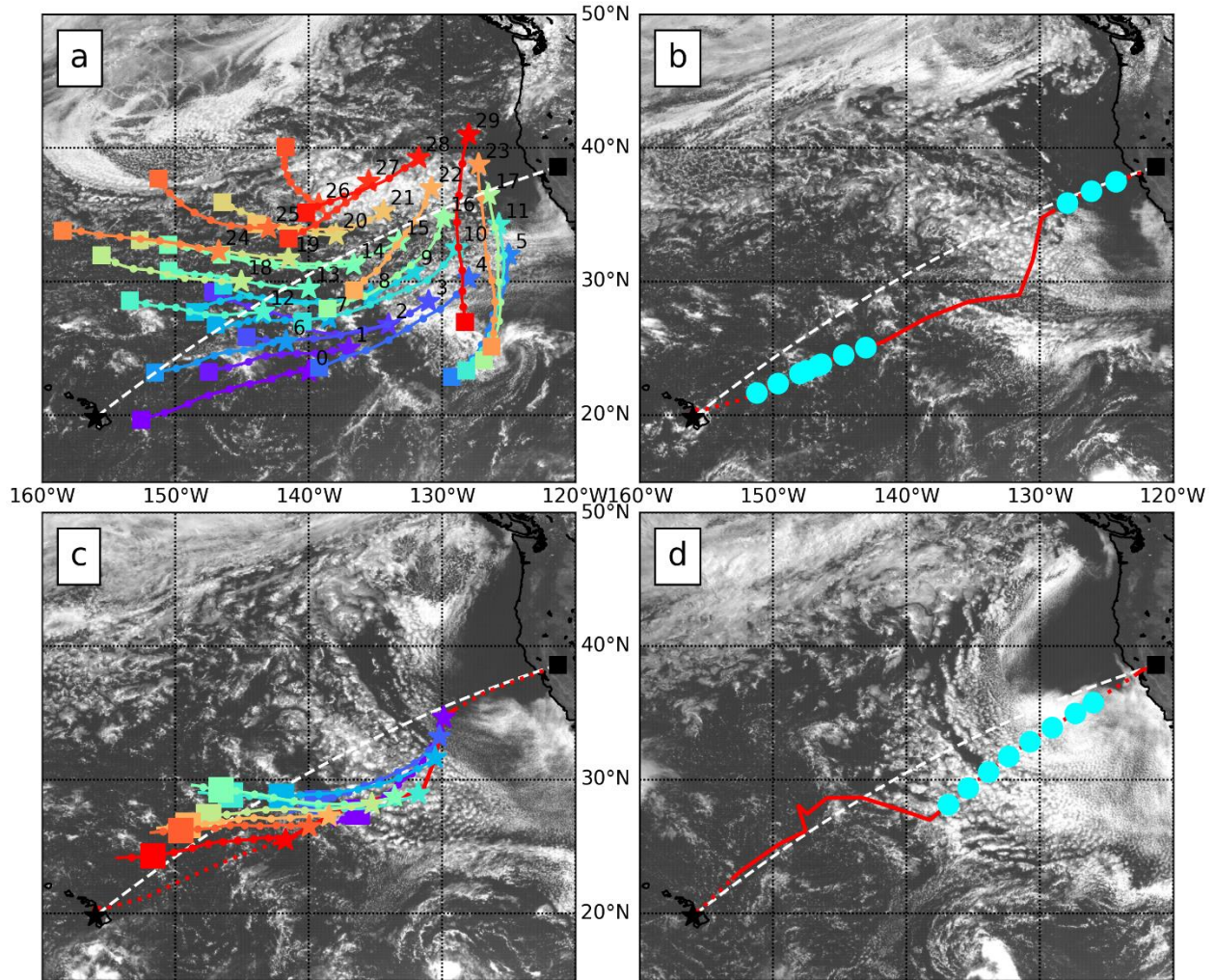
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4 Figure 2: Photos of HCR on wing of GV and HSRL pointing up and down inside the GV.

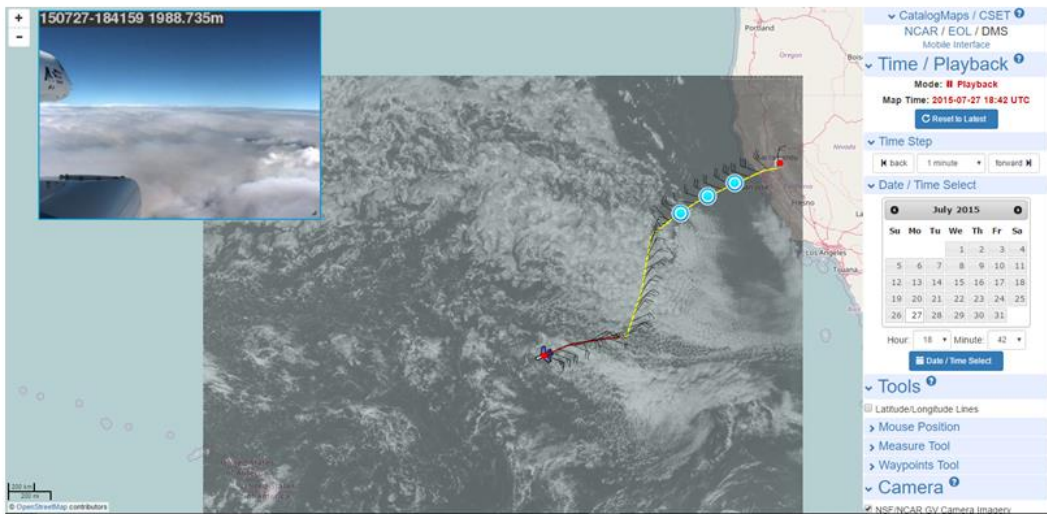
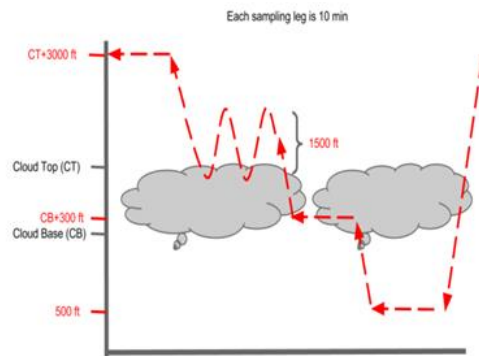
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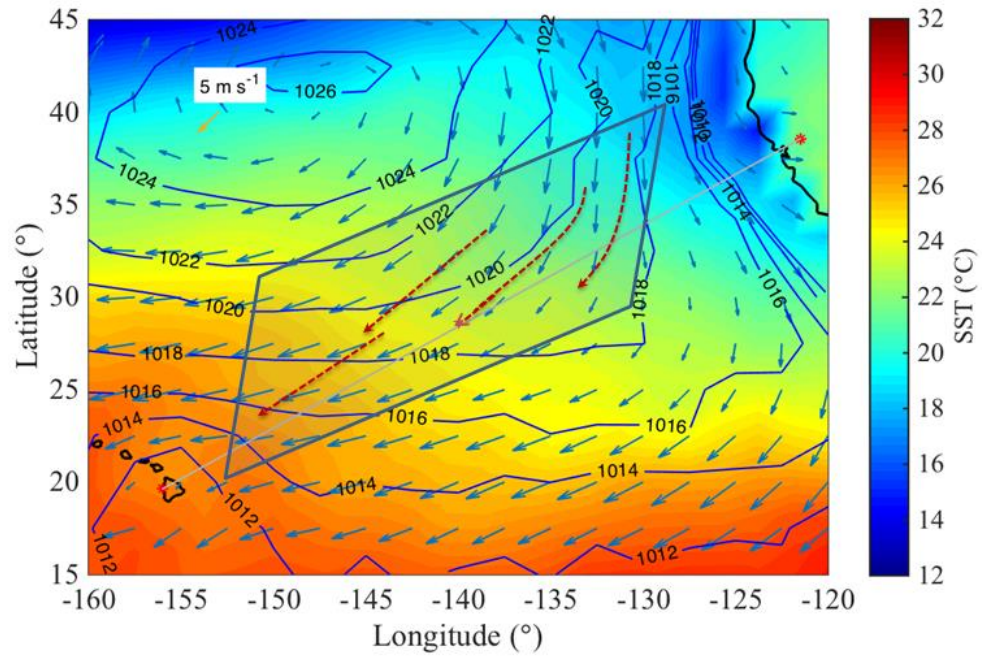


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 3 Figure 3: Visible satellite images with trajectories used for mission planning and flight
 4 operations. White dotted line indicates great circle from Sacramento, CA to Kona, HI. a)
 5 Trajectory swarm used on 26 June 2015 for RF-10 flight planning, with GOES visible imagery
 6 from the morning of June 26; b) RF-10 flight path with dropsonde locations marked by closed
 7 circles, GOES visible imagery from morning of June 27 (day of flight); c) RF10 flight path and
 8 RF11 planning trajectories (return flight planned through squares at trajectory ends), GOES
 9 visible imagery from morning of June 28 (day between flights); d) return flight path flown for
 10 RF-11 with dropsonde locations, GOES visible imagery for June 29 (day of return flight).
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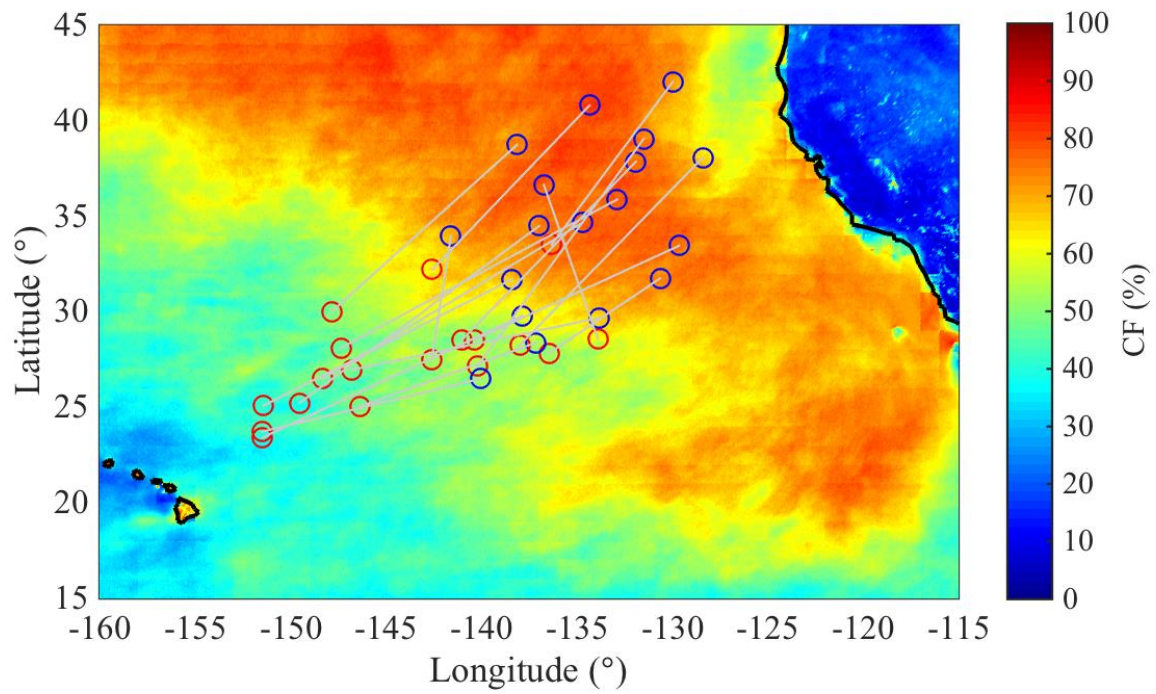


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Figure 4: a) Flight pattern plan for low-level sampling legs. Level legs are typically 8-10 minutes in duration. b) Screen shot of display from EOL Field Catalog II during RF 10; 27 July 2015 at 1042 UTC. Yellow line shows flight path with wind barbs overlain on high resolution visible GOES image and real-time photo from camera mounted on starboard (right) wing of GV.

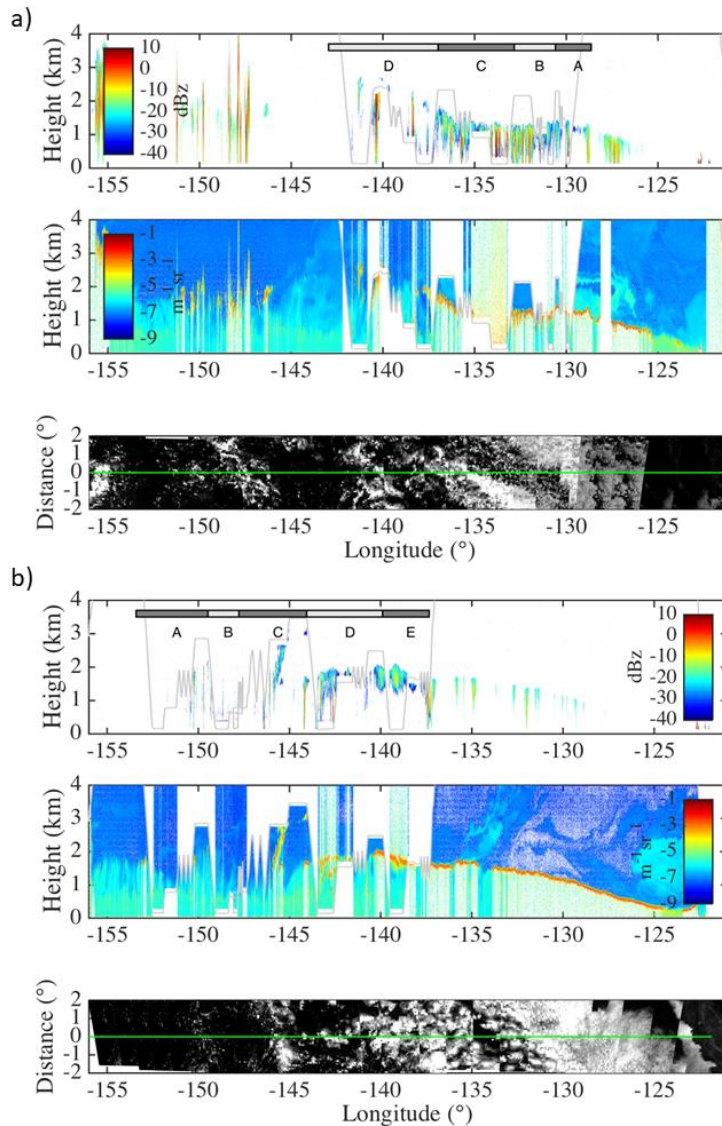


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 2 Figure 5: Mean surface pressure, SST, and surface wind vectors for CSET (July 6-August 12)
 3 from NCAR/NCEP Reanalysis (Kalany et al. 1996). Study area is indicated by shaded areas and
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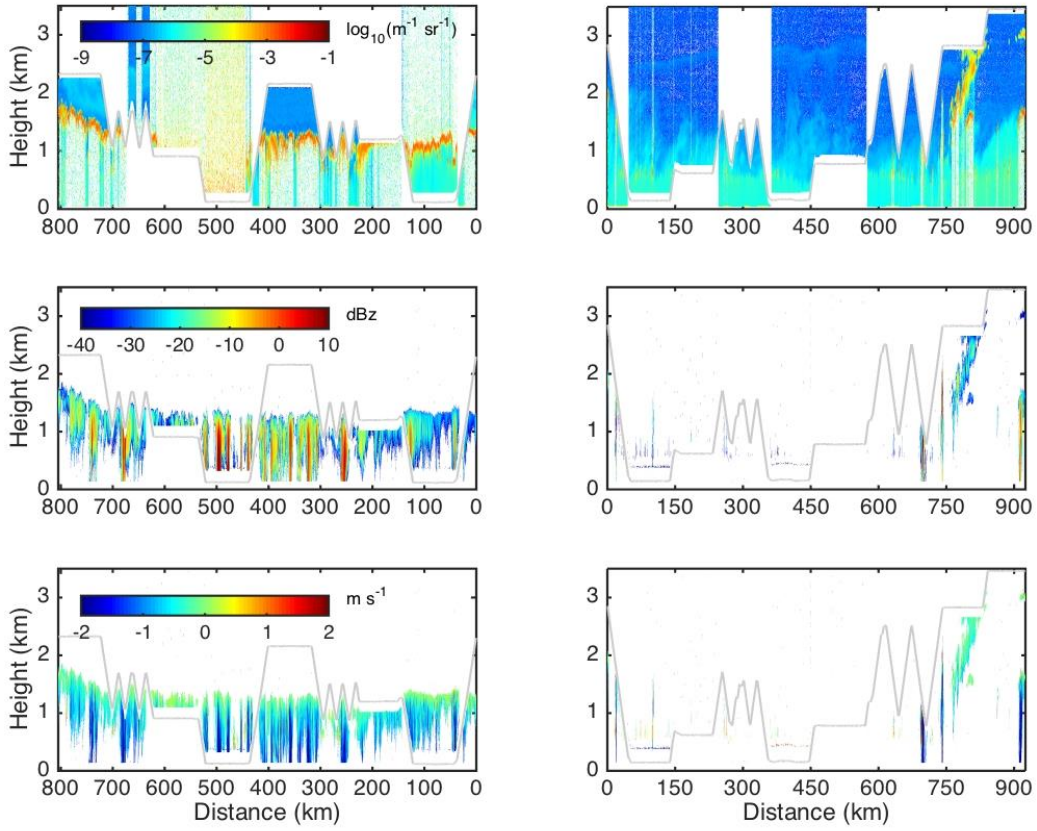
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 2 Figure 7: HSRL and HCR returns for RF 10 (27 July 2010) shown as a function of
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 6 plotted on the longitudinal axes can be relatively compressed during parts of the flight
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 8 RF-11 (July 29 2010).

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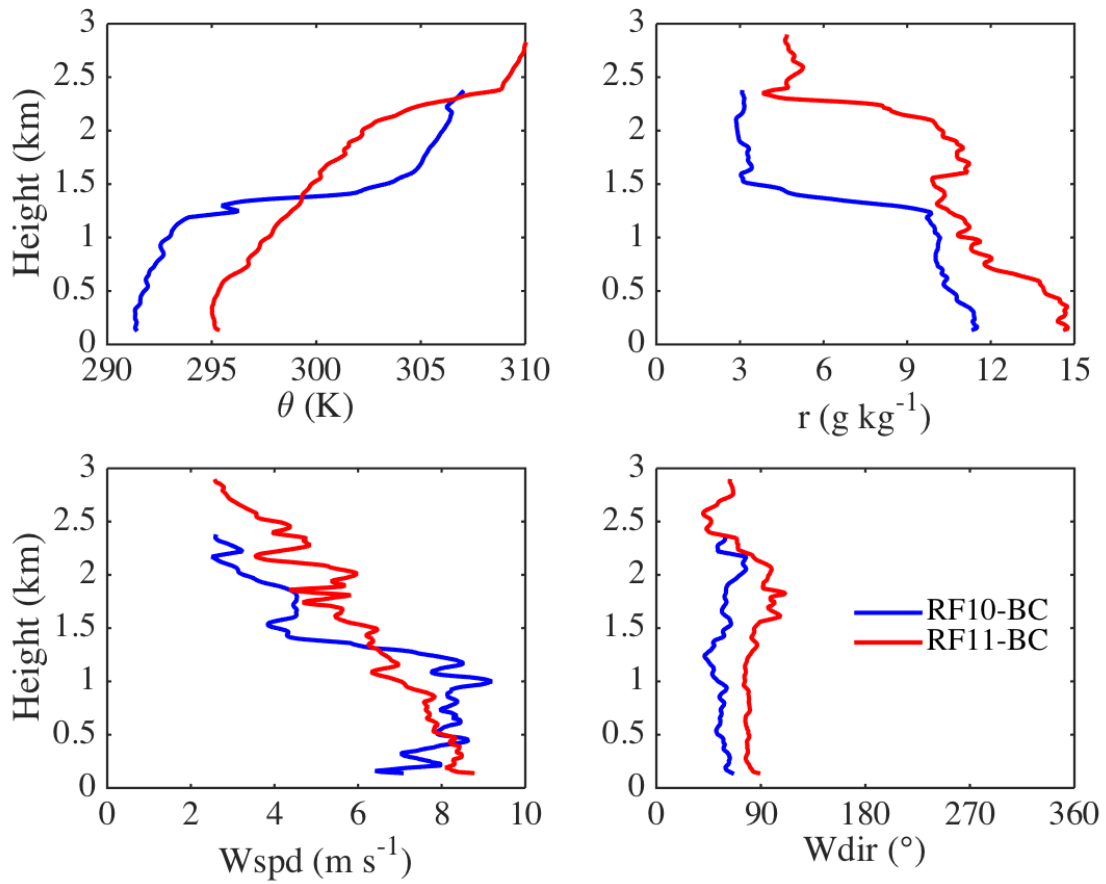


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5 Figure 8: HSRL backscatter with HCR reflectivity and Doppler velocity for a) RF-10 segments

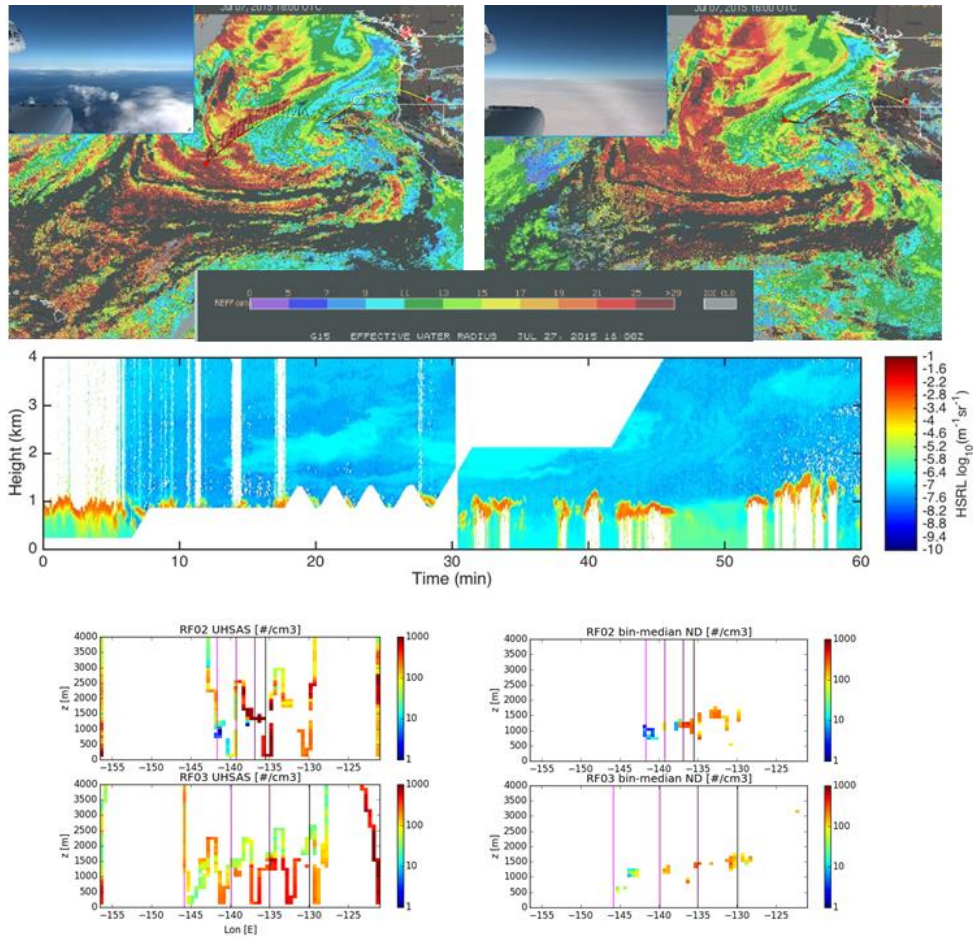
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3 Figure 9: Soundings from G-V ascents and descents comparing the thermodynamic and wind
 4 structure differences between equivalent air masses sampled on outbound RF-10 on segments
 5 BC in Fig. 7a and on inbound RF-11 BC segments shown in Fig. 7b

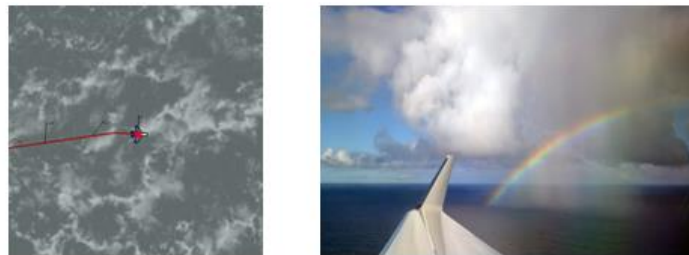
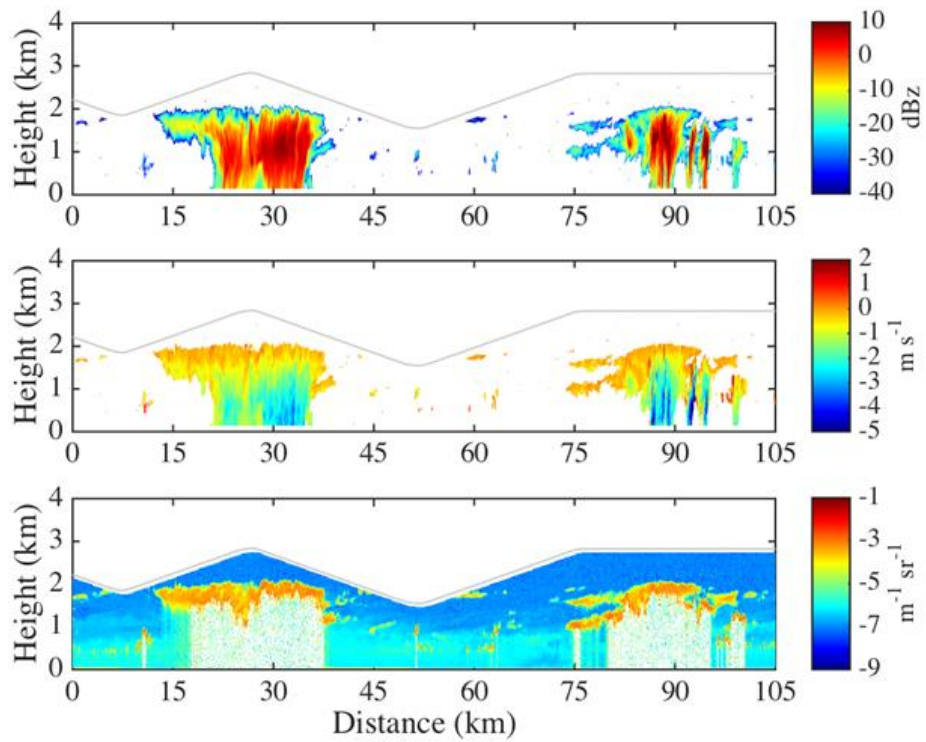


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 3 Figure 10: Effective droplet radius from GOES analyses for the outbound RF02 on July 7 at
 4 1600 and 1800 UTC. The path of the G-V is indicated by a yellow line where the red marker at
 5 the end of the line is the location of the G-V. Photos from camera on G-V and the GOES images
 6 are from screenshots of the Field Catalog. The HSRL scattering returns are for the hour starting at
 7 1700 UTC. The GV flight path is shown by yellow line and aircraft location by red dot. The
 8 UHAS particle concentrations and the median cloud droplet sizes from the cloud probe are
 9 shown as functions of longitude and altitude on both the RF02 outbound and RF03 inbound
 10 flights.

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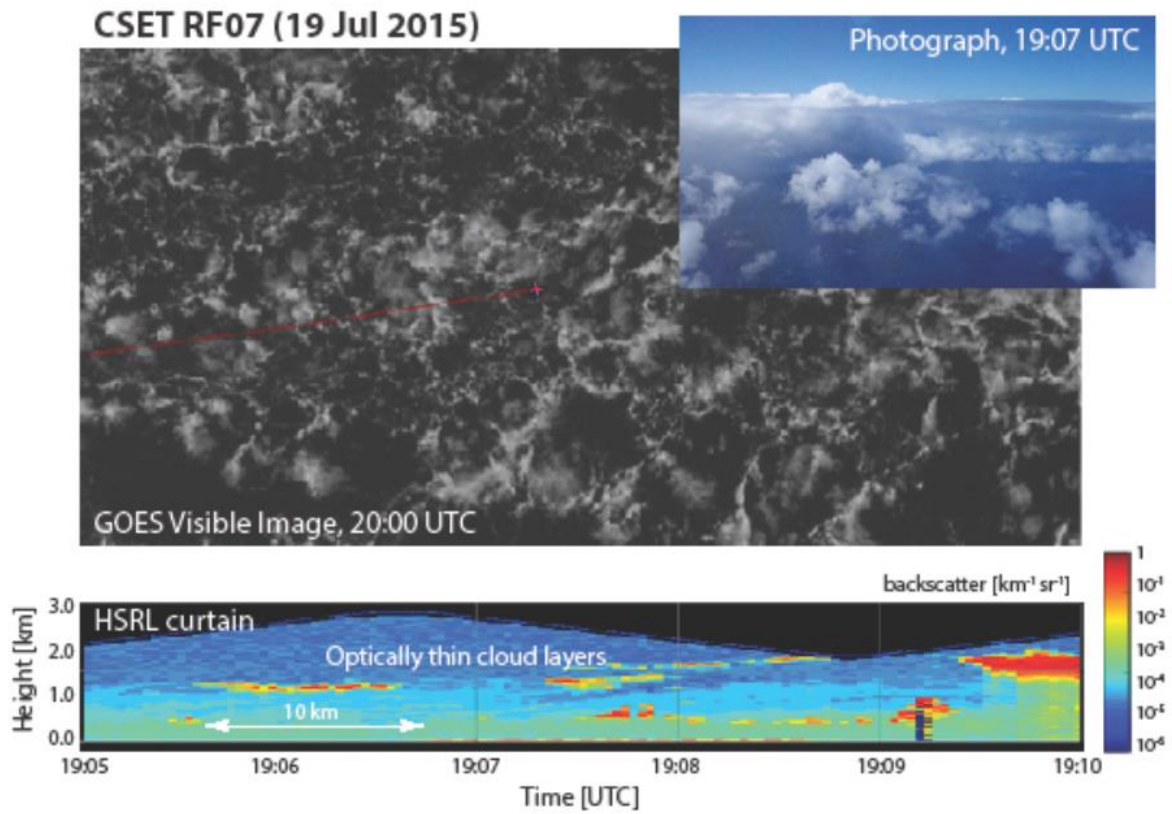
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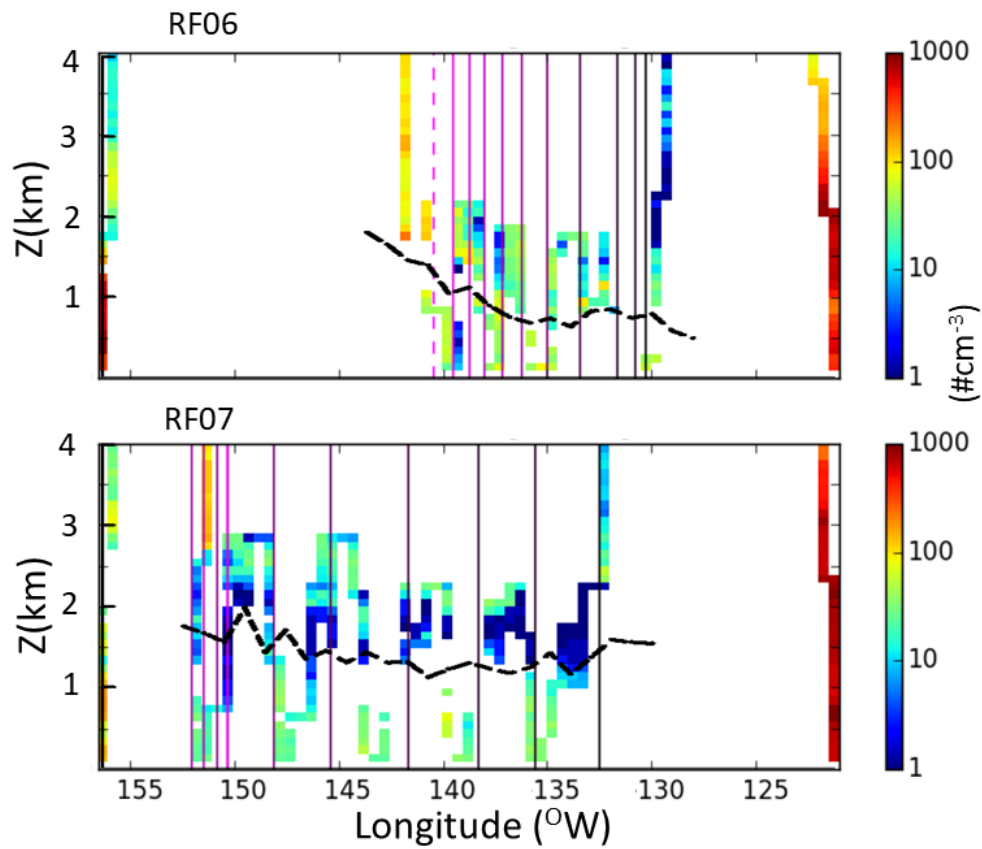
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Figure 11: HCR and HSRL returns from mesoscale cloud and precipitation complexes observed on RF-07 (July 19 2015) at 1910-1920 UTC. GOES high-definition visible image for this time period showing location of the aircraft near the time of the measurements. The photo of rainbow was taken on a 500' leg at 1802 UTC (courtesy of Jonathan Emmett).



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Figure 12: Optically thin clouds and ultra clean layers sampled from GV on 19 July 2015 by HSRL starting at 1900 UTC. Path of aircraft during these measurements is overlaid (red line) on high resolution visible GOES image at same time. Photo was taken at 1905 UTC from GV.



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 3 Figure 13: UHSAS aerosol concentrations observed on outbound July 7 (RF06) and inbound July
 4 9 (RF07) flight showing dominance of ultra clean layer (UHSAS concentration of $<10 \text{ cm}^{-3}$)
 5 near cloud top on return flight RF07. The dashed black line is the cloud top height from
 6 (Schwartz, 2018). Some of the UHSAS points missing below the top are from samples made
 7 within the cloud where aerosol measurements tend to be unreliable.

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