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The VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx): goals, platforms, and field operations

R. Wood[1], C. S. Bretherton[1], C. R. Mechoso[2], R. A. Weller[3], B. Huebert[4], F. Straneo[3], B. A. Albrecht[5], H. Coe[6], G. Allen[6], G. Vaughan[6], P. Daum[7], C. Fairall[8], D. Chand[1], L. Gallardo Klenner[9], R. Garreaud[9], C. Grados Quispe[10], D. S. Covert[1], T. S. Bates[11], R. Krejci[12], L. M. Russell[13], S. de Szoeke[14], A. Brewer[8], S. E. Yuter[15], S. R. Springston[7], A. Chaigneau[17], T. Toniazzo[16], P. Minnis[18], R. Palikonda[23], S. J. Abel[19], W. O. J. Brown[20], S. Williams[20], J. Fochesatto[21], and J. Brioude[22,8]

[1]Department of Atmospheric Sciences, University of Washington, Seattle, USA
[2]UCLA, Los Angeles, USA
[3]Woods Hole Oceanographic Institution, USA
[4]University of Hawai’i, Honolulu, USA

[5] Rosenstiel School of Marine and Atmospheric Science, University of Miami, USA
[6] School of Earth, Atmospheric and Environmental Sciences, University of Manchester, UK
[7] Brookhaven National Laboratory, Upton, USA
[8] NOAA Earth System Research Laboratory, Boulder, USA
[9] Departamento de Geofisica, Universidad de Chile, Chile
[10] Instituto del Mar del Perú, Perú
[11] NOAA Pacific Marine Environmental Laboratory, Seattle, USA
[12] Dept. of Applied Environmental Science (ITM), Stockholm University, Sweden
[13] Scripps Institution of Oceanography, University of California, San Diego, USA
[14] Oregon State University, Corvallis, USA
[15] North Carolina State University, Raleigh, USA
[16] Department of Meteorology, University of Reading, UK
[17] L'Institut de Recherche pour le Développement, Marseille, France
[18] NASA Langley Research Center, Hampton, USA
[19] The Met Office, Exeter, UK
[20] National Center for Atmospheric Research, Boulder, USA
[21] Department of Atmospheric Sciences, Geophysical Institute and College of Natural Sciences and Mathematics, University of Alaska, Fairbanks, USA
[22] Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado, USA
[23] Science Systems and Applications, Inc., Hampton, USA

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Correspondence to: R. Wood (robwood@atmos.washington.edu)

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Abstract

The VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx) was an international field program designed to make observations of poorly understood but critical components of the coupled climate system of the southeast Pacific. This region is characterized by strong coastal upwelling, the coolest SSTs in the tropical belt, and is home to the largest subtropical stratocumulus deck on Earth. The field intensive phase of VOCALS-REx took place during October and November 2008 and constitutes a critical part of a broader CLIVAR program (VOCALS) designed to develop and promote scientific activities leading to improved understanding, model simulations, and predictions of the southeastern Pacific (SEP) coupled ocean-atmosphere-land system, on diurnal to interannual timescales. The other major components of VOCALS are a modeling program with a model hierarchy ranging from the local to global scales, and a suite of extended observations from regular research cruises, instrumented moorings, and satellites.

The two central themes of VOCALS-REx are designed to improve understanding of (a) links between aerosols, clouds and precipitation and their impacts on marine stratocumulus radiative properties, and (b) physical and chemical couplings between the upper ocean and the lower atmosphere, including the role that mesoscale ocean eddies play. A set of hypotheses designed to be tested with the combined field, monitoring and modeling work in VOCALS is presented here. VOCALS-REx involved five research aircraft, two ships and two surface sites in northern Chile. We describe the instrument payloads and key mission strategies for these platforms and given a summary of the missions conducted.

1 Introduction

1.1 Scientific motivation

Interactions between the South American continent and the Southeast Pacific (SEP) Ocean are extremely important for both the regional and global climate system. Figure 1 indicates some of the key features associated with these interactions. The great height and continuity of the Andes Cordillera forms a sharp barrier to zonal flow, resulting in strong winds (coastal jet) parallel to the coasts of Chile and Peru (Garreaud and Muñoz, 2005). This, in turn, drives intense oceanic upwelling along these coasts, bringing cold, deep, nutrient/biota rich waters to the surface. As a result, the coastal SEP sea-surface temperatures (SSTs) are colder along the Chilean and Peruvian coasts than at any comparable latitude elsewhere. The cold surface, in combination with warm, dry air aloft, is ideal for the formation of marine stratocumulus clouds, and supports the largest and most persistent subtropical stratocumulus deck in the world (Klein and Hartmann, 1993). The presence of this cloud deck has a major impact upon the earth's radiation budget by reflecting solar radiation. This helps maintain cool SSTs, resulting in tight couplings between the upper ocean and lower atmosphere in this region. The unique climate of the SEP has been very sparsely observed, yet has great economic impact, with fishing in the Humboldt Current system representing 18–20% of the worldwide marine fish catch (source: UN LME report).

Global and regional models have great difficulties in the successful simulation of such a complex system. Most coupled GCMs obtain SSTs that are too warm and have too few clouds over the SEP, and show unrealistic features in the simulation of the warm tropics downstream (deSzoeke and Xie, 2008). There are major uncertainties in the representation of key physical processes in these models, which may be contributing to these errors (e.g. Mechoso et al., 1995; Ma et al., 1996). There are still significant problems with the representation of stratocumulus in large scale models over the SEP (Bretherton et al., 2004; Wyant et al., 2010). Observations are highlighting the importance of drizzle precipitation to SEP marine stratocumulus (e.g. Bretherton et al., 2004; Caldwell et al., 2005; Comstock et al., 2005), and observations and models are

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indicating an important role for drizzle in determining the cloud cover and radiative properties, in particular in promoting transitions from closed to open mesoscale cellular convection (e.g. Comstock et al., 2007; Savic-Jovcic and Stevens, 2008; Wang and Feingold, 2009; Wang et al., 2010) and the formation of so-called "pockets of open cells" (POCs) (Bretherton et al., 2004; Stevens et al., 2005). Physical parameterizations currently used in large scale models do not yet attempt to represent the mesoscale interactions between precipitation and cloud cover.

There is evidence that precipitation in marine stratocumulus may be influenced by anthropogenic aerosols (e.g. Geoffroy et al., 2008; Brenguier and Wood, 2009), which suggests a potential role for aerosols to influence cloud macrostructure in addition to their microphysics. Aerosol indirect effects on warm clouds are poorly understood (e.g Lohmann and Feichter, 2005). Satellite and research cruise data show strong gradients in aerosol and cloud microphysical properties between the near-coastal and more remote marine region of the SEP (Wood et al., 2008), making this a region where the Twomey effect may be particularly strong (see e.g. George and Wood, 2010), and a region potentially well-suited to the study of aerosol-cloud interactions.

In the SEP region there are important contributions to the atmospheric aerosol from both natural and anthropogenic sources (Tomlinson et al., 2007; Hawkins et al., 2010). Cloud droplet effective radii are low off the coast of Northern Chile, implying elevated concentrations of cloud droplets (Wood et al., 2008; George and Wood, 2010; Painemal and Zuidema, 2010). These elevated concentrations are broadly downwind of major copper smelters whose combined sulfur emissions total approximately 1 TgS yr^{-1}, comparable to the entire sulfur emissions from large industrialized nations such as Mexico and Germany. Offshore transport events have been shown to lead to elevated droplet concentrations offshore (Huneeus et al., 2006). However, little is actually known about the aerosol composition in the region since there have been very few measurements. We do not yet know the extent of the anthropogenic influence, nor do we fully understand the complex chemistry occurring in the pristine boundary layers further offshore.

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In the absence of cloud macrophysical responses, the reduced droplet effective radii resulting from increased concentrations of cloud droplets would increase the reflected solar radiation, and estimates of the component of the TOA solar radiation due to geographic variability in effective radius alone are ~10–20 W m^{-2} or 20–40% of the mean reflected shortwave (George and Wood, 2010). The magnitude of these estimates is such that the indirect effects of aerosols on clouds could lead to significant decreases in the amount of solar radiation entering the ocean, with significant implications for the ocean heat budget. However, we are beginning to understand that cloud responses to aerosols are not solely due to the Twomey effect alone, and that fast feedbacks can both enhance and counteract the Twomey effect (Ackerman et al., 2004; Xue et al., 2008, e.g.).

Early estimates of surface heat fluxes from climatologies and numerical weather prediction models showed diverse conclusions as to whether or not the offshore ocean gained from or lost heat to the atmosphere. Observations from deployment of the IMET surface mooring beginning in 2000 near the location of the annual maximum in stratus cloud cover showed that the ocean gains about 40 W m^{-2} annually and was subject to over 1 meter in evaporation. This surface forcing was applied to a relatively thin ocean surface mixed layer (annual maximum thickness of about 150 m) that overlays a cold, fresh water mass formed to the south. For oceanographers, the challenge is to understand how the shallow surface layer under the clouds maintained it temperature and salinity under this surface forcing.

Studies of the upper ocean heat budget offshore of the coastal upwelling zone indicate weak mean advection, energetic eddies, and the need for a source of cold, fresh water (Colbo and Weller, 2007). The supply mechanism, presumably including by a combination of mesoscale and submesoscale processes and the interaction between eddies and mixed layer dynamics, is unclear at the present time. Oceanic eddies which may contribute to advecting cold, fresh water anomalies westward from the coastal zone. Mixing processes may result in a vertical cold, fresh flux across the base of the ocean mixed layer. In general, little is known about eddy processes in the SEP, not only

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regarding their role in influencing the mixed layer properties over the broader SEP but also their potential rolein modulating the concentration of aerosol precursors such as dimethylsulfide and complex organic species.

Clouds over the SEP exhibit a much stronger diurnal cycle of cloud cover and liquid water path LWP (Rozendaal et al., 1995; Wood et al., 2002) than MBL clouds at comparable latitudes in the Northern Hemisphere. Regional model simulations (Garreaud and Muñoz, 2004) suggest that a large-scale diurnal subsidence wave formed by the interaction of the coastal jet along the Chilean coast with dry convective heating over the western Andean slopes travels at least 1000 km over the SEP and leads to a strong diurnal cycle of subsidence at remote locations. Using improved observations of how this wave influences the diurnal cycle of marine stratocumulus should be useful for assessing whether the diurnal variations of clouds in large scale models are well represented.

1.2 Motivation for the VOCALS regional experiment

The science issues described above are central to VOCALS (VAMOS Ocean-Cloud-Atmosphere-Land Study), an international CLIVAR program to develop and promote scientific activities leading to improved understanding, model simulations, and predictions of the southeastern Pacific (SEP) coupled ocean-atmosphere-land system, on diurnal to interannual timescales. VOCALS is ultimately driven by a need for improved numerical model simulations of the coupled climate system in both the SEP and over the wider tropics and subtropics. At the root of VOCALS's approach to the problem is the premise that its solution requires the synergy between numerical modeling, field studies, and extended observations such as buoys and satellites. With this in mind, the VOCALS Regional Experiment (VOCALS-REx) was conceived. In this manuscript we present an overview of the hypotheses, instrumentation, sampling platforms, sampling strategies, and missions conducted in pursuit of the science goals.

VOCALS-REx provided intensive observations of key processes contributing to the climate of the SEP. The observations are being used to help test a coordinated set of

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hypotheses presented in Table 1, to evaluate our ability to model the important physical and chemical processes in the SEP, and to help evaluate the performance of satellite retrievals. The VOCALS-REx hypotheses are organized into two broad themes: (1) testing hypotheses related to the impacts of aerosols upon the microphysical and structural properties of stratocumulus clouds and drizzle production; (2) testing hypotheses related to the coupled ocean-atmosphere-land system.

2 VOCALS-REx study region and dates

VOCALS-REx took place during October and November 2008, engaging over 150 scientists from 40 institutions in 8 nations. A variety of operations within a limited domain of the SEP coupled climate system were conducted (Fig. 2). REx operations took place in the domain 69–86° W, 12-31° S, with a concentration of sampling close to the 20° S latitude line. This parallel was chosen as it transects the heart of the SEP stratocumulus sheet (Klein and Hartmann, 1993; George and Wood, 2010), exhibits strong longitudinal microphysical contrasts (Bennartz, 2007; Wood et al., 2008; George and Wood, 2010; Bretherton et al., 2010), crosses a region where open cell formation is frequently observed (Wood et al., 2008), and is impacted by mesoscale ocean eddies (e.g. Colbo and Weller, 2007; Toniazzo et al., 2010a).

Overall, the VOCALS-REx period was characterized by near normal atmospheric conditions off northern Chile and southern Peru. However, significant variations in MBL depth occurred during October when midlatitude troughs reached the VOCALS region leading to four episodes (1–2 day long) of mid-tropospheric upward motion. In contrast, November exhibited less synoptic forcing and almost continuous subsidence (Rahn and Garreaud, 2010a,b; Toniazzo et al., 2010b).

In the following sections we first discuss the research platforms and the instrumentation used to make observations during VOCALS-REx, followed by the chief mission types and sampling strategy.

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3 Platforms and Instrumentation

A total of five aircraft (NSF/NCAR C-130, the DoE G-1, the CIRPAS Twin Otter, the FAAM BAe-146, and the NERC Dornier 228, see Table 2) two research vessels (the NOAA R/V Ronald H. Brown, RHB, and the Peruvian IMARPE José Olaya, see Tables 3 and 4 respectively) sampled the lower atmosphere and upper-ocean during REx. These mobile platforms were complemented by a number of ground-based observational sites (Table 5).

3.1 Aircraft platforms

Three of the aircraft deployed in VOCALS-REx (C-130, G-1 and Twin Otter) were operational from 14 October to 15 November 2008, with the other two aircraft (BAe-146 and Do-228) operational from 26 October-15 November 2008. Table 2 shows the dates over which missions were flown, and Fig. 3 provides a graphical representation of the aircraft sampling as a function of day and longitude. Tables describing the specific aircraft missions are disussed below. The aircraft measurements are designed to critically address several of the VOCALS hypotheses (Table 1), particularly those related to aerosol-cloud-drizzle interactions and those involving the sources and sinks of atmospheric aerosols.

3.1.1 NSF/NCAR Lockheed C-130

The NSF/NCAR C-130Q is operated by the Research Aviation Facility (RAF) at the National Center for Atmospheric Research (NCAR) in the United States. During REx the C-130 flew missions up to 9 h in duration reaching 1600 km offshore, making it the longest range aircraft used in REx. The C-130 has a large payload and carries instruments and sensors in pods and pylons on both wings. Details of the instrumentation payload on the C-130 are given in Table 2. The aircraft is flown at an airspeed of approximately 100 m s^{-1} for boundary layer sampling. Details of the missions flown in REx are given in Table 6.

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3.1.2 FAAM BAe-146

The Facility for Airborne Atmospheric Measurements (FAAM) BAe-146 aircraft is operated by a joint agreement between the Met Office and the Natural Environment Research Council (NERC) in the United Kingdom. The BAe-146 served as the medium range aircraft operated in REx, flying missions of typically 5 hours and sampling up to 900 km offshore. The BAe-146 has a large payload and carries instruments and sensors in pods and pylons on both wings. Details of the instrumentation payload on the BAe-146 are given in Table 2. The aircraft is flown at an airspeed of approximately 100 m s^{-1} for boundary layer sampling. Details of the missions flown in REx are given in Table 7.

3.1.3 DoE Gulfstream-1 (G-1)

The Department of Energy Gulfstream-1 (G-1) is operated by the Research Aircraft Facility (RAF) at the Pacific Northwest National Laboratory in the United States. The G-1 served as a medium range aircraft in REx, with sampling out to 800 km from the coast. The aircraft is flown at an airspeed of approximately 100 m s^{-1} for boundary layer sampling. Details of the instrumentation payload on the G-1 are given in Table 2. Details of the missions flown in REx are given in Table 8.

3.1.4 NERC Dornier-228 (Do-228)

The NERC Dornier-228 is operated by the Airborne Research and Survey Facility (ARSF) of the Natural Environment Research Council (NERC) in the United Kingdom. Its main role in VOCALS-REx was remote sensing of clouds out to 76° W, using lidar, a hyperspectral imager and polarimeter. Details of the instrumentation payload on the Do-228 are given in Table 2. Details of the missions flown in REx are given in Table 9. Most flights took place at an altitude of 4–5 km, with the remainder profiling the free troposphere to measure in-situ aerosol concentration. Typically, the Dornier overflew

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the flight path of the FAAM BAe146 with a similar airspeed (~ 100 m s^{-1}) and/or C-130 especially during the 20° S missions (see below).

3.1.5 CIRPAS Twin Otter

The Twin Otter operated by the Center for Interdisciplinary Remotely Piloted (CIRPAS) was instrumented to make turbulence, cloud microphysics, and aerosol measurements (Table 2) in the near coastal region of the VOCALS domain at 20° S, 72° W (a location termed here as Point Alpha). This relatively slow-moving aircraft (~60 m s^{-1}) made 5 hr flights originating from Iquique Chile that allowed for 3 hrs of sampling at Point Alpha on 18 flights (Table 10).

3.2 Ship platforms

The two ships in VOCALS-REx sampled different locations at different times. The R/V Ronald H. Brown was operational for two phases, the first from 25 October to 3 November 2008 and the second from 10 November to 2 December 2008. The Peruvian R/V José Olaya operated from 2–17 October 2008. Figure 3 provides a graphical representation of the ship sampling as a function of day and longitude. Figures describing the specific ship sampling strategies are disussed below. The ship measurements are designed to critically address several of the VOCALS hypotheses (Table 1), particularly those related to the upper ocean, aerosol-cloud-drizzle interactions, the physical and chemical interactions between the upper ocean and the lower atmosphere, and those involving the sources and sinks of atmospheric aerosols.

3.2.1 NOAA R/V Ronald H. Brown

The R/V Ronald H. Brown is operated by the National Oceanographic and Atmospheric Administration (NOAA), and served as the primary shipborne sampling platform for measurements in the vicinity of 20°S from the coast out to 85° W. The RHB

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also provided the means to deploy and recover moorings, drifters, and profiling floats during VOCALS REx. The RHB payload was designed to sample both the upper ocean and the lower atmosphere during REx, and details are given in Table 3. The multi-week RHB cruises with 6 daily upper air soundings and continuous measurements by most sensors are able to capture details of the MBL diurnal variations and aerosol-cloud-drizzle evolution in a way that the aircraft platforms cannot.

3.2.2 Peruvian R/V José Olaya

The José Olaya is operated by the Instituto del Mar del Perú (IMARPE) and operated in Peruvian near-coastal waters to provide extensive sampling of the upper ocean, with additional atmospheric measurements (Table 4). The sampling strategy (see below) was designed to examine the coastal upwelling region off Pisco-San Juan and extended from the Peruvian coast to 100–300 km offshore. The upper and lower atmosphere, the upper ocean property distribution and circulation, the biogeochemical characteristics, the plankton community structure as well as fishery responses were measured in a comprehensive, multidisciplinary basis. Details on the instrumentation onboard the Olaya are provided in Table 4.

The NCAR Earth Observing Laboratory (EOL) deployed a GAUS (GPS Advanced Upper-air Sounding systems) radiosonde station on the José Olaya during VOCALS with sondes launched by IMARPE and IGP (Instituto Geofsico del Perú) and IRD (Institut pour le Récherche et Devéloppement) scientists. A total of 133 soundings were launched at varying intervals from 30 September to 17 October 2008. The launch sites were predominately within an area about 200 km off the coast of the Ica region of southern Peru. Vaisala RS92G radiosondes were used throughout.

3.3 Fixed location sites

3.3.1 Paposo

Extensive aerosol and meteorological measurements were made at two sites near Paposo (25°01′ S, 70°28′ W) on the Northern Chilean coast (see map Figs. 2 and 4). In terms of the flow in the MBL, Paposo sits upwind of the primary focus area along the 20° S parallel and the measurements are designed to help constrain the physical and aerosol properties of airmassess leaving the continent to be advected over the broader SE Pacific region. Two sites were used near Paposo (Table 5) on the Northern Chilean coast. In-situ aerosol physical and chemical measurements, and meteorological sampling, were conducted at an elevated (upper) site (25°00′22.55″ S, 70°27′02.01″ W, 690 m a.s.l.) in the coastal range immediately adjacent to the ocean (1.7 km east of the shore). Lidar profiles and sounding launches were made from a lower site near sea-level in the village of Paposo (25°00′34.41″ S, 70°27′53.64″ W, 20 m asl) situated 100 m from the shore and 1.5 km to the WSW of the elevated site.

The elevated Paposo site is close to the peak of the hill in the coastal range in which it is situated (Fig. 4). Meteorological measurements from an automatic weather station at the upper Paposo site were started on 24 July 2008 and continued through the end of November 2008. During the period of intensive REx sampling at Paposo (17 October–15 November 2008), the upper site was almost continually within the marine boundary layer (MBL), although earlier in the season the inversion was occasionally lower which allowed sampling above the MBL. Table 5 details the measurements made at the upper Paposo site. Aerosol sampling was carried out using a custom-made multidirectional aerosol inlet and a multiport sampling configuration (see Fig. 4), with additional sampling lines for aerosols during 4–15 November. The sampling lines were used to connect with the scanning mobility particle spectrometer (SMPS), optical particle counter (OPC), nephelometers, aethalometer and ozone analyzer, and to collect submicron (< 1 µm diameter) aerosols on filters for chemical analysis. Aerosol filter measurements are described further in Chand et al. (2010). Meteorological and radiation measurements at the upper site were made by the University of Chile, and these measurements are described further in (Munoz et al., 2010).

At the lower Paposo site, an eye-safe 1.574 μm lidar, a weather station, and a sounding system were installed at the Paposo foothill site near the coast (Table 5 and map Fig. 4). The lidar was primarily vertically-pointing but some slant path scans were also performed. An identical set of meteorological parameters to that measured at the upper site was measured at the lower site. Multiple soundings per day were made from the site (Table 5 provides details of the launch times).

3.3.2 Paranal

A suite of aerosol measurements (see Table 5) in the free-troposphere were also made for just under three weeks (17 October to 4 November) at the high altitude European Southern Observatory at Paranal (24°37′39.00″ S, 70°24′17.85″ W, 2625 m a.s.l.), see map Fig. 4.

3.3.3 Iquique

The NCAR Earth Observing Laboratory (EOL) deployed a GAUS (GPS Advanced Upper-air Sounding systems) radiosonde station located in Iquique at the Universidad Arturo Prat Marine Sciences Campus (20°16'15"S, 70°07'52"W, 15 m asl). The stations was operated with the assistance of staff and students (see map Fig. 4). The launch site was on a steep slope, approximately 100 meters inland and 20 meters above the shoreline. A total of 192 radiosondes were launched at 4 hourly intervals from 15 October to 15 November 2008. Weather conditions at the site were generally clear and calm, with light sea (daytime) and land (nighttime) breezes. Vaisala RS92G radiosondes were used throughout.

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3.4 IMET Buoy

The Improved Meteorology (IMET) moored buoy is situated at approximately 20° S, 85° W (see Table 5 for precise location) at the western end of the sampling conducted during VOCALS-REx. The mooring has been operational since October 2000 and has provided an excellent intermediate-term record of both the surface meteorology/radiation, and of the upper ocean thermodynamic and dynamic structure. The meteorological and radiation measurements (Table 5) on the IMET buoy are described and their performance evaluated in Colbo and Weller (2009). The upper ocean measurements include temperature profiles, sea-surface temperature, salinity and currents. Further details can be found on the Upper Ocean Processes group at WHOI website (Table 5).

3.5 DART/SHOA Buoy

The Deep-ocean Assessment and Reporting of Tsunamis/Servicio Hidrográfico y Oceanográfico de la Armada de Chile (DART/SHOA) moored buoy at approximately 19.5° S, 74° W (see Table 5 for precise location) has been instrumented with meteorological and oceanographic measurements from October 2006 through January 2010. Meteorological measurements similar to those on the IMET buoy (Colbo and Weller, 2009) were made during much of this period. Upper ocean measurements of temperature and salinity at 14 depths were also made from 2006 onwards.

4 Sampling strategies

4.1 Matching sampling strategy to the VOCALS hypotheses

The REx sampling strategy was carefully designed and coordinated between platforms to test key VOCALS hypotheses listed in Table 1. Briefly, the VOCALS *aerosol-cloud-drizzle* hypotheses can be paraphrased as

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- *H1a*: aerosol variations significantly affect drizzle formation.
- *H1b/d*: drizzle-induced aerosol scavenging is required for POC formation and maintenance.
- *H1c*: cloud droplet radii are smaller near the coast due to anthropogenic aerosol emissions from South America.

In the REx region, both repeated surveying and sampling of specific features are useful for testing these hypotheses. Repeated sampling of the persistent gradients in aerosols, clouds and precipitation between nearshore and offshore regimes allows robust features of the gradient region to stand out and can be used to control for the covariability between aerosols, cloud macrostructure, and meteorology present on individual days. POCs present extreme examples (typically POCs are among the very cleanest and most strongly drizzling of airmasses in the SEP) that challenge our physical understanding of cloud-aerosol-precipitation interaction. Thus, an aircraft sampling strategy mainly focused on repeated sampling across the aerosol gradient region (with a few missions at the end parallel to the coast to characterize the offshore aerosol distribution upwind of the main REx study region), interspersed by opportunistic sampling of any POCs within range. Because of the desire for repeated sampling strategies, the aircraft favored particular times of day and did not attempt to characterize the diurnal variability of the cloud-topped boundary layer. The ship, mooring, and land-based sampling was aimed at complementing the aircraft through a better characterization of diurnal variability along 20° S (particularly with the RHB and the Iquique sounding site) and of the upstream anthropogenic aerosol sources (the Paposo and Paranal land sites).

The observational VOCALS *coupled ocean-atmosphere* hypotheses in Table 1 can be summarized:

- *H2b/d*: the offshore ocean mixed layer SST and salinity are decreased by ocean mesoscale eddy transports and entrainment from below. Oceanic DMS affects the boundary layer aerosol both in the upwelling zone and far offshore.

– *H2c*: a subsidence wave driven by slope heating on the Andes measurably affects the diurnal cycle of stratocumulus.

REx tackled these hypotheses mainly with a ship-based strategy (RHB and José Olaya), through sampling of clouds and atmospheric profiles through the diurnal cycle for H2c and survey-style sampling for H2b/d.

For both sets of hypotheses, IMET/DART mooring observations, satellite observations, and modeling on a range of scales are envisioned as vital complements to the in-situ observations.

4.2 Aircraft missions

The following aircraft mission strategies were used during REx:

1. *Cross-Section (XS) missions* along 20° S latitude (or other proximal latitudes) from the coast to close to the IMET buoy at 85° W (mission plan shown in Fig. 5) aimed to sample longitudinal gradients in clouds, the MBL, and aerosols. A total of 12 Cross-Section missions were flown along 20° S during REx (mission details shown in Fig. 6), with more flown along nearby latitudes (especially by the G-1 aircraft, see Table 8).

2. *POC-drift missions* which target either existing pockets of open cells (POCs) within overcast stratocumulus, or areas prone to POC development, and track these as they advect with the flow. A typical flight plan is shown in Fig. 7. On one occasion (27/28 October 2008) it was possible to sample the same advected POC with two aircraft missions spaced approximately 12 h apart;

3. *Stacked cloud and/or radiation missions* in which one or two aircraft sample a cloudy boundary layer airmass, typically using stacked legs 50–100 km in length. For two-aircraft missions, the upper aircraft primarily served as a radiation/remote sensing platform. All the aircraft other than the C-130 carried out missions of this

type. All Twin Otter missions were of this type, and additionally were carried out at the same location (at so-called "Point Alpha", 20° S, 72° W);

4. *Pollution Survey missions* in which aircraft sampled within a few hundred km of the Peruvian and Chilean coasts, with the aim of characterizing the lower atmosphere in the vicinity of pollution source regions. Figure 2 shows the typical locations of these flights;

5. *Intercomparison flights*, either aircraft-aircraft or to compare aircraft and ship measurements. The summary of intercomparisons is given in Table 11.

Tables 6, 7, 8, 9, and 10 present the specific missions flown by the C-130, BAe-146, G-1, Do228, and Twin Otter respectively.

4.3 Ship sampling

4.3.1 Peruvian R/V José Olaya

Figure 8 shows the track of the R/V José Olaya during the VOCALS REx cruise (2–17 October 2008). A total of 133 radiosonde soundings were acquired at varying spatio-temporal intervals from 30 September to 17 October 2008. Launch sites were predominately within the upwelling zone, about 200 km from the coast of the Pisco-San Juan upwelling region. Temperature, salinity and currents were measured to characterize the physical properties of the upwelling plume and the associated thermal front. A cluster of 8 surface drifters were deployed across the upwelling front in order to study the advective and diffusive processes inside this feature. The glider (autonomous underwater vehicle) mission was designed to examine the high-resolution structure and dynamics of the upwelling plume and thermal front off Pisco between 10 km and 100 km from the coast. The distribution of biogeochemical and biological parameters as well as fish abundance were also sampled to study the feedback of ocean/atmosphere interactions on biological and fishery activity.

4.3.2 NOAA R/V Ronald H. Brown

Figure 9 shows the track of the NOAA R/V Ronald H. Brown (RHB) during the VOCALS REx cruise (25 October to 2 December 2008). The cruise was planned and carried out as two legs: Leg 1 took place between 29 September to 3 November 2008 (arriving in the VOCALS-REx domain on 24 October 2008) and the RHB spent the majority of the time stationed at the IMET and DART mooring where recovery and redeployment of the moorings took place; Leg 2 took place between 9 November and 2 December 2008) and involved mapping the structure of the upper ocean and observing the atmosphere exclusively in the VOCALS-REx domain. After the RHB arrived in the VOCALS-REx domain, all of the sampling took place between 18° S and 22° S. Both Legs 1 and 2 involved studies of the ocean, the atmosphere, and their coupling as part of VOCALS-REx. Coordinated sampling with research aircraft working from Arica and Iquique took place during both cruises, with the majority of coordinated sampling taking place during Leg 2 (see Tables 6 to 9 for details of RHB-aircraft cosampling.

A total of 210 radiosondes were obtained at 4 hour intervals within the marine stratocumulus region. The ship sampled multiple times across relatively sharp transitions of cloud coverage including clear to broken to overcast stratocumulus cloud conditions. It was overcast approximately 80% of the time. Drizzle was prevalent: drizzle-containing cells with significant radar reflectivity ($Z > 0$ dBZ) were observed within a 60 km radius of the ship roughly half the time. The RHB research cruise for VOCALS-Rex was designed to address important aspects of both (1) aerosol-cloud-drizzle hypotheses and (2) coupled ocean-atmosphere hypotheses.

Aerosol-cloud-drizzle interactions vary in both space and time at a multitude of scales. The ship provided a platform to investigate in detail aerosol distributions and composition, including diurnal patterns during slow transects over much smaller regions of the marine boundary layer than is covered by the aircraft in a single hour. For this reason, the nearly 60-day cruise provided measurements of marine aerosol with a greater range of statistical variability, more chemical detail (such as organic functional groups, see Hawkins et al. (2010)), and highly accurate standards as references (such as ion chromatography) that are complementary to the aircraft-based data sets. In addition, the measurement of Radon on the RHB permits an assessment of the time that airmasses have spent over the ocean. The RHB studies of aerosol properties provide a comprehensive basis for addressing the variability in physicochemical properties. These measurements also serve as the basis for comparison of the sources and composition of the aerosol particles, providing comprehensive information with which to compare to satellite-retrieved properties.

The main objectives of the oceanographic field work conducted from the R/V Ron Brown (Legs 1 and 2) were: (i) to map the mean and eddy (mesoscale/submesoscale) property distribution within the upper ocean during VOCALS-REx; (ii) to deploy Lagrangian floats and drifters within the SEP; (iii) to recover and re-deploy the STRATUS and DART moorings. The synoptic survey across the SEP region included the collection of 35 CTD (Conductivity, Temperature, Depth profiles) up to 2000 m, and of 438 UCTD (Underway CTD) profiles, ranging between 200 and 800 m, to map the meridional distribution of properties across the SEP along three distinct latitude lines (Fig. 9). During the surveys, spatial and temporal sampling was increased to resolve a number of fronts and eddies, including 4 cyclones, 2 anticyclones, the current system and upwelling front at 21.5° S, and several fronts. Microstructure profiles to quantify mixing rates were obtained using a Vertical Microstructure Profiler (VMP) at 15 different locations that included the centers and margins of several of the eddies/fronts. The velocity structure of the upper 300–500 m, along the ship track, was observed by the ship's Acoustic Doppler Current Profiler (ADCP) – thus providing direct observations of the velocity field within the eddies, fronts and boundary currents to complement the property measurements. The ensemble of eddy measurements, in particular, is critical to assess their role in influencing the upper ocean's properties within the SEP. In addition to the synoptic measurements conducted during VOCALS-REx, the deployment of 10 profiling Lagrangian floats (SOLO floats, equipped with an oxygen sensor) and 19 surface drifters – some in eddies and some throughout the SEP – were designed to provide long-term context to the synoptic measurements – together with the instruments recovered and re-deployed on the IMET/STRATUS and DART buoys.

5 Satellite datasets produced specifically for VOCALS-REx

5.1 Geostationary Operational Environmental Satellites, GOES-10

5.1.1 Visible Infrared Solar-Infrared Split Window Technique (VISST)

Cloud and radiation parameters at 4-km resolution were derived from the Tenth Geostationary Operational Environmental Satellite imager (GOES-10), located at 60° W, using techniques developed at NASA Langley Research Center (LaRC). The GOES-10 data were analyzed every half hour for bounded by 10° S, 30° S, 65° W, and 90° W for the period between 11 September and 1 December 2008 and provided in near-real time for mission planning and analysis. Clouds were detected using the method of Minnis et al. (2008) and cloud properties were retrieved during the daytime using the Visible Infrared Shortwave-infrared Split-window Technique (VISST). At night, cloud properties were retrieved using the Shortwave-infrared Infrared Split-window Technique (SIST). The methods are described in detail for application to MODerate-resolution Imaging Spectroradiometer (MODIS) data by Minnis et al. (2009). The VISST uses the 0.65, 3.9, 10.8, and 12.0 µm channels, while the SIST uses the same channels minus the 0.65 µm data. The GOES-10 0.65 µm channel was calibrated against the Terra MODIS 0.64 µm channel using the technique of Minnis et al. (2002). The available derived parameters and means of accessing the data are similar to those described by (Palikonda et al., 2006). Both pixel-level and 0.5×0.5° averages are available each hour in image and digital form[1]. The VISST and SIST assume that only single-layer clouds are in a given pixel. In addition to the standard approach described by Minnis et al. (2010), cloud-top height and pressure were also retrieved using the method described by Zuidema et al. (2009). One additional parameter, a multilayer cloud identifier was computed

[1] Available from http://www-angler.larc.nasa.gov/cgi-bin/site/showdoc?mnemonic=VOCALS

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for each pixel using the approach of Pavolonis and Heidinger (2004). In addition to the cloud properties, spectral radiances and estimates of the top-of-atmosphere shortwave albedo and outgoing longwave radiation are included.

Figure 10 shows an example of three parameters for a GOES-10 image taken at 15:45 UTC, 27 October 2010. The pseudo-color RGB image (Fig. 10a) shows low clouds in the orange and peach shades with high cirrus clouds appearing white, gray, and magenta. The effective cloud temperatures T_c are displayed in Fig. 10b for an abbreviated range of 273 K< T_c <300 K to better show variations in stratocumulus cloud temperatures. Temperatures less than 273 K are indicated in the maroon shade. For this case, T_c ranges from 274 K to 284 K for the marine stratocumulus clouds. Smaller values are evident where thin cirrus clouds occur over the low clouds. Cloud optical depths (Fig. 10c) range from less than 1 at some cloud edges to more than 40 near 18° S, 78° W. The VISST-derived droplet effective radius, re, (Fig. 10d) varies from about 7 to 25µm across the scene with most of the largest values occurring around the edges of the POCs. The smallest droplets are mostly near the coast. The pixel-level products, exemplified in Fig. 10a–d, are used to produce 0.5×0.5° regional means at each half hour for many of the cloud and radiation parameters (Palikonda et al., 2006). Examples of 0.5×0.5° regionally-averaged cloud top-height Z_t and liquid water path (LWP) are shown in Fig. 10e, f. The Z_t values estimated as in Minnis et al. (2008) range from less than 1 km up to more than 3 km in the southwestern portion of the domain. Higher clouds near the center of the domain correspond to the thin cirrus clouds over the stratocumulus deck. The heights based on the Zuidema et al. (2009) technique are generally lower (not shown). The cloud LWP ranges from less than 50 g m^{-2} along the coast to over 200 g m^{-2} near the center of the domain. The LaRC cloud properties are based on near-real time retrievals. A refined dataset using the latest GOES-10 calibrations, a higher resolution sea surface temperature dataset, and algorithm updates is being generated to provide a more accurate set of cloud properties for stratocumulus research and for comparison with the other experiment measurements to better define the uncertainties in the satellite products.

5.1.2 Gridded cloud cover product from the University of Manchester/Met Office

Thermal infrared data from GOES-10 (Channel 4, 10.7 µm), converted to netCDF format and archived on the VOCALS data archive (see Sect. 8), have been used to generate a dataset documenting the variability in cloud amount during the VOCALS-REx period. The GOES-10 data were analyzed between 1 October and 8 December 2008 in a region from 3.5–31.5° S and 68.5–96.5° W. Note that this is a more extensive region than for the VISST GOES-10 products described above. Cloud-classification is performed on all available GOES-10 scans (typically every 15 to 30 min) at a horizontal resolution of 4 km, and cloud cover fractions are gridded at 0.25×0.25° resolution. Further details are given in Abel et al. (2010), and the dataset is available on the VOCALS archive, described below.

6 MODIS subset

To browse available MODIS imagery from NASA's Terra and Aqua satellites for the VOCALS-REx study region, there is a dedicated subset available on the MODIS Rapidfire website http://rapidfire.sci.gsfc.nasa.gov/subsets/?subset=VOCALS.

7 Other complementary products for VOCALS-REx

7.1 FLEXPART particle dispersion model

The FLEXPART Lagrangian particle dispersion model (Stohl et al., 2005) is used to simulate pollution transport and back-trajectories in support of VOCALS[2]. FLEXPART has been used successfully to study aerosol-cloud interactions (Avey et al., 2007; Brioude et al., 2009). FLEXPART was driven by the Global Forecast System (GFS)

[2]Available at http://www.esrl.noaa.gov/csd/metproducts/flexpart/

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data of the National Centers for Environmental Prediction (NCEP) with a horizontal resolution of 0.5×0.5°, with a temporal resolution of 3 h (analyses at 00:00, 06:00, 12:00, 18:00 UTC; 3 h forecasts at 03:00, 09:00, 15:00, 21:00 UTC), and 26 vertical levels. Millions of particles in FLEXPART were transported both by the resolved GFS winds and parameterized subgrid motions.

Forward simulations were performed to simulate air pollution transport from anthropogenic and biomass burning sources. A sulfur dioxide passive tracer (including direct emissions of sulfate) is released separately from each copper smelters and power plants and from the Lascar vocalno in Chile and South America, based on an inventory provided by Laura Gallardo. A sulfur dioxide passive tracer is also released from anthropogenic area sources in South America using the EDGAR 3.2 emission inventory. Emissions of a CO passive tracer from Southern Hemisphere biomass burning (south of 15° N) have been calculated using fire detection data, information on land use with emission factors from Andreae and Merlet (2001). All species are transported in the model for a duration of up to 10 days, after which they are removed from the simulation. Concentration fields were output every hour as 1 h averages at 1×1° grid spacing above the broader Pacific Ocean and South America, and 0.25×0.25° grid spacing over the VOCALS-REx domain. The FLEXPART tracers are only 10 days old and must be considered as mixing ratios above background.

In addition, backward simulations started along the DOE G-1 flight tracks were calculated[3]. Back-trajectories are started from boxes along the flight track every time the altitude of the aircraft varies by more than 100 m, or the difference in latitude or longitude is larger than 0.1°, or if 2 min of flight have elapsed. A total of 10 000 particles were released randomly from each box. The so-called “retroplumes” are then calculated backward in time over 8 days. The model output consists of the residence time of the particles in a given volume weighted by the local atmospheric density. When convolved with gridded emission fluxes from an emission inventory, a model-calculated

[3]Back-trajectory products for each individual G-1 flight are vailable at http://www.esrl.noaa.gov/csd/metproducts/flexpart/#back

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mixing ratio of the emitted species at the aircraft is obtained. The available products from each box include the surface residence time of the particles, the total column residence time, the anthropogenic CO and SO_2 contribution using the EDGAR 3.2 inventory, the SO_2 contribution from point sources and urban area using an emission inventory provided by Scott Spak[4]. Similar products are also available for the Ronald H. Brown (RHB). Specifically, backtrajectories are released every 3 h along the RHB track. EDGAR 3.2 inventory and the point source inventory provided by Laura Gallardo are used.

8 VOCALS data management

The NCAR/EOL provided data management support, coordination, and a long-term archive for VOCALS datasets. Details regarding VOCALS Data Management can be found on the VOCALS Project web page or directly[5]. This web page contains the VOCALS data policy, instructions for data submission, relevant documentation, links to related projects data, and access to the distributed VOCALS long-term archive [i.e. Master List (ML) of VOCALS International Datasets]. The ML contains direct access to all datasets organized by data category and data source site with associated dataset documentation. In addition, the VOCALS-Rex Field Catalog[6] used during the field phase to provide operations and mission/scientific reports, operational and preliminary research imagery/products is available as “browse” tool for use by researchers in the post-field analysis phase and is included as part of the archive.

[4] Available at http://www.cgrer.uiowa.edu/VOCA_emis/

[5] Available at http://www.eol.ucar.edu/projects/vocals/dm/index.html

[6] Located at http://catalog.eol.ucar.edu/vocals/

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9 Conclusions

The VOCALS Regional Experiment (VOCALS-REx) was an international field experiment designed to examine critical aspects of the coupled climate system of the Southeast Pacific region. VOCALS-REx took place during October and November 2008 in a domain 69–86° W, 12–31° S. Sampling with a variety of platforms including two ship, five research aircraft, land sites and two instrument moorings will ensure that researchers have a number of different observational angles with which to test the VOCALS hypotheses. The purpose of this paper is to bring together in one document the scientific goals, the platforms and instrumentation, and the sampling strategies employed during the program. It is hoped that this will serve the VOCALS research community by providing a central location that describes the essence of the field program. Perhaps more importantly, we hope that it will help to provide an important legacy that will be available to researchers over the coming years.

Appendix A

Acronyms

Table A1 provides details of the common acronyms used in this manuscript.

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the CIRPAS Twin Otter, the UK NERC Dornier 228, and, in the 2010 CUpEx phase, the Chilean DGAC King Air), the two ships (the NOAA Ronald H. Brown, and the Peruvian IMARPE José Olaya), and the land stations at Iquique and Paposo. The NCAR Earth Observing Laboratory is thanked for their dedication to coordinating and executing field logistics and data archive support for VOCALS Rex. The cooperation of hosts and collaborators in Chile and Peru who provided various critical facilities and support during REx is gratefully acknowledged. These include dedicated staff from the Chilean Weather Service (DMC), Ana Maria Cordova at Universidad de Valparaiso, Ricardo Muñoz, José Rutllant and fellow students at Universidad de Chile, Rosalino Fuenzalida, and fellow staff and students at Universidad Arturo Prat, Iquique, Chile; Yamina Silva and Boris Dewitte at Instituto Geofísico del Perú, Lima, Peru. Sounding operations were led by Tim Lim and quality control by Kate Young, both of NCAR/EOL. We also thank the Natural Environment Research Council, UK, for supporting the UK University contribution to VOCALS through grant NE/F019874/1, and to FAAM, Directflight Ltd, Avalon Engineering Ltd, and ARSF, for providing the BAe146 and Dornier-228 aircraft respectively. Without the untiring efforts of the staff of these Facilities the science objectives of VOCALS would not have been met. The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS) provided support for Swedish participation in VOCALS-Rex. The European Souther Observatory (ESO) are thanked for their help and support for measurements at Paranal. The NASA Langley GOES-10 analyses were supported by the Department of Energy Atmospheric Radiation Measurement Program through Interagency Agreement DE-AI02-07ER64546.

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Table 1. The VOCALS Hypotheses.

	1. AEROSOL-CLOUD-DRIZZLE HYPOTHESES
H1a	Variability in the physicochemical properties of aerosols has a measurable impact upon the formation of drizzle in stratocumulus clouds over the SEP.
H1b	Precipitation is a necessary condition for the formation and maintenance of pockets of open cells (POCs) within stratocumulus clouds.
H1c	The small effective radii measured from space in the coastal region of over the SEP are primarily controlled by anthropogenic, rather than natural, aerosol production, and entrainment of polluted air from the lower free-troposphere is an important source of cloud condensation nuclei (CCN).
H1d	Depletion of aerosols by coalescence scavenging is necessary for the maintenance of POCs.
	2. COUPLED OCEAN-ATMOSPHERE HYPOTHESES
H2a	Improvement of CGCMs performance in the SEP is key to the successful simulation of the ITCZ/SPCZ, complex, which will also benefit simulation of other regions. A significant improvement can be achieved through better representing the effects of stratocumulus clouds on the underlying surface fluxes and those of oceanic mesoscale eddies in the transport of heat.
H2b	Oceanic mesoscale eddies play a major role in the transport of fresh water from the coastal upwelling region and in the production of sea-water and atmospheric DMS in the coastal and offshore regions. Upwelling, by changing the physical and chemical properties of the upper ocean, has a systematic and noticeable effect on aerosol precursor gases and the aerosol size distribution in the MBL over the SEP.
H2c	The diurnal subsidence wave ("upsidence wave") originating in northern Chile/southern Peru has an impact upon the diurnal cycle of clouds that is well-represented in numerical models.
H2d	The entrainment of cool fresh intermediate water from below the surface layer during mixing associated with energetic near-inertial oscillations generated by transients in the magnitude of the trade winds is an important process to maintain heat and salt balance of the surface layer of the ocean in the SEP.

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Table 2. Details of the aircraft used in VOCALS-REx.

Aircraft	Location[a]	Dates	Measurements
Lockheed C-130[b]	Arica	15 Oct–15 Nov	**Atmospheric state**: thermodynamics; winds/turbulence; cloud water; cloud and drizzle microphysics. **Remote sensing:** radar reflectivity and dopper winds (University of Wyoming Cloud Radar, 95 GHz,nadir/zenith/45° down); cloud base/aerosol scattering (Wyoming Cloud Lidar, zenith); liquid/vapor water path (G-Band Vapor Radiometer, 183 GHz, zenith); broad-band irradiances. **Aerosols:** size distributions from 20 nm to 3 µm (heated/unheated); total CN; refractory CN; ultrafine CN; aerosol composition (aerosol mass spectrometer, SP2, single particle analysis); scattering and absorption; CCN spectrum, Static Diffusion (0.1%< S < 2.0 %) ; cloud water composition (major anions and cations, formaldehyde, peroxides, soluble Fe and Mn, organic acids, S(IV), total organic carbon). **Trace gases:** CO; O_3; SO_2/DMS (quadrupole mass spectrometry).
BAe-146[c]	Arica	26 Oct–13 Nov	**Atmospheric state**: thermodynamics; winds/turbulence; dropsondes; cloud water; cloud and drizzle microphysics. **Remote sensing:** spectrally-resolved hemispheric shortwave irradiances (SHIMS); hyperspectral IR radiance (ARIES); SW broad-band irradiances. IR upwelling brightness temperature (Heimann), liquid/water vapor path (89–183 GHz, MARSS, scanning). **Aerosols:** size distributions from 50 nm to 3 µm; total CN; aerosol composition (aerosol mass spectrometer, impactors, single particle analysis); scattering and absorption; wet nephelometer (RH-scanning); CCN (2 supersaturations); volatility. **Trace gases:** CO, O_3, NO_x, PAN, SO_2 (Teco, low sensitivity).
Gulfstream-1 (G-1)[d]	Arica	14 Oct–13 Nov	**Atmospheric state**: temperature, humidity, winds/turbulence/turbulence dissipation, cloud water (200 Hz), cloud droplet size distributions from 0.6–1550 µm (CAPS probe in particle-by-particle mode), 3-axis acceleration (200 Hz) **Remote sensing:** UV zenith/nadir **Aerosols:** size distributions from 16-3000 nm (TSEMS, FIMS, PCASP), total CN (> 10 nm and > 2.5 nm), CCN (3 supersaturations), aerosol composition (aerosol mass spectrometer, particle into liquid sampler, TRAC), scattering and absorption (3-wavelength nephelometer, 3-wavelength PSAP, Photo-thermal interferometer, Single particle soot photometer) **Trace gases:** O_3 (UV absorbance), O_3 (5 Hz), CO (VUV-Fluorescence), SO_2 (TEI, high sensitivity), organics (PTRMS).
Dornier-228 (Do-228)[e]	Arica	26 Oct–14 Nov	**Atmospheric state**: temperature, humidity, winds/turbulence. **Remote sensing:** visible/near IR hyperspectral imagery (Specim AISA Eagle and Hawk); aerosol backscattering and cloud top height (Leosphere lidar, 355 nm, nadir); full-Stokes polarimeter (AMSSP); **Aerosols:** size distributions from 0.2–30µm.
Twin Otter[f]	Iquique	16 Oct–13 Nov	**Atmospheric state**: thermodynamics; winds/turbulence; cloud water; cloud and drizzle microphysics. **Remote sensing:** radar reflectivity and Doppler winds (ProSensing 95 GHz FMCW radar pointing horizontally from starboard wing); nadir/zenith brightness temperature (Heimann). **Aerosols:** size distributions from 20 nm to 3 µm (heated); total CN; ultrafine CN; CCN (2 supersaturations).

[a] See map, Fig. 2 [b] Operated by the National Center for Atmospheric Research and funded by the US National Science Foundation. [c] Operated by the Facility for Airborne Atmospheric Measurements (FAAM), funded jointly by The Met Office and the Natural Environment Research Council in the UK. [d] Operated by the Research Aircraft Facility at the Pacific Northwest National Laboratory and supported by the US Department of Energy (DoE). [e] Operated by the Airborne Remote Sensing facility of the Natural Environment Research Council, UK. [f] Operated by the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) and supported by the US Office of Naval Research (ONR).

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Table 3. Details of the Ronald H. Brown (RHB) measurements in VOCALS-REx.

Location[a]/Dates	Measurements
R/V Ronald H. Brown[b] See map Fig. 9 24 Oct–2 Dec	**Atmospheric state**: temperature, humidity, winds (flux tower), cloud observations and photography **Upper air**: 6×daily radiosonde launches. **Remote sensing**: C-band radar reflectivity and Doppler winds within drizzle (3-d volumetric and range-height scans every 3 min, 60 km range); W-band radar reflectivity profiles and Doppler velocity for cloud/drizzle (vertically pointing 95 GHz cloud radar); cloud base and drizzle backscatter (lidar ceilometer); volumetric lidar backscatter and winds (scanning High Resolution Doppler Lidar, also operated in vertically pointing mode, 6 km range); liquid water path and water vapor path (23/31/90/183 GHz microwave radiometers); broad band irradiances. **Aerosols**: size distributions from 20 nm to 10 µm diameter; CN (> 12 nm); ultrafine CN (> 3 nm), aerosol mass and composition (Aerosol Mass Spectroscopy 80–800 nm, super- and sub-micron impactors for ion and gravimetric mass analysis, 7-stage impactor for ion composition, single particle analysis, submicron FTIR for organic functional groups and mass, single particle STXM-NEXAFS and SEM-EDX analysis); super- and sub-micron scattering and absorption coefficients at three visible wavelengths; CCN spectrum (5 supersaturations from 0.1–0.6%); aerosol volatility at 230 C for 20–800 nm size interval; aerosol profiling (differential absorption spectroscopy, MAX-DOAS) **Trace gases:** Radon (^{222}Rn); O_3; atmospheric DMS (quadrupole mass spectrometry); seawater DMS/DMSP, chlorophyll-*a*, and dissolved CO_2; reactive trace gases (differential absorption spectroscopy, MAX-DOAS) **Oceanography:** 438 Underway CTD profiles (temperature, conductivity, pressure) to between 200 and 800 m depth, horizontal spacing from 1-30 km; 35 CTD profiles to 2500 m in and outside of eddies/fronts with associated water sampling for the collection of nutrients, salinity and oxygen samples; 10 SOLO profiling floats deployed with dissolved oxygen sensors; underway sea-surface salinity/temperature measurements; 19 surface drifters; 15 Vertical microstructure profiles (high resolution temperature, conductivity, velocity, pressure).

[a] See map, Fig. 2

[b] Operated and funded by the US National Oceanographic and Atmospheric Administration (NOAA), with additional support for shipborne sampling from the National Science Foundation.

Table 4. Details of the R/V José Olaya Balandra measurements in VOCALS-REx.

Location[a]/Dates	Measurements
R/V José Olaya Balandra[b] See map Fig. 8 2–17 Oct	**Atmospheric state**: temperature, humidity, winds, cloud observations, photography. **Upper air**: regular radiosonde launches predominately within an area about 200 km off the Pisco-San Juan region (see Fig. 8). **Oceanography:** 113 CTD profiles (temperature, conductivity, pressure) to 1000 m depth in the coastal upwelling off southern Peru extending from the coast to 80-320 km, horizontal spacing from 19 km (nearshore) to 32–45 km (offshore). The CTD was deployed with dissolved oxygen and fluorescence sensors. Continuous records of VM-ADCP data (bin size 8 m, ping rate 0.3 s^{-1}); underway sea surface temperature/salinity; 8 surface drifters. Collection of water samples for determination of oxygen, nutrients (phosphate, silicate, nitrate, nitrite), ph and chlorophyll-a concentrations in 78 stations. Underway measurements of partial pressure of carbon dioxide (pCO_2) complemented the biogeochemical observations. **Glider mission:** continuous physical and biogeochemical data (temperature, salinity, dissolved oxygen, fluorescence and turbidity) were collected by a repeating section between 10 km and 100 km from the coast off Pisco. Observations every 24 s, 5 m along the vertical over the upper 200 m depth started in 3 October to 14 November 2008. **Biology:** 37 Standard and 35 WP-2 net sampling for phytoplankton and zooplankton qualitative analysis, respectively; 17 Hensen net samples for zooplankton vertical distribution; 153 samples at depths 0–75 m (Niskin bottles) for phytoplankton quantitative analysis); 313 samples collected underway at 20 min interval with the Continuous Underway Fish Egg Sampler (CUFES). **Fishery hydroacoustics:** continuous records of echosounder EK60 at frequencies 38, 120 and 200 kHz to document fish (in particular anchovy) abundance and patterns of distributions for the upper 500 m on the vertical. Data averaged each 1 Basic Sample Unit (1 nm) horizontally.

[a]See map, Fig. 2

[b]Operated and funded by the Instituto del Mar del Perú (IMARPE), with additional support for upper air measurements and ship mobility from the National Science Foundation, Institut pour le Recherche et le Développement and Institut National des Sciences de l'Univers for the glider mission.

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Table 5. Details of the surface sites used in VOCALS-REx.

Paposo (upper site)	25°00′ S, 70°27′ W, 690 m a.s.l.	15 Oct–15 Nov (23 Jul–15 Nov for met. and radiation)	**Atmospheric state:** temperature, humidity, winds, pressure (weather station), downwelling shortwave and net (LW+SW) radiation (23 July–15 Nov). **Aerosols:** Aerosol size distribution (20 nm–5 µm, SMPS/OPC); total CN (CPC, 4–15 Nov only), aerosol composition (submicron impactors for ion and gravimetric analysis, elemental S-XRF and molecular analysis), light scattering (27 Oct–15 Nov, Radiance Research nephelometer, single wavelength); absorption (PSAP, Nov 4–15 only); black carbon (aethelometer, 4–15 Nov only); Cloud droplet residuals (4–18 Nov only, Counterflow virtual impactor with instrumentation as at Paranal [see below] behind, plus liquid water content); **Trace gases:** O_3.
Paposo (lower site)	25°01′ S, 70°27′ W, 31 m a.s.l.	15 Oct–15 Nov	**Atmospheric state:** temperature, humidity, winds, pressure (weather station), downwelling shortwave and net (LW+SW) radiation (23 July–15 Nov). **Upper air:** multiple daily radiosonde launches (2×daily at 00/12 UTC, 17–23 Oct; 3×daily at 00/12/21 UTC, 24 Oct–9 Nov; 4×daily at 00/06/18/21 UTC, 11–12 Nov; 5×daily at 00/06/12/18/21, 13–15 Nov) **Remote sensing:** lidar backscatter from aerosols and clouds, polarized (mostly vertical pointing, but some slant path scans, 1.574 µm wavelength, 1.5 m maximum vertical resolution, linear and circular polarizations)
Paranal	24°38′ S, 70°24′ W, 2635 m a.s.l.	17 Oct–4 Nov	**Aerosols:** Aerosol total concentration (TSI 3010 CPC, >10 nm); Aerosol size distributions (DMPS 20–300 nm, unheated/heated to 50–400 C; OPC 0.26–2.2 µm); Volatility TDMA (not continuous, only occasionally range 20–300 nm); Aerosol scattering (nephelometer) and light absorption (PSAP and Aethelometer); Samples for single particle analysis.
Iquique	20°16′ S, 70°08′ W, 15 m a.s.l.	15 Oct–15 Nov	**Upper air:** 6×daily radiosonde launches (00, 04, 08,...UTC)
IMET Buoy	19°43′S, 85°35′W	Entire period[a]	**Atmospheric state:** Winds (propeller/vane), temperature, pressure, humidity (capacitance), precipitation (tipping bucket); **Radiation:** downwelling longwave and shortwave irradiance. **Oceanography: upper ocean temperature, salinity and currents, with depth sampling varying over time.**
DART/SHOA Buoy	19°34′ S, 73°47′ W	31 Oct – end[b]	**Atmospheric state:** Winds (propeller/vane), temperature, pressure (from 31 Oct 2008 only), humidity (capacitance, from 31 Oct 2008 only); **Radiation:** downwelling longwave and shortwave irradiance. **Oceanography: temperature and salinity at 14 depths from 10–310 m**

[a] The IMET buoy has been providing data nearly continuously since October 2000. Data are available from the VOCALS data archive. A detailed description of the meteorological instruments and their performance can be found in Colbo and Weller (2009). Oceanographic measurements are detailed at http://uop.whoi.edu.

[b] The DART/SHOA buoy was operational 31 October 2008-3 Jan 2010. Data are available from the VOCALS data archive.

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Table 6. Details of C-130 aircraft missions conducted in the VOCALS Regional Experiment.

Flight	Date	Times [UTC] T/O	Land	Mission/Location	Notes
RF01	15 Oct	16:49	20:11	Partial 20° S to 20° S, 75° W	Day mission, solid cloud deck
RF02	18 Oct	13:04	21:27	20° S/POC Drift	Day mission, solid cloud deck, polluted with little drizzle. POC sampling of rift-like feature
RF03	21 Oct	06:02	14:22	20° S	Night mission, solid cloud deck, significant microphysical gradient; notably shallow MBL
RF04	23 Oct	06:01	14:20	20° S	Night mission, broken/open cells at far west
RF05	25 Oct	06:32	15:25	20° S	Overflight of RHB
RF06	28 Oct	06:20	15:10	POC Drift	Night mission, very clear POC edge sampled
RF07	31 Oct	06:03	14:58	POC Drift/20° S	Night mission,
RF08	2 Nov	06:00	15:20	POC Drift	Night mission, overflight of RHB
RF09	4 Nov	06:02	14:54	POC Drift/20° S	Night mission, POC sampling
RF10	6 Nov	06:10	14:19	20° S	Night mission, overcast with breaks and drizzling large mesoscale cells at west
RF11	9 Nov	12:59	21:34	Pollution Survey to 30° S	Day mission, Variable cloud morphology along coast, pollution plumes
RF12	11 Nov	12:56	21:44	Pollution Survey to 30° S	Day mission, Overcast cloud, overflight of RHB
RF13	13 Nov	13:00	21:55	POC/20° S	Day mission, Extensive clearing near coast, then thick cloud with POC
RF14	15 Nov	13:00	22:00	POC Drift	Day mission, rift/clearing sampled, high SO_2 just above MBL at 80° W

Table 7. Details of BAe-146 aircraft missions conducted in the VOCALS Regional Experiment.

Flight	Date	Times [UTC] T/O	Land	Mission/Location	Notes
B408	26 Oct	10:05	21:27	20° S XS	Profiling up to 1500 m out to 79.5° W with saw-tooth profile to 4800 m at west-most point. Reciprocal return. Increasing cloud base and tops with distance offshore
B409	Oct 27	19:59	14:22	POC Drift	Sampled open cellular (POC) region at ~78° W at dusk. Very low CN in POC.C-130 sampled same advected airmass 12 h later
B410	29 Oct	09:59	15:16	20° S XS	Detour to rendezvous with DART buoy on outbound leg only. Profiling to 1600 m with deep profile to 4600 m at west-most point.
B411	30 Oct	10:25	15:48	RHB cosampling	RHB on station near the DART Buoy. Cloud and MBL profiles en route. Several 20-min back and forth legs (parallel to mean wind) over RHB
B412	31 Oct	09:47	14:52	20° S XS	Profiling up to 1500 m out to 79.5° W. High level return with 7 dropsondes, every degree from 78° W to 72° W.
B413	3 Nov	11:03	16:05	Ilo pollution survey	Profiling from Arica to DART buoy to study coastal gradient in pollution, followed by coastal fly-by aligned to mean wind direction to study potential pollution from the Ilo smelter. No evidence of fresh pollution due to smelter down-time. 4 dropsondes
B414	4 Nov	09:44	15:04	20° S XS	Profiling up to 1500 m out to 79.5° W. High level return with 7 dropsondes, every degree from 78° W to 72° W
B415	5 Nov	09:12	14:33	POC Drift	Sampled open cellular (POC) region at ~78° W. Very low CN observed in POC. High-level return to base with 10 dropsondes released.
B416	7 Nov	10:32	15:27	POC Drift	Sampled open cellular (POC) region at ~78° W. Very low CN observed in POC. High-level return to base with 11 dropsondes released (2 into POC)
B417	9 Nov	09:58	21:34	20° S XS	Profiling to 1600 m with deep profile to 3200 m at west-most point. Reciprocal return. Transition in wind dynamics (coastal jet) observed at 75° W.
B418a	11 Nov	11:31	16:13	Coastal pollution Survey south from Arica	Fly-by along coast (100 km offshore) in straight line from Arica to Antofagasta, with MBL and cloud saw-tooth profiling. Refuel at Antofagasta.
B418b	11 Nov	17:49	21:17		Return to Arica with legs directed offshore and parallel to mean wind to study land source Lagrangians. Several point sources noted.
B419	12 Nov	11:29	16:51	RHB Cosampling	Straight run from Arica to Ron Brown whilst on station near the DART Buoy performing cloud and MBL profiles en route. Several 20-min reciprocal legs (parallel to mean wind) performed, centred on Ron Brown, with cloud, MBL and deep profiles to 3.2 km
B420	13 Nov	09:58	15:13	20° S XS/POC	profiling up to 1500 m out to 81° W with a high level return and 10 sonde drops at 1° intervals. POC sampled briefly at western point with 2 sondes dropped into cloud-clearing on return.

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Table 8. Details of G-1 aircraft missions conducted in the VOCALS Regional Experiment.

Flight	Date	Times [UTC] T/O	Land	Mission/Location	Notes
081014	14 Oct	15:54	18:26	19° S XS	Solid clouds
081017	17 Oct	13:00	16:50	19° S XS	Solid clouds, vertical sampling focus
081018	18 Oct	13:07	15:16	19° S XS	Solid clouds, flight aborted
081018	21 Oct	16:32	19:57	19° S XS	Strong longitudinal gradient cloud and aerosol properties
081023	23 Oct	12:49	16:35	SW to Point Alpha	Variable clouds
081025	25 Oct	13:03	17:07	SW to Point Alpha	Large patches of cloud-free air, strong longitudinal gradient in aerosol properties
081028	28 Oct	12:58	17:16	18.5° S XS	Strong latitudinal gradient in aerosol/cloud properties
081029	29 Oct	15:58	19:33	Coastal pollution survey to 23° S	Variable cloud coverage and aerosol properties
081101	1 Nov	12:57	16:57	18.5° S XS	Variable cloud cover, low aerosol concentrations
081103	3 Nov	12:58	16:51	18.5° S XS	Clear-air near coast and at 72° W
081104	4 Nov	11:57	16:02	SW to 19.5° S, 72° W	Clear-air near coast. Generally low aerosol concentrations
081106	6 Nov	11:57	16:21	18.5° S XS	Strong longitudinal gradient in cloud/aerosol properties
081108	8 Nov	12:55	16:31	18.5° S XS	Coastal clouds then mostly clear. Low aerosol concentrations offshore
081110	10 Nov	13:02	16:50	SW to 20° S, 75° W	Clear near coast, variable clouds elsewhere
081112	12 Nov	13:20	16:55	18.5° S XS	Generally low cloud droplet and aerosol concentrations; clouds variable
081113	13 Nov	12:54	16:41	18.5° S XS	Sky mostly clear, aerosol concentrations modest, no strong longitudinal gradient in properties

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Table 9. Details of Do-228 aircraft missions conducted in the VOCALS Regional Experiment.

Flight Date	Times [UTC] T/O	Land	Mission/Location	Notes
VA01 Oct 26	14:16	17:27	Test flight	
VA02 Oct 28	12:49	14:30	Test flight	
VA03 Oct 30	11:38	15:48	Overfly RHB at 19° 35.5'S, 74° 46.9'W	Stacked cloud/radiation over RHB and FAAM BAe146
VA04 31 Oct	11:30	15:26	20° S cross-section	To point alpha at 4800 m then west to 76° W, retracing path
VA05 2 Nov	11:54	15:11	Profiling, to 19.5° S, 74.5° W	Six vertical profiles, cloud top – 4800 m, followed by spiral descent and return to Arica at 3400 m
VA06 3 Nov	13:00	16:36	Coastal pollution gradient	Flew to Peruvian border at 4000 m, then followed same path as FAAM BAe146 to DART buoy; back at 3300 m
VA07 4 Nov	11:31	15:43	20° S cross-section	As VA04 except return leg at 3400 and 3200 m
VA08 5 Nov	13:00	16:11	Profiling flight south to 22° 39'S, 71° 10'W	Profiling coastal pollution between cloud top and 4800 m
VA09 6 Nov	18:35	20:14	Lidar test	Flew to point alpha and back between 4000 and 5000 m
VA10 9 Nov	13:39	17:52	20° S cross-section	as VA04
VA11 10 Nov	11:23	15:23	Loop south to 22.4° S	4800 m; overflight of FAAM BAe146
VA12 12 Nov	11:35	12:19	Flight aborted	Problem with aircraft
VA13 13 Nov	10:05	11:45	Intercomparison with BAe-146	Legs at 200 m - 3 km altitude
VA14 13 Nov	12:45	16:48	20° S cross-section	As VA04 except return leg at 4200 m
VA15 14 Nov	13:15	16:51	Vertical profiling to 22.5° S	8 vertical profiles, 100–4800 m

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Table 10. Details of Twin Otter aircraft missions conducted in the VOCALS Regional Experiment.

Flight	Date	Times [UTC] T/O	Land	Mission/Location	Notes
01	16 Oct	14:16	17:27	Stacked turbulence/aerosol/cloud	At Point Alpha (20° S, 72° W) 15:10–17:50
02	Oct 18	12:49	14:30	Stacked turbulence/aerosol/cloud	At Point Alpha 12:15–15:00
03	19 Oct	11:38	15:48	Stacked turbulence/aerosol/cloud	At Point Alpha 12:05–14:40
04	21 Oct	11:30	15:26	Stacked turbulence/aerosol/cloud	At Point Alpha 12:10–14:50
05	22 Oct	11:54	15:11	Stacked turbulence/aerosol/cloud	At Point Alpha 12:00–14:40
06	24 Oct	13:00	16:36	Stacked turbulence/aerosol/cloud	At Point Alpha 12:15–15:00
07	26 Oct	11:31	15:43	Stacked turbulence/aerosol/cloud	At Point Alpha 12:00–15:00
08	27 Oct	13:00	16:11	Stacked turbulence/aerosol/cloud	At Point Alpha 15:55–19:00
09	29 Oct	18:35	20:14	Stacked turbulence/aerosol/cloud	At Point Alpha 11:50–15:00
10	30 Oct	13:39	17:52	Stacked turbulence/aerosol/cloud	At Point Alpha 11:50–15:00
11	1 Nov	11:23	15:23	Stacked turbulence/aerosol/cloud	At Point Alpha 12:05–15:05
12	2 Nov	11:35	12:19	Stacked turbulence/aerosol/cloud	At Point Alpha 11:55–15:00
13	4 Nov	10:05	11:45	Stacked turbulence/aerosol/cloud	At Point Alpha 11:50–14:40
14	5 Nov	10:00	16:50	Stacked turbulence/aerosol/cloud	At Point Alpha 11:50–15:00. Cloud/aerosol probe data failed
15	8 Nov	12:45	16:48	Stacked turbulence/aerosol/cloud	At Point Alpha 11:50–15:00
16	9 Nov	13:15	16:51	Stacked turbulence/aerosol/cloud	At Point Alpha 11:50–15:05
17	10 Nov	13:15	16:51	Stacked turbulence/aerosol/cloud	At Point Alpha 14:45–18:00
18	12 Nov	13:15	16:51	Stacked turbulence/aerosol/cloud	At Point Alpha 11:50–15:15
19	13 Nov	13:15	16:51	Stacked turbulence/aerosol/cloud	At Point Alpha 12:00–14:50

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Table 11. Details of the intercomparisons conducted VOCALS-REx.

Platform	BAe-146	G-1	Twin Otter	Do-228	RHB	Paposo
C-130	1. 10/31 (RF07/B412) 2. 11/04 (RF09/B414)	1. 10/23 (RF04) 2. 11/04 (RF09)	None	None	1. 10/25 (RF05, IMET Buoy) 2. 11/02 (RF08, SHOA Buoy) 3. 11/11 (RF12, near SHOA buoy)	1. 11/9 (RF11, along 73W) 2. 11/11 (RF12, along 73W)
BAe-146	–	1. ground comparison 2. 11/12 (B419)	None	11/13 (B420/VA13)	1. 10/30 (near SHOA Buoy) 2. 11/12 (near SHOA buoy)	None
G-1	–	–	10/26	None	None	None
Twin Otter	–	–	–	None	11/10 (near SHOA buoy)	None
Do-228	–	–	–	–	10/30 VA03	None
RHB	–	–	–	–	–	None

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Table A1. Acronyms used in this manuscript.

CUpEx	Chilean Upwelling Experiment
FAAM	The Facility for Airborne Atmospheric Measurements (United Kingdom)
IMET	Improved Meteorology
VOCALS	VAMOS Ocean-Cloud-Atmosphere-Land Study
VAMOS	Variability of the American Monsoon Systems

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

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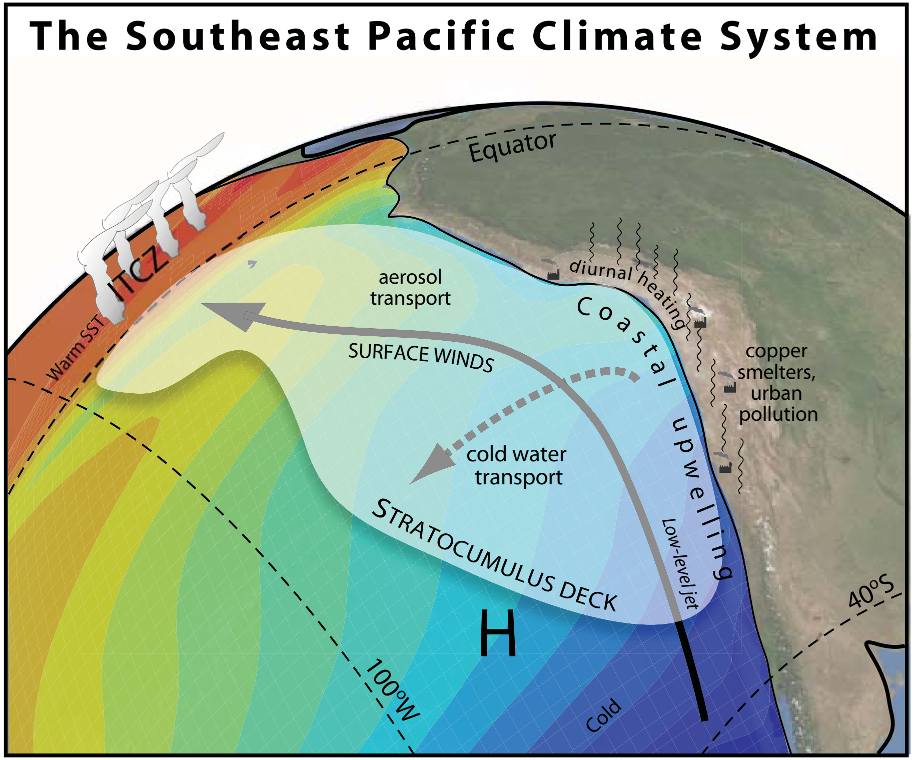

Fig. 1. Key features of the southeast Pacific (SEP) coupled climate system being explored in the VOCALS Program.

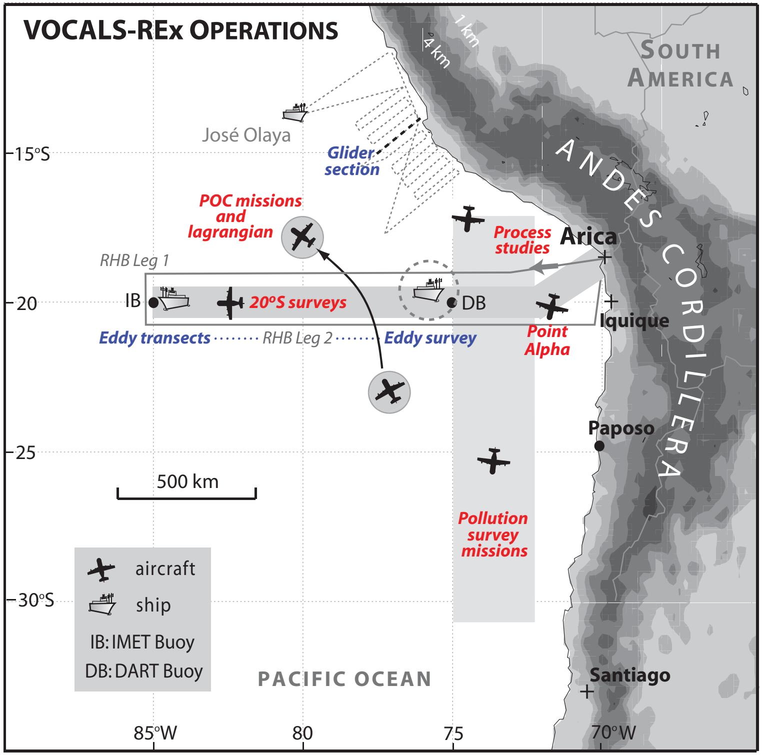

Fig. 2. VOCALS REx study region showing main sampling platforms and mission types. The land aerosol/meteorology site at Paposo, the sounding station at Iquique, and the instrumented IMET and DART buoys are also shown.

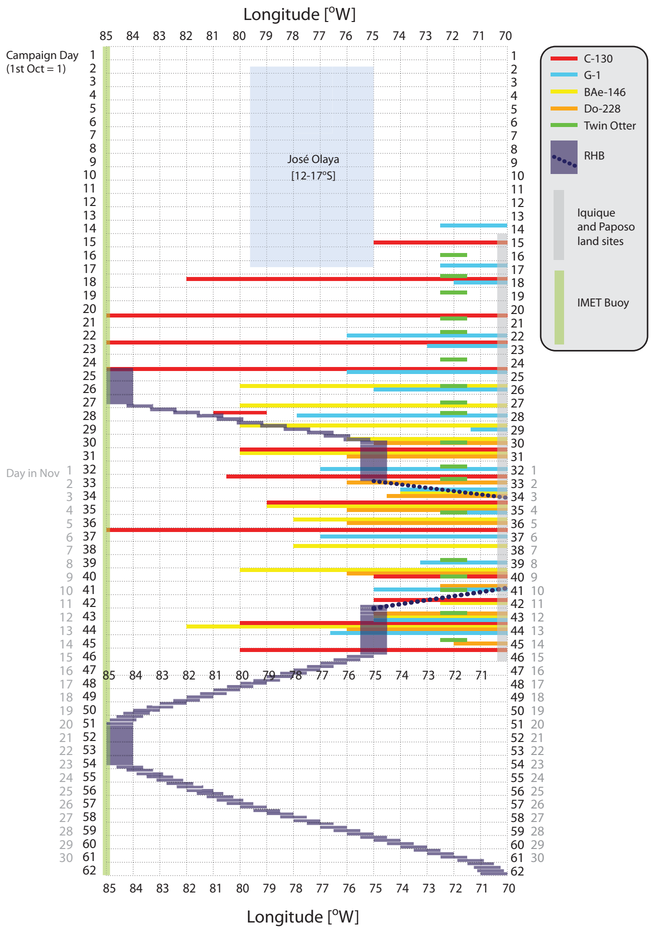

Fig. 3. Operations summary showing platform longitude against time during VOCALS-REx.

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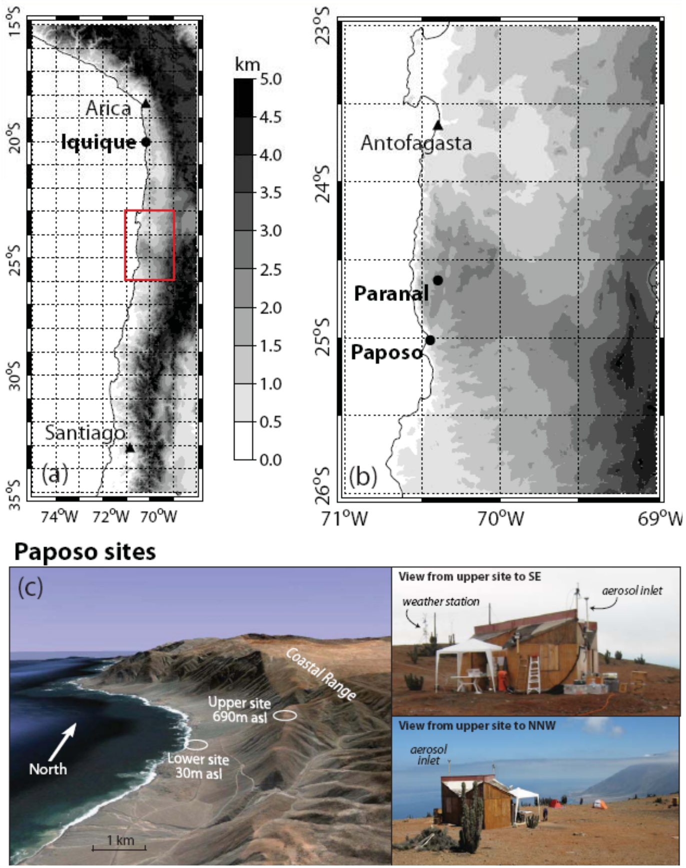

Fig. 4. (a) Map showing location of ground sites used in VOCALS-REx, with **(b)** a zoomed in map for the red boxed area in (a). Panel **(c)** shows a Google Earth terrain image showing the Paposo sites looking approximately northward, together with photographs from the upper (elevated) Paposo site.

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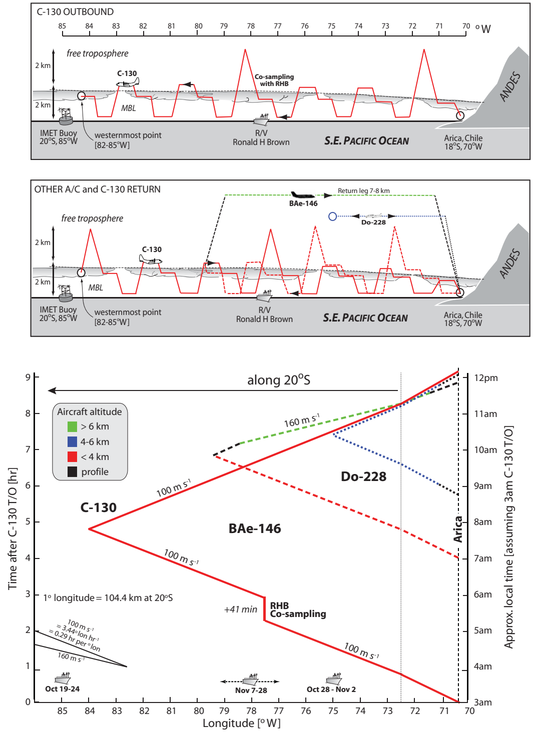

Fig. 5. Cross Section mission flight plan. Up to three aircraft (BAe-146, C-130, Do 228) were used in this mission, but in a number of cases only a single aircraft was used. In all cases, the aircraft flew from Arica to 20° S, 72° W and then flew westward along the 20° S parallel. The schematic shown here is for all three aircraft - the upper two panels show longitude-height diagrams while the lower panel shows a time-longitude plot color coded with altitude range. The C-130 flew 60 km (10 min) straight and level legs near the surface (150 m altitude), in the cloud (typically 800–1300 m altitude) and above cloud (300 m above cloud top), interspersed with profiles up to 3000–4000 m. The C-130 typically reached 85° W. The BAe-146 flew similar outbound legs, out to 79–80° W but then flew the return leg at high altitude releasing dropsondes and making radiation measurements when working in concert with the C-130. When operating alone the BAe-146 repeated the in-situ sampling on the return leg. The Do-228, when employed in this mission, flew legs at approximately 4000 m altitude using the nadir-viewing lidar and hyperspectral imagers to characterize clouds and aerosols below. There was a concerted effort for the three aircraft to sample the same location as closely in time as possible on the return leg (see bottom panel).

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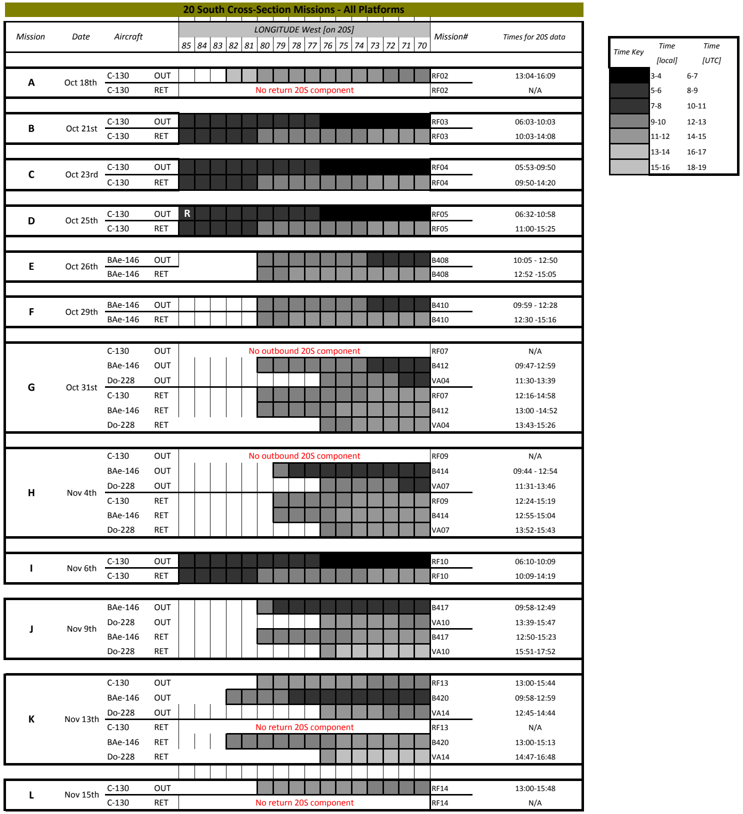

Fig. 6. Cross Section missions summary as a function of date and longitude along 20° S. Color coding shows the approximate local/UTC time of sampling. Times for which Cross-Section mission data is available are provided at right. Individual aircraft flight numbers are also given. Missions with missing outbound or return legs indicate that the aircraft was involved in a different mission for part of its flight.

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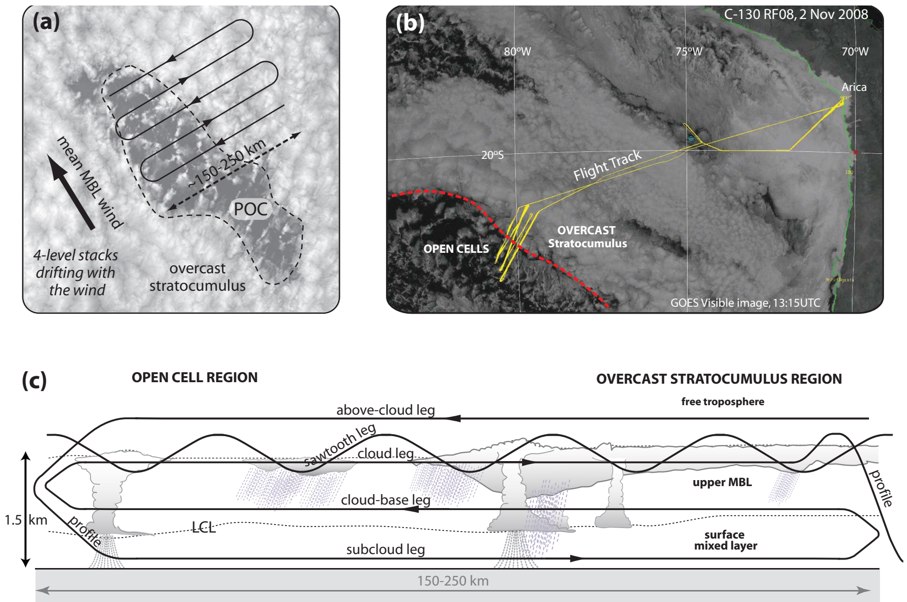

Fig. 7. POC-Drift mission flight plan. **(a)** schematic of plan view; **(b)** example POC-Drift misson flight track from C-130 Research Flight RF08 on 2 Nov 2008; **(c)** schematic cross section of boundary between open and closed cell regions showing sampling using long straight and level runs 150–250 km in length, profiles, and sawtooth sampling through the upper part of the MBL and lower troposphere. Due to its reduced range the BAe-146 sampled a subset of the C-130 flight plan when sampling POCs.

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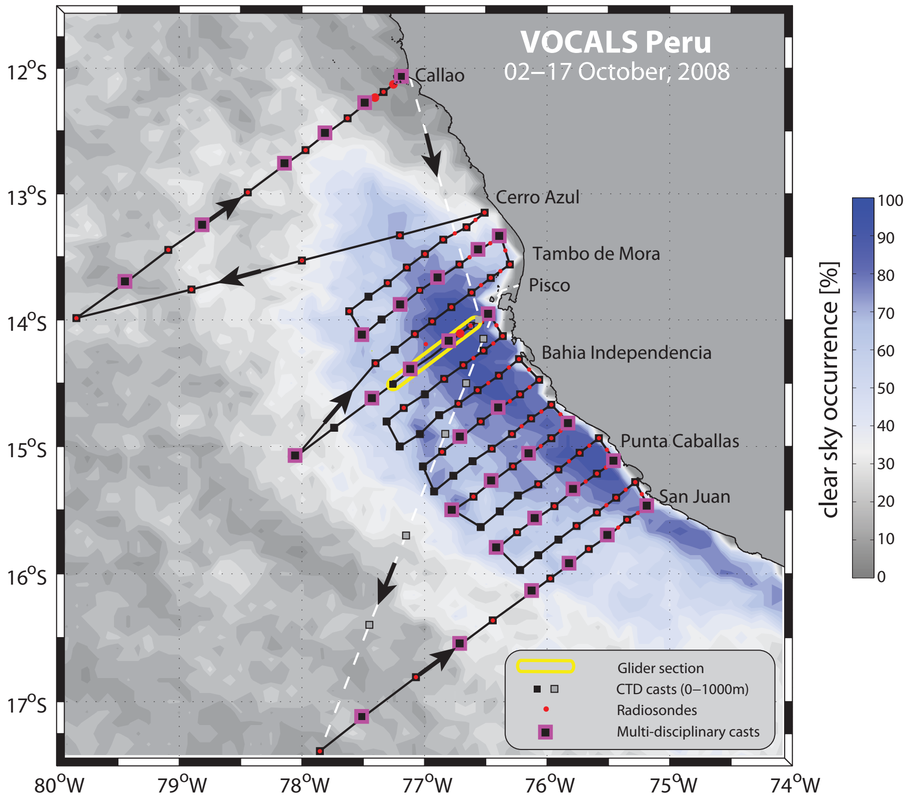

Fig. 8. Cruise track (black, with white for transit legs) and sampling from the IMARPE R/V José Olaya during the VOCALS Peru cruise (2–17 October 2008). The color contours show the October-mean (1997–2004) daytime clear sky fraction determined using the SeaWIFS cloud clearing algorithm.

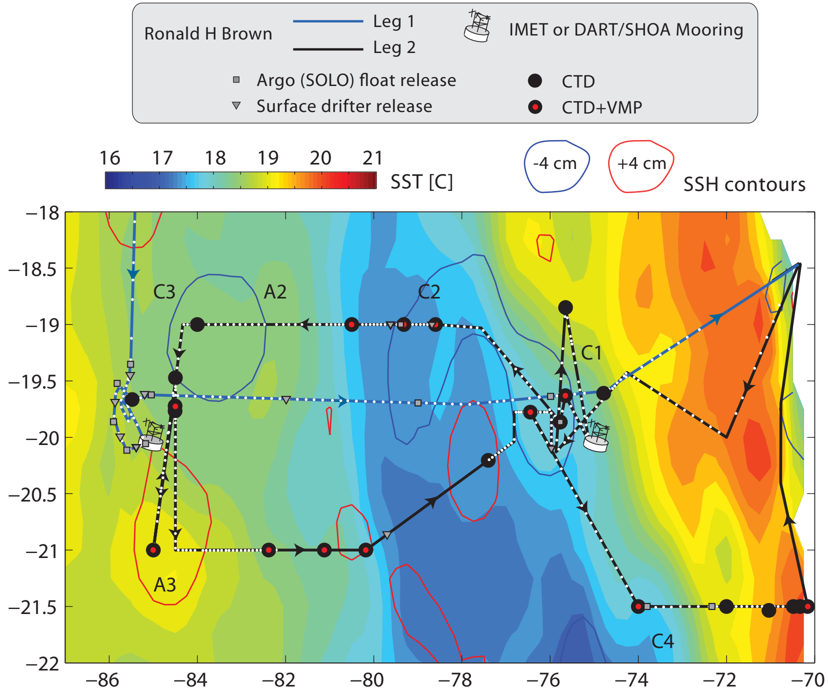

Fig. 9. Cruise tracks for Legs 1 and 2 of the NOAA R/V Ron Brown during VOCALS-REX superimposed on the sea-surface temperature (SST) and sea-surface height (SSH) from November 18th 2008 (middle of Leg 2; courtesy of P. Gaube and D. Chelton, OSU). The 438 underway CTDs (UCTD) are overlaid as white dots on the two tracks. Also shown are the locations of the 35 CTDs and 15 VMP (microstructure) profiles as well as those where 19 surface drifters and 10 profiling SOLO floats were deployed. Several of the sampled cyclones and anticyclones are indicated by a C and A, respectively, followed by a sequential number.

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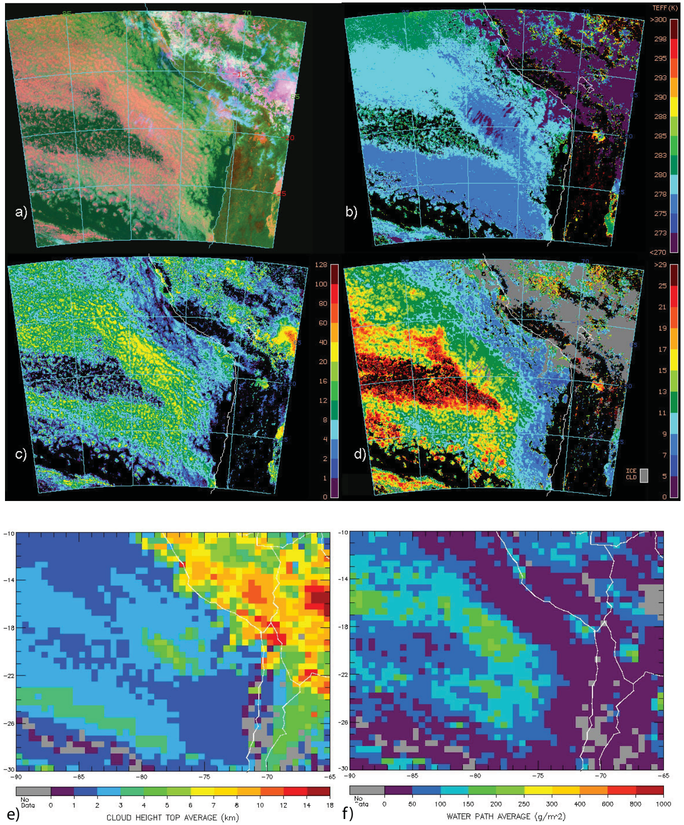

Fig. 10. GOES-10 imagery and retrieved cloud parameters, 1545 UTC, 27 October 2008: **(a)** pseudocolor RGB image; **(b)** cloud effective temperature [K]; **(c)** cloud optical depth; **(d)** cloud liquid water droplet effective radius [µm]. Regional (0.5×0.5°) average cloud properties, **(e)** cloud top height, and **(f)** cloud liquid water path for the same time.