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

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Abstract

The VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx) is an international field program designed to make observations of poorly understood but critical components of the coupled climate system of the southeast Pacific, a region dominated by strong coastal upwelling, extensive cold SSTs, and home to the largest subtropical stratocumulus deck on Earth. 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 northen 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 the cool SST, 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 and regional 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 and coauthors, 1995; Ma et al., 1996). There are still significant problems with the representation of stratocumulus in large scale models over the SEP (Wyant et al., 2010). Observations are highlighting the importance of drizzle precipitation to SEP marine stratocumulus (e.g. Caldwell et al., 2005; Comstock et al., 2005), and cloud modeling is 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. Savic-Jovcic and Stevens, 2008; Wang and Feingold, 2009; Wang et al., 2010) and the formation of so-called "pockets of open cells" (POCs) (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 is 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 addition, studies of the heat budget well offshore of the coastal upwelling zone indicate a complex and time-varying flow, and a deficit of cold, fresh water (Colbo and Weller, 2007). The supply mechanism is presumably controlled by subgridscale ocean processes and is unclear at the present time. One candidate is based on mesoscale ocean eddies advecting westwards from the coastal zone. Another candidate for mechanism is based on the entrainment of cold, fresh water from below the ocean mixed layer. Little is known about eddy processes in the SEP, not only regarding their role in cold water transport over the broader SEP but also their potential importance for transport 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 the 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 approach to the problem is the premise that its solution requires the synergy between numerical modeling, field studies, and extended observations such 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 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., 15921-15962), 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., 2009).

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

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 3) two research vessels (the NOAA Ronald H Brown [RHB] and the Peruvian IMARPE José Olaya, see Table 4) 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 October 15 to November 15 2008, with the other two aircraft (BAe-146 and Do-228) operational from October 26-November 15th 2008. Table 3 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 hours 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 3. 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.

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 3. 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 3.

Details of the missions flown in REx are given in Table 8.

3.1.4 NERC Dornier-228 (Do-228)

Details of the instrumentation payload on the Do-228 are given in Table 3 Details of the missions flown in REx are given in Table 9.

3.1.5 CIRPAS Twin Otter

Details of the instrumentation payload on the Twin Otter are given in Table 3. Details of the missions flown in REx are given in Table 10.

3.2 Ship platforms

The two ships in VOCALS-REx sampled different locations at different times. The NOAA R/V Ronald H Brown (RHB) was operational for two phases, the first from October 25 to November 3 2008 and the second from Nov 10 to December 2 2008. The Peruvian R/V José Olaya operated from October 2-17 2008. Fig. 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 RHB 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° from the coast out to 85°W. The RHB payload was designed to sample both the upper ocean and the lower atmosphere during REx, and details are given in Table 4.

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 National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL) deployed a GAUS (GPS Advanced Upper-air Sounding systems) radiosonde station on the 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 Ground-based 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). 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 Chilan 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 asl) 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, 31 m asl) situated 300 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 (Oct 17-Nov 15 2008), the upper site was almost entirely within the marine boundary layer (MBL), although earlier in the season the inversion was occasionally lower which allowed some free-tropospheric sampling. Table 5 details the measurements made at the upper Paposo site. Aerosol sampling was carried out using a custom-made multidirectional aerosol inlet (see Fig. **??**). Sampled air was drawn through a 5m long 2 inch diameter vertical stainless steel tube into the measurement systems situated inside a wooden hut. This sampling line was used to connect with the scanning mobility particles sizer (SMPS), optical counter (OPC), nephelometers, aethalometer and ozone analyzer, and the same line was used to sample submicron (<1 μm diamater) aerosols on teflo filters for chemical analysis. Aerosol filter measurements are described further in Chand et al. (2010). A separate sampling line installed at almost same height and at a short distance away (2-3 meters), was used for running the condensation particle counter (CPC), particle soot absorption photometer (PSAP), and system counterflow virtual impactor (CVI) for sampling the cloud droplets. This latter sampling line was active Nov 4-15 only. Meteorological and radiation measurements at the upper site were made by the University of Chile, and these measurements are described further in (**?**).

At the lower Paposo site, a micro pulse lidar (MPL), a weather station, and a sounding system were installed at the Paposo foothill site near the coast (Table 5 and map Fig. 4). 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 (October 17-Nov 4) at the high altitude European Southern Observatory at Paranal (24°37’39.00”S, 70°24’17.85”W, 2625m asl), see map Fig. 4.

3.3.3 Iquique

The National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL) deployed two GAUS (GPS Advanced Upper-air Sounding systems) radiosonde stations for VOCALS, one of which was located in Iquique Chile at the Universidad Arturo Prat Marine Sciences Campus (20°16'15"S, 70°07'52"W, 15 m asl), and 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.

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 (DART) 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 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 during REx (mission details shown in Fig. 6);
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. The flight plan is shown in Fig. 7. On one occasion (Oct 27/28 2008) it was possible to sample the same advected POC with two aircraft missions spaced approximately 12 hours apart;
3. **Stacked cloud and/or radiation missions** in which one or two aircraft sample an 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.

4.2 Ship sampling

4.2.1 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.

4.2.2 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).

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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)

[Pat Minnis: please provide a paragraph or two on the key products]

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

[Grant Allen/Steve Abel: please provide a paragraph or two on the key products, dataset availability etc.]

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/?s*

7 Other complementary products for VOCALS-REx

7.1 FLEXPART particle dispersion model

[Jerome Brioude: please provide a paragraph on the key products]

8 Meteorological conditions during VOCALS-REx

Here, we will present a brief overview of the mean state of the atmosphere and ocean during October and November 2008, and provide a descriptive summary of the day to day meteorological and cloud conditions. The aim of this is not to provide specific insight into physical processes but to provide some broader spatial and temporal meteorological context for the measurements made during VOCALS-REx.

VOCALS-REx measurements sampled the eastern flank of the southeastern Pacific subtropical high pressure system where surface winds are very steady and the south and southeast (Fig. 10a). The winds immediately above the boundary layer (e.g. 850 hPa) had a more easterly component, especially close to the coast where the surface winds are essentially coast-parallel. As is typical for austral spring, sea surface temperatures (SSTs) along the coast were cold offshore of the strongest upwelling zones to the south and north of the Arica bight (18°S, 70°W) where there was a local maximum (Fig. 10b). Away from the coastal zone, SSTs increase to the west and northwest, and the airmasses advecting through much of the region experienced increasing SSTs (cold advection) as they moved equatorward and westward.

Together with the large scale subsidence to the east of the subtropical high (and locally enhanced by the Andes), the cold advection and anomalously cold SSTs provide ideal conditions for the maintenance of extensive stratocumulus sheets. The mean cloud cover from water clouds (Fig. 10c, taken from MODIS Terra satellite at 10:30 LT where the cloud cover is close to its daily mean value) maximized in a belt ∼500 km from, and roughly parallel to, the Peruvian coast, where mean values exceeded 90%. This cloudiness maximum is situated a few hundred km downwind of the maximum in lower tropospheric stability (LTS, Fig. 10d), which is the difference between the potential temperature at 700 hPa and the surface. Over most of the region extensively sampled in VOCALS-REx (see Fig. 2) the mean warm cloud cover exceeded 70% except very close to the coast, where coastal irregularities lead to some local clearings (see e.g. Fig. 8 showing the climatological minimum in cloud off the southern Peruvian coast, which was sampled extensively by the Peruvian IMARPE José Olaya, see above).

We also compare mean liquid water path (LWP) for cloudy pixels determined using the visible/near-IR retrievals from MODIS with those from the passive microwave Advanced Microwave Scanning Radiometer (AMSR) in Fig. 10e,f. Here, we use the area mean diurnal mean LWP from AMSR (mean of 01:30 and 13:30 LT) divided by the mean warm cloud cover from MODIS, to provide an estimate of the cloudy sky LWP. Within about 500 km of the coast, where the VOCALS-REx aircraft observations indicated little drizzle (e.g. **??**), the MODIS and

AMSR LWP estimates agree very well. In this region, cloud LWP values were 70 g m^{-2} or less, especially to the north of 25-30°S. Liquid water paths increased westwards, in agreement with in-situ observations (Bretherton et al., 15921-15962). However, the microwave-derived LWP from AMSR, which includes both cloud and drizzle condensate, increased significantly more rapidly than that from MODIS (which samples the cloud top). This difference between microwave and visible/near-IR LWP estimates is indicative of increasing amounts of drizzle (see e.g. Shao and Liu, 2004) originating from the thicker clouds to the west, where the MBL is deeper (Wyant et al., 2010; Zuidema et al., 2009).

8.1 Day-to-day variability

The general meteorological conditions for the period of interest are shown in Fig. 11. For each day, we show the cloud field using the difference ΔT between the SST (as given by the daily-mean OSTIA product; Stark et al. (2007)) and the GOES Channel 4 (10.7 μm) brightness temperature. Since few low cloud tops occur below 600 m in the region (e.g. Zuidema et al., 2009), all values of $\Delta T < 6$ K are left in black to indicate virtually cloud-free regions, while all values above 35 K are considered to originate from high clouds and are marked in white. The contour interval for the shading is 2 K. The lower threshold is still somewhat problematic, as differences less than 8 K can still indicate either low, continuous cloud cover, or fields of broken cumulus with relatively high cloud tops. Comparison with GOES-10 day-time images in the visual band generally supports the above choice, and broken cumulus fields tend to be quite rare in the VOCALS-REx study area. We show this temperature difference field twice-daily: (a) during early morning before sunrise (where available, 10:28 UTC, i.e. 05:08 LT at 80°W), when the cloud cover is most extensive, and (b) in the afternoon (21:15 UTC, or 15:55 LT at 80°W) when the clouds are at their thinnest (Wood et al., 2002), and on many days the stratocumulus deck partially breaks up (Rozendaal et al., 1995; Bretherton et al., 2004; Abel et al., 2010).

Superimposed on the night time ΔT fields in Fig. 11 are sea-level pressure contours for the previous 00 UTC, and on the day time field contours of the zonally asymmetric part of the 500 hPa geopotential height field are drawn. The final two panels in Figure 11 show the average night-time and day-time cloud-top temperatures at each location whenever low cloud is diagnosed (i.e. whenever ΔT is within the stated thresholds of 6 K and 35 K), with contours for mean pressure and 500 hPa height overlaid as before.

We discuss here two important aspects of the variations in the cloud field in the VOCALS-REx area. Day-to-day variations in the cloud fields are comparable to diurnal variations, and in some cases dominate. These synoptic changes occur in coincidence with changes in sea-level pressure and the passage of mid-tropospheric synoptic-scale disturbances. In particular, there is a strong association between low 500 hPa heights and cyclonic flow at 500 hPa, and large-scale clearing and breaks in the cloud cover, particular towards the south of the VOCALS-REx study region. This is particularly evident when synoptic systems approach the South American coast (e.g. October 1-3, October 10-13, October 20-25, November 12-15, and after November 24).

Superimposed on this distinctly synoptic variability, circulation-related anomalies can be observed at both smaller and larger spatial and temporal scales. Near land, enhanced orographic subsidence associated with synoptic-scale ridging is responsible for sudden, strong coastal clearings. This is accompanied by a localised reduction in sea-level pressure and the formation of a coastal low (CL), as discussed in Garreaud et al. (2002). The coastal clearings typically persist for up to 3 days after the initial mid-tropospheric ridging, and they tend to be located in the southern part of the domain of interest here, where the coastal jet is strongest, consistent with the dynamics discussed by Munoz and Garreaud (2005). Such "canonical" CLs are seen to occur during October 4-5, October 17-18, and November 10-11.

The association between mid-tropospheric ridging and sea-level troughing along the coast distinguishes CLs from mid-latitude synoptic disturbances (Garreaud et al., 2002). Nevertheless, their character is thought to depend principally on the interaction of synoptic-scale disturbances with the mountain topography, whereby changing up- and down-slope flows affect the temperature and moisture stratification of the lower atmosphere near the coast, thereby affecting the pressure field. These changes also affect the cloud-cover. Thus, on the one hand, CLs depend on the presence of large-scale ridging and troughing. On the other hand, height anomalies associated with synoptic disturbances generally tend to assume a baroclinic character as they interact with the orography, and to disturb the coastal cloud field in a way consistent with the associated mountain winds.

Thus, there are instances of weak coastal troughing, for example during November 1-2, but also of ridging, or growing 500 hPa height, hardly accompanied by sea-level changes, but nonetheless affecting the cloud field, sometimes quite significantly (e.g. November 7-9). This particular extensive cloud-clearing event is still associated with mid-latitude troughing further south (at the southern edge of the VOCALS-REx study region), but also with strong warming of the mid-troposphere overlying the coastal ocean north of about 25°S, seemingly emanating from the continent to the east. This results in an enhanced mid-tropospheric meridional temperature gradient, and strong cold advection over the southern hald of the domain (see Fig. 12).

Nevertheless, dynamics at sub-synoptic scales, as discussed e.g. by Munoz and Garreaud (2005), are always important near the coast, for example where an approaching mid-latitude disturbance appears to be associated with the development of a distinct coastal anomaly ahead of it (e.g. October 22-23). Similarly, during November 15-16, following the passage of a mid-tropospheric cyclone across the Andes, a rapid drop in pressure along the coast coincides with extensive coastal clearing. For reasons both of resolution and imperfect representation of the terrain, this dynamics is not captured by either global or regional forecast models (Wyant et al., 2010; Abel et al., 2010), which all appear to miss the coastal cloud anomalies (along with much of the diurnal cycle there).

Variability that appears associated with a longer temporal scale is most apparent in the second half of November. From November 19 onwards, a persistent north-westerly anomaly is seen at 500mb (Fig. 11). This in fact corresponds to west-north-westerly total mid-tropospheric flow throughout this period, corresponding to a large-scale cyclonic anomaly over the ocean to the west of South America. In spatial coincidence with the strongest poleward flow, reduced large-scale subsidence is diagnosed from the forecast model, consistently with vortex stretching. In the same areas, the day-time cloud images show a band of clearing. The low to the west is part of a slowly evolving wave-train that spans the south-Pacific basin, apparently emanating from the Maritime Continent, and probably associated with a positive phase of the Madden-Julian Oscillation (MJO).

More generally, one may note that during much of the month of October 2008, changes in cloud cover follow the succession of synoptic disturbances travelling through the region, with similar effects during the day and during the night. Cloud cover is generally high, with relatively small differences between night and day (in a few instances even negative over the oceanic area west of 82°W), but is characterised by rapid, near-complete clearing in large, dynamically well-defined areas, dominated by cyclonically turning mid-tropospheric flow, where a combination of cold advection and negative-vorticity advection occur.

Later in the Spring season, from the end of October to the middle of November, diurnal variations in cloud-cover become larger, and coastal and other smaller-scale clearing events (partly associated with POCs) more important on super-diurnal time-scales. During this period, there is little synoptic actvity from mid-latitude depressions, the cloud cover is nearly complete during night-time, while the day-time break-up, while variable, is never very large, except on November 8 (as discussed above).

By and large then, one may characterise the whole of October-November 2008 as divided into three periods each with different character: the first, until the end of October, has robust synoptic activity from mid-latitude depressions which largely control the cloud conditions; a second, in the first half of November is baroclinically stable, with high values of sea-level pressure, and sub-synoptic scale activity, including possible influences from continental convection, on time-scales of 2-3 days; and a final one, with moderate synoptic variability but dominated by a large-scale circulation anomaly which reduced mid-tropospheric subsidence and allowed for an extensive day-time break-up of the stratocumulus.

Away from the relatively narrow coastal strip, cloud-free areas tend to be zonally aligned, and tend to propagate northwards with the boundary-layer flow. This may be partly due to a memory of the air mass, which being depleted of CCN once a closed to open cell transition involving precipitation occurs (see e.g. October 27/28 case study of **?** and associated modeling work by Wang et al. (2010) and **?**), remains so, along its trajectory, for a length of time. However, at the relevant latitudes, synoptic disturbances themselves also tend to travel equatorwards as they approach the barrier of the Andes. [[[[This may or may not be shown in Figure XX+1, probably showing GPH anomalies and concomitant LTS anomalies.]]]]

8.2 Diurnal variability

In general, areas of day-time cloud-clearing tend to be associated with elevated night-time cloud-tops, i.e. deep MBLs. This relationship is valid at all time-scales of relevance here. In particular, the first period (October) has widely varying cloud-top heights, both spatially and temporally; the second, November 1-15, is characterised by consistently low cloud-top heights?????; and the third, until the end of the month, by higher, colder cloud-tops, prone to breaking up into shallow-cumulus systems. In general, areas of clouds with shallow MBLs (low ΔT) during night-time can be predicted to undergo less day-time break-up. Allowance, however, has to be made for both the coastal areas, where cloud-top height varies much less than their geometrical and optical thickness (the cloud layer sometimes being as thin as 10-20 metres), and there is a strong sensitivity to offshore winds; and the general gradient from a low to a high cloud layer going offshore and poleward.

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9 Conclusions

Appendix A

Appendix: Acronyms

Table 2 provides details of the common acronyms used in this manuscript.

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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.

Table 2. 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

Table 3. Details of the aircraft used in VOCALS-REx

Aircraft	Location[a]	Dates	Measurements
Lockheed C-130[b]	Arica	Oct 15 -Nov 15	**Atmospheric state**: thermodynamics; winds/turbulence; cloud water (PVM, King); cloud and drizzle microphysics (CDP, FSSP, 2D-C). **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 (SMPS/UHSAS/PCASP, SMPS heated/unheated); total CN; refractory CN; ultrafine CN; aerosol composition (AMS, SP2, single particle analysis); scattering and absorption (TSI/PSAP); CCN spectrum (continuous flow); 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	Oct 26 -Nov 13	**Atmospheric state**: thermodynamics; winds/turbulence; dropsondes; cloud water (JW, Nevzorov); cloud and drizzle microphysics (CDP, FSSP, 2D-C, 2DS). **Remote sensing:** spectrally-resolved hemispheric shortwave irradiances (SHIMS); hyperspectral IR radiance (ARIES); broad-band irradiances. IR upwelling brightness temperature (Heimann),bliquid/water vapor path (89-183GHz, MARSS, scanning). **Aerosols:** size distributions from 50 nm to 3 μm (SMPS/UHSAS/PCASP); total CN; aerosol composition (AMS, SP2, impactors, single particle analysis); scattering and absorption (TSI/PSAP); wet nephelometer (RH-scanning); CCN (DMT, 2 channels); volatility. **Trace gases:** CO, O_3, NO_x, PAN, SO_2 (Teco, low sensitivity).
Gulfstream-1 (G-1)[d]	Arica	Oct 15 -Nov 13	
Dornier-228 (Do-228)[e]	Arica	Oct 26 -Nov 14	**Atmospheric state**: temperature; 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). **Aerosols:** size distributions from 0.05-5μm (DMT F-CLAS).
Twin Otter[f]	Iquique	Oct 16 -Nov 13	

[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 Natural Environment Research Council (NERC) in the UK

[f]Operated by the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) and supported by the US Office of Naval Research (ONR).

Table 4. Details of the ships used in VOCALS-REx

Ship/Location[a]/Dates	Measurements
R/V Ronald H Brown[b] See map Fig. 9 Oct 25 -Dec 2	**Atmospheric state**: temperature, humidity, winds (flux tower) **Upper air**: 4×daily radiosonde launches. **Remote sensing**: C-band radar reflectivity and Doppler winds within drizzle (3-d volumetric and range-height scans every 3 mins, 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 (DMPS/APS, SMPS heated/unheated); CN (>12 nm); ultrafine CN (>3 nm), aerosol mass and composition (AMS, 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); submicron scattering and absorption at three wavelengths (TSI nephelometer/PSAP); CCN spectrum (5 supersaturations from 0.1-0.6%); aerosol volatility at 230 C (SMPS heated/unheated). **Trace gases:** Radon (^{222}Rn); O_3; atmospheric DMS (quadrupole mass spectrometry); seawater DMS. **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).
R/V José Olaya Balandra[c] See map Fig. 8 Oct 2-17	**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 (pCO2) 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 24sec, 5 m along the vertical over the upper 200 m depth started in October 3 to November 14 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 0-75m (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 US National Oceanographic and Atmospheric Administration (NOAA), with additional support for shipborne sampling from the National Science Foundation.

[c]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.

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

Paposo (upper site)	25°00’S, 70°27’W, 690m asl	Oct 15 -Nov 15 (Jul 23 -Nov 15 for met. and radiation)	**Atmospheric state:** temperature, humidity, winds, pressure (weather station), downwelling shortwave and net (LW+SW) radiation (July 23-Nov 15). **Aerosols:** Aerosol size distribution (20 nm-5 μm, SMPS/OPC); total CN (CPC, Nov 4-15 only), aerosol composition (submicron impactors for ion and gravimetric analysis); light scattering (Oct 27-Nov 15, Radiance Research nephelometer, single wavelength); absorption (PSAP, Nov 4-15 only); black carbon (aethelometer, Nov 4-15 only); Cloud droplet residuals (Nov 4-18 only, Counterflow virtual impactor with instrumentation as at Paranal [see below] behind); **Trace gases:** O_3.
Paposo (lower site)	25°01’S, 70°27’W, 31m asl	Oct 15 -Nov 15	**Atmospheric state:** temperature, humidity, winds, pressure (weather station), downwelling shortwave and net (LW+SW) radiation (July 23-Nov 15). **Upper air:** multiple daily radiosonde launches (2$\times$daily at 00/12 UTC, Oct 17-23; 3$\times$daily at 00/12/21 UTC, Oct 24-Nov 9; 4$\times$daily at 00/06/18/21 UTC, Nov 11-12; 5$\times$daily at 00/06/12/18/21, Nov 13-15) **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, 2635m asl	Oct 17 -Nov 4	**Aerosols:** Aerosol total concentration (TSI 3010 CPC, $>$10 nm); Aerosol size distributions (DMPS 20-300 nm, unheated/heated to 50-400 C; OPC 0.26-2.2 μm); Volatility TDMA (not continuous, only occasionally range 20 - 300 nm); Aerosol scattering (nephelometer) and light absorption (PSAP and Aethelometer); Samples for single particle analysis.
Iquique	20°16’S, 70°08’W, 15 m asl	Oct 15 -Nov 15	**Upper air:** 6$\times$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	Oct 31 -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 October 31 2008-Jan 3 2010. Data are available from the VOCALS data archive.

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	Oct 15	16:49	20:11	Partial 20°S to 20°S, 75°W	Day mission, solid cloud deck
RF02	Oct 18	13:04	21:27	20°S/POC Drift	Day mission, solid cloud deck, polluted with little drizzle. POC sampling of rift-like feature
RF03	Oct 21	06:02	14:22	20°S	Night mission, solid cloud deck, significant microphysical gradient; notably shallow MBL
RF04	Oct 23	06:01	14:20	20°S	Night mission, broken/open cells at far west
RF05	Oct 25	06:32	15:25	20°S	
RF06	Oct 28	06:20	15:10	POC Drift	Night mission, very clear POC edge sampled
RF07	Oct 31	06:03	14:58	POC Drift/20°S	Night mission,
RF08	Nov 2	06:00	15:20	POC Drift	Night mission,
RF09	Nov 4	06:02	14:54	POC Drift/20°S	Night mission, POC sampling
RF10	Nov 6	06:10	14:19	20°S	Night mission, overcast with breaks and drizzling large mesoscale cells at west
RF11	Nov 9	12:59	21:34	Pollution Survey to 30°S	Day mission, Variable cloud morphology along coast, pollution plumes
RF12	Nov 11	12:56	21:44	Pollution Survey to 30°S	Day mission, Overcast cloud
RF13	Nov 13	13:00	21:55	POC/20°S	Day mission, Extensive clearing near coast, then thick cloud with POC
RF14	Nov 15	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	Oct 26	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 $\sim$78°W at dusk. Very low CN in POC.C-130 sampled same advected airmass 12 hours later
B410	Oct 29	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	Oct 30	10:25	15:48	RHB cosampling	RHB on station near the DART Buoy. Cloud and MBL profiles en route. Several 20-minute back and forth legs (parallel to mean wind) over RHB
B412	Oct 31	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	Nov 3	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	Nov 4	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	Nov 5	09:12	14:33	POC Drift	Sampled open cellular (POC) region at $\sim$78°W. Very low CN observed in POC. High-level return to base with 10 dropsondes released.
B416	Nov 7	10:32	15:27	POC Drift	Sampled open cellular (POC) region at $\sim$78°W. Very low CN observed in POC. High-level return to base with 11 dropsondes released (2 into POC)
B417	Nov 9	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	Nov 11	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	Nov 11	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	Nov 12	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-minute reciprocal legs (parallel to mean wind) performed, centred on Ron Brown, with cloud, MBL and deep profiles to 3.2 km
B420	Nov 13	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.

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

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	Stacked cloud/radiation over RHB	
VA04	Oct 31	11:30	15:26	20°S XS	
VA05	Nov 2	11:54	15:11	Vertical profiling	
VA06	Nov 3	13:00	16:36	Coastal pollution gradient	
VA07	Nov 4	11:31	15:43	20°S XS	
VA08	Nov 5	13:00	16:11	Vertical profiling	
VA09	Nov 6	18:35	20:14	Lidar test	
VA10	Nov 9	13:39	17:52	20°S XS	
VA11	Nov 10	11:23	15:23	Coastal pollution gradient	
VA12	Nov 12	11:35	12:19	Stacked cloud/radiation over RHB	
VA13	Nov 13	10:05	11:45	Intercomparison with BAe-146	
VA14	Nov 13	12:45	16:48	20°S XS	
VA15	Nov 14	13:15	16:51	Vertical profiling	

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	Oct 16	14:16	17:27	Stacked cloud/radiation	At Point Alpha (20°S, 72°W) 15:10-17:50
02	Oct 18	12:49	14:30	Stacked cloud/radiation	At Point Alpha 12:15-15:00
03	Oct 19	11:38	15:48	Stacked cloud/radiation	At Point Alpha 12:05-14:40
04	Oct 21	11:30	15:26	Stacked cloud/radiation	At Point Alpha 12:10-14:50
05	Oct 22	11:54	15:11	Stacked cloud/radiation	At Point Alpha 12:00-14:40
06	Oct 24	13:00	16:36	Stacked cloud/radiation	At Point Alpha 12:15-15:00
07	Oct 26	11:31	15:43	Stacked cloud/radiation	At Point Alpha 12:00-15:00
08	Oct 27	13:00	16:11	Stacked cloud/radiation	At Point Alpha 15:55-19:00
09	Oct 29	18:35	20:14	Stacked cloud/radiation	At Point Alpha 11:50-15:00
10	Oct 30	13:39	17:52	Stacked cloud/radiation	At Point Alpha 11:50-15:00
11	Nov 1	11:23	15:23	Stacked cloud/radiation	At Point Alpha 12:05-15:05
12	Nov 2	11:35	12:19	Stacked cloud/radiation	At Point Alpha 11:55-15:00
13	Nov 4	10:05	11:45	Stacked cloud/radiation	At Point Alpha 11:50-14:40
14	Nov 8	12:45	16:48	Stacked cloud/radiation	At Point Alpha 11:50-15:00
15	Nov 9	13:15	16:51	Stacked cloud/radiation	At Point Alpha 11:50-15:05
16	Nov 10	13:15	16:51	Stacked cloud/radiation	At Point Alpha 14:45-18:00
17	Nov 12	13:15	16:51	Stacked cloud/radiation	At Point Alpha 11:50-15:15
18	Nov 13	13:15	16:51	Stacked cloud/radiation	At Point Alpha 12:00-14:50

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) 3. ?	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

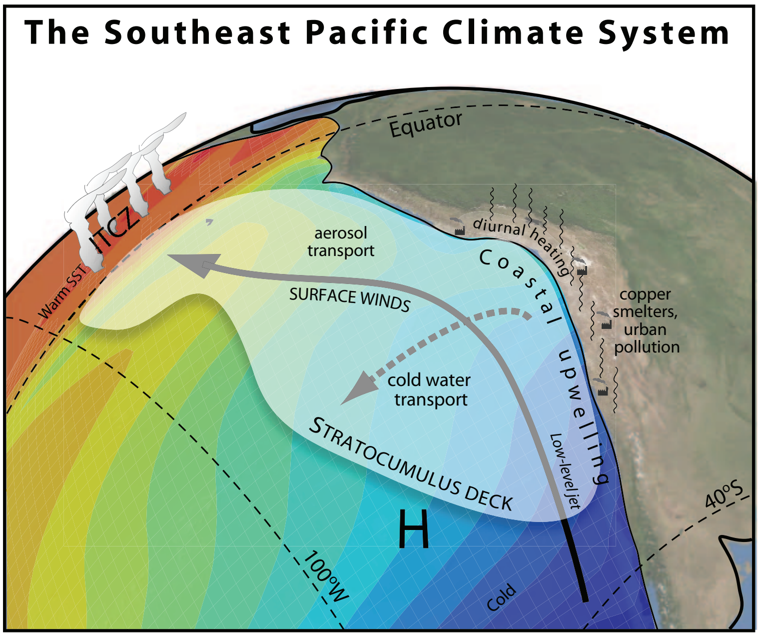

Fig. 1. Key features of the southeast Pacific (SEP) coupled climate system being explored in the VOCALS Program

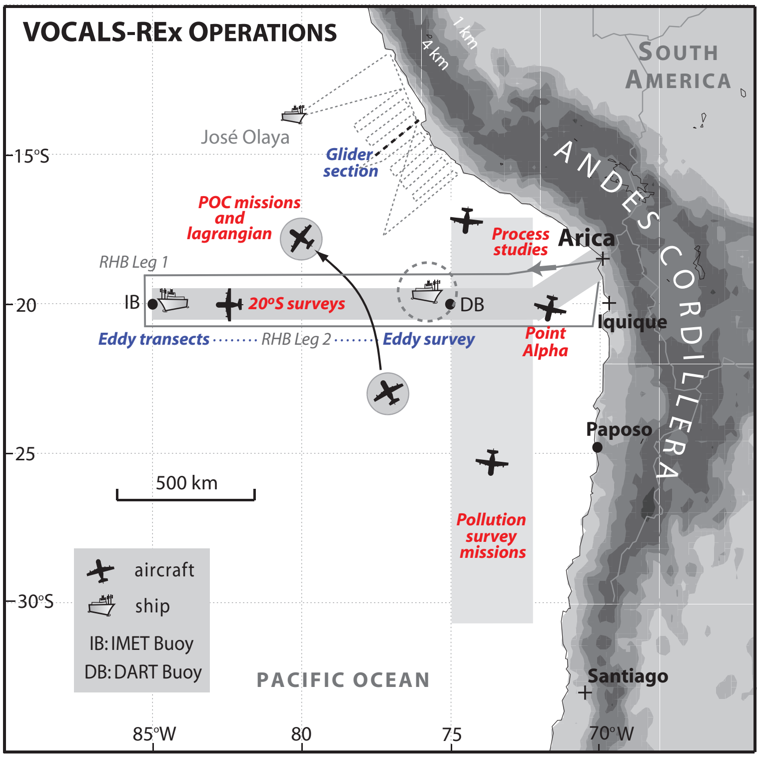

Fig. 2. VOCALS REx study region showing main sampling platforms and mission types. The land aerosol/meteorology site at Paposo, the sounding station at Iquique, and the instrumented IMET and DART buoys are also shown.

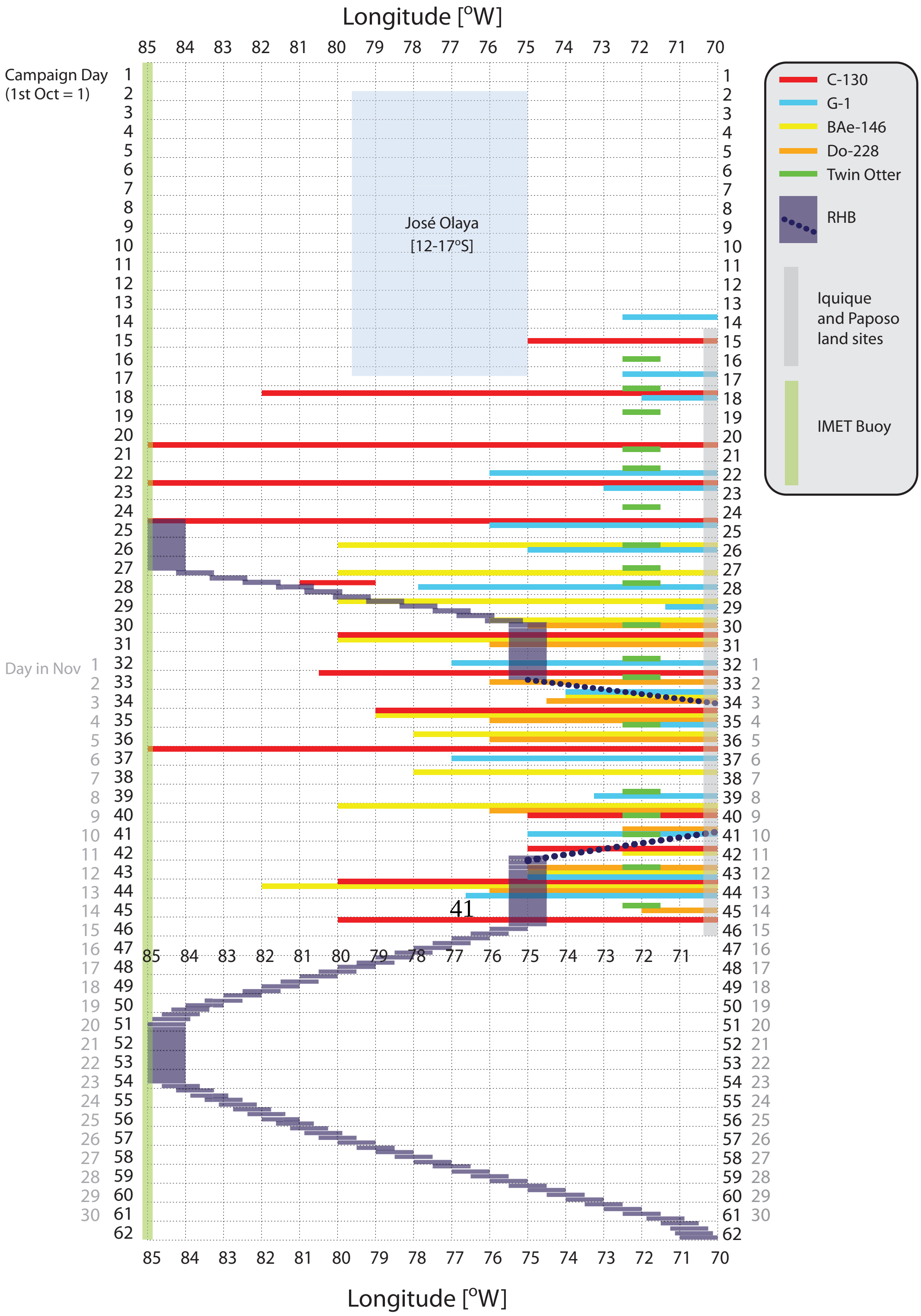

Fig. 3. Operations summary showing platform longitude against time during VOCALS-REx.

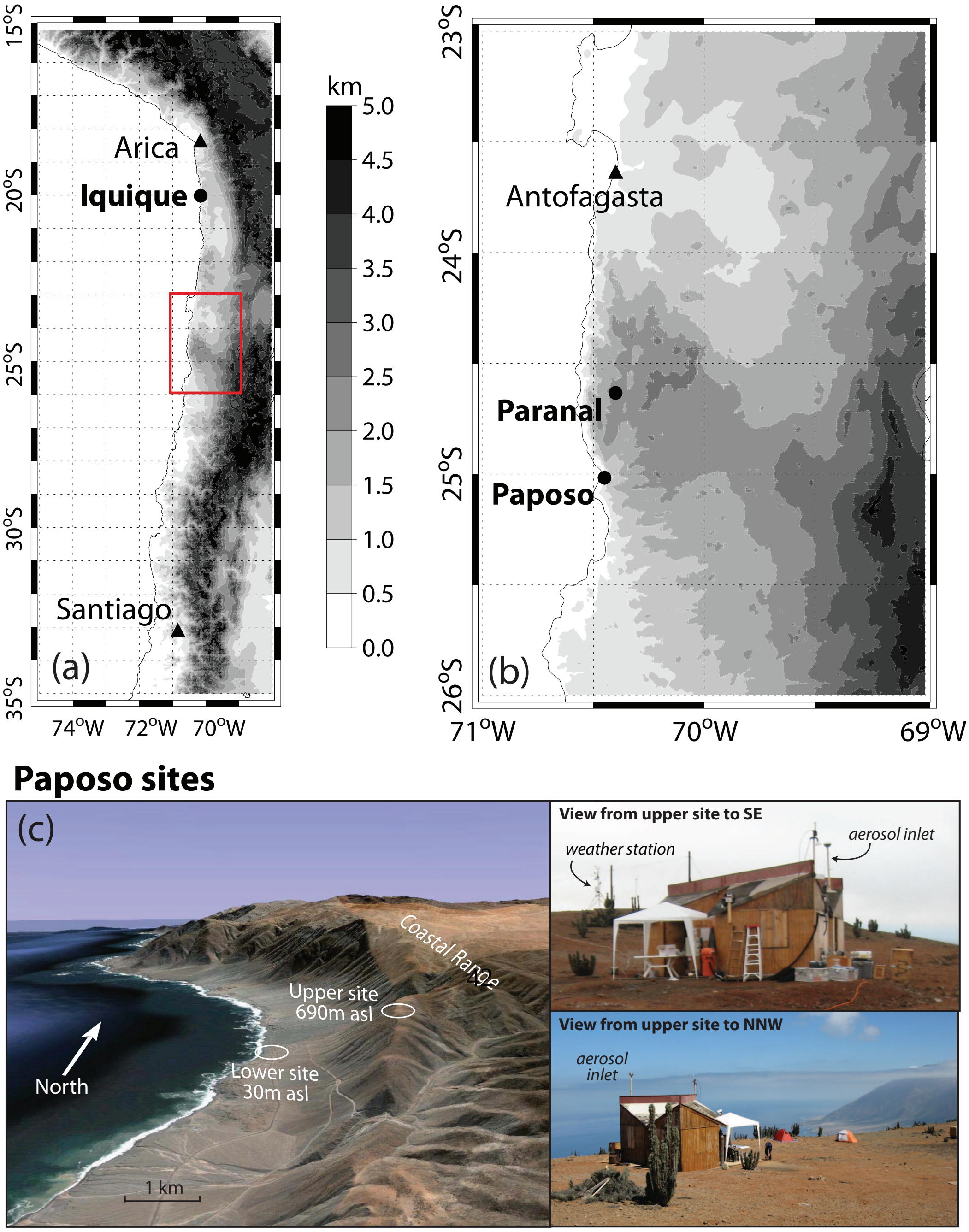

Fig. 4. (a) Map showing location of ground sites used in VOCALS-REx, with (b) a zoomed in map for the red boxed area in (a). Panel (c) shows a Google Earth terrain image showing the Paposo sites looking approximately northward, together with photographs from the upper (elevated) Paposo site.

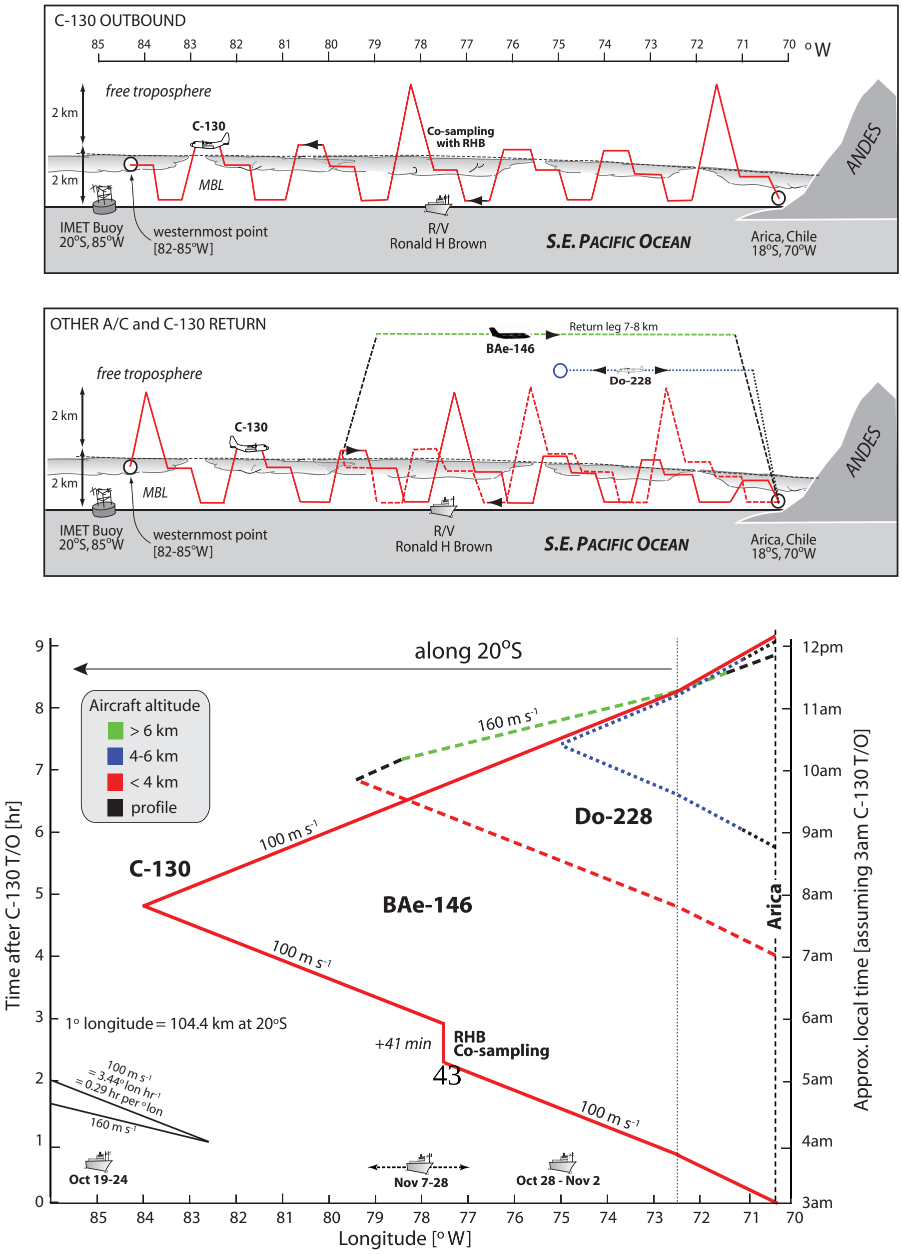

Fig. 5. Cross Section mission flight plan. Up to three aircraft (BAe-146, C-130, Do 228) were used in this mission, but in a number of cases only a single aircraft was used. In all cases, the aircraft flew from Arica to 20°S, 72°W and then flew westward along the 20°S parallel. The schematic shown here 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 minute) 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. The Do-228, when employed in this mission, flew legs at approximately 4000 m altitude using the nadir-viewing lidar 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.

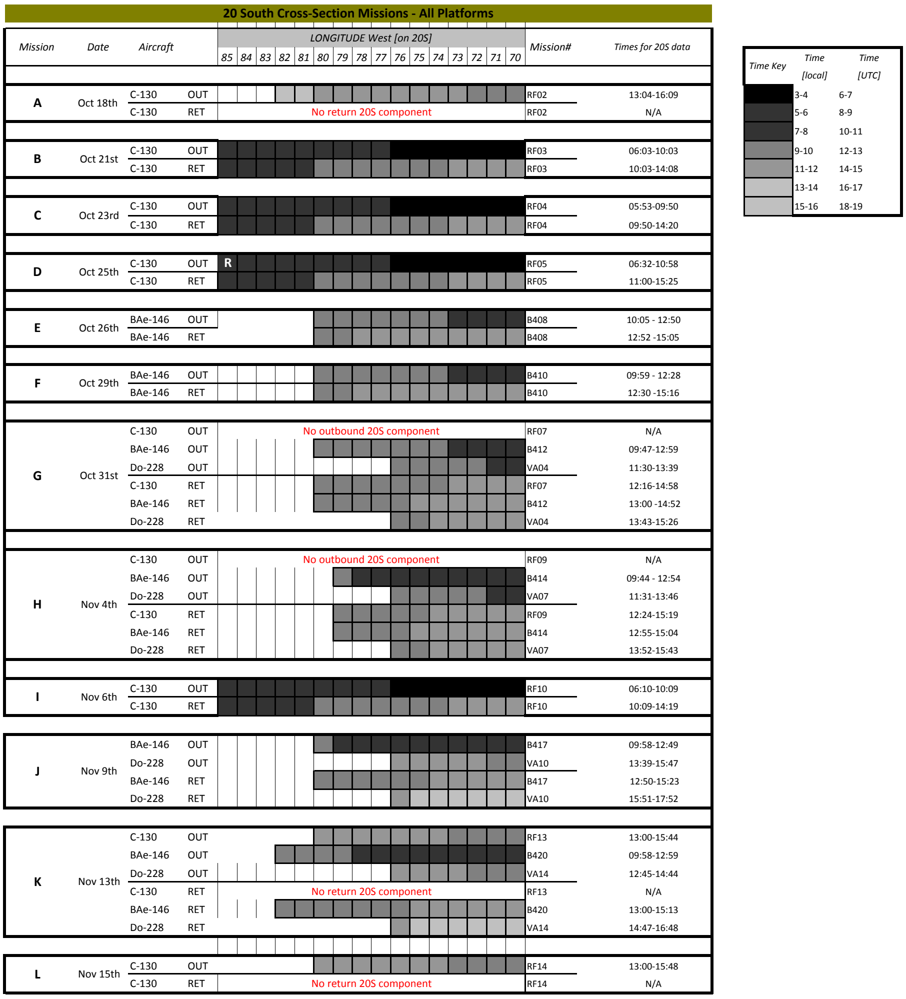

Fig. 6. Cross Section missions summary as a function of date and longitude along 20°S. Color coding shows the approximate local/UTC time of sampling. Times for which Cross-Section mission data is available are provided at right. Individual aircraft flight numbers are also given. Missions with missing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

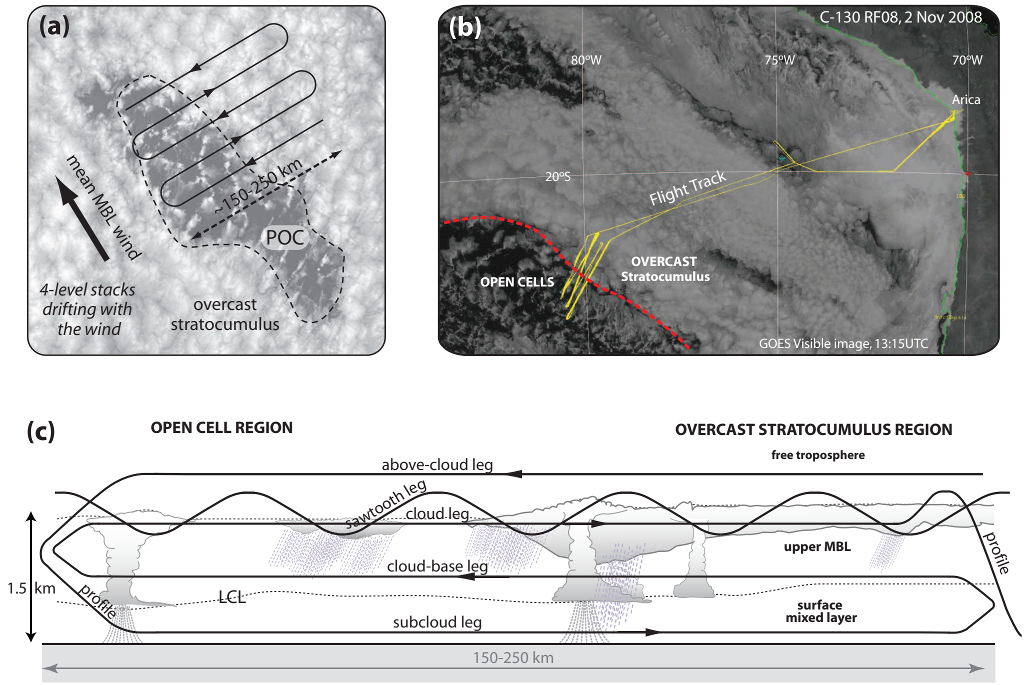

Fig. 7. POC-Drift mission flight plan. (a) schematic of plan view; (b) example POC-Drift misson flight track from C-130 Research Flight RF08 on 2 Nov 2008; (c) schematic cross section of boundary between open and closed cell regions showing sampling using long straight and level runs 150-250 km in length,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

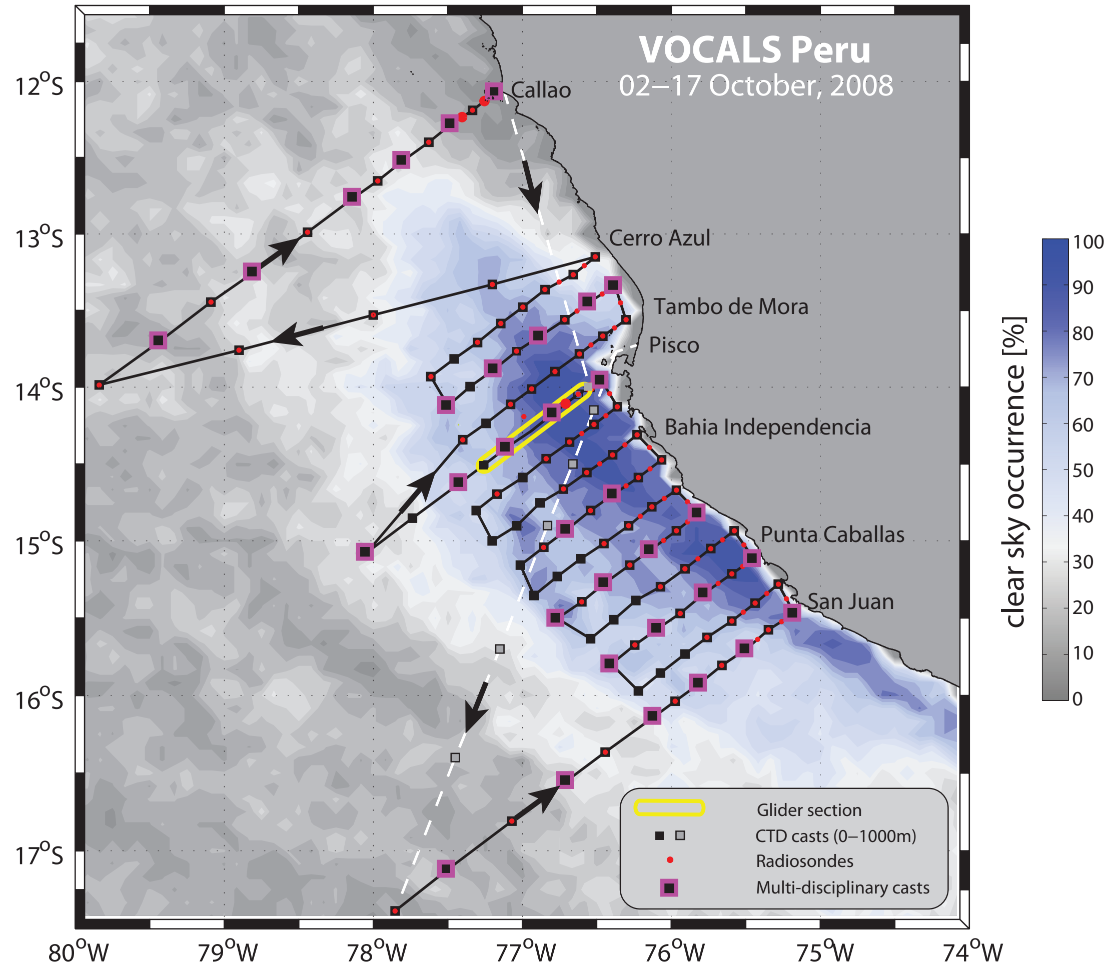

Fig. 8. Cruise track and sampling from the IMARPE R/V José Olaya during the VOCALS Peru cruise (2-17 October 2008). The color contours show the clear sky fraction

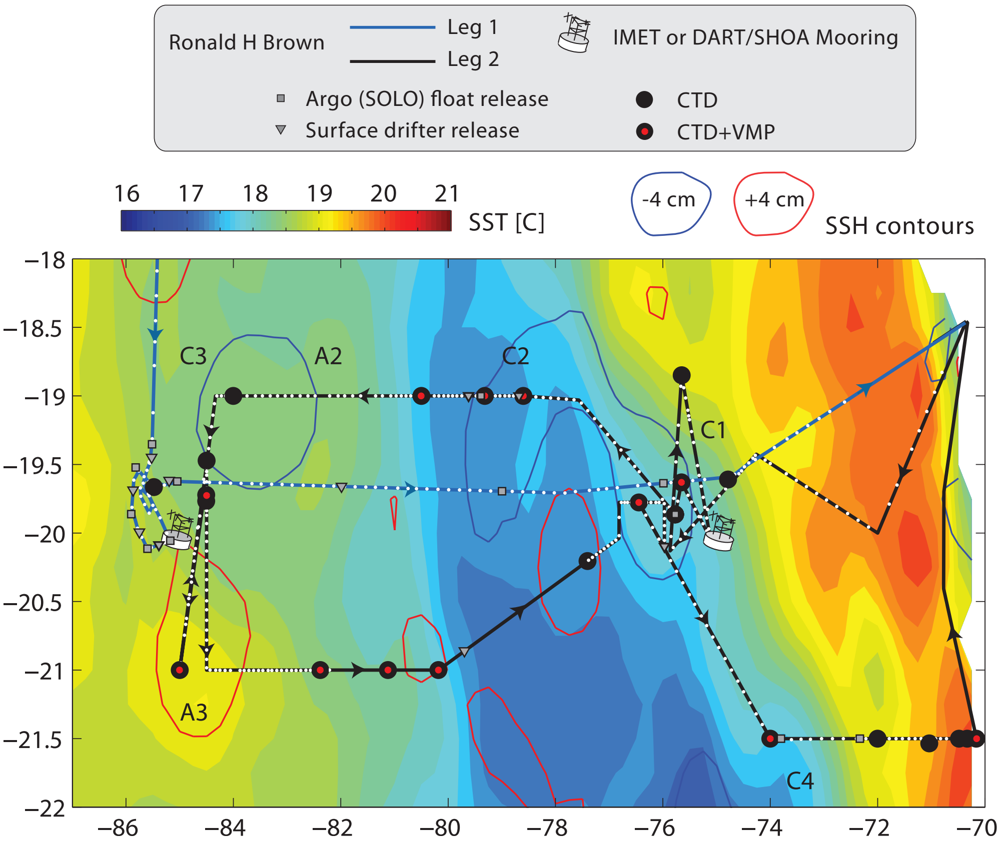

Fig. 9. Cruise track and sampling from the NOAA R/V Ronald H Brown during VOCALS-REx.

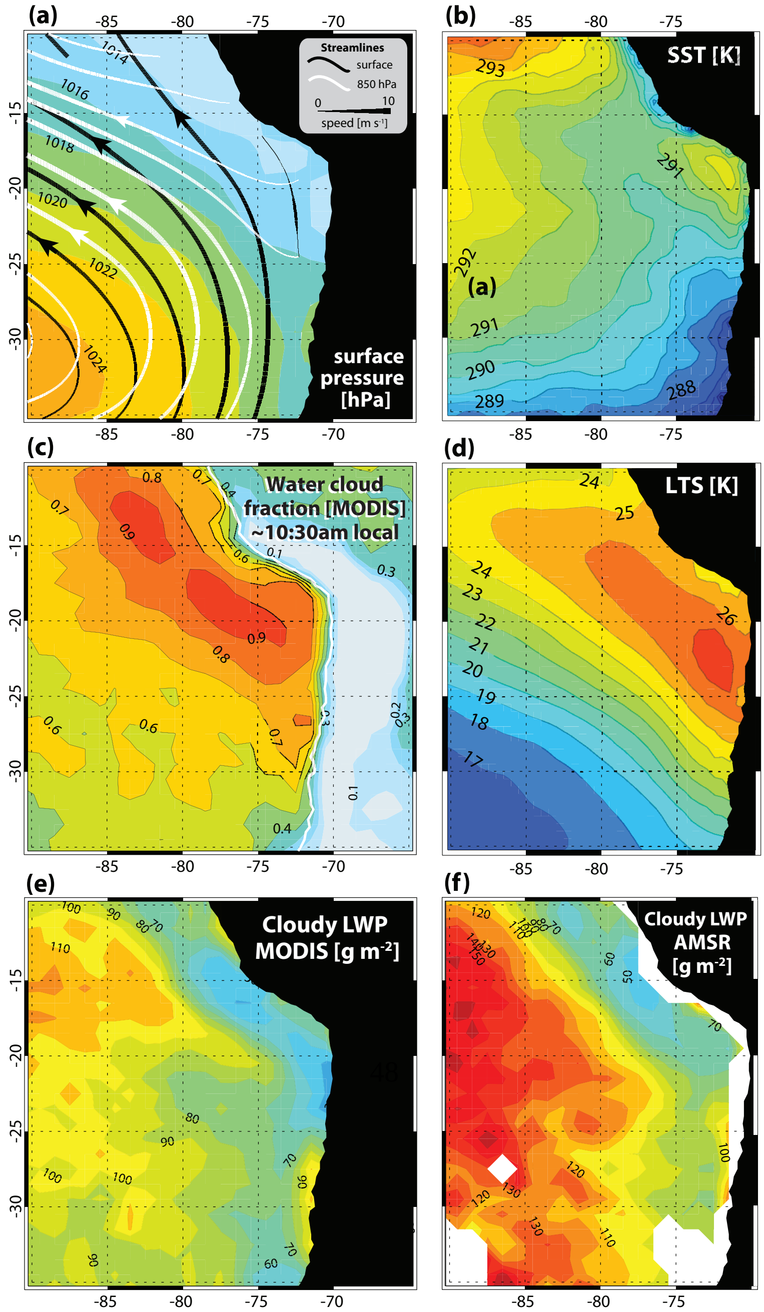

Fig. 10. October-November mean values of (a) sea level pressure (color contours) and flow streamlines at the surface (black) and at 850 hPa (white); (b) sea-surface temperature from the NOAA Optimal Interpolation analysis; (c) fractional cover of water clouds for October-November 2008 at 10:30am local time as determined by MODIS; (d) lower tropospheric stability (LTS, difference between potential temperature at 700 hPa and surface) from the ECMWF operational analyses; (e) mean LWP for cloudy pixels from MODIS; (f) mean LWP for cloudy pixels from AMSR (AMSR LWP/MODIS warm cloud fraction).

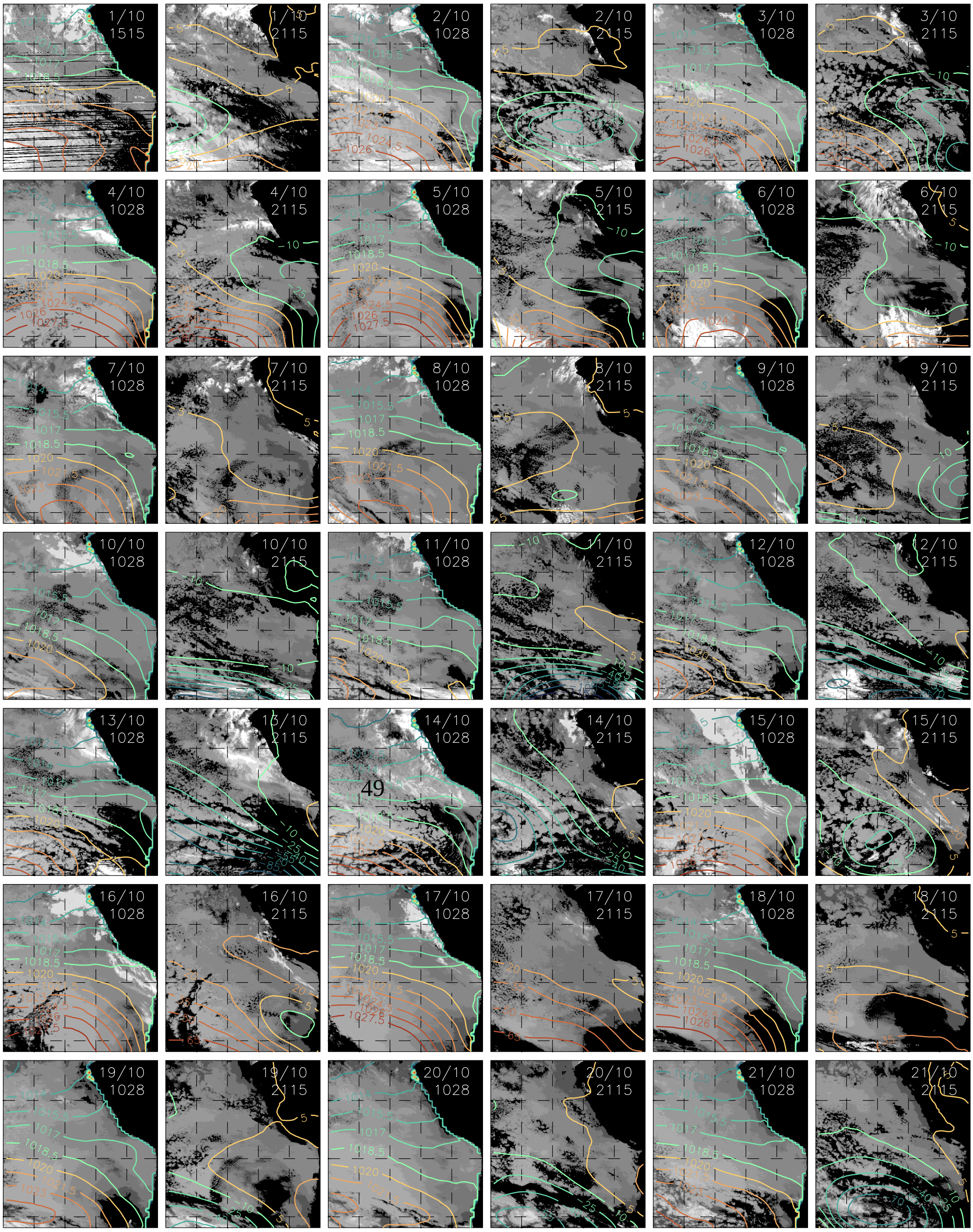

Fig. 11. Twice-daily snapshots (where available, 10:28 UTC, i.e. 05:08 LT at 80°W, and 21:15 UTC, or 15:55 LT) of the temperature difference ΔT between the SST (as given by the daily-mean OSTIA product; Stark et al. (2007)) and the GOES Channel 5 (12 μm) brightness temperature. Values of $\Delta T <$ 6 K are black and indicate virtually cloud-free regions. All values above 35 K are considered to originate from high clouds and are marked in white. Gray colors indicate low clouds, with lighter shades generally indicative of higher clouds in deeper boundary layers. The contour interval for the shading is 2 K. The GOES data have been interpolated onto the 0.05 degree-square OSTIA grid, conserving areal averages. Superimposed on ΔT imagery are meteorological data from the Met Office global forecast system. On the night-time fields are sea-level pressure contours from the operational analysis for the previous 00 UTC. The contour interval is 1.5 hPa; the 1020 hPa line is drawn in light orange colour, and the 1018.5 hPa line in light cyan. On the day-time panels, contours of the zonally asymmetric part of the 500 hPa geopotential height field are drawn, for 00 UTC following the image. A contour interval of 15 m is used, with positive values (at and above 5 m) in orange/red, and negative values (at and below -10 m) in cyan/blue.

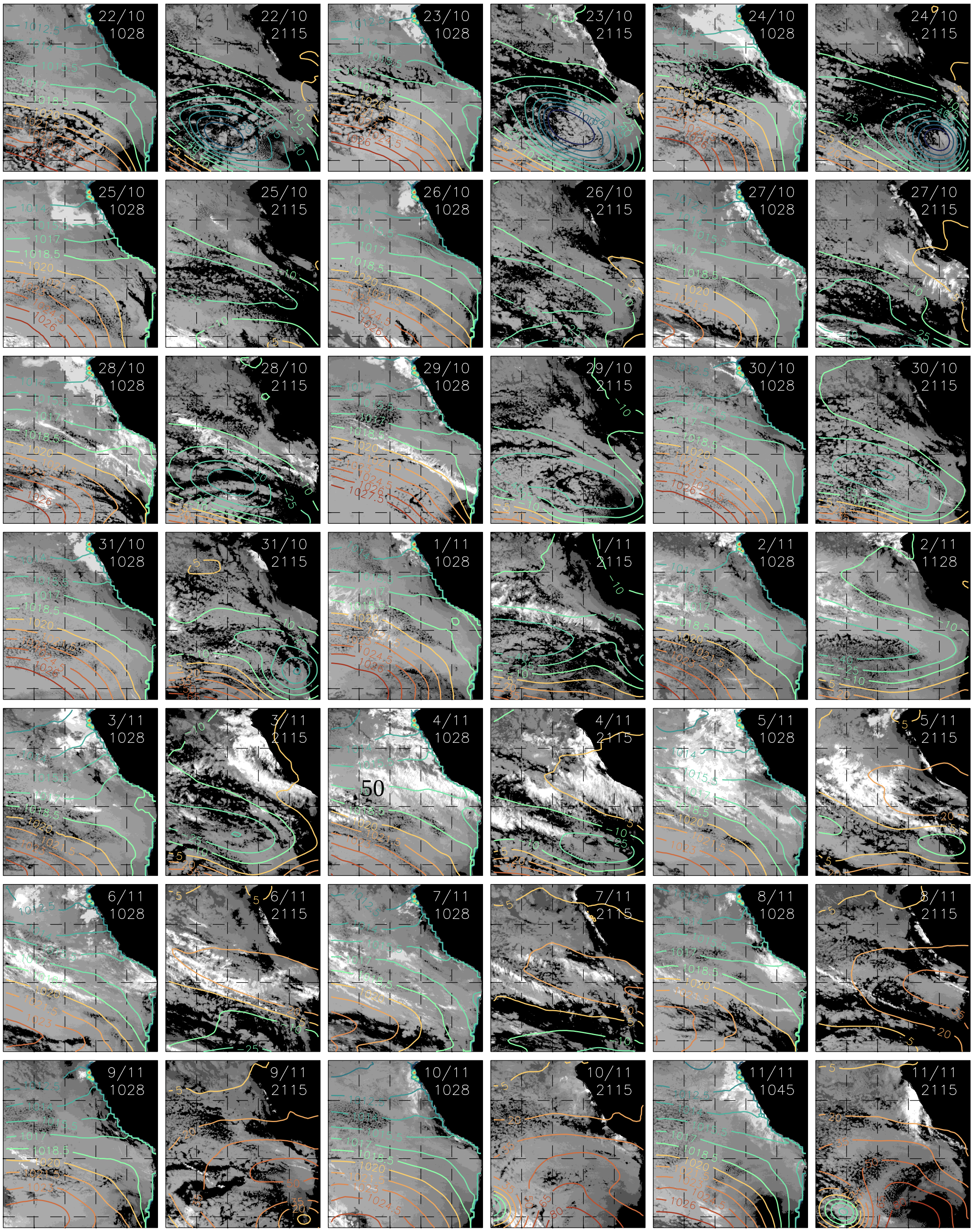

Figure 11 (continued)

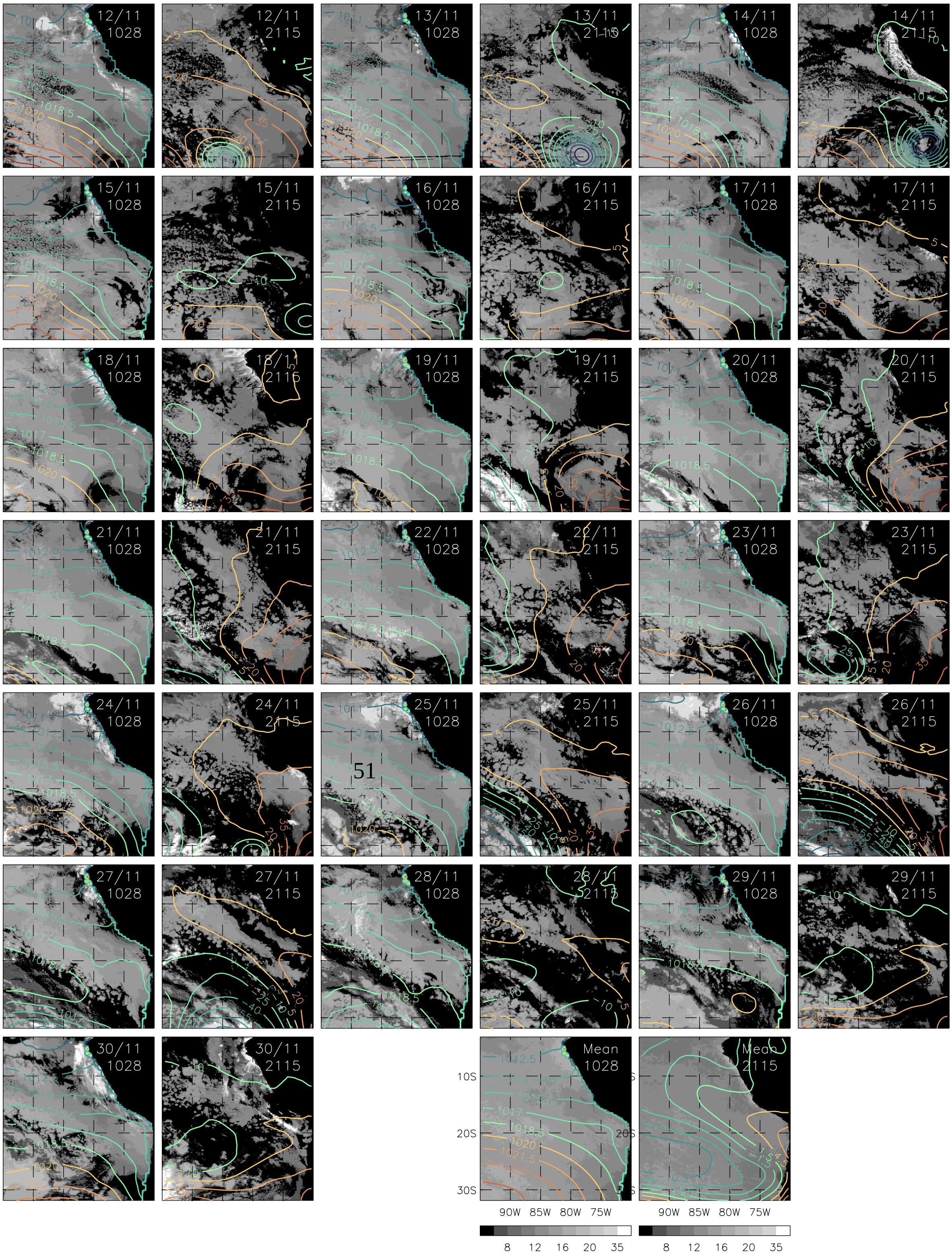

Figure 11 (continued) The final two panels show the October-November mean values of ΔT when cloud is present (determined as being when $3 < \Delta T < 35$ K) for the morning and afternoon times, with contours of mean pressure (overlaid on morning) and 500 hPa geopotential height (afternoon).

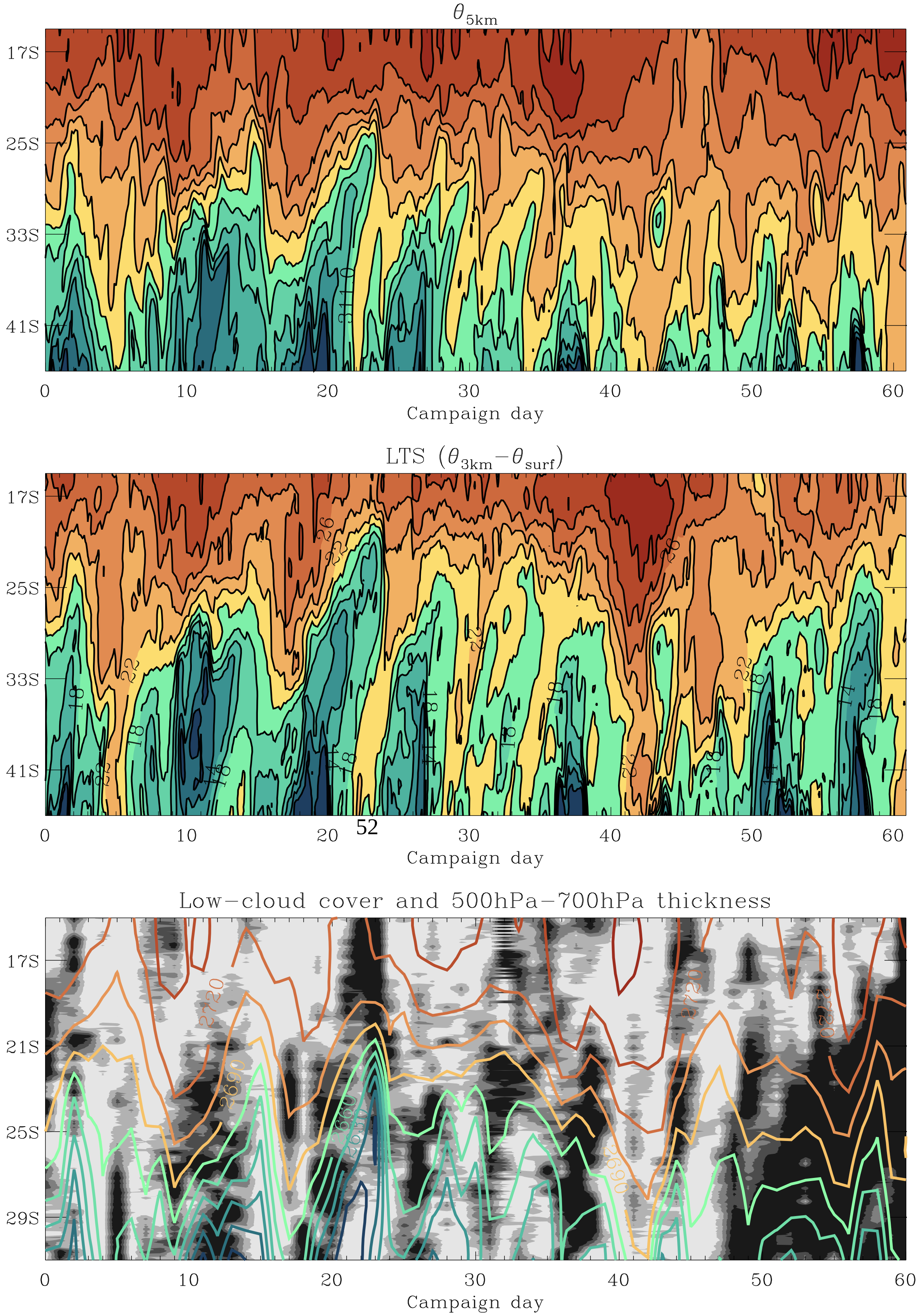

Fig. 12. (a) Lower tropospheric stability ($\theta_{700} - \theta_{surf}$) averaged over 80-85°W, as a function of time and latitude; (b) cloud fraction for the same time/latitude as (a) from GOES, and 500-700 hPa thickness contours.