Ocean-Cloud-Atmosphere-Land Interactions in the Southeastern Pacific: The VOCALS Program

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Abstract

The present paper describes the VAMOS Ocean-Cloud-Atmosphere-Land Study (VOCALS), an international research program focused on the improved understanding and modeling of the southeastern Pacific (SEP) climate system on diurnal to interannual timescales. In the framework of the SEP climate, VOCALS has two fundamental objectives: 1) improved simulations by coupled atmosphere-ocean general circulation models (CGCMs) with an emphasis on reducing systematic errors in the region, and 2) improved estimates of the indirect effects of aerosols on low clouds and climate, with an emphasis on the more precise quantification of those effects. VOCALS major scientific activities are outlined, and selected achievements are highlighted. Activities described include monitoring in the region, a large international field campaign (the VOCALS Regional Experiment), and two model assessments. The program has already produced significant advances in the understanding of major issues in the SEP: the coastal circulation and the diurnal cycle, the ocean heat budget, factors controlling precipitation and formation of pockets of open cells in stratocumulus decks, aerosol impacts on clouds, and estimation of the first aerosol indirect effect. The paper concludes with a brief presentation on VOCALS contributions to community capacity building before a summary of scientific findings and remaining questions.

Capsule

New focused measurements, analyses, and modeling of the Southeast Pacific climate system are helping to improve our understanding of key atmospheric and oceanic processes and their interactions in the eastern tropical ocean regions.

1. Introduction

The VAMOS[1] Ocean-Cloud-Atmosphere-Land Study (VOCALS) is an international research program focused upon improved understanding and modeling of the southeastern Pacific (SEP) climate system on diurnal to interannual timescales. The SEP is very important in many ways. The region produces nearly a fifth of the global fish catch (UNEP 2005) and variations in its climate can have global reach through teleconnections and aerosol indirect effects.

The SEP is characterized by strong coastal ocean upwelling, the coldest sea surface temperatures (SSTs) at comparable latitudes, the planet's most extensive subtropical stratocumulus deck, and a high and steep cordillera to the east (Fig. 1). The regional climate is defined by strong interactions between the ocean, atmosphere, land, clouds, and aerosol particles, providing extraordinary challenges to numerical simulations and model-based predictions of climate variability and change. Extreme spatial contrasts in aerosol and cloud microphysical properties exist due to anthropogenic emissions of pollutants along the Chilean and Peruvian coasts entering otherwise extremely pristine air masses over the Pacific. A deeper and broader understanding of the physical-chemical processes that shape such a complex climate system is

[1] VAMOS stands for Variability of the American Monsoon Systems, a panel of the World Climate Research Programme (WCRP)/Climate Variability Programme (CLIVAR). VOCALS researchers acknowledge the community that originated and nurtured the program.

invaluable and will provide guidance on how these processes may be better represented in numerical models. In the framework of the SEP climate, VOCALS has been addressing two fundamental objectives: 1) improved simulations with coupled atmosphere-ocean general circulation models (CGCMs) with an emphasis on reducing systematic errors in the region (Mechoso et al. 1995; Davey et al. 2001; de Szoeke et al. 2008), and 2) improved estimates of the indirect effects of aerosols on low clouds and climate, with an emphasis on a more precise quantification of those effects (Lohmann and Feichter 2005; Quaas et al. 2009).

The VOCALS program is built on several research activities in SEP climate research (Mechoso and Wood 2010). The preceding Eastern Pacific Investigation of Climate (EPIC) provided important insight on the Intertropical Convergence Zone (ITCZ)/cold-tongue complex and marine boundary layer (MBL) clouds over the SEP (Bretherton et al. 2004). A unique dataset on the diurnal to interannual variability of regional meteorology, clouds, and upper ocean structure is available from an instrumented mooring installed at 20°S, 85°W by the Woods Hole Oceanographic Institution in October 2000 (hereafter the WHOI buoy; Colbo and Weller 2007, 2009). A second mooring maintained by the Chilean Navy Hydrographic and Oceanographic Service close to (20°S, 75°W) with supplementary instrumentation by WHOI (hereafter the SHOA buoy) has produced additional data. Annual buoy-tending cruises generate opportunities for shipborne atmospheric and ocean sampling (e.g., Tomlinson et al. 2007; Serpetzoglou et al. 2008; Zuidema et al. 2009; de Szoeke et al. 2010; and references therein). Other cruises and field campaigns organized in the region with invaluable participation from scientists from Chile and Peru keep providing major contributions to the knowledge of the coastal atmospheric and ocean circulations (e.g., the CIMAR-5 cruise, Garreaud et al. 2001, Painemal et al, 2010).

These activities have resulted in a substantial body of knowledge on the SEP clouds. Satellite data and the first cloud-focused research cruise over the SEP show that the clouds are typified by extremely strong gradients in the concentration of cloud droplets (Bretherton et al. 2004; Bennartz 2007) and that gradients could have major impacts on the radiative budget of the region. The existence of open cellular convection termed Pockets of Open Cells (POCs) that frequently punctuate the stratocumulus deck in the SEP was known and documented (Stevens et al. 2005; Wood and Hartmann 2006). Furthermore, it was agreed that stratocumulus cloud albedo is sensitive to both natural and anthropogenic atmospheric aerosols (Twomey et al. 1974, 1977), both of which are produced in the SEP by desert dust, the ocean, copper smelters (Huneeus et al. 2006) and urban areas.

VOCALS is also built on an important body of modeling work on the SEP climate. Several studies have led to the wide recognition that clouds in the subsiding regions of the eastern tropical oceans drive uncertainty in climate sensitivity simulated by numerical models (e.g., Bony and Dufresne 2005). In the specific context of the eastern Pacific climate, modeling has shown that stratocumulus cloud decks are essential for key features, such as the asymmetry about the equator in SST and precipitation and an annual cycle dominated by the semi-annual component (Philander et al. 1996; Ma et al. 1996; Yu and Mechoso 1999a,b; Zhang et al. 2005). Large eddy simulation (LES) studies have demonstrated that low aerosol concentrations could promote open cell formation (Savic-Jovcic and Stevens 2008).

Despite such extensive background, major gaps and difficulties remained in the knowledge and simulation of the SEP climate. Most notably, analyses of the data coming from the WHOI buoy raised questions on the processes that balance the net positive heat flux into the ocean surface under the stratocumulus clouds (Colbo and Weller 2007). Systematic errors in the SEP of CGCMs of the type used in reports of the Intergovernmental Panel on Climate Change (IPCC) stood out as examples of shortcomings of those important tools for climate studies (Mechoso et al. 1995). The sea surface temperatures (SSTs) simulated in the region were too warm by ~ 2-4 K and cloudiness was too low by ~ 50% (e.g., Ma et al. 1996). The regional information required for GCM validation and development to reduce these errors and hence improve quantification of the Earth's climate sensitivity was either unavailable or incomplete. The SEP was perceived as a good test bed to examine and quantify key issues on the aerosol indirect effects (AIEs), such as the impacts of aerosols on precipitation and cloud mesoscale organization, the transport of continental aerosols to the remote ocean, and the processing of aerosols by clouds. Research on the AIEs in the context of the SEP was viewed as a way to reduce numerical models difficulties with these effects (Lohmann and Feichter 2005; Quaas et al. 2009). The knowledge of POCS was substantial but incomplete. The few in-situ measurements of POCs prior to VOCALS had shown the association of POCs with strong drizzle (Van Zanten and Stevens 2005; Sharon et al. 2006; Comstock et al. 2005, 2007) and very low aerosol concentrations (Petters et al. 2006; Sharon et al. 2006; Wood et al. 2008), consistent with strong precipitation scavenging. These suggestions required further testing. Gaps and difficulties in the knowledge and simulation of the SEP climate such as those just listed motivated the VOCALS program.

The present paper describes VOCALS, outlines key scientific activities within the program, and highlights selected achievements. We start in section 2 by describing the major research activities in the program. Section 3 details the coastal circulations in the SEP. Section 4 narrows down on issues associated with the ocean heat budget in the SEP. Section 5 highlights research on aerosol-cloud-precipitation interactions. Section 6 discusses how regional and large scale modeling is been applied to address VOCALS science questions. Section 7 briefly presents some of the program's contributions to community capacity building before a summary of science findings and a selection of remaining questions.

2. Research Activities

VOCALS research has been organized around two sets of broad hypotheses on coupled ocean-atmosphere-land interactions and aerosol-cloud-precipitation (Wood et al. 2011a). Starting from the hypotheses, a verification strategy was designed to provide the strongest possible synergy between long-term observations and monitoring, intensive field measurements, and modeling. The following subsections highlight activities in these three categories.

a. Monitoring: Surface fluxes and drivers over the SEP

Data collected by the WHOI buoy has allowed for the compilation of a surface climatology and air-sea fluxes during the period 2001-2010. At the mooring location and in the annual mean, a remarkably consistent southeasterly wind of ~ 6 m s^{-1} drives latent heat fluxes exceeding 100 W m^{-2}. Surface precipitation on the buoy's rain gauge is negligible. The net annual mean surface heat flux is ~ 35 W m^{-2} (positive values corresponding to ocean warming), with values ranging from 21 W m^{-2} (in 2009) to 60 W m^{-2} (in 2001). Wind speed, air temperature, SST, and shortwave radiation have marked annual cycles. The annual cycle of net surface heat flux is driven primarily by that in net shortwave radiation. The upper ocean responds to the surface forcing, with the warmest temperatures and shallowest surface mixed layers occurring in austral fall and the coolest temperatures and deepest mixed layer seen in early spring (Fig. 2). Salinity in the upper ocean also has a seasonal cycle with the shallow summer mixed layer becoming saltier in response to the evaporation. A layer of fresher water (the Eastern South Pacific Intermediate Water; Schneider et al. 2003) lies at a depth of 150 to 250 m below the surface layer.

b. The field campaign: VOCALS-REx

The VOCALS Regional Experiment (VOCALS-Rex) took place during October and November 2008, when some 150 scientists from 40 institutions in 8 nations gathered on the coast of northern Chile to conduct the field study (Wood et al. 2011a; see Fig. 3). Operations took place in the domain 12-31°S, 69-86°W. In this region, conditions in the atmosphere and upper ocean were near-average with El Niño/Southern Oscillation (ENSO) in its neutral phase. The synoptic forcing (upper-level troughs and cutoff lows) was significant during the first half of VOCALS-REx and weak with uninterrupted subsidence during the second half (Rahn and Garreaud 2010b; Toniazzo et al. 2011). Sampling was concentrated along 20°S from the Chilean coast (70°W) to the WHOI buoy (85°W). This latitude line was chosen because it transects the heart of the SEP stratocumulus deck (Klein and Hartmann 1993; George and Wood 2010), exhibits strong longitudinal microphysical contrasts (Bennartz 2007; Wood et al. 2008; George and Wood 2010; Painemal and Zuidema 2010; Bretherton et al. 2010a), crosses a region of frequent open cell formation (Wood et al. 2008), shows evidence of mesoscale ocean eddy activity (e.g. Colbo and Weller 2007; Toniazzo et al. 2009; Colas et al. 2012a,b), and had already been sampled on six previous buoy-tending cruises (e.g., Zuidema et al. 2009; de Szoeke et al., 2010; and references therein). A total of five aircraft (the NSF/NCAR C-130, the DoE G-1, the CIRPAS Twin Otter, and the British FAAM BAe-146 and NERC Dornier 220) launched from locations on the Chilean coast sampled clouds, aerosols, precipitation, and lower tropospheric structure. The long range of the C-130 and BAe-146 allowed them to operate over the remote ocean over 1000 km offshore. The other aircraft operated primarily in the region to the east of 80°W. A number of different flight patterns were flown (Wood et al. 2011a). Several aircraft flew missions along lines of constant latitude (primarily 20°S) from the coast westward. The Twin Otter flew all its missions in the near coastal region from Iquique to Point Alpha (20°S 72°W, Zheng et al. 2011). Two research vessels (the NOAA Ship Ronald H Brown (RHB) and the Peruvian IMARPE R/V José Olaya) participated in REx from ports in Chile and Perú. The RHB carried an extensive suite of aerosol instruments, cloud/precipitation remote sensing devices, rawinsondes, and oceanographic instruments to map the structure of the upper ocean, and in particular to locate and investigate mesoscale ocean features (Whelan et al. 2009). The R/V Olaya (Grados et al. 2010; Wood et al. 2011) obtained many profiles and radiosonde launches off the Pisco-San Juan area in southern Perú (13-15°S) and gathered biochemical data and hydroacoustic estimates of fish abundance. In addition, an autonomous underwater vehicle (glider) completed 9 transects perpendicular to the continental slope obtaining very high resolution information of the ocean currents and other physical properties. A coastal supersite situated in Paposo in northern Chile (25.0°S, 70.3°W) provided a suite of meteorological (surface and upper air; Rutllant et al. 2012), and air chemistry and aerosol measurements (Grados et al. 2010; Chand et al. 2010). Radiosonde launches were also performed at Iquique (20.3°S, 70.1°W) and were complemented at Antofagasta (23.5°S) where the Chilean Weather Service maintains a regular station.

c. Model assessment

In preparation for VOCALS, a Preliminary Model Assessment (PreVOCA) contrasted simulations of the SEP climate for October 2006 by operational forecast, regional, and global climate models (Wyant et al. 2010). In general, the Pre-VOCA models agreed on large-scale dynamics, but performed poorly on cloud properties having great difficulties with the geographic distribution of low cloud cover. Most models underestimated MBL depth near the coast at 20°S, and the liquid water path and its diurnal cycle at the WHOI buoy and to the east of it. The near-coastal inversion base height simulated by regional numerical models was about one-half the observed values. Other studies have shown that increasing resolution or changing turbulence schemes does not eliminate this model problem (Garreaud and Muñoz 2006; Rahn and Garreaud 2010a,b; Wang et al. 2011; Abel et al. 2010). Recent work with a high-resolution version of the Weather and Research Forecast (WRF) model has indicated that the bias in simulated inversion height is at least partly caused by increased subsidence aloft due to excessive onshore flow that in reality is strongly blocked by the coastal range (Rahn and Garreaud 2010a,b; Wang et al. 2012). The shallow MBL in the PreVOCA models is usually accompanied by the lack of clouds in the near coastal region; but the near-shore surface wind field parallel to the coast is well reproduced in general.

A follow-on VOCALS assessment, VOCA, has been completed (see www.atmos.washington.edu/~mwyant/vocals/model/VOCA_Model_Spec.htm). This assessment focuses on four global models including aerosol-cloud processes and four regional chemical transport models (three of which are versions of WRF-Chem). The period selected was 15 October - 15 November 2008 to use the extensive in-situ observations from VOCALS-REx. Figure 4 compares the model simulations with aircraft observations of mean cloud droplet number and MBL boundary layer sulfate aerosol mass concentrations along 20^0S averaged over the selected period. All models show increases of sulfate near the Chilean coast due to upwind anthropogenic sources, but the magnitude and effect of such increases on cloud droplet number vary widely between models. The models also showed consistent underestimation of free-tropospheric cloud condensation nuclei (CCN) concentration over the remote SEP.

Another model assessment addressed the simulations of the October mean heat budget along the 20°S line from 75-85°W (between the WHOI and the SHOA buoys) by CGCMs in the Third Coupled Model Intercomparison Project (CMIP3; de Szoeke et al. 2010). The data from annual cruises servicing those moorings (section 2a) proved to be in good agreement with three satellite and reanalysis-based surface flux data sets. In October, the mean net solar heating warms the ocean by about 200 W m^{-2}, longwave radiation and evaporation cool by 25 W m^{-2} and 90 W m^{-2} respectively, and sensible heat flux cools by only 5 W m^{-2} (Fig. 5a). A residual cooling of some 30 W m^{-2} must be provided to a ~ 50 m thick ocean mixed layer to limit the seasonal SST warming to the observed value of ~ 0.7° K month^{-1}. Some 10 W m^{-2} of solar radiation is estimated to penetrate the 50 m mixed layer (Zhang et al. 2011). The ocean must provide 20 W m^{-2} cooling, therefore, to balance its heat budget. All CGCMs analyzed have at least 30 W m^{-2} too much solar warming, of which about half is compensated by increased longwave cooling (Fig. 5b). The lateral ocean cooling found as a residual varies among models, but is usually underestimated and can even have the wrong sign.

3. The coastal circulation

a. Winds, MBL structure, ocean upwelling and mesoscale eddies

The data collected by the R/V Olaya reveal a great deal of alongshore variability of the near surface wind field with local maxima just to the north of major headlands and minima father downstream (e.g., Rahn et al. 2011). Along the coast for more than 700 km between Arica (18°S) and Paposo (25°S), the seasonal mean height of the MBL inversion is remarkably uniform at about 1000 m above sea level, which is the approximate elevation of the coastal range, although SST cools gradually from north to south (Rahn and Garreaud 2010a). The inversion height remains around this altitude at least up to 200 km offshore. In the near coastal zone the MBL tends to be cloud capped and well mixed, with the maximum inversion strength about 100-200 km off the coast.

Synoptic-scale disturbances (upper-level troughs and cutoff lows) propagating from midlatitudes into the subtropics can intermittently lower the height of the coastal MBL down to 700 m (Rutllant et al. 2012) in northern Chile and also offshore (Rahn and Garreaud 2010b; Toniazzo et al. 2011). This is associated with more polluted air but also thinner coastal clouds, which limits the overall radiative impact of the increased pollution (Painemal and Zuidema 2010; George and Wood 2010; Twohy et al. 2012).

The coastal ocean along the Chilean and Peruvian coasts is characterized by upwelling that drives ocean biological productivity and is a key source region for mesoscale ocean eddies (Grados et al. 2010; Garreaud et al. 2011). The surface alongshore ocean circulation in the northern boundary of the most intense upwelling cell of Peru - the Pisco-San Juan upwelling - was studied at a weekly frequency during VOCALS-REx with a Slocum glider. A glider measured temperature, salinity, fluorescence and oxygen at a high spatial resolution (2 km) along a ~ 100 km cross-shore section near 14°S. Using the drift of the glider between two dives and temperature-salinity profiles for thermal wind allowed for estimates of the absolute geostrophic current over a 200-m deep surface layer (Fig. 6). The offshore surface equatorward jet and nearshore subsurface poleward undercurrent display a high variability at weekly time scales. These measurements have provided invaluable insight on the submesoscale upwelling dynamics responsible for the subsurface cross-isopycnal salinity intrusions (Pietri et al. 2012).

Chaigneau et al. (2011) used Argo float profiles and satellite altimetry data to estimate the mean vertical structure of mesoscale eddies in the Peru-Chile Current System. Their estimates are consistent with the core of cyclonic eddies being centered at ~150 m depth, and that of the anticyclonic eddies below the thermocline at ~400 m depth. They also argued that each cyclonic and anticyclonic eddy yields to a heat and salt transport anomaly of $\pm 1–3 \times 10^{11}$ W and $\pm 3–8 \times 10^{3}$ kg s^{-1}, respectively. These eddies propagate westward across the area of VOCALS region, contribute the dominant signal in oceanic velocities at the WHOI buoy, and influence biology (Chelton et al. 2011).

b. Diurnal cycle of cloud and precipitation over the SEP

Ship observations capture diurnal cycles of cloud fraction, liquid water path, thermodynamic decoupling between the surface and cloud, and precipitation (de Szoeke et al. 2012; Burleyson et al. 2013). Cloud fraction, cloud thickness, liquid water path, and precipitation increase at night when solar warming of the cloud top ceases but longwave cooling continues (see Fig 7). The displacement between cloud base and lifting condensation level (LCL) of air at the surface is a thermodynamic proxy for turbulent decoupling and suppressed mixing between the surface layer and the cloud. Cloud base-LCL displacement grows during the day, but the cloud rapidly recouples to the surface layer at night. Cloud fraction is reduced during the day as the cloud rises and entrains dry air, while moisture flux from the surface layer to the cloud is suppressed through the stable sub cloud boundary layer. Precipitation averaged over the MBL length has a diurnal maximum in the early morning. West of 80°W, the precipitation begins to decrease before the sun rises, raising the possibility that precipitation limits itself in the region. Sub-cloud evaporative cooling of rain may establish a local stable layer sufficient to reduce the precipitation. Decoupling and precipitation are stronger and have stronger diurnal cycles in the mean west of 80°W than east of 80°W.

The cloud properties over the SEP show significant semidiurnal and diurnal components with especially strong amplitude close to the Peruvian and Chilean coastline in October reaching locations over 1500 km offshore (Garreaud and Muñoz 2004; O'Dell et al. 2008; Wood et al. 2009; Zuidema et al. 2009; Rahn and Garreaud, 2010a, de Szoeke et al. 2012). Toniazzo et al. (2011) examined the diurnal variability over the SEP on the basis of simulations with the WRF model. A deep wave with a 24-hour period is generated over the Peruvian orography and moves southwestward, while a weaker and shallower wave with a significant semi-diurnal component propagates westward from the Chilean orography. These waves are primarily confined to the lower troposphere and their impact on the inversion at the top of the MBL is substantial within ~ 5 km away from the coast. As perturbations move towards the open ocean, the remotely generated down and upwelling waves can be either in phase, out of phase or phase lagged with respect to variations locally forced by solar radiation. Since the waves gradually disperse or dissipate while propagating, a clear semidiurnal signal appears only near coastal regions.

4. The ocean heat budget

The essential question in the oceanic heat budget is how a surface ocean heated by air-sea exchange can remain cool enough to sustain the wide stratus cloud deck. In a vertical integral in the ocean depth, this requires a lateral supply of cool water or, equivalently, an export of warm water. Colbo and Weller (2007) using the WHOI Buoy data estimated indicate that the mean ocean circulation, including geostrophic and Ekman transport, was insufficient to provide the required lateral flux of cold water. Addressing these issues has been one of VOCALS main concerns.

Numerical modeling has provided new insight on the oceanic heat budget. Toniazzo et al (2009) examined heat transport by ocean eddies away from the coast by using HiGEM, a CGCM with relatively high resolution in the global ocean ($1/3^o \times 1/3^o$). In the SEP, HiGEM simulates significant contributions to the long-term mean heat budget of the water column from heat advection by ocean transients with length scales of 200-450 km, and time scales between four month and one year. At least part of the heat advection is due to transients associated with an intrusion of fresh water from higher latitudes along the east-Pacific coast. This contribution is highly variable both in space and time, and its mean magnitude at the location of the WHOI buoy is consistent with the estimate by Colbo and Weller (2007). The contribution of transients further out at 85°W is unclear and can be of either sign in the ocean interior (see also Zheng et al. 2010).

Colas et al. (2012, 2013) addressed the ocean budget problem in the vicinity of the coastal current system using a regional, eddy resolving ocean model (7.5km×7.5km). The results showed an important component of the lateral heat flux by mesoscale eddies in the pycnocline. This heat flux is primarily shoreward and upward providing a conduit between the warmer offshore waters and the cooler coastal waters caused by wind-driven upwelling. Colas et al

(2012) also found that cyclonic vortices tend to dominate the surface field, whereas anticyclonic vortices dominate the subsurface. The undercurrent sheds coherent subsurface anticyclones with warm and salty cores, in agreement with the observational results of Chaigneau et al. (2011; see subsection 3c).

The offshore vertical heat balance is then completed by exchange between the surface and pycnocline. In the results of Colas et al. (2013), a significant part of this is the submesoscale re-stratification buoyancy and heat flux in a shallow cell of eddy-induced circulation within the surface boundary layer and upper pycnocline. Some controversy remains in the understanding of the vertical heat fluxes in the upper ocean and their role on the SST. Another possible contributor is diabatic transport by near-inertial wave motions. This is yet to be determined, and a better understanding of their effects may require long time series of upper ocean measurements. A recent analysis with additional observations by Holte (2013) has suggested that the contribution of the eddy heat flux to the surface layer balance is on average small over the SEP.

5. Aerosol-cloud-precipitation interactions.

One of VOCALS central goals is the better understanding of interactions between clouds, aerosols and precipitation. VOCALS-REx observations were collected to address factors controlling precipitation and POC formation, how anthropogenic pollution is transported to the MBL and affects cloud microphysics, and the role played by precipitation in removing aerosol particles from the atmosphere. This section highlights a few of the new findings.

a. Structure of a stratocumulus region: clouds, MBL structure and aerosols along 20°S.

The 20°S synthesis constructed using data from the five aircraft and the RHB participating in VOCALS-REx (see Fig. 8) provides insight into the processes controlling stratocumulus variability on regional and synoptic scales (Bretherton et al. 2010a; Allen et al. 2011), and is being used to test climate models (section 6c). Cloud top, situated immediately beneath a strong inversion, rises sharply from the coast offshore (Fig 8a). (Here data from the seven research cruises in the VOCALS region were used to build a climatology.) A concomitant rise in cloud base means that about one-half of the clouds sampled were considered decoupled from the surface (Jones et al. 2011). Low cloud cover remains above 80% over the entire transect, but the amount of condensate almost doubles offshore (Fig 8b) because cloud thickness increases. This helps to drive stronger precipitation offshore (Fig 8c). Reduced cloud droplet concentrations due to lower aerosol concentrations offshore (Fig 8d) act also likely to increase the offshore precipitation gradient (Terai et al. 2012), but studies with cloud resolving models (CRMs) suggest that cloud top height may have a stronger control on precipitation than aerosols (Mechem et al. 2012). Along 20°S the submicron aerosol is dominated by sulfates (Fig. 8e), with organic species accounting for less than 30% of the aerosol mass (Hawkins et al. 2010; Allen et al. 2011) and even less in the less polluted airmasses over the remote ocean (Shank et al. 2012). The increased sulfate loading near the coast is driven by anthropogenic pollutants primarily from the Santiago megacity and secondarily from smelters (Yang et al. 2011; Saide et al. 2011; Twohy et al. 2013) rather than by enhanced DMS near the coast. On the other hand, DMS is the primary source in the sulfate mass budget over the remote ocean west of 80°W (Yang et al. 2009). The increase in near-coastal cloud droplet number concentrations attributed to activated sulfate particles increases their cloud brightness or albedo significantly for the same cloud liquid water path, known as the first or Twomey aerosol indirect effect (Painemal and Zuidema 2013; Yang et al. 2012). However, because the polluted near-coastal clouds are also thinner, the overall top-of-atmosphere reflected shortwave radiation decreases, rather than increases, when near-coastal aerosol loading increases (Painemal and Zuidema 2010; Twohy et al. 2013). Figure 9 summarizes the key aerosol, cloud and precipitation changes from the coast to the remote ocean along 20^0S.

b. Pockets of open cells: extreme coupling between clouds, aerosols and precipitation

Flights were dedicated during VOCAL-REx to study the spatial transition between POCs and overcast stratocumulus, and the relative influence of aerosols and meteorology on POC formation. The RHB also sampled POCs (Waliser et al. 2012) during REx. All of the POCs sampled showed strong microphysical gradients across the boundaries (Painter et al. 2012) and ultraclean layers (Wood et al. 2011b) near the MBL top. The microphysical contrasts between POCs and the surrounding cloud is a robust feature, therefore, appears to be a robust feature. At the very low droplet concentrations that typify POCs, model studies show a strong sensitivity of cloud cover to cloud droplet concentration (Ackerman et al. 2003; Wang and Feingold 2009a,b; Wang et al. 2010; Berner et al. 2011). Thus it seems reasonable to posit that strong depletion of aerosols is a fundamental component of a POC. That said, studies also suggest that relatively small meteorological differences and gravity waves can also drive POC formation (Wang et al. 2010; Allen et al. 2012). Precipitation in POCs is also locally heavier but less frequent than that in the surrounding cloud (Comstock et al. 2005; Wood et al 2011a; Painter et al. 2012), is central for maintaining the cold pools that drive the open cell dynamics (Feingold et al. 2010) and is the main cause of aerosol depletion in the POC.

Thus POCs constitute a remarkably extreme case of aerosol-cloud-precipitation coupling shown by a comparison between satellite imagery and a model that explicitly includes these interactions (see Fig. 10). POCs are also strongly coupled to the surrounding stratocumulus clouds through secondary circulations atop the MBL that are important for maintaining the height of the MBL despite reduced entrainment in the POC (Bretherton et al. 2010b; Berner et al. 2011). Since many regions of stratocumulus clouds produce precipitation in sufficient quantity to make an important impact on the MBL heat and moisture budgets (Leon et al. 2008), it is reasonable to posit that this close aerosol-cloud-precipitation coupling seen in extreme form in POCs is also important for controlling marine cloud systems more generally (Wood et al. 2012).

VOCALS is also shedding light on how an aerosol population is maintained within POCs against losses to precipitation. Recent modeling work (Kazil et al. 2011) indicates that surface sea-salt, new particle formation from the oxidation of DMS, and entrainment of particles from the free troposphere may all contribute significantly to POC aerosol maintenance. Accumulation mode aerosol concentrations near the surface within POCs are remarkably similar from case to case (Painter et al. 2012) despite differences in the sources. This hints at possible self-regulating aerosol populations within POCs that are yet to be fully understood.

c. Aerosol impacts on clouds: the importance of the free-troposphere

In an MBL with a nominal inversion at 1 km height and cloud top entrainment rates of 0.3-0.6 cm s^{-1} (Wood and Bretherton 2004; Caldwell et al. 2005), such as in the VOCALS region, CCN concentrations would be rapidly diluted if the free troposphere (FT) air were particle-free. FT air over the VOCALS region, however, contains aerosols that vary markedly in total aerosol number, size, and geographical distribution, and can be entrained into the MBL.

Figure 11a shows, for a C-130 aircraft flight RF3 on 21 October 2008, the characteristic patchiness in carbon monoxide (CO, a gas phase combustion tracer) over a distance of ~ 1000 km along 20°S. CO concentrations in the MBL are relatively low and distributed relatively homogeneously with height, while concentrations in the FT are higher in patches or “rivers” a few tens of meters to a few hundred meters thick and tens to hundreds of kilometers in horizontal extent. The region to the west of ~ 78°W is representative of the remote SEP, where MBL air is typically advected from the pristine South Pacific (Toniazzo et al. 2011). On 21 October 2008, a layer of enhanced CO and combustion aerosol from the western Pacific could be found just above the stratocumulus deck. Aerosol size distributions in the FT (Figure 11b) indicate a shift toward larger particles as CO increases. These particles are effective CCN and so entrainment of high CO air from the FFT can introduce CCN into the MBL. The concentration of particles larger than 50 nm in the remote FT west of 78°W (Fig. 9c) increases with black carbon aerosol mass (an additional combustion aerosol that correlates well with CO) from values between ~ 100 cm^{-3} to twice that number for the highest values of CO. In the MBL west of 78°W, therefore, the strong sink for aerosol by drizzle (Wood et al. 2012) can be buffered by entrainment of FT aerosol. Hence, improved understanding of the FT aerosol and factors that modulate its entrainment into the MBL will be essential to a better understanding of the MBL CCN budget and associated cloud properties.

6. Modeling

a. Regional and global dynamical models

Several studies have used WRF in support of VOCALS, and the analysis of results has raised some questions on the model's representation of various physical processes. Andrejczuk et al. (2012), for example, reported that WRF captures the formation of mesoscale cloud-free regions that resemble POCs. However, the mechanisms at work seem more dominated by dynamical processes associated with variations in subsidence, while those in LES models seem to be more dominated by physical processes associated with drizzle. Toniazzo et al. (2012) reported a clear sensitivity of their WRF simulations to the choice of vertical grid, limiting the possibility of solid quantitative statements on the amplitudes and phases of the diurnal and semidiurnal components across the domain.

The association based on an analysis of in-situ data between marine low cloud cover in the Southeast Pacific and lower-tropospheric stability (LTS) proposed by Klein and Hartmann (1993) has been widely used in diagnostic studies as well as in parameterizations. Sun et al. (2011) showed that this relationship is strongly modulated by the seasonal cycle and by ENSO. Sun et al. (2010) demonstrated that errors in stratocumulus cover over the SEP in the NCEP Global Forecast System (GFS) model can be alleviated by limiting the strength of shallow convective mixing across the inversion with algorithms based on the implementation of direct and physically-based improvements in the model parameterizations. Abel et al. (2010) showed that in the remote maritime region the Met Office forecast model provides a good representation of synoptically induced variability in both cloud cover and MBL depth. The simulation of the diurnal cycle phase is also successful, but the coastal clearing of the cloud is missed in certain days. Drizzle is likely to be too strong, and POCs are not captured (section 4b).

b) Regional modeling with integrated chemistry and aerosols

The WRF-Chem model couples dynamical, chemical, aerosol, and cloud processes and can be run at the regional scale (Grell et al. 2005, Fast et al. 2006). Studies with high resolution WRF-Chem and other LES are demonstrating that coupled cloud-aerosol-radiation processes are important for the successful simulation of SEP stratocumulus (Wang et al. 2010; Kazil et al. 2011). Yang et al. (2010) used WRF-Chem to show that inclusion of full aerosol-cloud couplings leads to significant improvements in many key features of the simulated stratocumulus clouds (e.g., cloud top effective radius, cloud water path, and cloud optical thickness). The model is able to capture daily/synoptic scale variations of aerosol and cloud properties. Saide et al. (2011) argued that WRF-Chem simulates marine cloud-aerosol interactions at a level sufficient for applications in forecasting weather and air quality and studying aerosol climate forcing, and may do so with the reliability required for policy analysis. Both studies emphasize the importance of reproducing gradients of aerosol and cloud droplet concentrations that typify the SEP. Saide et al. (2012), on the basis of the remarkably robust correspondence of satellite-derived cloud droplet concentrations to in-situ VOCALS data (Painemal and Zuidema 2011; King et al. 2012; Min et al. 2012), are assimilating satellite-observed cloud droplet concentration into WRF-Chem to better constrain aerosol properties below the clouds. WRF-Chem has also been used to provide the first model-based regional quantification over the SEP of the aerosol indirect effects on climate (Yang et al. 2012), and to describe a free-tropospheric transport pathway for aerosol transport to the remote SEP (George et al. 2013).

c. Model development

Process-level understanding developed from VOCALS observations and large eddy simulation modeling is being applied to improve physical parameterizations in global models. It can be said that VOCALS has contributed significantly to accelerate the improvement in the representation of MBL clouds in models at major centers around the world. For example, in-situ cloud and drizzle observations from REx have been used to refine the microphysical parameterization in the Met Office Unified Model (Boutle and Abel 2012). One of the VOCALS case studies is being used in the WMO Cloud Modeling program (http://slayoo.github.com/icmw2012-case1/) to examine how different models represent the processing of aerosols by clouds.

Observations from REx are a central component of two NSF/NOAA sponsored Climate Process Teams (CPTs) that began in 2010. The CPTs bring together observational scientists, process modelers, and model developers in order to accelerate the rate at which field observational knowledge is translated into improved large-scale models. Both CPTs focus on cloud processes. One CPT, led by Vincent Larson at the University of Wisconsin-Milwaukee, concentrates on the improved representation of subgrid variability in the NCAR Community Atmospheric Model (CAM) and the GFDL Atmospheric Model based on the incorporation of a higher order closure parameterization that accounts for the covariability of moisture, temperature and vertical velocity. REx observations are being exploited in a number of different ways to evaluate the parameterization and the models into which it is being incorporated (Yamaguchi et al. 2012). A second CPT, led by Joao Teixeira at the NASA/Jet Propulsion Laboratory, aims to improve the representation of the stratocumulus-to-cumulus transition in the CAM and the NCEP Global Forecast System models.

7. Community capacity building

Many students participated in VOCALS-REx alongside seasoned scientists, both out at sea and in the air. Students served as flight scientists on many aircraft missions and helped in mission planning and debriefing. These activities are leading to numerous PhD theses and student-led publications in refereed journal (e.g., Berner et al. 2011; George and Wood 2010; Hawkins et al. 2010; Jones et al. 2011; Painemal et al. 2010, 2011; Shank et al. 2011; Terai et al. 2012; Zheng et al. 2011).

VOCALS-Rex participants also reached out to both English and Spanish-speaking K-12 classrooms through the 'Windows to the Universe' (W2U) project led by R. Johnson at NCAR. Within W2U, dozens of "Postcards from the Field" were sent describing research experiences to inspire the next generation of scientists. VOCALS also provided learning opportunities to K-12 students and teachers. NOAA's Teacher at Sea Program permitted one teacher to participate in the RHB cruise.

8. Summary of findings and remaining questions

VOCALS set very ambitious goals, and progress has been achieved in several fronts.

- VOCALS-REx produced a unique dataset, which is available to the research community through the VOCALS Data Archive (http://www.eol.ucar.edu/projects/vocals/). The data provide constraints on the representation of aerosol-chemistry-cloud interactions to be used in climate and chemical transport models.
- The WHOI buoy data are currently not used for model assimilation and so they represent a unique independent resource for model validation.
- The air-sea exchanges across the region at 20°S, from 85°W to 75°W, are well described, and is providing in-situ data for model validation and improvement.

- It is firmly established that mean advection and eddy advection both contribute importantly to the heat budget of the ocean column in the SEP, though to varying degrees depending upon location along the coast and offshore distance.
- The existence of a daytime wave initiated by Andean slope heating that propagates over 1500 km offshore over the southeastern Pacific stratocumulus region was confirmed. The wave impacts clouds by strengthening the diurnal cycle, which reduces cloud albedo and increases nocturnal precipitation.
- Precipitation in POCs has a fundamentally distinct character from that in the surrounding cloud, with cold pools driving a reorganization of the mesoscale structure and dynamics. The interaction between these cold pools helps regenerate clouds.
- Strong depletion of aerosols driven by precipitation losses appears to be a fundamental component of a POC. Slow aerosol replenishment in the ultra-clean POC environment permits the maintenance of open cells.
- Along 20°S the submicron aerosol is dominated by sulfates. The increased sulfate loading near the coast is driven by anthropogenic pollutants primarily from the Santiago megacity and secondarily from smelters rather than by enhanced DMS near the coast. DMS is the primary source in the sulfate mass budget over the remote ocean west of 80°W.
- The first aerosol indirect effect has been observationally quantified over the SEP, with cloud thinning of the more polluted coastal clouds mitigating the overall radiative impact. The effects were also quantified using a regional model.

However, several issues and questions remain. The VOCALS community is actively engaged in research motivated by these questions.

- Some controversy remains in the understanding of the vertical heat transports by turbulence, sub-mesoscale eddies, and possibly other processes, and on the role of such processes in determining the SST in the SEP.
- The relative contributions of surface, entrainment, and nucleation aerosol sources to the aerosol budget in the remote MBL remains poorly understood.
- The frequency and climatic importance of POCs remains poorly characterized. The ability of anthropogenic pollutants to hinder the formation of POCs is also not yet known, with the implied significant increase in albedo important for geoengineering (Rosenfeld et al., 2006).

The impetus on the research on VOCALS issues continues unabated. One year after VOCALS-REx - in late spring 2009 - the Chilean Upwelling Experiment (CUpEx) in the near-shore region of 30°S focused on the ocean-atmosphere interaction in a major upwelling center off northern Chile (Garreaud et al. 2011). CUpEx included two radiosonde stations, several ground stations, buoys, and marine radars. This experiment has confirmed findings of VOCALS-REx in the coastal SEP and provided additional detailed information on coastal processes.

VOCALS is also motivating research in other major upwelling regions. Coupled GCMs suffer from common biases in the eastern Atlantic Ocean that resemble those in the Pacific. Observational research has an active history in the equatorial Atlantic also, e.g., the PIRATA buoy array and research cruises, aircraft campaigns, and the recent AMMA program. VOCALS and Atlantic researchers are planning joint activities under the U.S. CLIVAR Working Group on Eastern Tropical Ocean Synthesis (http://www.usclivar.org/working-groups/etos) with the ultimate goal of further reducing the SST biases of CGCMs using targeted process studies and model assessments.

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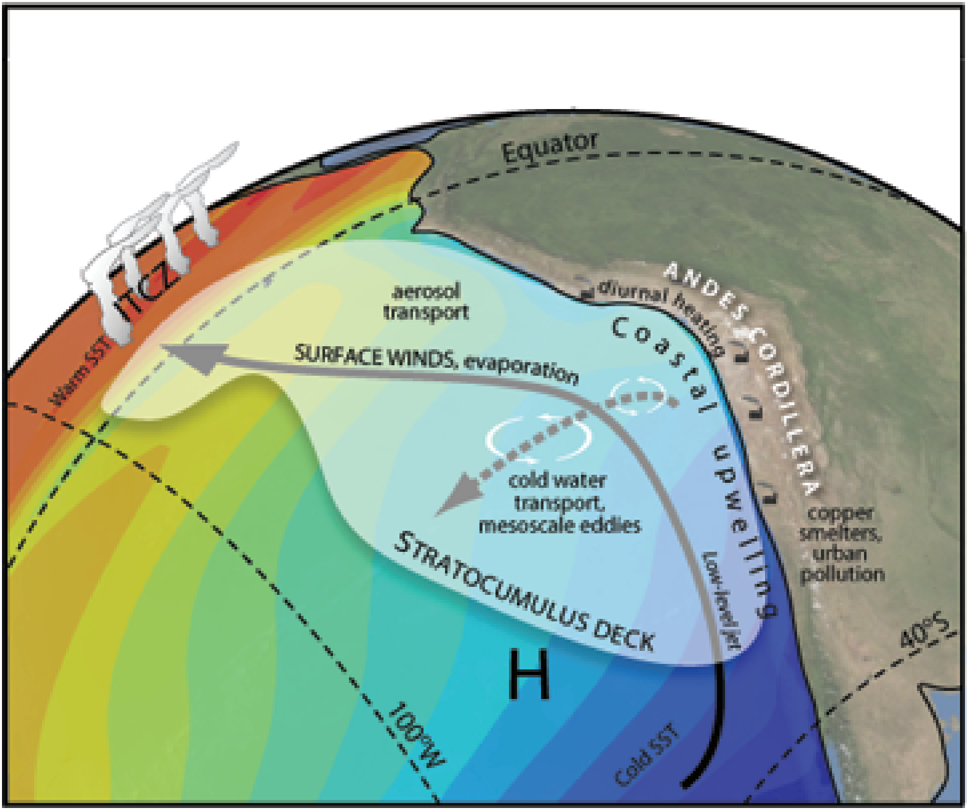


Fig. 1. The Southeast Pacific Climate System

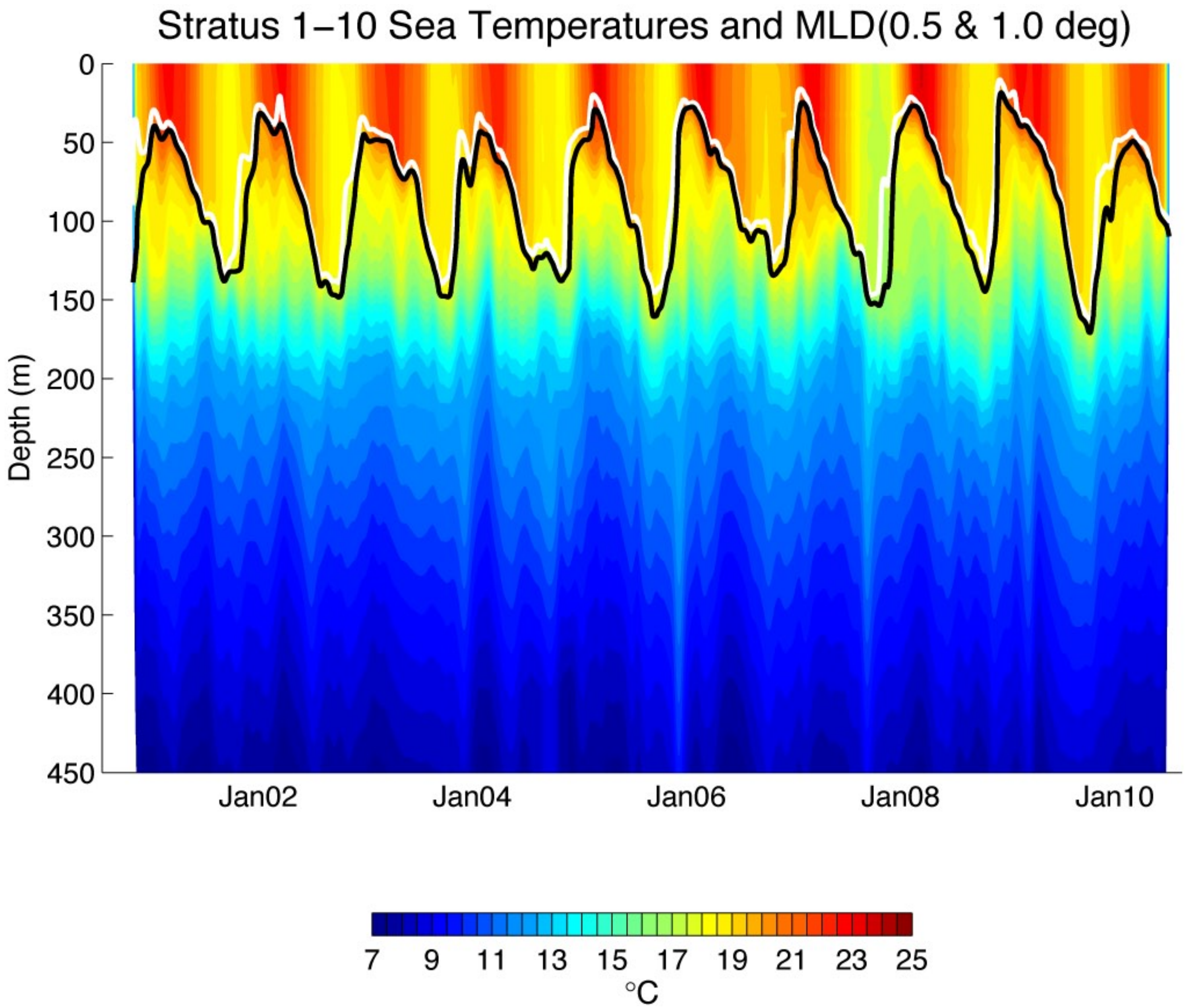


Fig. 2. The first ten years (2001-2010) of upper ocean temperature data from the WHOI buoy, daily averaged and contoured and with two mixed layer depth estimates, the white line showing where temperature is 0.5°C cooler than the surface and the black line showing when temperature is 1.0°C cooler than the surface.

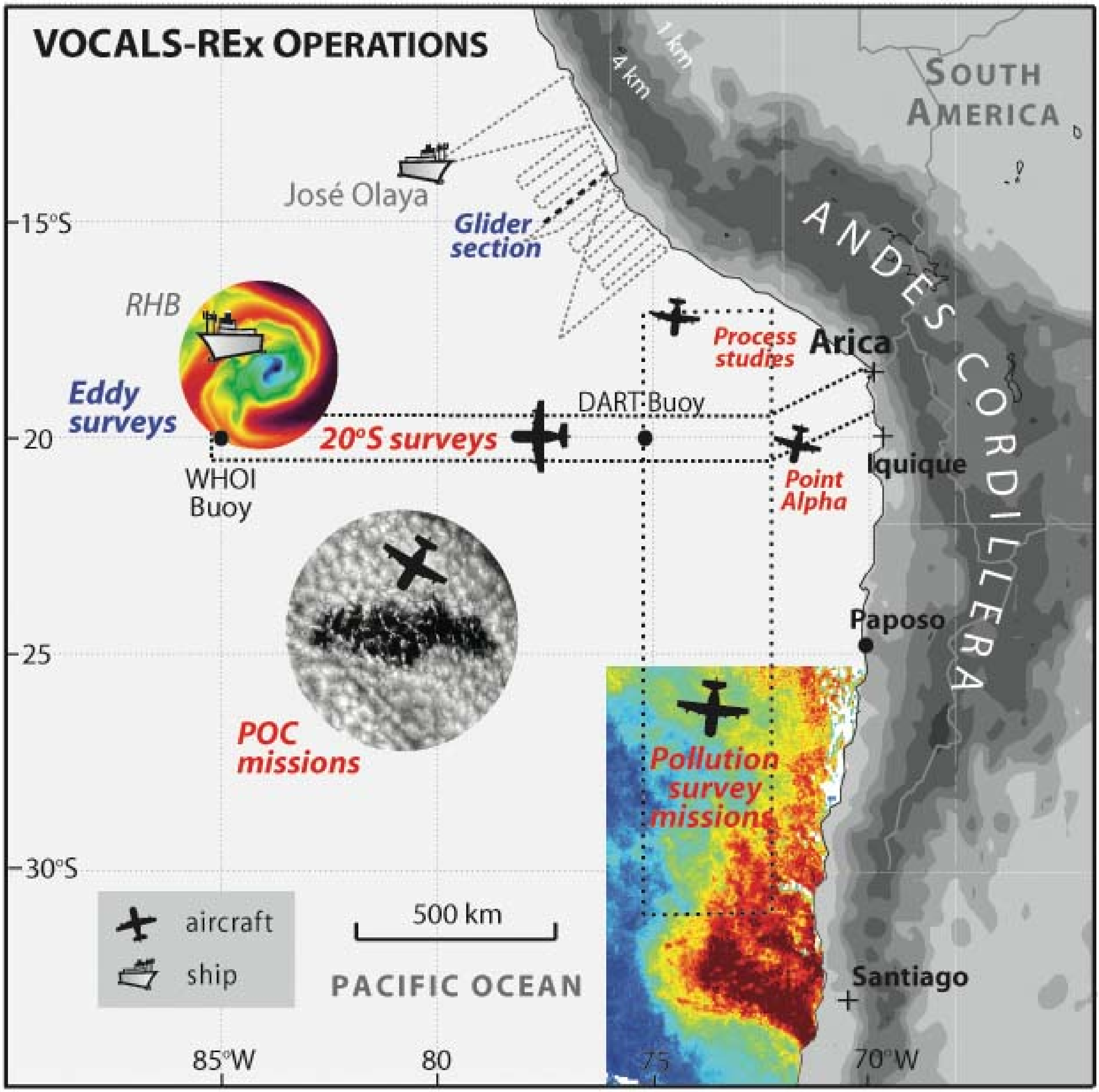
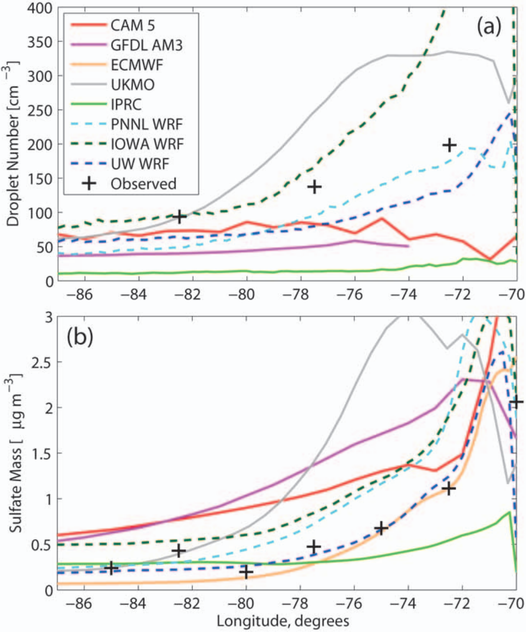


Figure 3. Schematics of the VOCALS-Regional Experiment (REx)



(a) Model mean cloud droplet number concentration along 20^{0}S compared with C-130 aircraft in-cloud measurements during VOCALS. (b) Comparison of C-130 and BAe-146 aircraft-measured boundary layer sulfate aerosol mass with model boundary layer mean values. The models include the National Center for Atmospheric Research Community Atmosphere Model 5.0 (CAM 5), the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) AM3 (Donner et al. 2011), the European Centre for Medium-Range Weather Forecasts (ECMWF) Monitoring Atmospheric Composition and Climate (MACC) model, the UK Met Office (UKMO) Unified Model (MetUM, Davies et al. 2005), the International Pacific Research Center (IPRC) iRAM 1.2 (Lauer et al. 2009), and various configurations of the WRF-Chem model from the Pacific Northwest National Laboratory (PNNL, Yang et al. 2011), University of Iowa (UIOWA, Saide et al. 2012), and University of Washington (UW, similar to George et al. 2013).

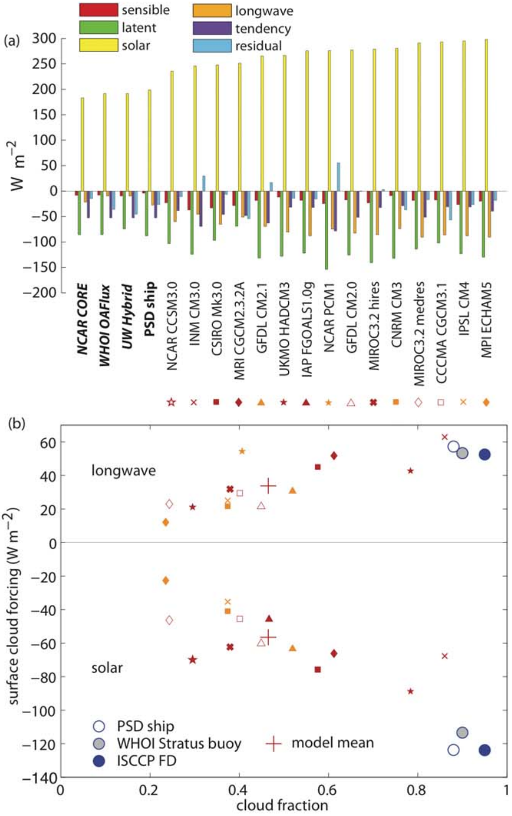


Fig. 5. (a) October mean components of the surface heat budget in CGCMs participating in CMIP3 averaged over a 5 latitude band centered on 20^{0}S and from 75^{0}W to 85^{0}W. Also shown are reanalysis products and ship observations (PSD). The observational products and models are organized from left to right according to solar flux. The storage term assumes a mixed layer depth of 50 m. (b) Surface cloud forcing (Wm^{-2}) as function of cloud fraction averaged over the same domain for observational products and models. See de Szoeke et al. (2010) for an explanation of the acronyms.

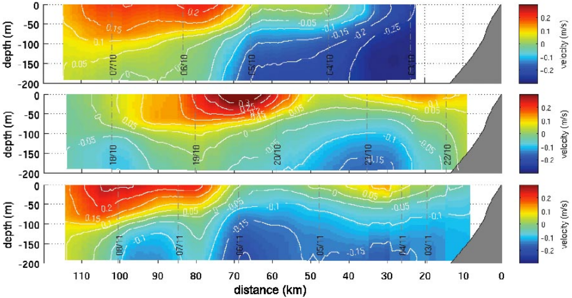


Fig. 6. Alongshore absolute geostrophic velocity (ms^{-1}) near the Perú shelf (14°S) in 2008: (a) October 4th-8th, (b) October 18th-22th, and (c) November 3rd-8th. See Pietri et al. (2012) for more details on the data.

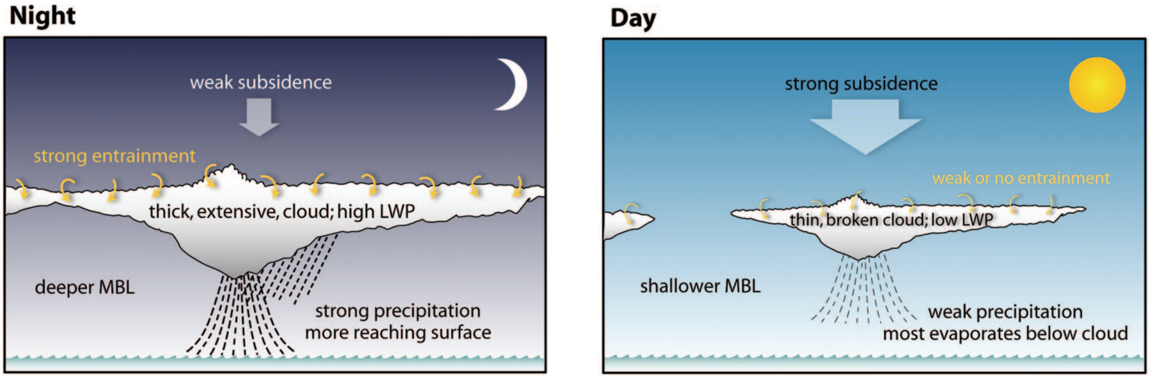


Fig. 7. Schematic of the diurnal cycle of cloud and precipitation over the SEP

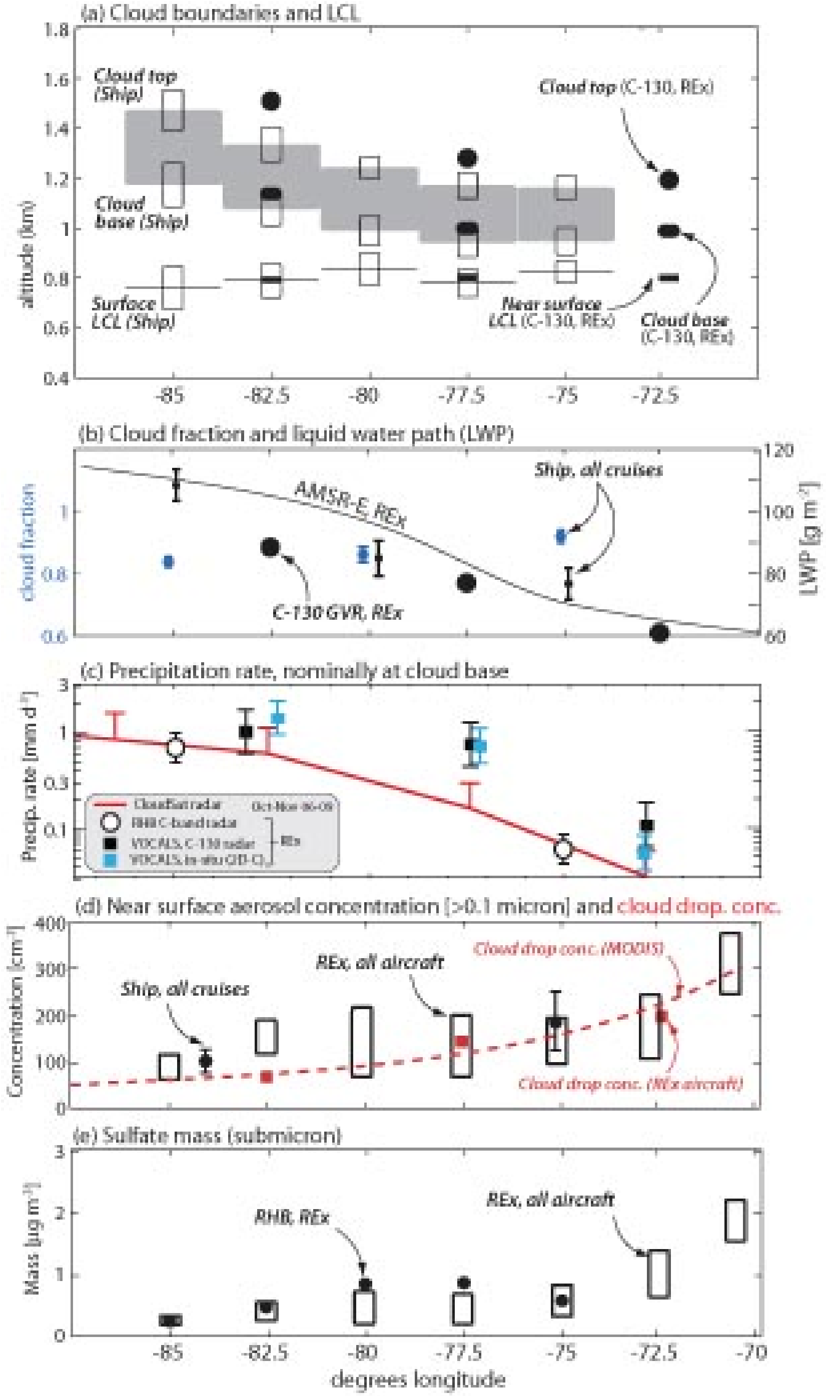


Fig. 8. Cloud, precipitation and aerosol mean statistics taken along the 20^{0}S cross section. (a) cloud top, base and lift condensation level (LCL) from the VOCALS ship cruises and from the C-130 during REx. (b) cloud fraction (blue) and liquid water path (LWP, black) from the C-130, from the ship cruises, and from passive microwave satellite (AMSR-E) during REx. (c) Precipitation rate estimates from four instruments on three platforms: RHB C-band scanning radar (black circles), CloudSat cloud radar (red line), C-130 aircraft zenith and nadir-pointing cloud radar (black squares), and the C-130 2D-C drop probe (blue squares). Error bars show estimated uncertainties. Radar cloud base rain rates are derived from the maximum reflectivity in each boundary layer column sampled. (d) Near-surface aerosol concentrations for particles larger than 0.1 μm (black) from the RHB and the aircraft (Allen et al. 2011) and cloud droplet concentrations (red) from aircraft and from MODIS (Bretherton et al. 2010). (e) Submicron sulfate aerosol mass loadings from the RHB and from the aircraft in REx.

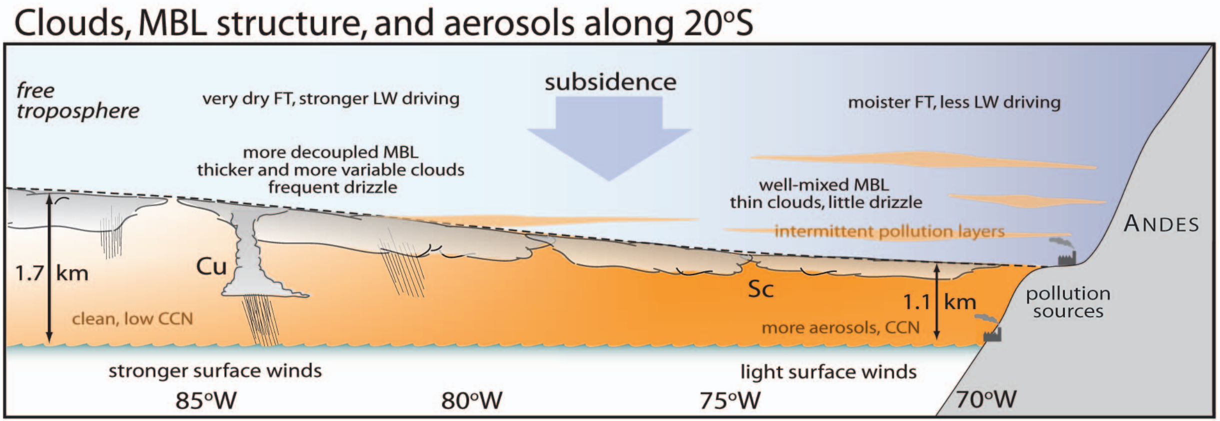


Fig. 9. Schematic summarizing the key aerosol, cloud and precipitation changes from the South American coast to the remote ocean along 20^0S.

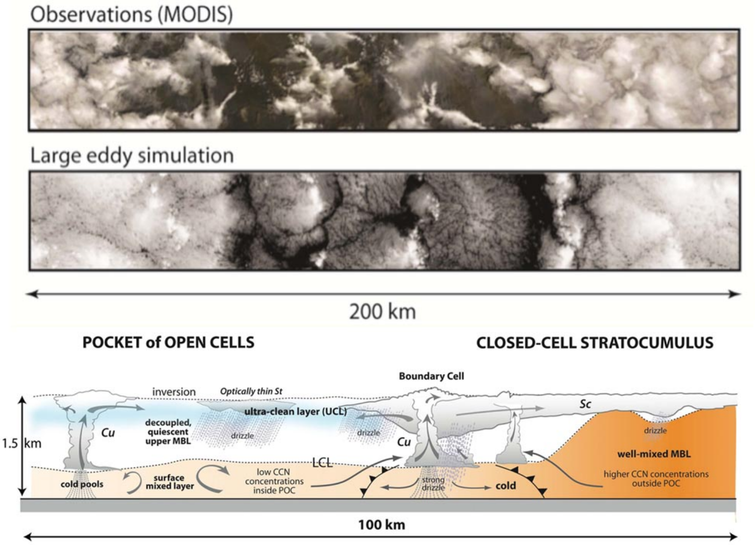


Fig. 10. Top: Satellite- observed POC-overcast structure for C-130 flight RF06 POC sampled on 28 Oct 2008 (NASA MODIS instrument, image time 10:30am local). Center: Approximate visible reflectance estimated from LES after 14.5 hours of simulation, at the same time of day (simulation from Berner et al. 2011). Bottom: Schematic of the boundary region between a pocket of open cells (POC, left)) and the overcast closed-cell stratocumulus (right).

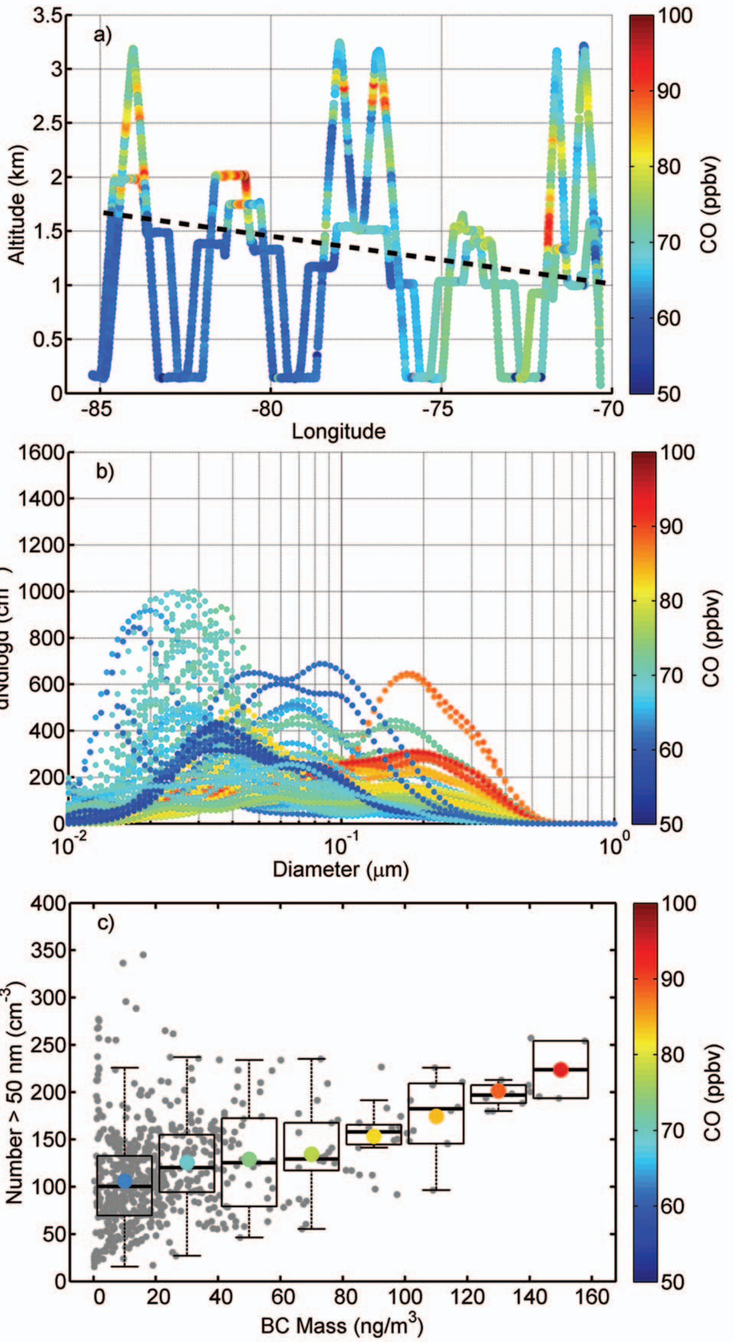


Fig. 11. (a) Aircraft flight RF3 (10/21/2008) profile along 20^{0}S color coded with CO concentrations that are in patchy layers in the FT above the inversion (dashed line). (b) Combined size distributions (see text) obtained in the lower FT above the inversion west of 78^{0}W from all 20^{0}S flights and considered to represent the remote SEP. Sizes larger than 0.050 um are typically effective as CCN in the SEP MBL and are greatly enhanced in more polluted air with higher CO. (c) Concentrations for sizes larger than 50nm (Ngt50) for each distribution (grey) and their bin averages over indicated BC mass intervals; heavy black line (median), circle (mean), box +/- 25% of data. Whisker (+/- 2 sigma). Mean number values are color coded with median of CO for each bin.