The VAMOS East Pacific Investigation of Climate (VEPIC)

A Science and Implementation Plan

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The overall goal of VEPIC is to develop and promote scientific activities leading to an improved understanding and model simulation of southeastern Pacific stratus decks, their interaction with weather systems (including deep convection), the seasonal cycle and interannual climate variations over South America, and their feedback with the underlying ocean. These activities include diagnostic and modeling studies, new sustained observations, and pilot and intensive enhanced observational programs. Participants currently include scientists from countries on the west coast of South America and the USA.

1. Background

The world's largest and most persistent subtropical stratocumulus region blankets the southeastern (SE) Pacific (Fig. 1). It is the only stratocumulus region reaching close to the Equator, and extends 1500 km offshore all the way south to central Chile almost year-round (Klein and Hartmann 1993).

Stratocumulus clouds are important modulators of climate. They are effective reflectors of shortwave radiation and thus limit the solar radiative energy that is available to the ocean surface. In addition, longwave radiation emitted by the clouds strongly cools the boundary layer. Nigam (1997) showed that the longwave radiative cooling associated with stratocu-

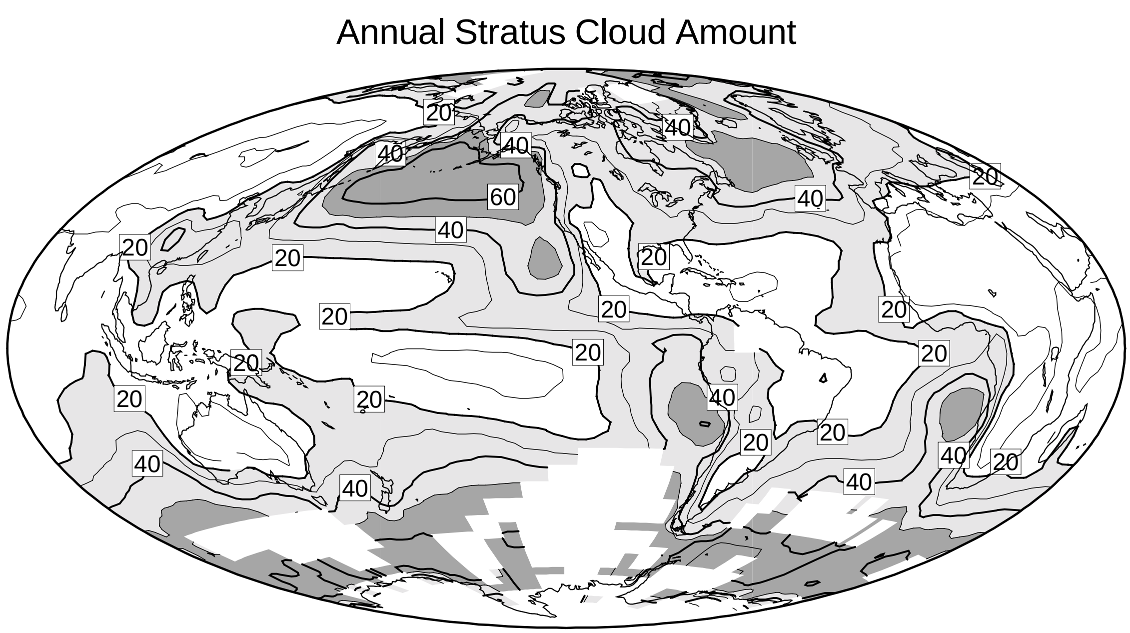


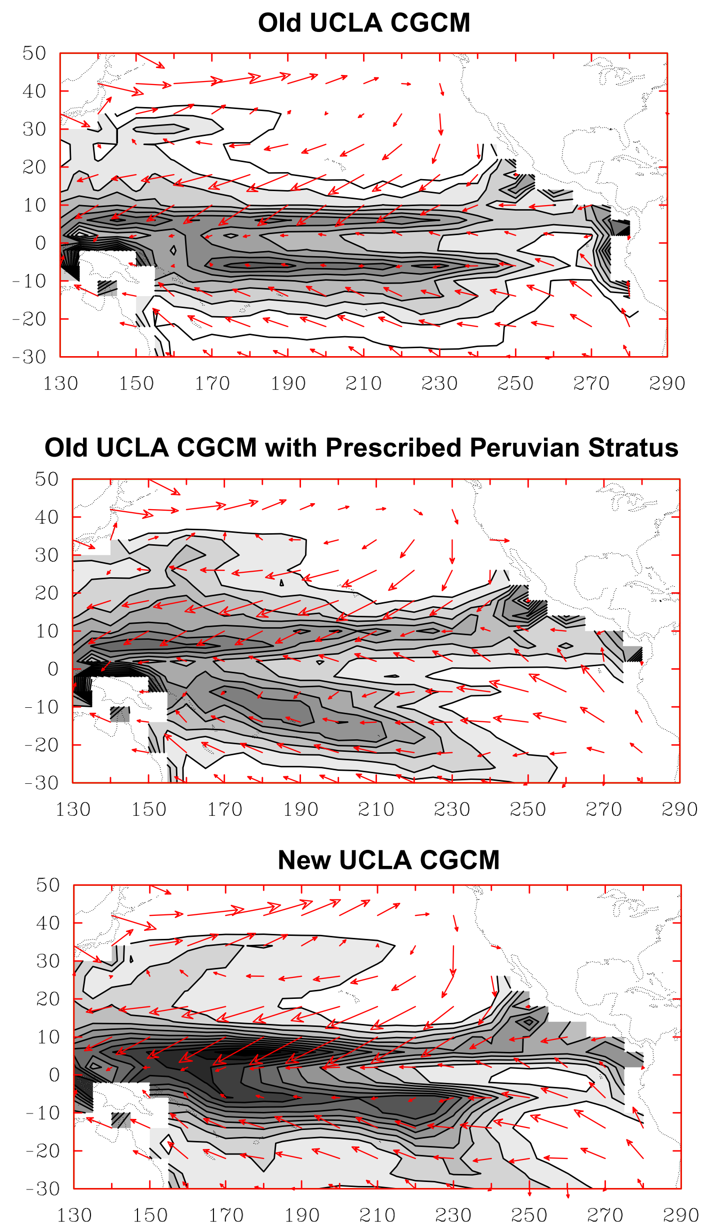
Fig. 1. Annually averaged fraction of boundary layer stratus, stratocumulus, and fog based on routine surface observations (from Klein and Hartmann 1993).

mulus clouds directly affects the regional low-level winds. It intensifies the subtropical SE Pacific anticyclone, almost doubling the intensity of the low-level southerly winds near the coast.

Coupled ocean-atmosphere models demonstrate the potential impact of stratocumulus on eastern Pacific sea surface temperatures (SSTs) and the realistic simulation of the ITCZ over the eastern Pacific (Ma et al. 1996; Philander et al. 1996). In an intercomparison of coupled models, Mechoso et al. (1995) documented large biases and intermodel variation in SSTs in this region, leading to errors in the distribution of tropical convection and the entire tropical circulation. Currently, no atmospheric GCM adequately predicts the correct seasonal cycle and interannual variability of subtropical stratocumulus cloud cover and its radiative effects, even when SST is appropriately prescribed. However, some groups are beginning to achieve encouraging results through improved representations of moist turbulent processes, inversion structure, and entrainment of air into the boundary layer. As an example, one model in which recent improvements have been documented is the UCLA coupled GCM. This model is unique in explicitly including a turbulent well-mixed PBL (with a depth prognosed by the model), that may be cloud-topped, below the remaining levels of the atmospheric model. Before 1998, this model, like most others, greatly underestimated subtropical stratocumulus cloudiness. At that time, a more accurate vertical interpolation scheme was introduced for calculating the temperature and humidity of air entrained into the PBL. This superficially small change greatly improved the spatial pattern of stratocumulus cloud. As a result, SE Pacific and equatorial E Pacific SSTs cooled several degrees, and as seen in Fig. 2, the simulated low level circulation and precipitation patterns were improved over the entire eastern Pacific, especially in March-May. In particular, a spurious double ITCZ was removed and the cross-equatorial flow near the S American coast was increased. The improved parameterization also increased the amplitude of the simulated El Nino more than twofold to very realistic levels. We should not regard the parameterization problem as solved. For instance, aspects of the UCLA-simulated stratocumulus (including cloud thickness and cloud base in some regions) are still unrealistic, and precipitation from PBL clouds is not allowed. However, parameterizations that can at least simulate stratocumulus clouds in the right regions are well positioned to use new insights into and measurements of stratocumulus characteristics and processes.

The SE Pacific stratocumulus regime (together with the underlying ocean and coastal zone) seems particularly ripe for focussed attention, due not only to its size, but to its strong, documented feedbacks with ENSO, its large north-south extent encompassing gradients in both microphysical and dynamical conditions, a rapidly developing, multinational ocean-atmosphere observing system in this region, and its potential for nurturing scientific collaborations between the countries along the west coast of South America. In addition, there are a variety of interesting feedbacks with the South American continent on many timescales that bear further investigation.

Simulated Stratus Cloud and Surface Wind Stress



From Jin-Yi Yu and C. R. Mechoso (2001)

Figure 2. Stratus cloud sensitivities in the UCLA coupled GCM..

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Stratocumulus clouds are affected by the differences between SSTs and free tropospheric temperatures, low-level winds, mean subsidence, aerosols, and synoptic variability. Many of these factors are intimately tied to the South American continent. The Andes are a formidable barrier to low-level zonal flow, helping isolate the E Pacific from Amazonia. Philander et al. (1996) suggested that the northwest-southeast orientation of the S American coast is favorable for coastal upwelling by the low-level winds, helping maintain cold SSTs and sustain stratocumulus clouds up to the equator. The cloud-induced cooling of SST is a positive feedback on this process. While the study of Ma et al. (1996) suggests that the effect of the stratus on precipitation patterns is strongest in the E Pacific ITCZ rather than over S America, further study with other GCMs is warranted.

Subtropical stratocumulus tend to occur under dry, subsiding airmasses. The strength of the subsidence helps determine the PBL depth and cloud properties. Well away from the S American coast, reanalyses suggest that the subsidence is fairly uniform and driven primarily by radiative cooling. However, near the coast, the subsidence is stronger. the PBL is shallower, and synoptic disturbances are often accompanied by regions of coastal clearing. Modeling and theoretical studies indicate that the subsidence over the eastern south Pacific may be coupled to convective heating over the Amazon and Altiplano (Rodwell and Hoskins 1996; Gandu and Silva Dias 1998). Fig. 3 shows a simulation of the vertical motion field at 500 mb in a dry primitive-equation model (including topography) in response to an idealized steady Amazonian heat source . The region of ascent (dashed contours) is collocated with the heat source. While the compensating subsidence is broadly distriburted throughout the tropics, it maximizes southwest of the heat source, directly over the region of maximum stratus cloud cover. We note that this subsidence is only about 10% of the climatological subsidence seen over the subtropical SE Pacific (Pacific heat sources are also of great importance), and that neither radiative cooling and zonal winds are included in this simulation, even though both are major potential contributors to the horizontal pattern of vertical motion. However, this type of study does suggest that seasonal, synoptic, and diurnal variations in the subsidence field (Silva Dias et al. 1987) may affect both the time-varying and time-mean cloud and boundary layer depth, upwelling, and SST.

The effect of the Andes on the feedbacks between stratus and South America, unique to this stratocumulus region, is little-studied. Like the stratocumulus, the steep, high terrain of

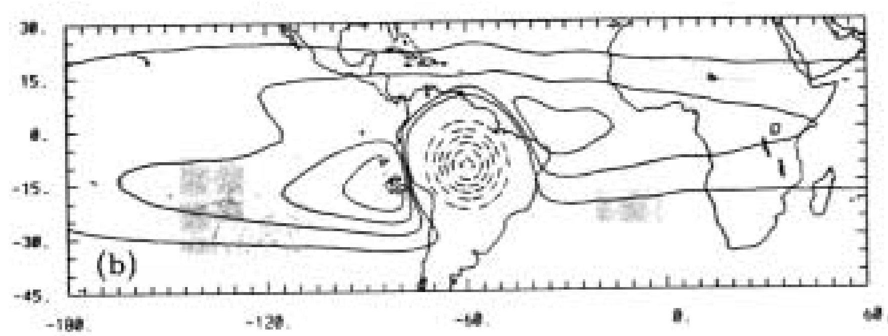

Fig. 3. 500 mb ω in a dry primitive-equation model (including topography) in response to a specified, realistically strong, deep convective heat source over Amazonia. Solid contours (interval 1 hPa d^{-1}) indicate subsidence, dashed contours (interval 20 hPa d^{-1}) indicate the forced ascent over the heating region. From Gandu and Silva Dias (1998).

the Andes is problematic for GCMs, which often have large mean precipitation errors over this region (Gates et al. 1998) that feed back on the modelled regional circulation. Gandu and Silva Dias (1998) stated that the effects of removing the Andes on their simulations were fairly minor, but one might argue that the Andes are crucial in determining where the convective heating occurs. Chou and Neelin (2000), using a simplified general circulation model in which the location of convection is predicted rather than prescribed, also showed that plausible simulations of the austral summer monsoon over South America do not require the presence of the Andes. However, they specified the stratocumulus cloud radiative effects according to climatology, removing the very feedback we are most interested in.

2. Scientific Issues

In VEPIC we hope to address several classes of scientific issues:

- Issues general to all stratocumulus regimes which can be effectively studied in the SE Pacific.
- Connections between stratocumulus and continental convection, on all timescales, including local thermally-forced circulations on the west slopes of the Andes.
- Coastally-trapped synoptic circulations along the west coast of South America
- Regional feedbacks between stratocumulus clouds, surface winds, upwelling, coastal currents and SST in the SE Pacific

We now discuss each of these topics and pose summary science questions around which to focus work in VEPIC.

2.1. *General issues*

Key scientific issues concerning the formation, maintenance, and dissipation of marine stratocumulus clouds remain, despite extensive studies that have been made of stratus in other regions of the world (e.g. Albrecht et al., 1988; Albrecht et al. 1995; Randall, 1996). Our understanding of entrainment and drizzle processes in both stratocumulus and shallow cumulus clouds remains inadequate. Both processes limit cloud thickness and fraction by drying out the cloud layer, but their relative importance is unclear and may differ between locations. These issues continue to impede our ability to realistically parameterize these clouds and their variability on all timescales in global and regional climate and weather prediction models. Transitional cloud types, such as cumulus under stratocumulus, which account for much of the subtropical stratocumulus regimes, are particularly sensitive to ill-constrained assumptions about entrainment and precipitation, and have proved particularly difficult to model.

Despite the scarcity of observations, it seems clear that the SE Pacific stratocumulus region has many similarities to other subtropical stratocumulus regimes. Klein and Hartmann's (1993) study, based on surface synoptic ship reports (quite sparse in this area) showed that there is a close relation of monthly average low cloud fractional coverage to the 'lower tropospheric stability', defined as the difference between 700 mb temperature and SST, that is similar over the SE Pacific as in other stratocumulus regimes worldwide. However, because of the closeness to the equator, the 700 mb temperature varies less than the SST in this region. Hence, the cloud cover near the equator maximizes in austral spring, when SST is minimum.

ERBE-derived cloud radiative forcing (Klein and Hartmann 1993) and microwave-derived liquid water path (Weng et al. 1997) are comparable to the NE Pacific stratocumulus regime. The tropical SE Pacific is even more devoid of high cloud and synoptic disturbances than other stratocumulus regimes. Although surface ships report occasional light drizzle in this region, the TRMM radar detected precipitation above its measurement threshold of about 1 mm/hr over a $(4\ \mathrm{km})^2$ region less than 0.5 % of the time (Short and Nakajima 2001).

Even given its apparent similarities to the better studied NE Pacific stratocumulus, there are several reasons that SE Pacific stratocumulus regime is an attractive region for studying general characteristics of stratocumulus for several reasons. These involve both its physical characteristics and prospective improvements in the observational infrastructure that may reverse the current data sparsity and provide better measurements of some processes than in other stratocumulus regimes.

The first physical attraction of this region is its tight feedbacks to ENSO, which means that interannual variations in the cloud characteristics in this region are substantial, and appear to have substantial impacts on ENSO evolution. This makes it an important focal area for climate modeling and testing of improved parameterizations. Bajuk and Leovy (1997) showed a large ENSO modulation of cloud amount and type, especially within 10 degrees of the equator, consistent with the changes in SST.

Second, because the stratocumulus extend far into the tropics, the free-tropospheric conditions vary greatly between the north and south ends of the stratus regime. Near the equator, there is usually lower-tropospheric easterly flow, with large humidity variations on synoptic timescales associated with intermittent injection of moisture into the flow by deep convection over central and south America. This can dramatically impact the effectiveness of entrainment drying in limiting cloud thickness.

Third, the SE Pacific stratocumulus may be a good natural laboratory for looking at feedbacks between aerosols, precipitation, and boundary layer cloud evolution. Preliminary retrievals of cloud droplet size using polar-orbiting satellite data from Aug. 1998 by P. Minnis of NASA (Fig. 4) show a large and persistent meridional gradient across the stratocumulus, with droplet effective radii twice as large poleward of 15 S as near the equator, except very near the coast, where effective radii are uniformly small. Similar gradients are not seen in the NE Pacific. We hypothesize that these gradients are due to large meridional variations in the ambient aerosol concentrations, perhaps driven by entrainment of aerosol-rich continental air from the tropical easterly flow. This suggests that in the south part of the regime, the stratus should be more susceptible to drizzle-induced thinning, decoupling, and partial breakup

As discussed further in Section 3.2 (and see Fig. 7), the atmosphere and ocean observing system over the SE Pacific is rapidly improving, providing a unique infrastructure for studying the stratocumulus and their coupling to the upper ocean. An array of buoys that will make surface meteorological and upper ocean measurements, called OSEPA (the Oceanographic SE Pacific Array) has also been proposed by the four Pacific Rim nations of S America (Colombia, Ecuador, Peru and Chile) to the Global Environment Fund of the World Bank. This will consist of 6 zonally oriented lines of 4 buoys each, at 5, 37, 370, and 1850 km from the coast . Peru has already deployed four buoys, and Chile is currently deploying two buoys from separate funding. One buoy in this array, deployed in 2000 at 20 S, 85 W and maintained by NOAA (USA), also provides continuous real-time measurements of all surface turbulent radiative and turbulent flux components. San Felix Island (27 S, 80 W), a small,

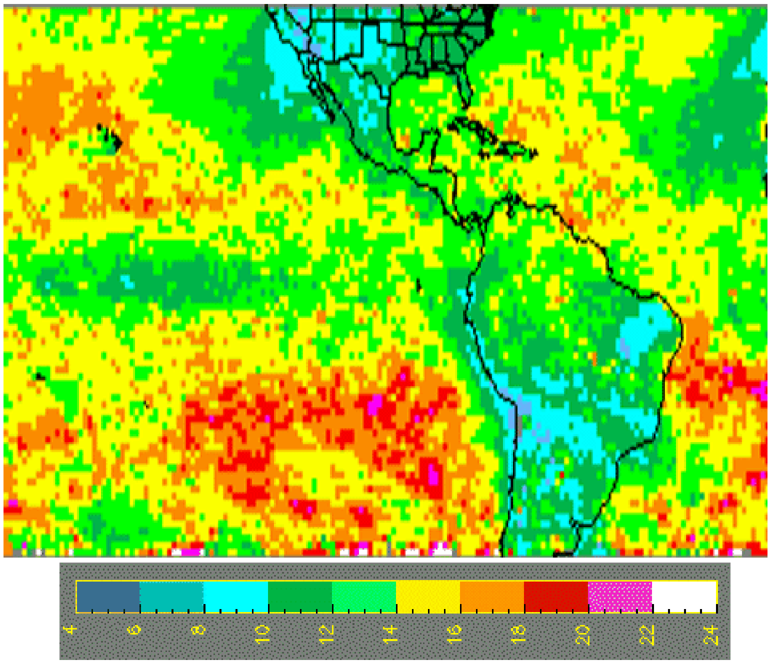

Fig. 4. Satellite retrieval of mean cloud droplet effective radius for August 1998 (courtesy P. Minnis, NASA). Note the large increase in effective radius from 10 S to 20 S off the west coast of S America, the lack of a corresponding feature in the NE Pacific stratocumulus, and the coastal band of small effective radius.

remote island nearly 1000 km offshore of Chile, is a unique potential location for more sophisticated long-term surface-based measurements in an open-ocean stratocumulus regime. The network of coastal meteorological observations is also improving, particularly in Peru.

The Chilean CIMAR-5 cruise (Garreaud et al. 2001) along 27 S from 70-110 W, during March, provided a unique cross-section through the south end of the stratocumulus regime, documenting the general rise of the inversion and reduction of cloud of the inversion offshore, episodes of drizzle, and the interaction of cloud and boundary layer properties with synoptic scale variability.

The US-supported EPIC 2001 field study will include a two week exploratory cruise into the equatorial part of the SE Pacific during October 2001, starting southward along the 95 W TAO buoy line and then heading to the NOAA buoy for a six day stay. This cruise should help characterize spatial gradients in the boundary layer clouds in the southeasterly trades and up through the equatorial cold tongue. The ship will carry a large suite of surface-based remote sensing instruments, including lidar, and cm and mm-wavelength Doppler radar for sensing of clouds, precipitation, and aerosols, will measure radiative and turbulent flux components, and ocean mixed layer characteristics along its track.

Neither of these cruises was designed to quantify the roles of entrainment, subsidence and drizzle in limiting stratocumulus cloud thickness, and the roles of natural vs. anthropogenic and marine vs. continental aerosol in determining the cloud droplet concentrations. One particular controversy at present is the role of large sea-salt particles in broadening the droplet spectrum and promoting drizzle even in relatively polluted marine stratocumulus. In addition, lidar measurements from aircraft or satellite might illuminate the relation between subsidence and inversion height in this area, especially if combined with ship or buoy measurements of near surface winds, from which horizontal mass divergence in the atmospheric boundary layer could be computed and used to infer subsidence rates (otherwise, these must be taken from numerical weather prediction or mesoscale model analyses.) This would provide useful constraints on the entrainment rate and its relation to cloud properties.

Summary science questions include:

- What is the interplay between entrainment, drizzle and SST in limiting the thickness and extent of marine stratocumulus clouds over the SE Pacific? How much does this vary by season and location?
- What is the effect of both natural and anthropogenic aerosol from South America on stratocumulus properties over the eastern Pacific?
- How can the radiatively important effects of stratus clouds over the eastern Pacific be represented realistically in numerical models to provide improved simulations of the variability of the American Monsoons?

1.2 *Connections with continental convection and thermally-driven coastal circulations*

There has been remarkably little discussion in the literature regarding the relationship of seasonal and longer anomalies in subtropical stratocumulus clouds with continental convection. These long timescales are particularly important for the feedback of clouds on SST. The Rodwell-Hoskins (1996) mechanism of Rossby-wave subsidence induced by monsoon heating provides a theoretical framework which could be investigated using existing data. It suggests that the maximum in subsidence and low cloud cover should be westward and poleward of the convection maximum, that these maxima should seasonally co-migrate with one another, and that the subsidence should be more localized and intense as the maximum in convection moves furthest off the equator. Radiative cooling in the stratocumulus may help to amplify this Rossby wave subsidence. Systematic analysis of existing data and re-analysis products, and simple models such as the QTCM (Neelin and Zeng 2000) could shed more light on these relations and help guide subsequent observational and theoretical work. The circulations driven by the convection (see Fig. 3) also help transport moisture and aerosol both horizontally and vertically, which may influence the stratocumulus directly through entrainment and indirectly by affecting the downwelling radiation incident on the cloud tops and hence the radiative forcing for turbulence

The proximity and height of the Andes to the coast also seems likely to play an important role in the stratocumulus regime. First, the Andes affect local circulations along the coast driven by diurnal continental-ocean contrasts. There are slope flows both within and above the marine layer; the coupling between these is uncertain. There is little documentation how far offshore the diurnal circulations impact the cloud properties. Rozendaal et al. (1995) compiled a global climatology of the diurnal variability of low cloud amount from surface observer reports that shows significant daytime cloud reduction throughout the stratus regime, but due to the sparsity of data in the SE Pacific this dataset is not adequate for studying coastal effects. A study based on currently available geostationary satellite imagery could be a fruitful addition. Modelling studies could help illuminate the diurnal variation of vertical motions in the coastal zone. Second, the Andes affect the distribution of deep convection, which presumably impacts circulations over and off the west coast and perhaps the lower tropospheric thermodynamic characteristics and hence the stratocumulus. Third, they provide a barrier along which coastally trapped waves in the inversion can propagate , and which inhibits low-level zonal flow. We will address the latter two points in the next section, since they are associated with synoptic-scale (2-14 day) variability.

Summary scientific questions include:

- How do topography and deep convection over South America affect the seasonal and diurnal cycle of the characteristics of eastern Pacific stratus and SST?
- Are there any plausible mechanisms for the radiative cooling in the stratus clouds to affect warm-season precipitation over South America?

2.3 *Synoptic-Scale Variability over the SE Pacific*

Synoptic variability in the SE Pacific is important to inhabitants of the W coast of S America. The fishing industry uses forecasts of winds and coastal upwelling to position boats in nutrient and fish-rich waters. Urban pollution in the inland valleys is synoptically modulated. Even a temporary cessation of upwelling in austral fall off the coast of Peru can permit SSTs to rise high enough to support deep convection and coastal flooding. Further south, in central and southern Chile, the SE Pacific blends into the storm track; here there are strong teleconnections between ENSO and winter-season precipitation. The statistical character of synoptic variability is a key aspect of the climate of the region. Thus, even though the focus of VAMOS is climate variability and prediction, we feel that this can only be achieved with a high level of understanding of typical patterns of synoptic variability along the west coast of subtropical South America. The few published works on this subjecty have mostly focused on individual cases and their local effects, and have been limited by scant observational data. However, some basic features are apparent.

The subtropical anticyclone over the Southeast Pacific (SEP) is a well-defined feature in monthly or seasonal averages of the SLP (or any related variable) in all seasons. Inspection of daily SLP maps, however, reveals significant variability in the intensity and position of the high-pressure cell , especially during the austral winter (Fig. 5). These synoptic-scale fluctuations in SLP field over the SEP have a large impact in the coastal and open ocean wind regime (which affect SST) and the structure of the SCu cloud deck off the west coast of South America and especially Chile. During the austral winter, most of the synoptic variability along the subtropical west coast seems associated with mid-latitude, baroclinic disturbances approaching the southern tip of the continent. Synoptic disturbances commonly found at these subtropical latitudes are (a) mid-latitude air incursions, (b) lower-level coastal lows,

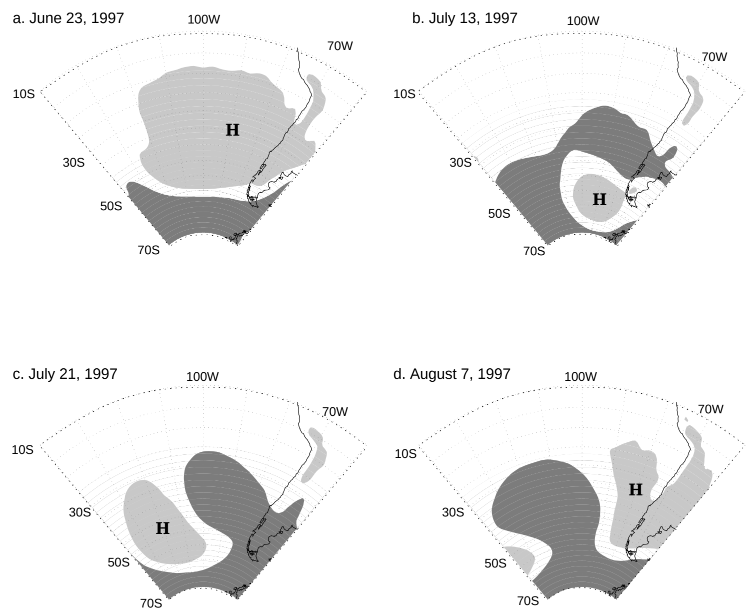

Fig. 5. Synoptic sea-level pressure (SLP) variations over the SE Pacific during austral winter. Light shading: SLP > 1020 hPa. Dark shading: SLP < 1005 hPa.

and (c) upper-level cutoff lows.

Active, sharp cold fronts are hardly observed to the north of 30 S, although under special circumstances they can reach northern Chile and southern Peru (e.g. Garreaud and Rutllant 1996). However, the cold, post-frontal mid-latitude air can reach northern Chile and southern Peru, causing thickening of the MBL and coastal stratus, and occasionally producing drizzle (Fuenzalida and Orgaz, 1981).

Coastal lows (CLs) are shallow, mesoscale low-pressure centers commonly observed in north-central Chile as an upper-tropospheric ridge passes overhead (Garreaud et al. 2001b). Their importance in terms of their related weather changes, from shallow MBL and sunny conditions at their leading edge (i.e., to the south of the pressure minimum) to overcast, cool and moist conditions in connection with their trailing edge, has been subject of applied studies on air pollution episodes in Santiago (33.2-S) (Rutllant 1981; Rutllant and Garreaud 1995); on the occurrence of water-collection episodes from coastal stratocumulus (Fuenzalida et al. 1990); and ocean upwelling-favorable wind events along the north-central coast of Chile (Rutllant 1993, 1997). CLs appears to be initiated by the adiabatic warming of forced downslope flow in connection with easterly flow in the lower and middle troposphere off the subtropical coast. While most of the research on CLs have focused on the 27-37 S latitude span, similar fluctuations in the depth of the MBL and coastal weather have been reported at Antofagasta (23 S) and southern Peru (Rutllant et al. 2000).

Cutoff lows to the west of the subtropical Andes occur between 2-10 times per year. Most of the cutoff lows in this region develop in-situ, as the equatorward wedge of a deep trough becomes segregated from its mid-latitude counterpart (Montecinos and Pizarro 2000). Cutoff lows can produce intense precipitation and severe windstorm at high elevations in northern Chile. To the south of the cutoff low center, easterly flow prevails through the troposphere, producing extreme cases of coastal lows in central and southern Chile. Coastal lows can produce extensive clearing of the SE Pacific stratocumulus; the mechanism is as yet unexplored.

Synoptic-scale variability during the austral summer is weaker than its winter counterpart, as the mid-latitude storm track shifts poleward. On the other hand, the austral summer is the wet season over the Altiplano, with intense deep convection along the central Andes. The rainy days over the Altiplano tends to cluster in rainy episodes 1-2 weeks long, interrupted by dry episodes of similar length. These episodes are associated with changes in the strength and position of the upper-tropospheric Bolivian high (e.g. Garreaud 1999). They are most prominent at subtropical latitudes just to the east of the Andes. Whether the convection over the Altiplano and the associated circulation anomalies have an impact along the west coast of South America has yet to be addressed.

Fragmentary evidence is suggestive. For instance, Fig. 6 shows an east-west cross section of vertical velocity averaged over the Altiplano for a rainy (active convection) and dry (suppressed convection) day from a regional numerical weather prediction model (Eta/CPTEC). On the rainy day, mid-tropospheric subsidence over the SEP is enhanced in connection with the strong upward motion and convective heating over the Altiplano. There is also some enhancement of subsidence in the lower troposphere, but it is much weaker. This suggests that the main impact of the convection on the PBL may be indirect, promoting a drier mid-troposphere and increased cloud-top radiative cooling, rather than the direct effect of shallowing the PBL. While modeling studies are illuminating, the correlation between stratocumulus clouds, lower tropospheric circulation, and outbreaks of deep convection over the Altiplano, could also profitably be studied using existing reanalysis, satellite, and local station data.

Synoptic scale variability along the west coast of South America is modulated by ENSO. During El Nino, an equatorward shift of the storm track enhances the synoptic variability at subtropical latitudes (Rutllant and Fuenzalida 1991). In fact, extreme cases of active fronts reaching northern Chile have occurred during El Nino years. On the other hand, El Nino years are typically associated with decreased convection over the Altiplano, as a strengthened subtropical jet stream inhibits eastward moisture transport from the interior of the continent toward the central Andes (Garreaud and Aceituno 2001).

Summary scientific questions include:

- Do downslope flow / coastal lows episodes occur at tropical latitudes ?
- How and when do coastal lows produce extensive clearing of stratocumulus? Is a similar phenomenon apparent in the NE Pacific?
- What impacts do the episodes of summertime deep convection over the Altiplano have on the low-level circulation and the stratocumulus over the SE Pacific ?
- Do incursions of midlatitude air in and above the MBL also affect the tropical SE Pacific stratocumulus? How large is synoptic scale variability of albedo, and of above-MBL temperature and humidity in different parts of the SE Pacific stratocumulus regime?
- Does warm-season synoptic-scale variability over this region also show interannual variability?

Preliminary studies of these questions can be done with existing observations, but improved

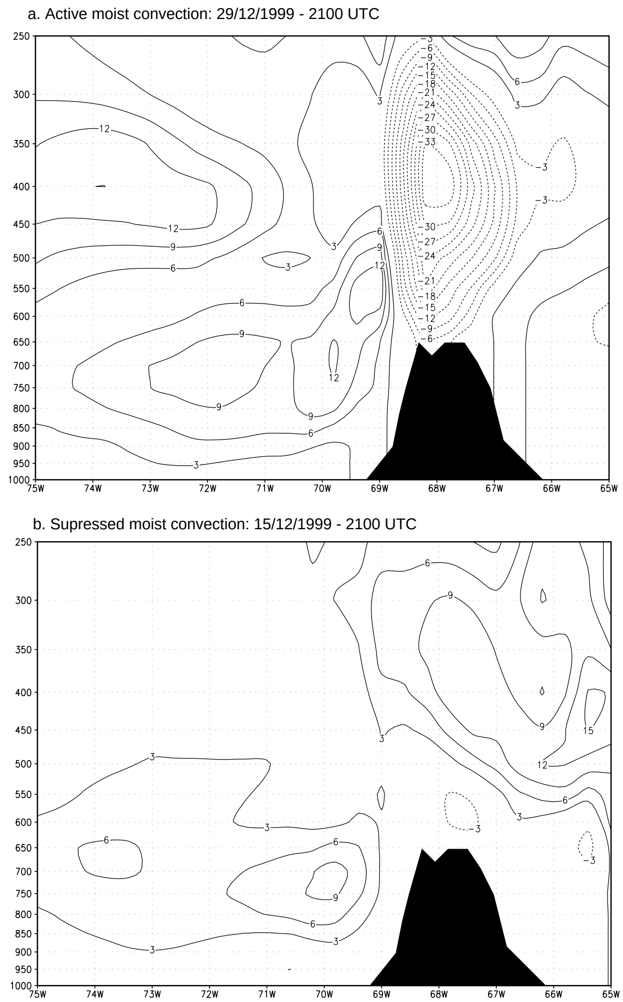

Fig. 6. Cross section of vertical motion across the Altiplano during active and suppressed episodes of Andean convection (in units of 0.01 Pa s^{-1}).

synoptic observations in the coastal zone would be of great benefit.

2.4 *Regional feedbacks with the underlying ocean*

Stratocumulus decrease the surface insolation and strengthen the northerly winds in the SE Pacific. Both of these effects presumably contribute to cooling of SSTs. Wind-induced coastal upwelling further cools the upper ocean near the coast. In turn, cooling of SST promotes maintenance of the stratus (Klein and Hartmann 1993; Norris and Leovy 1994). Theoretical/numerical modeling studies have clearly indicated that the thermal structure of the eastern Pacific is strongly affected by the presence of MBL clouds (e.g., Ma et al. 1996, Philander et al. 1996, Gordon et al. 2000).

However, the response of the regional distribution of SSTs to the overlying clouds is not well explored or understood. The connections between the cold water upwelled along the coast and the equatorial cold tongue, and the relevance of enhanced coastal upwelling to SST further offshore (e. g. through horizontal advection of upwelled water) is less clear. Longshore coastal currents may also play a role in heat transport in this region. There are even possible feedbacks between phytoplankton blooms induced by upwelling, the clarity of the water column, the depth of shortwave heating, the mixed layer structure further offshore, the SST, and stratocumulus. Synoptic meteorological variability of winds and subsidence modulates all of these processes. In addition, remote forcing by coastally trapped oceanic Kelvin and topographic Rossby waves may also be a major contributor to SST variation. The proposed OSEPA buoy array should provide very useful measurements to look at the interplay of processes, as will the soon-to-be deployed broad-scale ARGO profiling float network further offshore. Two current meter arrays are already deployed along the Chilean coast, as is a network of tide gauges along the entire S American coast. A rough heat and salt budget at the NOAA buoy, constructed with the help of this data when it becomes available, might be illuminating. Coastal profiling using underwater gliders could be used to monitor the coastal currents. Analysis of regional and large-scale ocean models could help guide us toward problem areas.

Summary science questions:

- How do stratocumulus cloud feedbacks alter the underlying regional distribution of SST, currents, and upper ocean thermal/salinity structure in the SE and eastern equatorial Pacific?
- Is SST variability in this region on subseasonal timescales mainly controlled by local processes or remote wave forcing?

3. Implementation of VEPIC

VEPIC will blend diagnostic studies of existing observations, mesoscale and global model studies, new observations, and periodic meetings organized through VAMOS for exchange of scientific information. The new observations will include a blend of sustained improvements to the atmospheric and oceanic observing systems, small-scale pilot intensive field studies, and potentially a larger-scale intensive field experiment. Currently, VEPIC does not have dedicated funding, either at the international or national level, though this may ultimately change as the program spins up. International coordination of VEPIC implementation will help efficiently organize and motivate the international effort, and give participating scientists more leverage and recognition when working with national agencies. We propose a VEPIC meeting of interested scientists early in 2002, perhaps as part of VPM5, to broaden the scientific base of participation and extensively discuss the scientific issues central to VEPIC

3.1 *Diagnostic and modeling studies.*

A variety of possible diagnostic studies based on currently available data were mentioned in section 2. These are a central component of VEPIC, and a vital foundation for further work, especially in better understanding the connection between SE Pacific cloud properties, ENSO, continental convection, and thermally-driven circulations along the Andes and west coast. Such studies can be best carried out within existing national research programs, assuming that VAMOS activities are acknowledged as a priority for such funding. Specific topics include:

- Correlations between the diurnal cycle of stratocumulus cloud, subsidence, and coastal circulations.

- Correlations between Andean and Amazonian deep convection, stratus clouds, the lower-level circulation over the SE Pacific, with special attention to the seasonal cycle and qualitative predictions of the Rodwell-Hoskins Rossby-wave subsidence mechanism.
- Evidence in reanalyses or local observations for coastally trapped waves on the MBL capping inversion within the tropical region (equatorward of 15 S).
- Correlations between convection in the E Pacific ITCZ and SE Pacific clouds, including possible associations of the Madden-Julian Oscillation.
- The roles of cloud cover, wind velocity changes, and remote oceanic forcing in explaining interannual variations in the SST, surface fluxes, and upper ocean heat budget in the SE Pacific.

In addition, it would be useful to VEPIC scientists to coordinate assembly of an archive (or, where appropriate, WWW links) to daily and monthly-mean satellite analyses for cloud properties and surface wind over the subtropical SEP region. This archive could be a part of the VAMOS data center.

There is a hierarchy of models including ocean boundary layer, LES, cloud-resolving, mesoscale, large-scale forecast, climate, and coupled ocean-atmosphere models that will be integral to addressing the scientific questions relevant to VEPIC. R. Garreaud at the University of Chile is using the MM5 mesoscale model for regional simulations of coastal lows and Andean convection, and is starting to look at its simulation of the SE Pacific MBL. He plans further diagnosis of the diurnal cycle over the west coast, relation between convection and subsidence, and synoptic variability along the west coast. The IGP in Peru, represented by Pablo Lagos, runs real-time forecasts on a 54-18-6 km resolution nested grid with the MM5, and are working toward coupling it to a coastal ocean model.

The VEPIC study area is ripe for more attention both from coarse-resolution atmospheric, oceanic, and coupled GCMs, and from atmospheric mesoscale models that can better resolve topographic effects and boundary-layer processes. VEPIC includes representation from two coupled GCM groups, the NCAR-centered Community Climate Simulation Model (CCSM) and the UCLA GCM. In both groups, the members involved in VEPIC are actively working on improved parameterizations for cloud-topped boundary layers, and regard the SE Pacific as a critical area. Model diagnoses of the seasonal cycle and interannual variability within these models, as well as sensitivity studies are a vital component of VEPIC, and will play an important role in the design of VEPIC observational programs.

A small-scale process-modeling component to VEPIC has not yet been defined (except for the parameterization activities); neither has a regional high-resolution ocean modeling study. Both would be desirable interfaces for VEPIC.

3.2 *Observations*

In VEPIC we will initially rely heavily on currently available data to direct our research. During the course of VEPIC, a variety of externally-funded observational enhancements will also be available to enrich our perspective on the SE Pacific. We are proposing as part of VEPIC a few additional sustained enhancements of the atmospheric observing system. We also discuss possible intensive field periods looking at coastally trapped atmospheric disturbancies and their impact on upwelling and SST. Lastly, we discuss what components might be involved in a large-scale intensive field study of clouds and the upper ocean in the SE Pacific stratus region and their relation to summertime variability of convection and large-scale circulation over S America.

<u>Sustained currently available atmospheric data products</u>

a) Soundings

b) Synoptic observations

It should be noted that neither soundings nor surface observations are currently freely available from any of the countries of the west coast of South America; VAMOS should aim to rectify this situation and make a database of such available observations if possible.)

c) Gridded reanalyses

NCEP (freely available), ECMWF (not freely available), NASA(not as extensively tested).

d) Global satellite products

GOES, polar orbiters, ISCCP, QUIKSCAT, TRMM, TERRA, etc.

<u>Ongoing and externally-planned enhanced monitoring</u>

a) EPIC/PACS (USA)

NOAA moored IMET buoy at 20 S 85 W (R. Weller, WHOI, USA)

Satellite analyses of cloud properties (P. Minnis, NASA, and B. Albrecht) and surface winds/SST (S. Esbensen and Dudley Chelton, Oregon St. U., USA) over the stratus regions.

SONET pilot balloon network.

b) NOAA wind profilers (USA)

Hourly wind profiles from 915 MHz (lowest 4 km) profiler at San Cristobal Is (Galapagos) and 50 MHz (full-tropospheric) profiler at Piura, Peru . Funding for continuing these observations, which have been taken since ase part of NOAA's Trans-Pacific Profiler Network, is uncertain. Data is available from K. Gage of NOAA.

c) ARGO profiling float array (2003-2015, International ARGO deployment committee, chaired by Howard Freeland, Canada)

A global array of floats profiling the upper 1500 m of the ocean every ten days, with approximately 300 km resolution, and telemetering the data in real time to a central data archive for use in ocean data assimilation. The ocean data assimilation will be done through a program called GODAE, and should provide an unprecedented view of the temperature and salinity structure of the upper SE Pacific Ocean and its seasonal and interannual variability.The floats are currently being deployed by a consortium of international partners; it is hoped that the VEPIC region will be populated by the end of 2003. Floats have a lifetime of 4 years, and the array is to be maintained until 2015.

d) Coastal buoys, current meters, tide gauges, and meteorological stations.

Fig. 7 shows all components of this array. Colors distinguish between components that are already deployed, those that are funded but not yet deployed, and those that will be deployed if the OSEPA proposal to the GEF is funded. Buoys will measure wind speed

Fig. 7 placeholder...to be drafted by Rodrigo

and direction, air temperature, atmospheric pressure, solar radiation, humidity, wave height, direction and period, temperature and salinity profiles (0-500 m), with real-time data transmission via Argos and GTS.

f) CloudSat/PICASSO (NASA, 2003-2008)

Downward-pointing lidar and 94 GHz cloud-sensing radar for accurate measurements of column aerosol backscatter, cloud-top height, cloud vertical extent and light precipitation(with 500 m/1 km vertical/horizontal resolution).

g) Enhanced meteorological and oceanographic observations from VOS and TAO tender cruises (US NSF/NOAA)

US CLIVAR is proposing enhanced (high-resolution) XBT observations along a VOS-based oceanographic survey line PX81, between Honolulu and Valparaiso,jointly supported by the USA and Chile. This line is being considered for enhanced IMET instrumentation for surface flux component measurements. US CLIVAR is also considering the utility of more frequent soundings from the TAO cruises.

<u>Enhanced coastal atmospheric monitoring proposed for VEPIC</u>

The following atmospheric measurements along the Chilean coast would improve our ability to track coastally trapped disturbances and synoptic variability by augmenting the current coastal station reports (see Fig. 7). Chilean funding would be required.

- Automatic weather station and/or ceilometer observations at Antofagasta (23.5 S, 70.5 W) and/or Iquique (20.5 S, 70.5 W).
- Wind profiler and RASS at Caldera (27 S, 71 W)..

<u>VEPIC San Felix Island Pilot Study</u>

San Felix Island (27 S, 80 W) is a small (size?), low (height?) island nearly 1000 km west of Chile, in the southern part of the region of maximum low cloud cover. Its location makes it attractive for both cloud and aerosol measurements in a relatively pristine and rarely sampled part of the SE Pacific Ocean. It is permanently occupied as a Chilean Navy station, includes a substantial runway, and is serviced every few weeks by planes and ships. It is particularly suitable for extended unattended measurements, or equipment that can be supervised by Chilean Navy personnel (e.g. sondes), although there may also be opportunities for scientists to visit the island to make more intensive measurements of limited duration. Cmdr. R. Nunez, head of the Department of Oceanography of the Chilean Navy, and a member of the VEPIC scientific steering committee, has offered to act as a liaison to obtain the needed permissions for VEPIC measurements.

We propose a six month enhanced monitoring period at this site starting in August 2002 or 2003ar, including the following elements.

- Daily radiosondes
- mm-wave vertically pointing Doppler radar and ceilometer (Albrecht?)
- Aerosol size/chemical characterization and CCN measurements
- Automatic weather station, including logwave and shortwave radiation measurements.

The observations will be analyzed primarily in a statistical fashion, to understand the seasonally varying mean properties of the stratus and their variability on diurnal and synoptic timescales, and to look at correlations between drizzle, cloud and boundary layer structure, above boundary layer properties and drizzle. This approach is analogous to EPIC 2001, but the measurements would take place for the entirety of the season of maximum stratus, and are further south, in a presumably cleaner aerosol regime. Joint US and Chilean funding would be required for both the field and analysis phase.

Possible VEPIC intensive field phase (September 2005 or later)

This large-scale, international field experiment would focus on relations between cloud cover, boundary layer processes, upper ocean dynamics and thermodynamics, coastal currents and upwelling, large-scale subsidence, regional circulations on the west slope of the Andes, and synoptic-scale variations in continental convection, with enhanced observations focussed in the region 15-25 S, 65-90 W. By this time, CloudSat-PICASSO should be deployed. Observational platforms migh include:

- Array of ships and islands as platforms to make divergence estimates (off Northern Chilean coast), including San Felix Island.
- Aircraft – Instrumented to make turbulence, microphysics, and radiation measurements
- Ships – Instrumented for surfaced meteorology, upper-air, and remote sensing of cloud properties.
- Enhanced surface observations, soundings and profilers in the coastal zone and up to the Altiplano/Andean crest.

This IOP would combine resources from all the west coast countries and the USA. Herve LeTreut of France has also indicated interest in using such an IOP for ground validation of the PICASSO-CENA lidar.

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