GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L24108, doi:10.1029/2004GL020814, 2004

Orographic influences on the annual cycle of Namibian stratocumulus clouds

I. Richter and C. R. Mechoso

Department of Atmospheric Sciences, University of California, Los Angeles, California, USA

Received 22 June 2004; revised 6 September 2004; accepted 3 November 2004; published 30 December 2004.

[1] The impact of African orography on the persistence and seasonal cycle of Namibian stratocumulus is examined in the context of an atmospheric general circulation model. A control simulation with realistic orography and simulated stratocumulus is compared to a sensitivity experiment, in which African orography is removed. In the absence of orography, stratocumulus incidence off the Namibian and Angolan coast is significantly reduced during austral winter and spring. It is argued that through the combined effects of obstruction and deflection of atmospheric flow, orography acts to enhance static stability of the lower troposphere over the Atlantic off the Namibian coast, which provides an environment conducive to the development of stratocumulus in that region. *INDEX TERMS:* 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3319 Meteorology and Atmospheric Dynamics: General circulation; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation. **Citation:** Richter, I., and C. R. Mechoso (2004), Orographic influences on the annual cycle of Namibian stratocumulus clouds, *Geophys. Res. Lett.*, *31*, L24108, doi:10.1029/2004GL020814.

1. Introduction

[2] Marine stratocumulus clouds cover a considerable portion of the world's oceans. They are particularly prevalent along the western coasts of continents. Owing to their high reflectivity, stratocumulus play an important role in Earth's radiation budget [*Paluch and Lenschow*, 1991; *Klein et al.*, 1995]. In the context of climate studies, it is therefore important to understand the processes governing the formation, maintenance and destruction of these clouds. Even though significant progress has been made in this regard, the successful simulation of the amount and geographical distribution of stratocumulus clouds remains a difficult problem. In models of the coupled ocean-atmosphere system, such difficulties are readily amplified by positive feedback mechanisms, which can lead to unrealistic climate drifts in simulations [*Mechoso et al.*, 1995; *Davey et al.*, 2002].

[3] One intriguing aspect of marine stratocumulus concerns the geographical dependence of the way in which their evolution is tied to the seasonal cycle. In the Namibian and Peruvian stratus region, for example, maximum cloud cover develops when the underlying sea surface temperature (SST) is coldest in austral spring. Along the coast of California, on the other hand, maximum stratocumulus cover is found in June, while the minimum in underlying SST occurs around April.

[4] Subtropical stratocumulus decks are located in regions of large-scale subsidence associated with the descending branch of the Hadley circulation [see *Ma et al.*, 1996]. There can also be a contribution to regional subsidence by convection and orographic effects in the adjacent continents [*Rodwell and Hoskins*, 2001]. The possible role of orographic effects in the behavior of coastal stratocumulus has received little attention so far. A recent study on the influence of the Andes on the eastern Pacific climate with a regional atmospheric model suggests that this impact is indeed significant [*Xu et al.*, 2004]. In this study, we focus on the impact of African orography on stratocumulus incidence near the Namibian coast. Different mechanisms of influence are expected in view of the fact that African orography is less steep and less high than the Andes.

2. Experiment Design

[5] The UCLA atmospheric GCM (AGCM), when forced with a time-varying SST distribution from an observed monthly-mean climatology, produces a fairly realistic simulation of the incidence, geographical distribution and seasonal cycle of subtropical stratocumulus. More details of the model can be found at www.atmos.ucla.edu/esm/agcmdir/, and a discussion on the reasons for the model's success in simulating marine stratocumulus is given by *Mechoso et al.* [1995].

[6] In order to investigate whether the distribution and evolution of Namibian stratocumulus is sensitive to the orography on the adjacent African continent, we performed two experiments with the UCLA AGCM: 1) Control, which features realistic orographic boundary conditions everywhere, and 2) No-Orography, in which orographic surface heights over the African continent are set to sea-level. The SST distribution used in both experiments was obtained from the Global Sea Ice and Sea Surface Temperature (GISST) data set. After an initial adjustment period, Control and No-Orography were run for 20 years and 10 years, respectively. The resolution used for these integrations is 2.5° longitude by 2° latitude with 29 σ-levels in the vertical. The model's orographic boundary conditions are shown in the auxiliary material[1]. We note that the distribution of orographic heights has been smoothed considerably as is typically done in AGCMs to avoid computational difficulties. As a result, mountain heights rarely exceed 1500 m anywhere on the African continent. In nature, however, the mountain range along the Namibian-Angolan coast

---

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL020814.

0094-8276/04/2004GL020814$05.00

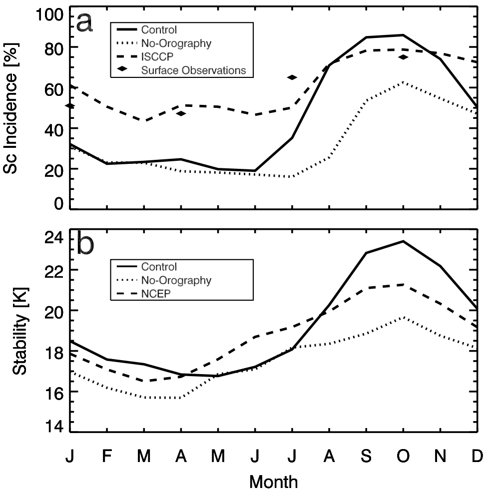

Figure 1. Annual cycle of a) stratocumulus incidence and b) lower tropospheric stability, area-averaged over the Namibian stratocumulus region (as defined in the text). Control and No-Orography are denoted by the solid and dotted line, respectively. The diamonds in a) show seasonal averages of surface observations of low level clouds as presented by *Klein and Hartmann* [1993], while the dashed line shows monthly means of ISCCP satellite data. The dashed line in b) corresponds to NCEP reanalysis data. Lower tropospheric stability is defined as the potential temperature difference between 700 hPa and 1000 hPa.

reaches up to 2500 m. The degree to which our results might be sensitive to this smoothing is briefly discussed in section 4.

3. Results and Analysis

[7] We first examine the annual cycle of monthly mean stratocumulus incidence over the Namibian region in both observations and simulations. In order to facilitate comparison with the surface observations presented by *Klein and Hartmann* [1993], this region is defined as 0°E–10°E, 20°S–10°S. Figure 1 shows that Control realistically simulates the seasonal evolution of stratocumulus when compared to the International Satellite Cloud Climatology Project (ISCCP) data [*Rossow and Schiffer*, 1991], or surface observations. However, incidence is underpredicted in the first half of the year and slightly overpredicted in the second half of the year. The former feature may be expected since the observational data represent all low-level clouds rather than just stratocumulus clouds. Another possible reason is that the AGCM does not allow for partial cloudiness in the planetary boundary layer (PBL) (i.e., stratocumulus incidence is either 0 or 1), which tends to exaggerate lower values. Turning to our results, we note that No-Orography produces significantly lower stratocumulus incidence than both Control and the observations.

[8] *Klein and Hartmann* [1993] report a positive correlation between stratocumulus incidence and lower tropospheric stability. Figure 1b presents the area averaged static stability, which is taken as the difference in potential temperature at 700 hPa and 1000 hPa. (The 700 hPa level also coincides with a maximum in the temperature difference between the two experiments.) A comparison between Figure 1a and 1b shows that the model captures the high positive correlation of stratocumulus incidence with lower tropospheric stability [see also *Klein*, 1997]. The vertical profiles of potential temperature shown in Figure 2 for the months of August and October confirm that static stability in the lower troposphere is higher in Control than in No-Orography. In August, for example, potential temperature at 700 hPa is about 4 K warmer in Control than in No-Orography, while at 950 hPa it is approximately 1.5 K colder. In October, the corresponding values are 3 K (700 hPa) and 2.5 K (950 hPa).

[9] The temperature differences in the Namibian stratus region are linked to circulation changes induced by the orography. This can be seen in Figure 3, which shows wind and temperature at 700 hPa in Control and No-Orography. According to Figure 3, easterlies associated with the trade winds pass over the southern African orography at 700 hPa. In the process, they acquire anti-cyclonic rotation due to the conservation of potential vorticity. The resulting anti-cyclonic circulation over southern Africa extends to the west of the continent (Figure 3a). The horizontal southward flow associated with this circulation advects warm air toward the Namibian stratus region. The effect of this transport of warm air is also apparent in the zonally anti-symmetric temperature pattern in Control. In comparison, No-Orography, features a far more zonal pattern of winds and temperature. Warm horizontal advection over the Namibian stratus region is therefore much weaker in No-Orography, and, accordingly, temperatures at the 700 hPa level are lower in that experiment. A comparison with NCEP reanalysis data at 700 hPa (see auxiliary material) shows that the anti-cyclonic circulation in Control is corroborated by observational data. The distribution of temperature simulated at that level is also realistic.

[10] To obtain a more quantitative description of the changes in lower tropospheric circulation, we examine the thermodynamic energy balance over the Namibian stratus

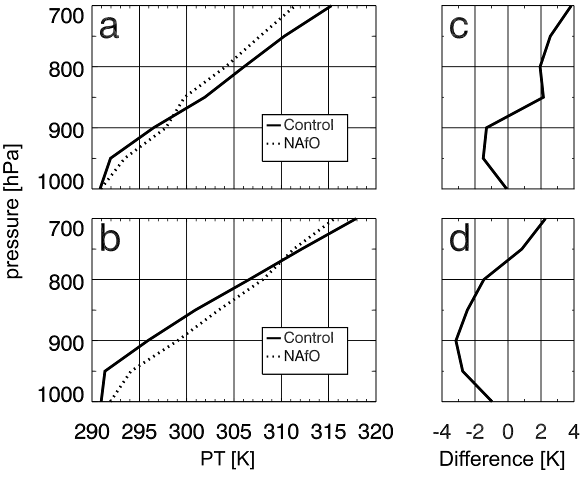

Figure 2. Vertical profiles of potential temperature in (a) August and (b) October. The solid line shows Control, the dotted line shows No-Orography. (c) and (d) correspond to (a) and (b), respectively, but show the difference Control minus No-Orography.

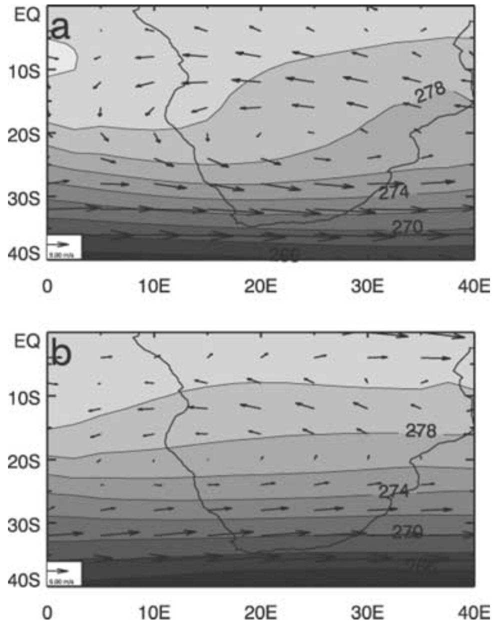

Figure 3. Wind and temperature [K] at 700 hPa in August for (a) Control, and (b) No-Orography. The contour interval is 2 K. The reference vector shown in the bottom left corner of each panel denotes a magnitude of 5 m/s.

region at 700 hPa. In pressure coordinates, this balance can be written in the form

$$\frac{\partial \overline{T}}{\partial t} = \frac{\overline{Q}}{c_p} - \left(\frac{p}{p_0}\right)^{\kappa} \overline{\omega}\frac{\partial \overline{\theta}}{\partial p} - \overline{\mathbf{v}} \cdot \nabla_p \overline{T}, \tag{1}$$

where T is temperature, t is time, Q is diabatic heating, c_p is the specific heat of dry air at constant pressure, p_0 is a constant reference pressure, $\kappa = R/c_p$, R is the gas constant for dry air, $\omega = Dp/Dt$ is vertical p velocity, $\theta = (p/p_0)^{-\kappa}T$ is potential temperature, $\mathbf{v}$ is horizontal velocity, and overbars denote monthly means. In this equation, advection by transients is neglected and only the time averaged terms are retained. This is a reasonable approximation in the subtropics, and we verified that it holds in our case. The left-hand side of equation (1) represents the temperature tendency, while the three terms on the right-hand side represent the contributions from diabatic heating, vertical temperature advection and horizontal temperature advection.

[11] Figure 4 shows the annual cycle of the three terms on the right-hand side of equation (1) for our selected region. During July to August, when the difference in stratocumulus incidence between Control and No-Orography starts to develop and reaches its peak (Figure 1), neither diabatic heating nor vertical advection contribute significantly to the positive temperature difference between simulations (Figures 4a and 4b). In fact, both terms are smaller in Control than in No-Orography, which, in the absence of any other compensating effects, would lead to colder temperatures in Control. Horizontal advection (Figure 4c), on the other hand, is significantly larger in Control than in No-Orography precisely for July and August. Thus, we find that changes in horizontal advection explain the positive temperature difference between the two experiments at 700 hPa in July and August.

[12] In September and October, temperature differences at 700 hPa are small and we turn to the surface level (950 hPa). Here the effect of orography is twofold. Along the western coast of southern Africa, impinging midlatitude westerlies are deflected equatorward, leading to cold advection into the Namibian stratus region. Toward the east, comparatively dry and warm easterlies are blocked from reaching the Namibian stratus region. The combined effect is a significant negative temperature difference at 950 hPa, which is associated with increased lower tropospheric stability in Control.

[13] Thus, the impact of orography on static stability is dominated by circulation changes at 700 hPa during July and August, whereas circulation changes at the surface levels dominate during September and October.

4. Discussion

[14] Our model results suggest that, if other boundary conditions are unchanged, removal of African orography has a significant impact on the incidence of Namibian stratocumulus clouds. The increased incidence from July through October in the presence of orography results in an increase in the amplitude of the annual cycle of cloud cover, which is correlated with an increase of lower tropospheric stability. During July and August, temperatures are higher at 700 hPa in Control, when orography is present. This positive temperature difference is associated with the advection of warm air toward the Namibian stratus region by an anti-cyclonic circulation centered over the southern African continent. The anti-cyclonic circulation, which is most prominent during austral winter and virtually absent during

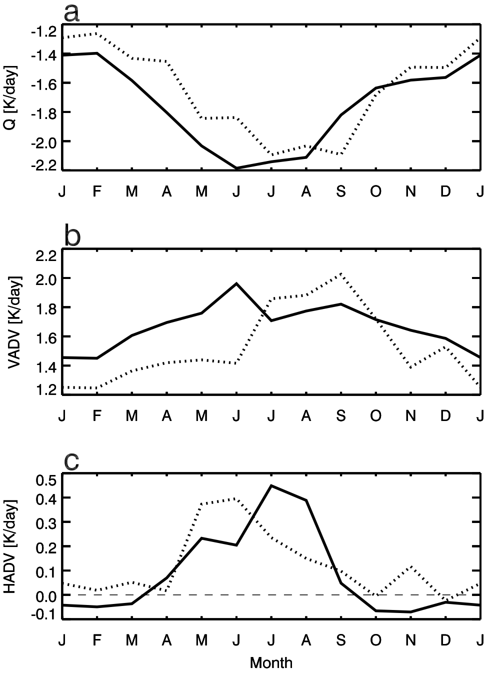

Figure 4. Annual cycle of terms in the thermodynamic energy budget for Control (solid line) and No-Orography (dotted line). The curves represent area averages over the Namibian stratus region of (a) diabatic heating, (b) vertical temperature advection, and (c) horizontal temperature advection.

austral summer, is part of the response of the large-scale flow to the presence of orography. During austral winter, midlatitude westerlies intensify and extend furthest equatorward to approximately 25°S, contributing to the poleward branch of the anti-cyclonic circulation. At the same time, convection over southern Africa is at its minimum, the intertropical convergence zone being at its northernmost latitude, well north of the equator. This decreased convection allows the equatorial easterlies to pass over the southern African continent, contributing to the equatorward branch of the anti-cyclonic circulation. During austral summer, low pressure and intense convection over southern Africa discourage such flow across the orography. This is consistent with the findings of *Ringler and Cook* [1999] who examined the wintertime and summertime response to orographic forcing. In their study, anti-cyclonic circulation over a mountain is encouraged during the wintertime, but blocked during the summertime.

[15] September and October see a strengthening of the subtropical high over the southern Atlantic, owing to the increasing land-sea contrast during that time of the year. Close to the surface, orography acts to block and divert the associated flow along the west coast of southern Africa. Thus cold air is advected toward the Namibian stratus region. Concurrently, orography provides shelter from the warm equatorial easterlies. In the absence of orography, this continental air is able to pass freely over the continent and invade the Namibian stratus region. Thus temperatures at the surface level are colder in Control than in No-Orography, leading to an increased stability in the former simulation.

[16] It might be expected that the advection of warm continental air in No-Orography would also lead to a drying of the PBL, but we found that this drying effect is balanced by increased evaporation in such a way that specific humidity is approximately the same in the PBL for both Control and No-Orography. Therefore, the different incidence of stratocumulus is associated with the increased static stability.

[17] Studies on the dependence of orographic forcing on height using idealized mountain shapes [*Ringler and Cook*, 1997; *Cook and Held*, 1992] suggest that a non-linear response sets in at approximately 2 km, which is a height reached by some features of the orography of southern Africa (factors other than orographic height are important too, however). The anti-cyclonic circulation obtained over southern Africa in our simulation is consistent with a linear response as described by *Rodwell and Hoskins* [2001]. As noted in the introduction, orographic boundary conditions are smoothed to some extent in our model. To test the sensitivity of our results to this, we performed another simulation using orographic heights in south-equatorial Africa that were not subjected to any smoothing, giving the highest realistic elevations possible at our model's resolution. No qualitative changes in the circulation over Africa resulted from this experiment, and stratocumulus incidence off the Namibian coast was not affected significantly. This suggests that the flow is well within the linear range in our results.

[18] *Xu et al.* [2004] conducted a study of the impact of the Andes on the South American climate, using a regional atmospheric model. In their experiments, the Peruvian stratocumulus were reduced when the Andes were removed. They attributed this effect entirely to the warm advection in the PBL as the trade easterlies flow across the continent. We find a similar warm advection in the PBL during September and October in our experiments. However, we also find that during July and August circulation changes above the PBL contribute significantly to the enhanced stability in Control. The reason for this difference might lie in the limitations of the models used. Although our GCM has a coarser vertical and horizontal resolution than the regional model used by *Xu et al.* [2004], it is able to capture the orographic effects on the large-scale flow, while the regional model must prescribe the same boundary conditions from NCEP reanalysis. Neither model takes into account the change in SST which would accompany the circulation changes. Since the Andes are much steeper and higher than African orography, it might also be possible that the mechanisms at work are fundamentally different in the two regions. A companion study on the impact of South American orography on the Peruvian stratus clouds is in progress.

[19] **Acknowledgments.** This research was supported by NOAA under Grant NA030AR4310095. Model integrations were performed at the NCAR computing facilities. The authors would like to thank Dr. John D. Farrara for assistance with the model integrations and helpful discussions. Thanks also to the anonymous reviewers for their helpful and constructive comments.

References

Cook, K. H., and I. M. Held (1992), The time-mean response of the atmosphere to large-scale atmospheric flow, *J. Atmos. Sci.*, *49*, 525–539.

Davey, M. K., et al. (2002), STOIC: A study of coupled model climatology and variability in tropical ocean regions, *Clim. Dyn.*, *18*, 403–420.

Klein, S. A. (1997), Synoptic variability of low-cloud properties and meteorological parameters in the subtropical trade wind boundary layer, *J. Clim.*, *10*, 2018–2039.

Klein, S. A., and D. L. Hartmann (1993), The seasonal cycle of low stratiform clouds, *J. Clim.*, *8*, 1140–1155.

Klein, S. A., D. L. Hartmann, and J. R. Norris (1995), On the relationship among low-cloud structure, sea surface temperature, and atmospheric circulation in the summertime northeast Pacific, *J. Clim.*, *8*, 1140–1155.

Ma, C.-C., C. R. Mechoso, A. W. Robertson, and A. Arakawa (1996), Peruvian stratus clouds and the tropical Pacific circulation: A coupled ocean-atmosphere study, *J. Clim.*, *9*, 1635–1645.

Mechoso, C. R., et al. (1995), The seasonal cycle over the tropical Pacific in coupled ocean-atmosphere general circulation models, *Mon. Weather Rev.*, *123*, 2825–2838.

Paluch, I. R., and D. H. Lenschow (1991), Stratiform cloud formation in the marine boundary layer, *J. Atmos. Sci.*, *48*, 2141–2158.

Ringler, T., and K. H. Cook (1997), Factors controlling nonlinearity in orographically induced stationary waves, *J. Atmos. Sci*, *54*, 2612–2629.

Ringler, T., and K. H. Cook (1999), Understanding the seasonality of orographically forced stationary waves: Interaction between mechanical and thermal forcing, *J. Atmos. Sci*, *56*, 1154–1174.

Rodwell, M. J., and B. H. Hoskins (2001), Subtropical anticyclones and summer monsoons, *J. Clim.*, *14*, 3192–3211.

Rossow, W. B., and R. A. Schiffer (1991), International Satellite Cloud Climatology Project (ISCCP) cloud data products, *Bull. Am. Meteorol. Soc.*, *72*, 2–20.

Xu, H., Y. Wang, and S.-P. Xie (2004), Effects of the Andes on eastern Pacific climate: A regional atmospheric model study, *J. Clim.*, *17*, 589–602.

C. R. Mechoso and I. Richter, Department of Atmospheric Sciences, University of California, Los Angeles, Los Angeles, CA 90095, USA. (richter@atmos.ucla.edu)