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IMPLICATIONS OF SUMMERTIME MARINE STRATOCUMULUS ON THE NORTH AMERICAN CLIMATE

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INTRODUCTION

The advent of global satellite coverage has triggered renewed interest in monitoring the atmosphere for evidence of climate change. While it is suspected that the atmosphere is susceptible to warming because of increasing CO_2 concentrations, there is considerable doubt as to the magnitude (and even sign) of the resulting temperature change (Lindzen, 1990). This uncertaintity mainly arises because of our lack of understanding of the response of cloud cover to increasing CO_2 (Lindzen, 1990). Cloud can have either a positive or negative feedback on global temperature changes. For instance, Randall et al. (1984) showed that a mere 4% increase in global cloud cover by low-level stratiform cloud could more than offset the predicted 2-4 K global warming due to a doubling of CO_2.

Even though the dominent cloud type at mid- and high latitudes is low-level stratiform, there has been little study of the effect of semi-permanent areas of this cloud on intra- and inter-annual climate variability. Much more effort has been focused on the effects of cumulus cloud, which dominates at equatorial latitudes. For instance, it is known that changes in deep convective cloud over the western Pacific warm pool impact climate anomalies over North America (Wallace and Gutzler, 1981). However, the climatic impact of alterations in the semi-permanent stratiform cloud deck off the west coast are not known. Because of its proximity compared to western Pacific convective cloud, the North American climate could be much more sensitive to eastern Pacific stratocumulus cloud.

This study focuses on the effects of summertime stratocumulus over the eastern Pacific. This cloud is linked to the semi-permanent sub-tropical highs that dominate the low-level circulation over the Pacific and Atlantic. Subsidence on the eastern flank of these highs creates an inversion based about 800 m above sea level that caps moist air near the surface. This air overlies cool waters driven by upwelling along the coastal regions of North America. Strong surface north-westerlies mix the boundary layer enough to saturate the air just below the capping inversion. Widespread stratocumulus is thus formed.

All calculations were carried out using the GENESIS general circulation model that was run at MSFC. Among the more important properties of the model is that it includes radiative forcing due to absorption of solar radiation and the emission of infrared radiation, interactive clouds (both stratocumulus and cumulus types), exchanges of heat and moisture with the lower boundary. Clouds are interactive in the sense that they impact the circulation by modifying the fields of radiative heating and turbulent fluxes of heat and moisture in the boundary layer. In turn, clouds are modified by the winds through the advection of moisture.

In order to isolate the effects of mid- and high-latitude stratocumulus, two run were made with the model: one with and the other without stratocumulus. The runs were made for a year, but with perpetual July conditions, i.e., solar forcing was fixed. The diurnal solar cycle, however, was allowed for. The sea surface temperature distribution was fixed in both runs to represent climatological July conditions. All dependent variables were represented at 12 surfaces of constant $\sigma = p/p_o$, where p is pressure and p_o surface pressure. To facilitate analysis, model output was transformed to constant pressure surfaces. Structures no smaller in size than 7.5 degrees longitude and 4.5 degrees in latitude were resolved. Smaller features of the circulation were parameterized. The model thus captures synoptic- and planetary-scale circulation features.

RESULTS

Cloud effects were isolated by comparing features of the runs with and without stratocumulus present. All dependent variables, i.e., temperature (T) and wind components (u,v,ω), were divided into time mean and deviations at each location. Thus, for example, $T(x,y,p,t)=\overline{T}(x,y,p)+T'(x,y,p,t)$, where $\overline{T}$ is the mean and $\overline{T'}=0$. First, changes in the time-mean summertime circulation over North America were considered. Next, properties of the cloud-generated transient or time-dependent part of the circulation were studied. Finally, the interaction of transients and the time-mean circulation are studied by separately looking at how transients are generated from the mean flow and how the transients feed back onto the mean flow.

A broad range of frequencies make up the transients, spanning periods from a few days to six months. It was convenient to break up this spectrum into two broad regimes:

RANGE	PERIODS
Low frequency	10 to 90 days
High frequency	2.5 to 6 days

Low-pass and bandpass filters, Blackman and Lau (1980), were applied to the daily anomaly fields, u',v',T' etc., to isolate the low and high frequency bands respectively. Transient behavior and structures sharply contrast between these ranges.

CLOUD EFFECTS ON MEAN CIRCULATION

A preliminary check was made on the model-generated time-mean summertime circulation to ensure that it matched observations. Agreement was surprizingly good considering some of the crude parameterizations that were used. For example, the fractional cloud cover due to stratocumulus closely matched the marine climatological cloud cover data of Hanson (1991).

Model-generated time-mean states with and without stratocumulus will now be compared so that the consequences of stratocumulus can be isolated. Important findings are:

1. by reflecting more incoming solar radiation back to space, stratocumulus can decrease the net solar radiation absorbed by the atmsphere by up to 60 W/m^2 over regions of high cloud fraction such as off the coast of California,
2. lower troposphere temperatures are decreased everywhere by the stratocumulus especially over marine areas,
3. over central Canada where there is very little summertime stratocumulus, there was a large region of cloud-induced cooling of up to 4C,
4. the effects of stratocumulus were clearly not localized to the region of large cloud fraction,
5. everything else being equal, cooling due to stratocumulus was larger at high latitudes than at low latitudes because increased solar reflection was more effective where the day length is largest,
6. the zonally-averaged north-south temperature gradient was increased by cloud especially in the latitude belt from 45N to 60N,
7. the semi-permanent Pacific and Atlantic anticyclones were weakened by the cloud (this is quite unexpected),
8. subsidence that normally occurs on the eastern flank of the Pacific anticyclone was weakened by the stratocumulus (this is another unexpected result),
9. an approximately barotropic (structure independent of height) stationary wave was forced by the cloud, and
10. this wave was approximately out of phase with the climatological mean wave pattern such that the ridge (trough) over the west (east) coast of North America was slightly weakened by the cloud.

Items 8. contradicts conventional thinking about the response of a stably stratified atmosphere subjected to a diabatic cooling perturbation as with the marine stratocumulus. The cooling is normally compensated for by compressional heating due to enhanced subsidence. Model results indicate suggest the opposite: adiabatic cooling in the eastern Pacific upward motion anomaly supplements the cloud radiative cooling. It turns out that a horizontal warm air advection anomaly balances the radiative plus adiabatic cooling. Northwesterly surface winds off the California coast are associated with cold air advection since the flow is directed from the cool marine regions toward the considerably warmer inland areas over California. Since, according to itme 7., stratocumulus weakens the anticyclone, the northwesterly wind speeds also decrease. A warm air advection anomaly results over the offshore region and thermal balance is maintained.

TRANSIENT EFFECTS OF STRATOCUMULUS

As mentioned in items 3. and 4. above, the effects of marine stratocumulus near NorthAmerica are not just localized to the coastal regions. Properties of synoptic-scale transients triggered by the cloud are now considered. Their structure, propagation characteristics, and interaction with the time-mean tropospheric flow are of interest.

BAROCLINIC INSTABILITY

Stratocumulus increased the zonally-averaged north-south temperature gradient and, as verified, the corresponding vertical shear of the mean tropospheric westerlies. The baroclinic instability of the time-mean summertime could be enhanced thus facilitating the generation of baroclinic waves. The above-mentioned non-local effects of marine stratocumulus might be accounted for. The background stability was measured by calculating the associated maximum growth rate according to the Eady model: $\nu=0.31fU_Z/N$ where f is the Coriolis parameter, U_Z the vertical wind shear, and the buoyancy frequency $N^2=(g/\theta_o)\partial\theta/\partial z$. The e-folding time, $1/\nu$, did indeed decrease due to the cloud-induced enhanced vertical shear. The change, however, was small ~ O(0.01 days) compared to typical values of a few days. Thus the stratocumulus does not impact the stability of the summertime westerlies.

STRUCTURE OF CLOUD-INDUCED WAVES

The lag-correlation technique, Blackmon and Lau (1980), was applied to the transient part of the daily 500 and 850 mb temperature fields, thereby revealing the spatial and temporal scales of propagating disturbances triggered by stratocumulus. Important findings are:

1. cloud-triggered eastward propagating high frequency disturbances occur at 500 mb in the region of strong westerlies over Alaska (horizontal wavelength ~ 4000 km), and
2. the cloud also triggered a smaller-scale high frequency disturbance over the Gulf of Alaska (wavelength ~ 2500 km) at both 500 and 850 mb that propagated southeastward approximately parallel to the west coast of North America.

FEEDBACK OF CLOUD-FORCED TRANSIENTS ON MENA FLOW

The divergence of the E-vector, Trenberth (1986), quantifies how the transient eddies are forcing the time-mean winds at any location. Low-frequency transients tended to weaken the mean westerlies over Alaska and the eastern U.S.A. thus dampening the barotropic stationary long-wave pattern. High-frequency propagating waves triggered by the cloud had neglegible feedback on the mean flow.

DISCUSSION

Summertime stratocumulus off the west coast of North America had small but not neglegible *in situ* as well as downstream continental effects. The cloud was shown to enhance the contrast between the warm continental regions and adjacent offshore regions. In spite of this increased continentality, the stationary wave pattern over North America is weakened by the cloud. Simple linear stationary wave theory cannot explain this finding. This study reveals that low-frequency disturbances triggered by the cloud feedback through nonlinear effects on the standing wave pattern to weaken it. This feedback is mostly driven by barotropic processes. High frequency propagating baroclinic waves are also triggered by the cloud. The process responsible for these waves is not know; enhanced baroclinic instability over their Alaskan source region was ruled out.

Results from this study suggest the stratocumulus is coupled to regional summertime climate fluctuations over North America. It would be interesting to examine linkages between eastern Pacific stratocumulus global-scale mechanisms involving inter-annual climatic fluctuations. Then it might be possible to relate regional climate anomalies such as the 1993 mid-west flooding to global climate anomalies.

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