How Will Low Clouds Respond to Global Warming?

By Axel Lauer & Kevin Hamilton

Persistent low clouds that predominate over the subtropical ocean basins exert a major effect on the global radiation budget by reflecting incoming solar radiation. In collaboration with colleagues at IPRC, the University of Hawai‘i meteorology department, and the University of Wisconsin, we have been studying the simulation of the clouds over the eastern Pacific Ocean using the IPRC Regional Atmosphere Model (iRAM). The eastern Pacific region (away from the equator in both hemispheres) is notable for the presence of extensive low cloud decks, and displays interesting transitions from dominant stratus, to stratocumulus, to trade wind cumulus regimes as one moves away from the coast. Our iRAM simulations cover 160°W–50°W, 40°S–40°N and

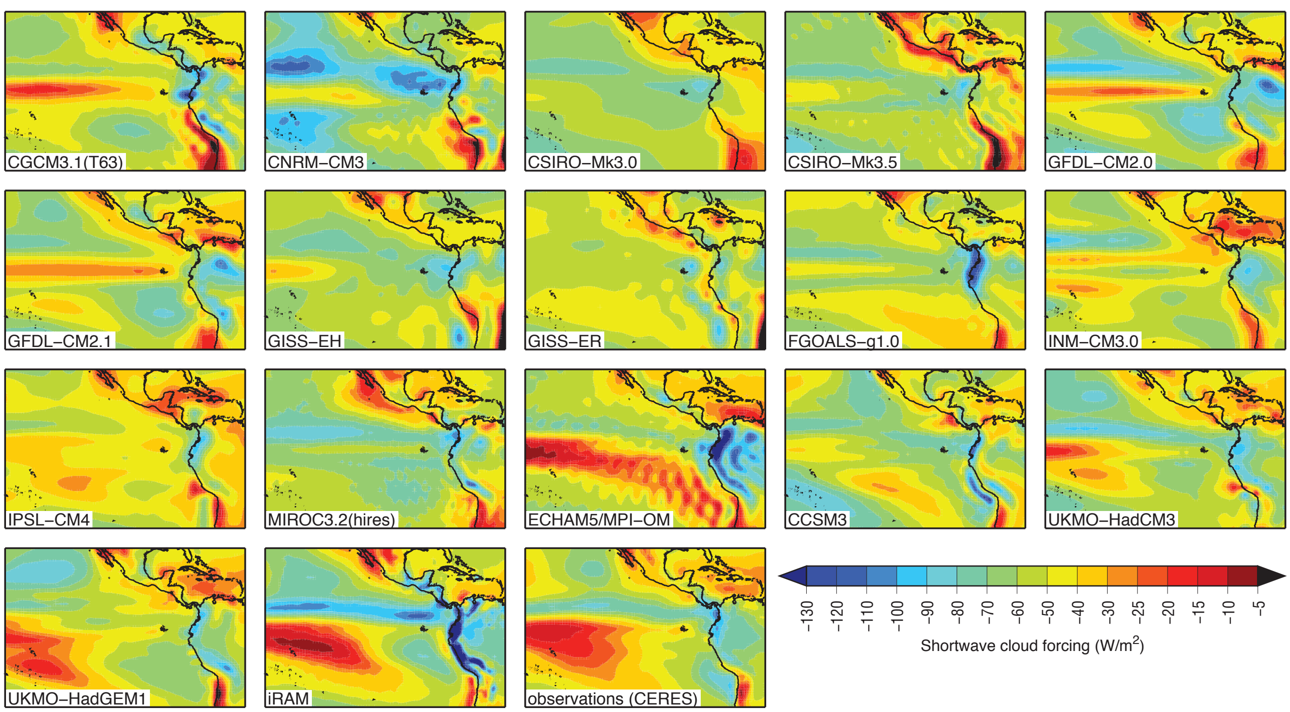


Figure 1. Annual average top-of-the-atmosphere shortwave cloud forcing for present-day conditions from 16 IPCC-AR4 models and iRAM compared with the CERES satellite observations of Loeb et al., 2009. Blue shades represent more reflection (strongly negative shortwave cloud forcing), red shades less reflection (weakly negative shortwave cloud forcing) of solar radiation.

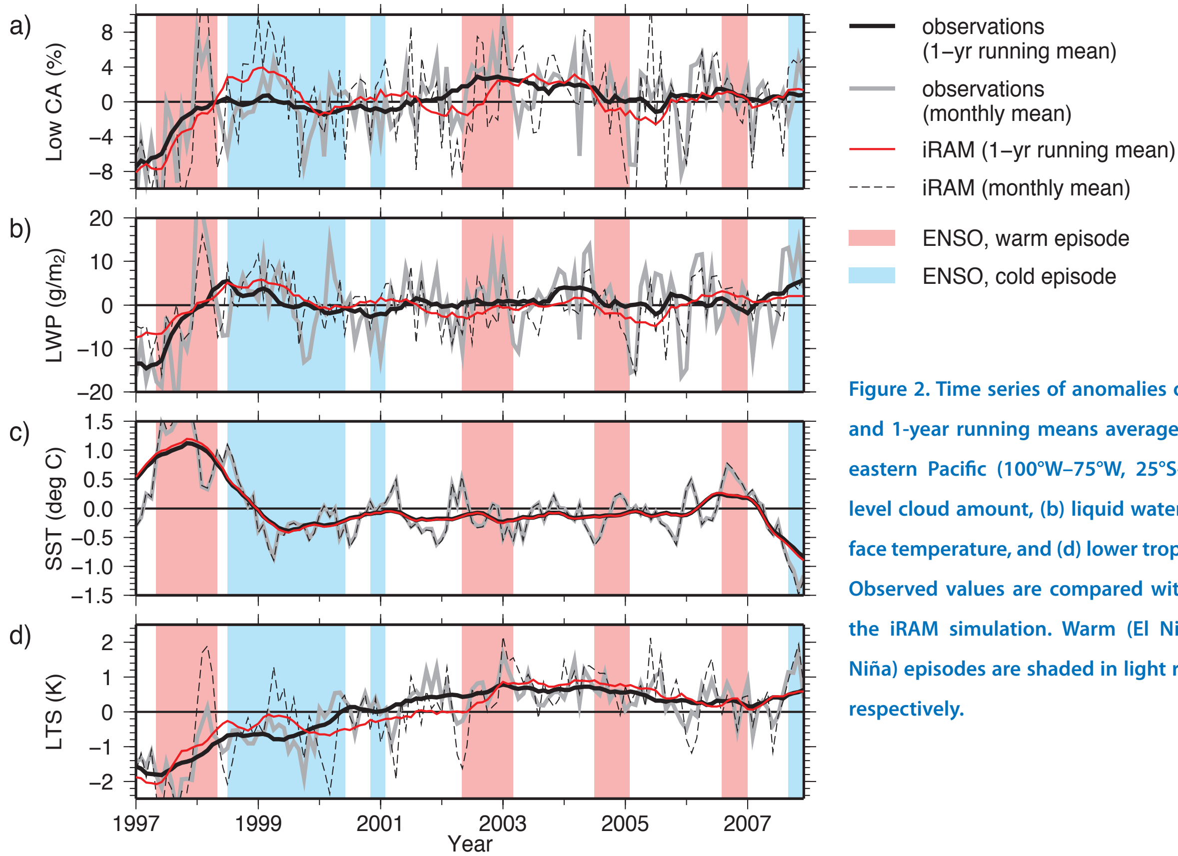


Figure 2. Time series of anomalies of monthly means and 1-year running means averaged over the southeastern Pacific (100°W–75°W, 25°S–5°S) for (a) low-level cloud amount, (b) liquid water path, (c) sea surface temperature, and (d) lower tropospheric stability. Observed values are compared with the resultsfrom the iRAM simulation. Warm (El Niño) and cold (La Niña) episodes are shaded in light red and light blue, respectively.

are forced by horizontal boundary conditions taken from 6-hourly observational analyses and from observed daily sea surface temperatures (SSTs) for the period 1997– 2008. The analysis of results is restricted to the interior region more than 10 degrees away from the boundaries.

As the preceding article "How Much Will the World Warm?" shows, state-of-the-art global climate models (GCMs) do a rather poor job in reproducing the observed long-term mean cloud properties in this region (and in other low-cloud dominated regions). By contrast, we have found that iRAM simulates realistically both the long-term mean cloud properties and the interannual fluctuations in the clouds in this region. Figure 1 presents for the region of interest the shortwave cloud radiative forcing, i.e. the reflected solar radiation at the top of the atmosphere attributable to the presence of clouds, in present-day simulations from iRAM and from 16 coupled GCMs. The results are compared with long-term mean values from satellite observations.

Figure 2 has the time series of monthly means of several quantities in the iRAM simulation averaged over 100°W–75°W and 25°S–5°S, also compared with observations. El Niño and La Niña periods in the equatorial Pacific are denoted by pink and blue shading. The research covers the extremely strong 1997 El Niño. The largest changes in SST and other area-averaged quantities during the 10-years happened during the transition from that El Niño to the extended La Niña starting in 1998. The iRAM successfully simulated the observed increases in low-level cloud amount, cloud-liquid water path and lower tropospheric stability during the 1997–1998 transition, as well as many of the smaller amplitude fluctuations in these quantities seen later in the record.

In order to investigate cloud climate feedbacks in iRAM, several global warming scenarios were run with boundary conditions appropriate for late 21st century conditions. In these

Stratocumulus clouds over the South Pacific. Image courtesy NASA Earth Observatory.

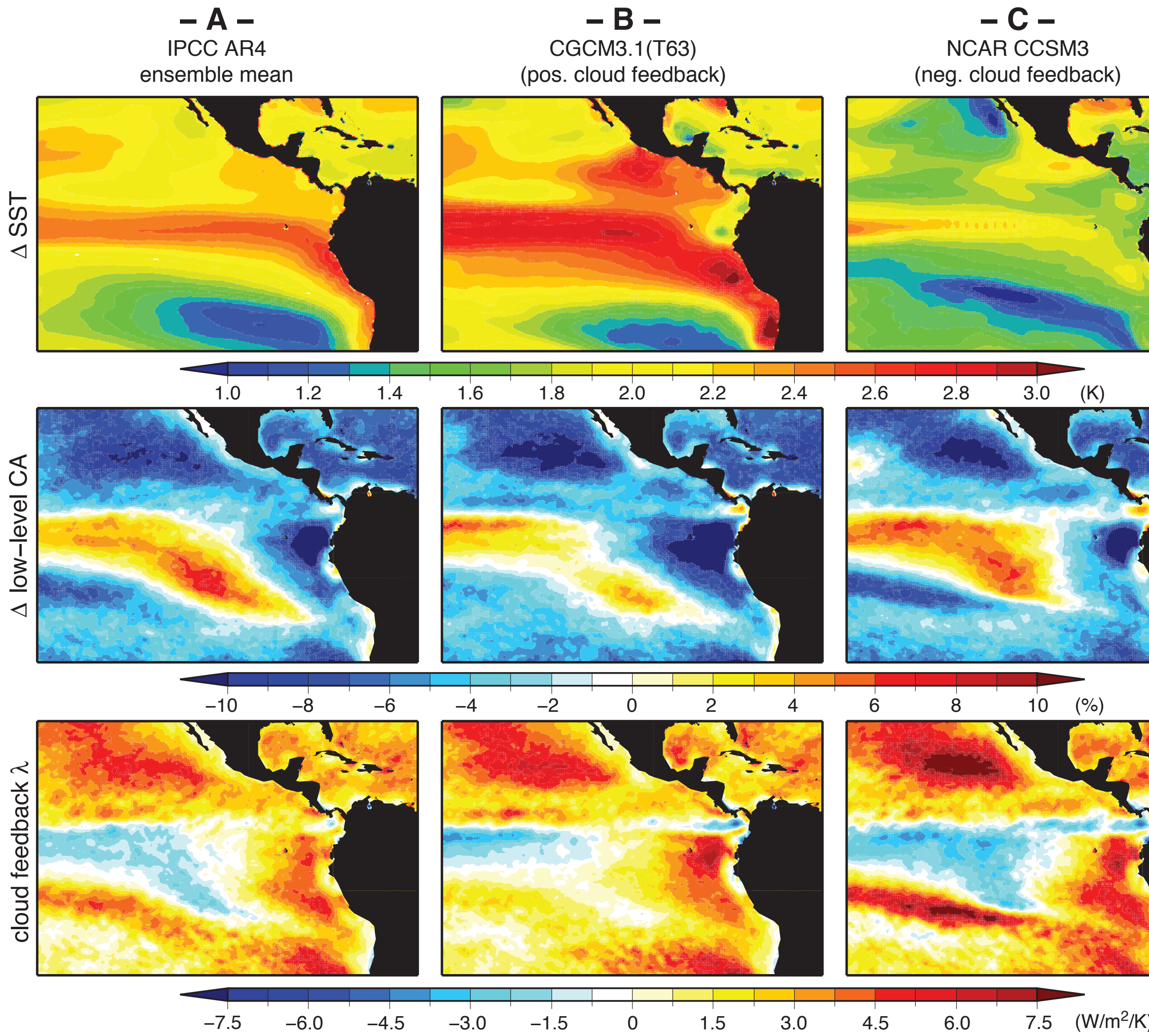
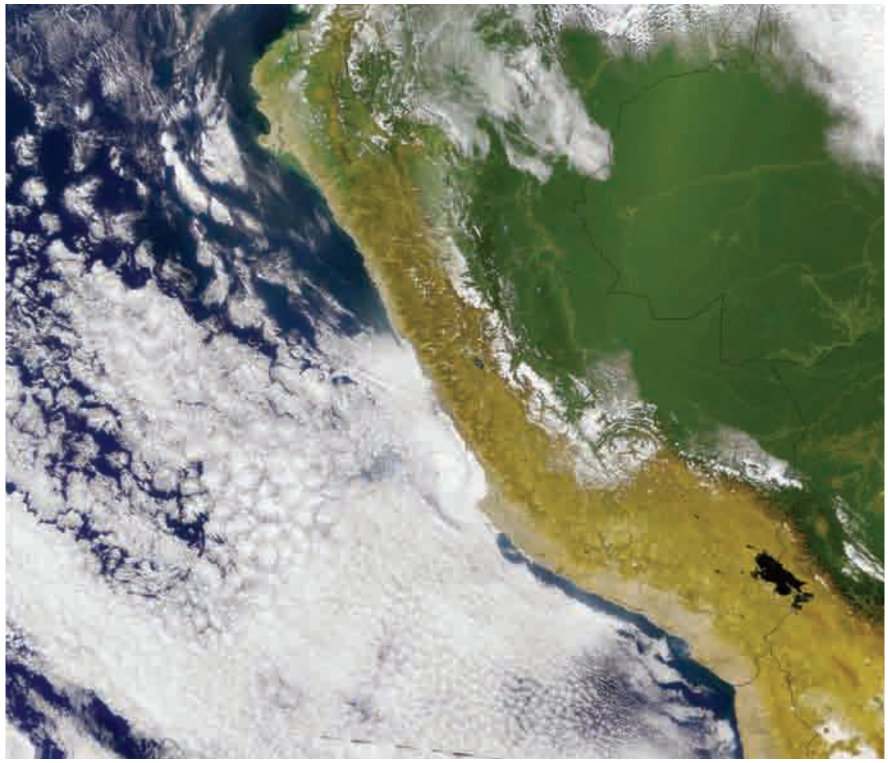


Figure 3. Top: the SST warming increment imposed in each of the three iRAM global warming experiments. Middle: change in the low cloud amount in each of the global warming iRAM simulations relative to the present-day simulation. Bottom: cloud feedback parameter derived from the iRAM global warming simulations.

runs the lateral boundary conditions for the model integration were given by the sum of the 6-hourly reanalysis data used for the present-day experiment plus a climate-change "increment." We based the climate-change increments imposed in these runs on the monthly averaged differences between present-day climate and projections for the end of the 21st century made by coupled GCMs, or ensembles of such models, included in the IPCC Fourth Assessment Report (AR4). Specifically, we adopted a climate-change signal computed as the difference between the 10-year means for each calendar month in the late 20th century [1990–99 in the AR4 20th century forced runs (20C3M)] and in the late 21st century [2090–99 in the Special Report of Emissions Scenarios (SRES) A1B runs].

We performed three experiments, each having a different global-warming increment. In *Case A* the climate change signal is averaged over 19 AR4 models; in *Case B* the signal is taken from version 3 of the Canadian Centre for Climate Modelling and Analysis (CCCma) GCM; and in *Case C* the signal is taken from results of the NCAR Community Climate System Model version 3 (CCSM3). The SST warming patterns in these three cases is shown in the top panels of Figure 3. Among the AR4 GCMs, the NCAR CCSM3 has one of the lowest global climate sensitivities and also has a negative cloud-climate feedback over the eastern Pacific, while the CCCma model displays a much higher global sensitivity and a positive cloud-climate feedback over the eastern Pacific.

The response of the low-level cloud amounts to the imposed warming is shown for each case in the middle row of Figure 3. All the global warming cases simulated with iRAM show a distinct reduction in low-level cloud amount, particularly in the stratocumulus regime, resulting in positive local cloud-climate feedback in these regions. We defined a local cloud-climate feedback parameter as the change in total (shortwave plus longwave) cloud forcing between the control and the warming case, normalized by the local SST change. The feedback parameter for each of the three warming cases is shown in the bottom row of Figure 3. The magnitude and pattern of the feedback parameter is remarkably similar in the three cases. Domain-averaged (30°S–30°N, 150°–60°W) feedback parameters from iRAM range between +1.8 and +1.9 in $W/m^2/K$ in the 3 cases.



Clouds off the Coast of Peru. Courtesy NASA/Goddard Space Flight Center.

The reduction in low-level cloud amount in the global warming simulations is largely caused by a general thinning of the boundary layer clouds. This thinning reduces their ability to reflect sunlight and consequently amplifies the warming (positive cloud-climate feedback). On average, cloud thickness in the eastern Pacific stratocumulus regions is reduced by 50–100 m by the end of the 21st century. The thinning is thought to result from a reduction in the mean height of the inversion layer that usually caps the marine boundary layer clouds by preventing further vertical growth. This is found to be consistent with the boundary layer becoming shallower as a result of reduced entrainment and weaker turbulence in the global warming simulations.

The cloud-climate feedback parameters averaged over the same eastern Pacific region were also calculated from the SRES A1B simulations for each of the 16 GCMs shown in Figure 1. Averaged over our east Pacific

Photo taken during the 2008 VOCALS (VAMOS Ocean-Cloud-Atmosphere-Land Study) field campaign. Image courtesy Cameron McNaughton.

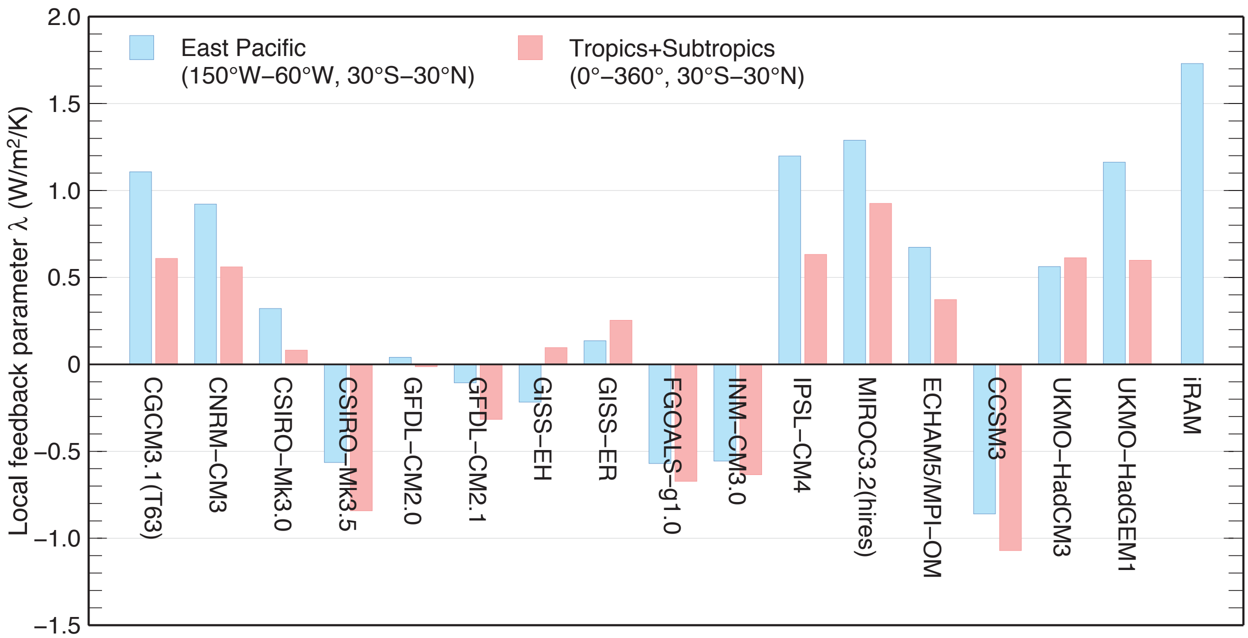


Figure 4. Annual average local feedback parameter λ in W/m²/K for the East Pacific region and the latitude belt 30°S–30°N from 16 IPCC-AR4 models and calculated by iRAM.

region (30°S–30°N, 150°–60°W), the simulated feedbacks varied from −1.0 to +1.3 W/m²/K — all considerably less than the values obtained in the iRAM simulations!

This is seen in the blue bars in Figure 4 that compare the east Pacific average feedback parameters in each of the 16 GCMs and in iRAM (*Case A* simulation result shown). The pink bars show the feedback parameters averaged over the whole 30°S–30°N latitude band for each of the 16 GCMs. The strong correlation between the latitude-band-average feedback (pink bars) and eastern Pacific feedback (blue bars) is apparent.

This work comes with some caveats. Rather than attempting a fully self-consistent calculation of the response of the climate system to external forcing, we have relied on results from another model to provide the surface warming and large-scale changes in wind, stability, and humidity that are then used to force our regional model. This calculation is in the same spirit as numerous earlier calculations of climate feedbacks that have imposed SST changes in an atmospheric GCM that were determined from a separate coupled GCM experiment. Our calculation falls as well into the class of dynamical downscaling simulations of global model climate projections.

The iRAM results by themselves cannot be connected definitively to global climate feedbacks, but the implications for global climate change are likely significant. Cloud feedback largely determines the global climate sensitivity, and among the global GCMs, the cloud feedback in the full tropical-subtropical zone is correlated strongly with eastern Pacific cloud feedback. The iRAM results suggest that all the GCMs underestimate the cloud-climate feedbacks in that region, supporting the high end of current estimates of global climate sensitivity.

This story is based on A. Lauer, K. Hamilton, Y. Wang, V. Phillips and R. Bennartz, 2010: The impact of global warming on marine boundary layer clouds over the eastern Pacific – a regional model study. *J. Climate*, **23**, 5844-5863.