# IPCC Climate Models and Tropical Climates

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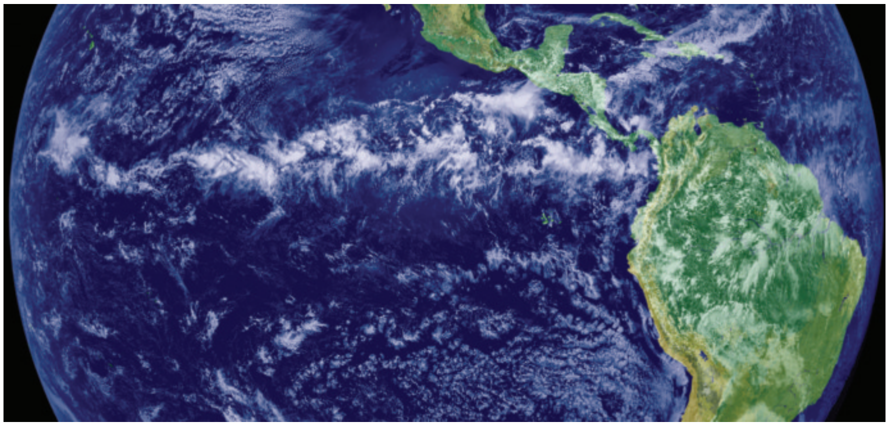
The credibility of global warming projections from numerical models rests on their skillful simulation of current and past climates, and on their seasonal forecasts of climate variability such as the El Niño–Southern Oscillation (ENSO). Deep convection in the tropics is the major driver of global atmospheric circulation, and climate anomalies in the tropics affect climate around the world through so-called atmospheric *teleconnections*. Thus it is important for climate models to simulate accurately the mean state and seasonal cycle of tropical climates.

This article highlights IPRC's effort to assess the simulations of the climate over three tropical oceans by the state-of-the-art coupled ocean–atmosphere general circulation models (GCMs) participating in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). Over the Pacific and Atlantic Oceans, most models fail to maintain the intertropical convergence zone (ITCZ) north of the equator. The ITCZ is the zone of deep convection separating the northeasterly trade winds of the Northern Hemisphere from the southeasterly trade winds of the Southern Hemisphere. A huge amount of condensational heat is released from this zonal band of convective clouds and rainfall that drives the global atmospheric circulation.

**Simon de Szoeke's** analyses of model simulations of the eastern tropical Pacific climate, a region climatically important for ENSO, show that failure of models' ITCZ to stay north of the equator causes errors in simulation of the Pacific equatorial sea surface cold tongue and its seasonal cycle (see section on Tropical Eastern Pacific).



The Intertropical Convergence Zone. Credit: GOES Project Science Office

The model errors in the climate over the equatorial Atlantic are even greater than those over the equatorial Pacific (see section on Tropical Atlantic Climate). While a cold tongue develops in observations in the Gulf of Guinea and extends westward during boreal summer, in the models it is either severely under-developed or completely absent. This error in equatorial Atlantic simulations was identified several years ago but its cause has remained unclear. **Ingo Richter** shows that the error in coupled simulations stems from the models' atmospheric component, which simulates too much rain over equatorial Africa and too little rain over the Amazon. This *zonal dipole* of rainfall weakens the Atlantic equatorial easterly winds, hampering the development of the equatorial cold tongue.

The Indian Ocean differs from the Pacific and the Atlantic in that it lacks the prevailing easterly winds and an equatorial cold tongue. In fact, the Indian Ocean is part of the largest warm pool on Earth, supporting deep atmospheric convection. Only occasionally (every ten years or so), an equatorial cold tongue starts westward from Sumatra during so-called *Indian Ocean dipole* (IOD) events. **N.H. Saji** and colleagues performed the first intercomparison of the AR4 coupled model simulations for the Indian Ocean (see 2006 IPRC Annual Report; Saji et al. 2006). All the models correctly simulate a warm Indian Ocean without a cold tongue on the equator. Many models also capture the major modes of Indian Ocean climate variability: the IOD mode that cools the eastern equatorial Indian Ocean, and the basin-wide warming shortly after El Niño in the Pacific. The skill in simulating the latter is limited by the simulation of El Niño—many models simulate an El Niño  that peaks in boreal summer instead of winter as observed.

Coupled ocean–atmosphere models have demonstrated a degree of skill in reproducing salient features of the observed climates. As detailed below, however, they still suffer from major errors in simulating tropical climate over oceans. Knowing the limits of these models is the first step towards improving them and helps us to apply them judiciously for seasonal predictions and climate projections.

## Tropical Eastern Pacific Climate

Typically the seasonal cycle of solar heating is rather symmetric around the equator, with the Northern Hemisphere receiving its strongest solar heating during April–August, and the Southern Hemisphere during October–February. In the eastern tropical Pacific, however, the seasonal cycle is quite asymmetric, with the warmest SST and strongest ITCZ rainfall found from May through February at 8–12°N. Southerly winds blow across the equator and toward the northern ITCZ year-round. Atmospheric heating becomes somewhat more symmetric across the equator during February–April, causing the southerlies to slacken. During this period of weak southerly winds the equatorial SST warms, and briefly during March–April, the season of the double ITCZ, the Southern Hemisphere also has an ITCZ.

Coupled GCMs have long had difficulties correctly simulating this seasonal cycle and north–south asymmetry in the tropical eastern Pacific. Models tend to simulate either a double ITCZ that lasts too long (*persistent double ITCZ error*), or an alternating ITCZ with warm SST and rainfall migrating symmetrically between the hemispheres (*alternating ITCZ error*). This latter error is associated with a warm bias in the southeastern tropical Pacific SST off the coast of South America. Other common errors include a warmer-than-usual equatorial cold tongue near the coast and an extension of the cold tongue too far west. Such errors in equatorial SST and seasonal cycle can be expected to affect the strength, frequency, and period of ENSO.

For our paper we assessed errors in coupled model simulations of the seasonal cycle and north–south heating asymmetry in the eastern tropical Pacific. We analyzed the *20th century* climate simulations of 14 models included in the IPCC AR4 and the IPRC Regional Ocean–Atmosphere Model (IROAM).

Differences among the model solutions can arise from random differences in model configuration and are amplified by coupled feedbacks in the models. We analyzed the collection of model solutions as if they were an ensemble of realizations of the climate. We used relationships among the ensemble members to diagnose coupled feedbacks and systematic errors that are similar among models.

We noted considerable improvement in coupled models since Mechoso's last comprehensive multimodel assessment of the seasonal cycle over the tropical Pacific in 1995. Figure 1 shows the north–south seasonal cycle of SST in color shades, and of rain in gray, for observations and 6 of the 15 models. Rain follows the warmest SST. Observations (top left panel) show rainfall ex-

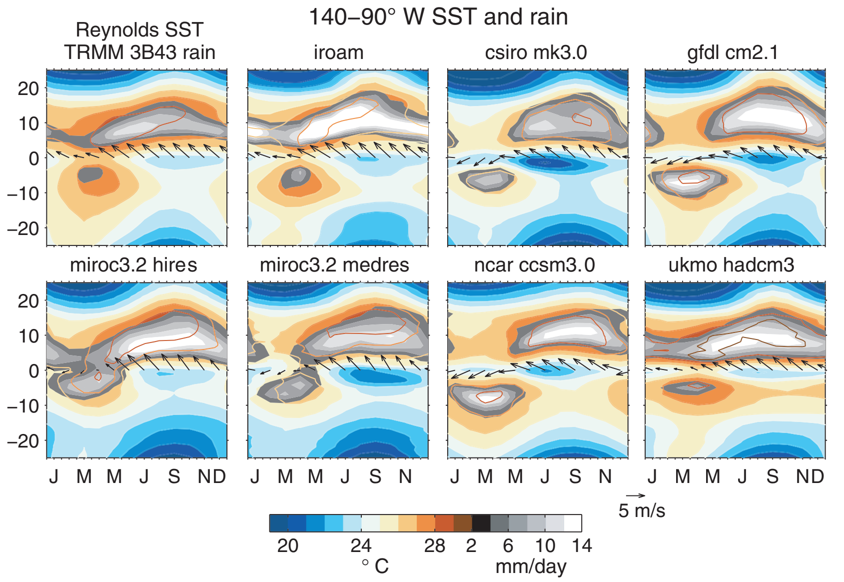


**Figure 1.  Hovmoeller plots of the seasonal climatology of SST (color shades and contours) and rain (gray) in the tropical eastern Pacific Ocean averaged over 140–90°W. The horizontal axis is month of the year and the vertical axis is latitude. Vectors on the equator denote the seasonal cycle of wind on the equator. Reynolds SST, TRMM 3B43 rain, and QuikSCAT wind analyses are shown in the top left panel. Other panels are climatologies of the *20th century* runs from six of the coupled GCMs used for the IPCC AR4 and from the IROAM regional model.**

ceeding 4 mm/day year-round in the Northern Hemisphere, and the brief double ITCZ in March–April. Models such as the IPRC Regional Ocean–Atmosphere Model (IROAM) and the UKMO HadCM3 have north–south seasonal SST and rain patterns that resemble observations. Most of the models analyzed, however, still have errors. Three of the 15 models have a persistent double ITCZ: that is, they have a perennial northern ITCZ and a southern ITCZ that lasts longer than two months. Eight models have a seasonally alternating ITCZ. The seasonally alternating but north–south symmetric rainfall associated with this error appears in the annual mean as a double ITCZ error, but its seasonal cycle is very different.

The alternating ITCZ error results in a wrong seasonal cycle for the winds, which in turn affects equatorial SST. Figure 1 shows the wind vectors on the equator. In the observed climate, southeasterlies blow across the equator towards the Northern Hemisphere ITCZ year-round. Southerly winds cool the sea surface around the equator by evaporation, by turbulent entrainment of cold sub-thermocline water into the mixed layer, and by a north–south circulation in which wind stress drags surface water across the equator and cold water upwells south of the equator. The brief slackening of the southerlies in March–April allows equatorial water to warm up. In models with an alternating ITCZ, however, winds reverse toward the Southern Hemisphere ITCZ during this time rather than weaken. This erroneous second maximum in meridional wind speed causes a cooling, resulting in a spurious second cold season on the equator in spring in some models. The wind effect on the spring equatorial cold error is confirmed by the correlation (r=-0.61) across models between March SST and cross-equatorial wind speed. Thus, in addition to easterly wind-driven equatorial Ekman divergence—the canonical explanation of the equatorial cold SST error—our study shows that the alternating ITCZ error contributes to the cold bias on the equator by simulating the wrong seasonal cycle of wind.

Models that simulate a more symmetric north–south climate than observed tend to have southerlies that are too weak within 1000 km of the South American coast. The mechanisms for equatorial cooling are weaker (less evaporation, less entrainment of cold sub-thermocline water, and less upwelling on the equator) than in alternating ITCZ models, and weaker southeasterly winds are related to the warm bias of the sea surface around the equator near the coast (r =-0.66; Figure 2a).

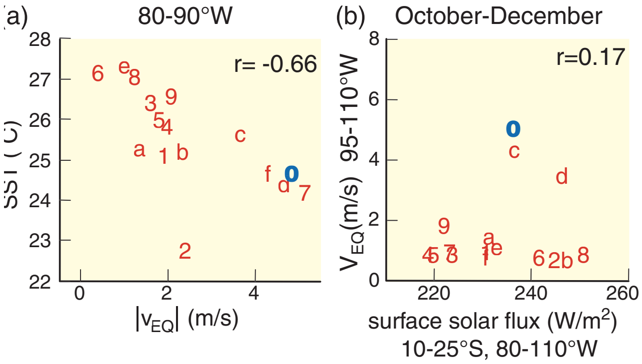


Figure 2. (a) Southerly wind speed and SST near the South American coast: models with higher wind speed have cooler SST; **O** refers to observations, the other numbers and letters refer to the results for each of the 15 models assessed (models not identified). (b) Surface solar radiation and meridional equatorial wind. Though the model spread in the surface solar flux in the southern stratocumulus region (mostly due to clouds) includes the observed surface solar flux, no model is as asymmetric (measured by east-Pacific equatorial southerly wind) as observed.

Studies that others have conducted to determine the reasons for difficulties in simulating eastern tropical Pacific have focused on representations of the southeastern tropical stratocumulus cloud deck. Our analysis of AR4 models shows that in the stratoculumus region the models have downward solar radiation at the surface that scatters around the observed values, but in no model is the equatorial southerly wind as strong as in the observations (Figure 2b, observations indicated by **O**, and each model is indicated by another character). Although clouds are important in maintaining the north-south asymmetry of the climate by cooling southeastern tropical Pacific Ocean, our study suggests that their realistic representation in models is necessary but insufficient to eliminate the tropical eastern Pacific errors in coupled GCMs. Few models simulate the correct seasonal cycle of north–south climate asymmetry and year-round southerly wind on the equator. The wind error is reflected in well-known SST errors on the equator.

## Tropical Atlantic Climate

Of the three major ocean basins, the tropical Atlantic may be the most difficult one to simulate in coupled GCMs. A study conducted in 2002 showed that all the models examined (except one) reversed the SST gradient along the equator compared with observations. This was largely due to the fact that the models did not capture the development of the eastern equatorial cold tongue during June–August. Other errors commonly encountered in the tropical Atlantic include a southward shift of the ITCZ and too few marine stratocumulus clouds in the subtropical southeast Atlantic. These model shortcomings seriously affect seasonal-to-interannual climate predictions, and model predictions are matched or even outperformed by statistical and persistence forecasts. This lack of skill undermines the results from climate warming scenarios for the region, such as the *$CO_2$ doubling* experiments. To get a better understanding of the errors related to Atlantic climate simulations, we have examined the tropical Atlantic climate in the *$20^{th}$ century* experiments.

Figure 3 depicts the annual mean SST across the equatorial Atlantic. The models' SST shows a wide spread, the coldest (CNRM CM3) being about 3°C colder than the warmest (UKMO HadCM3). Clearly, the SST representation has not improved much since the 2002 IPCC Third Assessment Report. All the models feature a warming from the central Atlantic eastward, whereas observations show a cooling.

As in the 2002 assessment, the models fail to simulate the seasonal development of the equatorial cold tongue. This is illustrated in Figure 4, which shows the equatorial winds and SST across the Atlantic over the year of the ensemble mean from several IPCC coupled GCMs. The greatest warm SST bias occurs during June–August and is most pronounced off the African coast.

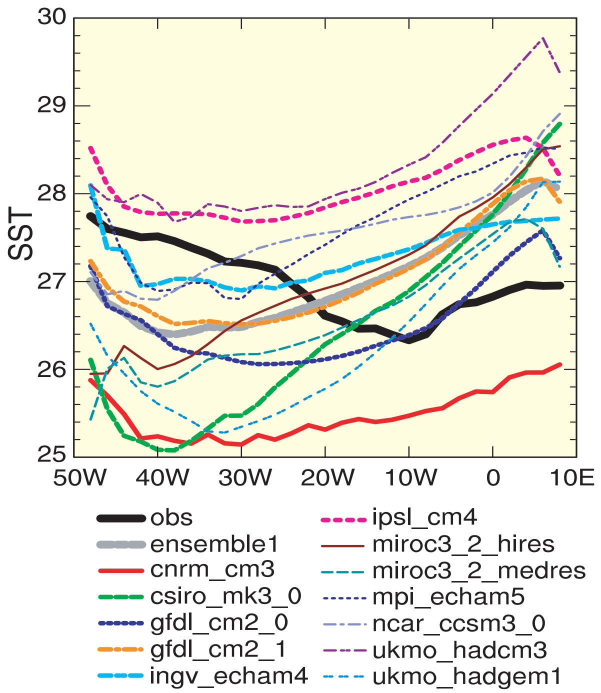
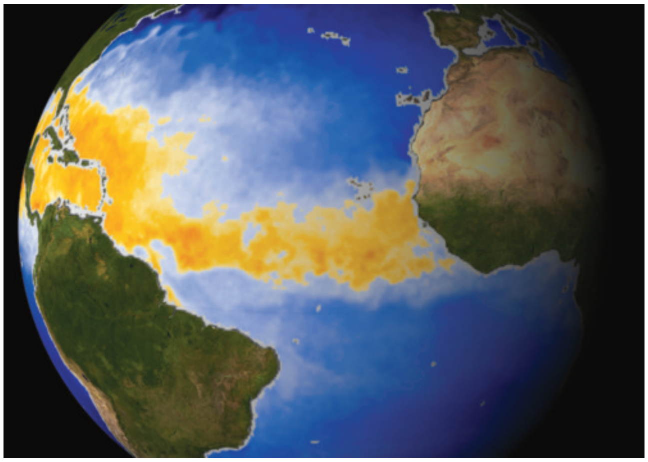


**Figure 3: Annual mean of SST (°C) along the equator, averaged between 2°S and 2°N. The thick black and grey lines denote COADS SST and the ensemble mean, respectively. None of the models is able to capture the eastward decrease of SST in the observations between 50°W and 10°W.**



**Sea Surface Temperature. Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio**

Compared to observations, the models' equatorial easterly winds are too weak and sometimes even reversed (Figure 4), especially during March–May. This bias leads to a deepening of the thermocline in the eastern basin, the 20°C isotherm depth increasing eastwards (not shown). In summertime, the equatorial wind errors become small and winds

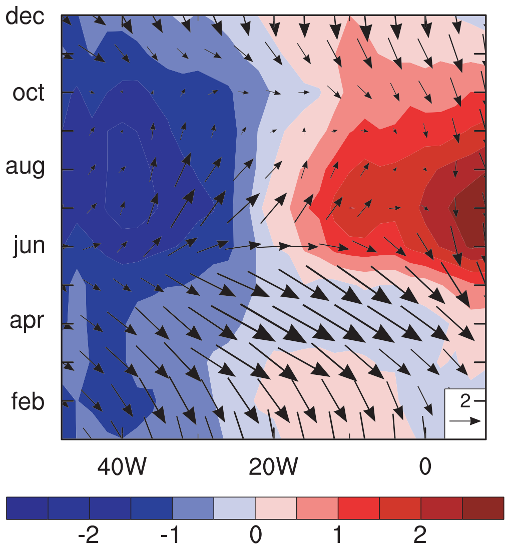


**Figure 4: Equatorial longitude-time section of SST (K) and surface wind (m/s) biases for the ensemble mean of IPCC AR4 models. The reference dataset is ICOADS. Fields are averaged between 2°S and 2°N. A strong westerly wind bias during boreal spring precedes the maximum SST bias in boreal summer.**

are more favorable to upwelling (Figure 4). Because the model thermocline is too deep, however, a cold tongue cannot form in the east. Our results thus show that the warm SST bias in June–August is due to westerly winds that are too strong during the preceding season.

For some of the models in the IPCC database, atmosphere-only simulations with prescribed climatological SSTs are available. Analyses of these simulations provide an opportunity to determine whether model errors are due to the atmospheric components or due to unrealistic SST patterns. Studying the same models as above, we analyzed these atmosphere-only experiments. Figure 5 shows that even when forced with "perfect" SSTs, the models have surface westerly winds along the Atlantic equator that are too strong, simulating too little rain over the western Atlantic and South America and too much rain over the eastern Atlantic and Africa. Further analysis showed that these rainfall errors are linked to an erroneous sea-level pressure gradient that maintains the westerly wind bias in the models. All these model errors are associated with a weaker Atlantic Walker cell than observed.

Comparison of the atmosphere-only with their coupled model runs shows that coupling amplifies the surface-wind and rainfall errors. The westerly wind bias, for example, doubles in the ensemble mean, indicating amplification by the Bjerknes feedback.

Apart from the zonal biases along the equator, both coupled and uncoupled models suffer from an erroneous southward shift of the ITCZ. This shift is accompanied by an anomalous southerly wind at the equator, which can be seen in Figures 4 and 5. These errors, too, are amplified by coupled feedbacks, namely the windstress–evaporation–SST feedback.

In summary, our results show that tropical Atlantic biases remain a serious problem in the AR4 models. To a large extent these biases originate in the atmospheric components of the models and are amplified by SST feedbacks in the coupled simulations. Analyses not presented here suggest, furthermore, that rainfall errors over equatorial South America and Africa increase the westerly wind biases. Improving simulation of rainfall over land may, thus, hold the key to a realistic simulation of the tropical Atlantic climate in general circulation models.

Our results are described in more detail in Richter and Xie, 2007.

## References

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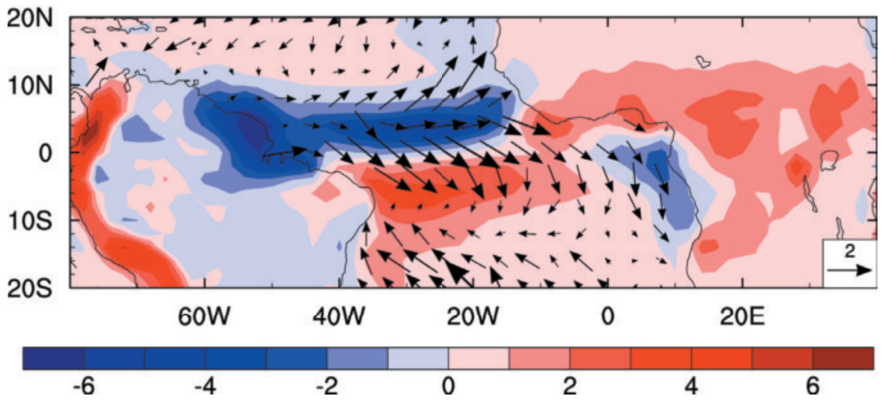

**Figure 5: March–May precipitation (mm/day) and surface wind (m/s) biases for the uncoupled atmospheric model ensemble. The reference datasets are CMAP (precipitation) and ICOADS (surface winds). The westerly wind bias along the equator is similar to the one seen in the coupled models. Precipitation errors over the ocean indicate a southward shift of the ITCZ. Furthermore, precipitation is too low over tropical South America and too high over tropical Africa.**