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Response time of an atmospheric general circulation model to changes in ocean surface temperature: Implications for interactive large-scale atmosphere and ocean models

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ABSTRACT

To ensure efficient coupling strategies in asynchronous coupling experiments with atmospheric and oceanic general circulation models (GCMs), knowledge of the atmospheric model's response time to altered ocean surface temperature (OST) forcing is a necessary prerequisite. A general estimate of atmospheric response time of 30 days is obtained by analysis of the time evolution between different quasi-equilibrium states in response to altered OSTs in several atmospheric GCM experiments. It is recognized, however, that this estimate may be too conservative (longer than necessary) for lower atmospheric layers in the tropics. For a completely optimized asynchronous coupling strategy, an estimate of oceanic response time to altered atmospheric forcing is also necessary.

1. Introduction

A variety of coupling strategies is possible in the design and execution of interactive large-scale atmospheric and oceanic general circulation models (GCMs). Two of the more straightforward techniques are, using the terminology of Schlesinger (1979), synchronous and asynchronous coupling.

In a synchronous coupling experiment, atmospheric and oceanic GCMs run simultaneously with a continuous two-way feedback between the atmosphere and ocean. This procedure is necessary if we are interested in the detailed time evolution of the climate system from one quasi-equilibrium state to another. Lorenz (1975) referred to this prediction problem as *climatic prediction of the first kind.* Because of the short time step required in the integration of atmospheric GCMs, however, synchronous coupling experiments lasting more than a year or two of simulated time are not practical on present-day computers and thus are inappropriate for the study of processes involving the deep ocean.

The alternative technique, asynchronous coupling, takes advantage of the disparity between oceanic and atmospheric time scales and saves considerable computer time by allowing a stepwise approach to an ultimate quasi-equilibrium through several intermediate or virtual quasi-equilibrium states. In an asynchronous coupling experiment, atmospheric and oceanic GCMs run sequentially with the time-averaged output of one model used to force the other during alternate half-cycles. Manabe and Bryan (1969), Manabe et al. (1975), Bryan et al. (1975) and Manabe et al. (1979) followed this procedure in coupled model experiments. Obviously, the somewhat artificial nature of an asynchronously coupled model prevents the model from duplicating the time evolution of the real climate system. Nevertheless, this technique appears to be applicable to climate experiments in which we are concerned only with determining an ultimate quasi-equilibrium state. Such experiments have been characterized by Lorenz (1975) as *climatic prediction of the second kind.* The current

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interest in determining the compatible atmosphere and ocean quasi-equilibrium state with a prescribed increase in the atmospheric CO_2 burden is just one of many experiments possible with an asynchronously coupled model.

To minimize the number of asynchronous cycles and to maximize the impact of each climate system component on the other during each half-cycle in an asynchronously coupled model experiment, we need to know the atmospheric response time to altered ocean forcing and the oceanic response time to altered atmosphere forcing. Since coupled model development is still in its early stages, we can use the results of some past atmospheric GCM experiments to estimate the atmospheric response time and to demonstrate some of its spatial and regional aspects. Although oceanic response time is also important, addressing that issue is beyond the scope of this paper.

2. Atmospheric response time

There have been a number of atmospheric sensitivity experiments in which ocean surface temperature (OST) has been changed in atmospheric GCMs and the time-averaged response examined (e.g., Rowntree, 1972; Shukla, 1975; Chervin et al., 1976; Washington et al., 1977; Julian and Chervin, 1978). The integration time of each of these experiments is of the order of two months or less. In the sense of Lorenz, these experiments may be considered "atmospheric prediction experiments of the second kind" in that only the final quasi-equilibrium state is of interest. Here we examine the time behavior of experiments performed with the six-layer tropospheric GCM at the National Center for Atmospheric Research (NCAR) to determine the evolution for various measures between atmospheric states in response to altered OST forcing. In this way, a variety of estimates of atmospheric response time is possible.

Fig. 1 shows, for the NCAR GCM described by Kasahara and Washington (1971), the evolution of globally averaged temperatures at different heights from an isothermal (240 K), at-rest atmospheric state to a quasi-equilibrium January atmosphere. This model atmosphere starts from an artificial state and, commencing at Day 0, the model is forced by physical processes such as radiation, precipitation, convection and boundary layer physics, in addition to the imposed climatological OST distribution. Estimating atmospheric response time to the OST forcing from the "flattening out" time for the curves in Fig. 1 probably results in a conservative (longer than necessary) response time estimate for globally averaged temperature measures of atmospheric states. The choice of an optimum objective measure of response time is not readily apparent and hence we simply present the time evolution curves as quasi-quantitative indicators of the dependence of response time on altitude and spatial averaging of atmospheric

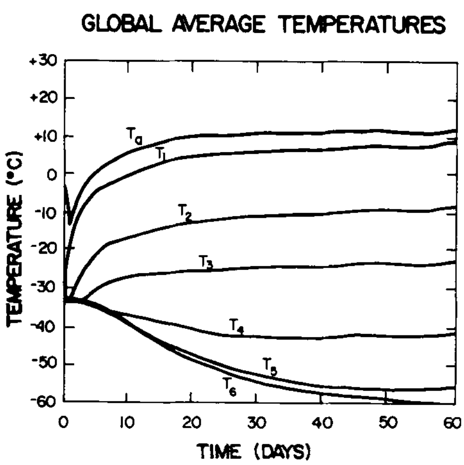

Fig. 1. Globally averaged temperatures as a function of time at anemometer-height level (T_a), 1.5 km (T_1), 4.5 km (T_2), 7.5 km (T_3), 10.5 km (T_4), 13.5 km (T_5) and 16.5 km (T_6). Units are °C.

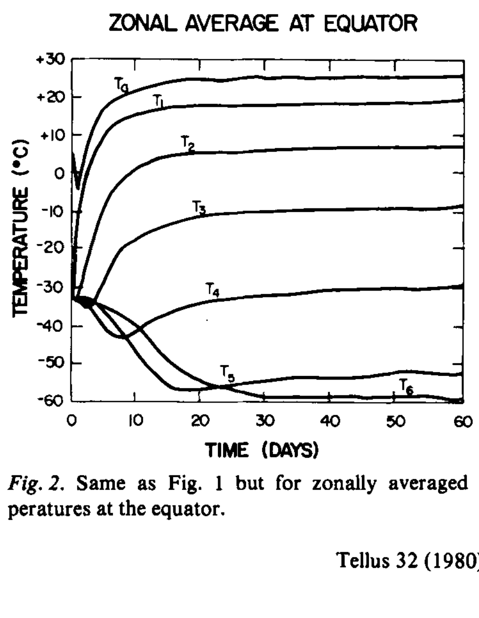

Fig. 2. Same as Fig. 1 but for zonally averaged temperatures at the equator.

states. The anemometer-height and 1.5 km temperature adjust to the altered forcing rapidly (20–30 days) because they are directly influenced by the imposed OST distribution. This result is consistent with that obtained by Chervin and Schneider (1976) for a GCM forced by small random perturbations. The temperatures in the upper two layers reach quasi-equilibrium in 50–60 days.

For the same model integration, Fig. 2 shows the evolution of the vertical distribution of zonally averaged temperatures at the equator. At all levels, this zonally averaged measure adjusts more rapidly

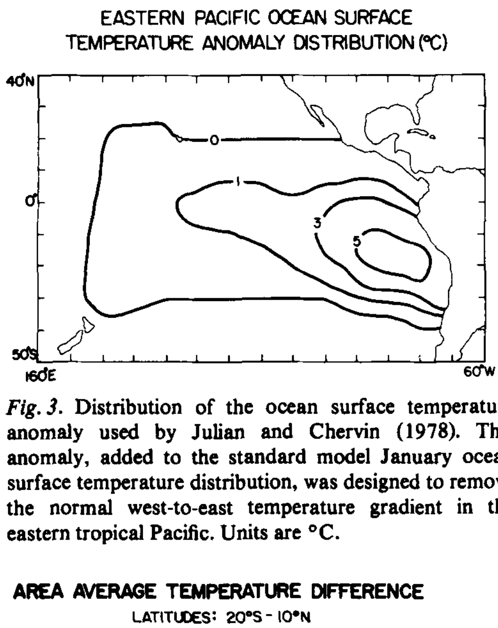

Fig. 3. Distribution of the ocean surface temperature anomaly used by Julian and Chervin (1978). This anomaly, added to the standard model January ocean surface temperature distribution, was designed to remove the normal west-to-east temperature gradient in the eastern tropical Pacific. Units are °C.

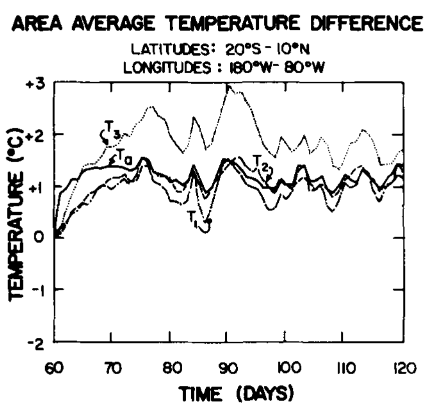

Fig. 4. Regionally averaged temperature differences between anomaly and control experiments for the area 20° S to 10° N and 180° W to 80° W at anemometer-height level (T_a), 1.5 km (T_1), 4.5 km (T_2) and 7.5 km (T_3). Units are °C.

than the globally averaged measure, 10–20 days at 1.5 km and 20–30 days at the upper two layers. These results suggest that the tropical atmospheric response time is considerably less than that over the globe as a whole. Presumably, in the model the convective parameterization is a major contributor to this short response time in the tropics.

Perhaps a more pertinent estimate of atmospheric response time for developing asynchronous coupling strategies is possible from the consideration of the local atmospheric response to a local OST anomaly of reasonable magnitude imposed in a fully developed, more realistic atmosphere. In the Southern Oscillation and Walker Circulation study by Julian and Chervin (1978), the OSTs were changed in the eastern tropical Pacific. Their OST anomaly pattern (Fig. 3) was inserted on model Day 60 into the previously described quasi-equilibrium January atmosphere. Figs. 4 and 5 show the evolution of the temperature difference between the anomaly and control experiments at the different model heights averaged over the anomaly region from 20° S to 10° N and 180° W to 80° W. For the lower three atmospheric layers, this regionally averaged measure adjusts in about 10–15 days. The anemometer-height temperature adjusts most rapidly of all, in about 5 days. Estimates of atmospheric response times are not obvious from the temperature difference time series for the upper three layers in Fig. 5, indicating that at these levels there is little direct atmospheric temperature response to the OST anomaly.

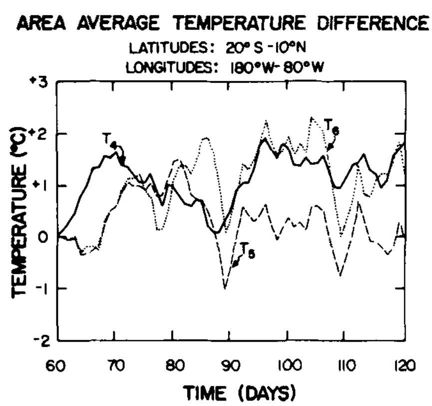

Fig. 5. Same as Fig. 4 but for 10.5 km (T_4), 13.5 km (T_5) and 16.5 km (T_6).

3. Conclusion

Analysis of the time evolution of different measures of atmospheric states in atmospheric GCM experiments with altered ocean surface temperature forcing provides several different estimates of atmospheric response time dependent to a great extent on the degree of spatial averaging and other regional aspects of the particular measure. In the case of temperature, the response time is less for a smaller change in ocean surface temperature and for regions closer to the surface and the tropics. Although no single value for atmospheric response time resulted from our analysis, a 30-day integration of an atmospheric GCM during the atmospheric half-cycle in an asynchronous coupling experiment should ensure the efficient progression to an ultimate quasi-equilibrium state through a series of virtual quasi-equilibrium states. Further experiments are needed to determine how our general estimate of atmospheric time response would be altered for a model that included longer time-scale land surface processes such as soil moisture, snow cover, vegetation and a seasonal cycle. To optimize asynchronous coupling strategies, estimates of oceanic time response to altered atmosphere forcing are necessary as well.

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ВРЕМЯ РЕАКЦИИ МОДЕЛИ ОБЩЕЙ ЦИРКУЛЯЦИИ АТМОСФЕРЫ НА ИЗМЕНЕНИЯ ТЕМПЕРАТУРЫ ПОВЕРХНОСТИ ОКЕАНА: СЛЕДСТВИЯ ДЛЯ ВЗАИМОДЕЙСТВУЮЩИХ КРУПНОМАСШТАБНЫХ МОДЕЛЕЙ АТМОСФЕРЫ И ОКЕАНА

Для обеспечения эффективной согласованной стратегии экспериментов по асинхронной связи моделей общей циркуляции атмосферы и океана необходимой предпосылкой является знание времени реакции модели атмосферы на изменение температуры поверхности океана (ТПО). Общая оценка времени реакции атмосферы в 30 дней получена путем анализа временнóй эволюции

между различными квазиравновесными состояниями, отвечающими на изменения ТПО в нескольких экспериментах с моделями общей циркуляции атмосферы. Однако представляется, что эта общая оценка может быть слишком завышенной для нижних слоев атмосферы в тропиках. Для полностью оптимизированной стратегии асинхронной связи необходима также оценка времени реакции океана на изменение возбуждения со стороны атмосферы.