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Large sensitivity to initial conditions in seasonal predictions with a coupled ocean-atmosphere general circulation model

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[1] An ensemble of one-year forecasts differing only in details of the atmospheric initial conditions was produced with a coupled ocean-atmosphere general circulation model (GCM) in order to investigate the predictability of the coupled system. For some ocean initial conditions, the evolution of the tropical Pacific ocean thermal structure seems to be relatively deterministic for lead times out to one year. However, there are other ocean initial conditions, mostly in the mid 1990's for which coupled model forecasts of the tropical Pacific are much more sensitive to details of the atmosphere initial conditions. In some cases, the ensemble forecasts appear to split, with some ensemble members predicting El Niño-like conditions, and others predicting La Niña. Very large ensembles were run for several of these cases. Very slight perturbations added to the atmospheric initial conditions led to large spread in predicted SST anomalies in some years. These are model results, however, they do suggest the possibility that seasonal predictions of the coupled tropical system may be highly non-deterministic in some years. *INDEX TERMS:* 0312 Atmospheric Composition and Structure: Air/sea constituent fluxes (3339, 4504); 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4504 Oceanography (Physical): Air/sea interactions (0312)

1. Experimental Design

[2] This experiment was designed to increase understanding of the prediction and predictability of the coupled GCM and the coupled atmosphere-ocean system. Six member ensembles of coupled ocean-atmosphere GCM one year forecasts have been produced, starting from 1 January and 1 July for each of the years 1979–1997. Ocean initial conditions are identical for all six members of each ensemble and are from the Geophysical Fluid Dynamics Laboratory (GFDL) ocean data assimilation system [*Rosati et al.*, 1997]. The ocean assimilation uses the GFDL modular ocean model (MOM) forced by observed wind stress and assimilates sea surface temperature (SST) and sub-surface thermal data, a scheme found to give the most skill in coupled forecasts. Atmosphere initial conditions for the coupled forecasts come from a set of six simulations using an atmospheric GCM forced by the SSTs from the ocean data assimilation. These atmosphere-only runs extend from 1 January, 1979 to 31 December 1997 and differ only in their initial conditions (starting times were staggered by 12 hours). Coupled model atmospheric initial conditions are taken from conditions for the corresponding date (1 January, 1 July) in the atmosphere-only integrations. This procedure attempts to minimize inconsistencies between the atmospheric and oceanic initial conditions, thus reducing "initial shock" errors.

[3] The atmospheric GCM is the GFDL Experimental Prediction group's spectral GCM [*Anderson and Ploshay*, 2000] with triangular T42 truncation (about 2.8° by 2.8°) and 18 vertical sigma levels. Included in its physical parameterizations are: orographic gravity wave drag; large-scale condensation; relaxed Arakawa-Schubert (RAS) convection; shallow convection; diagnostic cloud prediction; bucket hydrology; diurnal radiation, radiative transfer (2-hour averaged); seasonally varying, stability-dependent vertical eddy fluxes of heat, momentum and moisture throughout the surface layer, planetary boundary layer and free atmosphere; and horizontal diffusion.

[4] The ocean model is GFDL's modular ocean model version 2 (MOM2) [*Pacanowski*, 1995], with a nearly global grid, realistic bottom topography and horizontal resolution of 1° longitude by 1° latitude except with enhanced meridional resolution of 1/3 degree within the equatorial band from 10°N–10°S. There are 15 unequally spaced vertical levels with most of the levels concentrated in the upper ocean above 500 m. Some of the physical parameterizations are penetration of solar insolation to the ocean subsurface, Mellor-Yamada level 2.5 vertical mixing, and horizontal mixing adapted from the Smagorinsky nonlinear viscosity approach.

[5] The coupled GCM uses a 2 hour coupling interval involving an atmospheric GCM integration with a time step of 800 seconds forced by averaged SSTs from the previous two hour ocean GCM integration. Resulting two-hour averages of windstress, heat flux and precipitation minus evaporation are used to force the next 2 hour ocean GCM integration which has a time step of 1 hour for both momentum and temperature/salinity.

2. Results

[6] This paper focuses on the central equatorial Pacific ocean, primarily the Niño 3 region (5°N–5°S, 150°W–90°W). Figure 1 shows time series of observed Niño 3 SST anomalies and anomalies from the six coupled GCM one year forecasts starting on 1 July for the years 1979 through 1997. A model SST seasonal cycle climatology is computed by averaging over the 114 (= 6 members × 19 years) forecasts. Forecast SST anomalies are computed for each forecast by subtracting the model SST seasonal cycle climatology from the forecast's SST.

[7] The six ensemble members often produce similar forecasts of SST anomalies (see most of the 1980's and 1991, 1997). In 1982 and 1997, the two major El Niño years, forecast SST anomalies from the six ensemble members display the least dispersion with all members of the ensemble producing peak warmings that are cooler than observed and a premature cooling. On the other hand, during the mid 1990's the ensemble SST anomalies tend to diverge from one another much more rapidly than during other years.

[8] Figure 2 focuses on the Niño 3 region SST anomalies from the coupled forecasts for the years 1994–96. In 1994 and 1996, four ensemble members predicted warm anomalies and two cold for boreal autumn and winter, while the observed was somewhat warm in 1994 and cold in 1996. The 1995 forecasts split with three cold and three near neutral, while the observed anomaly was cold. The only difference in the ensemble members for each year is the atmospheric initial condition.

[9] Figure 3 shows a longitude-time diagram of SST anomalies over the central tropical Pacific averaged from 5°N to 5°S over the region from 120°E to 80°W for each of the 1995 ensemble

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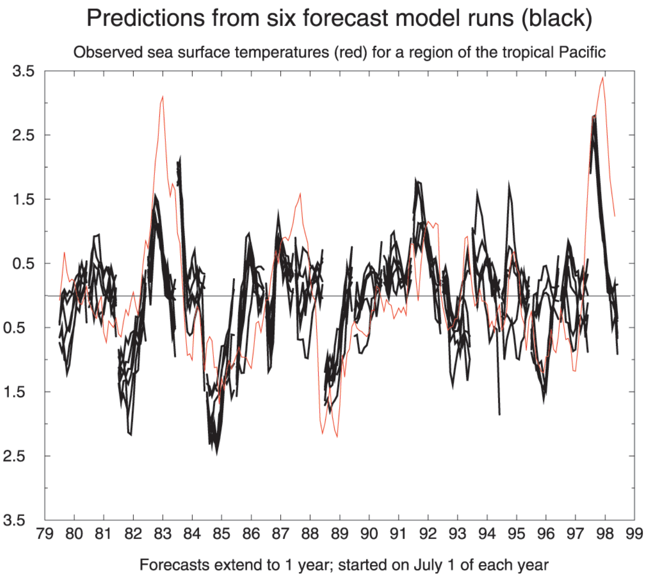

Figure 1. SST anomaly predictions from six coupled model forecast runs (black), and observed SST (red) anomalies for the Niño3 region. Forecasts extend to one year, starting on July 1 of each year.

members (C1–C6). Three cases where SST anomalies remained below average and three above average over the eastern Pacific (El Niño region) are clearly seen. The zonal component of the surface windstress (not shown) has a stronger mean westerly component during July through September in the three warmest forecast cases as compared to the colder cases.

[10] Additional ensembles of six coupled one year forecasts were run starting 1 July of each year 1994–96 (the bifurcation cases). Six very slight perturbations (VSP) were added to each of the six previous atmospheric initial conditions for 1 July of 1994, 1995 and 1996, resulting in six new six member initial condition groups (A–F). VSP perturbations were made only to the 850 mb temperature field and were independently selected at each grid point from a normal distribution with variance equal to one percent of the climatological variance from the original 19 one year forecasts.

[11] Figure 4 depicts the velocity potential anomalies from the ensemble mean of one group of 6 VSP forecasts (C2A–C2F) for July 1995. It shows the evolution of the velocity potential anomalies during the first month (July 1–31) of the six forecasts. Apparently, there is a preferred region of sensitivity to the atmospheric initial conditions that develops in the vicinity of 120°E to 150°E, 5°N to 5°S during the first 7–10 days of the coupled forecasts. These results are quantitatively similar for all of the VSP groups generated from the C1–C6 atmospheric initial conditions.

[12] In Figure 5 the forecast Niño 3 SST anomalies for each of the 36 new VSP cases from 1 July 1995 are compared to the anomalies for the corresponding original forecasts. Even though the initial conditions are nearly identical in the VSP cases for 1994–96, the spread of forecast SST anomalies in some instances (Figure 5b) is of comparable magnitude to that found with the six original members of the ensemble (Figure 2b). Similar SST anomaly spread comparisons were found in the 1994 and 1996 VSP cases.

[13] The same type of "VSP" experiment was conducted for the 1997 El Niño cases, in which the Niño3 SST anomaly spread between ensemble members was minimal, and the resulting spreads were also minimal. This indicates that when there is a very strong SST forcing that the coupled model may tend to have greater predictability.

3. Discussion and Conclusions

[14] The coupled model results presented here suggest that some predictions of the thermal structure of the tropical Pacific cannot be reasonably viewed as deterministic even for lead times as short as one or two seasons. In some of the cases shown, the Niño 3 SSTs appear to split, making the ensemble mean a poor forecast choice that may never be realized. The results also have implications for the use of two-tiered prediction systems [*Bengtsson et al.*, 1993]. In some of these systems a single prediction of the ocean is made and the resulting SSTs are used to force an ensemble of atmospheric GCM predictions [*Barnett et al.*, 1993]. This would clearly be inappropriate if the evolution of the SSTs is as unpredictable as suggested in the coupled model results presented here. More recently, two-tiered forecasts in which ensembles of "tier-one" ocean predictions are produced have been developed [*Livezey et al.*, 1996]. The very strong coupling on short time scales suggested by the rapid impact of atmospheric initial conditions suggests that even this type of two-tiered forecast might be problematic.

[15] Apparently, in the coupled model being studied, there are certain ocean initial conditions that are much more sensitive to the details of the atmospheric windstress forcing. In these cases, slight differences in atmospheric initial conditions can have significant impact on the tropical ocean thermal structure after only a few months even with ocean initial conditions pre-conditioning using ocean data assimilation.

[16] A number of caveats apply to these results. The most important is that these are model results from a coupled model with

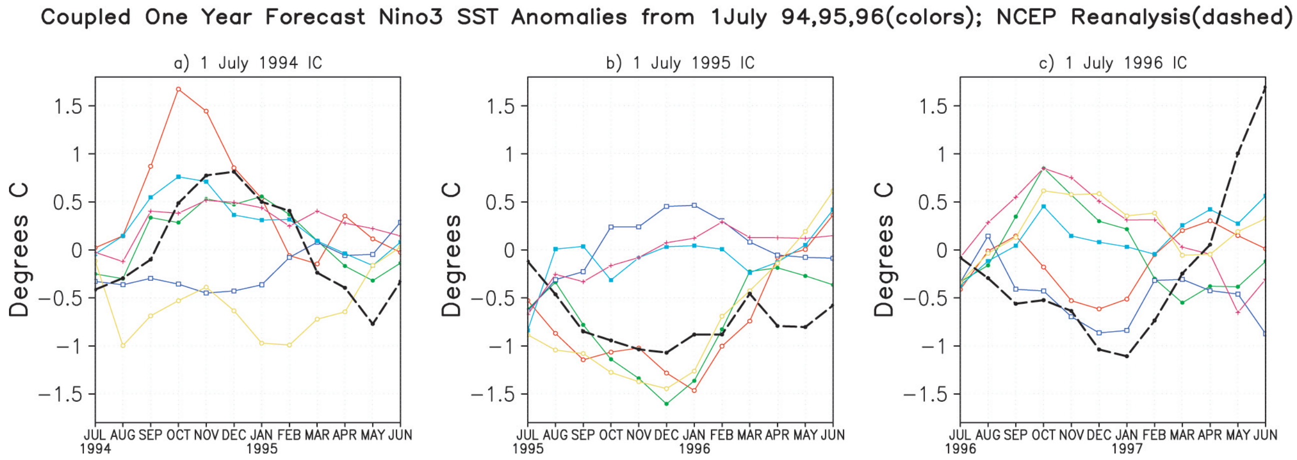

Figure 2. SST anomaly predictions from six coupled model forecast runs (colors) and observed SST (dashed) anomalies for (a) July 1994–June 1995, (b) July 1995–June 1996, and (c) July 1996–June 1997.

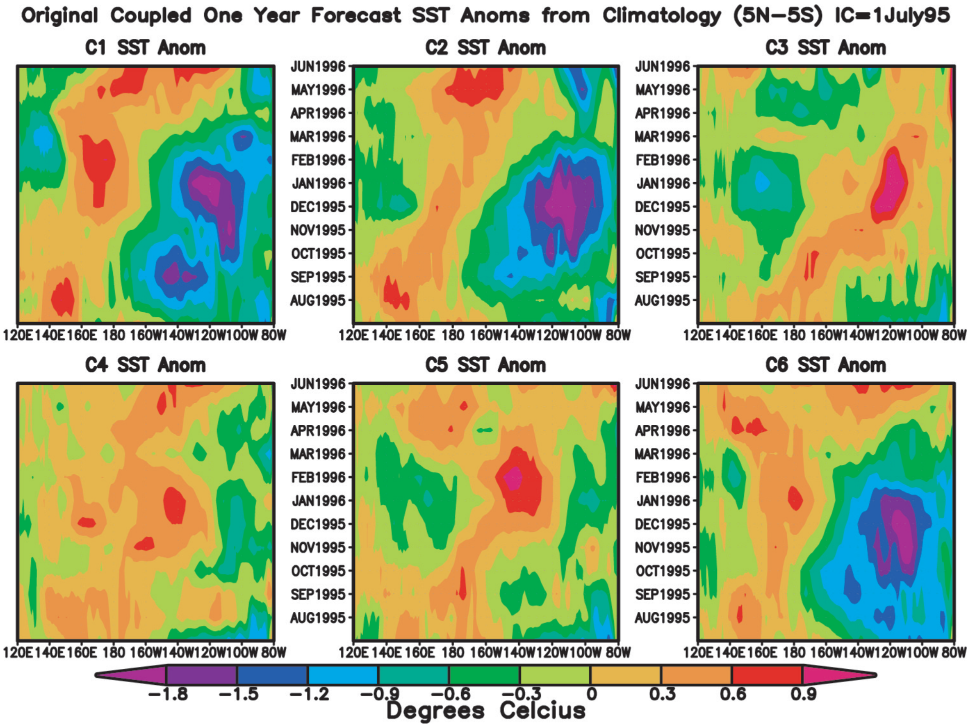

Figure 3. Time-longitude plots of SST anomalies, averaged from 5°N to 5°S, from six coupled model forecast runs for differing atmospheric initial conditions starting 1 July 1995.

significant systematic biases. In particular, the model has a tendency to produce weak SST gradient across the Pacific by warming the eastern and cooling the western parts of the basin. This results in weak equatorial easterly winds which lead to unrealistically small thermocline slope across the basin. This bias might predispose this model towards the type of ensemble prediction splits seen in certain years. A second caveat is that the atmospheric initial conditions are not necessarily consistent with atmospheric obser-

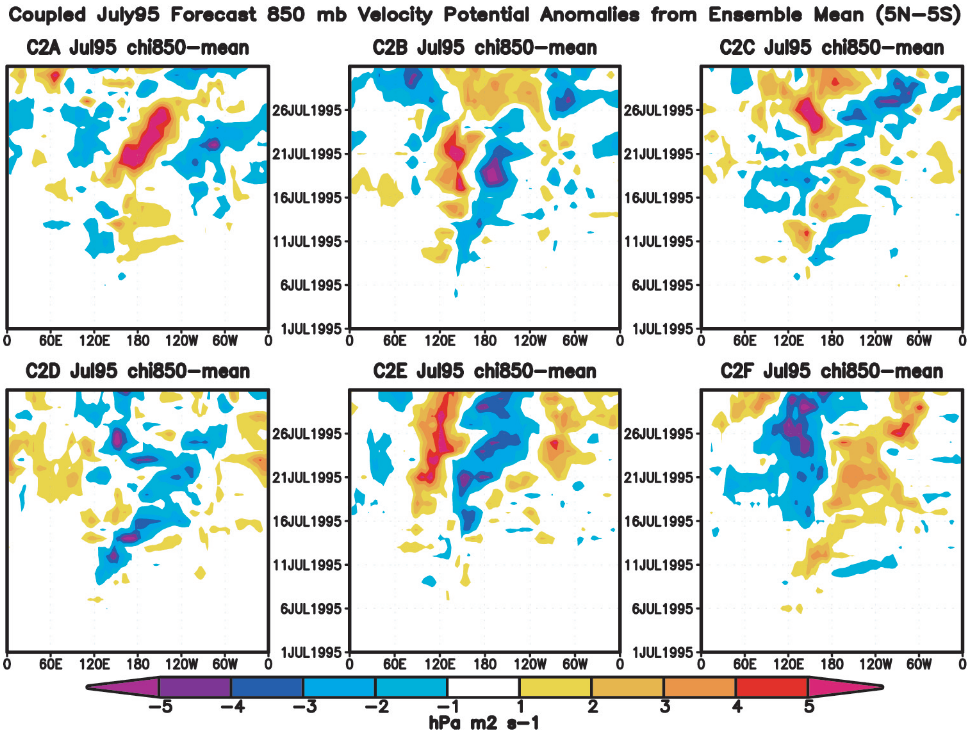

Figure 4. Time-longitude plots of 850 mb velocity potential anomalies from the ensemble mean of one group of six very slight perturbation (VSP) forecasts (C2A–C2F), averaged 5°N to 5°S, during July 1–31, 1995. Perturbations (A–F) were applied to the C2 atmospheric initial conditions.

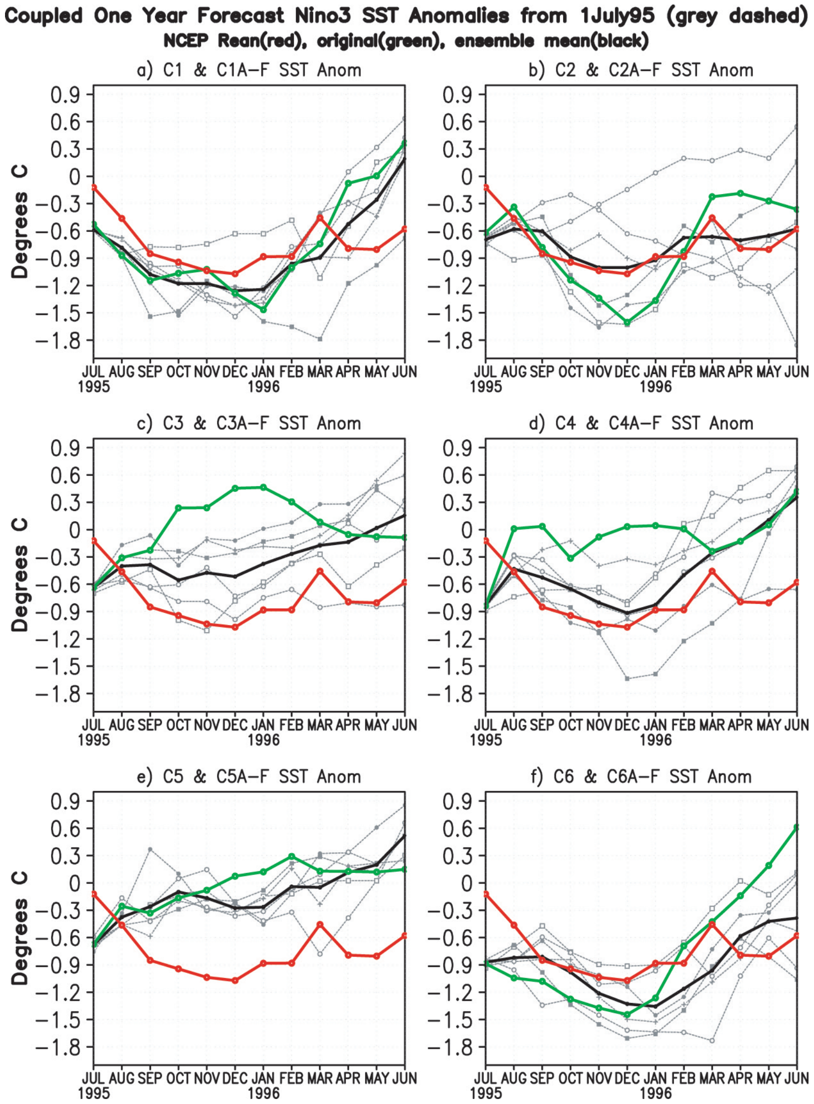

Figure 5. SST anomaly predictions from six very slight perturbation (VSP) coupled model forecast runs (grey dashed), their ensemble mean (black) and the original coupled model forecasts (green) for the Niño3 region. Forecasts extend to one year, starting on July 1 of each year. Observed SST anomalies are represented by the red lines.

vations since they are not generated by direct assimilation. In the first set of coupled model runs it is possible that the initial conditions are unrealistically disparate given the current atmospheric observing system and that making use of appropriate atmospheric assimilation would lead to more deterministic SST predictions. However, the large spreads in SST anomaly for some of the VSP cases gives more weight to the possibility that the predictability of this system over the Niño3 region may be low in certain years. With improved models and better observing systems, the predictability limits exposed here should be extended, but may not be eliminated.

[17] Further work needs to be done to resolve some of these issues. However, until that time, these results suggest that caution is advised when making statements about the fundamental predictability of the coupled tropical ocean-atmosphere system.

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