# Investigating the Influence of Systematic Biases on the Annual Cycle and ENSO Variability in the Coupled GCMs using Flux Correction Method

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## MODELS

### COLA-Poseidon Coupled GCM:

- COLA Atmospheric GCM (Version 2) (Schneider 2002) – T42, L18
- Poseidon Oceanic GCM (Schopf & Loughe 1995, Yu & Schopf 1997) – quasi-isopycnal, reduced-gravity, 14 layers, domain 70°S–65°N, resolution 1° lat x 1.25° lon, 0.5° lat x 1.25° lon within 10°S–10°N

### NCEP Climate Forecast System (CFS) (Saha et al. 2006):

- NCEP Global Forecast System AGCM – T62, L64
- Modular Ocean Model V.3 (MOM3) OGCM – 40 layers, domain 74°S–64°N, resolution 1° lat x 1° lon, 1/3° lat x 1° lon within 10°S–10°N

## EXPERIMENTS

**CTRL** – no flux adjustment; integrated for 800 years; years 101–300 used for analysis.

**HFA_Trop** – heat flux adjustment in the Tropics (30°S–30°N); const = –15 W/m²/K; integrated for 200 years; years 26–200 used for analysis.

**CFS CTRL** – no flux adjustment; integrated for 51 years from Jan 1985 ICs.

**CFS HFA_Reg** – heat flux adjustment in the southeast Pacific and Atlantic; const = –10 W/m²/K; integrated for 88 years from 12/31/2036 restart files of the CTRL; years 19–88 used for analysis.

**CFS MFA** – momentum flux adjustment within 50°S–50°N; currently integrated for 65 years from 12/31/2036 restart files of the CTRL; years 19–65 used for analysis.

## METHOD

### Heat Flux Adjustment (HFA) and Momentum Flux Adjustment (MFA):

$$HFA(x,y) = const * (SST_{CTL} - SST_{OBS}) \qquad MFA(x,y) = -1.0 * (TAU_{CTL} - TAU_{OBS})$$

- ✓ Correction terms are constant in time; their magnitude is proportional to the annual mean local error in the directly coupled GCM integration (CTRL).
- ✓ HFA term is kept at a minimum and targets errors with relatively clear physical error sources.
- ✓ $SST_{OBS}$ is CPC SST data for 1950-2001.
- ✓ $TAU_{OBS}$ is National Oceanography Centre, Southampton NOC1.1 wind stress climatology.

## RESULTS: Mean Climate

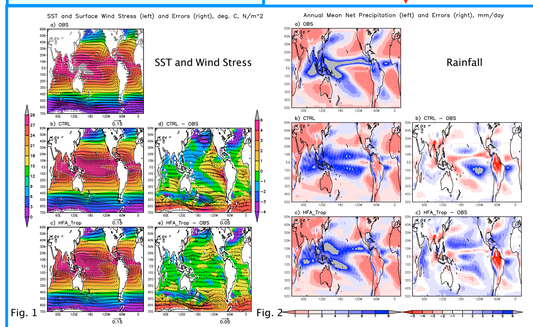


Fig. 1




Fig. 2

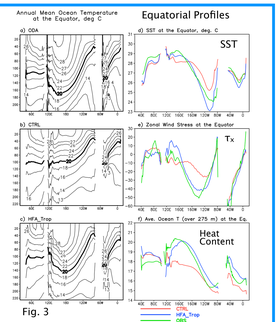


Fig. 3

- HFA eliminates major SST errors in the whole tropical belt of the global ocean (Fig. 1e).
- In response to this SST correction, the erroneous convergent surface winds are reduced. However, the HFA_Trop still shows weak trade winds in all oceans (Fig. 1e).
- In the HFA_Trop double ITCZ is not present in the Pacific (Figs. 2b and 2c). Amount of precipitation within the tropical ocean is increased and SPCZ is better simulated. However, in the Indian Ocean the center of precipitation is pushed further westward. (Fig. 2e).
- These changes lead to stronger **cross-equatorial asymmetry of the mean climate** in the eastern Pacific.
- HFA_Trop shows improved simulation of the equatorial thermocline depth (Fig. 3c) which is consistent with the enhanced zonal wind stress along the equator (Fig. 3e).
- Simulated equatorial easterlies are still too weak. In the western equatorial Pacific zonal wind is westerly, as opposed to weak easterly.

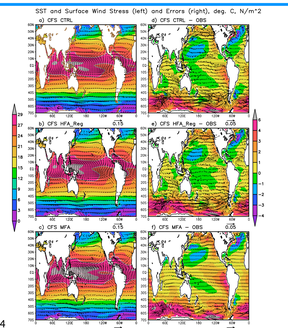


Fig. 4

- CFS HFA_Reg reduces mean SST bias in the southeast Pacific and Atlantic. Resultant southeasterlies are a bit too strong, and northeasterlies are too weak (Fig. 4e).
- CFS MFA effectively corrects mean wind stress bias. However, resultant SST bias is enhanced almost globally (Fig. 4f).

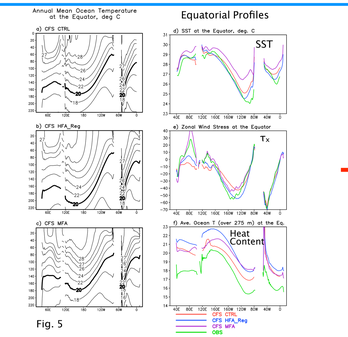


Fig. 5

- In the HFA_Reg, as a result of stronger SST gradient, equatorial easterlies are enhanced and are closer to the observed, which is likely responsible for deepened equatorial thermocline (Figs 5b,e,f).
- Equatorial easterlies in the CFS MFA are weaker than observed in the central Pacific, and the equatorial thermocline bias is reduced compared to the CFS HFA_Reg.

## RESULTS: ENSO Variability

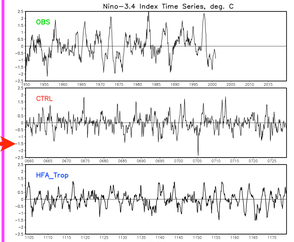


Fig. 15 Niño-3.4 index time series.

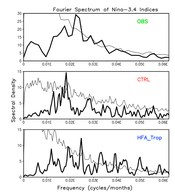


Fig. 16 Power spectrum of Niño-3.4 indices.

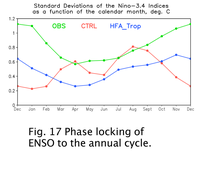


Fig. 17 Phase locking of ENSO to the annual cycle.

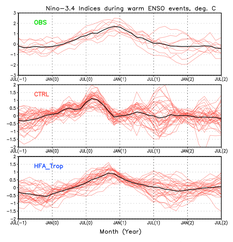


Fig. 18 Niño-3.4 SST anomalies during warm ENSO events.

- In the Niño-3.4 region SST variability is underestimated in both experiments, but more so in the HFA_Trop (Fig. 15).
- The dominant period of ENSO cycle is more realistic in the HFA_Trop compared to the CTRL, though variability at higher frequencies is too strong (Fig. 16)
- HFA has markedly improved simulation of phase locking of ENSO to the annual cycle (Fig. 17). It appears that in the CTRL ENSO *is* properly phase locked to the model's dynamical annual cycle, it's just that the relation of the annual cycle to the calendar year is incorrect.
- The onset and termination of warm ENSO events is also well reproduced in the HFA_Trop (Fig. 18).

## RESULTS: Annual Cycle

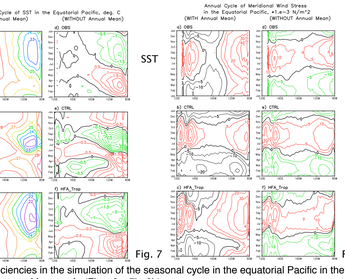


Fig. 6




Fig. 7




Fig. 8

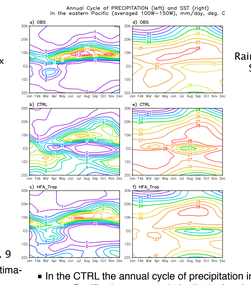


Fig. 9

- The main deficiencies in the simulation of the seasonal cycle in the equatorial Pacific in the CTRL are related to the overestimation of its **semi-annual harmonic** (Figs. 6e, 7b, 8b).
- As a result of HFA, the seasonal cycles of SST and surface wind stress get corrected and become primarily **annual**, though seasonal variations extend too far to the west (Figs. 6f, 7c, 8c).
- Seasonal deviations of meridional wind stress from the annual mean are realistic both in the CTRL and the HFA_Trop (Figs. 7d, e, f). However, due to the asymmetry of the model mean state in the HFA_Trop the mean is not zero at the equator in the eastern Pacific. As a result, the magnitude of seasonal variations of $\tau_y$ exhibits an annual cycle vs. semi-annual in the CTRL (Figs. 7b, c). This has important implications on the annual cycle of heat budget (see below).
- In the CTRL the annual cycle of precipitation in the eastern Pacific shows strong latitudinal migration of the ITCZ and the presence of a double ITCZ (Fig. 9b).
- In the HFA_Trop this annual cycle becomes more realistic partly as a result of the improved annual cycle of the SST (Figs. 9c and f).

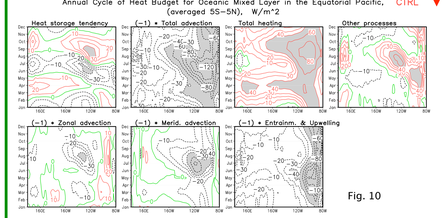


Fig. 10

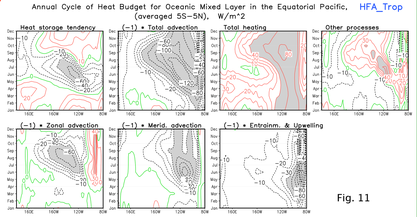


Fig. 11

- **Annual cycle of heat budget of the oceanic mixed layer in the equatorial Pacific** in the CTRL shows semi-annual variations both in the horizontal advection terms and total heating.
- Early termination of the cold tongue in the CTRL (Fig. 6b) is primarily due to premature weakening of the zonal and meridional heat advection terms (Fig. 10) likely related to the errors in the seasonal cycle of the zonal and meridional surface wind stress (Figs. 7 and 8).
- As a result of HFA, annual cycle of heat storage becomes more realistic mainly due to better simulation of horizontal heat advection: semi-annual component in the annual cycle of horizontal advection is absent, and associated cooling extends for the longer part of the year more in line with other model simulations (e.g. Huang & Schneider 1995).
- Enhancement of the annual component in the seasonal cycle of SST is therefore related to more realistic simulation of the seasonal cycle of surface wind stress as a result of improved cross-equatorial asymmetry of the model mean state (see also Li & Hogan 1999).

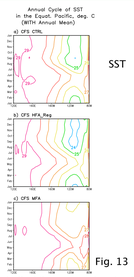


Fig. 12

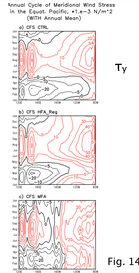


Fig. 13

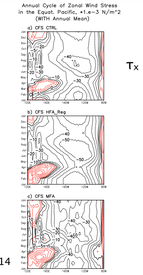


Fig. 14

- Both HFA and MFA do not affect the seasonal cycle of SST in a major way. Cold season SSTs are more realistic in the CFS HFA_Reg (Fig. 12b). However, both in the CFS CTRL and the CFS HFA_Reg cold season starts about two months later. Despite of larger mean positive SST bias in the CFS MFA, the timing of SST seasonal variations is not changed, except the cold season shifts closer to the end of the year (Fig. 12c).
- Seasonal variations of surface wind stress are most realistic in the CFS MFA even though only annual mean is corrected in this run. The CFS HFA_Reg shows better simulation of meridional wind stress (northward wind) in the eastern Pacific in spring compared to the CFS CTRL. However, in the central Pacific the northward wind stress is too strong in summer compared to other simulations and observations (Fig. 13). All experiments show too strong westerlies in spring in the western Pacific (Fig. 14).

## CFS

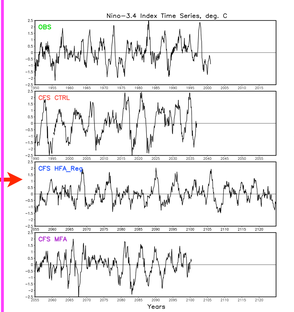


Fig. 19 Niño-3.4 index time series.

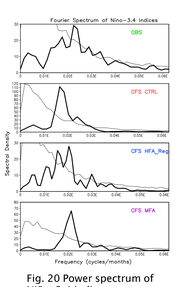


Fig. 20 Power spectrum of Niño-3.4 indices.

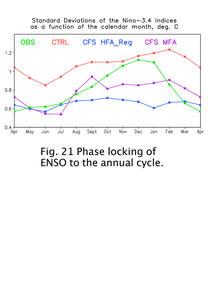


Fig. 21 Phase locking of ENSO to the annual cycle.

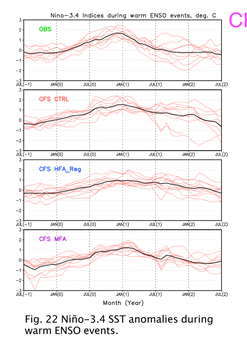


Fig. 22 Niño-3.4 SST anomalies during warm ENSO events.

- The CFS MFA shows modest improvement of some aspects of ENSO variability: the dominant period of ENSO cycle is more realistic (Fig. 20); the onset and termination of warm ENSO events is closer to the observed compared to other experiments (Fig. 22).

## CONCLUSIONS:

✓ Elimination of large warm SST bias in the southeast Pacific can lead to marked improvement in the simulation of the annual cycle at the equator and some aspects of ENSO variability like phase locking of ENSO to the annual cycle.

✓ Analysis of the mean annual cycle of heat storage in the oceanic mixed layer shows that enhancement of the annual harmonic in the seasonal cycle of SST is related to more realistic simulation of the seasonal cycle of surface wind stress as a result of improved cross-equatorial asymmetry of the model mean state.

✓ The efficiency of heat flux adjustment method in reducing systematic biases in the coupled GCMs and improving simulated variability appears to be model-dependent. Using the same strategy, we were not able to fully eliminate the warm SST bias in the southeast Pacific and Atlantic in the NCEP CFS without degrading the simulation of the cold tongue. These differences could also be related to different vertical discretizations in the component oceanic GCMs: Poseidon belongs to the category of isopycnal "layer" models, whereas MOM3 is a "level" model.

✓ Annual mean momentum flux adjustment applied to NCEP CFS shows moderate improvement in the simulation of some aspects of ENSO variability like the onset and termination of warm ENSO events which further suggests that ENSO simulation is sensitive to the model mean state.

## References:

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