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FINAL TECHNICAL REPORT

"THE IMPACT OF RECENT MODEL IMPROVEMENTS ON GISS GCM PREDICTIONS OF CLIMATE CHANGE"

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I. Accomplishments Under Previous Support, DE-FG02-92ER61477

1. Base-line experiments with 8x10° resolution Model II

The response of the 8x10° horizontal resolution version of Model II to the forcing of globally observed SST (1980-1986) was evaluated. The simulations showed a realistic interannual variability of interhemispheric gradients of layer mean temperatures in response to observed SST gradients, but modelled near-surface winds over the Atlantic Ocean were much weaker than observed, a symptom of the Model II planetary boundary layer (PBL). In addition, the interannual variability of peak-season rainfall rates over Northeast Brazil (Nordeste) from the experiment was considerably smaller than the observed, although the observed negative association between seasonal Nordeste rainfall and interhemispheric Atlantic SST differences was weakly present. (Hastenrath and Druyan, 1993- #1 below) Preliminary experiments at 4x5° resolution incorporating two of the new model parameterizations show more variability of the simulated Nordeste rainfall in response to the SST forcing, but only slight improvement in the correlation with observations (Fig. 1).

2. Model climatologies using climatological SST

Five-year simulations at 4x5 deg horizontal resolution were made for the basic GCM as well as for alternative versions, each including a change in one of the model's component parameterizations. These runs used climatological sea-surface temperatures (SST). January and July mean fields for each version were compared to each other and to climatology. The most noticeable impacts were improvements in tropical surface winds attributable to the new formulation of the planetary boundary layer (PBL). (Marengo and Druyan, 1994- #3 below)

3. Model validations of the June-August 1987, 1988 seasons

Simulations of the contrasting 1987 and 1988 June-August (JJA) seasons were found to be a suitable vehicle for making model intercomparisons, consistent with the recommendations of the Monsoon Experimentation Group of TOGA (WMO). By concentrating on this part of the 10-year AMIP period, validations of models' sensitivity to evolving SST are made at considerable savings in computer time relative to the required computer time for the full 10-year runs.

Interannual Var. of Nordeste Precipitation

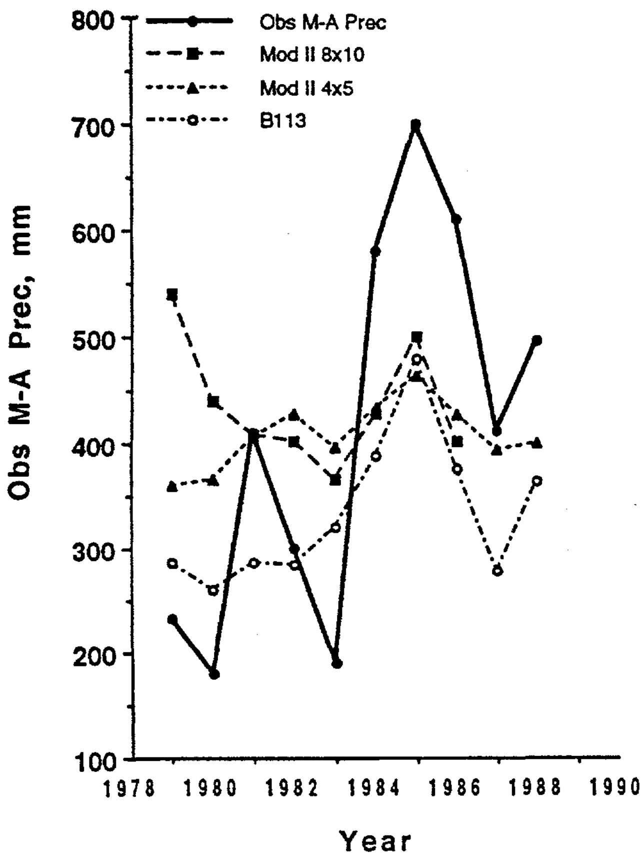


Fig. 1. March-April precipitation for Northeast Brazil, 1979-1988 (1979-1986 for Model II 8x10°). Model results at 4x5° resolution are shown for Model II and for a version incorporating the new moist convection and new PBL (B113). B113 has increased the interannual variability, but it underestimates Nordeste rainfall for most years. Correlation coefficients, observed vs.: Mod II 8x10, 0.12; Mod II 4x5, 0.80; B113, 0.84

The performance of the basic GCM for simulations forced by JJA 1987 and 1988 SST was thoroughly documented, highlighting several deficiencies in this model's tropical circulation (Druyan and Hastenrath, 1994- #4 below). The evaluation was aided by the development of computer graphics which depict seasonal means of the 200 mb velocity potential and streamfunction as diagnostic tools. Recently, parallel simulations based on five additional model versions (Table 1) were run. The analysis of the results of these experiments has shown dramatic improvements, especially in the representation of 1988 versus 1987 differences in the Pacific Walker circulation and the Asian/African monsoon (see below).

Table 1. Model versions validated by JJA 1987-88 comparisons
Parameterizations: PBL- Planetary Boundary Layer; MC- Moist Convection; GH: Ground Hydrology; MM- vertical Mixing of horizontal Momentum; LWB- Liquid Water Budget. See Appendix of renewal proposal for descriptions of these parameterizations.

	New PBL	New MC	New GH	MM	LWB
Mod II (B100)	-	-	-	x	-
B103	-	x	-	-	-
B114	x	x	x	-	-
B122	x	x	-	x	x

A. Comparisons of 200 mb velocity potential

1. Observations

ECMWF analyzed 200 mb velocity potential (Fig. 2a) describes a dipole pattern of negative values over the Western Pacific, Indian Ocean and Southern Asia, representing the outflow associated with the Asian/African summer monsoon, and positive values over the Eastern South Pacific, South America and the South Atlantic Ocean corresponding to convergence over the subtropical anticyclones of the winter hemisphere. The 1988 minus 1987 differences in the observed 200 mb velocity potential (Fig. 2b) are negative over the Indian Ocean and Southern Asia, emphasizing the stronger upper-tropospheric divergence in 1988, while the positive differences over the Eastern Pacific reflect the considerable upper-tropospheric convergence above the anomalously cold SST of 1988.

Wind V city Potential at 200mb (10**6 m**.) JJA 1988 ECMWF 4x5

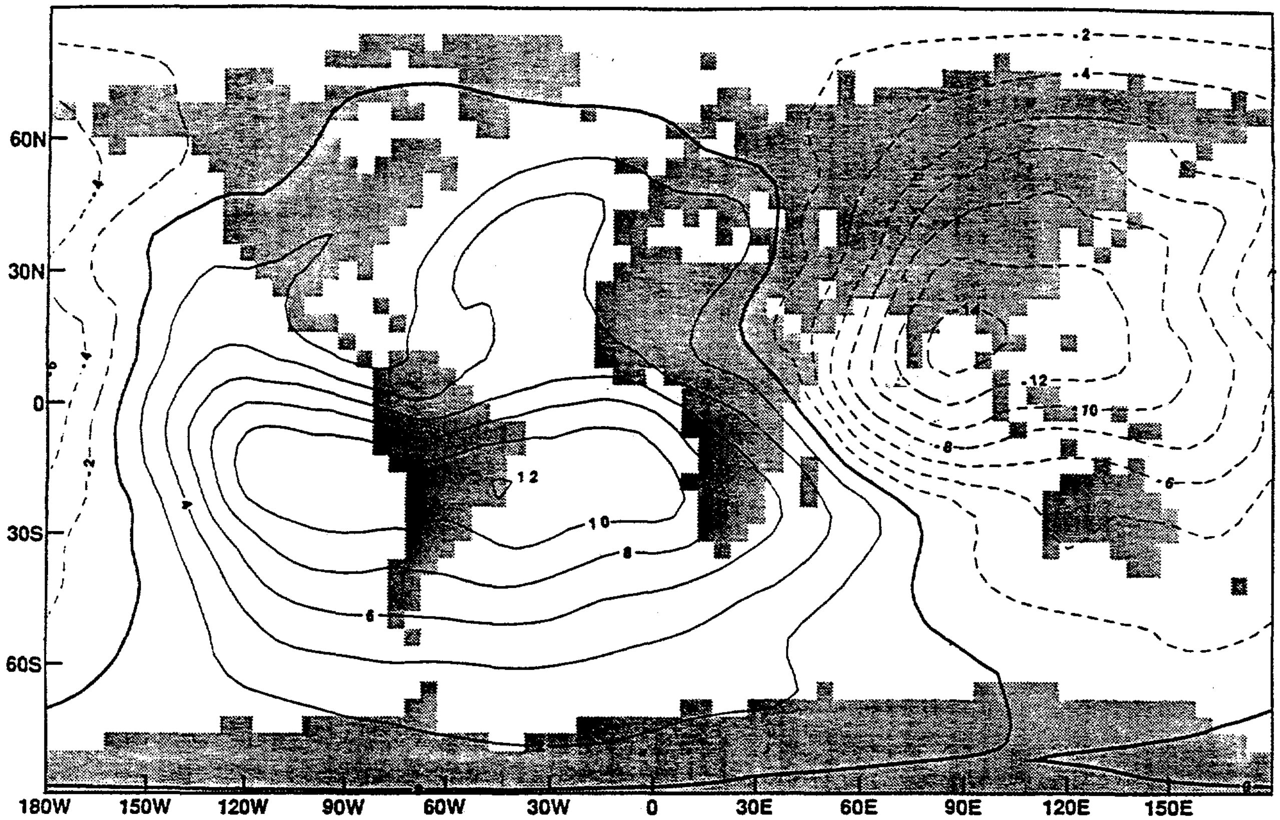
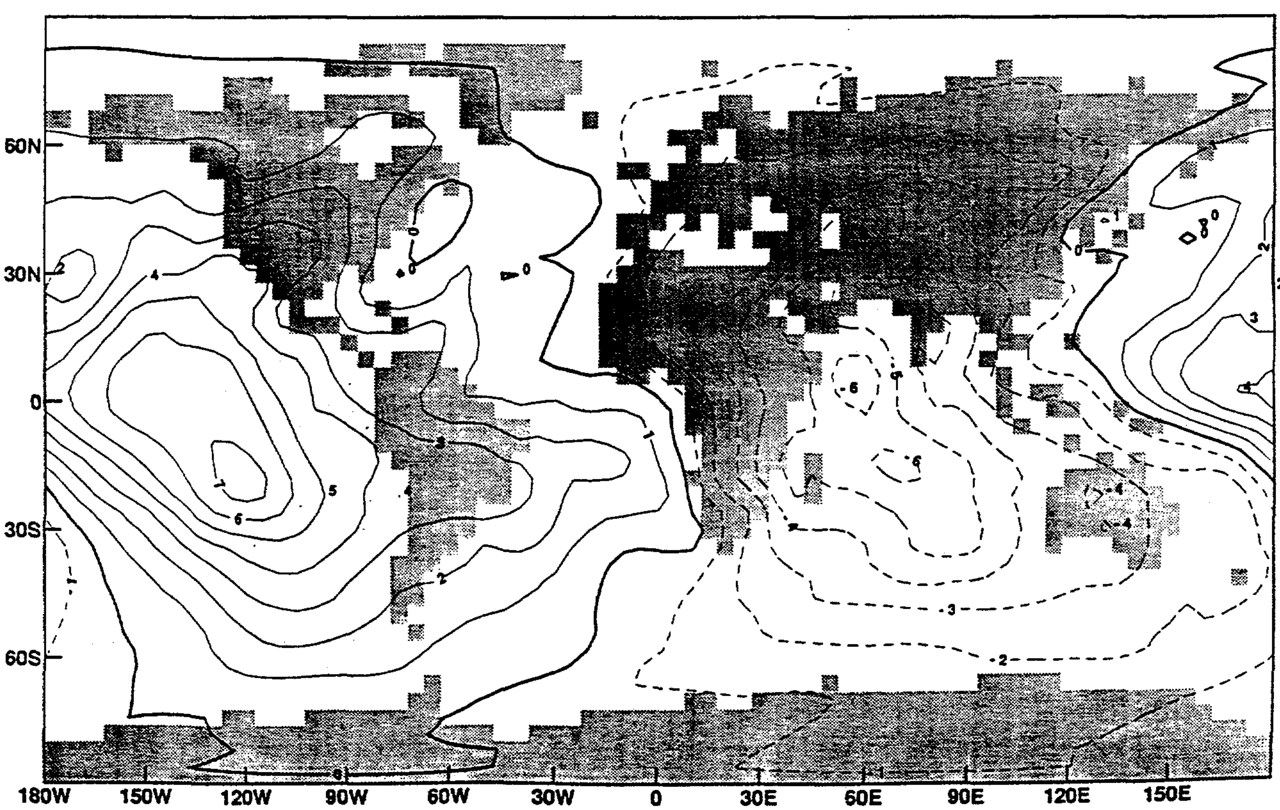


Fig. 2. a) Top: Velocity potential based on ECMWF gridded 200 mb winds for June-August 1988 showing the dipole nature of the irrotational planetary circulation.b) Bottom: June-August 1988 minus 1987 differences in the 200 mb velocity potential based on ECMWF gridded 200 mb winds, indicating a relatively stronger circulation in 1988.

Wind Velocity Potential at 200mb (10**6 m**2/s) Difference JJA 1988-1987 ECMWF



2. Models

NMC initial atmospheric conditions at 00 GMT on 1, 2 and 3 June 1987 and 1988 were interpolated to the three-dimensional GISS grid in order to initialize six 3- month simulations using Model II and other GCM versions (Table 1), creating two ensembles of three runs forced by the corresponding AMIP monthly mean SST (interpolated to daily values) for each of the two seasons.

Fig. 3a shows the 1988 200 mb velocity potential and Fig. 3b shows the 1988 minus 1987 differences in that field for the Model II simulation (*B100*) which is the control for the other model runs. The dipole pattern of the observed field (Fig. 2a) is captured by this depiction, but observed and modelled differ in a number of important details.

- The eastward displacement of the 1988 velocity potential minima and the implied excesses of upper-tropospheric divergence over the Pacific Ocean were discussed by Druyan and Hastenrath (1994). This departure from the observed climate is apparently related to the unrealistic convergence and spurious rainfall *B100* generates along 6-10 °S .

The 1988 minus 1987 differences in the modelled 200 mb velocity potential (Fig. 3b) depict the same general pattern as the corresponding ECMWF-based analysis (Fig. 2b). However:

- the minimum in the modelled difference field over the Northern Indian Ocean is only about one-third of the analyzed value.

Moreover:

- the center of negative differences over the South Pacific near 30 ^{o}S, 160 ^{o}W reflects modelled 1988 excesses in upper-tropospheric divergence which should be confined to the Western South Pacific.

3. Impacts of Model Versions (Figs. 4 and 5)

- All newer versions eliminated the spurious outflow in the South Pacific . Preliminary testing showed this to be a dividend of the new PBL with a corrolary contribution from the new moist convection scheme.

- The intensity of the divergence over South Asia was significantly increased by *B122*.

Velocity Potential of Layer 7 B100M9 JJA 88

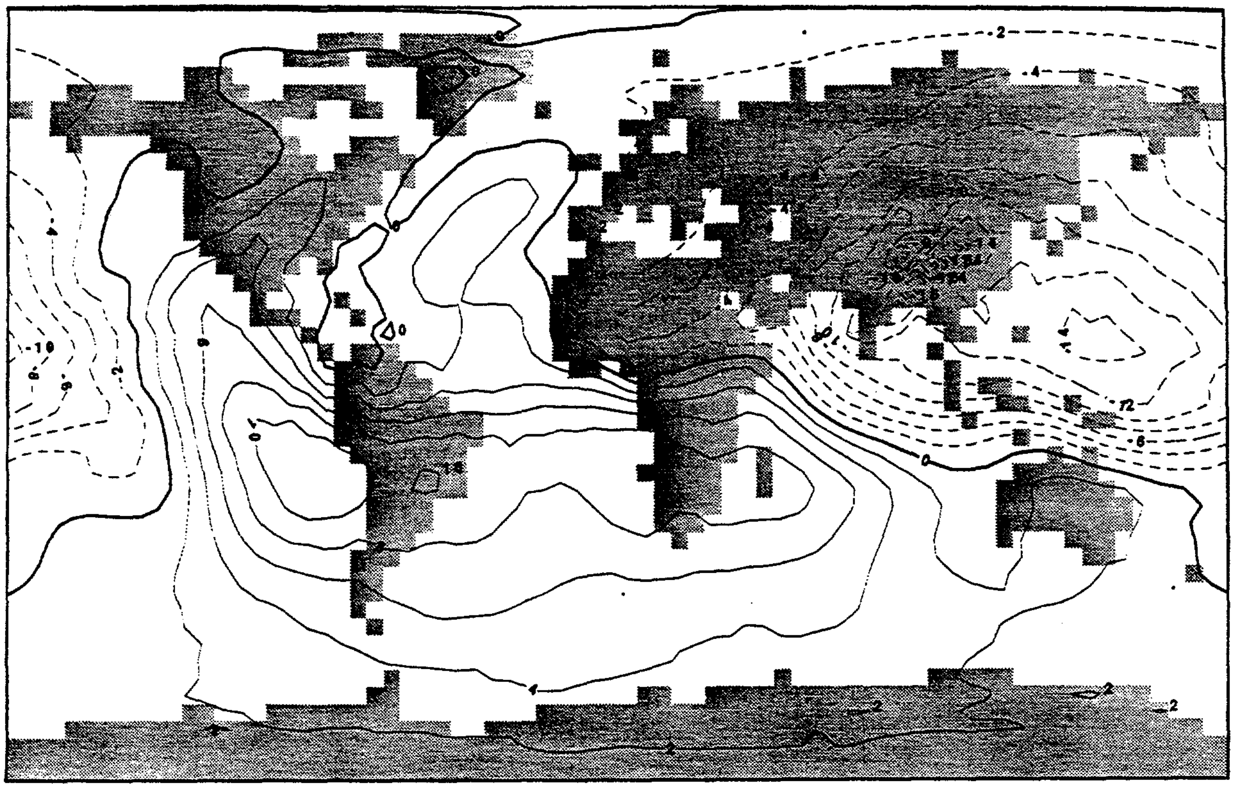
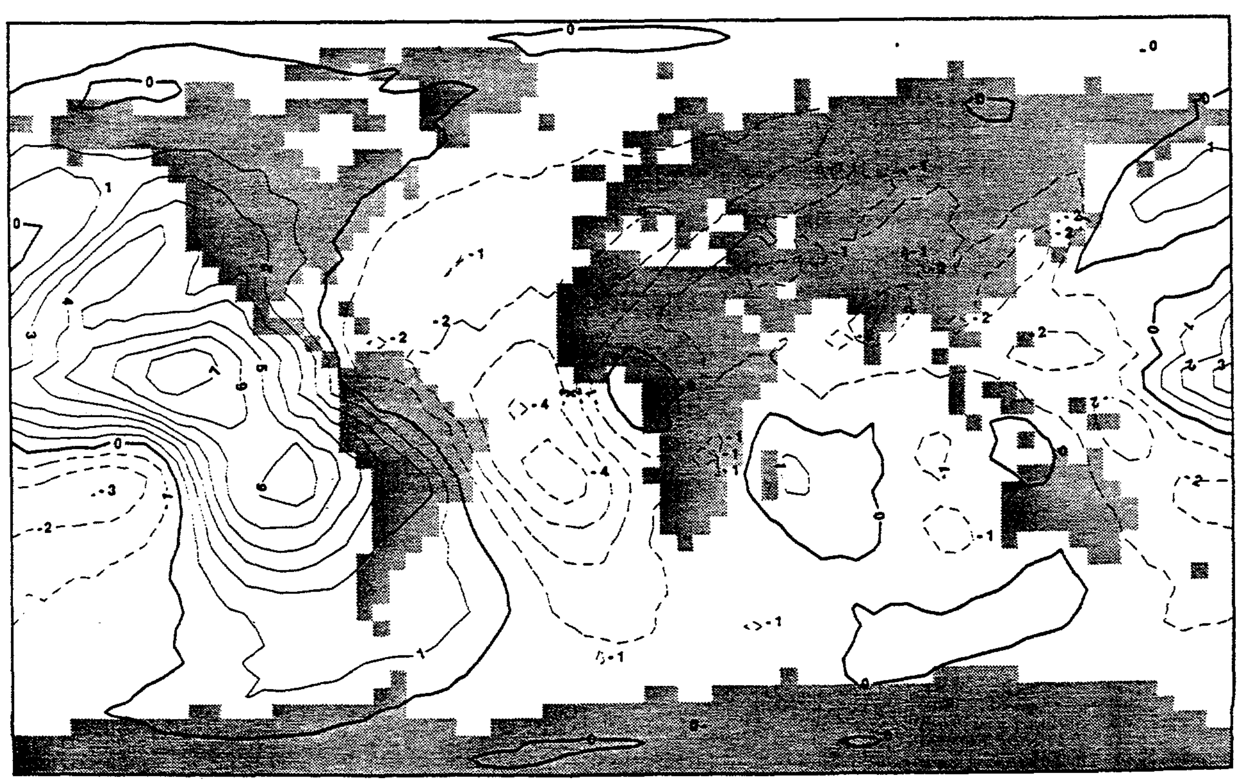


Fig. 3. Results for Model II (B100) a) Top: June-August 1988 200 mb velocity potential. b) Bottom: June-August 1988 minus 1987 differences in 200 mb velocity potential.

Veclocity Potential of Layer 7 B100M9 JJA 88-87



Velocity Potential of Layer 7   B114   JJA 88

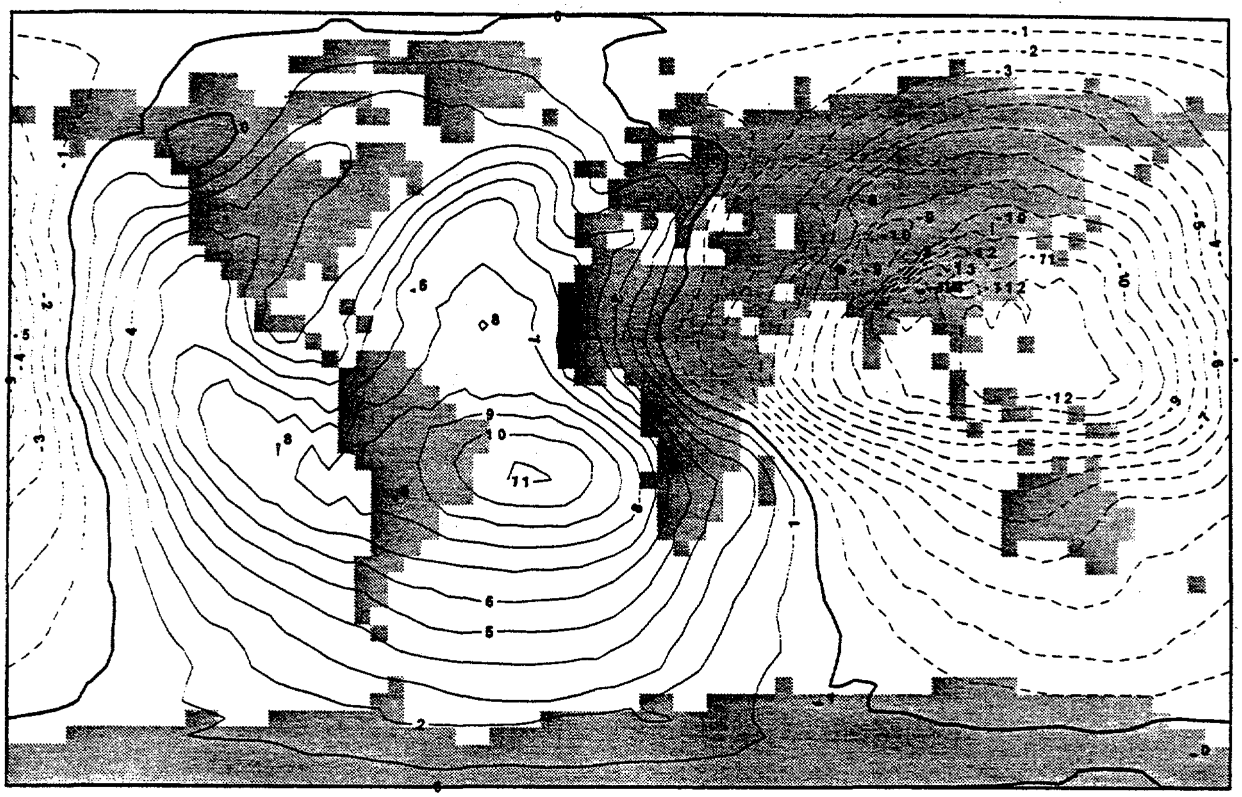
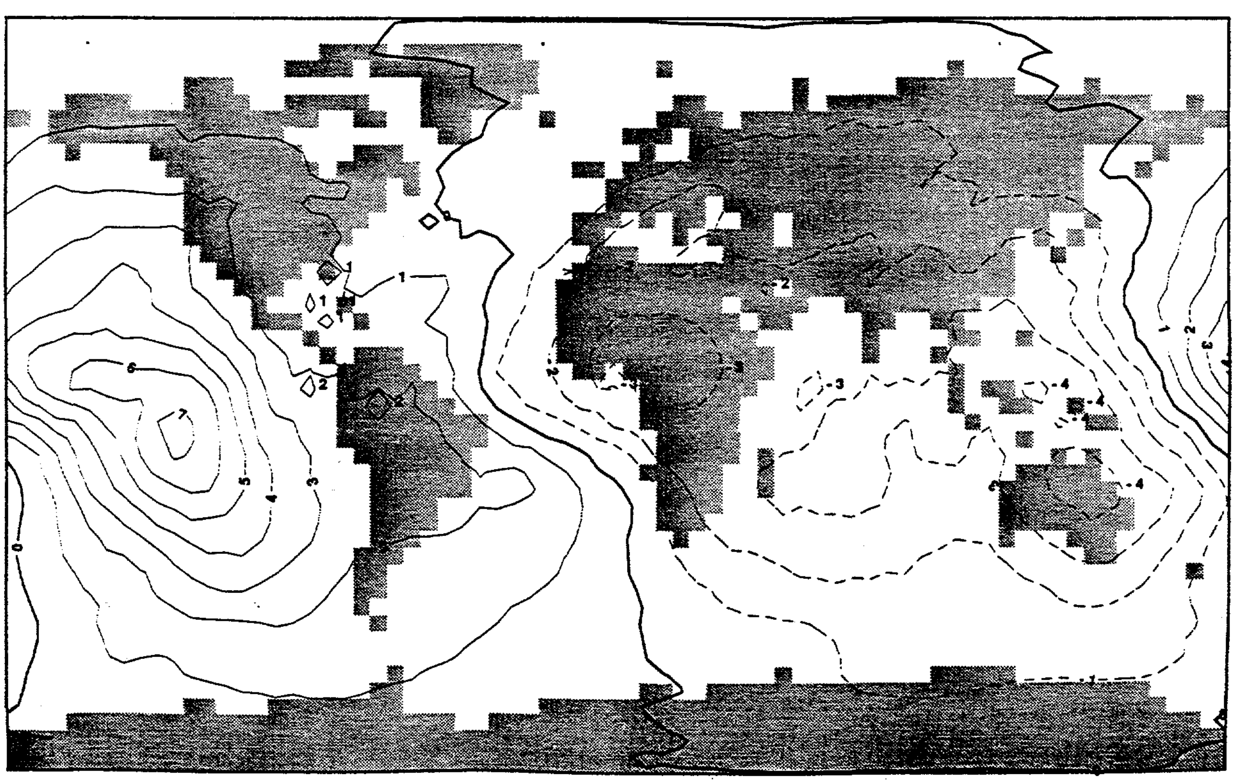


Fig. 4. Results for model version with new PBL, moist convection and ground hydrology (B114) a) Top: June-August 1988 200 mb velocity potential. b) Bottom: June-August 1988 minus 1987 differences in 200 mb velocity potential.

Velocity Potential of Layer 7   B114   JJA 88-87



Velocity Potential of Layer 7 B122A JJA 88

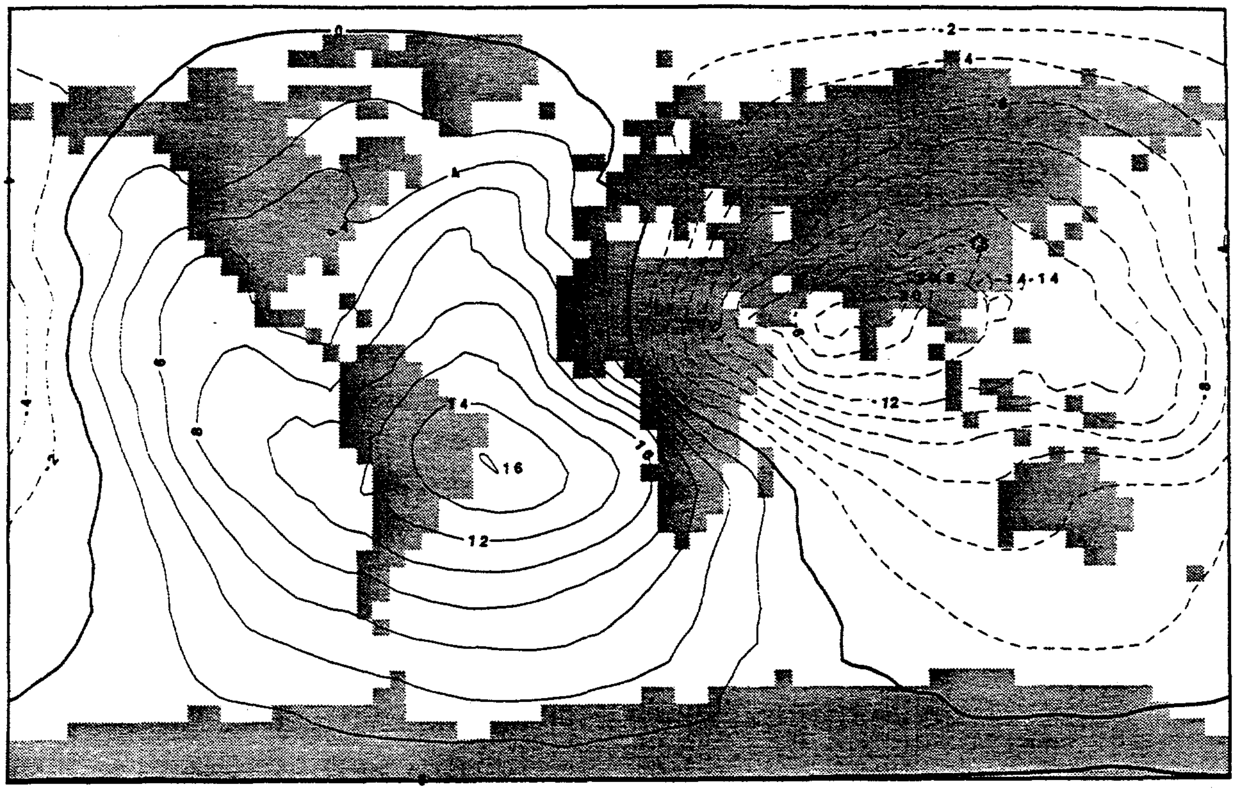
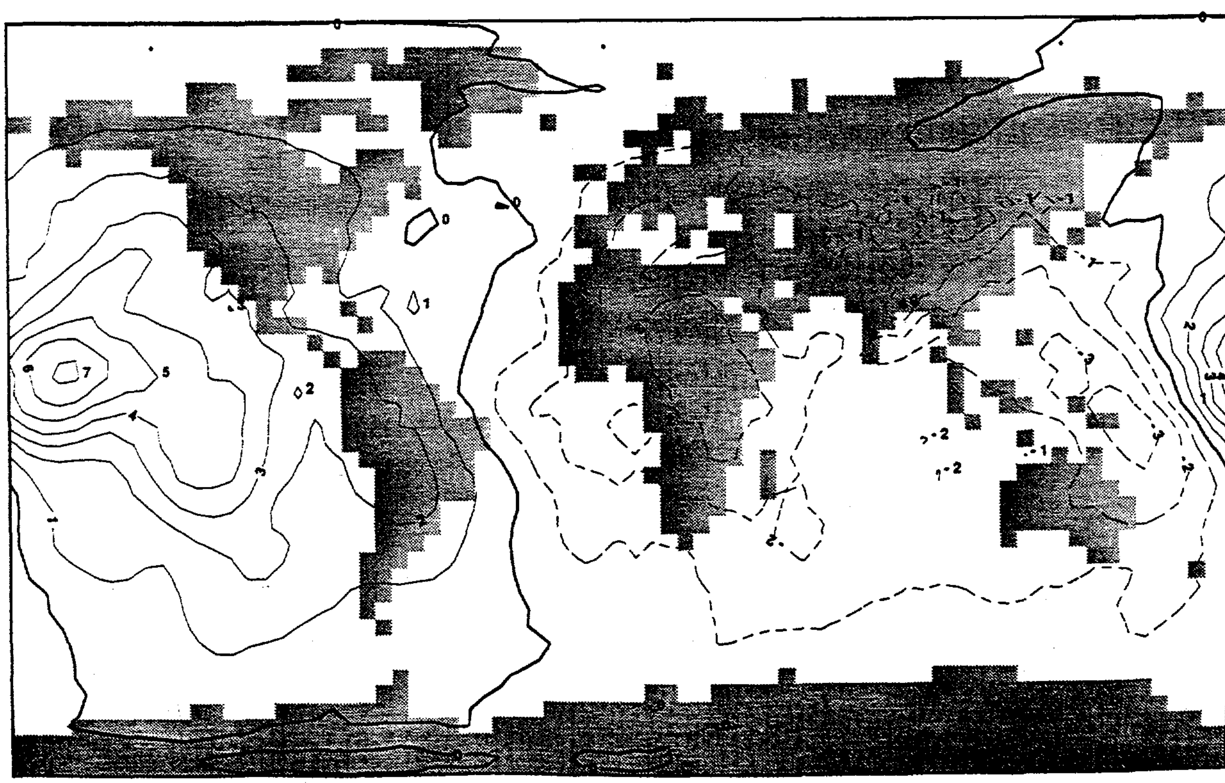


Fig. 5. Results for model version with new PBL, moist convection and liquid water budget (B122) a) Top: June-August 1988 200 mb velocity potential. b) Bottom: June-August 1988 minus 1987 differences in 200 mb velocity potential.

Velocity Potential of Layer 7 B122A JJA 88-87



- The strength of the irrotational circulation is proportional to the gradient of the velocity potential and between India and West Africa. This gradient, indicative of the strength of the TEJ, was increased by both new versions compared to *B100*.

- Stronger 1988 divergence over Africa/Indian Ocean was evident in the runs shown in Figs. 4 and 5.

B. Precipitation differences, JJA 1988 minus 1987 (Fig. 6)

- Positive differences in the *B100* rainfall rate along 6 °N over the Pacific are probably too close to the equator according to HRC and OLR 1988-87 difference distributions.

The various model versions show a number of contrasts in their depictions of the June-August 1988-87 precipitation rate differences (Figs 6b-d).

- *B114* and *B122* shift the positive difference area northward to about 15 °N, which is probably more realistic. *B103* is similar to the control in this case, implying that *the northward shift of the positive difference area can be attributed to the new PBL.*

- Of the model versions, only *B122* gave zonally coherent areas of 1988-87 rainfall differences greater than 2σ over the Sahel. *B103* and *B114* showed small positive differences over parts of the Sahel and this area was expanded by *B122*, *indicating a positive impact for the inclusion of the liquid water budget.*

- The *B100* run indicates positive differences east of the observed location near India. This displacement is probably related to the eastward bias of *B100*'s heavy monsoon rainfall.

- On the other hand, the *B114* and *B122* versions show some improvement in that their small positive rainfall differences penetrate to Central India. This presumably reflects the benefits of the new PBL and new moist convection scheme. *B103* which depends on the old PBL is not as successful in this regard.

- The *B100* simulated June-August 1988 deficits of precipitation of less than 1 mm day^{-1} relative to 1987 over only small areas of the US Great Plains and the lower Rockies. Positive differences over the Southeastern US are not realistic.

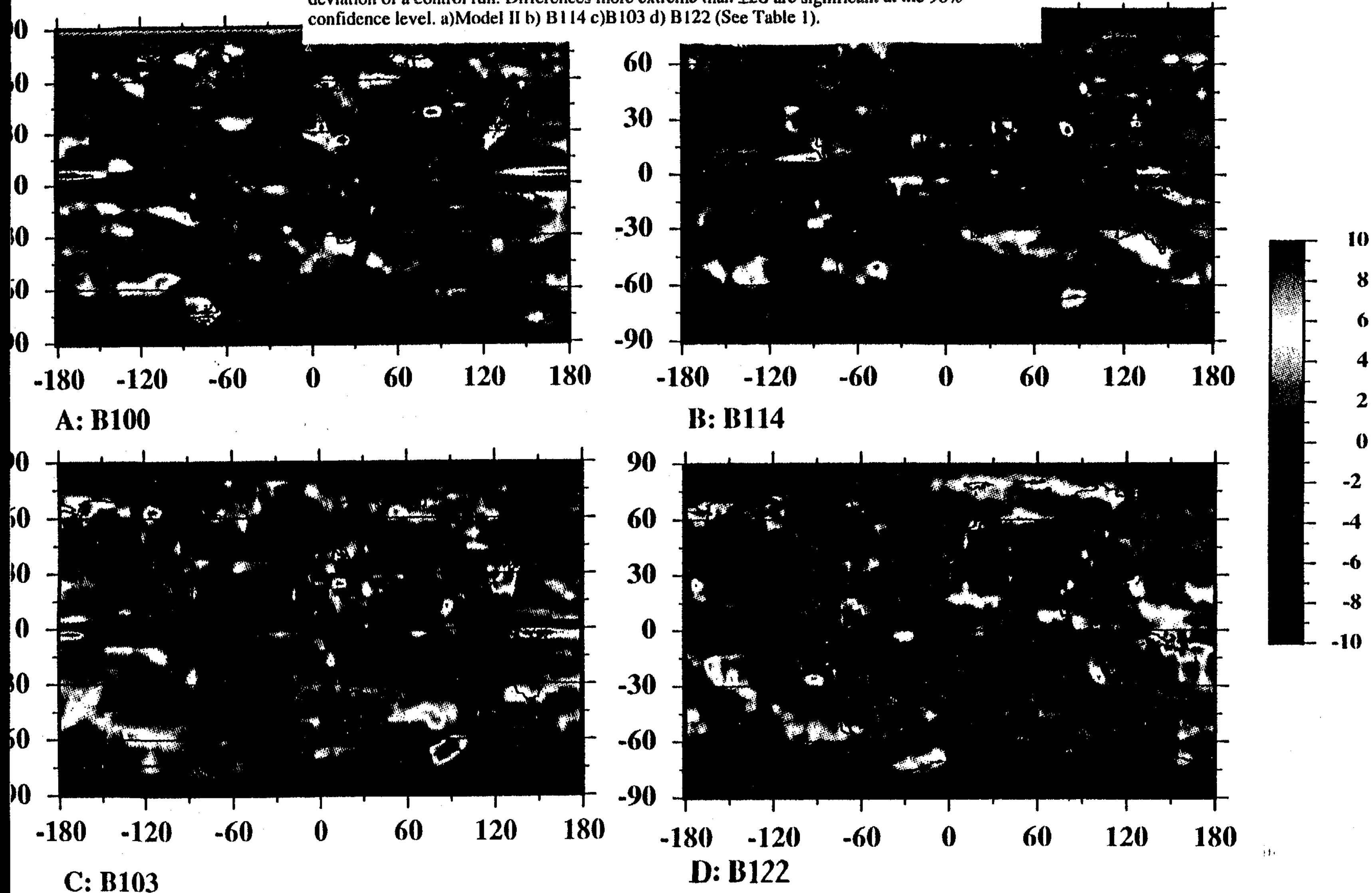


Fig. 6. June-Agust 1988 minus 1987 precipitation differences normalized by the 10-year standard deviation of a control run. Differences more extreme than ±2σ are significant at the 96% confidence level. a)Model II b) B114 c)B103 d) B122 (See Table 1).

- Only B122, of all the newer model versions, gave significant negative precipitation differences over the US Midwest and Great Plains areas affected by the 1988 drought, although other runs showed some reductions over parts of these regions.

- The relatively poor performance of B114 in this regard implies that the new ground hydrology formulation did not provide the required JJA 1988 relative deficit of soil moisture over the Central US which Atlas et al. (1993) showed is necessary to simulate that drought.

- The scheme in *B122 which keeps a running inventory of liquid water in the atmosphere apparently contributes to a more accurate representation of the hydrological cycle* than the more conventional moisture budget methods.

4. Ten-year simulations forced by AMIP SST

To date, five 10-year simulations have been made based on the AMIP SST 1979-1988. The differences in the model versions are summarized in Table 2.

Table 2. Versions of the GISS GCM validated by comparing 10-year AMIP simulations. Parameterizations: PBL- Planetary Boundary Layer; MC- Moist Convection; GH: Ground Hydrology; MM- vertical Mixing of horizontal Momentum; LWB- Liquid Water Budget. Note that B120 is like B114, discussed above (Table 1). See Appendix of renewal proposal for explanations of the parameterizations.

	New PBL	New MC	New GH	MM	LWB
Mod II	-	-	-	x	-
B113	x	x	-	-	-
B113'	x	x	-	x	-
B120	x	x	x	-	-
B122	x	x	-	x	x

A. Southern Oscillation Index (SOI)

- Large negative departures during 1982-83 and 1987 occurred during the warm phases of ENSO episodes in those respective years, while large positive ΔSOI in 1988 correspond to a cold ENSO phase (La Niña).

- Verification of simulated SOI is one measure of the sensitivity of a GCM to climate forcings which produce interannual variability.

Referring to Fig. 7:

- *The range of the modeled SOI anomalies is considerably less than observed.* For example, the best model response to the warm SST forcing of the El Niño events of 1982-3 and 1987 are ΔSOI values of -1.9 mb and -1.7 mb respectively, while the corresponding observed ΔSOI are -4.8 mb and -2.1 mb, respectively.

- *Model II ΔSOI are relatively unresponsive to the SST forcing compared to the newer versions.* Note the very shallow Model II responses, especially during 1982-83, 1987 and 1988, and its low correlation with the observed ΔSOI (below).

- *B122 improves the response in 1981 and 1988*, but otherwise does not have much positive impact on the interannual variability of *ΔSOI.*

- Correlation coefficients between the records:

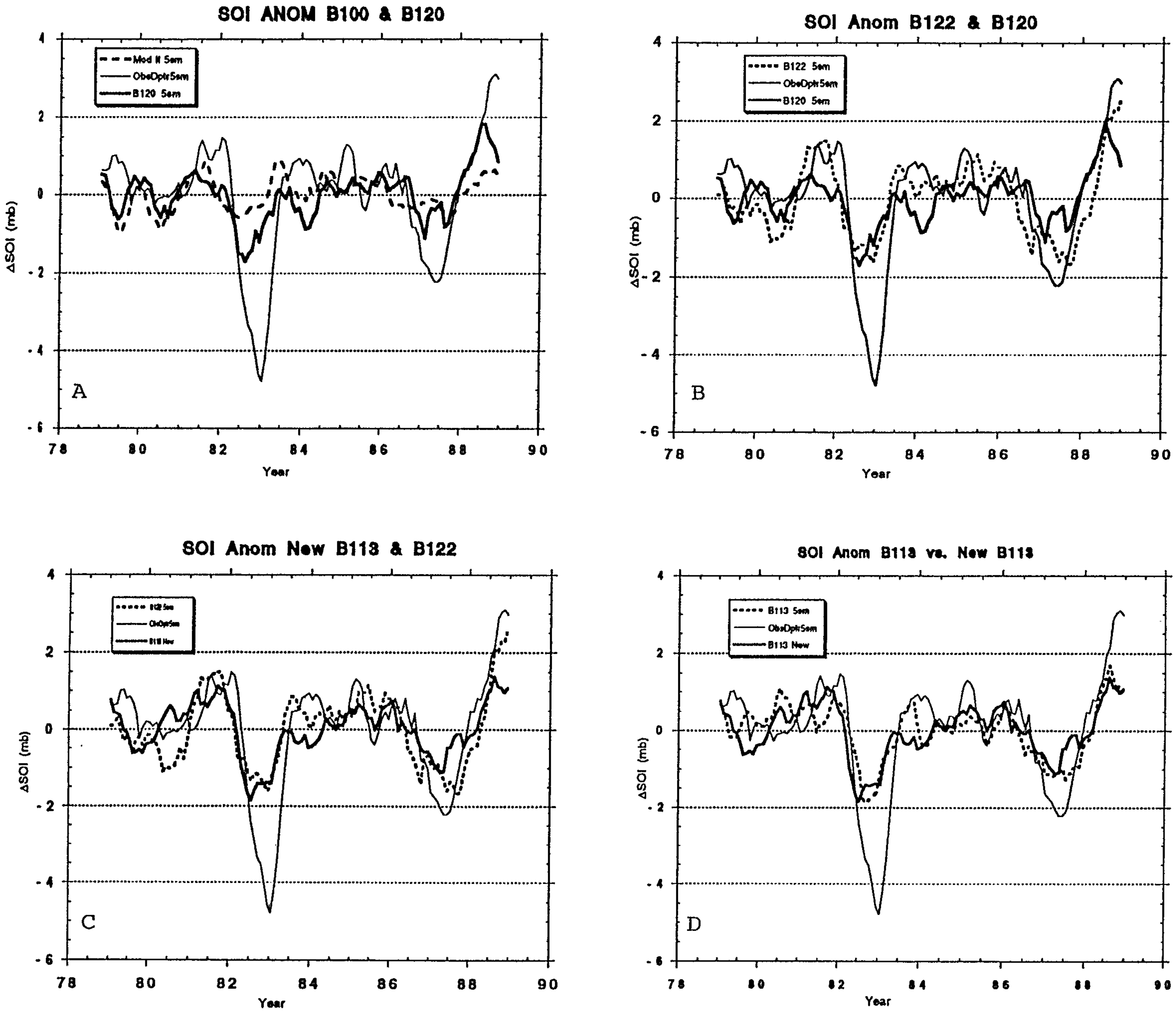
Observed vs.	Model II	0.35
Observed vs.	*B113*	0.81
Observed vs.	*B113'*	0.77
Observed vs.	*B120*	0.70
Observed vs.	*B122*	0.74

B. OLR Anomalies

1. <u>Observations</u>

The time-longitude cross-section of observed OLR anomalies over the Tropical Pacific (5N-5S) between July 1981 and January 1988 given by Kousky and Leetmaa (1989) is reproduced in Fig. 8.

Fig. 7. Five month running means of SOI anomalies, 1979-1988: a)B100 vs B120 b) B120 vs B122 c) B113' vs B122 d) B113 vs B113'. All versions improve on Model II.



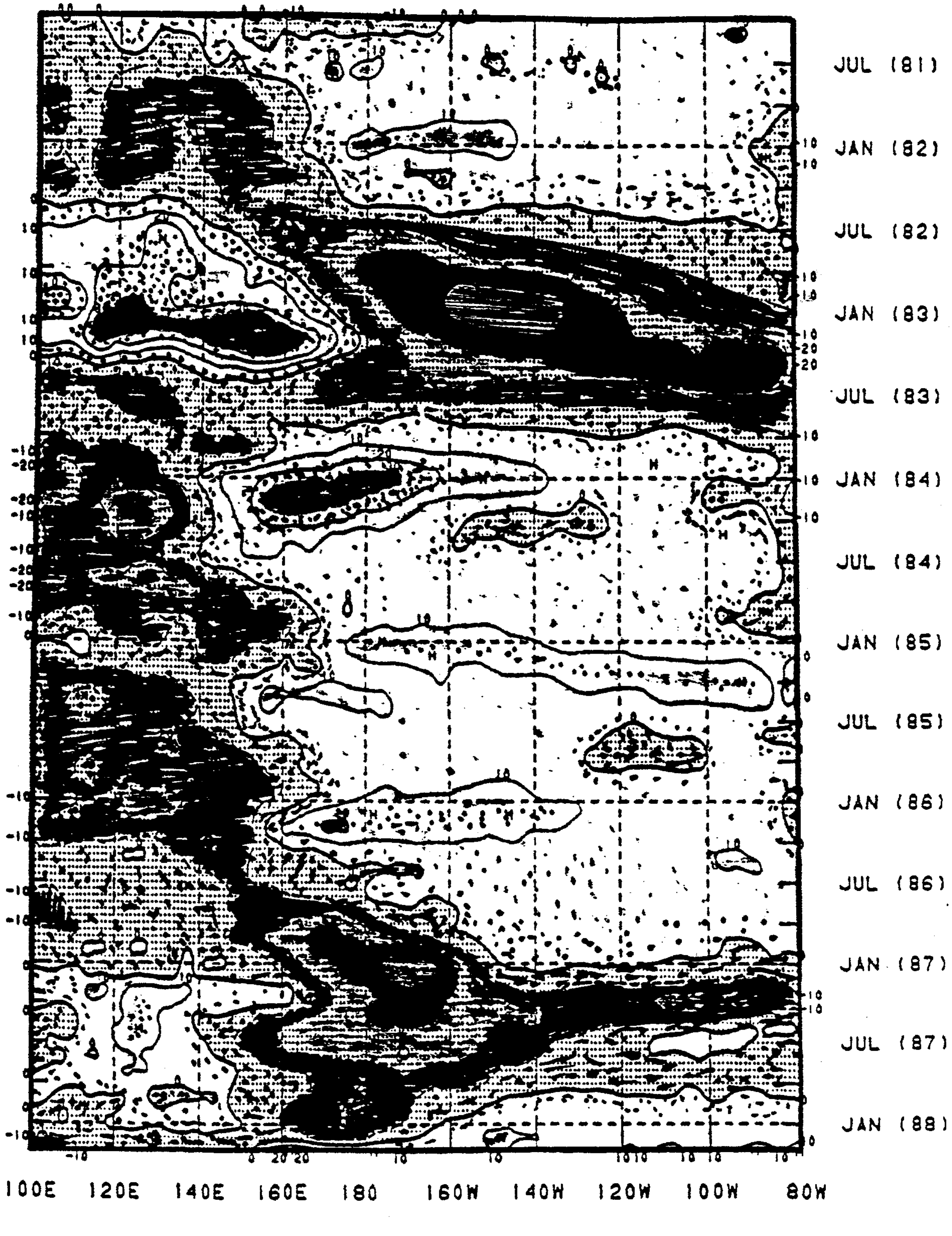


Fig. 8. Time-longitude cross-section of observed OLR anomalies, 1981-1988 over the equatorial Pacific (W M^{-2}, after Kousky and Leetmaa, 1989, *J. Climate*). See color bars in Fig. 9 for key.

2. Model II

Fig. 9a shows that Model II responded to the warm El Niño SST with approximately -30 W M^{-2} OLR anomaly minima over the Eastern Tropical Pacific, over a more extensive area during 1982-83 than during 1987. These areas of high cloud tops were realistically timed and spatially consistent with the observed pattern, but the negative departures were only about half of the observed extremum. On the other hand:

- The observed transitions over the Western Tropical Pacific from the convectively active regimes early in 1982 and in 1986 to the relatively inactive periods during the second half of 1982 to early1983 and during 1987 are *not* captured by the Model II simulation.

3. Other Model Versions

The 10-year, time-longitude cross-section of modeled OLR anomalies for the other model versions all show more temporal variability west of 180° than Model II, although B113' (Fig. 9b) is also rather poor in this respect.

- This is consistent with the more realistic pattern of moist convection and upper air divergence over the Tropical Western Pacific obtained by employing the new PBL and moist convection schemes in place of their Model II predecessors.

- The OLR anomaly pattern for B122 is the noisiest, but it also exhibits a wider, more realistic range of values.

- The liquid water and cloud ice budgets included in B122 provide more variability to the computed optical depths which in turn induce the higher variability and range to the OLR calculations.

In particular, simulated cumulonimbus anvils and cirrus clouds are likely to be optically thicker in this formulation than in Model II (no anvils), or B113' and B120 (no memory of cloud water/ice), allowing more frequent occurrence of very low OLR. The enhancement of the OLR signal in B122 also parallels an enhancement of positive westerly wind anomalies at 850 mb (discussed below). This correspondance between the circulation and cloud anomalies implies that *B122 experiences stronger and better organized convection prompted by stronger lower tropospheric convergence*. This may reflect lower vertical thermal stabilities brought about by colder cloud tops.

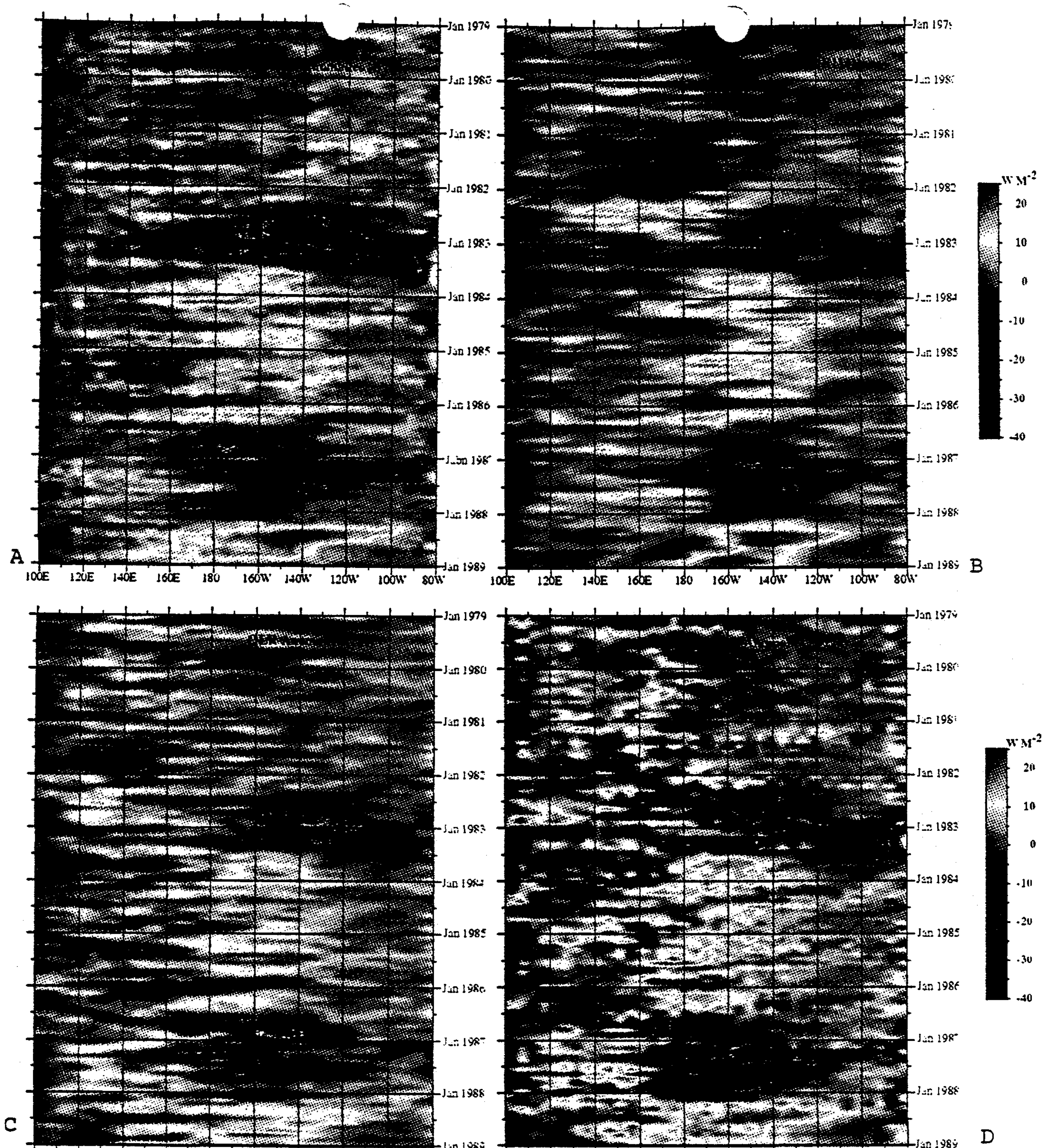


Fig. 9. Time-longitude cross-section of modeled OLR anomalies for simulations using AMIP SST for versions a) B100, b) B113', c)B120 and d) B122, 1979-1988.

C. 850 mb Wind Anomalies

1. Model II (Fig. 10b)

- Contrary to observations (Fig. 10a), Model II's alternating bands of easterly and westerly anomalies show very little west to east propagation , but rather appear almost simultaneously over broad zonal swaths.

- The maximum westerly anomalies for Model II are some 4-5 ms^{-1} too weak. Moreover, the observed, rather strong easterly anomalies in the Western Tropical Pacific which occur early in 1983 are absent in this simulation.

2. Other Model Versions (Figs. 10c,d,e)

- The *B122* version achieves the strongest westerly anomalies during 1982-83, underestimating the observations by only 1-2 ms^{-1}. All other versions show westerly anomalies stronger than Model II.

- Both *B122* and *B113* indicate realistic easterly anomalies propagating from 120E at about January 1983 to 150E by the middle of that year.

The more extreme westerly anomalies of *B122* can be attributed to the inclusion of the liquid water budget scheme which is the unique feature of this run. There is a close correspondence between these westerly wind anomalies and the OLR anomalies (discussed above) in all of the simulations. Vigorous moist convection associated with near-surface convergence apparently initiates westerly circulations that are less pronounced or absent altogether in the otherwise unperturbed easterly trade wind regime. The inclusion of the liquid water budget increased the spatial coverage of high cloudiness and decreased the OLR minima, indicating lower cloud top temperatures. Lower column thermal stability caused by the colder cloud tops is consistent with more vigorous convection and therefore stronger westerly wind anomalies.

5. Synthesis

The current project has interfaced recent achievements of the GISS modeling group with AMIP related objectives. As of this writing some five GISS GCM versions have been applied to the complete 10-year AMIP simulation. In addition to conclusions drawn from results of these 10-year simulations, evaluations of several model climatologies was made

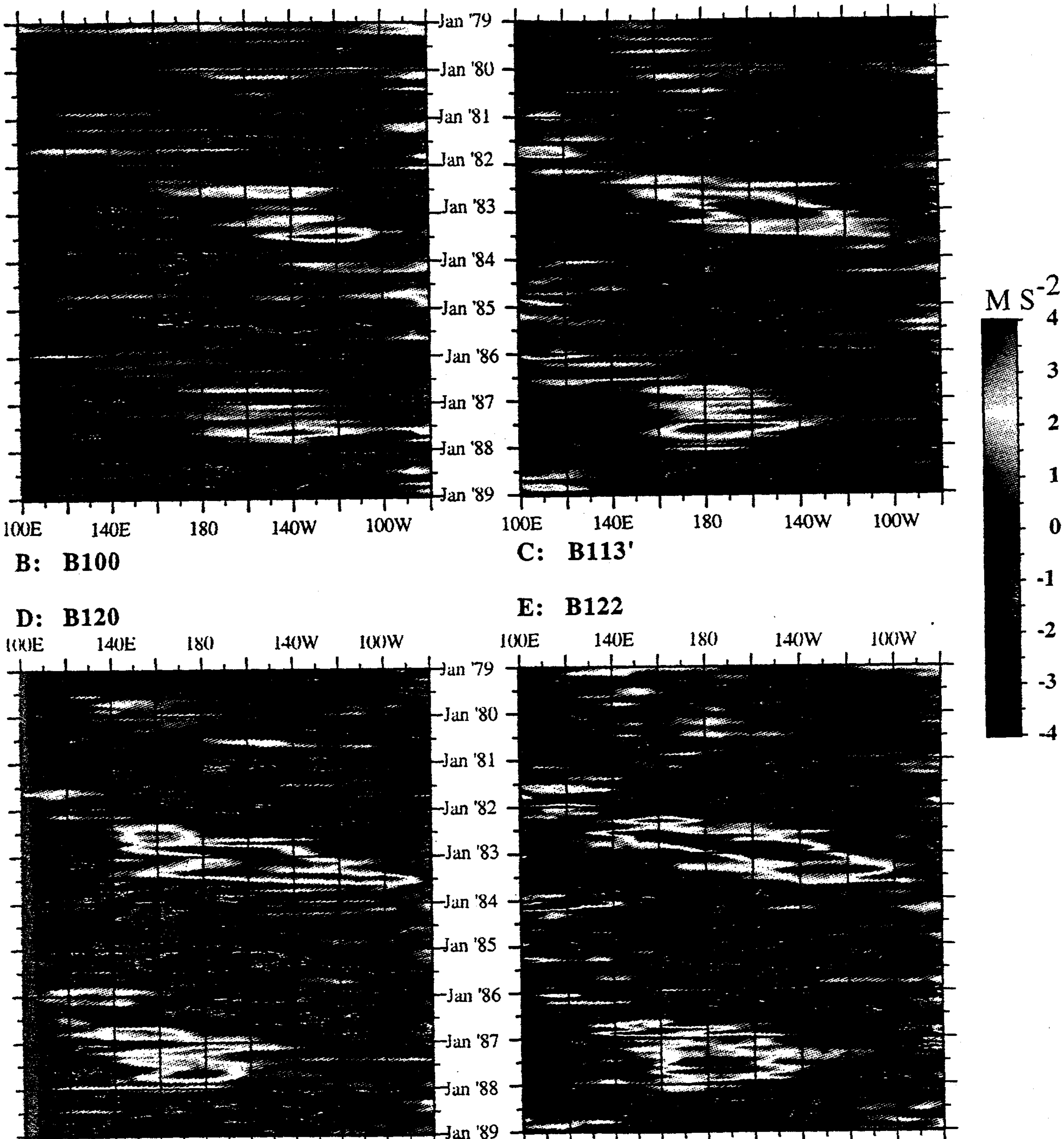


Fig. 10 (cont'd) Time-longitude cross-sections of modelled 850 mb zonal wind anomalies (m s^{-1}) for four GCM versions. Compare to observations in Fig. 10a. Note that B122 propagates strong anomalies from west to east (as observed) while B100 favors more zonally symmetric patterns.

from multi-year runs based on climatological SST. Moreover, the project is analyzing a series of simulations of the very contrasting June-August seasons of 1987 and 1988 which represent a convenient subset of the longer integrations.

Feedback from the analyses of the aforementioned simulation experiments has contributed to the evolution of the next generation of GISS GCM, although much additional testing and evaluation is also carried out by the GISS model development group. Decisions about which model versions justify the dedication of the considerable computer time required for 10-year runs are made in consultation with GISS modelers and may reflect their experience as well as the results presented here.

The project continues as of this writing, but preliminary conclusions can be formulated based on the results to date:

- The combination of the new PBL and new moist convection improves the modeling of the mean atmospheric state, especially the positions and intensities of the ITCZ and the planetary-scale circulation features. Results using the combined parameterizations are better than those obtained from using each individually.

- Inclusion of the liquid water budget, which keeps a running inventory of liquid water in the atmosphere, contributes to a more accurate representation of the hydrological cycle than the more conventional moisture budget methods. This is reflected by more realistic simulations of interannual variability of OLR, regional precipitation and circulation.

- No beneficial feedbacks on the simulated climate from the very sophisticated ground hydrology scheme incorporated into several of the experiments described here have yet been demonstrated. Either additional development is required, or such positive impacts are awaiting future improvements in the modelled meteorological variables which serve as input to the relevant computations of the ground hydrology scheme.

6. Publications citing DOE support

1. Hastenrath and Druyan, 1993: Circulation anomaly mechanisms in the tropical Atlantic sector during the Northeast Brazil rainy season: results from the GISS GCM, *JGR-Atmospheres*, **98**, 14917-14,923.

2. Druyan and Hall, 1994: Studies of African wave disturbances with the GISS GCM, *J. Climate*, **7**, 261-276.

3. Marengo and Druyan, 1994: Validation of model improvements for the GISS GCM, *Climate Dynamics*, in press.

4. Druyan and Hastenrath, 1994: Tropical impacts of SST forcing: a case study for 1987 versus 1988, *J. Climate.*, in press.

5. Druyan, Lo, Shah, Marengo and Russell, Impacts of model improvements on GCM sensitivity to SST forcing, in preparation.

7. Conference Presentation

"The impact of recent model improvements on GISS GCM tropical rainfall anomalies"
Proposed for the *European Conference on Global Energy and Water Cycle*
The Royal Society, London, 18-22 July 1994.