THE IMPACT OF EL NINO ANOMALY ON MEAN MERIDIONAL CIRCULATION AND TRANSFER PROPERTIES OF THE ATMOSPHERE

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Abstract

High resolution experiments with the operational ECMWF model starting from observed data were used to test the impact of the 1982/83 El Nino sea surface temperature anomaly on the zonal mean meridional circulation and transfer properties of the atmosphere.

The increased sea surface temperature in the Eastern Pacific Ocean along the Equator amplifies the Hadley circulation. This enhances the convergence of moisture and sensible heat towards the tropics, inducing positive feedback between tropical diabatic heating and direct mean meridional circulation. The amplification of the Hadley circulation also results in an equatorward extension of the mid-latitude westerlies.

Equatorial SST anomaly makes the zonal mean eddy transfer properties in the winter hemisphere undergo substantial changes, and the maxima of transfer of heat and momentum are all shifted to high latitudes. An extra indirect meridional circulation is thereby forced in high latitudes in the northern hemispheric winter.

It seems that in a time scale of about one month and in a sense of zonal mean, the impact of the El Nino is to cause a warmer and wetter climate in the tropics and in high latitudes in the northern hemisphere, but a drier one in the subtropics.

I. Introduction

During recent years a number of papers have been published covering various aspects of the impact of sea surface temperatures on the atmospheric circulation. For a comprehensive review, see Shukla and Wallace[1].

All these studies, however, do not make any attempt to diagnose the changes in the mean meridional transfers invoked by the altered SST, but rather limit themselves to side by side comparisons and/or statistical evaluations. This is somewhat surprising since Bjerknes[2,3] in his observational study of the impact of the El Nino SST anomalies on the atmospheric circulation speculated that a warmer SST in the tropical ocean strengthens the Hadley circulation though local-

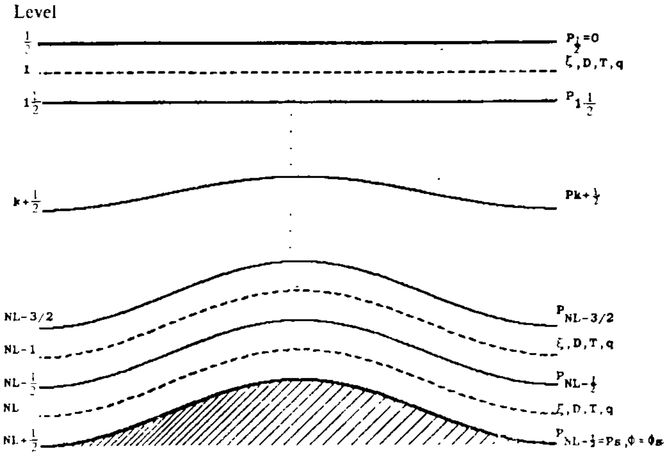
* The experiments were completed when the author was working at the ECMWF as a visiting scientist.

ly but over a large range of longitudinal areas. Also, he concluded from momentum balance considerations that the westerlies in the mid-latitudes have to increase. While Cubasch[4] verified most of Bjerknes' hypothesis using a synoptic evaluation of model simulations, this investigation concentrates upon the influence of an SST anomaly on the mean meridional circulation and on the meridional transfer of heat and moisture. Even though the El Nino SST anomaly covers only a quarter of the globe, it appears to be large enough for its effects to be diagnosed in the zonal mean. The results described in this report provide information about the mean meridional circulation, which may be of use to scientists dealing with two-dimensional models.

After a short description of the model and the data involved (Section II), the zonal mean

$A_{k+1/2}$(hPa)	$B_{k+1/2}$
0	0
50	0
99	0.002
142	0.013
173	0.042
191	0.094
194	0.170
182	0.268
157	0.384
125	0.511
89	0.638
54	0.756
26	0.856
8	0.929
0	0.973
0	0.992
0	1

Vertical Coordinate Table (NL = 16)



Disposition of variables in the vertical

Disposition of variables in the vertical

Fig. 1. The ECMWF forecasting model.

Dependent variables	ξ, D, T, q, ln(ps)
Vertical coordinate	Hybrid, $P_{k+1/2} = A_{k+1/2} + B_{k+1/2}ps$, details as above.
Vertical representation	Finite-difference, energy and angular-momentum conserving.
Horizontal representation	Spectral, with triangular truncation at wavenumber 63.
Horizontal grid	96×192 points on a quasi-regular (≈1.875°) "Gaussian" grid.
Time integration	Leapfrog, semi-implicit ($\Delta t = 20$ min), time filter ($V = 0.06$).
Horizontal diffusion	Linear, fourth-order ($K = 2\times10^{15}\text{m}^4\cdot\text{s}^{-1}$).
Orography	Grid-scale average from high resolution data set, spectrally-fitted, "mean" orography.
Vertical boundary conditions	Kinematic
Physical parameterisation	(i) Boundary eddy fluxes dependent on local roughness length and stability (Monin Obukov).
	(ii) Free-atmosphere turbulent fluxes dependent on mixing length and Richardson number.
	(iii) Kuo convection scheme.
	(iv) Interaction between radiation and model-generated clouds. Albedo dependent on model snow cover.
	(v) Large-scale condensation when grid-square saturated. Evaporation of precipitation.
	(vi) Computed land temperature, no diurnal cycle.
	(vii) Computed soil moisture and snow cover.
	(viii) Fixed, analysed sea-surface temperature.

circulation (Section III, 1) and the meridional transfers (Section III, 2) will be discussed. This is followed by a consideration of the budgets of heat and moisture (Section III, 3).

II. The Experiment

1. *The Model*

The model used for all the experiments was the operational forecasting model (spring, 1984) of the ECMWF (Louis[5]). It has a horizontal resolution up to zonal wavenumber 63 and a vertical resolution of 16 levels. For further details, see Fig. 1.

The physical parameterisation is performed on a Gaussian grid, which has a resolution of 1.875°; it includes a full hydrological cycle. The radiation scheme includes the diurnal cycle and the angle of the sun according to the date. The surface boundary conditions (SST, soil-moisture, soil-wetness) are kept constant at their initial value. The orography used was the version referred to as the "mean" orography, which was used operationally until March, 1983.

2. *The Data*

The initial condition for the simulations was the operational ECMWF analysis for 1 January, 1983. The SST for the control experiment was the mean January climate (Alexander and Mobley[6]). In the anomaly case the climatological SST has been changed in the Pacific region by the addition of the El Nino anomaly as observed during January, 1983 (Fig. 2). This anomaly was made available by the CAC in Washington (Reynolds[7], pers. com.).

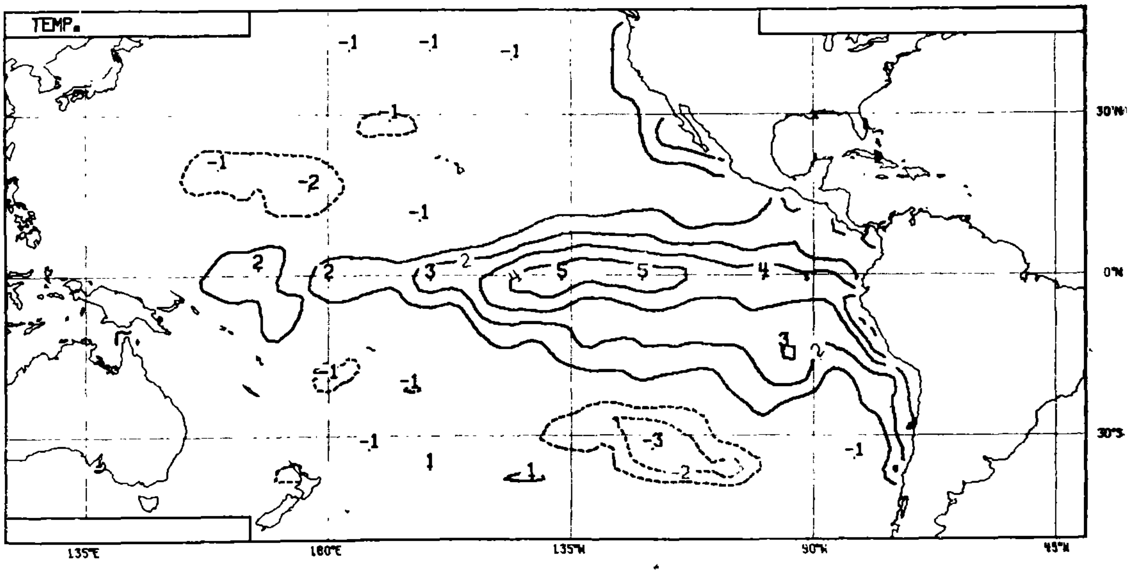


Fig. 2. The observed SST anomaly in the Pacific during January, 1983[7].
Unit: °C.

III. Results

Both experiments were integrated for 40 days. In this study the mean fields taken from day

11 to day 40 are considered. The short integration time, which is too short to allow the model to reach its equilibrium (Cubasch[8]), was chosen for economic reasons. However, comparison with longer integrations (Cubasch[4]) indicates that the predominant effects of the SST anomaly emerge during 40 day integrations. In addition, results revealed by this study may help us in understanding the atmospheric response to the tropical SST anomaly in a time scale of about one month. Statistical significance of the experiments may refer to Cubasch[4].

1. *Zonal Mean Quantities*

Fig. 3 shows the temperature differences between the control and anomaly cases. During the integration the troposphere in the tropics is warmed by the El Nino with a maximum of more than 2°C at 250 hPa, while the stratosphere has been cooled by a maximum of 1.4°C. In the mid-latitudes of the northern hemisphere the atmosphere is cooled by about 1°C. Most strikingly, the north polar region is warmed by about 6°C in the lower troposphere and 3°C in the stratosphere above 100 hPa. The tropospheric warming in the tropics and subtropics has a similar structure to that found in longer integrations (Cubasch[4]). It is interesting to note the warming in the stratosphere which could also be found in the observations (Greb and Nanjokal[9]), but could not be linked with the El Nino.

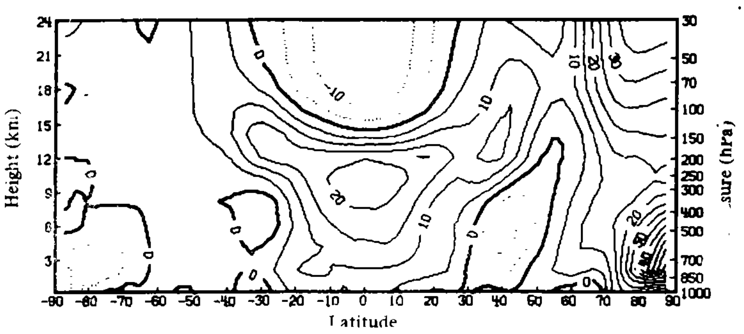


Fig. 3. The difference in the zonal mean temperature (El Nino-Control). Unit: 0.1°C.

The experiments also show that the moisture content in the tropical areas appears to be increased by the SST anomaly, but decreased in the subtropics. Table 1 shows the vertical distribution of specific humidity at the equator for the two experiments and the difference between them. Clearly, the El Nino SST anomaly causes an increase in the humidity. Although the increases have a maximum near the surface, the relative changes are more intense in the middle and upper troposphere, i.e. from 500 to 250 hPa, where the specific humidity has increased between 25% and 50%.

The intensities of the tropical easterlies in the stratosphere and the westerly jets in the two hemispheres do not change substantially (Fig. 4). However, the mid-latitude jets extend more equatorwards, resulting in narrower tropical easterlies. The increase of mid-latitude surface westerlies, as observed in the Pacific sector during the El Nino winters of 1957/58, 1963/64 and 1965/66 reported by Bjerknes[2,3], occurs only to the south of 39°N in the zonal mean in our anomaly experiments.

However, in order to assess this mechanism a detailed study of the momentum balance is

Table 1

Time and Zonal Mean Specific Humidity at Equator for the Two Cases

Level (mb)	El Nino (g/kg)	Control (g/kg)	El Nino-Control (g/kg)	(El Nino-Control) / Control (%)
1000	18.3	17.2	1.16	7
850	11.0	9.7	1.28	13
700	5.6	4.9	0.66	13
500	2.4	1.9	0.47	25
400	1.3	0.9	0.33	37
300	0.4	0.3	0.11	37
250	0.2	0.1	0.05	50
200	0.1	0.1	0.01	10

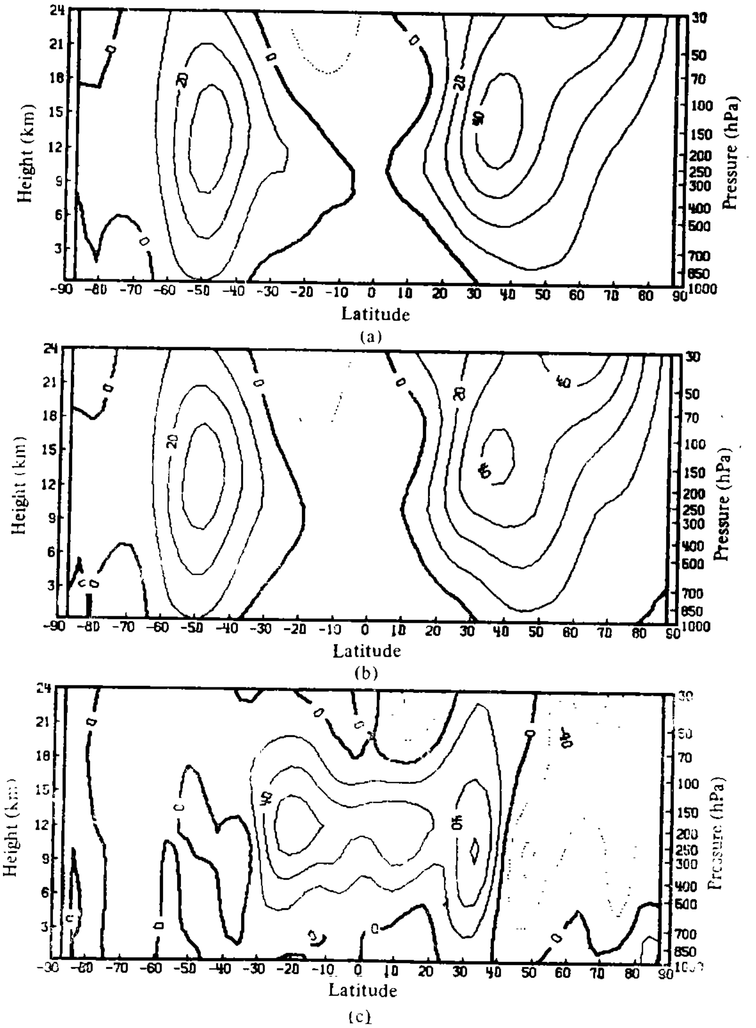


Fig. 4. The zonal mean of the zonal wind for (a) the El Nino case, (b) the Control and (c) the difference (El Nino-Control).

Units: top, m/s; middle, m/s; bottom, 0.1 m/s.

necessary, but this would exceed the scope of our investigation. It is also not clear to what extent the fact that the model has not reached its equilibrium influences this result.

It is interesting to consider the implications of this finding to model integrations in general. It has been established that in the ECMWF model (as well as in other models) the subtropical jet is shifted too far towards the poles (Hollingsworth et al.[12]; Cubasch[11]). This implies that one of the causes of this poleward shift of the jets might well be a Hadley circulation which is too weak and/or an underestimation of the forcing which drives the Hadley circulation.

The weakening of the westerlies in high latitudes in the northern hemisphere is in accordance with the weakening of the temperature gradients, as shown in Fig. 3.

Table 2 shows the tropical maxima of the zonal mean meridional wind in the two cases, and the near-surface equatorward flow and their upper return flow are intensified in the El Nino case, similar again to the results of long integrations by Cubasch[4].

Table 2

Wind Speed (m/s) and Latitude of Centres of Zonal Mean Meridional Wind in Tropics in the Two Experiments

		El Nino		Control	
		Speed ($m \cdot s^{-1}$)	Lat.	Speed ($m \cdot s^{-1}$)	Lat.
Southern Hemisphere	upper level	−0.38	20°S	−0.28	26°S
	lower level	1.66	20°S	1.47	30°S
Northern Hemisphere	upper level	1.55	9°N	1.49	12°N
	lower level	−3.49	15°N	−3.17	15°N

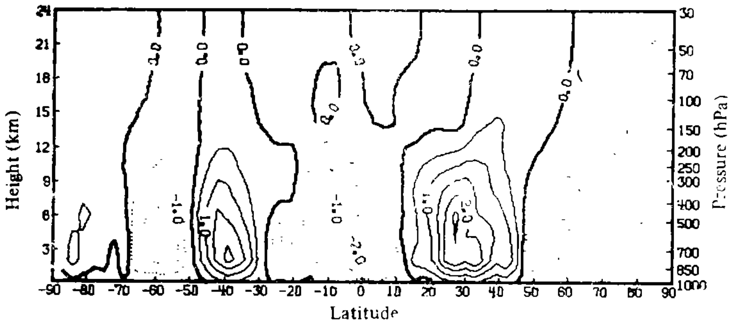


Fig. 5. As Fig. 4 (a), but for the zonal mean vertical wind. Unit: 10^{-4} hPa/s.

Substantial changes occur in the tropics in the vertical velocity component (Fig. 5). In the control case the ascending motion in the tropics is split into two branches, whereas in the El Nino case the vertical motion is more organized with a strong centre of about 3×10^{-4} hPa/s at 700 hPa at the equator.

The intensification of the equatorward low-level flow in the tropics and of the ascending motions at the equator lead to an intensification of the Hadley cells, as shown in Fig. 6 and Table 3. In particular, the northern Hadley cell is enhanced by 12%. The two Ferrel cells appear to be slightly weakened. The mass flux difference shows clearly an intensification of the

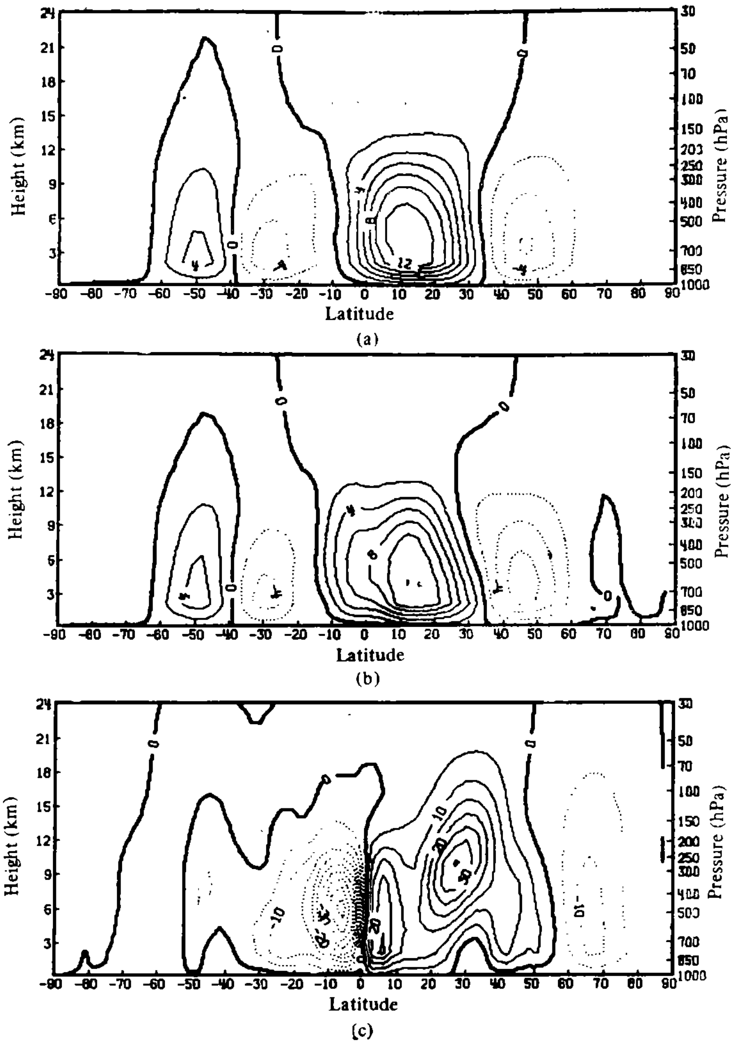


Fig. 6. As Fig. 4, but for the mean meridional circulation. Units: top and middle, 10^7 t/s; bottom, 10^6 t/s.

Table 3

Intensity (10^6t/s) and Location of Mean Meridional Mass Flux in the Two Experiments

		El Nino		Control	
		Int.	Lat.	Int.	Lat.
Southern Hemisphere	Ferrel Cell	50	48°S	51	48°S
	Hadley cell	−57	27°S	−50	30°S
Northern Hemisphere	Hadley cell	138	12°N	123	13°N
	Ferrel cell	−65	46°N	−73	45°N

toroids (i.e. the direct circulation) over the whole globe except in high latitudes, where an indirect cell can be found in the northern hemisphere. This is caused by the shift of the Ferrel cell, resulting from the enhanced eddy flux of heat and momentum in high latitudes and intense direct cell in low latitudes. The global intensifications of the direct cells implies that the diabatic heating must be the dominant driving factor.

2. *Transfer Properties of the Model Atmosphere*

Fig. 7 presents cross-sections of eddy momentum flux for the El Nino case and the difference

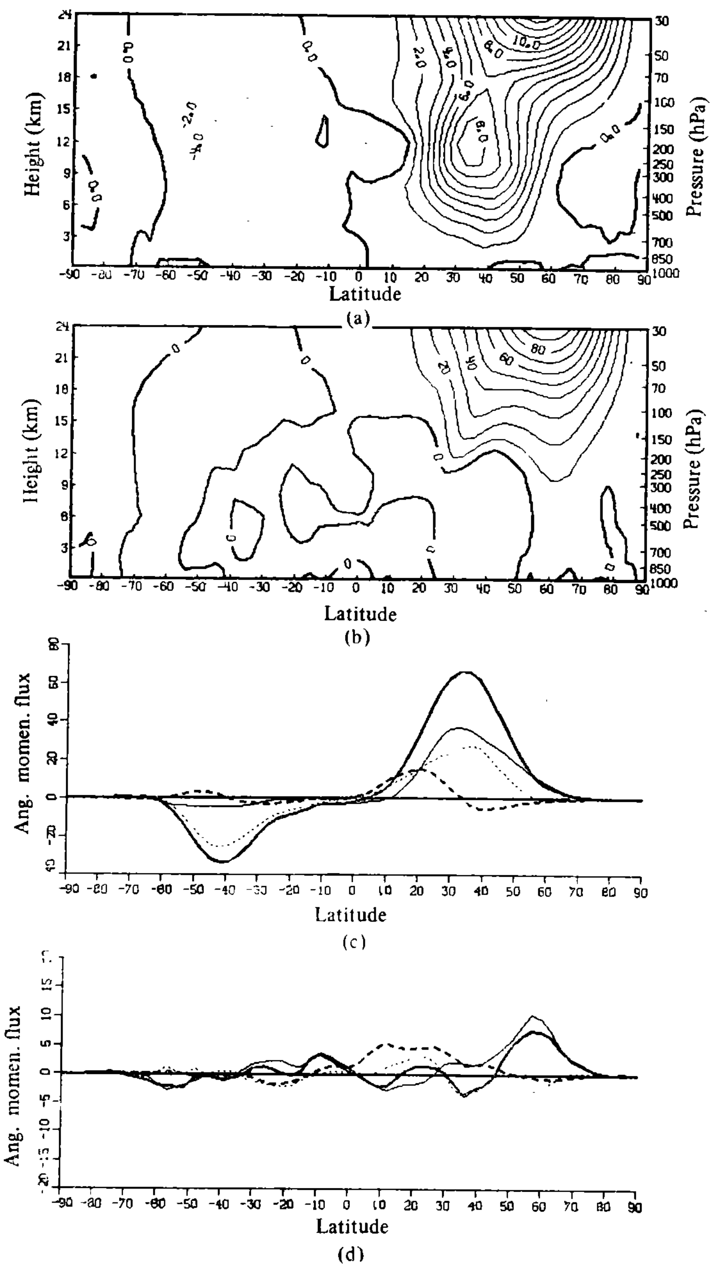


Fig. 7. The zonal mean momentum flux of the eddies for (a) the El Nino case (Unit: $10m^2/s^2$); (b) the difference (El Nino-Control) (Unit: m^2/s^2). Also the vertically integrated momentum fluxes for (c) the El Nino case (Unit: Hadley); (d) the difference (El Nino-Control) (Unit: Hadley).

in the flux between the two cases, as well as the vertical integrals.

The changes of eddy momentum flux occur mainly in the winter hemisphere, especially in the upper stratosphere. These can be attributed to planetary scale waves. The decrease of momentum flux in the troposphere indicates a less asymmetric wave system, whereas the strong in-

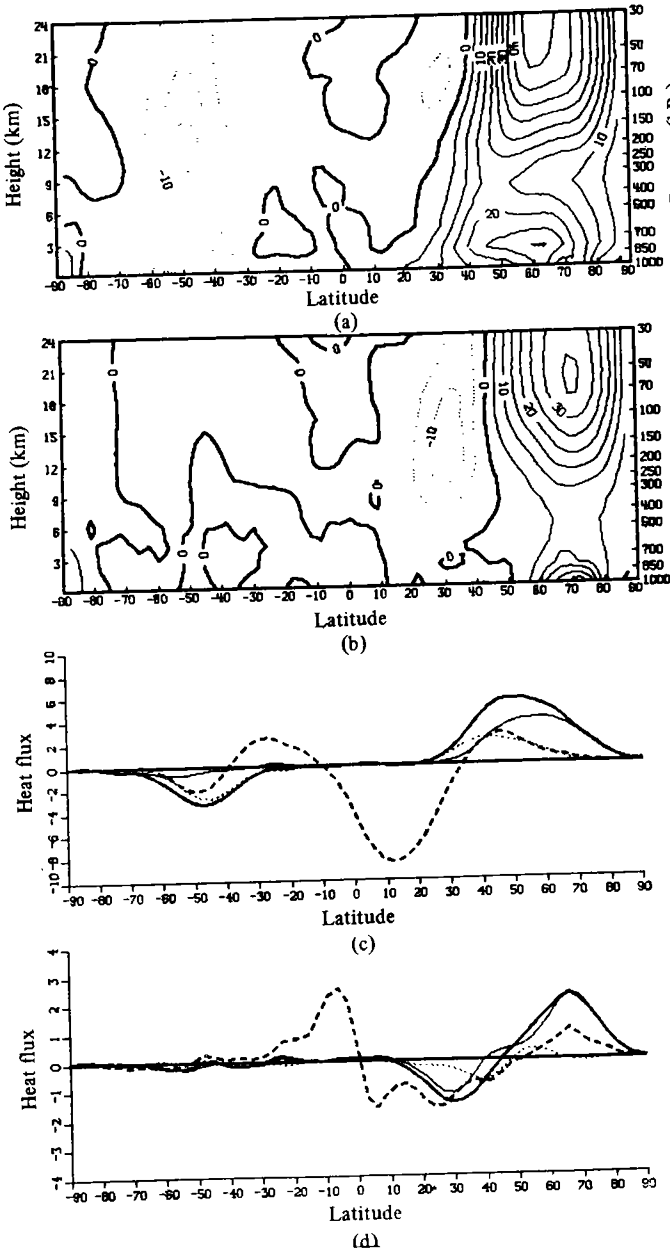


Fig. 8. The zonal mean sensible heat flux of the eddies for (a) the El Nino case (Unit: K m/s); (b) the difference (El Nino-Control) (Unit: K m/s). Also the vertically integrated fluxes for (c) the El Nino case (Unit: 10^{12}kW); (d) the difference (El Nino-Control) (Unit: 10^{12}kW).

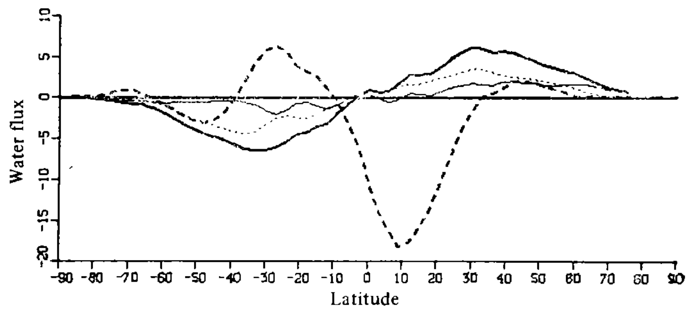
crease of momentum flux in the stratosphere corresponds to a substantial increase of amplitudes and horizontal tilting of planetary scale waves. The vertical integral of angular momentum flux

$$\int_{p_1}^{p_2} 2\pi a^2 \cos^2 \varphi \overline{uv} \frac{dp}{g},$$

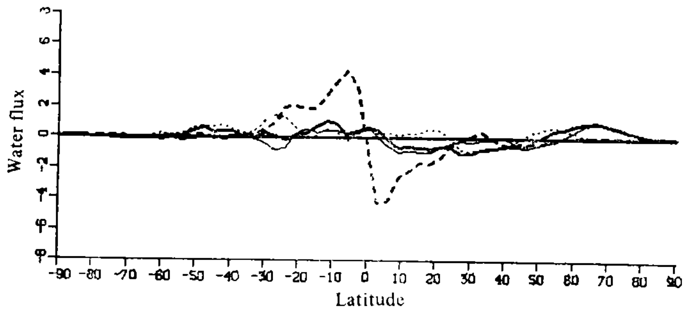
with $p_1 = 30$ hPa and $p_2 = 1000$ hPa does not change much in the two experiments. This is similar to the results of numerical experiments of mechanical forcing reported by Manabe and Terpstra[13], and Wu and Tibaldi[14]. The enhanced toroidal flux in low latitudes results from the intensification of the direct cells, while the enhanced eddy flux must be attributed to the increased horizonatal tilting of waves, and/or amplification of the forced waves emanating from the heat sources and propagating along two-dimensional Rossby wave rays (Horel and Wallace[15]).

Fig. 8 displays the heat flux in a similar fashion as in Fig. 7. The eddy heat flux in the northern stratosphere in the El Nino case reveals the existence of an equatorward heat flux centred in the subtropics of the northern hemisphere, which does not appear in the climate case. It is interesting to notice that its location coincides with the maximum gradient between the additional warming in mid-latitudes and the cooling in low latitudes (see Fig. 3).

The eddy heat flux appears to be shifted further north with one extremum located in the stratosphere and another near the surface. The changes in eddy heat flux are attributed mainly to planetary scale waves, which display an increased vertical tilt and increased amplitudes in high latitudes, especially in the stratosphere, and can also be accounted for by the excitations of



(a)



(b)

Fig. 9. The zonally and vertically integrated moisture flux for (a) the El Nino case, (b) the difference (El Nino-Control). Unit: 10^5 t/s.

two-dimensional Rossby waves by the SST anomalies.

The vertical integral of heat flux

$$\int_{p_1}^{p_2} 2\pi a \cos\varphi \overline{vT} \, \frac{dp}{g}$$

indicates that the eddies have a more important role in the mid-latitudes in transferring sensible heat polewards, while the toroid plays a major part of transferring heat equatorwards. The poleward shift of the heat flux in high latitudes is reflected in the eddies and toroids, while the intensified equatorward heat transport in low latitudes can be mainly attributed to the enhanced toroidal circulation. Fig. 9 shows the vertically integrated water flux. The toroidal flux appears to have a similar shape to the observed climatological mean (Newton[16]). In the El Nino case, much more water is transported towards the equator due to the intensification of the Hadley cells. The eddy flux is generally polewards in both hemispheres. In low latitudes its changes are relatively small in comparison to the toroidal flux. Even so, it is worthwhile mentioning that the eddy flux is reduced in the El Nino case, and therefore enhances the moisture convergence towards the equator.

3. *Budgets of Moisture and Heat*

In this section the dominant terms in the budget equations of moisture and heat are investigated. The term "residual" refers to sources or sinks in the corresponding budget equations. For details, see Wu and Tibaldi[10].

The vertical integrals of the moisture budget is shown in Fig. 10. They indicate that the

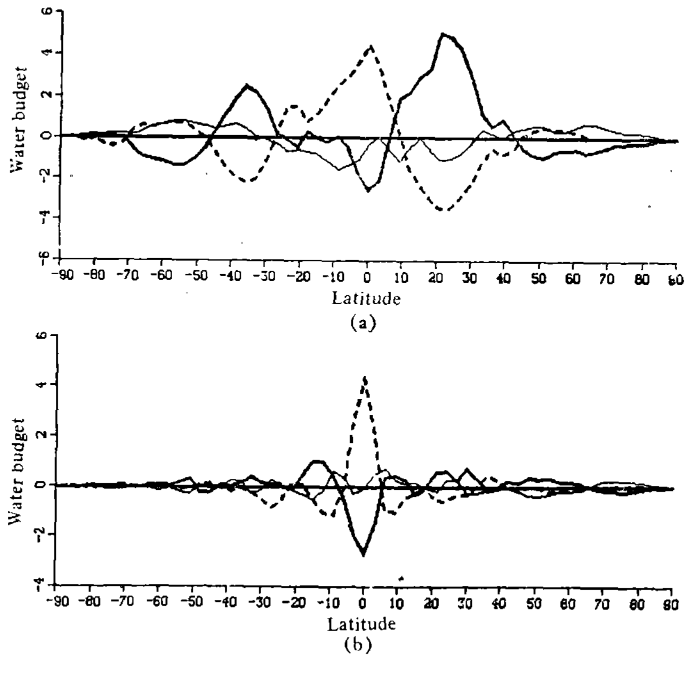


Fig. 10. The zonally and vertically integrated moisture budget for (a) the El Nino case, and (b) the difference (El Nino-Control).

Unit: 10^5 t/s.

toroids collect moisture from subtropical areas and transport it towards the tropics. Thus subtropical areas are important water sources whereas the equator is a water sink in both experiments. However, in the El Nino case, this cycle is intensified and results in a maximum of moisture convergence by the toroidal flux, and of moisture sinks in the subtropics.

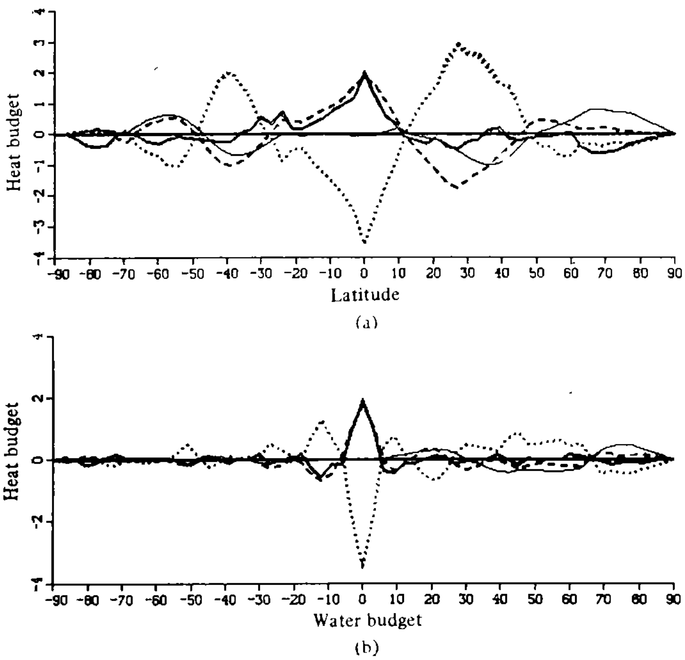


Fig. 11. As Fig. 10 but for the heat budget.
Unit: 10^{12}kW.

In the tropics there is a diabatic heat source (Fig. 11). The convergence of eddy heat flux is important in high latitudes, while the toroidal heat flux is dominant in the tropics. The adiabatic cooling resulting from the toroidal circulation balances to a large extent both the diabatic heating and the convergence of heat flux due to toroids and/or eddies. This agrees with the results of Wu and Tibaldi[14].

The difference budget between the two experiments shows an extremum of heating at the equator. To a large extent this heating must come from latent heat release. This, together with the additional convergence of toroidal sensible heat flux, is balanced by the adiabatic cooling from the intensified ascent in the Hadley cells.

In order to understand these variations better, various terms in the heat budget equation were calculated (figures are omitted). Results also show that in low latitudes the toroids are intensified to balance the additional diabatic heating during an El Nino event, whereas in high latitudes an additional circulation has been generated to counteract the additional poleward fluxes of heat (and momentum, as discussed above).

IV. Concluding Remarks

Even though the model atmosphere has not reached an equilibrium state, we see an impact of the equatorial SST anomalies on the simulated circulation. The dynamic and thermodynamic diagnosis allows the following interpretation of the main phenomena.

(1) The SST anomaly at the equator triggers a positive feedback between the mean meridional circulation and the tropical diabatic heating: the intensified Hadley cells converge more sensible and latent heat towards the equator. The increased release of latent heat in the tropics then accelerates the direct cells further. The stronger direct cells enhance the moisture convergence further and so on.

(2) In the horizontal plane, the stronger Hadly cells gain additional planetary momentum. This results in an equatorward shift of the subtropical jet rather than in an increase of its strength.

(3) The increased descent in the subtropical branches of the Hadley cells is compensated by a shift of the eddy heat flux in mid-latitudes. Owing to the intensification of both eddy momentum and heat flux in high latitudes during an El Nino event, an additional indirect toroidal circulation develops, which counteracts the eddy effects in order to retain the geostrophic and hydrostatic balance there. This additional circulation transfers heat and moisture more efficiently towards the polar regions.

(4) The simulated changes in the mean meridional circulation and in the eddy transfer behaviour occurring in a time scale of one month suggests a profound impact of the El Nino on the world climate. In the sense of zonal mean, its overall effect is to cause warmer and wetter winters in high latitudes and in the tropics, but drier weather in the subtropics.

ECMWF offered all the data and computing facilities and supported this study.

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