

High Baroclinic Equatorial Kelvin Waves and Central Pacific Surface Warming

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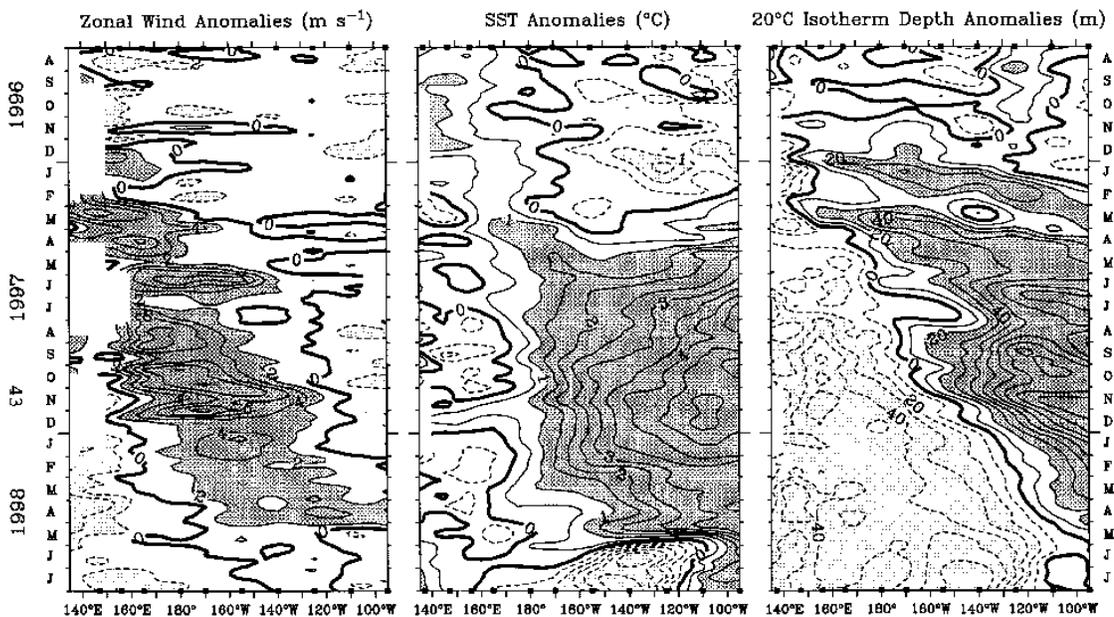
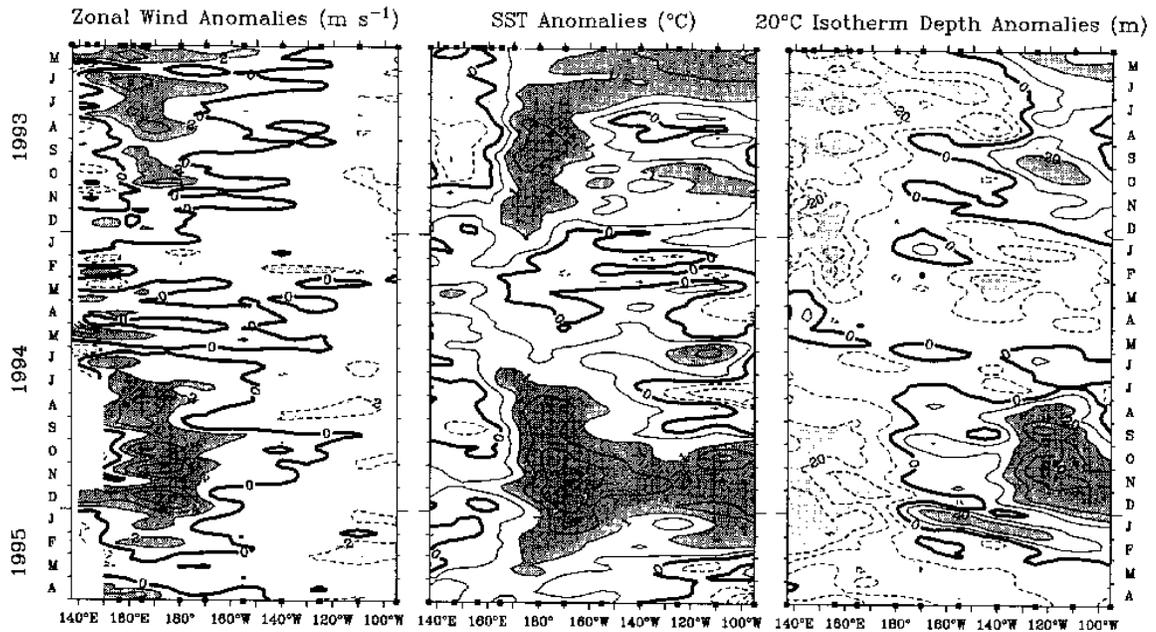
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Geophysical Union Meeting, Nice, France**

April 7-11, 2003.

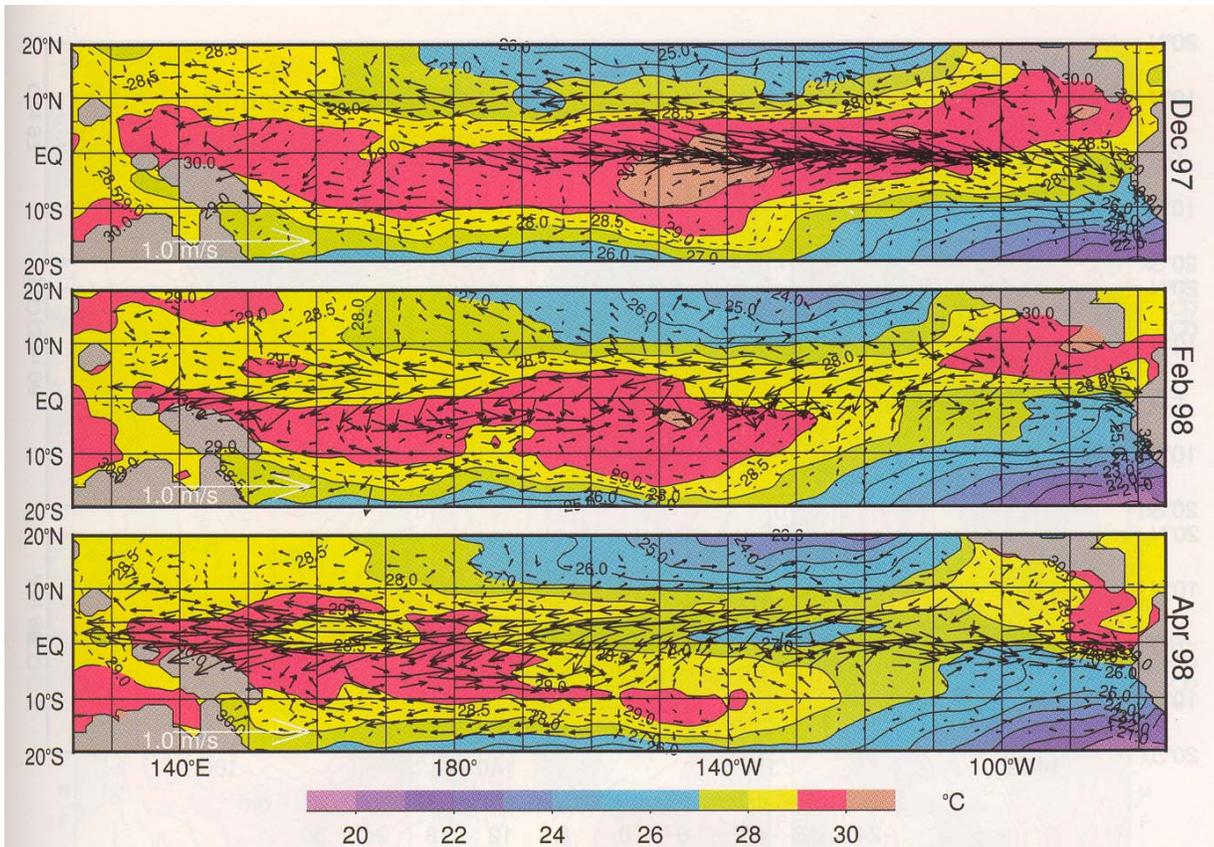
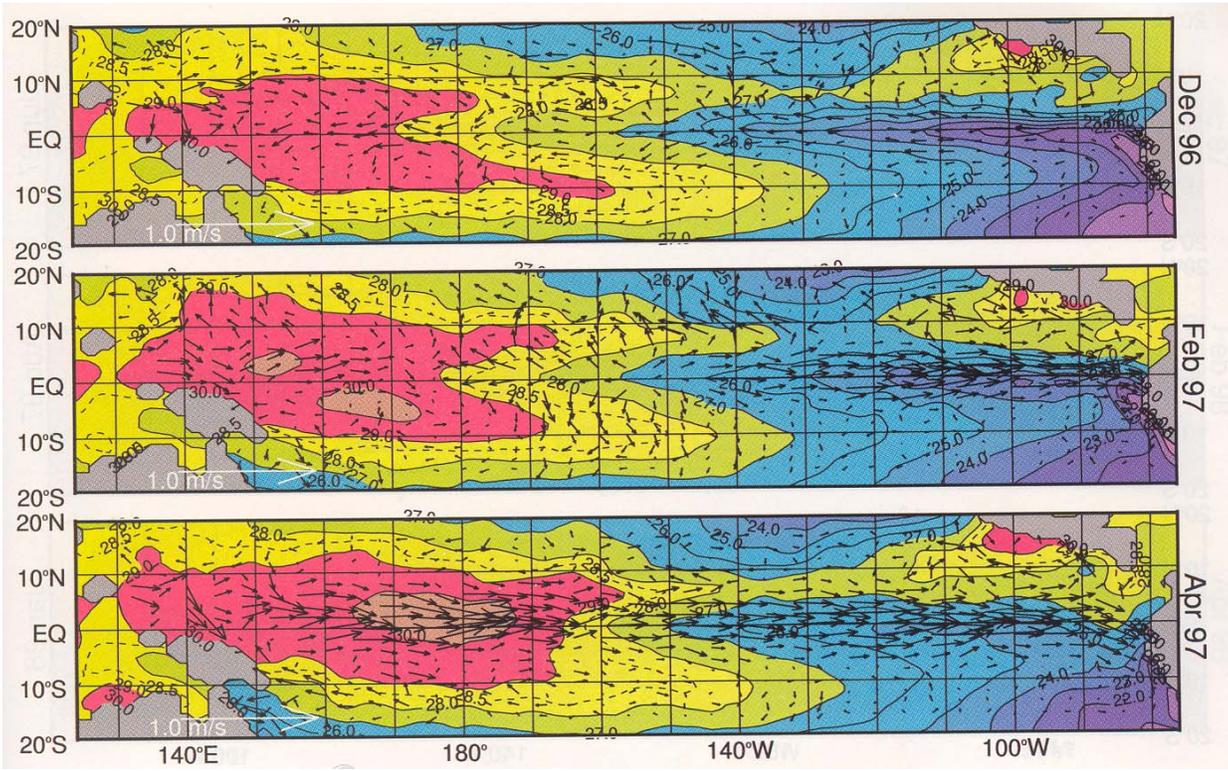
Outline

- Growing Counter Mode (GCM)
- Second Baroclinic Equatorial Kelvin Waves
- Two-Stage Air-Sea Interaction for the El Nino Onset

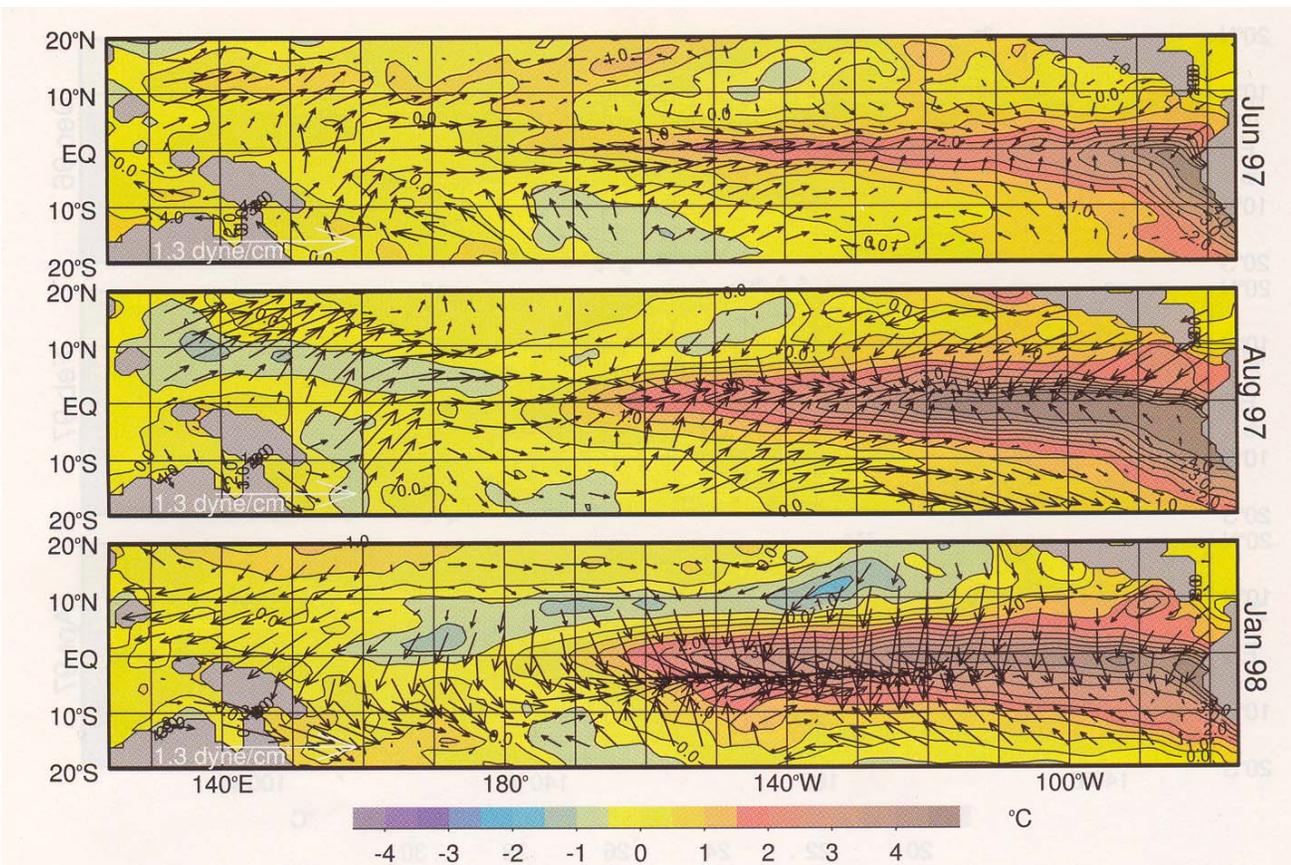
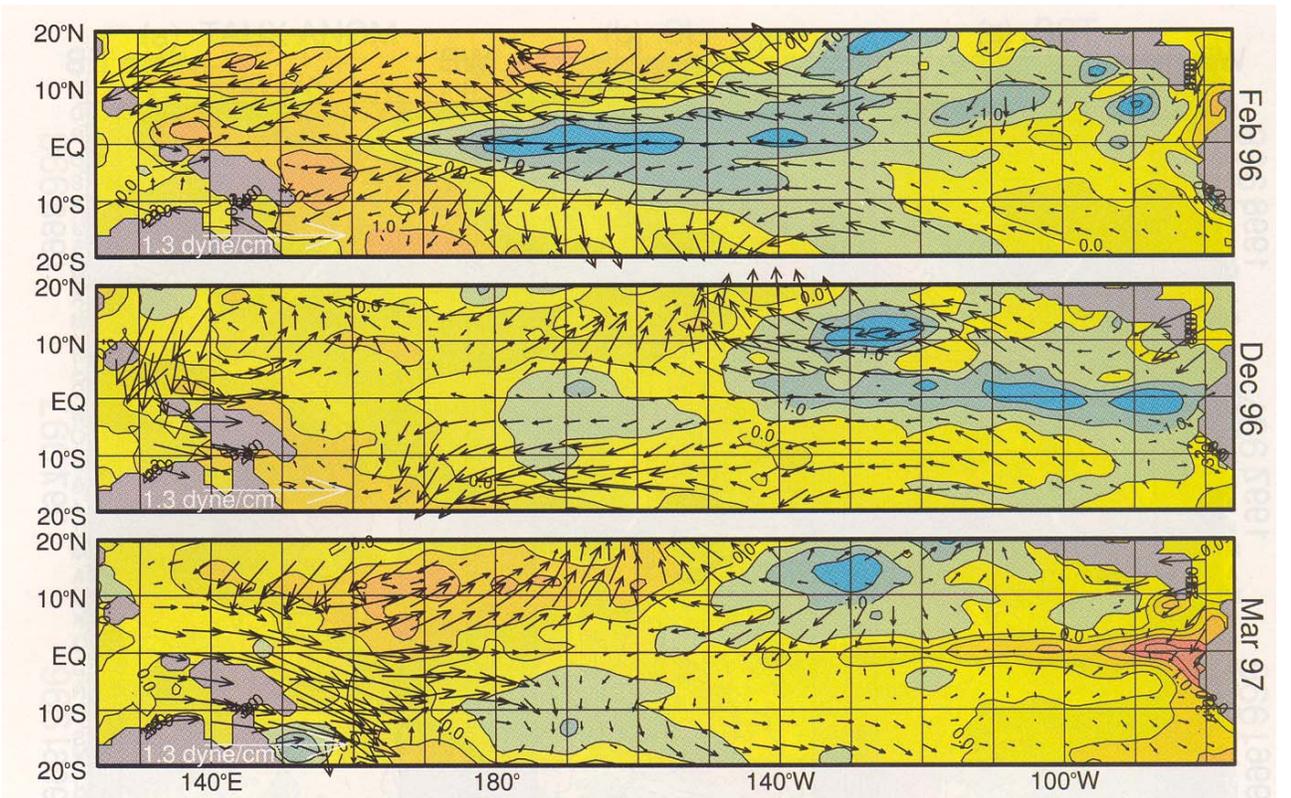
Central Pacific Warming Prior to the El Nino Onsets in 90's



1997 El Nino – Central Pacific Warming (Picaut et al. 2002)



1997 El Nino – Westerly Wind Burst (Picaut et al. 2002)



Equatorial Current System

Upper Layer:

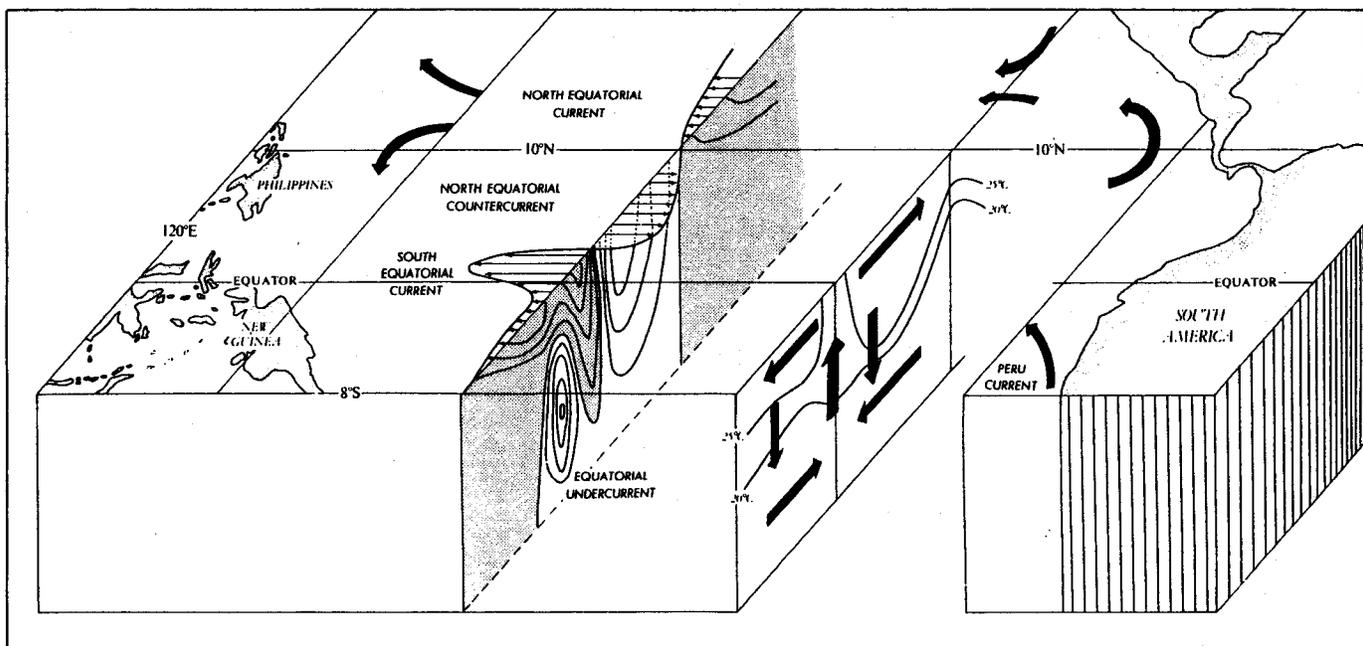
Westward Flowing

South Equatorial Current (SEC)

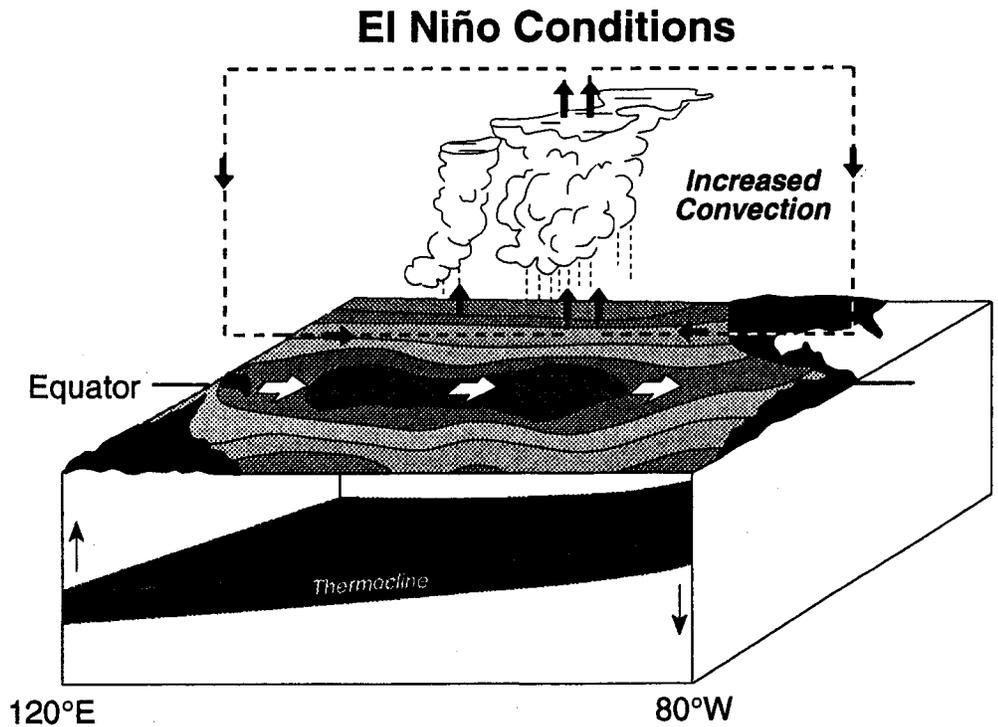
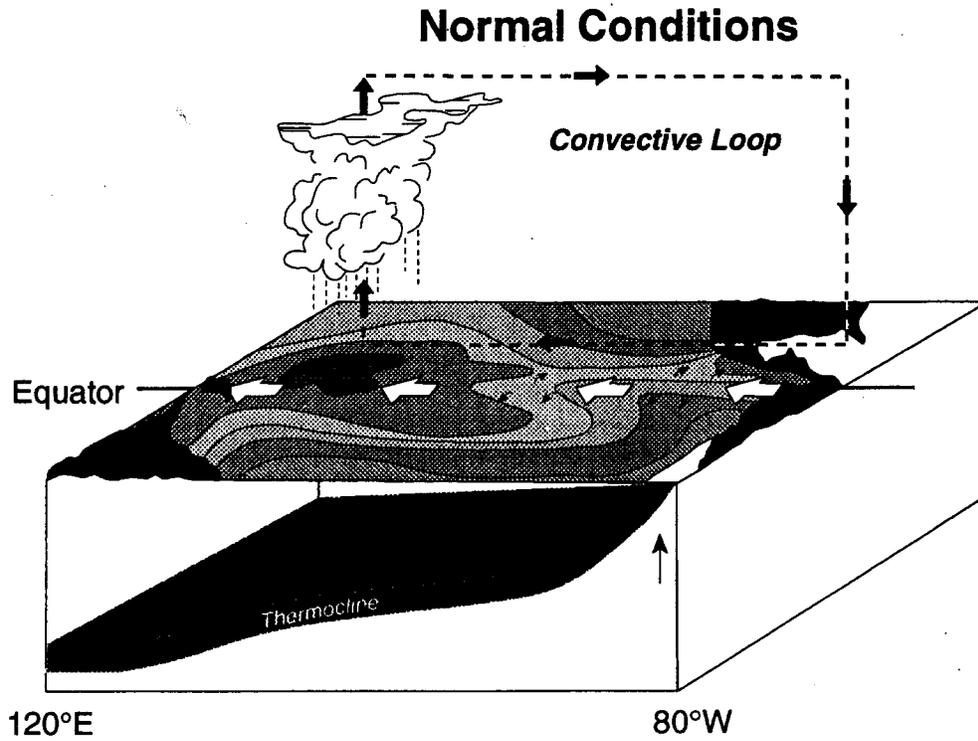
Thermocline:

Eastward Flowing

Equatorial Counter Current (EUC)



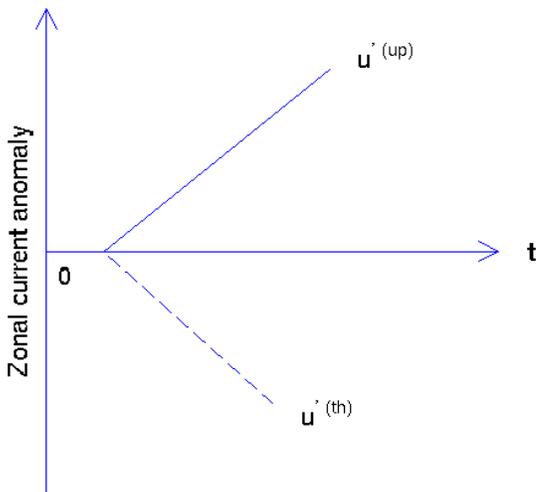
McPhaden et al. (JGR, 1998)



Mean Current System

- Upper Layer
 - SEC (Westward)
- Thermocline
 - EUC (Eastward)
- Mean Surface Cold Advection
(Mean Surface Temperature
Decreasing Eastward)

Perturbation Current System Growing Counter Mode (GCM)

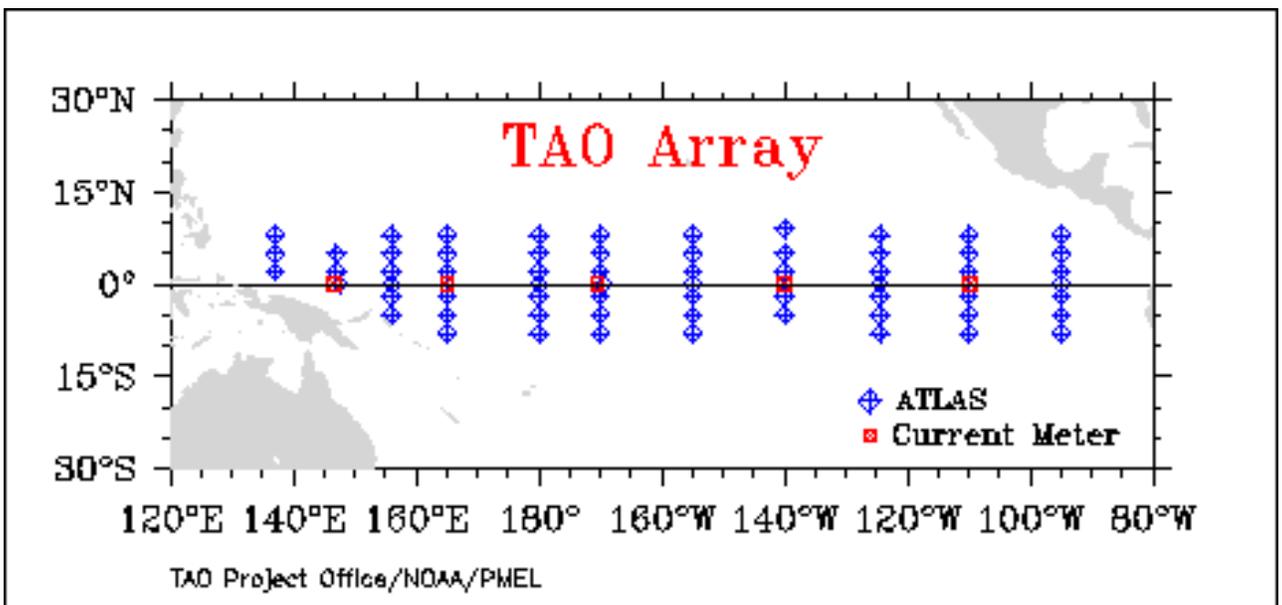
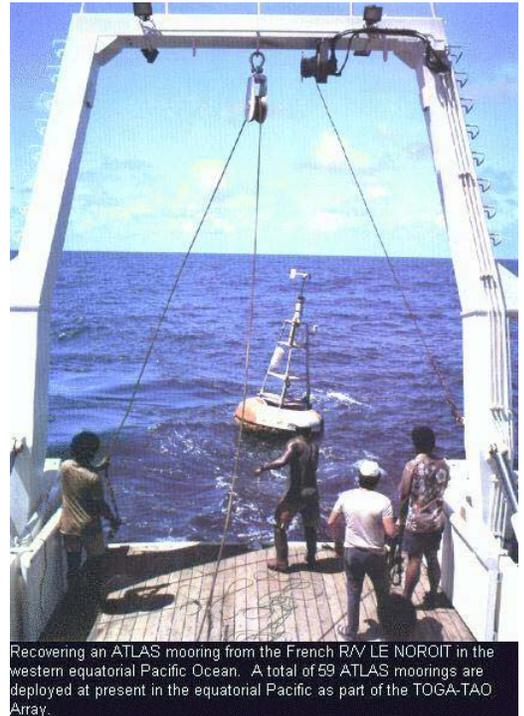
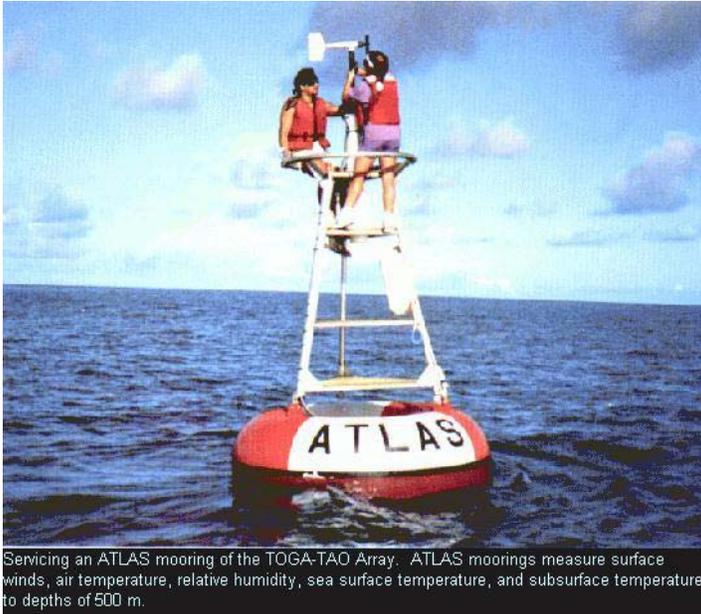


- Upper Layer
Eastward Flow
- Thermocline
westward Flow
- Reduction of
Mean Surface
Cold Advection

$$u^{(Up)} > 0, \quad \partial u^{(Up)} / \partial t > 0$$

$$u^{(Th)} < 0, \quad \partial u^{(Th)} / \partial t < 0$$

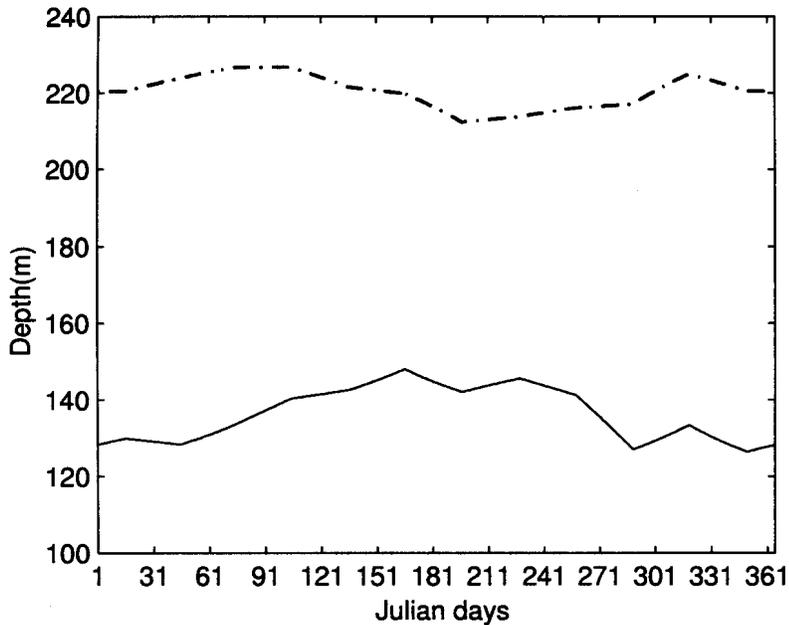
GCM Detected from TAO Data



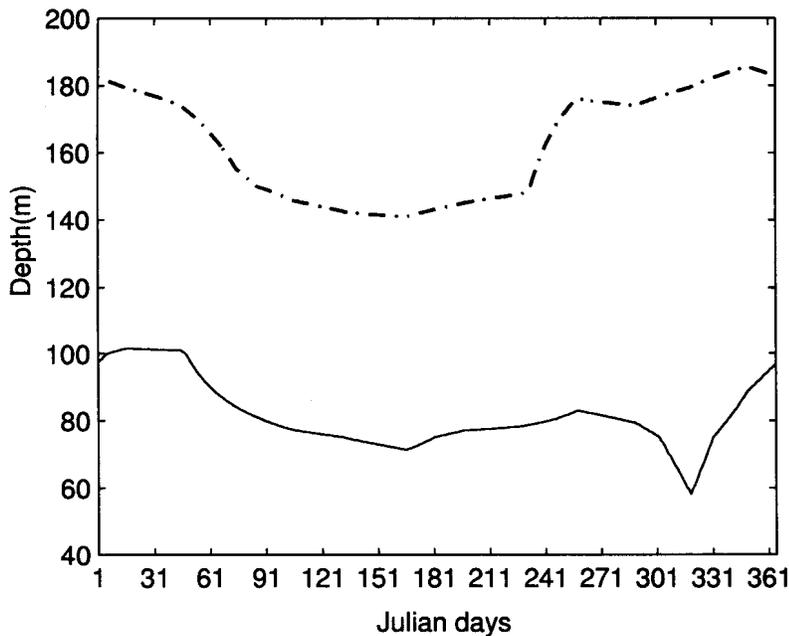
Upper Layer and Thermocline (Wyrтки and Kilonsky 1984)

- Hawaii to Tahiti Temperature Data (1978-1980)
- Upper Layer
 - Surface to 25°C depth
- Thermocline
 - 25°C depth to 15°C depth

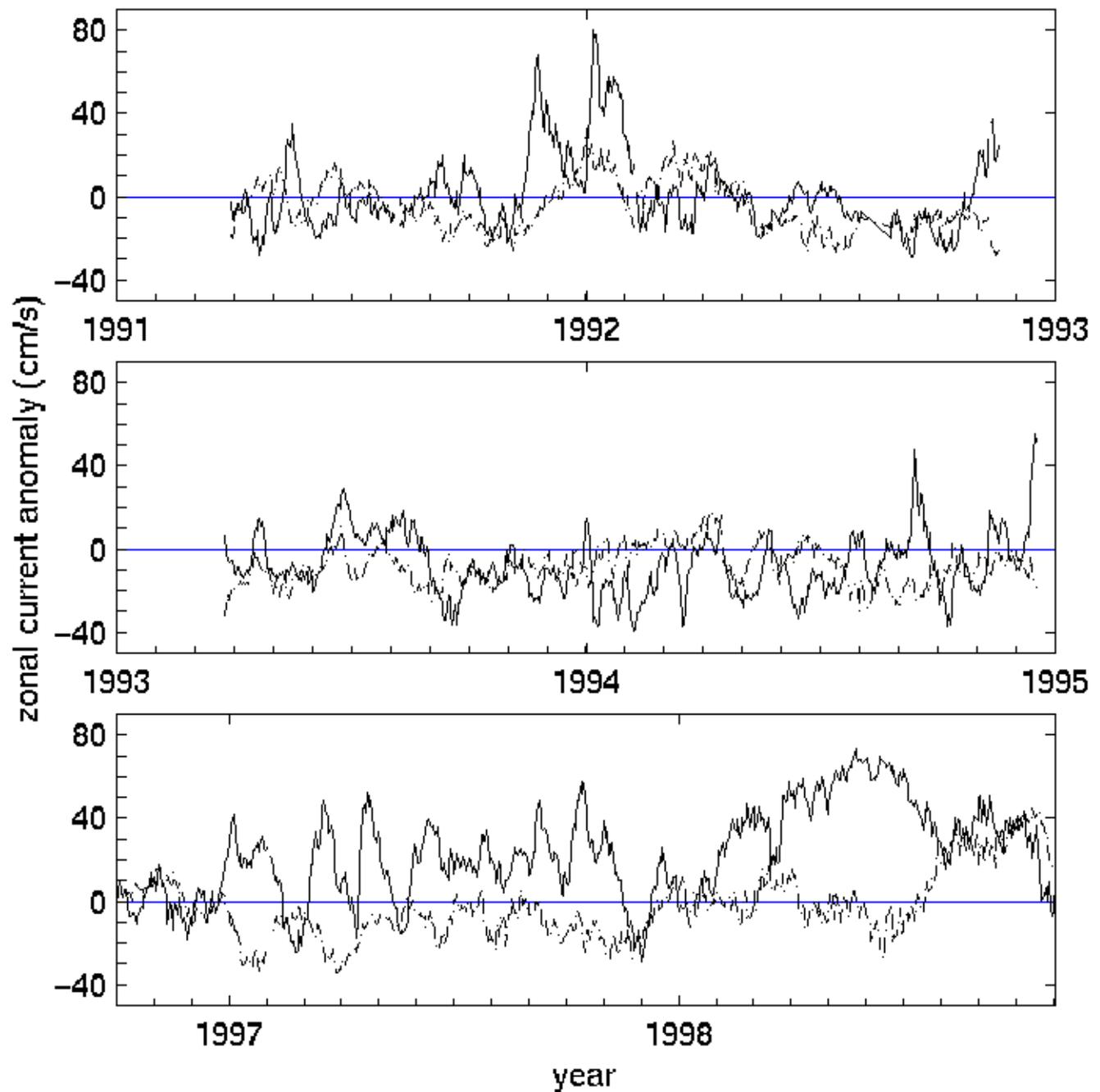
(a) 165°E



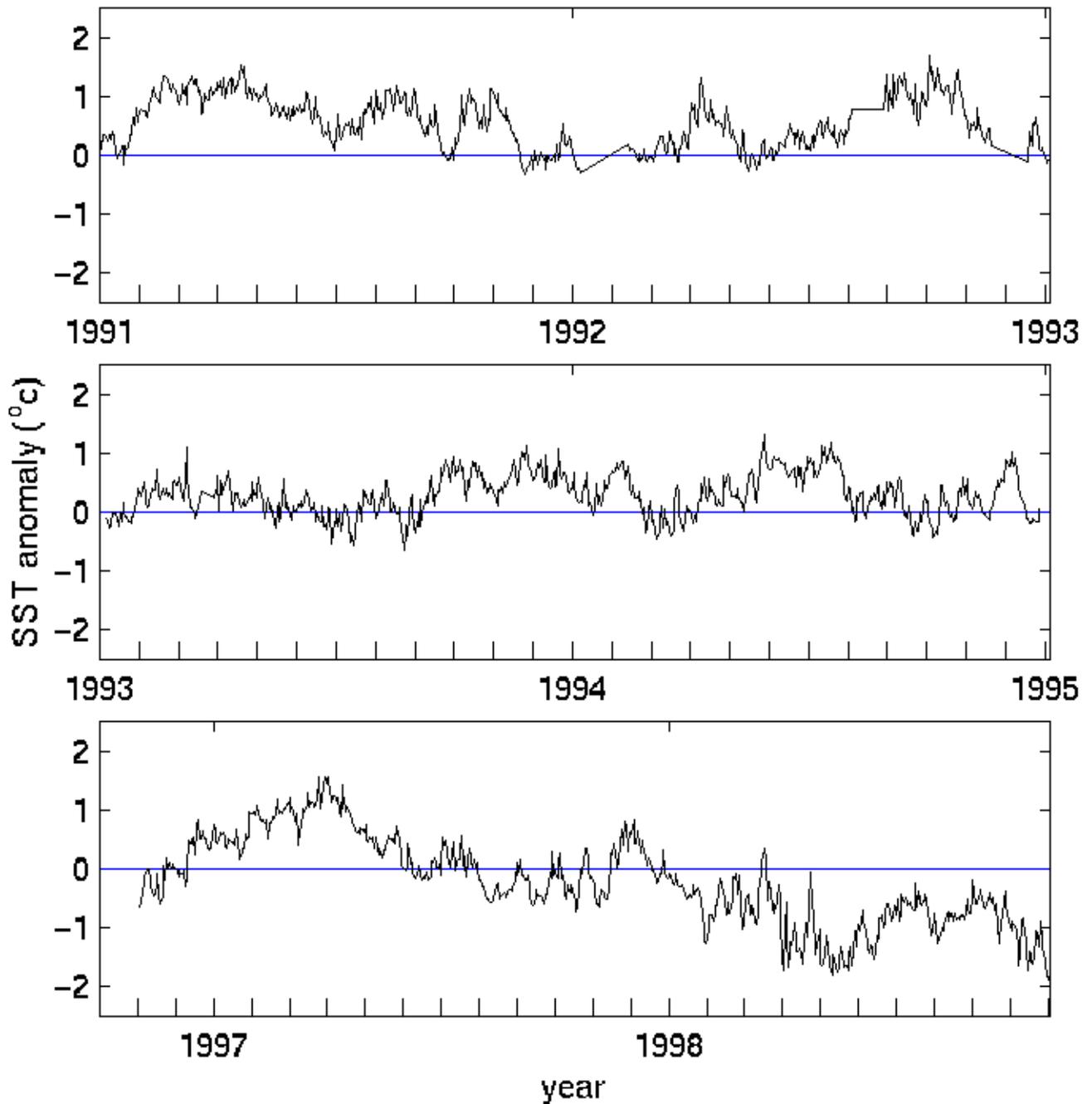
(b) 140°W



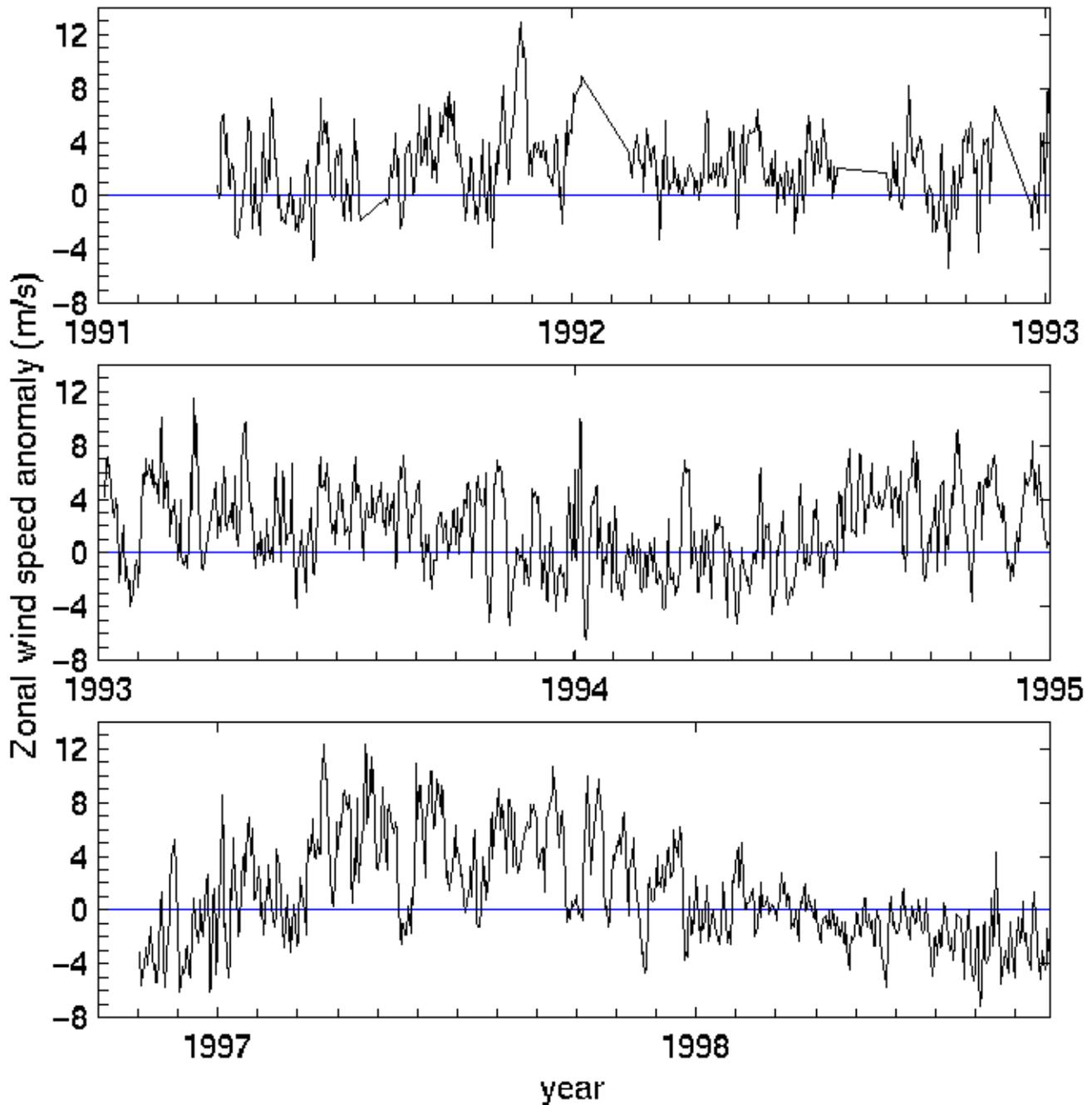
Daily Mean Depths of 25°C (Solid) and 15°C (dashed) Isotherms at (a) 165°E, and (b) 140°W along the Equator.



Growing counter mode detected from the TAO data at 165°E. Here solid (dashed) curve is the upper layer (thermocline) zonal speed anomaly.



Time evolution of SST anomaly at 165°E (solid). Note that SST warm anomaly appears during the growing counter mode periods.



Time evolution of zonal wind speed anomaly (m/s) at 165°E obtained from the TAO data. Note that the west wind anomaly (> 0) appears during the growing counter mode periods.

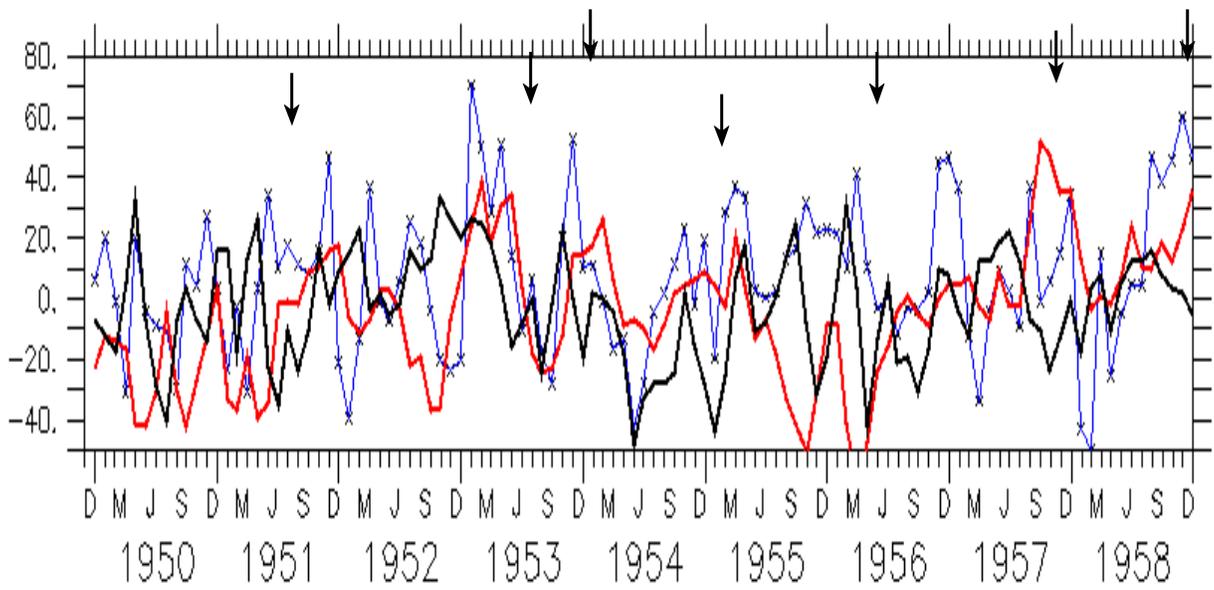
Simple Ocean Data Assimilation (SODA) System (Carton et al., 2000)

- MOM (NOAA/GFDL)
- 62°S – 62°N
- Data Assimilated
 - WOA-94
 - Satellite Altimetry (GEOSAT, ERS-1, T/P)
- Resolution:
 - Zonal 1°
 - Meridional Varying, 0.4286° near the equator

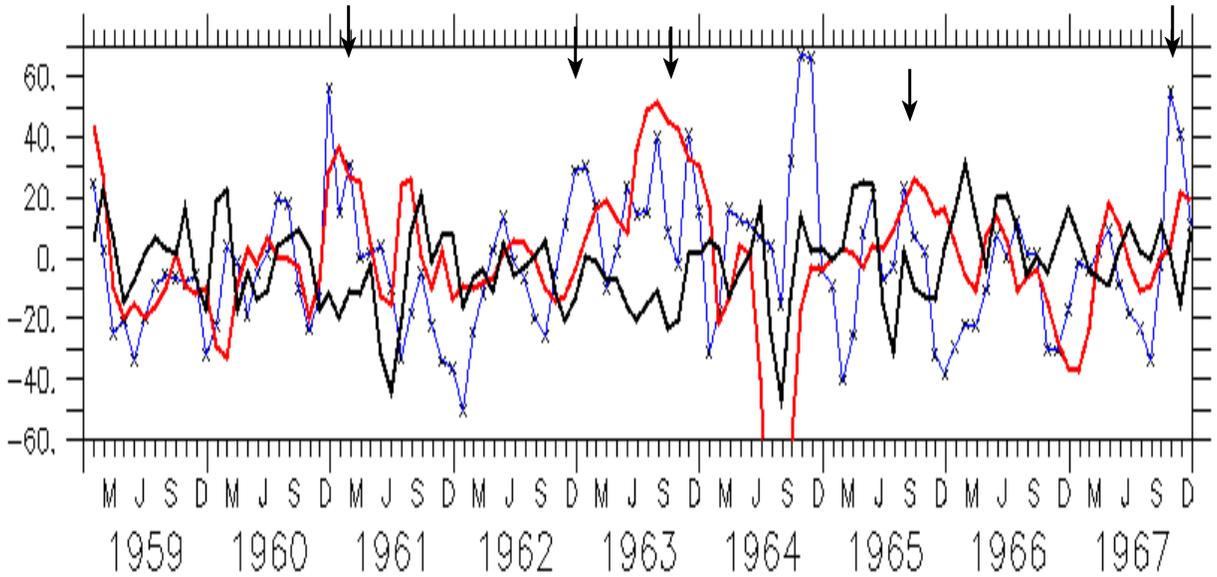
GCM Detected from SODA Data

- Monthly mean temperature and velocity data since 1950.
- SST
- Upper Layer Zonal Velocity
- Thermocline Zonal Velocity

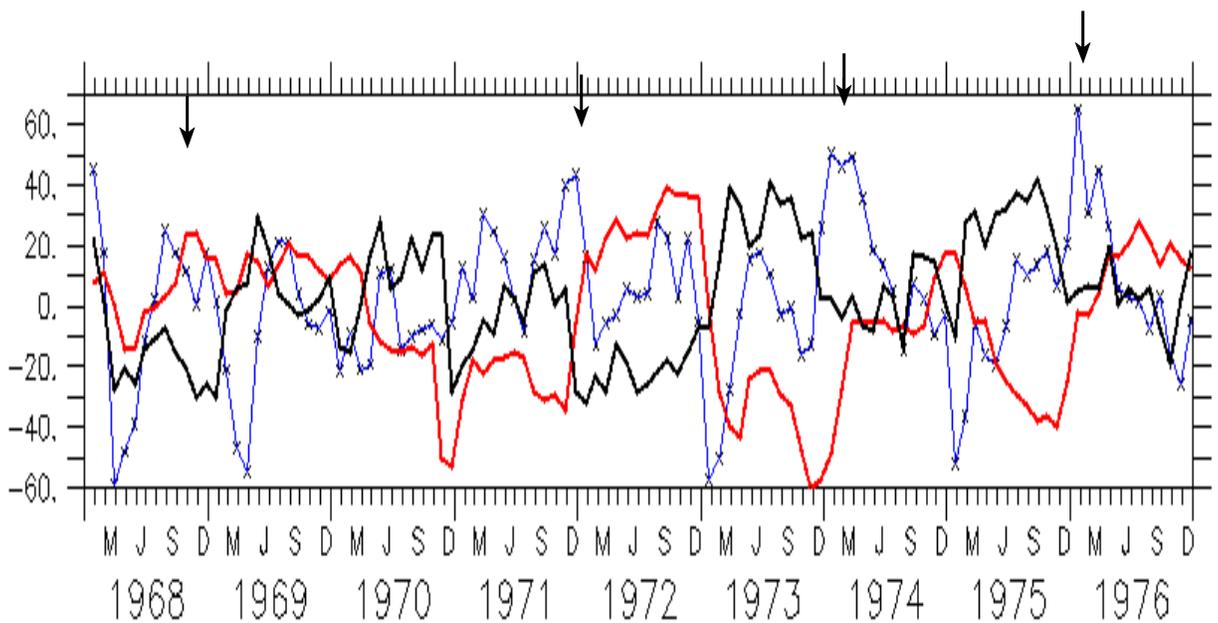
Upper Layer u' (cm/s, Blue)
Thermocline u' (cm/s, Black)
SST' ($^{\circ}\text{C} * 12$)
at 165°E



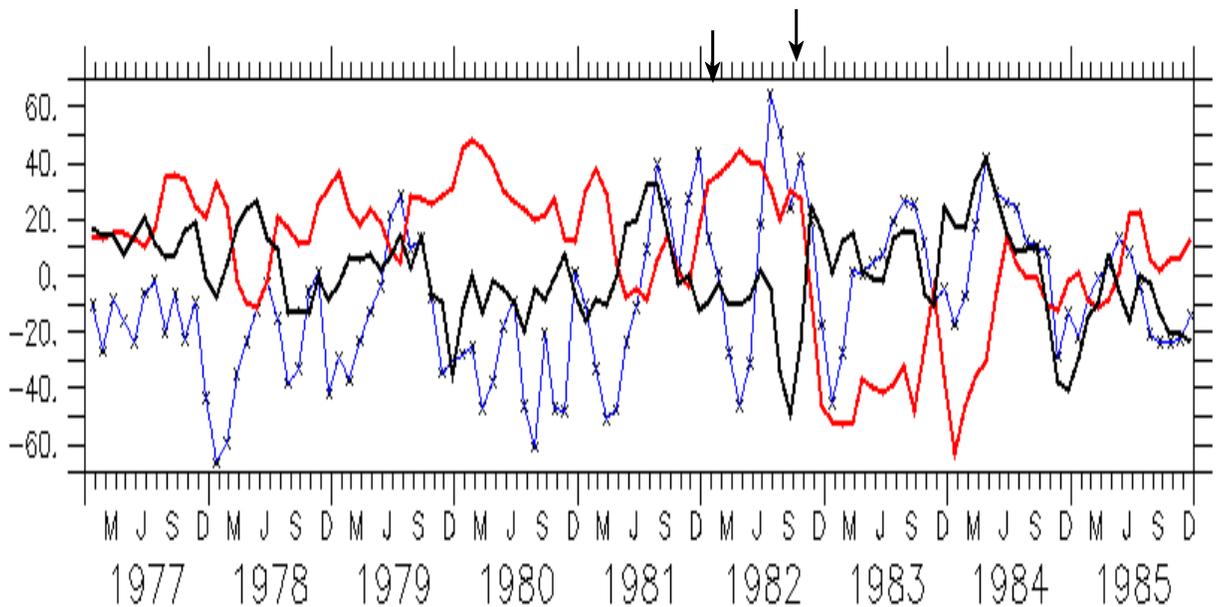
Upper Layer u' (cm/s, Blue)
Thermocline u' (cm/s, Black)
SST' ($^{\circ}\text{C} * 12$)
at 165°E



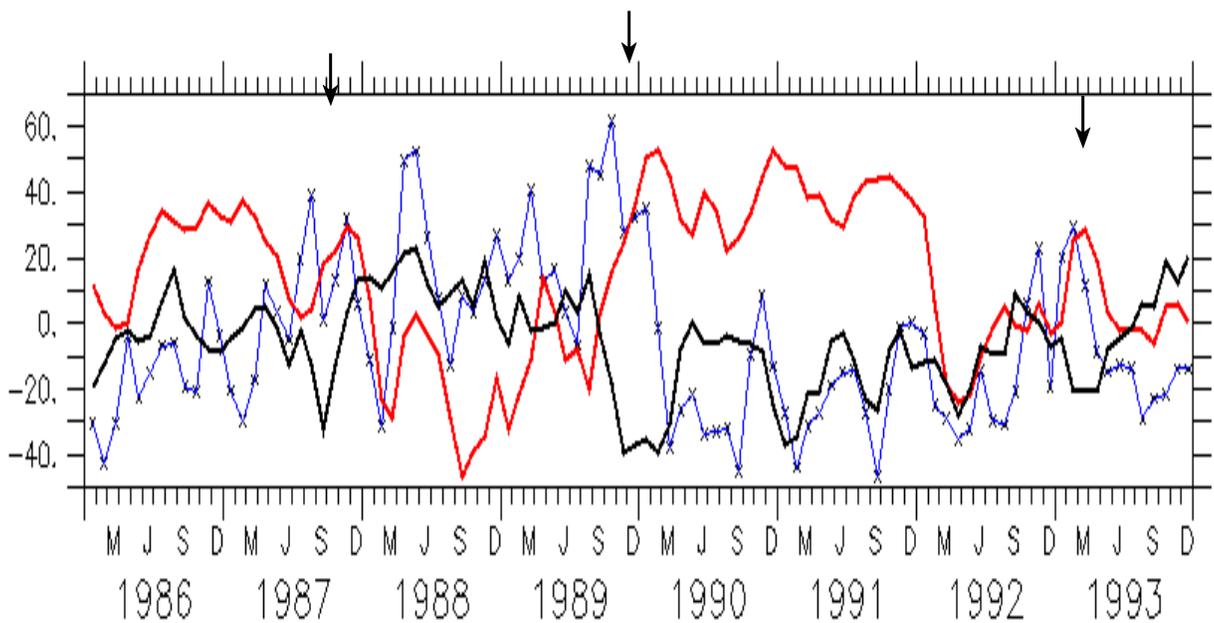
Upper Layer u' (cm/s, Blue)
Thermocline u' (cm/s, Black)
SST' ($^{\circ}\text{C} * 12$)
at 165°E



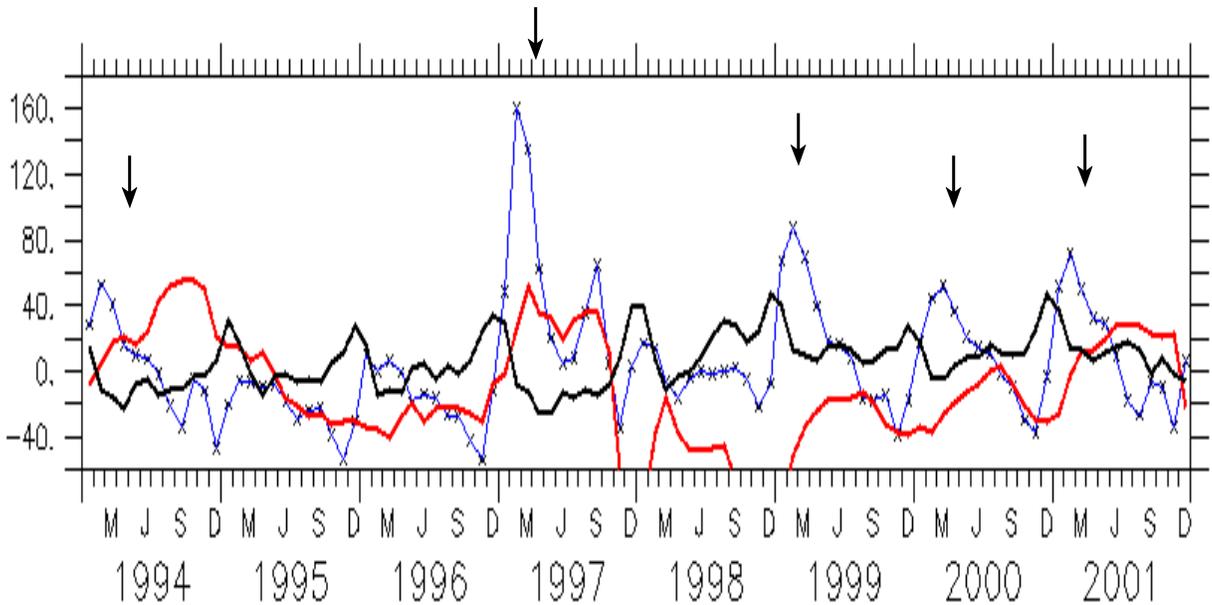
Upper Layer u' (cm/s, Blue)
Thermocline u' (cm/s, Black)
SST' ($^{\circ}\text{C} * 12$)
at 165°E



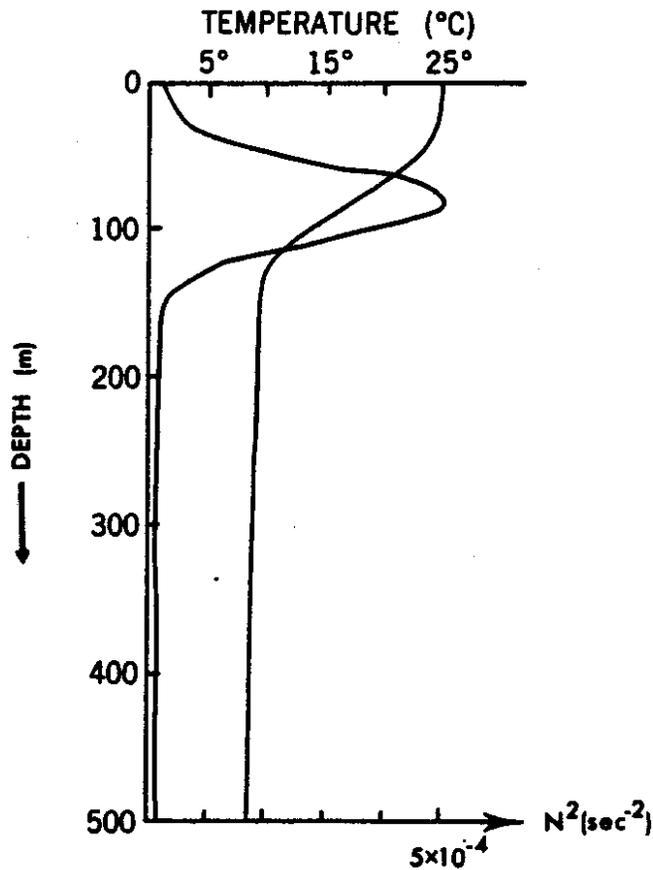
Upper Layer u' (cm/s, Blue)
Thermocline u' (cm/s, Black)
SST' ($^{\circ}\text{C} * 12$)
at 165°E



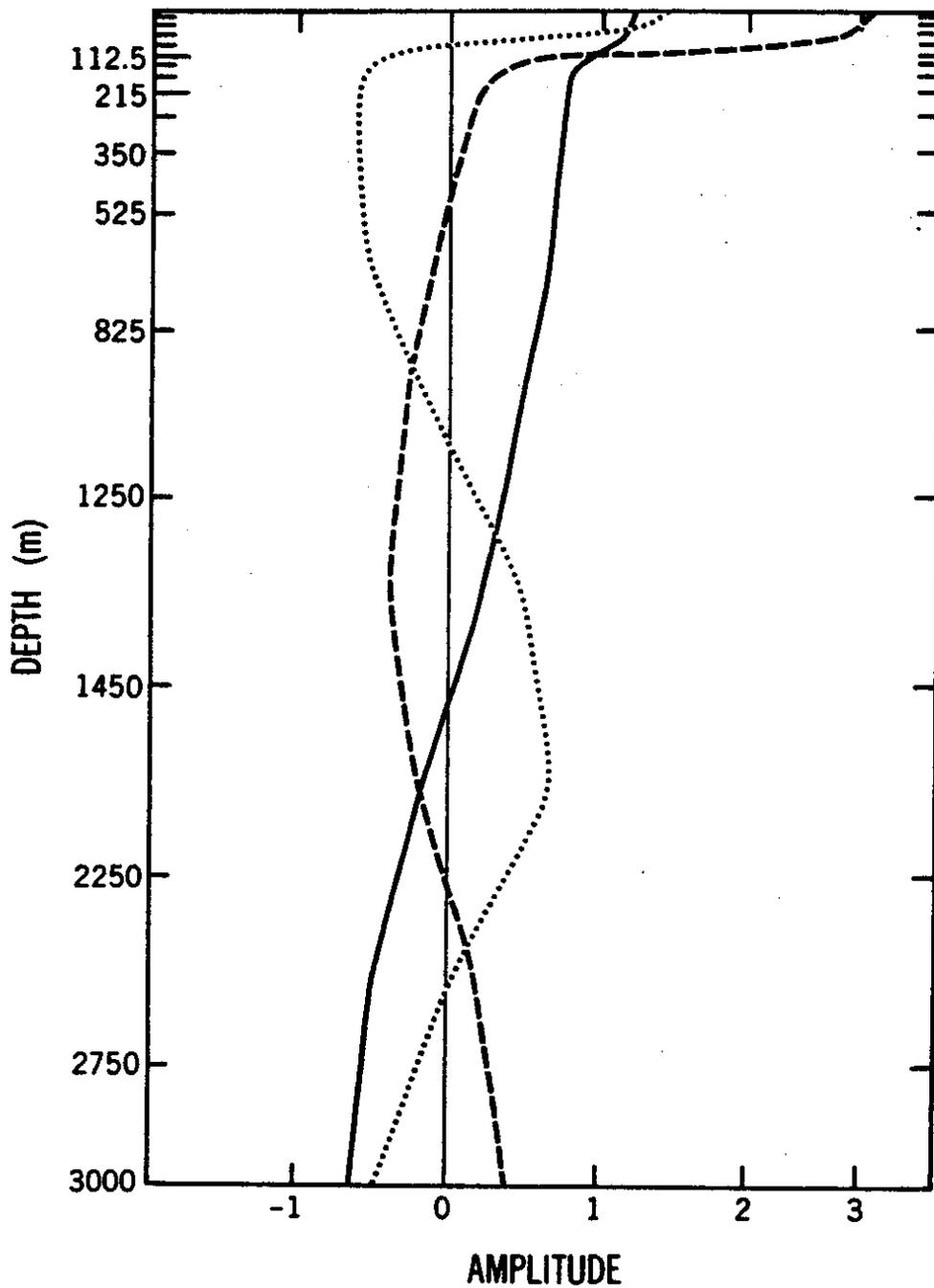
Upper Layer u' (cm/s, Blue)
Thermocline u' (cm/s, Black)
SST' ($^{\circ}\text{C} * 12$)
at 165°E



Propagation of Second- Baroclinic Kelvin Waves and GCM



Typical temperature profile and
Brunt-Vaisala Frequency at the
Equatorial Pacific



Three gravest vertical modes for u' calculated using a linear, continuously stratified, hydrostatic model with Boussinesq approximation [after *Philander, 1990*]. Note that the node for the first baroclinic mode is at around 1500 m depth.

Equatorial Layered Model (McCreary and Yu, 1992)

- $2\frac{1}{2}$ (or $1\frac{1}{2}$) - Layer
 - The First Two Layers Active
 - The Third Layer Motionless
- Momentum Balance
- Heat Balance
- Entrainment/Detrainment Rate
- Wind Forcing
- $1^\circ \times 1^\circ$ Resolution

$$(h_1 \mathbf{v}_1)_t + \nabla \cdot (\mathbf{v}_1 h_1 \mathbf{v}_1) + f \mathbf{k} \times h_1 \mathbf{v}_1 + h_1 \langle \nabla p_1 \rangle^2$$

$$= \tau + w_e \mathbf{v}_2 + w_d \mathbf{v}_1 - \nu_4 \nabla^4 (h_1 \mathbf{v}_1) - \gamma h_1 u_1 \mathbf{i},$$

$$h_{1t} + \nabla \cdot (h_1 \mathbf{v}_1) = w_e + w_d - \kappa_4 \nabla^4 h_1,$$

$$T_{1t} + \mathbf{v}_1 \cdot \nabla T_1 = Q_1/h_1 - w_e (T_1 - T_2)/h_1 - \kappa_4 \nabla^4 T_1,$$

$$(h_2 \mathbf{v}_2)_t + \nabla \cdot (\mathbf{v}_2 h_2 \mathbf{v}_2) + f \mathbf{k} \times h_2 \mathbf{v}_2 + h_2 \langle \nabla p_2 \rangle^2$$

$$= -w_e \mathbf{v}_2 - w_d \mathbf{v}_1 - \nu_4 \nabla^4 (h_2 \mathbf{v}_2) - \gamma h_2 u_2 \mathbf{i},$$

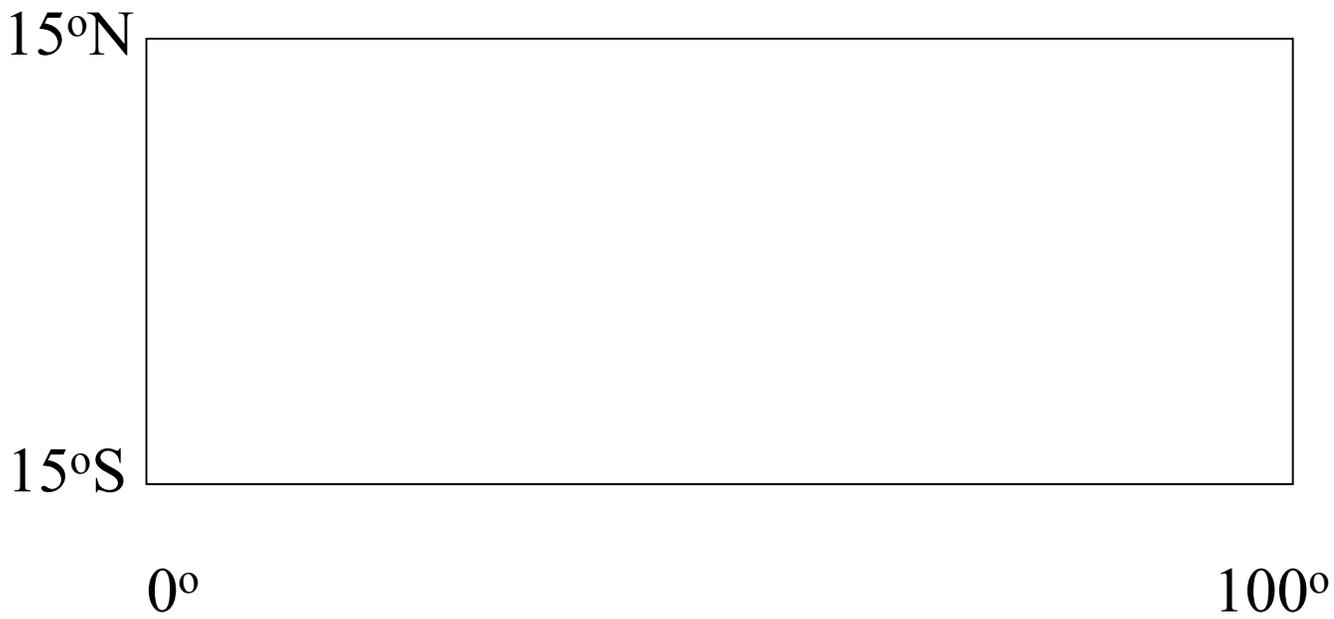
$$h_{2t} + \nabla \cdot (h_2 \mathbf{v}_2) = -w_e - w_d - \kappa_4 \nabla^4 h_2,$$

$$T_{2t} + \mathbf{v}_2 \cdot \nabla T_2 = Q_2/h_2 - w_d (T_1 - T_2)/h_2 - \kappa_4 \nabla^4 T_2.$$

Model Parameters (McCreary and Yu, 1992)

Biharmonic mixing coefficients	$\nu_4 = \kappa_4 = 2 \times 10^{21} \text{cm}^4 \text{s}^{-1}$
Maximum value of damper	$\gamma = 1 \text{ day}^{-1}$
Surface heating time scale	$t_1 = 100 \text{ day}$
Lower-layer heating time scale	$t_2 = 500 \text{ day}$
Entrainment time scale	$t_e = 1 \text{ day}$
Detrainment time scale	$t_d = 50 \text{ day}$
Entrainment depth	$H_e = 75 \text{m}$
Detrainment depth	$H_d = 75 \text{m}$
Coefficient of thermal expansion	$\alpha = 0.00025^\circ \text{C}^{-1}$
Characteristic speed of mode 1	$c_1 = 316 \text{cm s}^{-1}$
Characteristic speed of mode 2	$c_2 = 123 \text{cm s}^{-1}$

Model Area



Surface Winds (Trade Winds)

$$\tau^x = \tau_0 X(x) Y(y) T(t),$$

$$\tau_0 = -0.5 \text{ dyn cm}^{-2}.$$

$Y(y) = 1$ (No Latitudinal Variance).

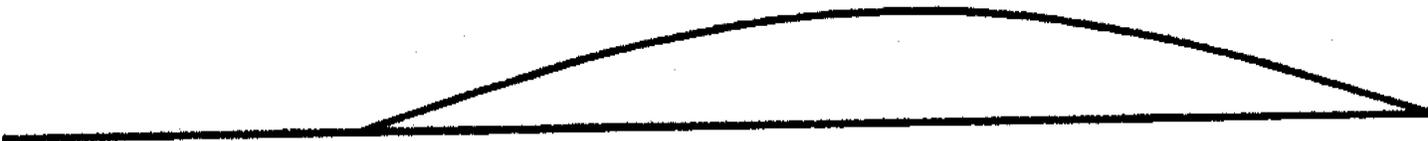
$T(t)$ = Ramp function that increases linearly from 0 to 1 in the first 5 days

Zonal Variation of the Trade Winds

$$X(x) = \cos[\pi(x - \bar{x})/L] \theta[(x - \bar{x})^2 - L^2/4],$$

$$\bar{x} = 62.5^\circ \text{ and } L = 75^\circ.$$

$X(x)$



Initial Conditions

Initial thickness of upper layer

$$H_1 = 75\text{m}$$

Initial thickness of lower layer

$$H_2 = 175\text{m}$$

Initial temperature of upper layer

$$T_1^* = 28^\circ\text{C}$$

Initial temperature of lower layer

$$T_2^* = 15^\circ\text{C}$$

Temperature of deep ocean

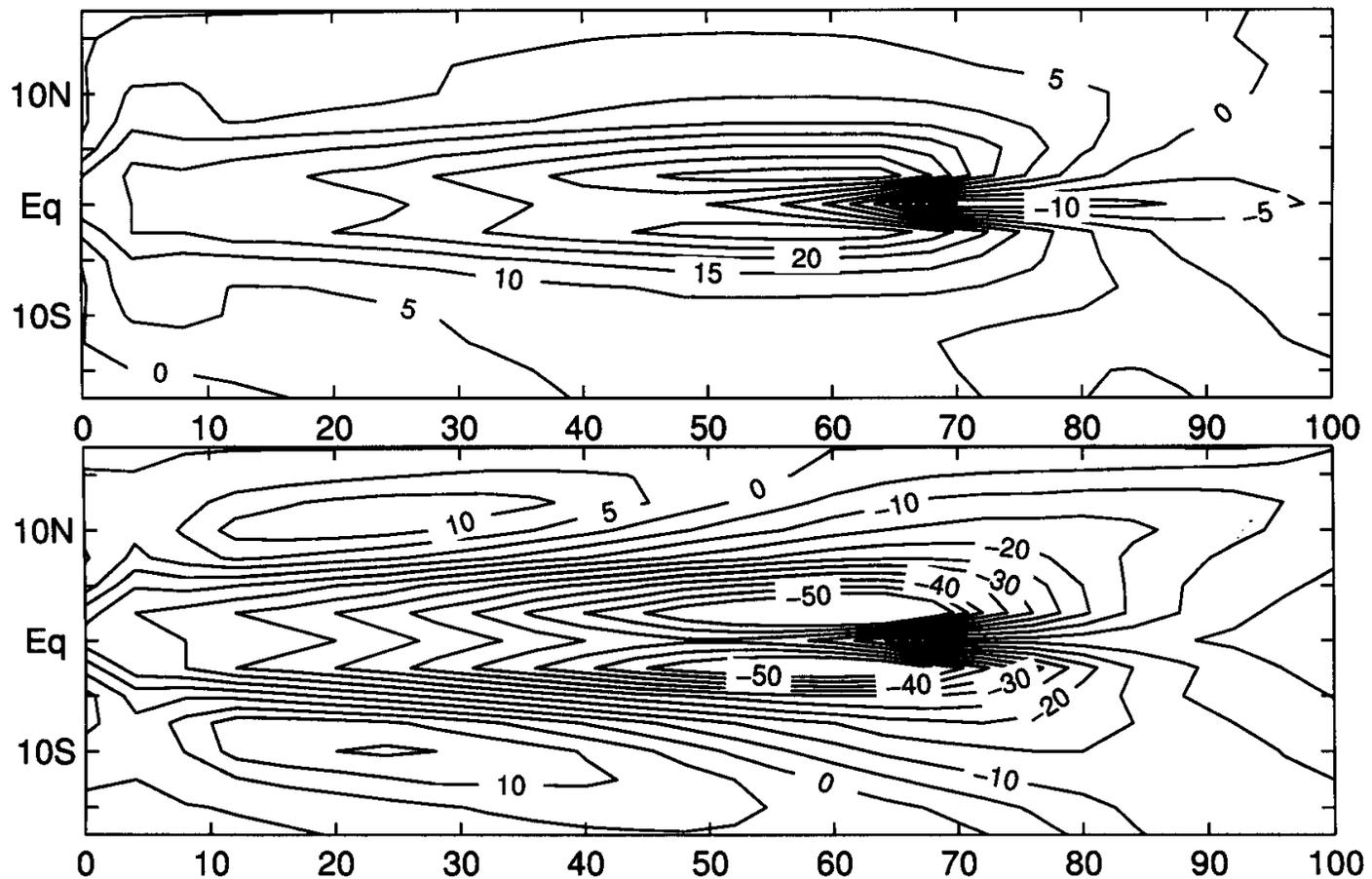
$$T_3 = 0^\circ\text{C}$$

Model Integration

- (1) Model is integrated for 1080 days to reach nearly equilibrium state.
- (2) Westerly wind patch is added at day-1080 for 25 days, and then is removed.
- (3) Model is integrated for 1000 days.

Control Run

Layer Thickness Anomaly (m) at Day-1080:
(a) 1st Layer, (b) 2nd Layer.

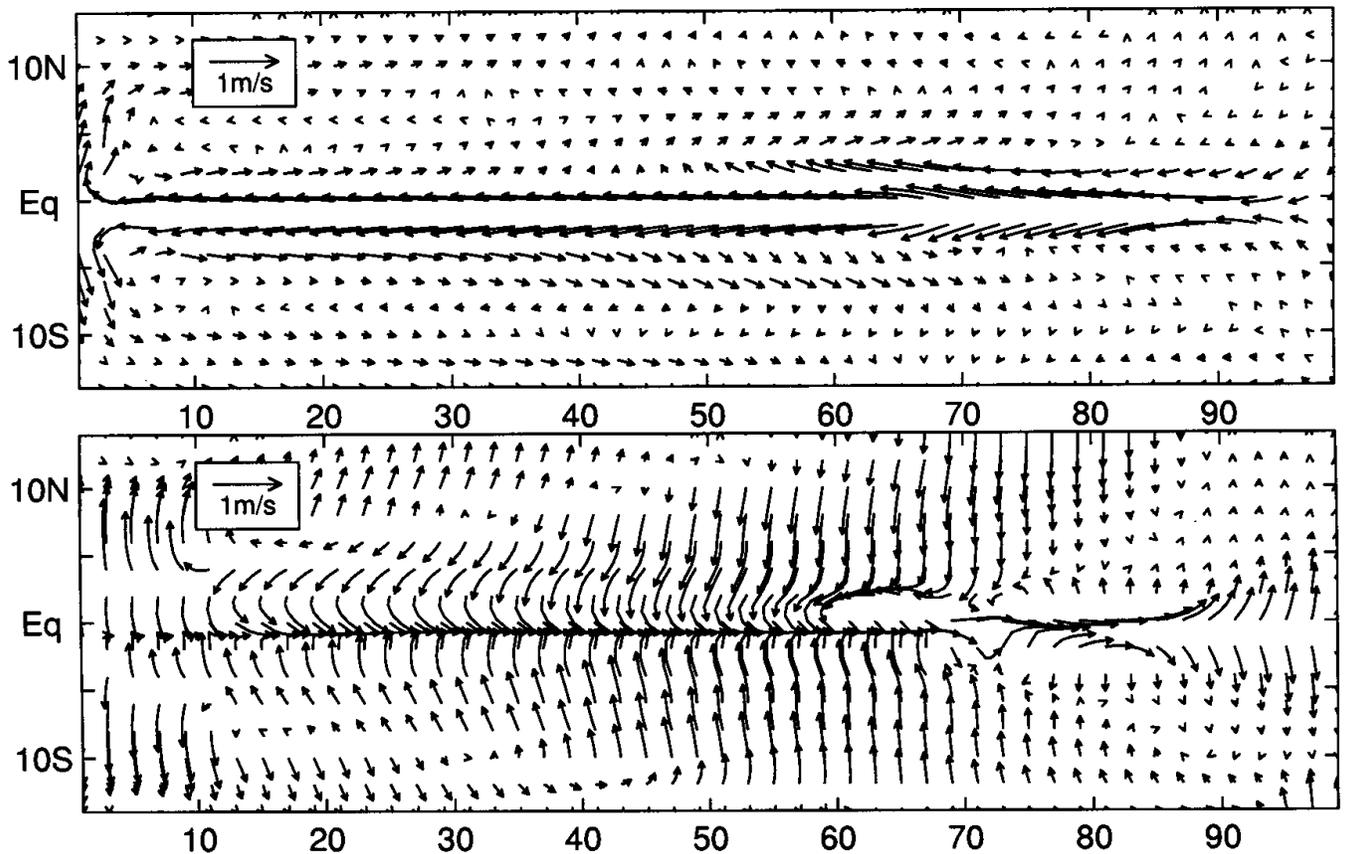


Control Run

Horizontal Currents at Day-1080.

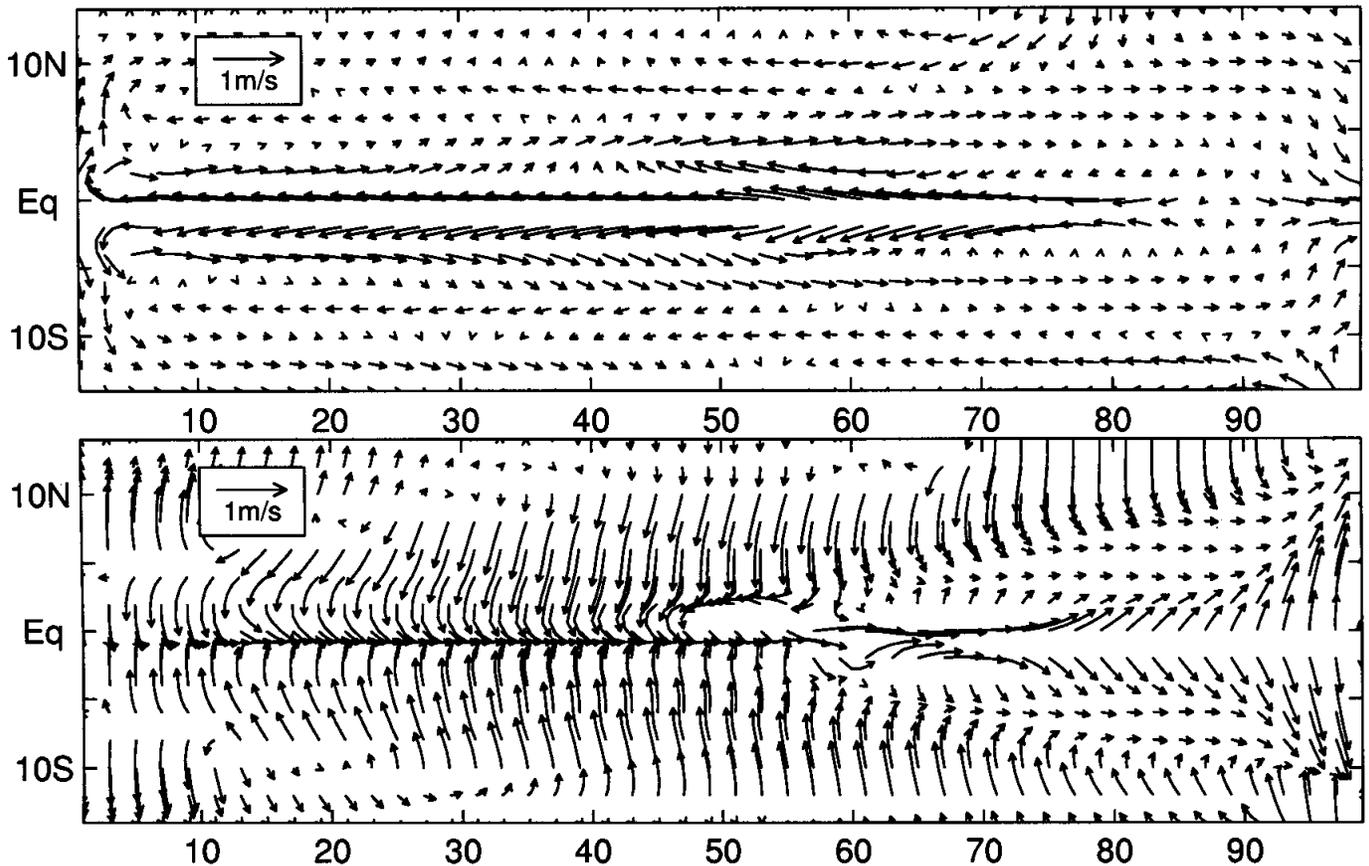
(a) 1st Layer: SEC

(b) 2nd Layer: EUC



Westward Shift of the Trade Wind Maximum $X = 53^\circ$

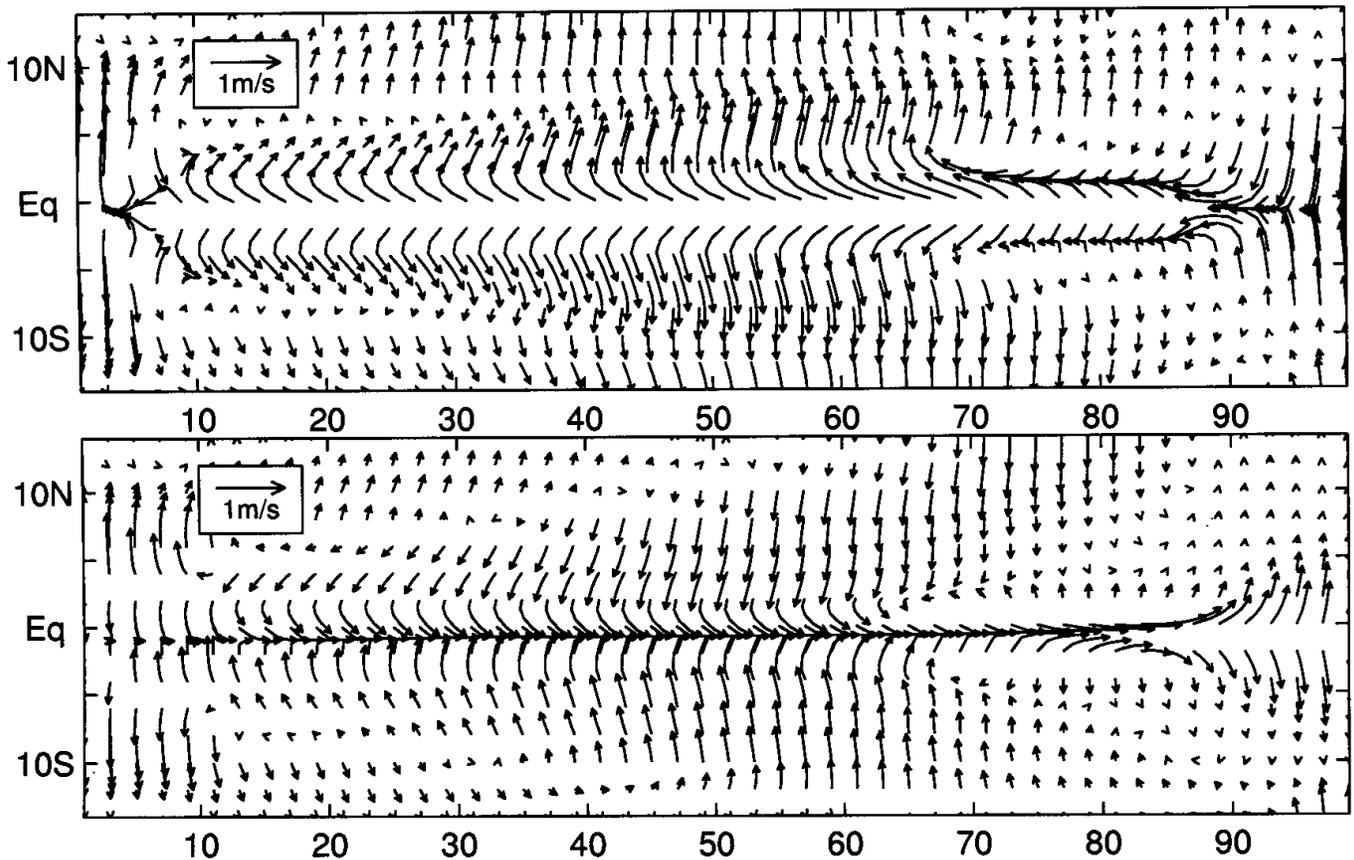
Westward Shift of Maximum Currents



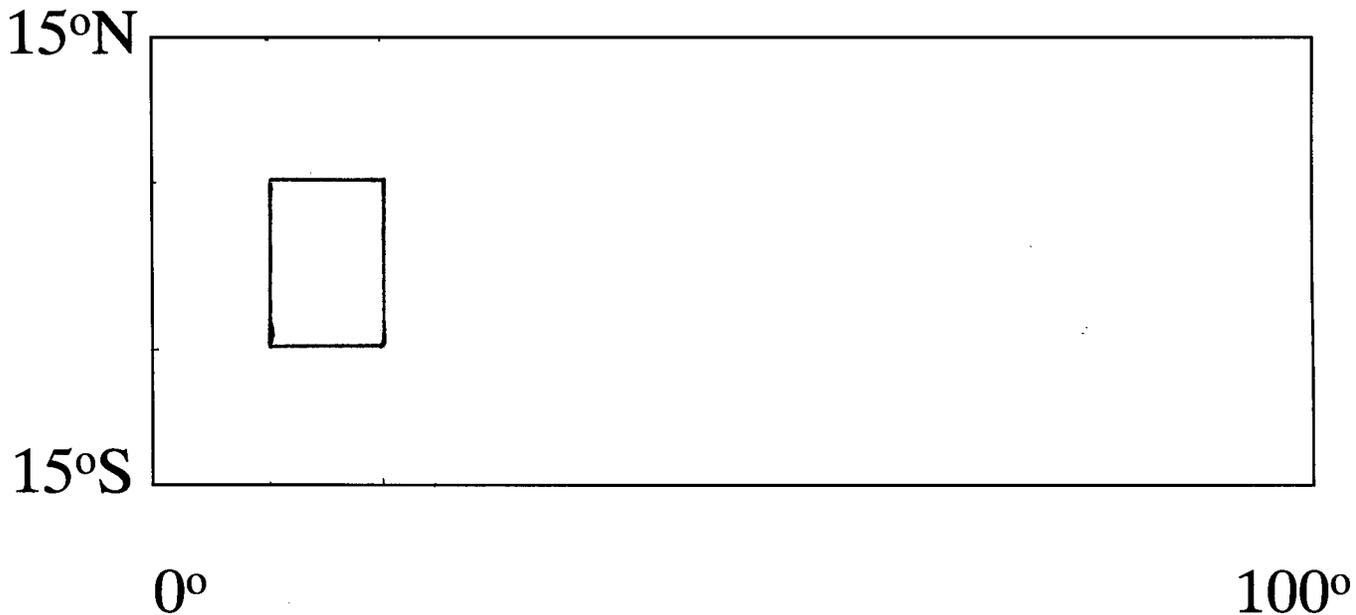
Trade Winds Reduced to 70%

(a) SEC weakens

(b) EUC weakens



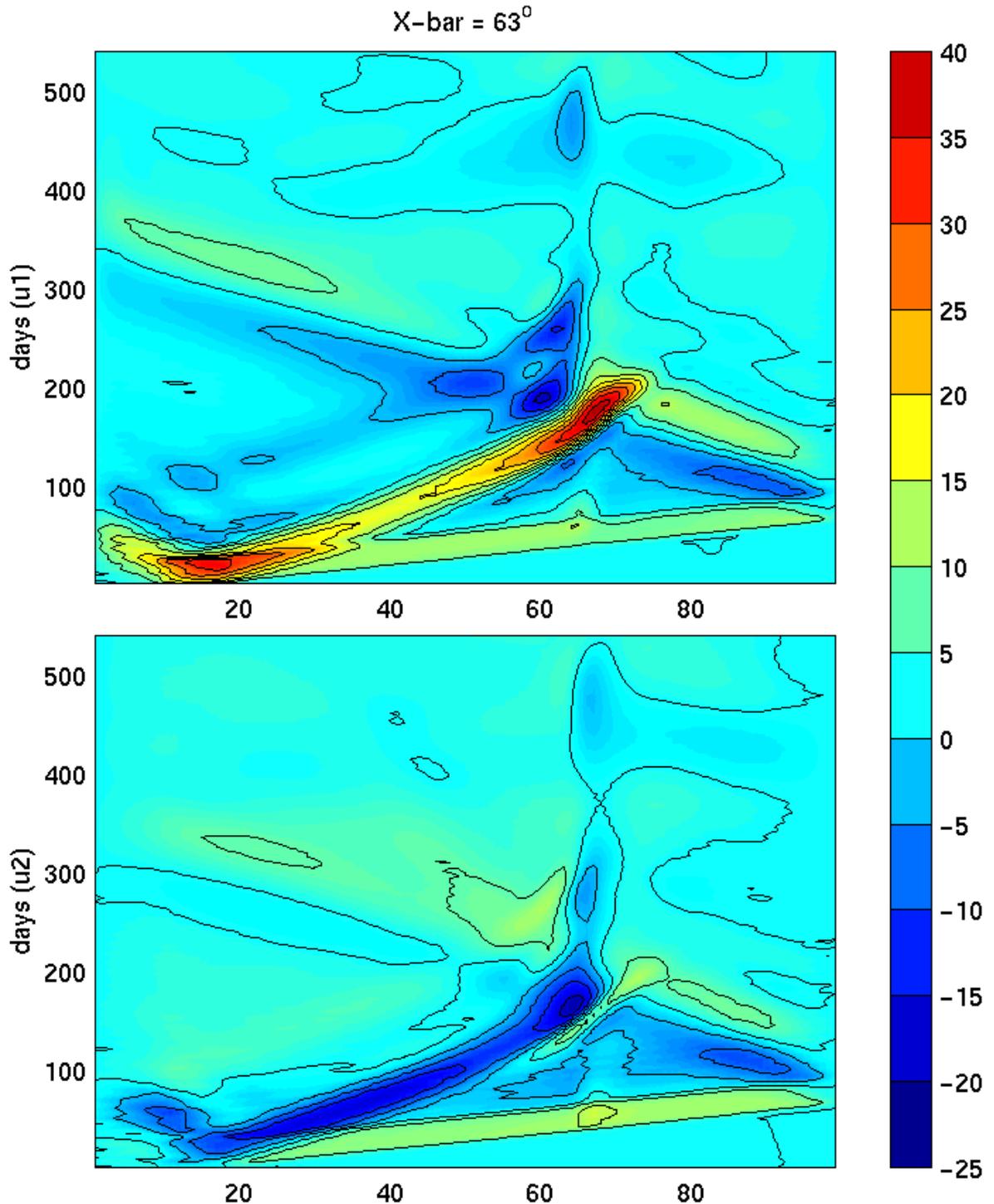
Westerly Wind Burst Patch



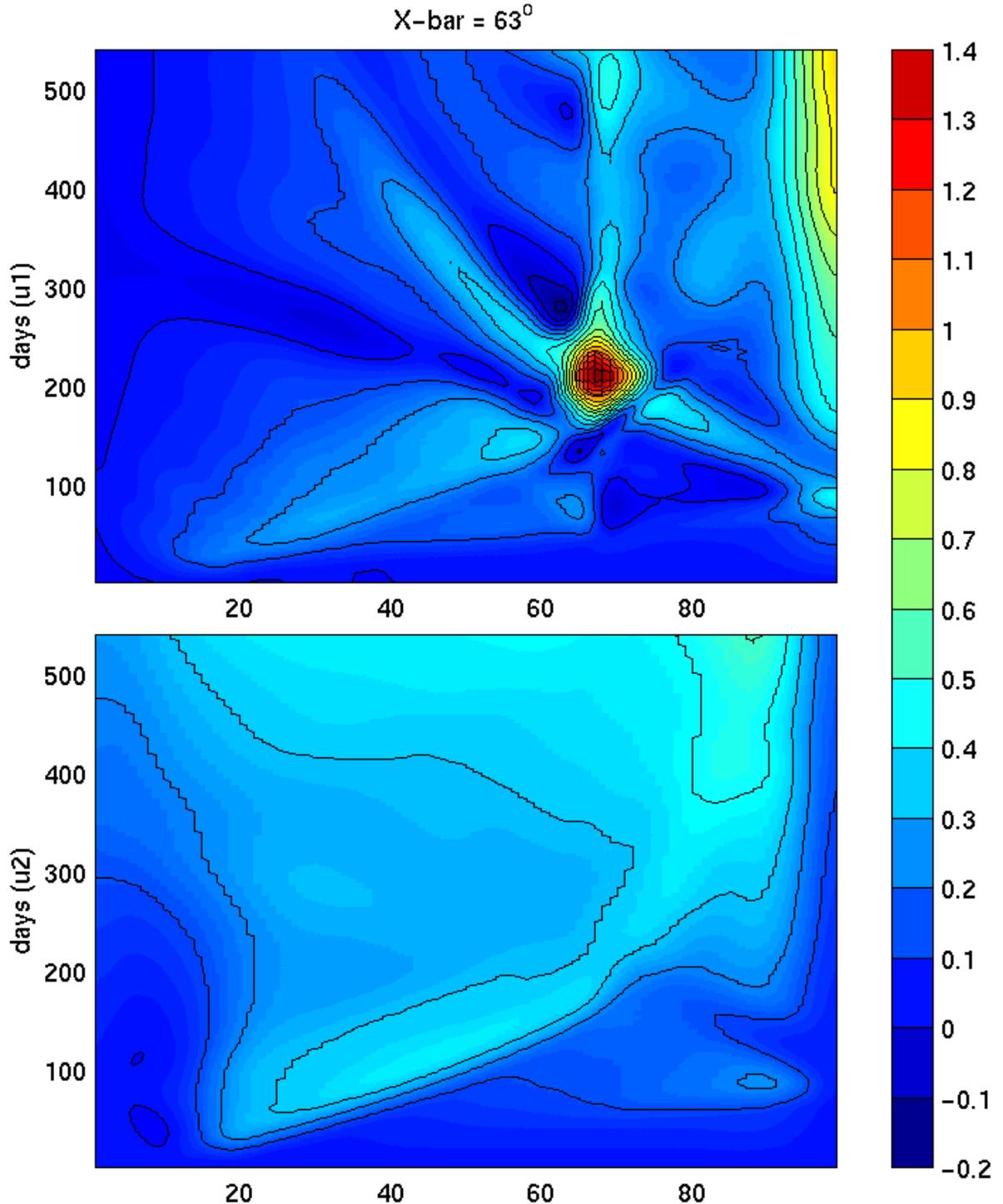
Westerly wind = 10 m/s

Westerly wind patch is added
at day-1080 for 25 days,
and then is removed.

Time-Longitude Cross Section of Zonal Velocity Anomaly (cm/s) : (a) 1st Layer, (b) 2nd Layer (Control Run)

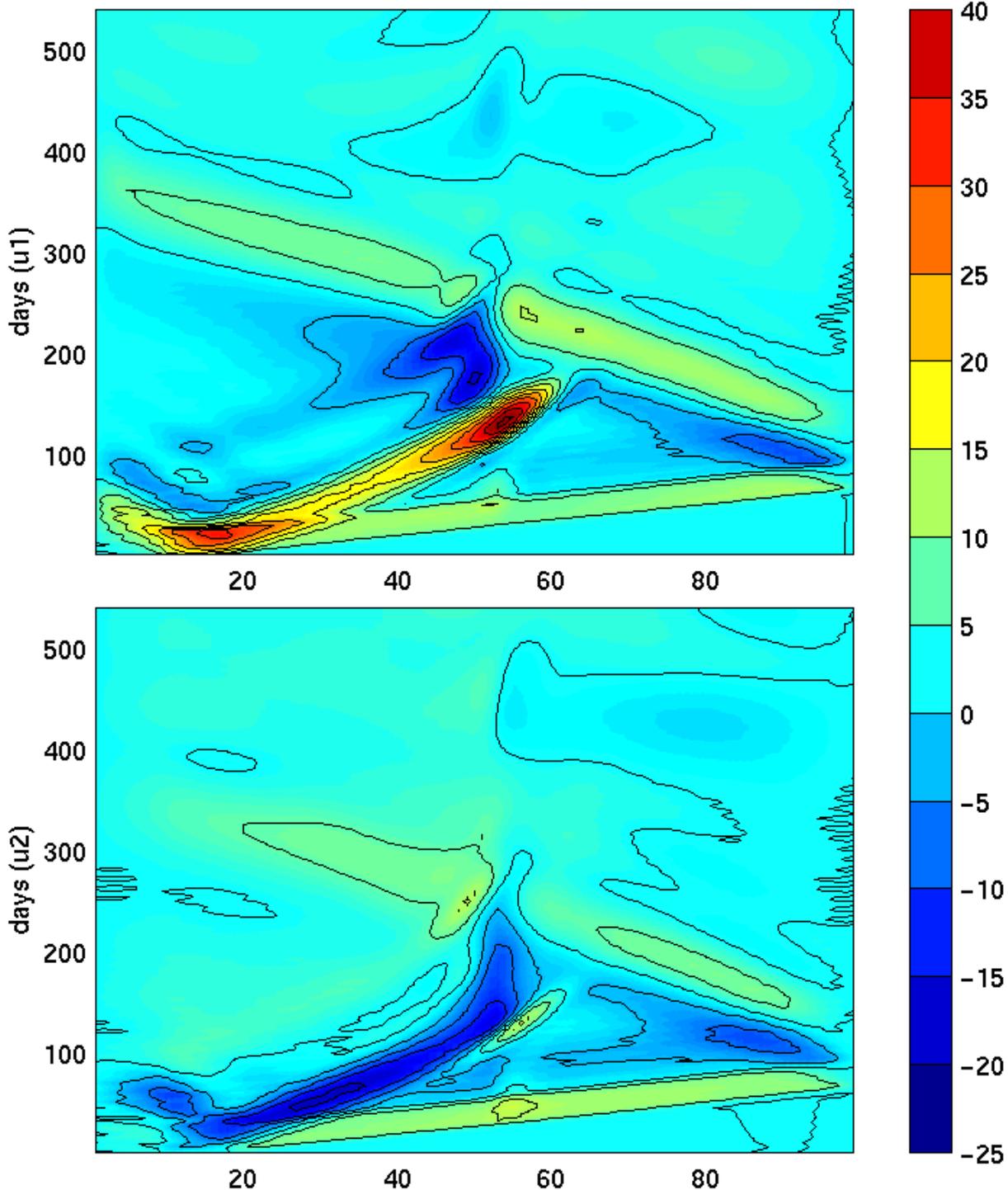


Time-Longitude Cross Section of Temperature Anomaly ($^{\circ}\text{C}$) : (a) 1st Layer, (b) 2nd Layer (Control Run)



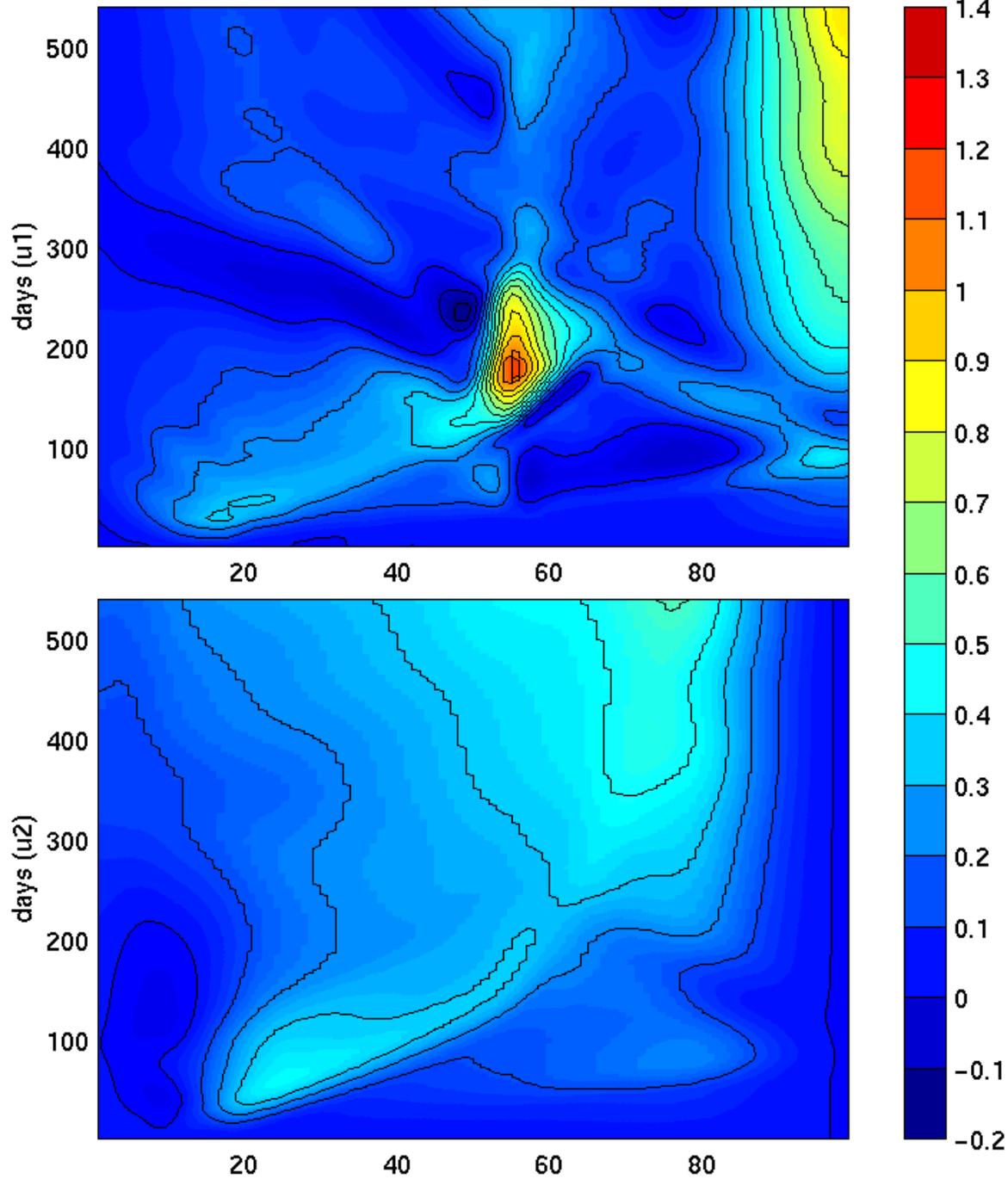
Time-Longitude Cross Section of Zonal Velocity Anomaly (cm/s) : (a) 1st Layer, (b) 2nd Layer (Trade Wind Maximum Shifted Westward)

$\bar{X} = 53^\circ$

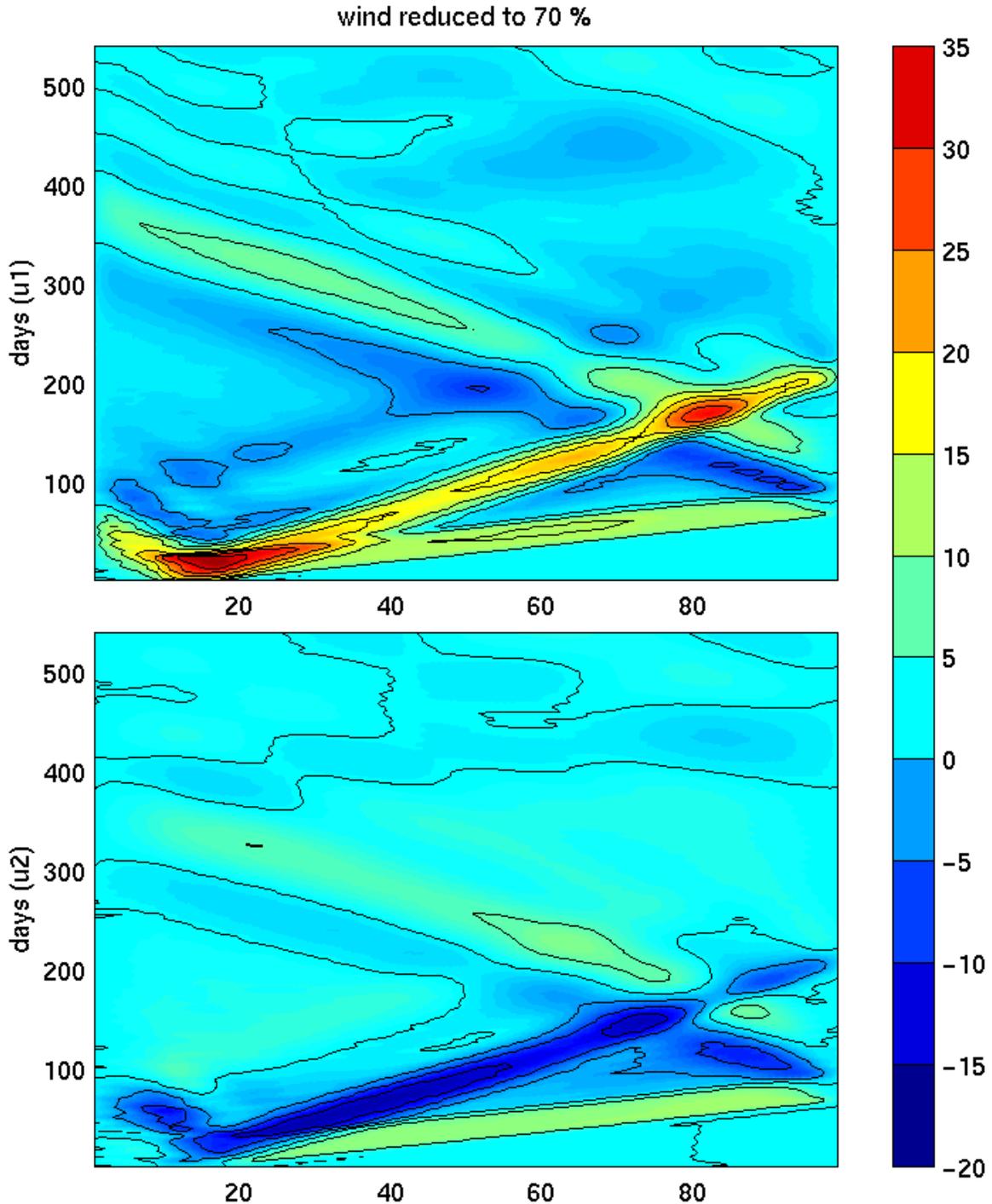


Time-Longitude Cross Section of Temperature Anomaly ($^{\circ}\text{C}$) : (a) 1st Layer, (b) 2nd Layer (Trade Wind Maximum Shifted Westward)

$\bar{X} = 53^{\circ}$

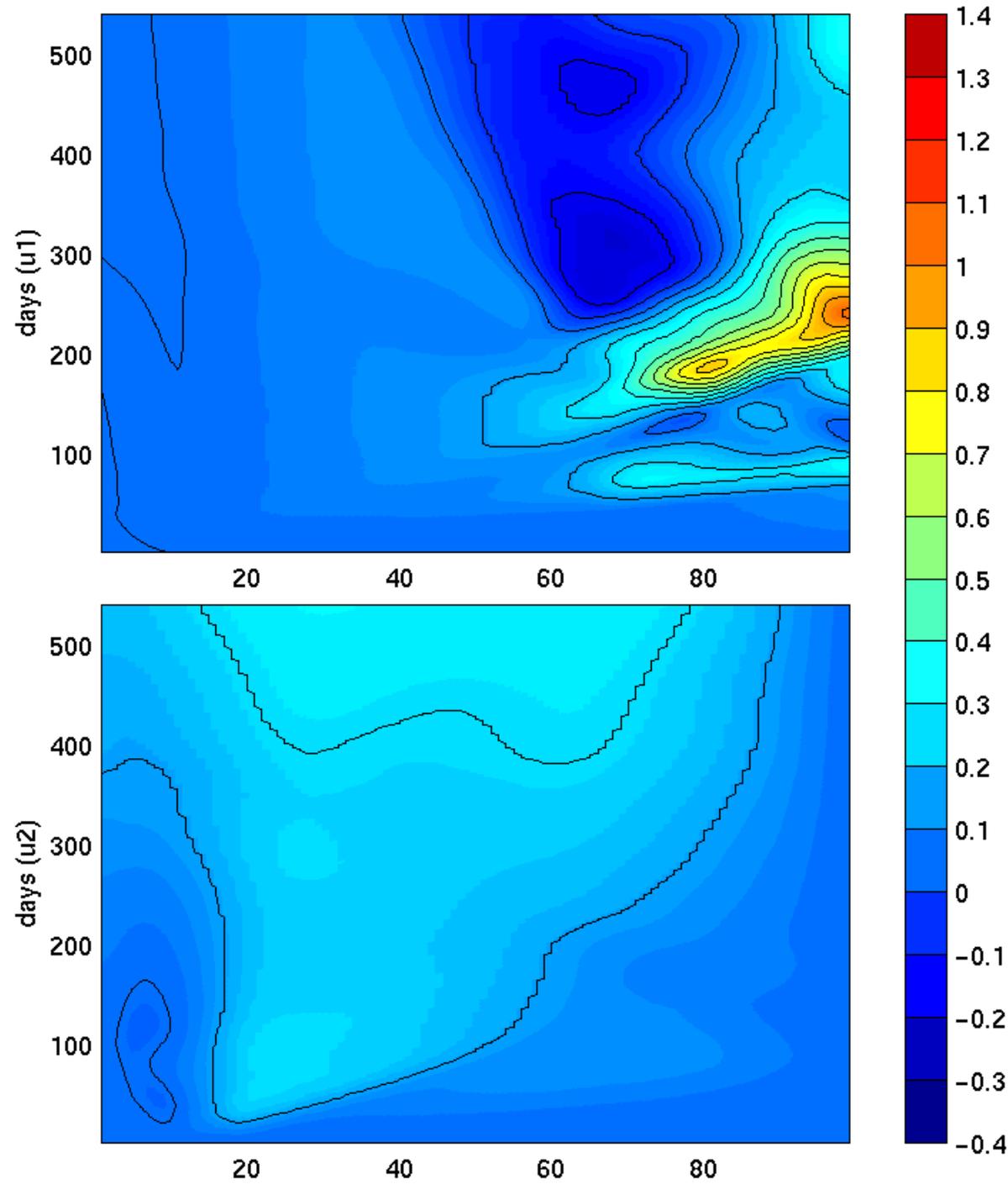


Time-Longitude Cross Section of Zonal Velocity Anomaly (cm/s) : (a) 1st Layer, (b) 2nd Layer (Trade Winds Reduced to 70%)



Time-Longitude Cross Section of Temperature Anomaly ($^{\circ}\text{C}$) : (a) 1st Layer, (b) 2nd Layer (Trade Winds Reduced to 70%)

wind reduced to 70 %



Conclusions

- GCM weakens the surface cold advection that may lead to central Pacific warming
- Second baroclinic Kelvin waves cause GCM.
- Two-stage air-sea interaction mechanism is proposed for the El Nino onset.

Two-Stage Air-Sea Interaction Mechanism

