High Baroclinic Equatorial Kelvin Waves and Central Pacific Surface Warming

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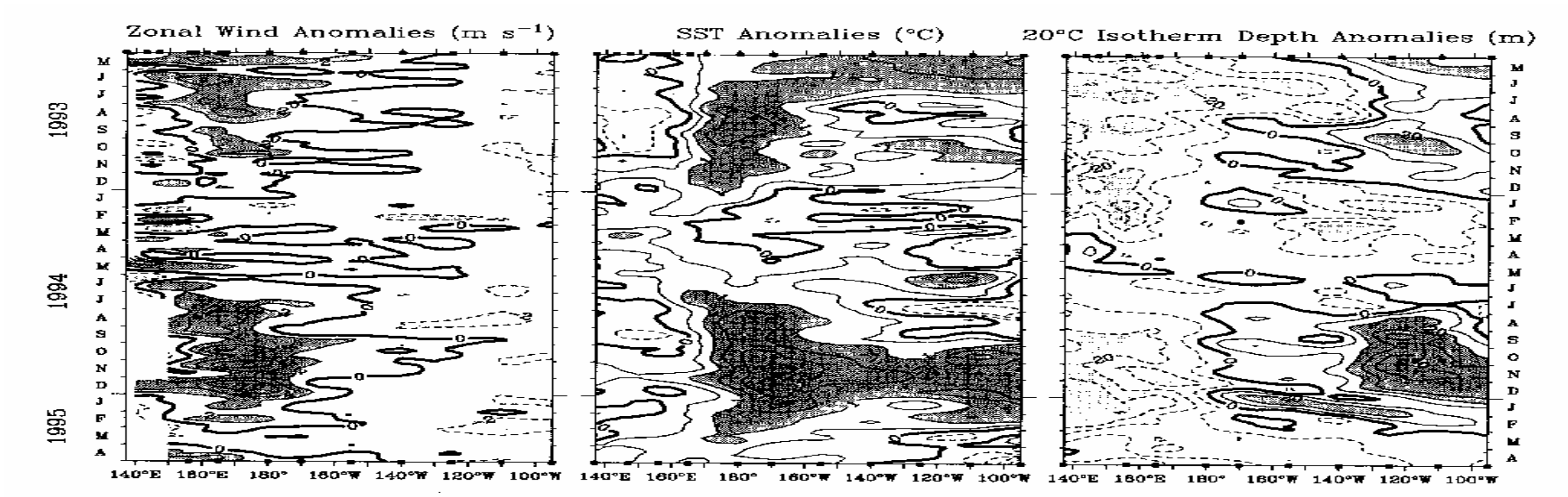
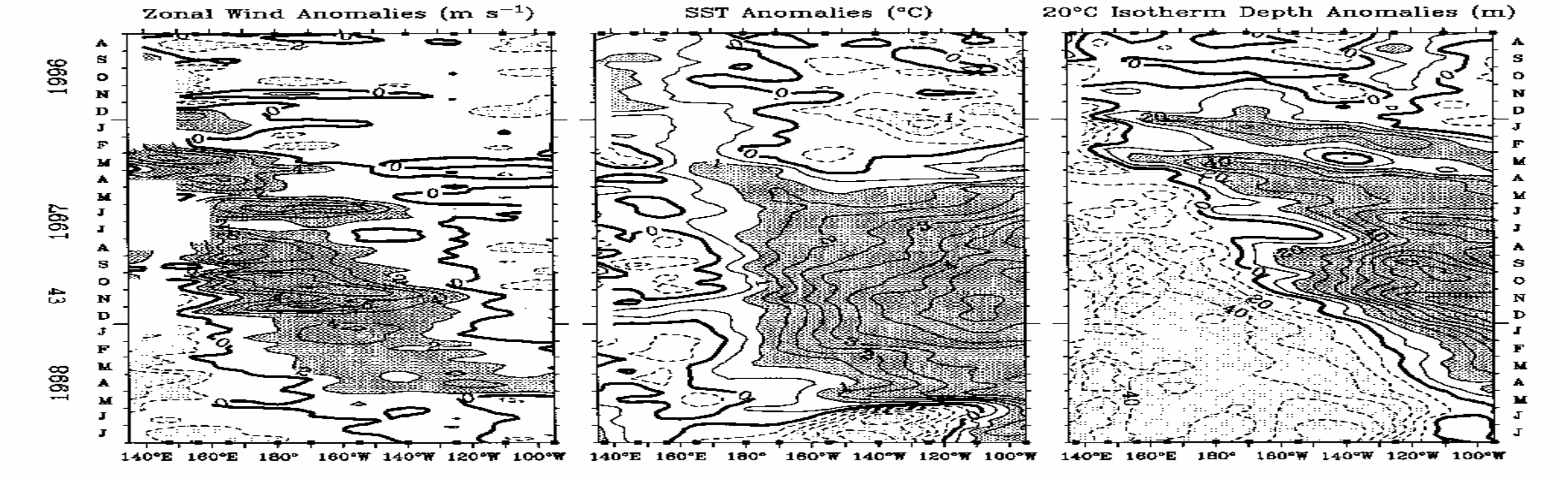
Outline

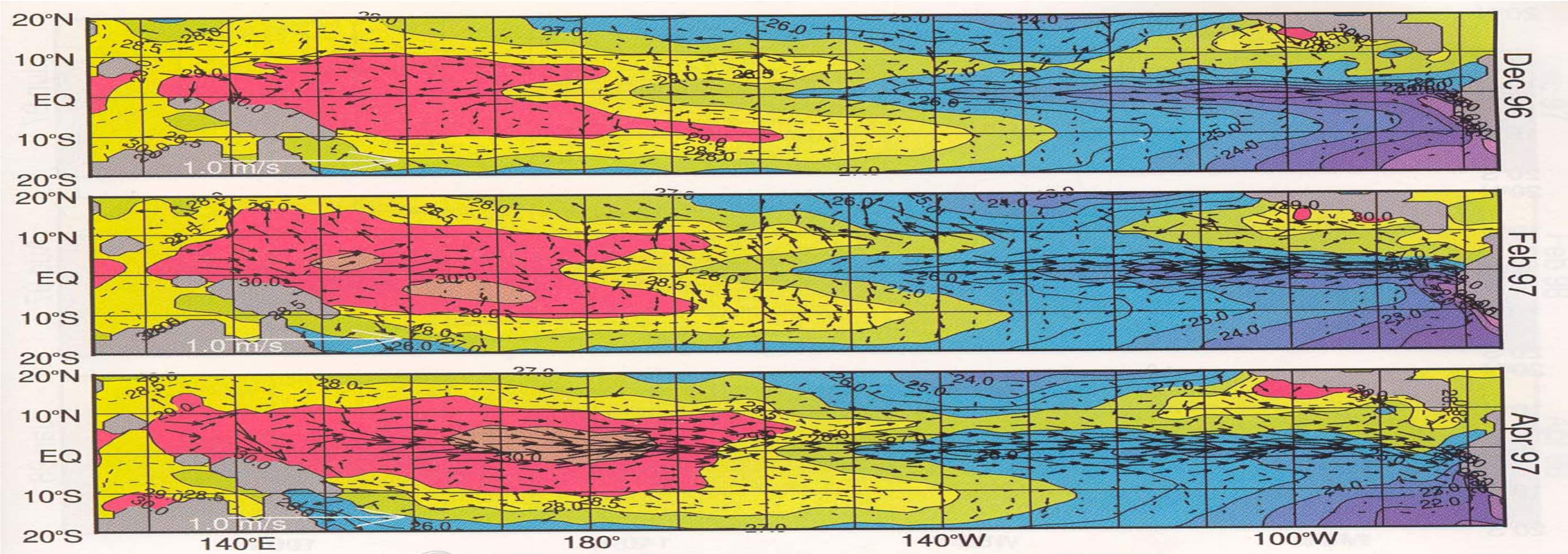
- Enhancing Counter Mode (ECM)
- Second Baroclinic Equatorial Kelvin Waves
- Two-Stage Air-Sea Interaction for the El Nino Onset

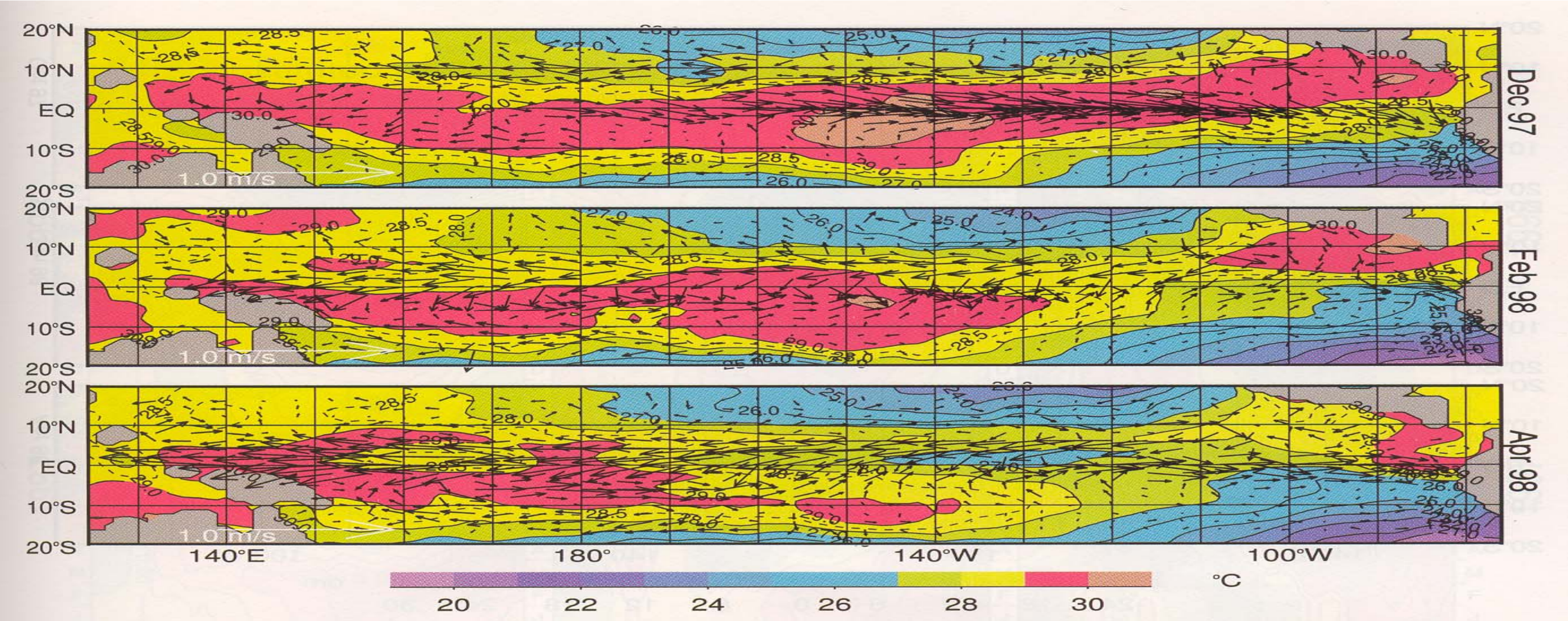
Central Pacific Warming Prior to the El Nino Onsets in 90's



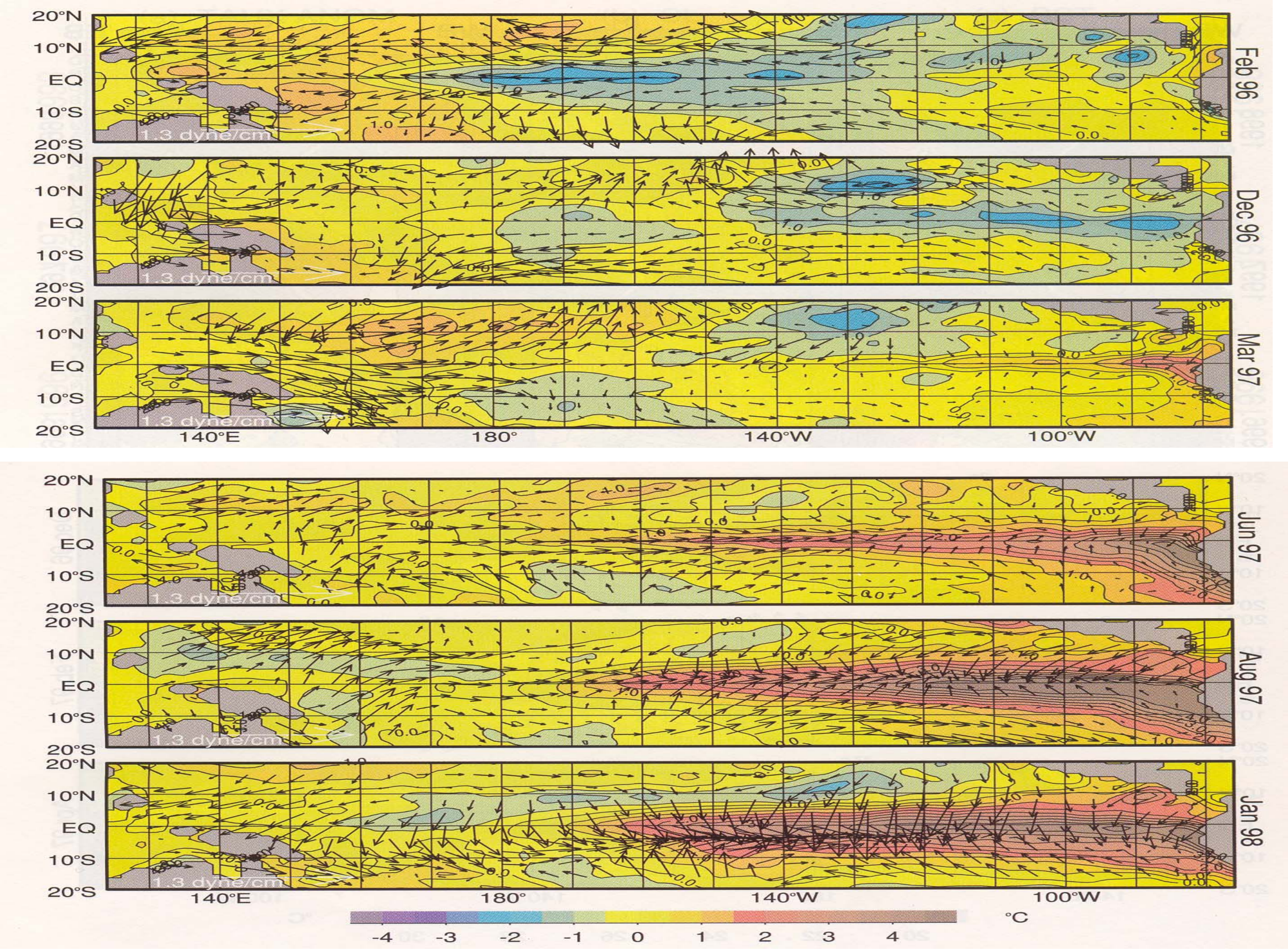


1997 El Nino – Central Pacific Warming (Picaut et al. 2002)





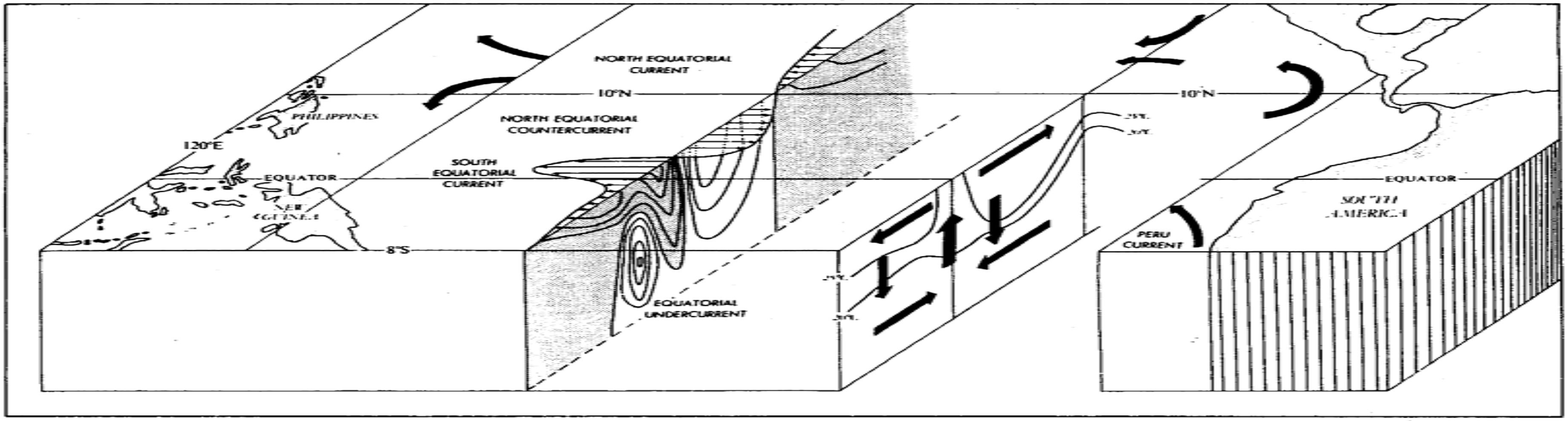
1997 El Nino – Westerly Wind Burst (Picaut et al. 2002)



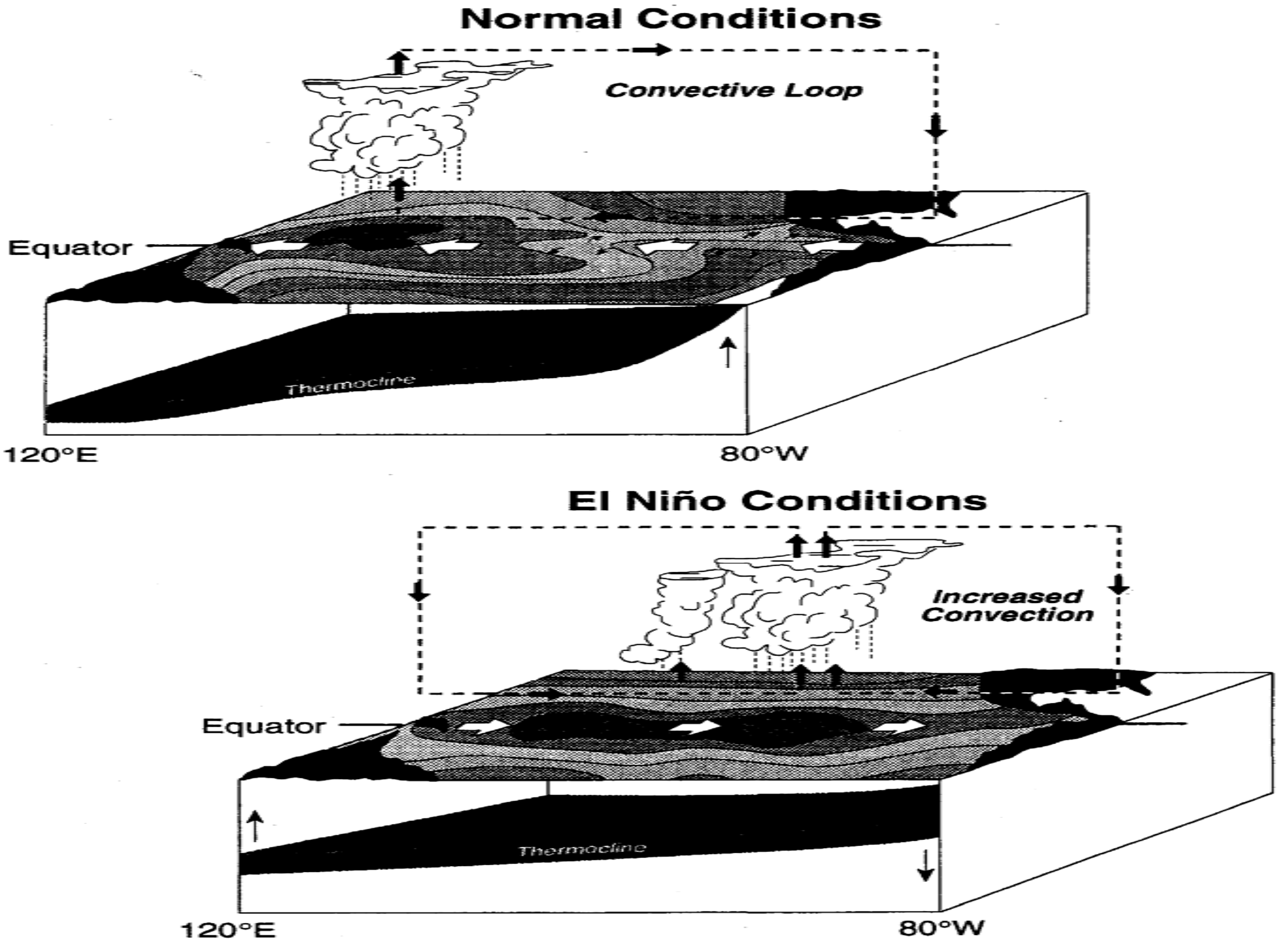
Equatorial Current System

Upper Layer:
Westward Flowing
South Equatorial Current (SEC)

Thermocline:
Eastward Flowing
Equatorial Counter Current (EUC)



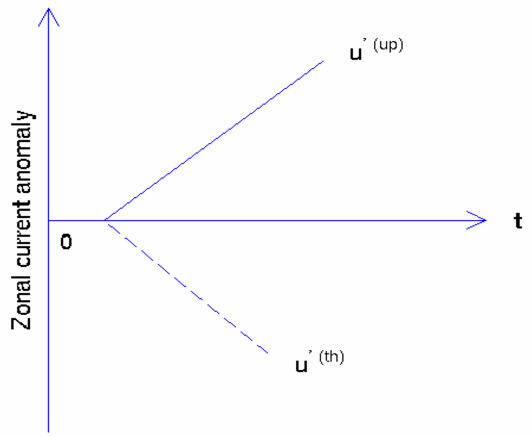
McPhaden et al. (JGR, 1998)



Mean Current System

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

Perturbation Current System Enhancing Counter Mode (ECM)



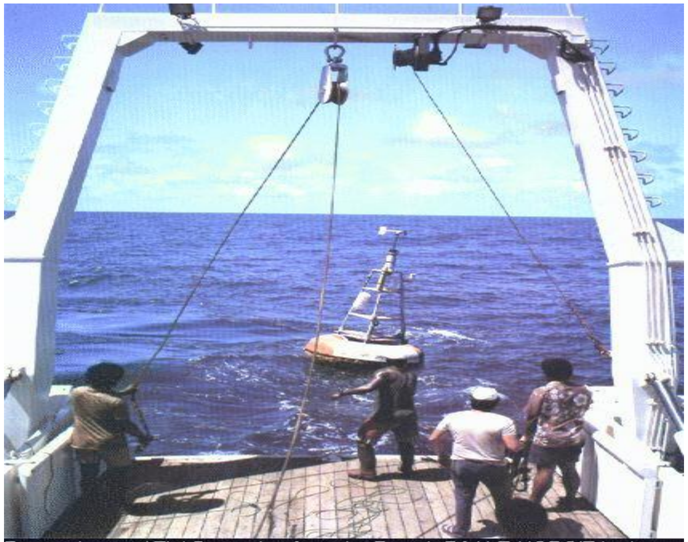
$$u'^{(Up)} > 0, \quad \partial u'^{(Up)}/\partial t > 0$$

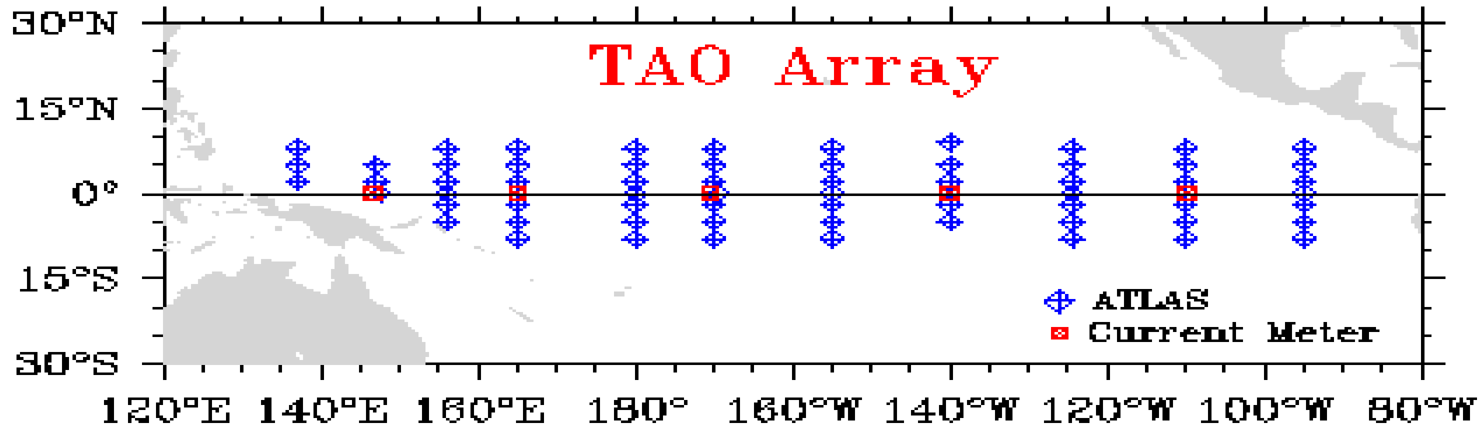
$$u'^{(Th)} < 0, \quad \partial u'^{(Th)}/\partial t < 0$$

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

Enhancing CM Detected from TAO Data


Servicing an ATLAS mooring of the TOGA-TAO Array. ATLAS moorings measure surface winds, air temperature, relative humidity, sea surface temperature, and subsurface temperature to depths of 500 m.

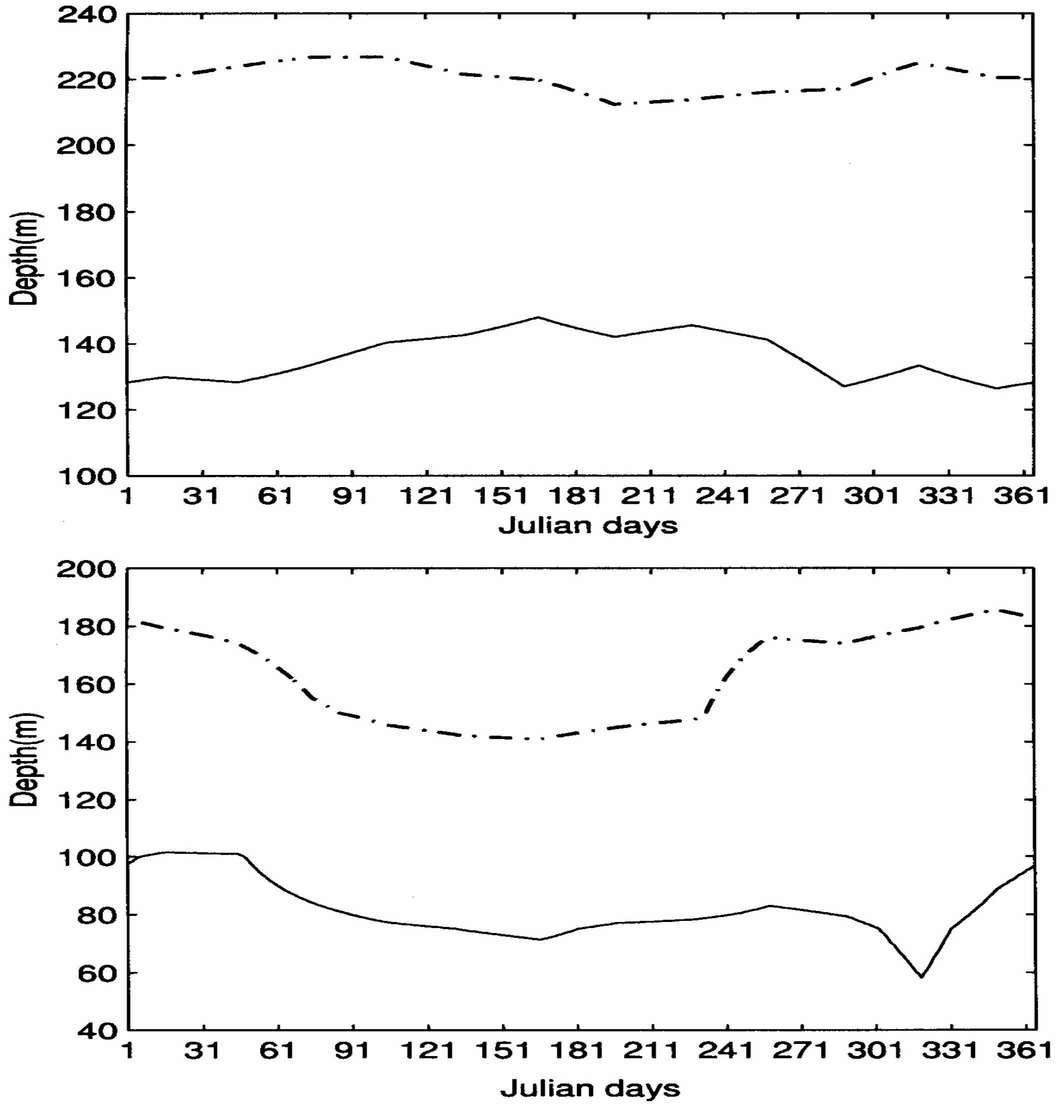

Recovering an ATLAS mooring from the French R/V LE NOROIT in the western equatorial Pacific Ocean. A total of 59 ATLAS moorings are deployed at present in the equatorial Pacific as part of the TOGA-TAO Array.



TAO Project Office/NOAA/PMEL

Upper Layer and Thermocline (Wyrtki and Kilonsky 1984)

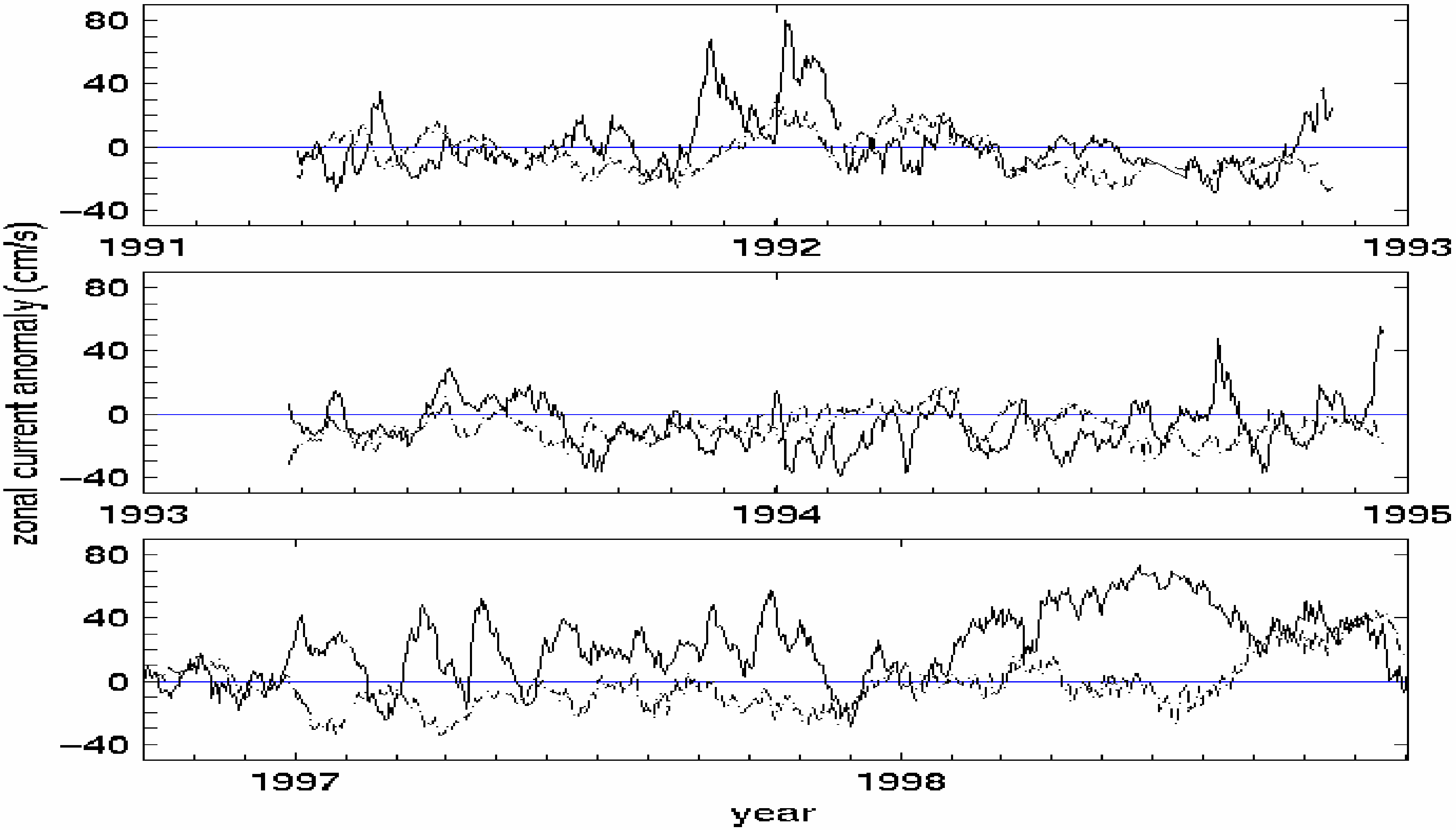
- Hawaii to Tahiti Temperature Data (1978-1980)
- Upper Layer
  - Surface to 25^{o}C depth
- Thermocline
  - 25^{o}C depth to 15^{o}C depth



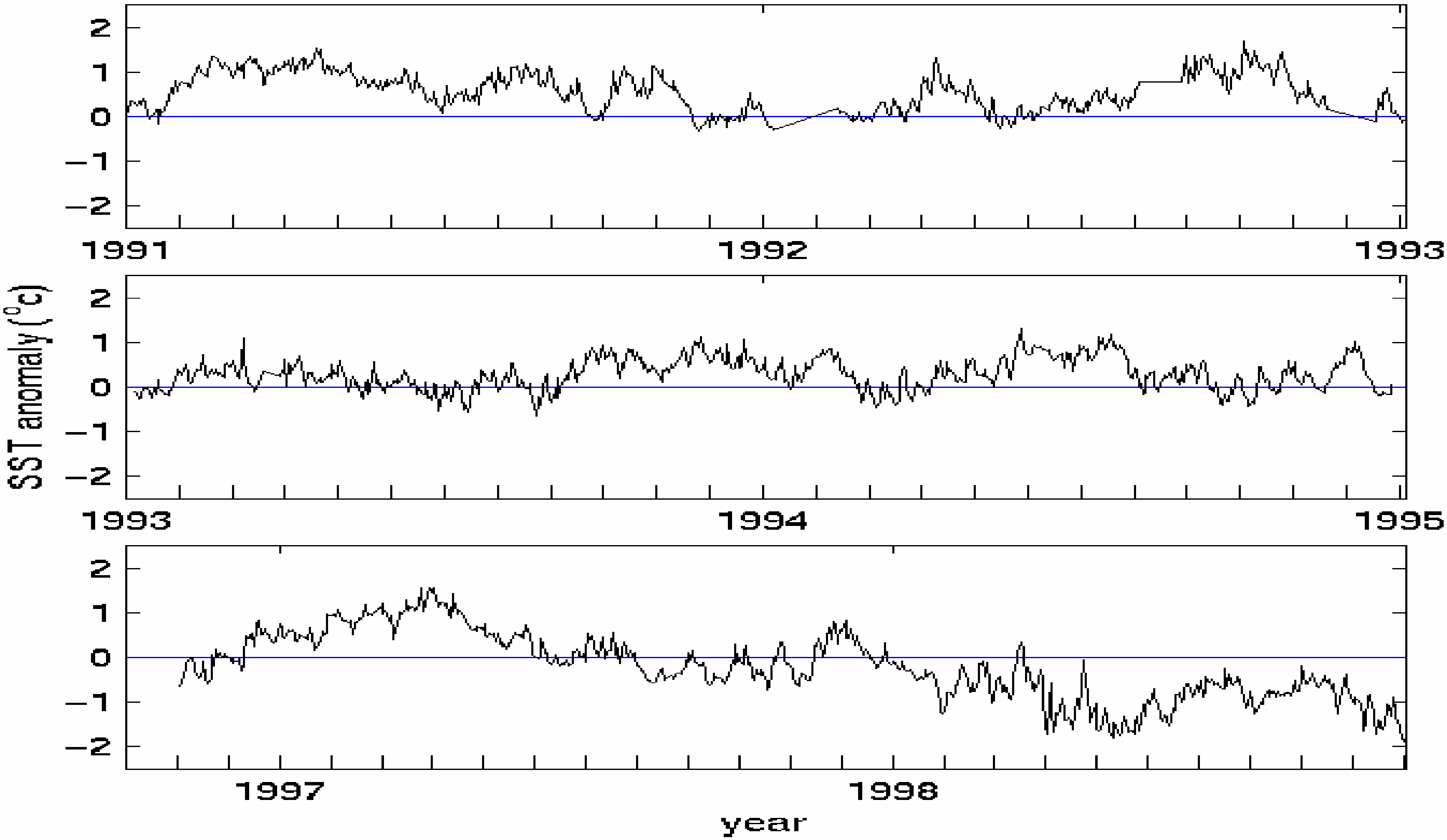
(a) 165^{o}E

(b) 140^{o}W

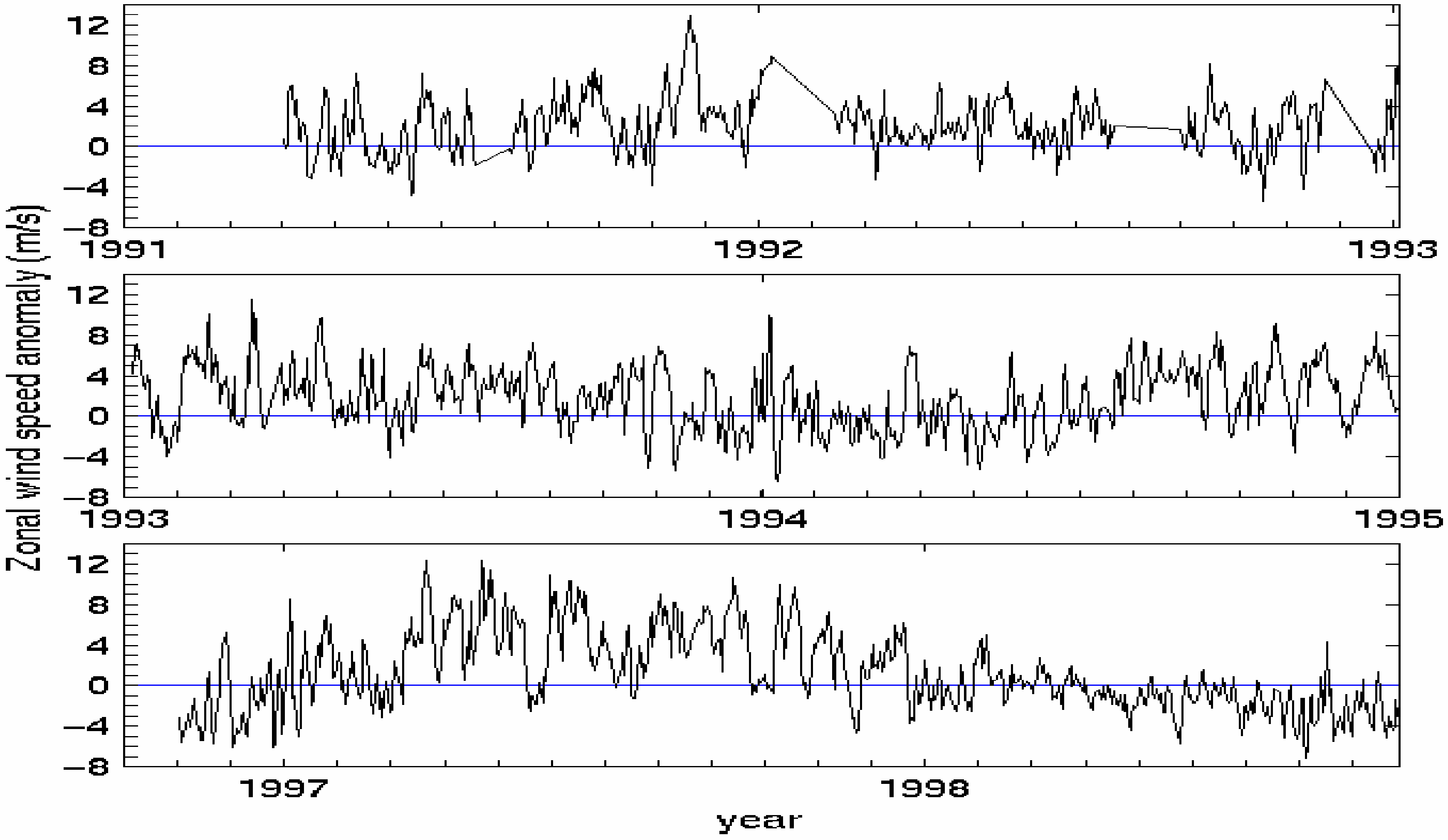
Daily Mean Depths of 25^{o}C (Solid) and 15^{o}C (dashed) Isotherms at (a) 165^{o}E, and (b) 140^{o}W along the Equator.



Enhancing CM detected from the TAO data at 165ºE. Here solid (dashed) curve is the upper layer (thermocline) zonal speed anomaly.



Time evolution of SST anomaly at 165^{o}E (solid). Note that SST warm anomaly appears during the ECM 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 ECM periods.

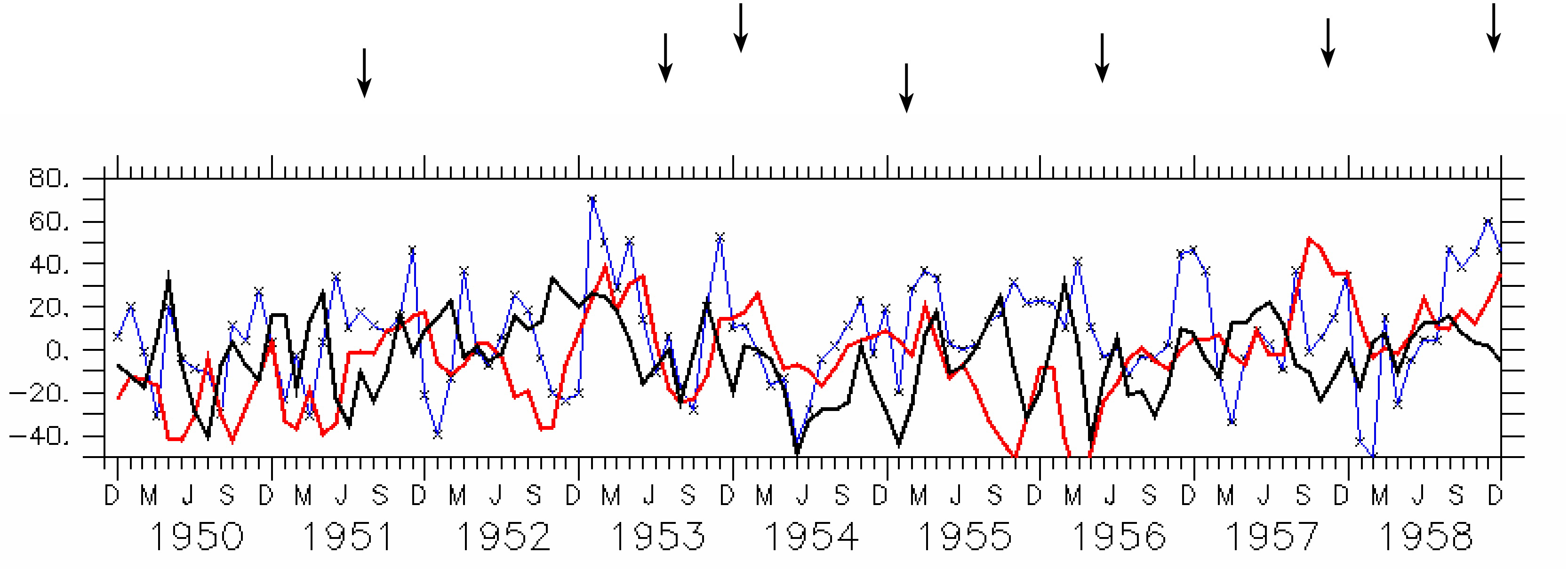
Simple Ocean Data Assimilation (SODA) System (Carton et al., 2000)

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

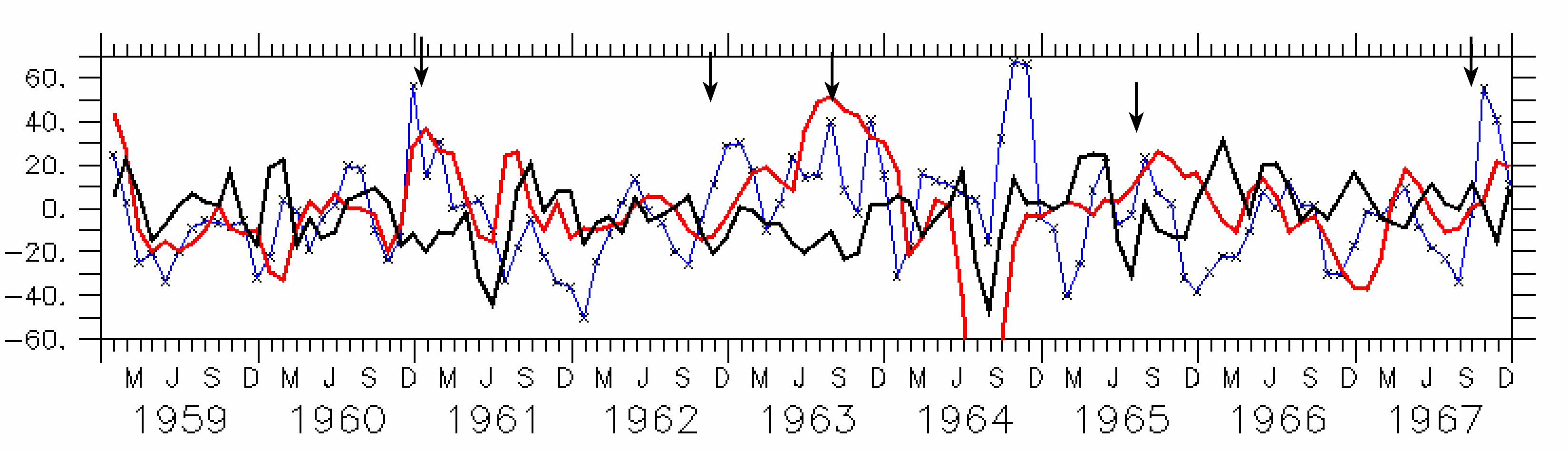
ECM Detected from SODA Data

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

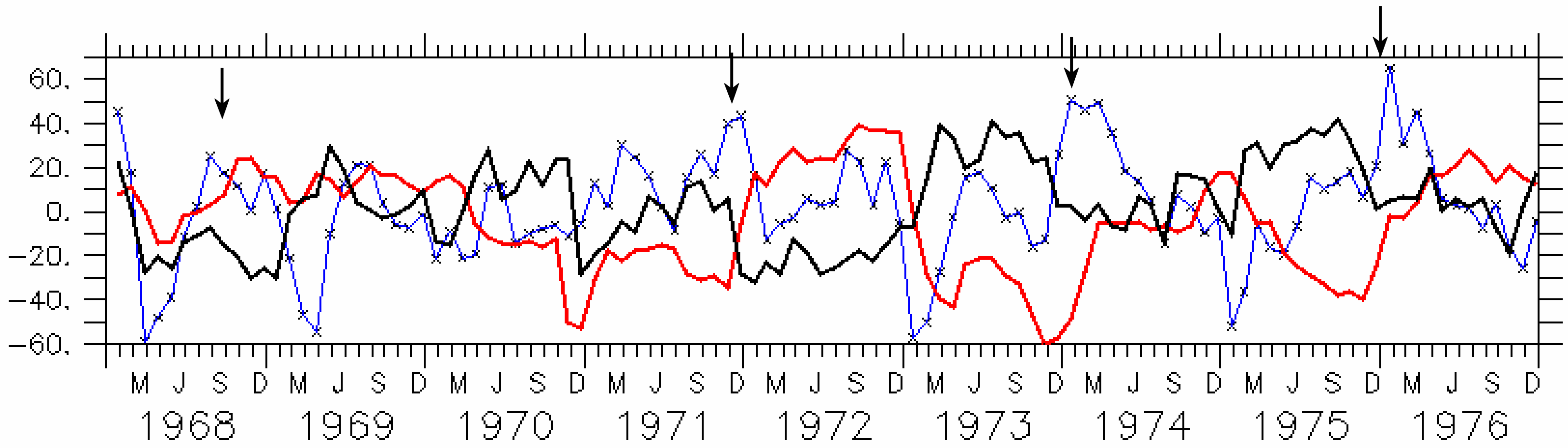
Upper Layer *u'* (cm/s, Blue)
Thermocline *u'* (cm/s, Black)
SST' (^{o}C * 12)
at 165^{o}E



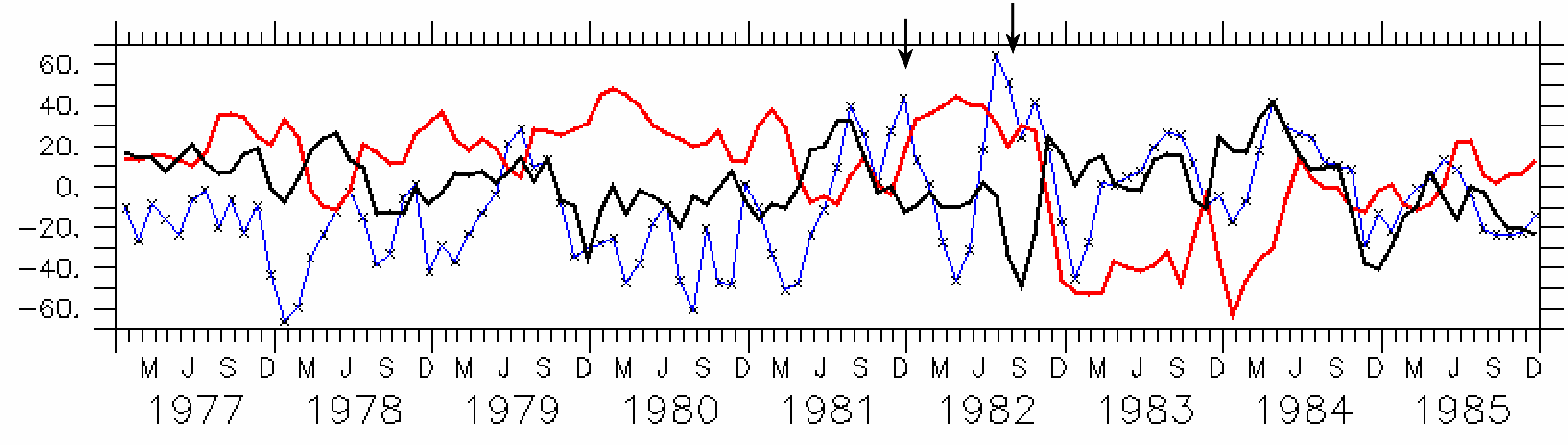
Upper Layer *u’* (cm/s, Blue)
Thermocline *u’* (cm/s, Black)
SST’ (^{o}C * 12)
at 165^{o}E



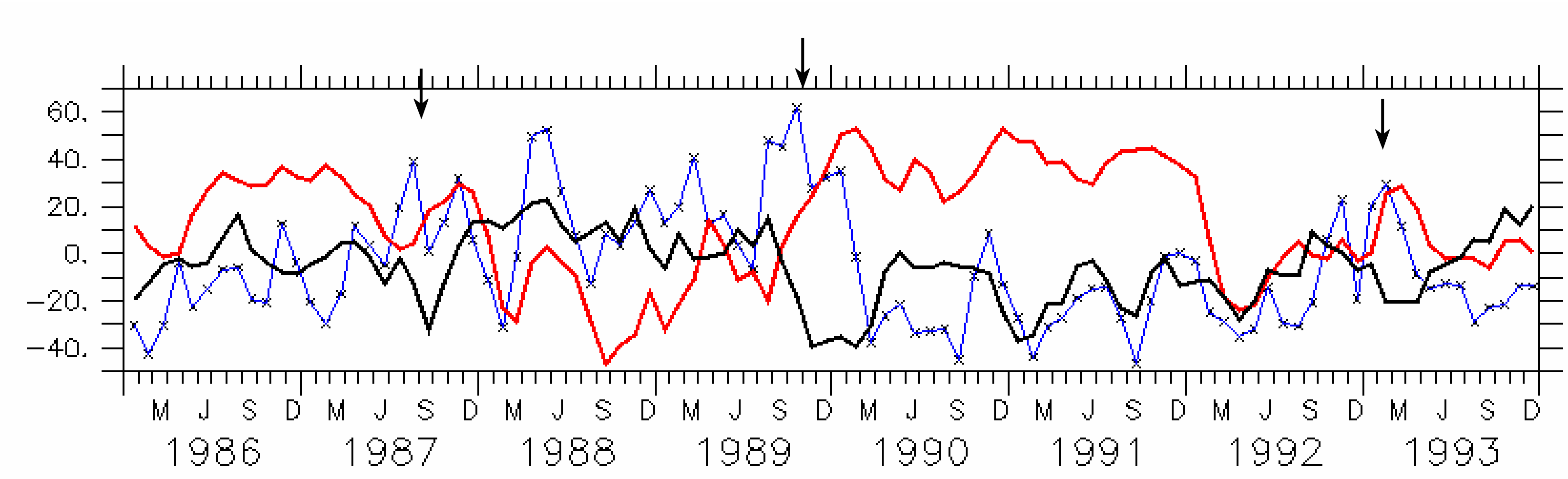
Upper Layer *u'* (cm/s, Blue)
Thermocline *u'* (cm/s, Black)
SST' (^{o}C * 12)
at 165^{o}E



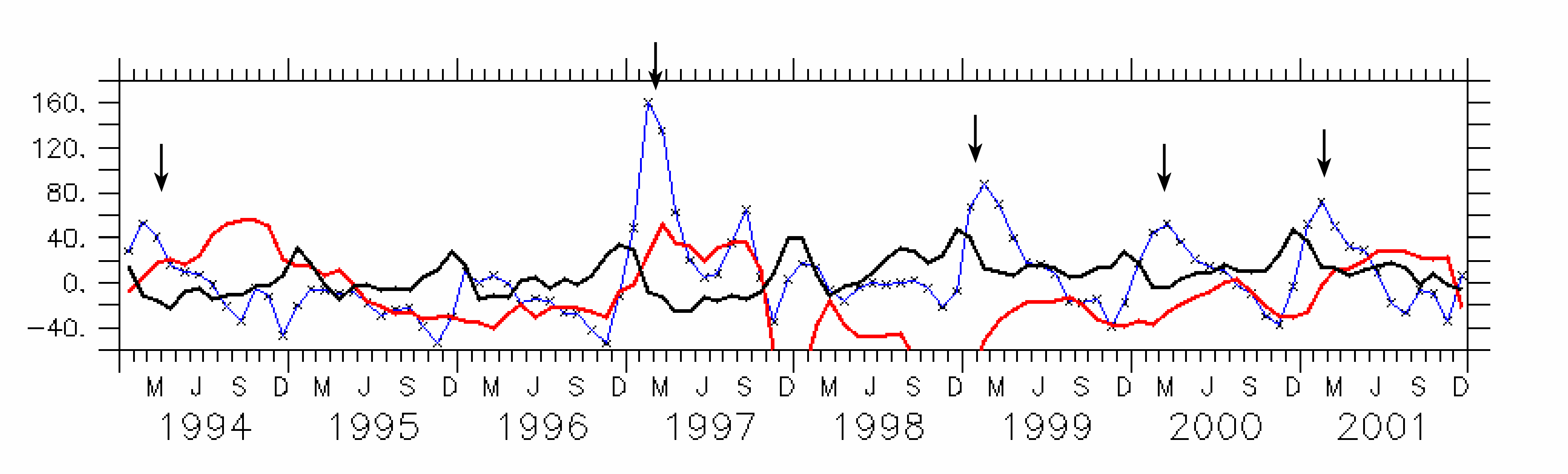
Upper Layer *u'* (cm/s, Blue)
Thermocline *u'* (cm/s, Black)
SST' (^{o}C * 12)
at 165^{o}E



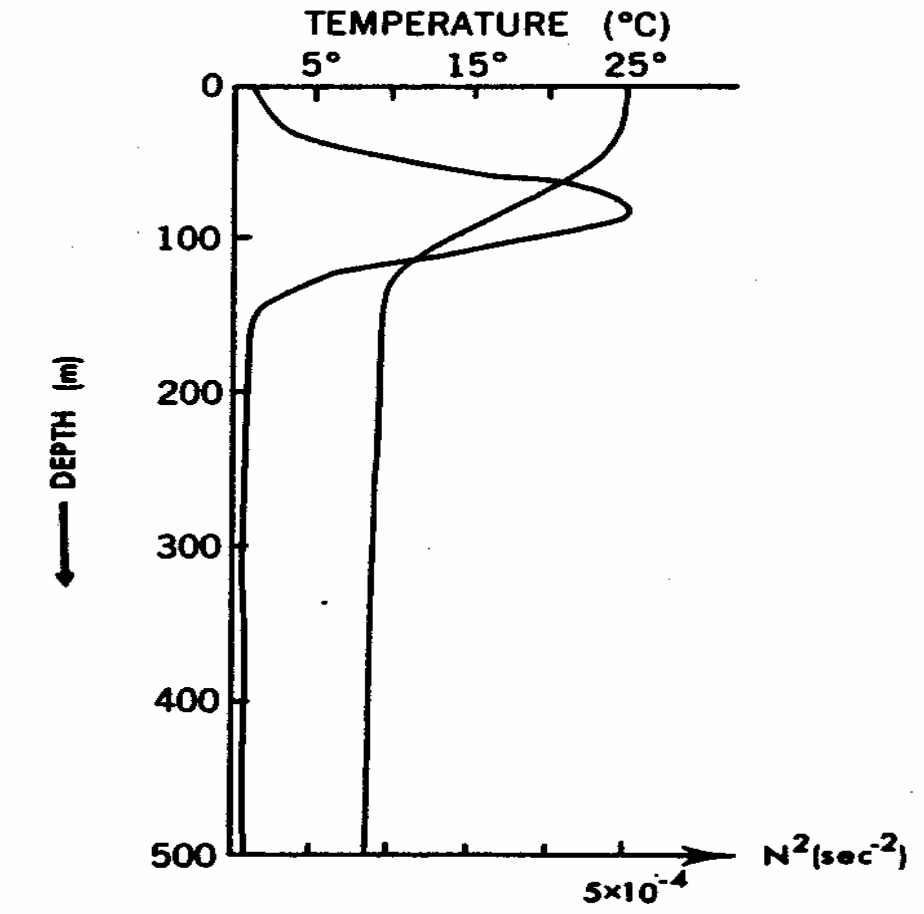
Upper Layer *u’* (cm/s, Blue) Thermocline *u’* (cm/s, Black) SST’ (^{o}C * 12) at 165^{o}E



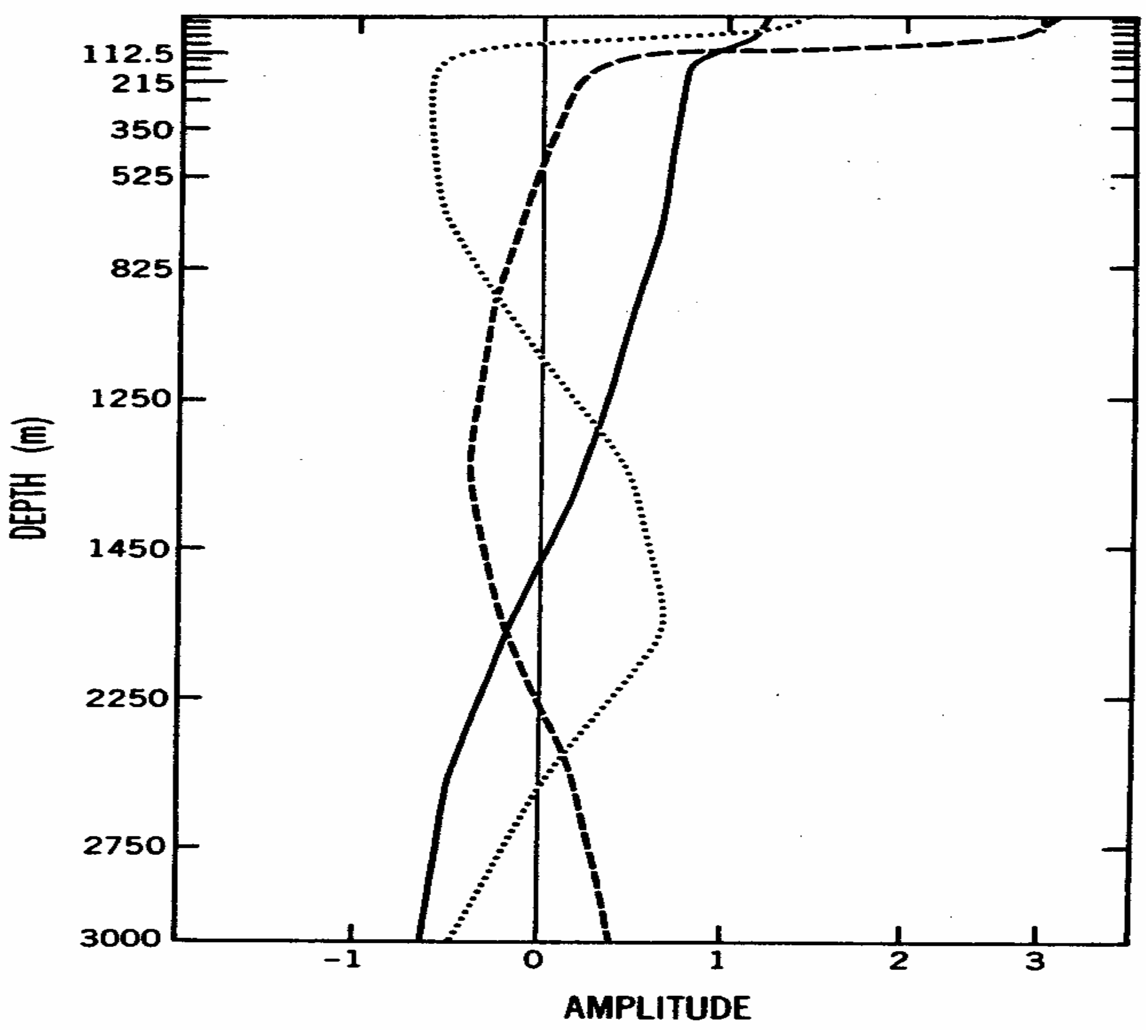
Upper Layer *u'* (cm/s, Blue)
Thermocline *u'* (cm/s, Black)
SST' (°C * 12)
at 165°E



Propagation of Second-Baroclinic Kelvin Waves and ECM



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 the 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 ½ (or 1 ½) - Layer
  - The First Two Layers Active
  - The Third Layer Motionless
- Momentum Balance
- Heat Balance
- Entrainment/Detrainment Rate
- Wind Forcing
- 1^o X 1^o Resolution

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

$$= \boldsymbol{\tau} + w_e\mathbf{v}_2 + w_d\mathbf{v}_1 - \upsilon_4 \nabla^4(h_1\mathbf{v}_1) - \gamma h_1 u_1 \mathbf{i},$$

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

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

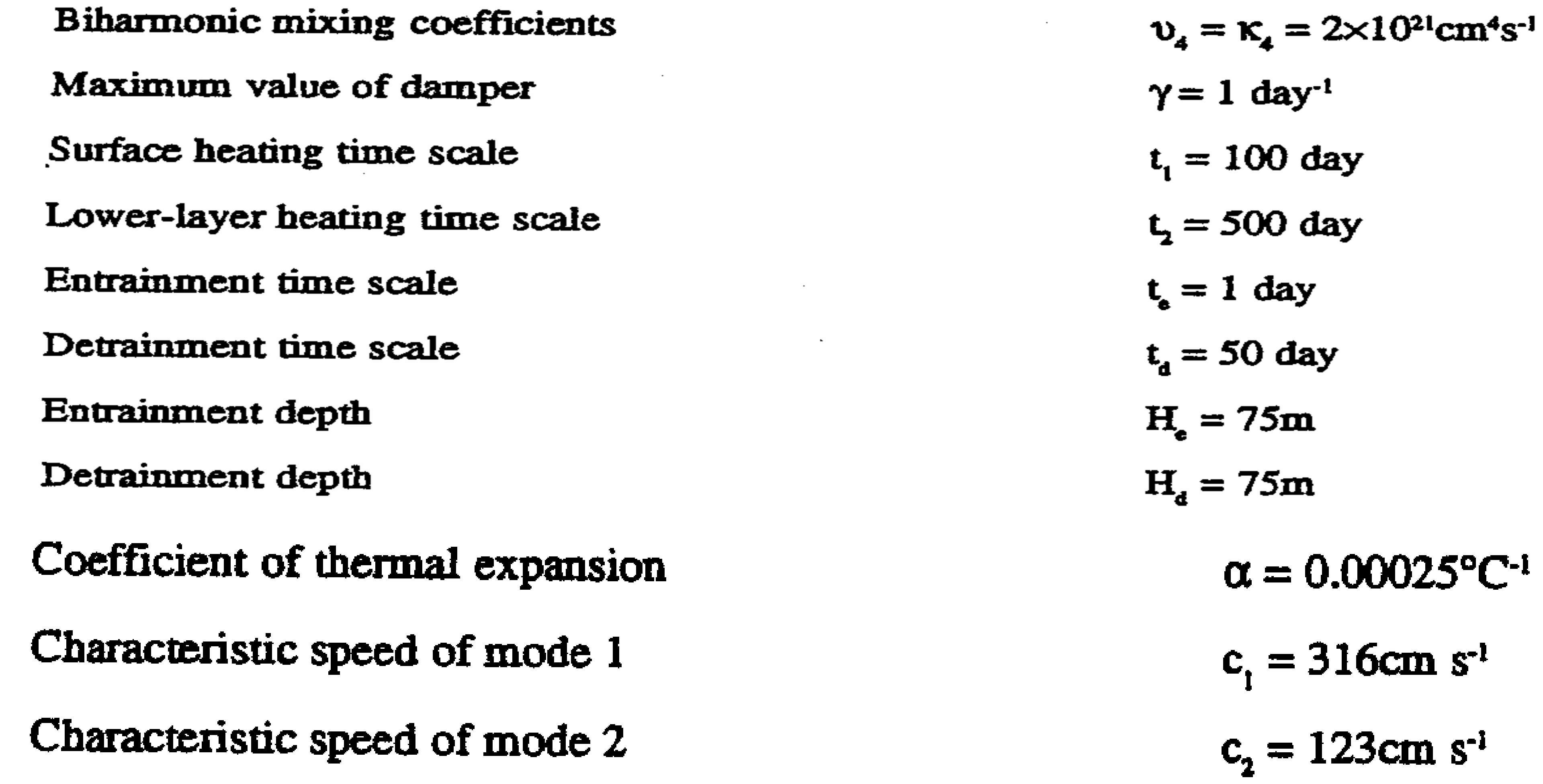
$$(h_2\mathbf{v}_2)_t + \boldsymbol{\nabla}\cdot(\mathbf{v}_2 h_2 \mathbf{v}_2) + f\mathbf{k} \times h_2\mathbf{v}_2 + h_2\langle \boldsymbol{\nabla} p_2 \rangle^z$$

$$= -w_e\mathbf{v}_2 - w_d\mathbf{v}_1 - \upsilon_4 \nabla^4(h_2\mathbf{v}_2) - \gamma h_2 u_2 \mathbf{i},$$

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

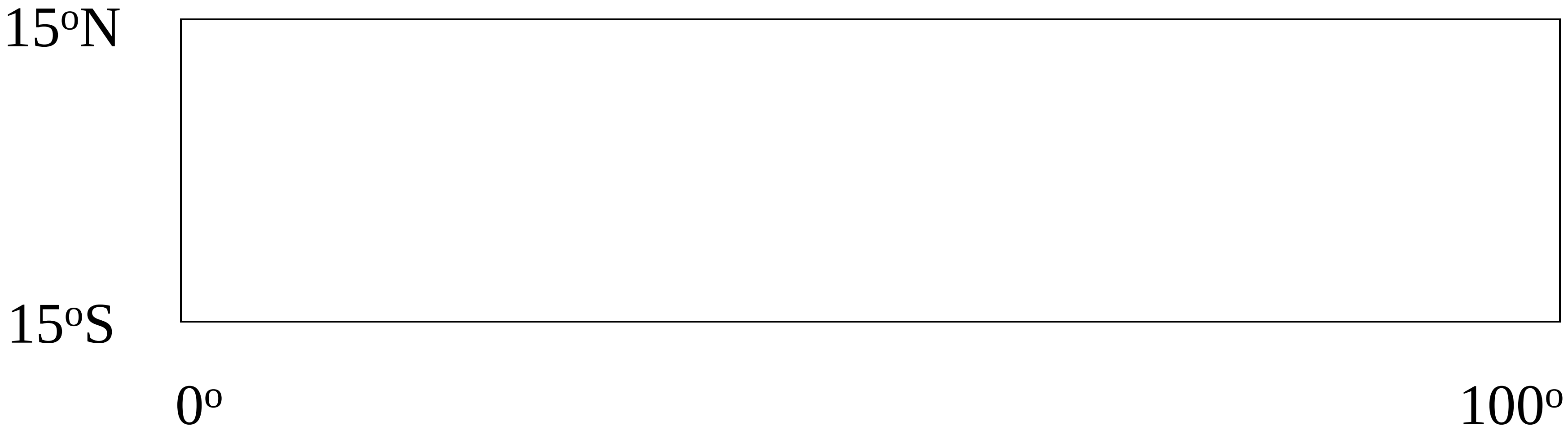
$$T_{2t} + \mathbf{v}_2\cdot\boldsymbol{\nabla} T_2 = Q_2/h_2 - w_d(T_1 - T_2)/h_2 - \kappa_4 \nabla^4 T_2.$$

Model Parameters (McCreary and Yu, 1992)



Biharmonic mixing coefficients	$\upsilon_4 = \kappa_4 = 2\times10^{21}\mathrm{cm}^4\mathrm{s}^{-1}$
Maximum value of damper	$\gamma = 1\ \mathrm{day}^{-1}$
Surface heating time scale	$t_1 = 100$ day
Lower-layer heating time scale	$t_2 = 500$ day
Entrainment time scale	$t_e = 1$ day
Detrainment time scale	$t_d = 50$ day
Entrainment depth	$H_e = 75\mathrm{m}$
Detrainment depth	$H_d = 75\mathrm{m}$
Coefficient of thermal expansion	$\alpha = 0.00025°\mathrm{C}^{-1}$
Characteristic speed of mode 1	$c_1 = 316\mathrm{cm\ s}^{-1}$
Characteristic speed of mode 2	$c_2 = 123\mathrm{cm\ s}^{-1}$

Model Area



Surface Winds
(Trade Winds)

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

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

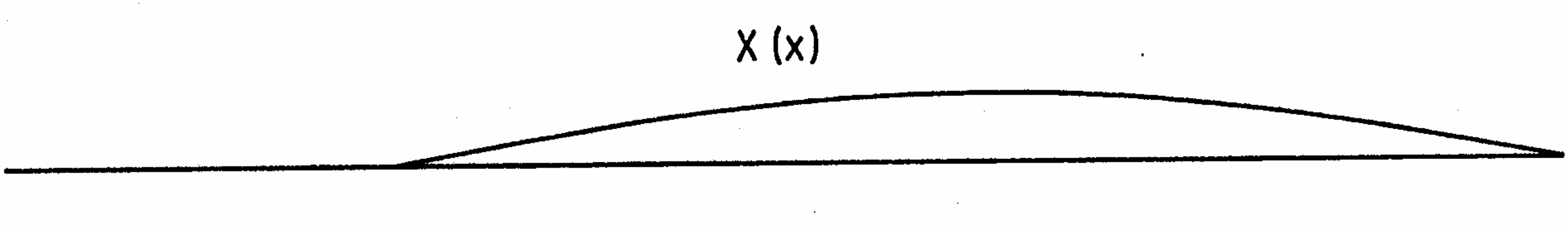
Y(y)=1 (No Latitudinal Variance).

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

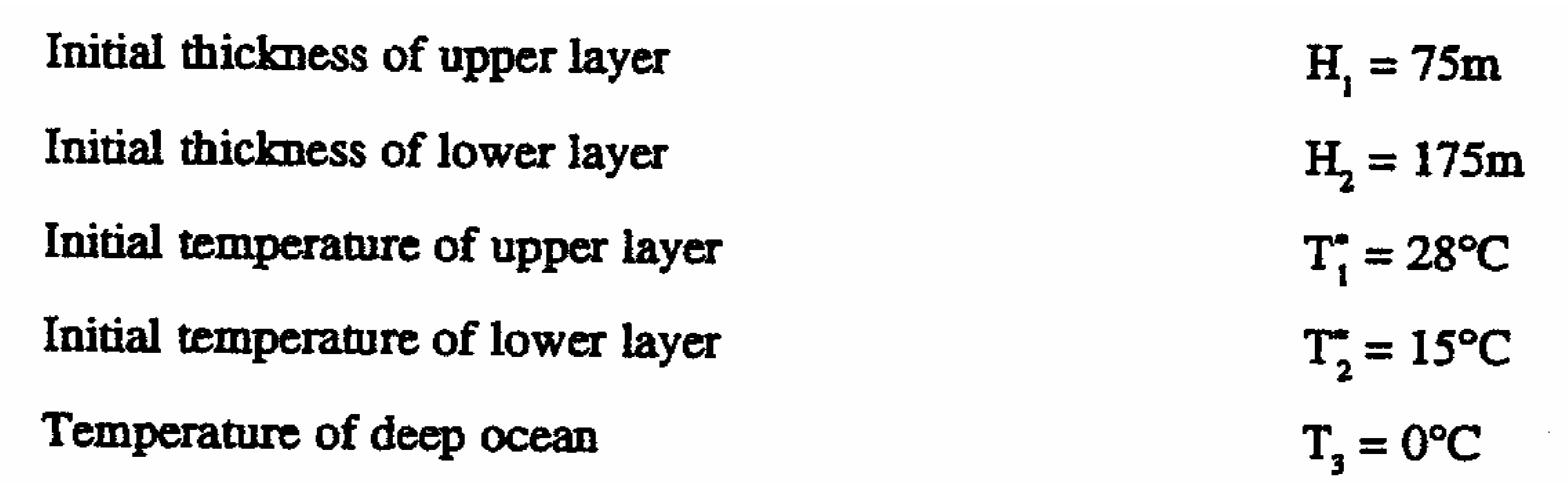
Zonal Variation of the Trade Winds

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

$$\overline{x} = 62.5° \text{ and } L = 75°.$$



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	$T_1^* = 28°\text{C}$
Initial temperature of lower layer	$T_2^* = 15°\text{C}$
Temperature of deep ocean	$T_3 = 0°\text{C}$

Model Integration

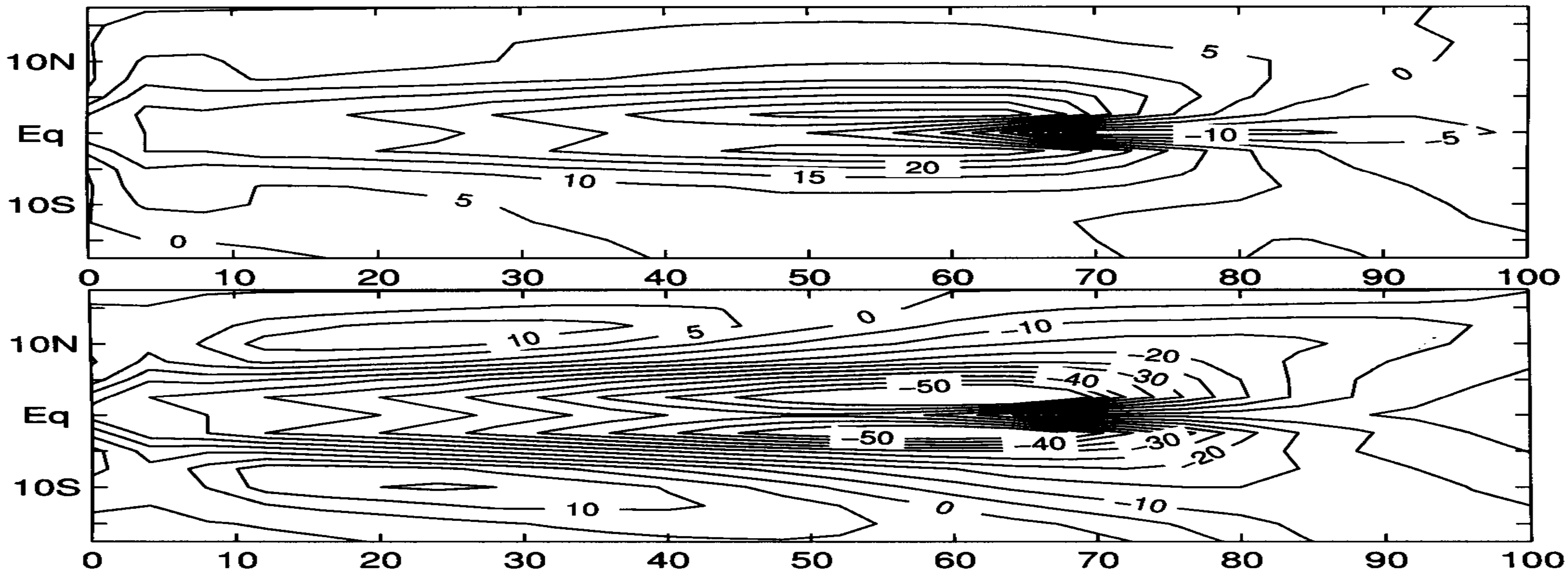
- (1) Model is integrated for 1080 days to reach nearly equilibrium state.

- (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

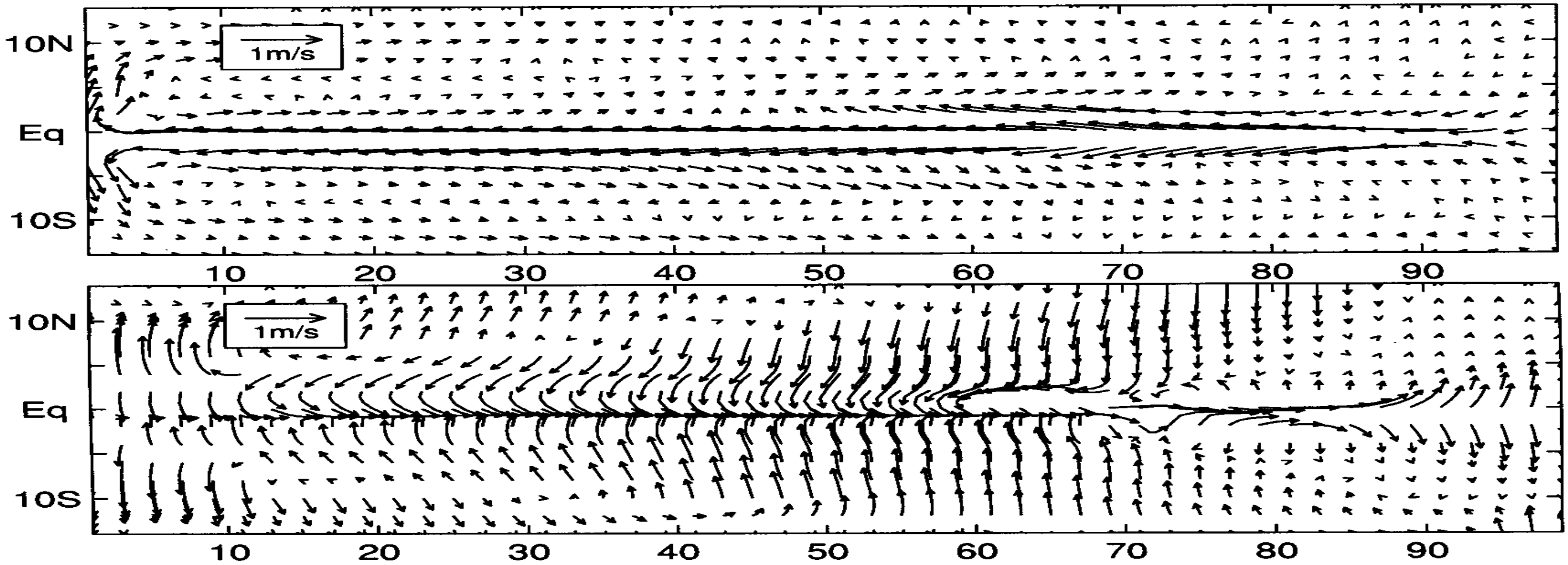
Layer Thickness Anomaly (m) at Day-1080:
(a) 1st Layer, (b) 2nd Layer.



Control Run

Horizontal Currents at Day-1080.

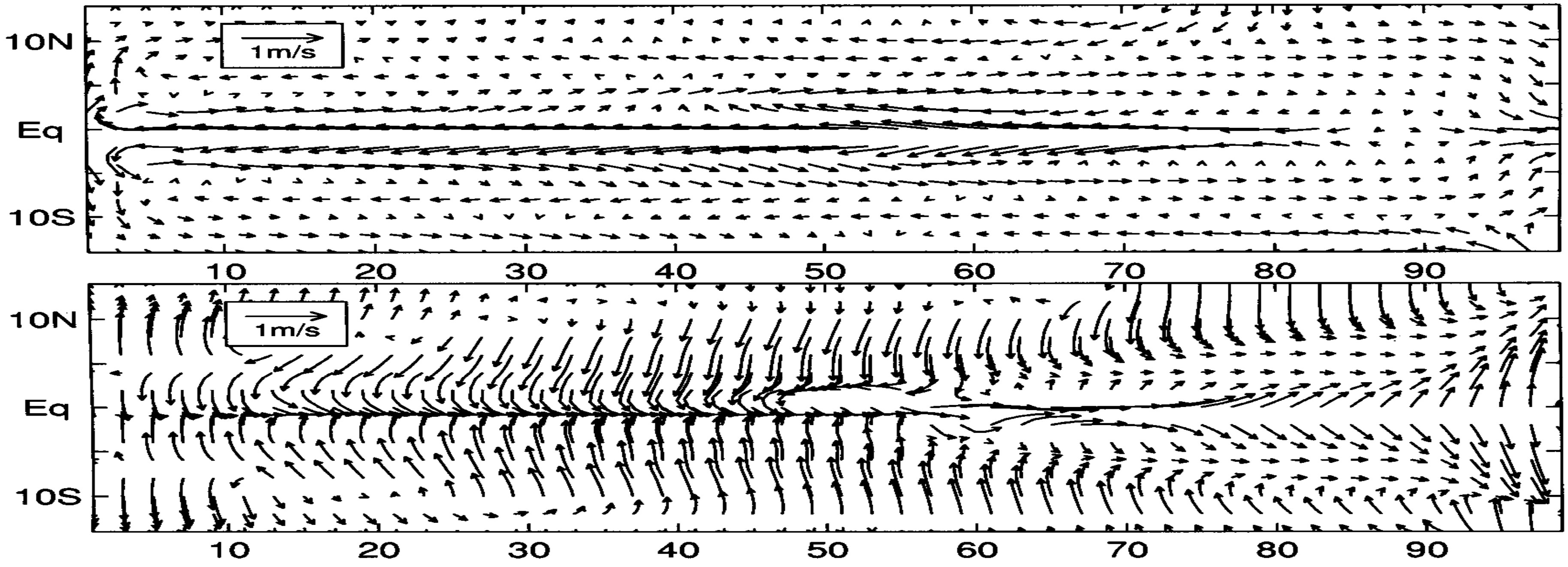
(a) 1st Layer: SEC; 2nd Layer: EUC



Westward Shift of the Trade Wind Maximum

X = 53^o

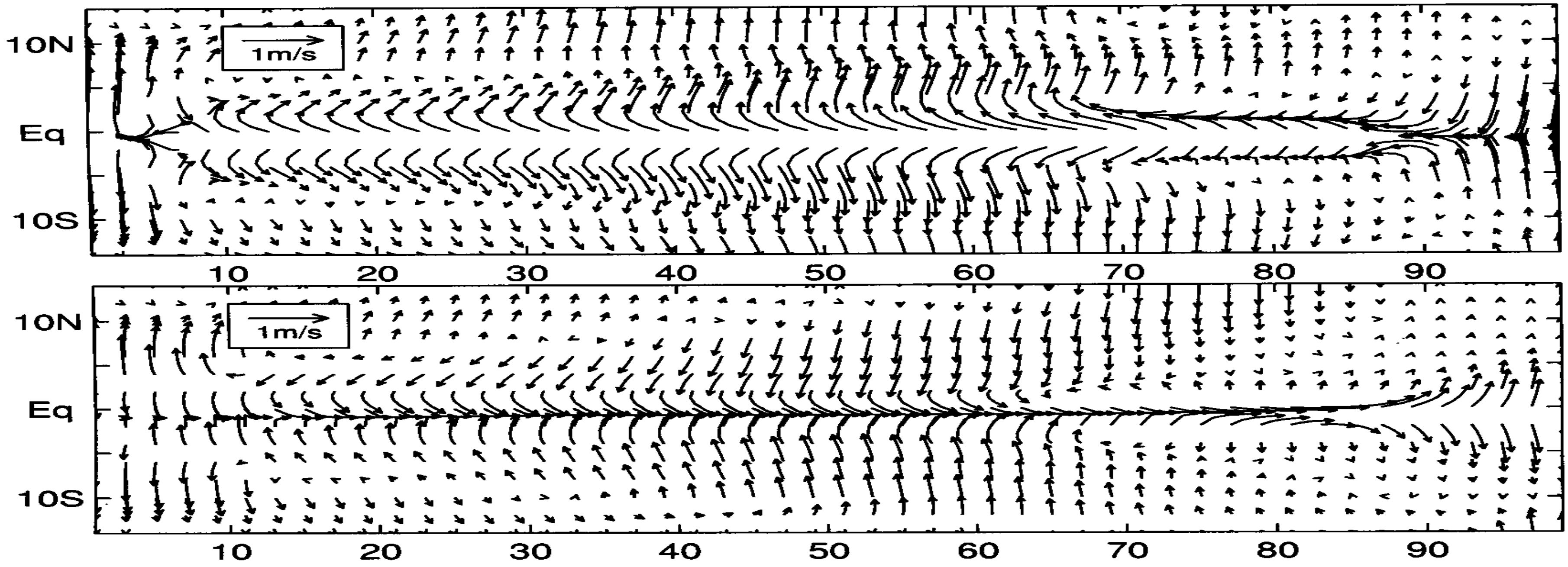
Westward Shift of Maximum Currents



Trade Winds Reduced to 85%

(a) SEC weakens

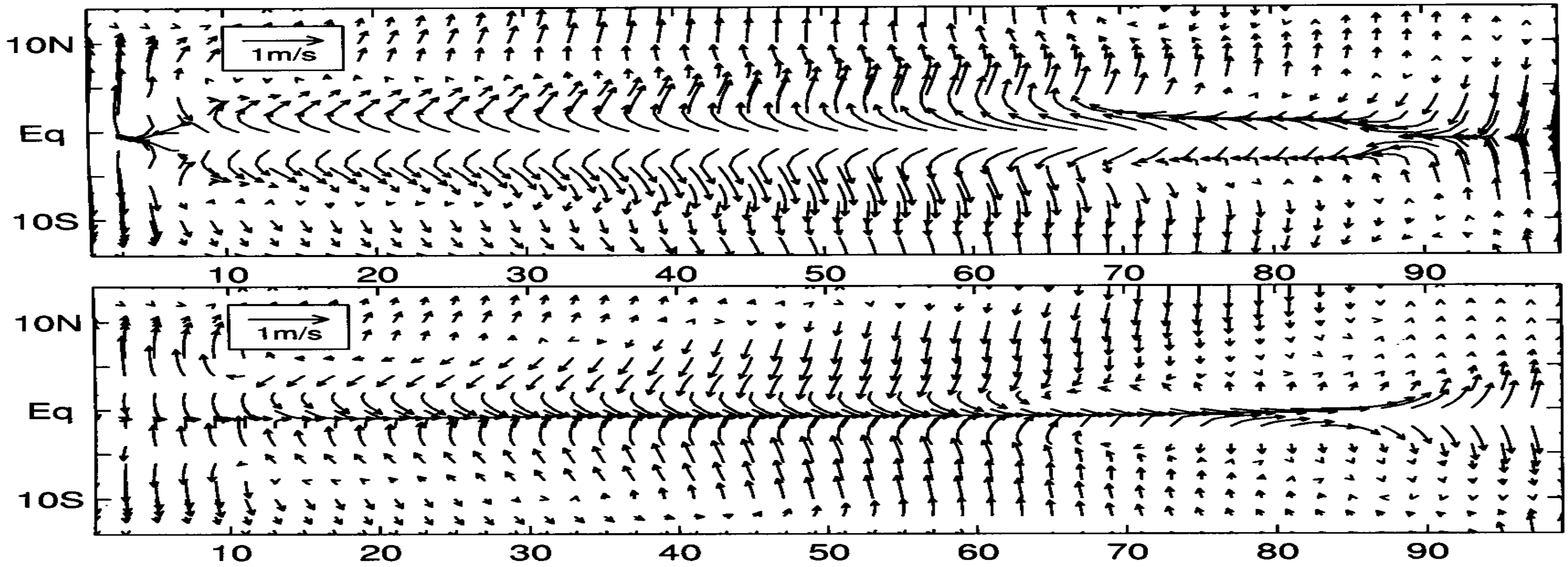
(b) EUC weakens



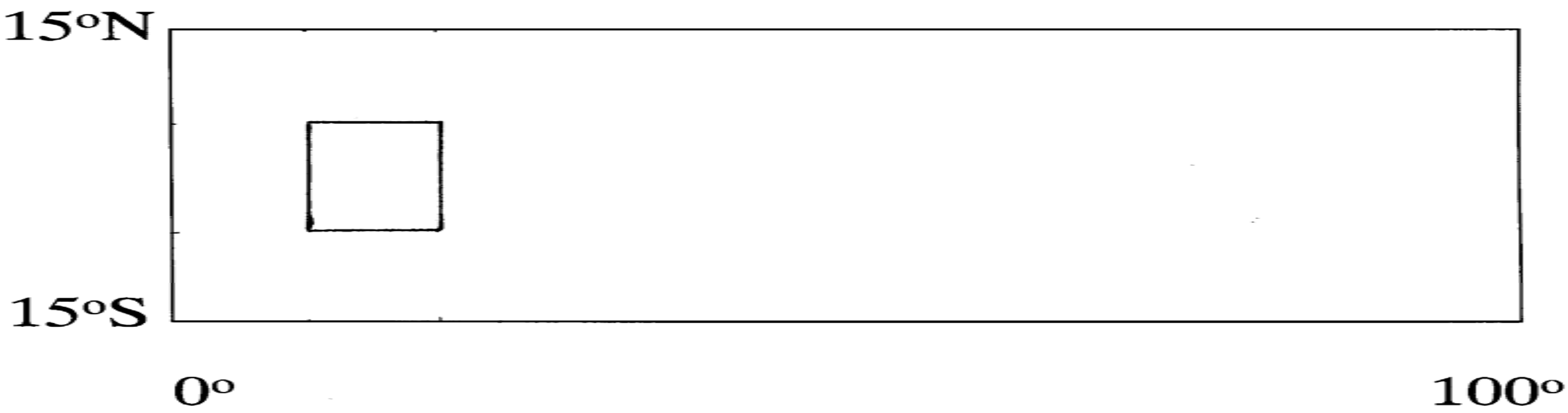
Trade Winds Reduced to 70%

(a) SEC weakens

(b) EUC weakens



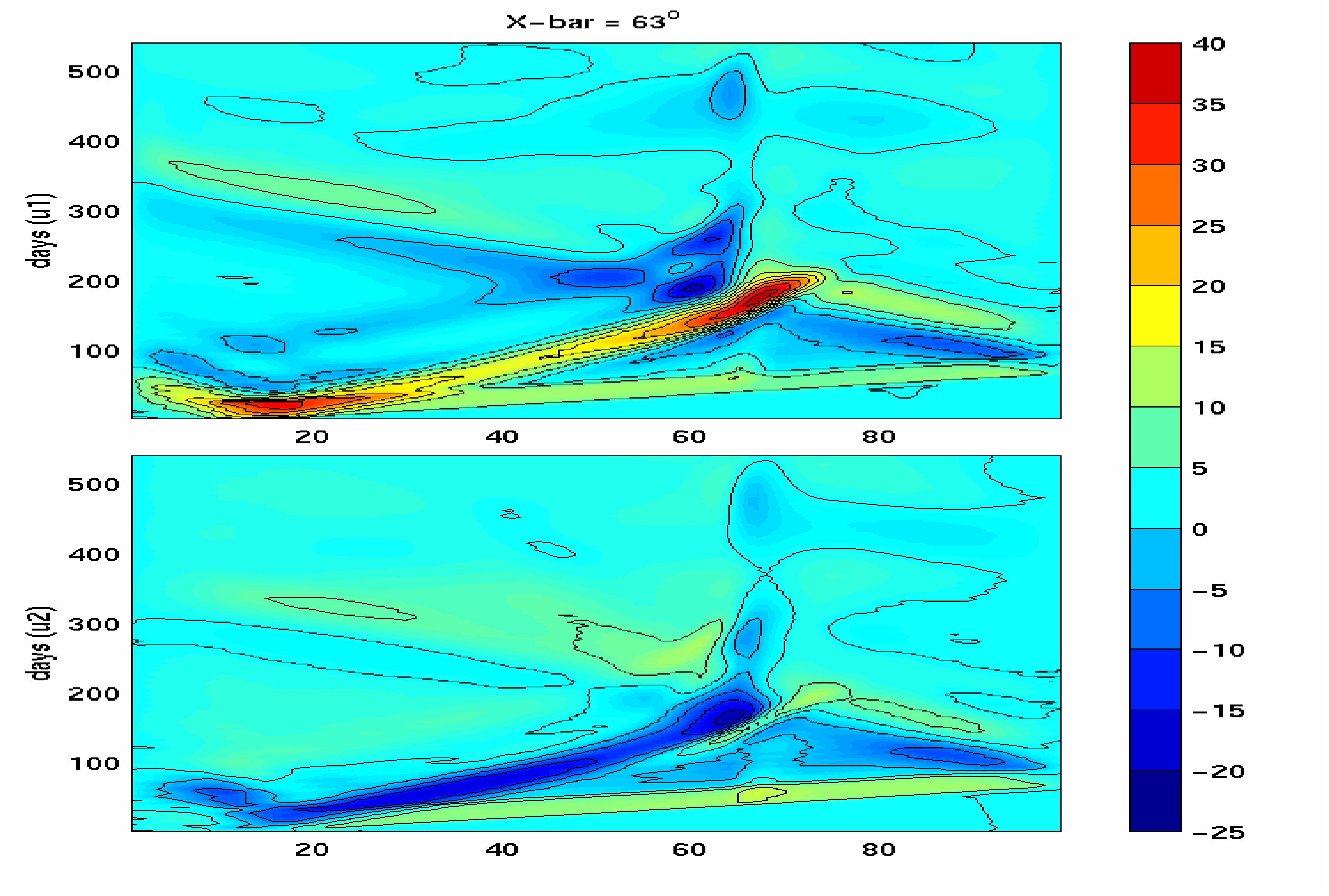
Westerly Wind Burst Patch



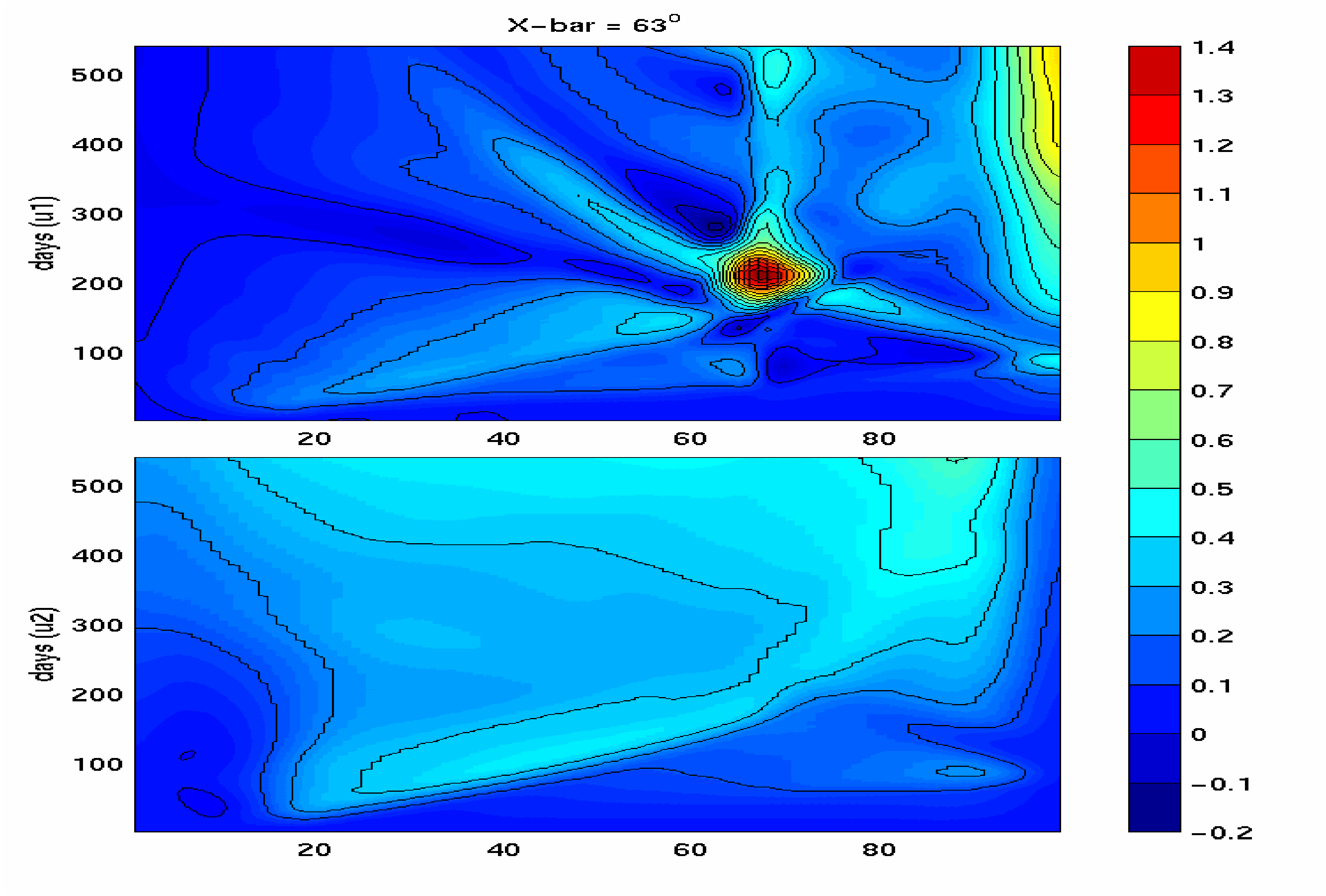
Westerly wind = 10 m/s

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

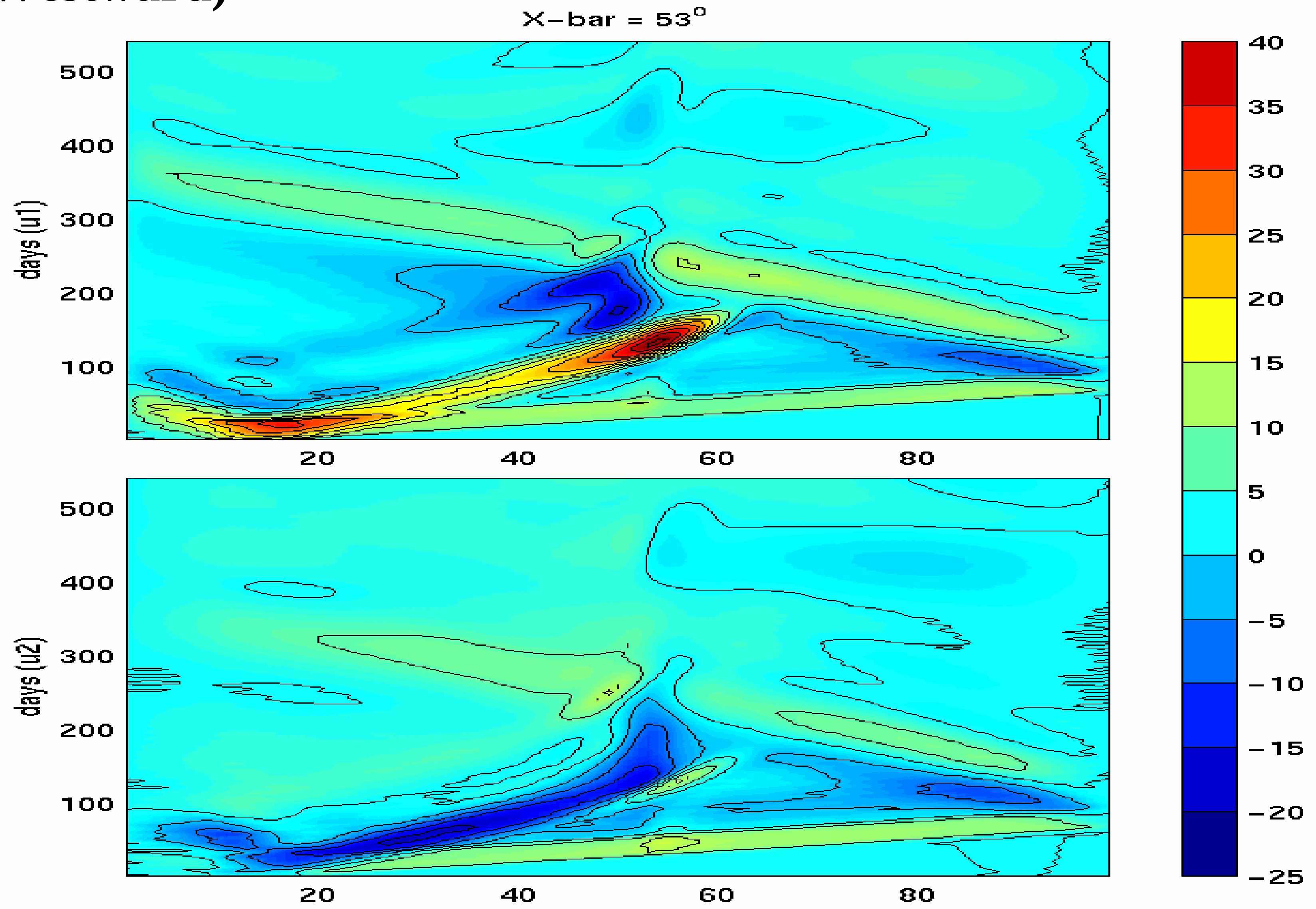
Time-Longitude Cross Section of Zonal Velocity Anomaly (cm/s) : (a) 1st Layer, (b) 2nd Layer (Control Run)



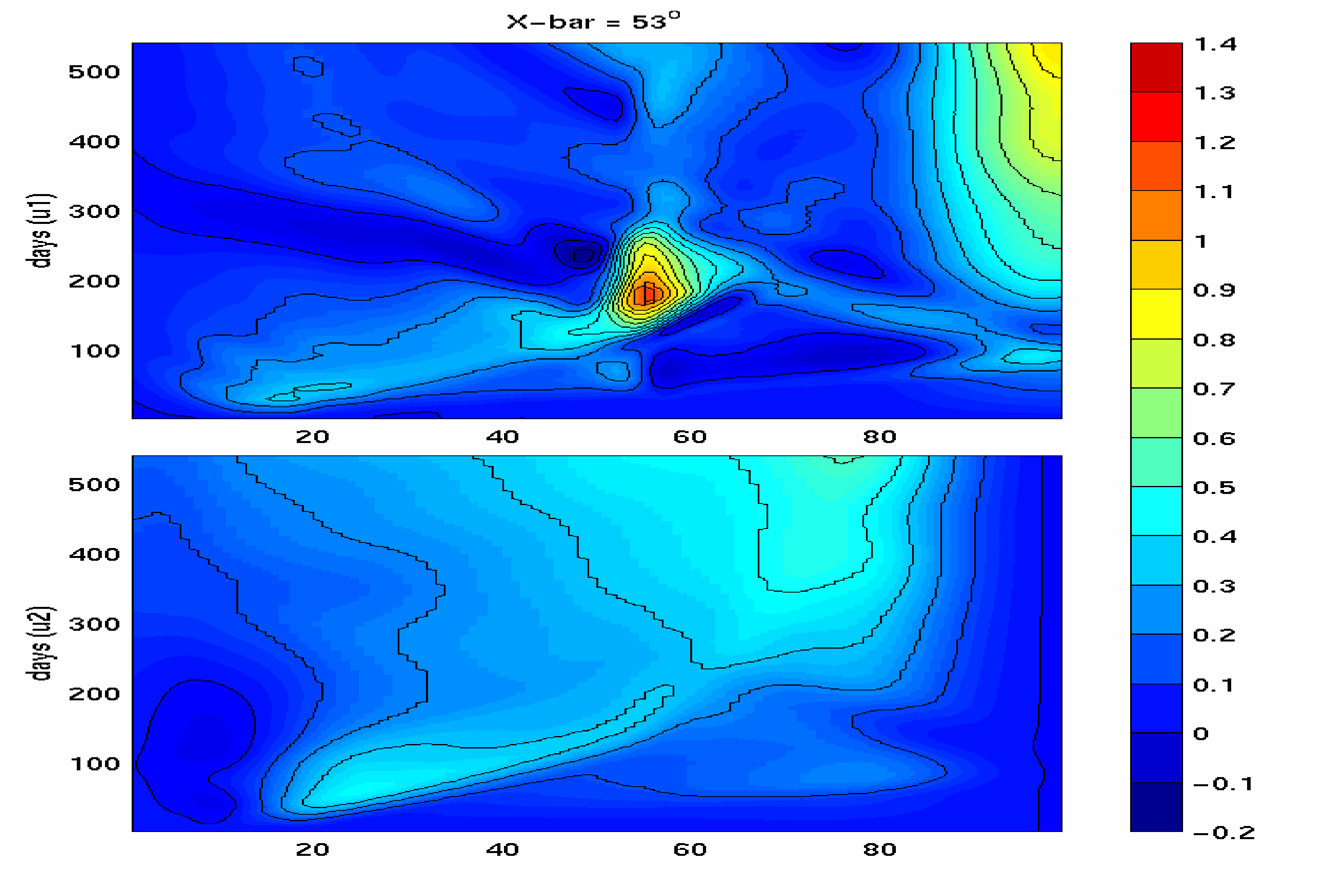
Time-Longitude Cross Section of Temperature Anomaly (^oC) : (a) 1st Layer, (b) 2nd Layer (Control Run)



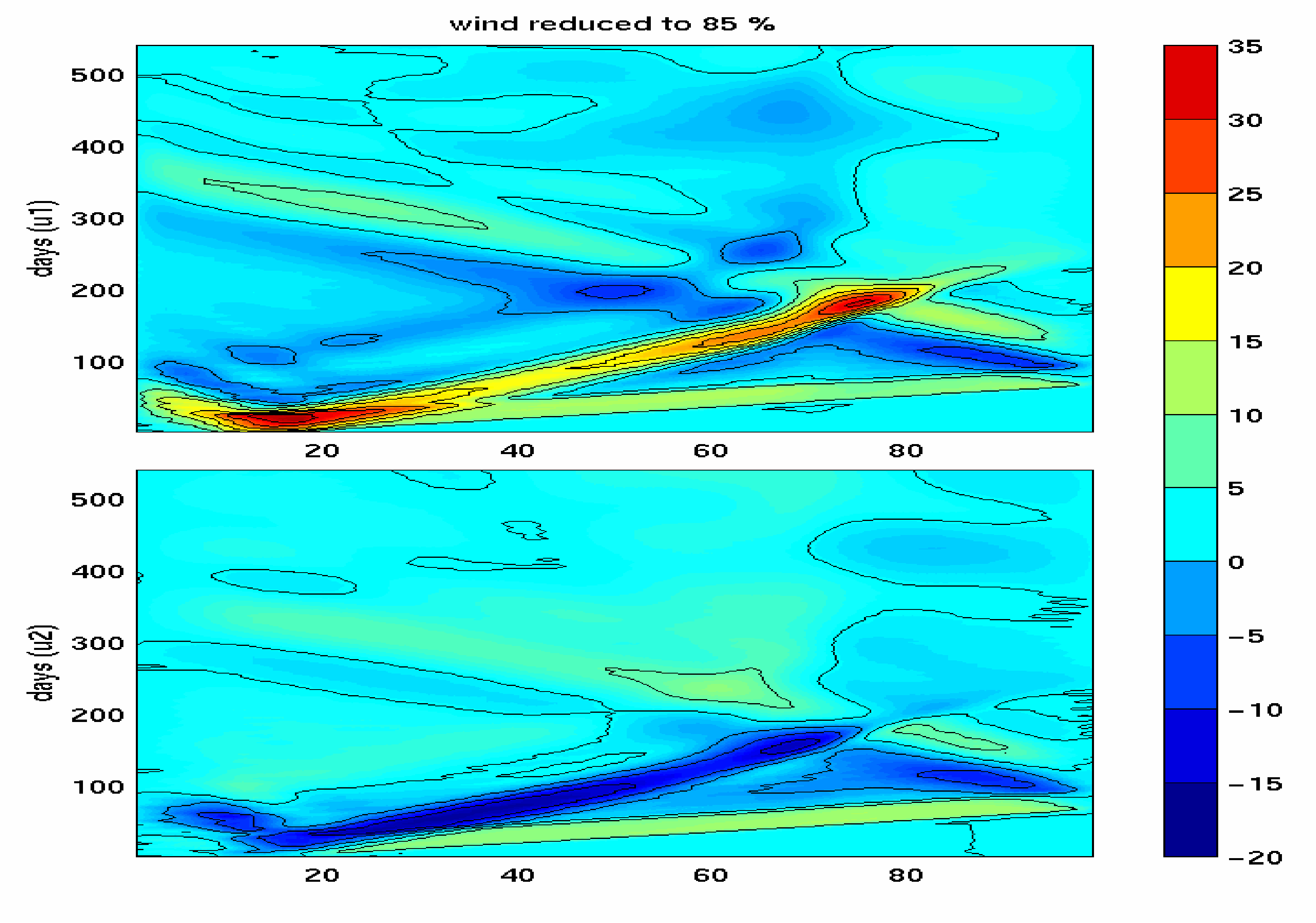
Time-Longitude Cross Section of Zonal Velocity Anomaly (cm/s) : (a) 1st Layer, (b) 2nd Layer (Trade Wind Maximum Shifted Westward)



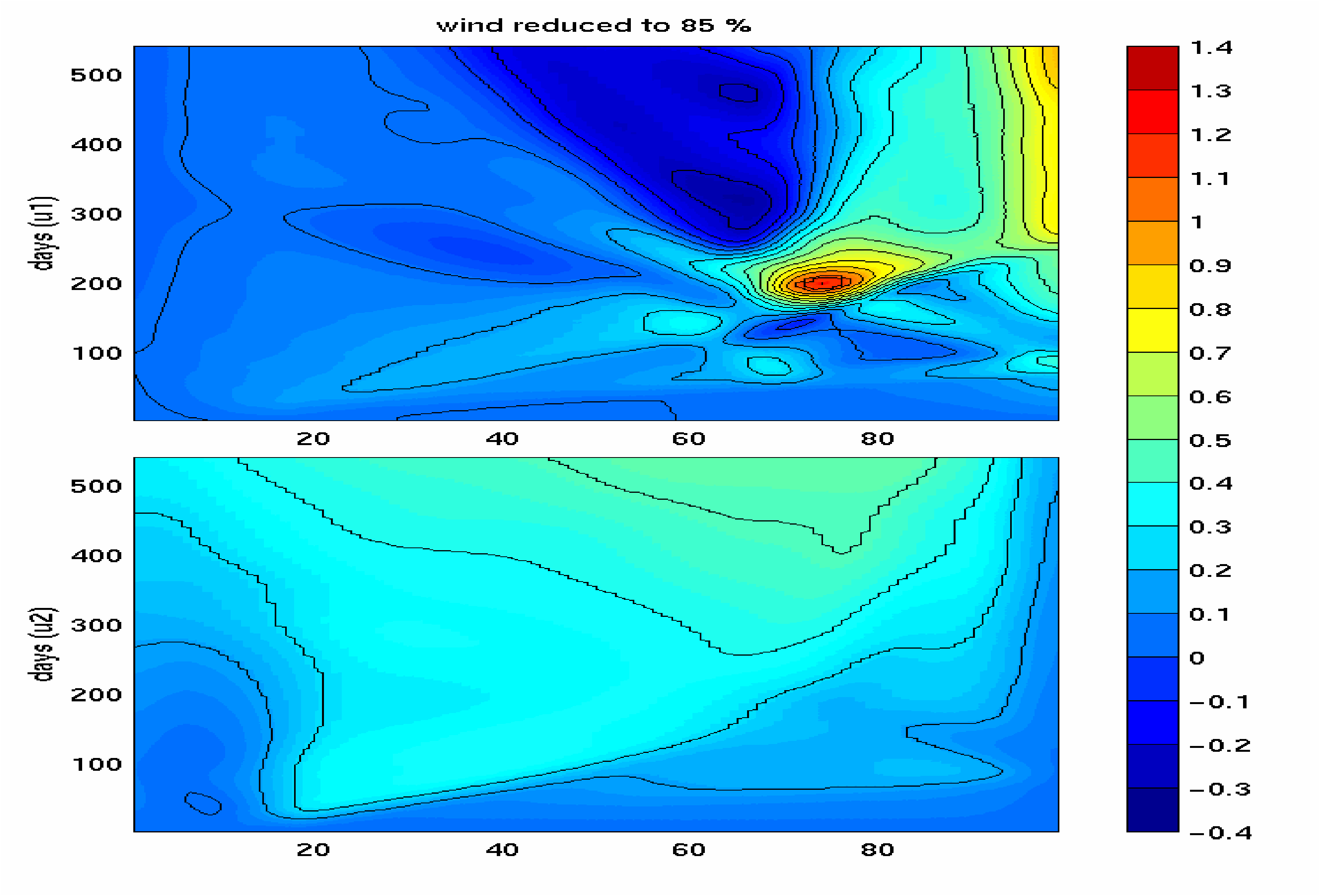
Time-Longitude Cross Section of Temperature Anomaly (^oC) : (a) 1st Layer, (b) 2nd Layer (Trade Wind Maximum Shifted Westward)



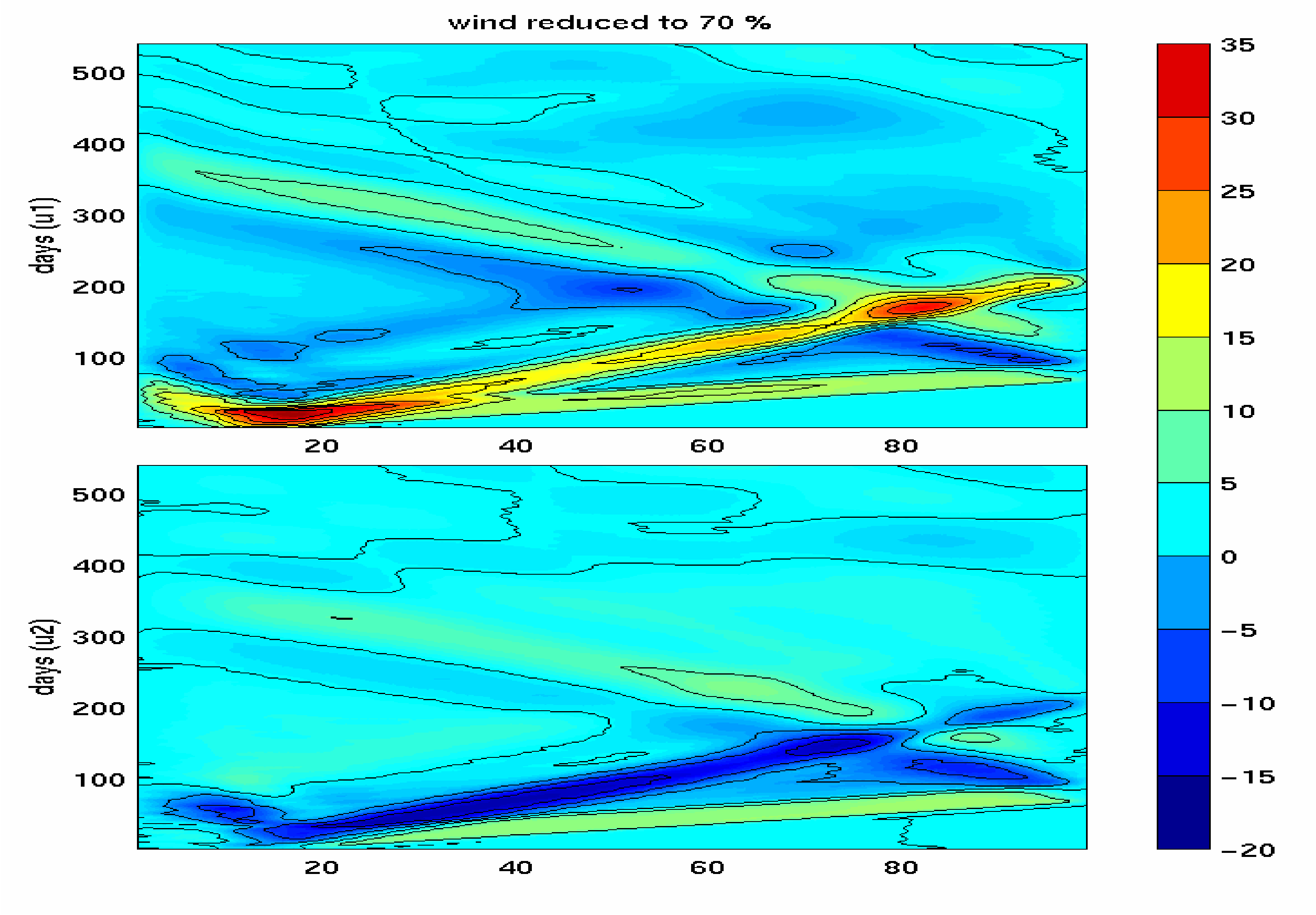
Time-Longitude Cross Section of Zonal Velocity Anomaly (cm/s) : (a) 1st Layer, (b) 2nd Layer (Trade Winds Reduced to 85%)



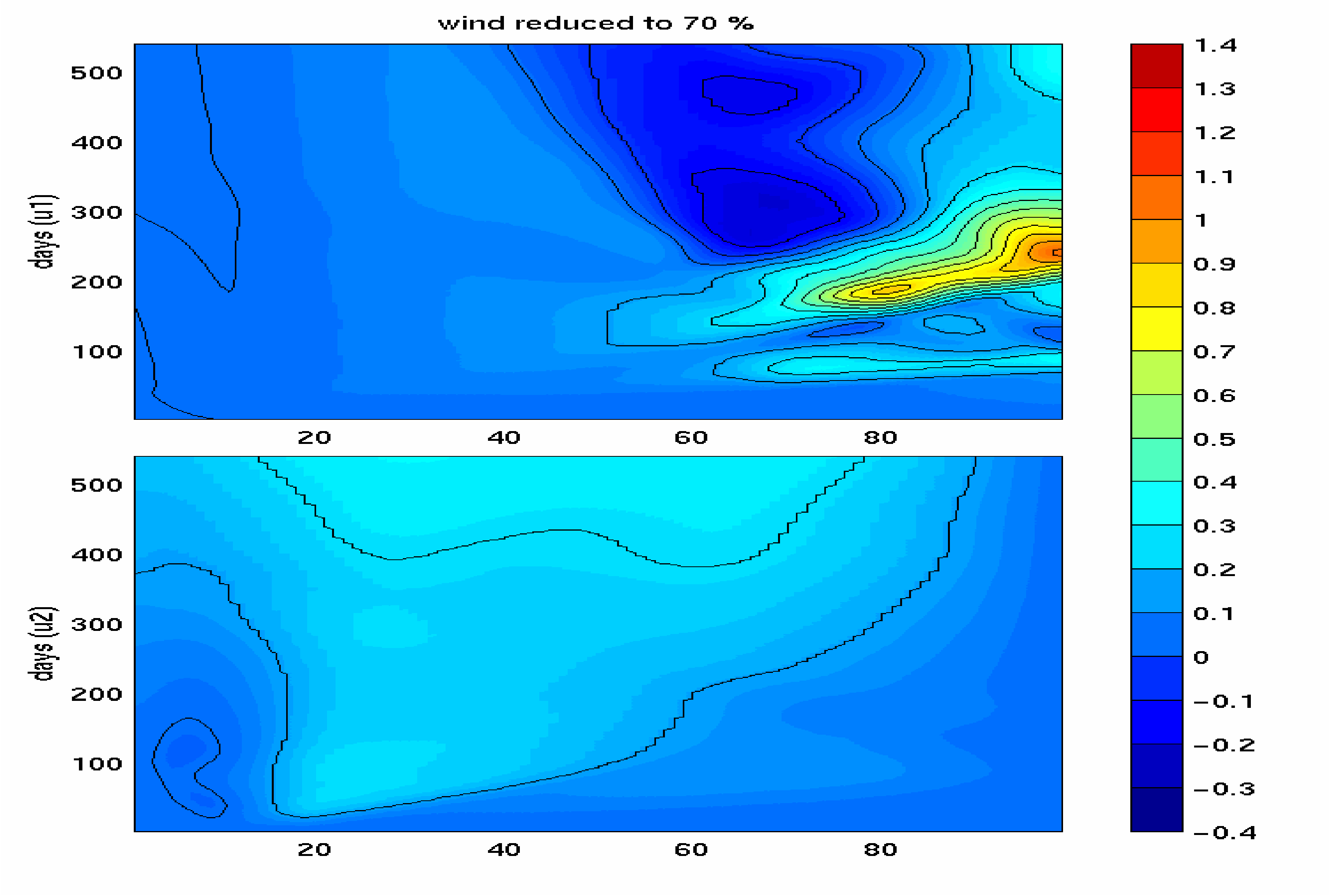
Time-Longitude Cross Section of Temperature Anomaly (^oC) : (a) 1st Layer, (b) 2nd Layer (Trade Winds Reduced to 85%)



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 (^oC) : (a) 1st Layer, (b) 2nd Layer (Trade Winds Reduced to 70%)



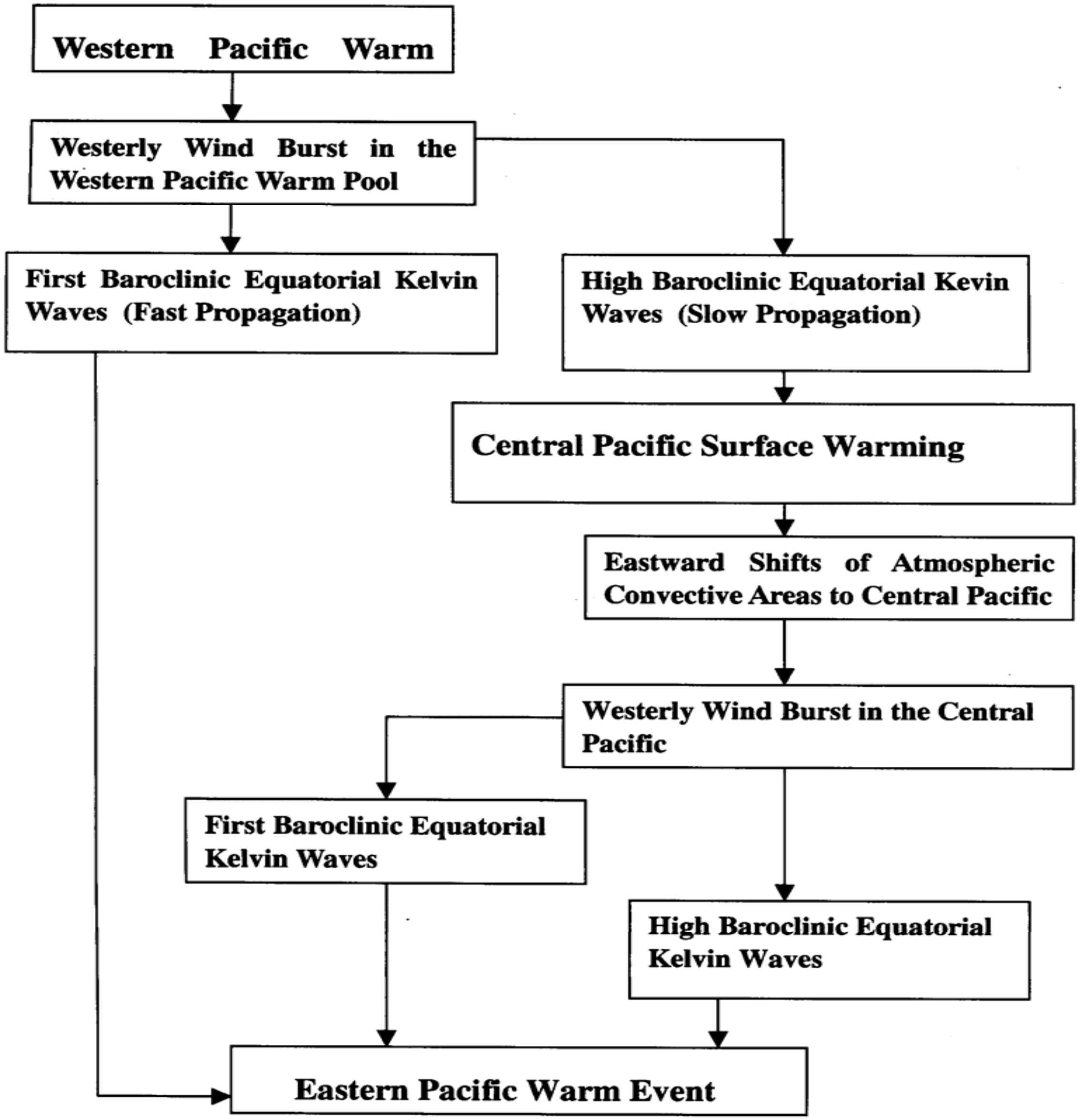
Conclusions

- ECM weakens the surface cold advection that may lead to central Pacific warming

- Second baroclinic Kelvin waves cause ECM.

- Two-stage air-sea interaction mechanism is proposed for the El Nino onset.

Two-Stage Air-Sea Interaction Mechanism



Western Pacific Warm

Westerly Wind Burst in the Western Pacific Warm Pool

First Baroclinic Equatorial Kelvin Waves (Fast Propagation)

High Baroclinic Equatorial Kevin Waves (Slow Propagation)

Central Pacific Surface Warming

Eastward Shifts of Atmospheric Convective Areas to Central Pacific

Westerly Wind Burst in the Central Pacific

First Baroclinic Equatorial Kelvin Waves

High Baroclinic Equatorial Kelvin Waves

Eastern Pacific Warm Event