High Baroclinic Equatorial Kelvin Waves and Central Pacific Surface Warming

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IUGG2003, Sapporo, Japan, June 30 – July 11, 2003
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)
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)

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

\[ u''^{(UP)} > 0, \quad \partial u''^{(UP)} / \partial t > 0 \]

\[ u''^{(Th)} < 0, \quad \partial u''^{(Th)} / \partial t < 0 \]
Enhancing CM Detected from TAO Data
Upper Layer and Thermocline (Wyrtki 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
Daily Mean Depths of 25°C (Solid) and 15°C (dashed) Isotherms at (a) 165°E, and (b) 140°W along the Equator.
Enhancing CM 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 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°S – 62°N

• Data Assimilated
  – WOA-94
  – Satellite Altimetry (GEOSAT, ERS-1, T/P)

• Resolution:
  – Zonal 1°
  – Meridional Varying, 0.4286° 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' (°C * 12)
at 165°E
Upper Layer $u'$ (cm/s, Blue)
Thermocline $u'$ (cm/s, Black)
SST' (°C * 12)
at 165°E
Upper Layer $u'$ (cm/s, Blue)
Thermocline $u'$ (cm/s, Black)
SST' ($^\circ$C * 12)
at 165$^\circ$E
Upper Layer $u'$ (cm/s, Blue)
Thermocline $u'$ (cm/s, Black)
SST' (°C * 12)
at 165°E
Upper Layer $u'$ (cm/s, Blue)
Thermocline $u'$ (cm/s, Black)
SST' (°C * 12)
at 165°E
Upper Layer \( u' \) (cm/s, Blue)
Thermocline \( u' \) (cm/s, Black)
\( \text{SST'} (\degree\text{C} \times 12) \)
at 165\degree 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° X 1° Resolution
\[(h_1 v_1)_t + \nabla \cdot (v_1 h_1 v_1) + f k \times h_1 v_1 + h_1 (\nabla p_1)^2\]

\[= \tau + w_e v_2 + w_d v_1 - \nu_4 \nabla^4 (h_1 v_1) - \gamma h_1 u_1 i,\]

\[h_{1t} + \nabla \cdot (h_1 v_1) = w_e + w_d - \kappa_4 \nabla^4 h_1,\]

\[T_{1t} + v_1 \cdot \nabla T_1 = Q_1 / h_1 - w_e (T_1 - T_2) / h_1 - \kappa_4 \nabla^4 T_1,\]

\[(h_2 v_2)_t + \nabla \cdot (v_2 h_2 v_2) + f k \times h_2 v_2 + h_2 (\nabla p_2)^2\]

\[= -w_e v_2 - w_d v_1 - \nu_4 \nabla^4 (h_2 v_2) - \gamma h_2 u_2 i,\]

\[h_{2t} + \nabla \cdot (h_2 v_2) = -w_e - w_d - \kappa_4 \nabla^4 h_2,\]

\[T_{2t} + v_2 \cdot \nabla T_2 = Q_2 / h_2 - w_d (T_1 - T_2) / h_2 - \kappa_4 \nabla^4 T_2.\]
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
$t_3 = 1 \text{ day}$

Detrainment time scale
$t_4 = 50 \text{ day}$

Entrainment depth
$H_e = 75 \text{m}$

Detrainment depth
$H_d = 75 \text{m}$

Coefficient of thermal expansion
$\alpha = 0.00025 \degree \text{C}^{-1}$

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)

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

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

\[ Y(y) = 1 \text{ (No Latitudinal Variance)}. \]

\[ T(t) = \text{Ramp function that increases linearly from 0 to 1 in the first 5 days}. \]
Zonal Variation of the Trade Winds

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

\[ \bar{x} = 62.5^\circ \text{ and } L = 75^\circ. \]
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) 1\textsuperscript{st} Layer, (b) 2\textsuperscript{nd} Layer.
Control Run

Horizontal Currents at Day-1080.

(a) 1st Layer: SEC; 2nd Layer: EUC
Westward Shift of the Trade Wind Maximum

\[ X = 53^\circ \]

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 (°C) : (a) 1st Layer, (b) 2nd Layer (Control Run)
Time-Longitude Cross Section of Zonal Velocity Anomaly (cm/s):
(a) 1\textsuperscript{st} Layer, (b) 2\textsuperscript{nd} Layer (Trade Wind Maximum Shifted Westward)
Time-Longitude Cross Section of Temperature Anomaly (°C) :
(a) 1\textsuperscript{st} Layer, (b) 2\textsuperscript{nd} Layer (Trade Wind Maximum Shifted Westward)
Time-Longitude Cross Section of Zonal Velocity Anomaly (cm/s): (a) 1\textsuperscript{st} Layer, (b) 2\textsuperscript{nd} Layer (Trade Winds Reduced to 85\%)
Time-Longitude Cross Section of Temperature Anomaly (°C) :
(a) 1\textsuperscript{st} Layer, (b) 2\textsuperscript{nd} 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 (°C): (a) 1st Layer, (b) 2nd Layer (Trade Winds Reduced to 70%)

![Temperature Anomaly Diagram](image-url)
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

1. Western Pacific Warm
   - Westerly Wind Burst in the Western Pacific Warm Pool
     - First Baroclinic Equatorial Kelvin Waves (Fast Propagation)
     - High Baroclinic Equatorial Kelvin 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