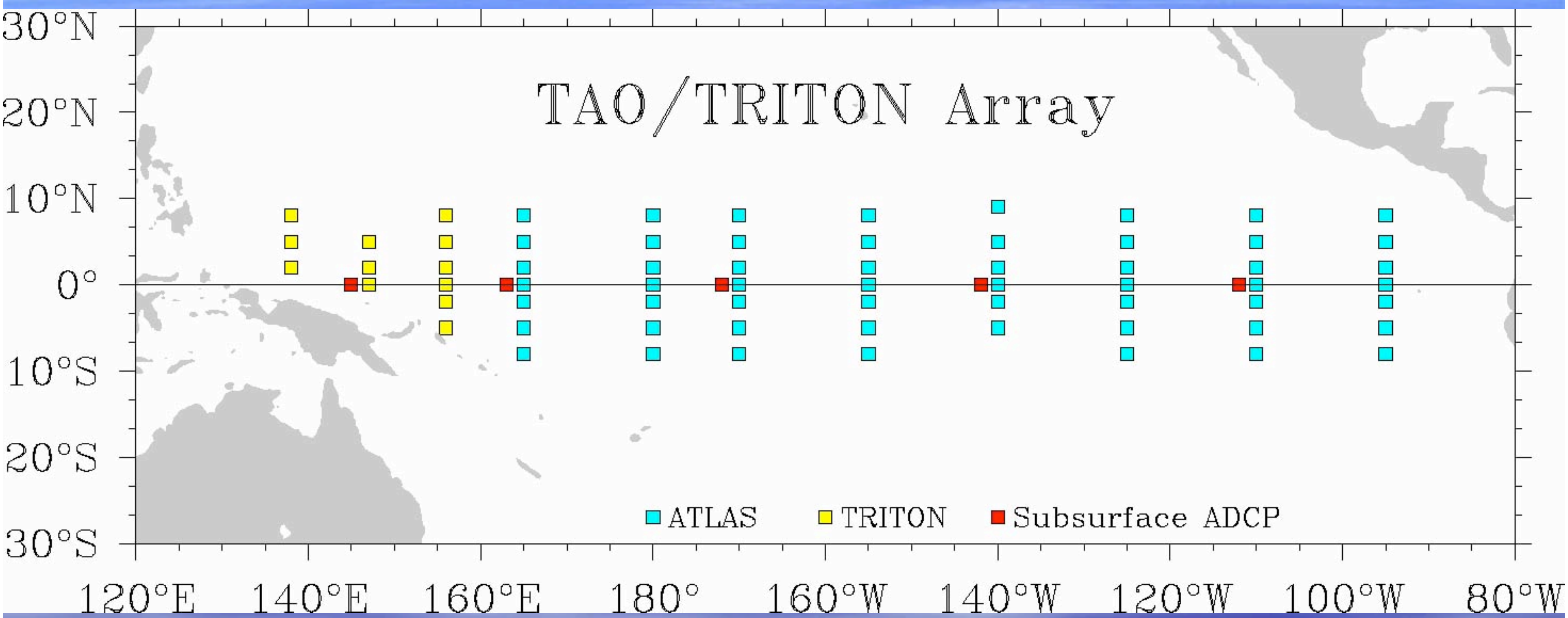
The Role of Intraseasonal Atmospheric Forcing in ENSO

Paul E. Roundy

NOAA/CIRES Earth System Research Laboratory

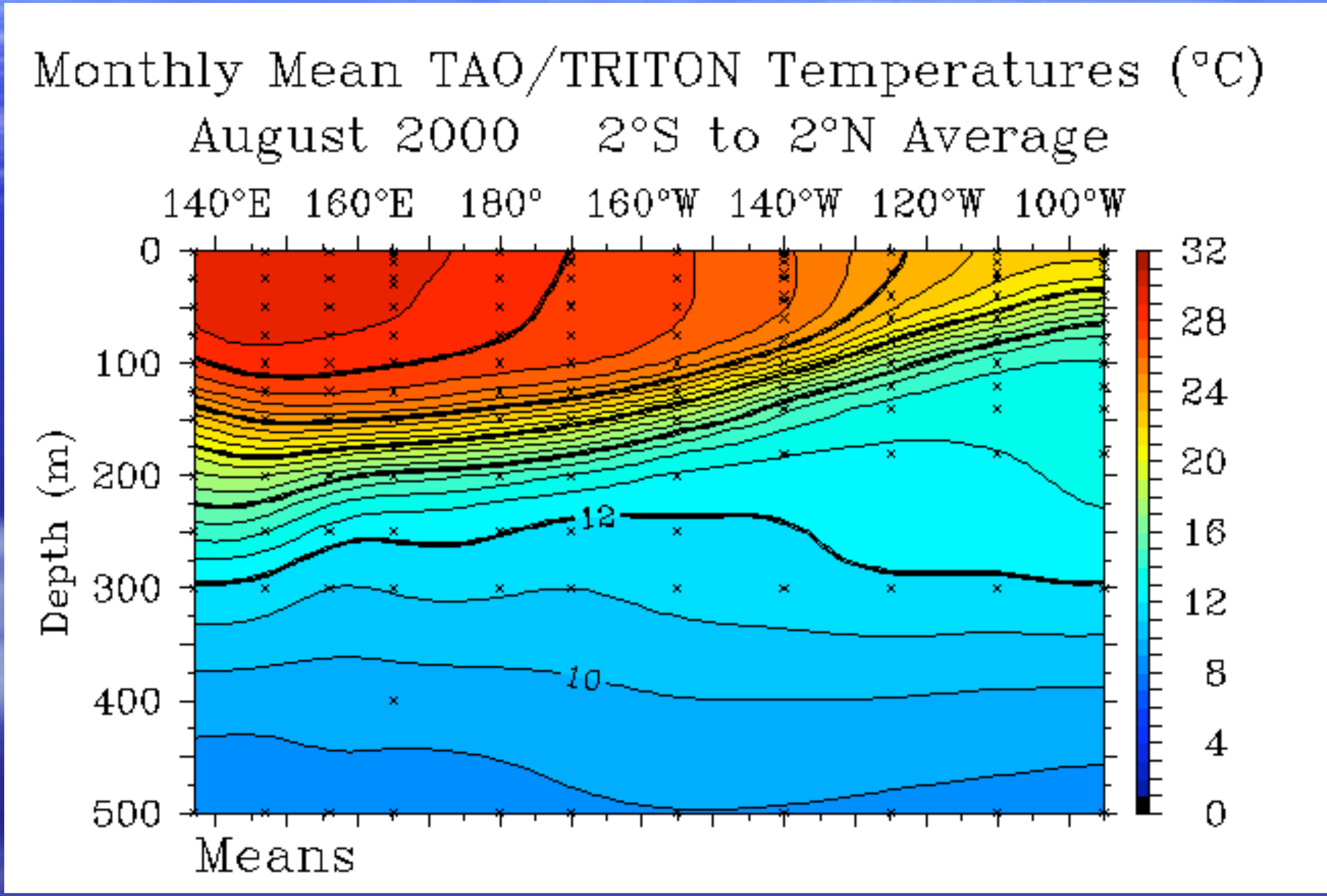
Paul.roundy@noaa.gov


TAO/TRITON Array
30°N
20°N
10°N
0°
10°S
20°S
30°S
120°E
140°E
160°E
180°
160°W
140°W
120°W
100°W
80°W
ATLAS
TRITON
Subsurface ADCP

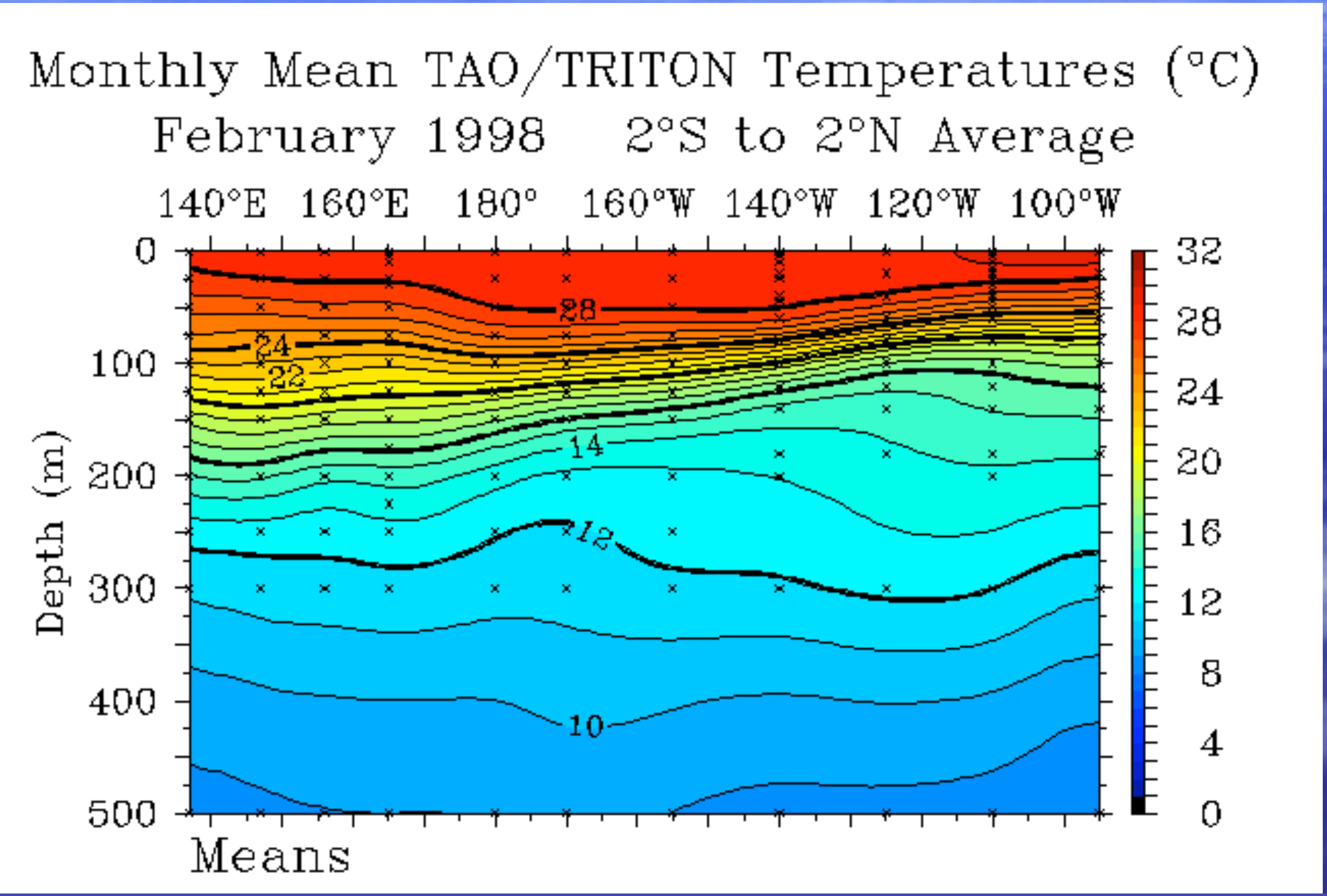
Critical Variables

- TAO dynamic height, sea level height records
  - Reconstruction
- Outgoing longwave radiation (OLR)
- Zonal Wind Stress (TAO and NCEP)
- ENSO indices
  - Nino3.4 dynamic height
  - Sea level height records

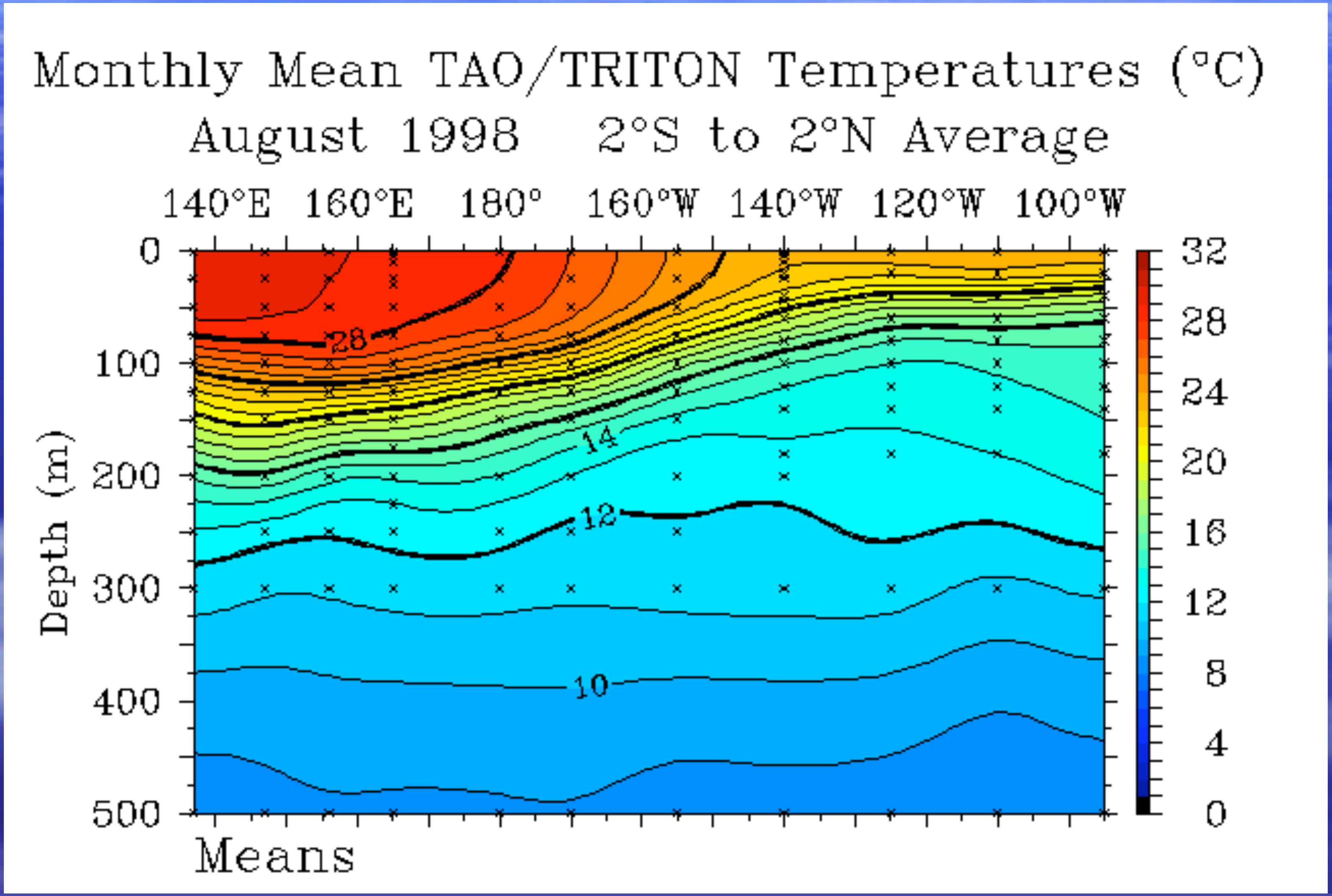
Thermal Structure of Equatorial Pacific



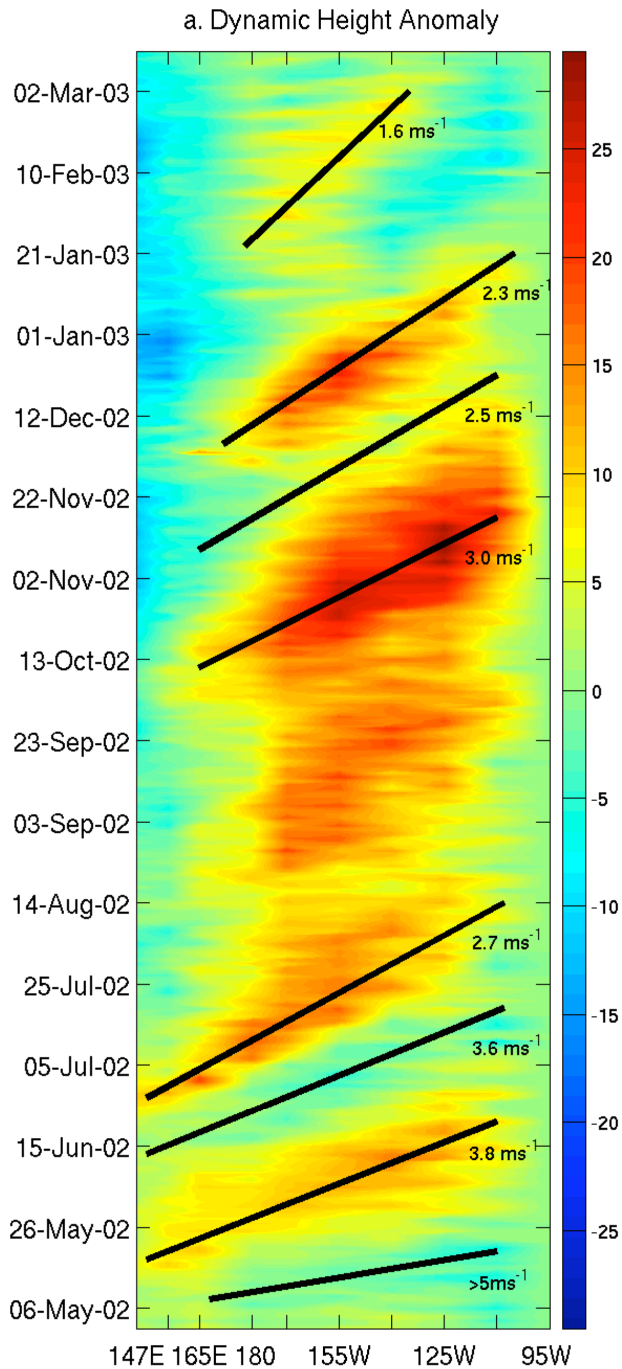
El Niño: Warm Phase



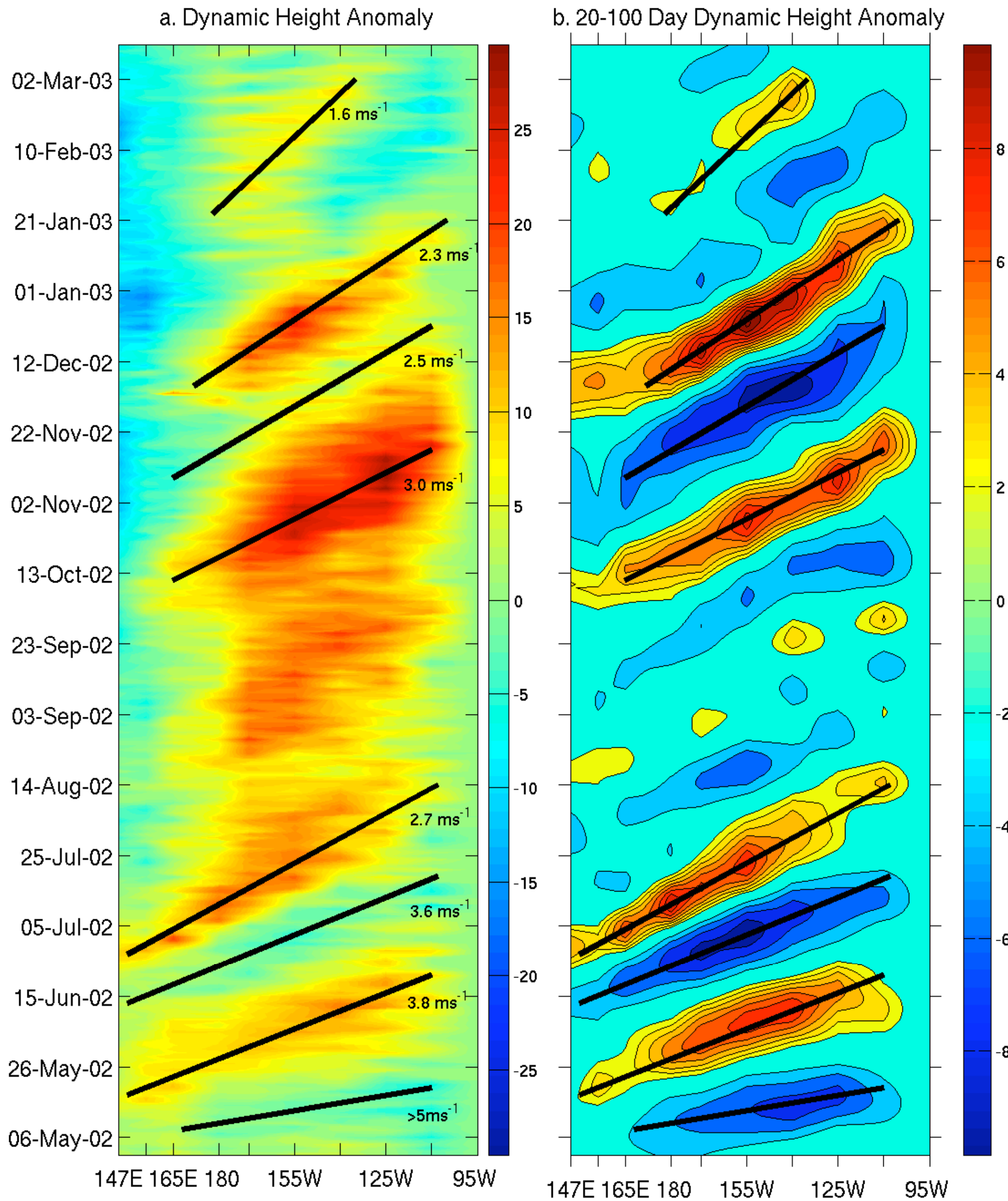
La Niña: Cold Phase

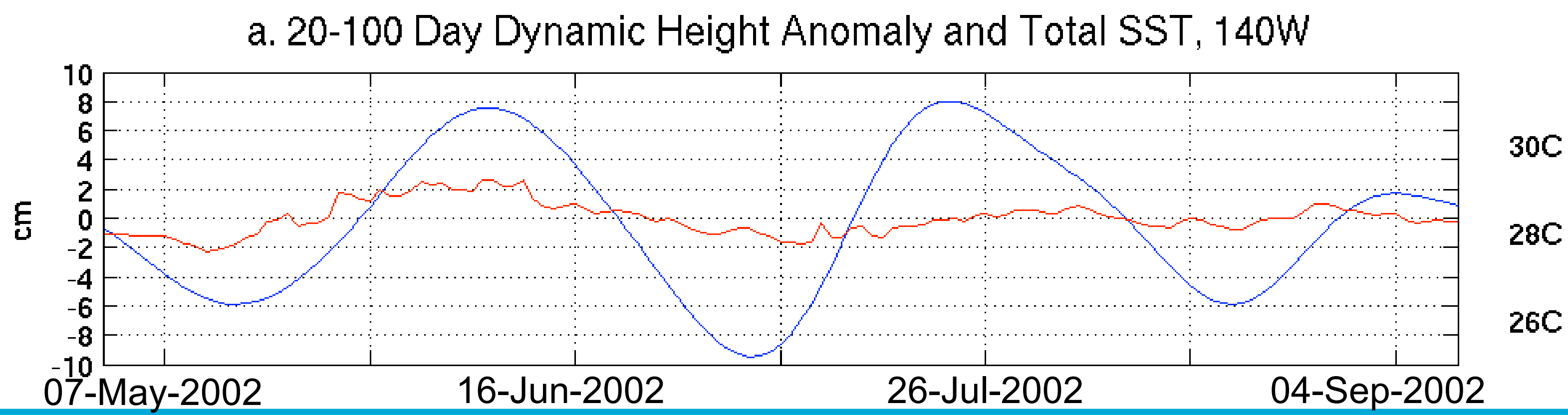


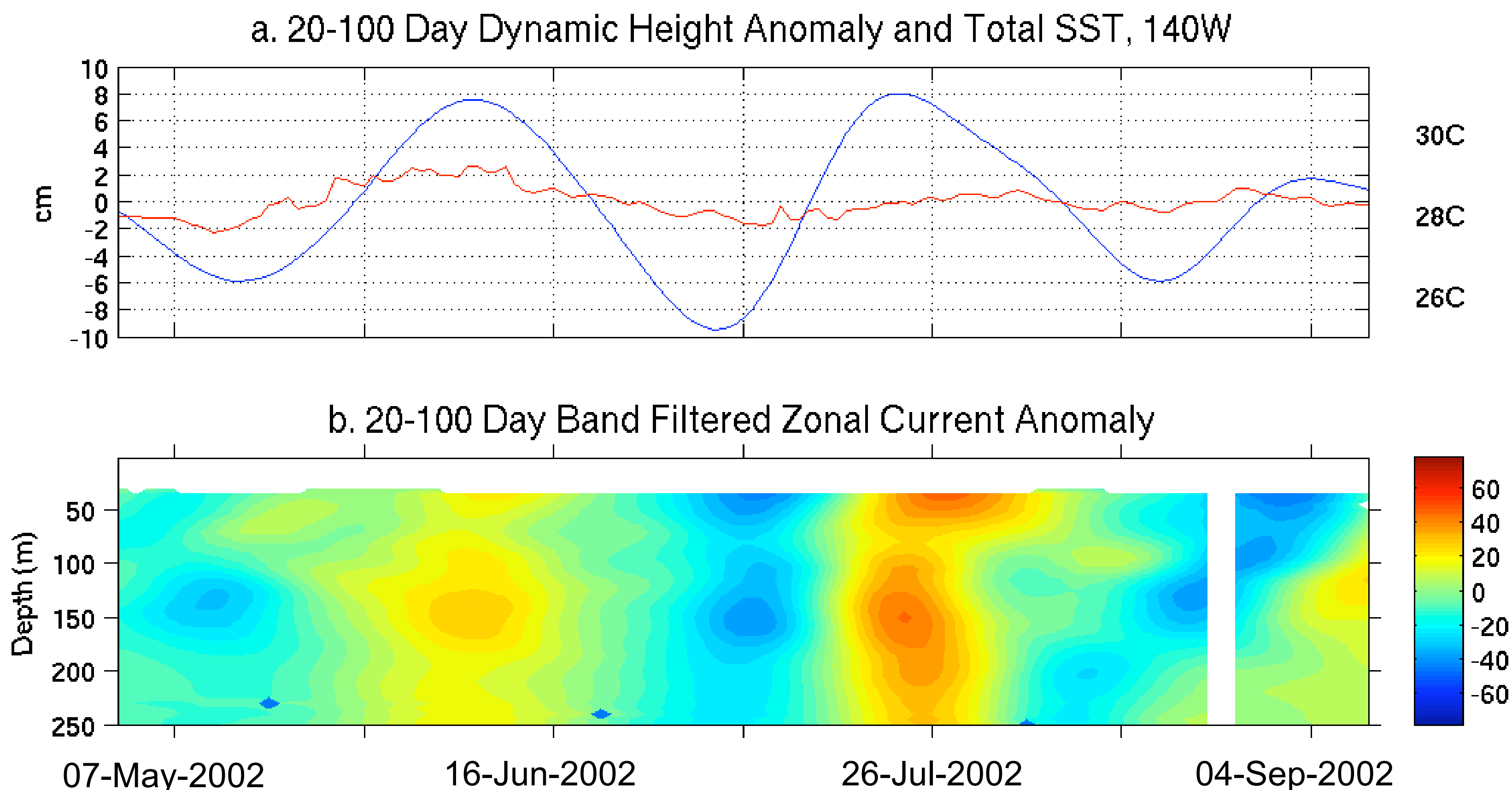
Roundy & Kiladis 2006



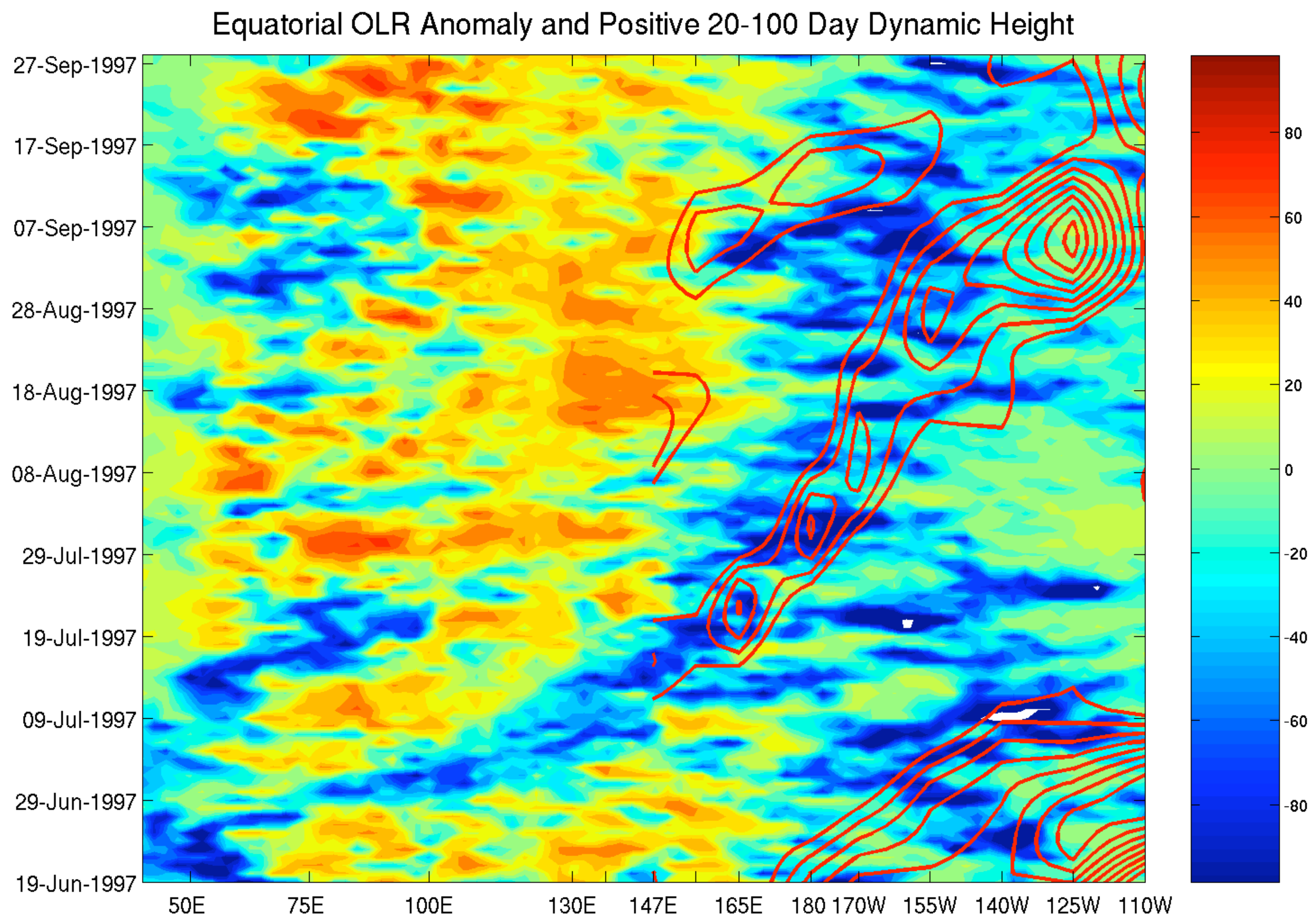
Roundy & Kiladis 2006



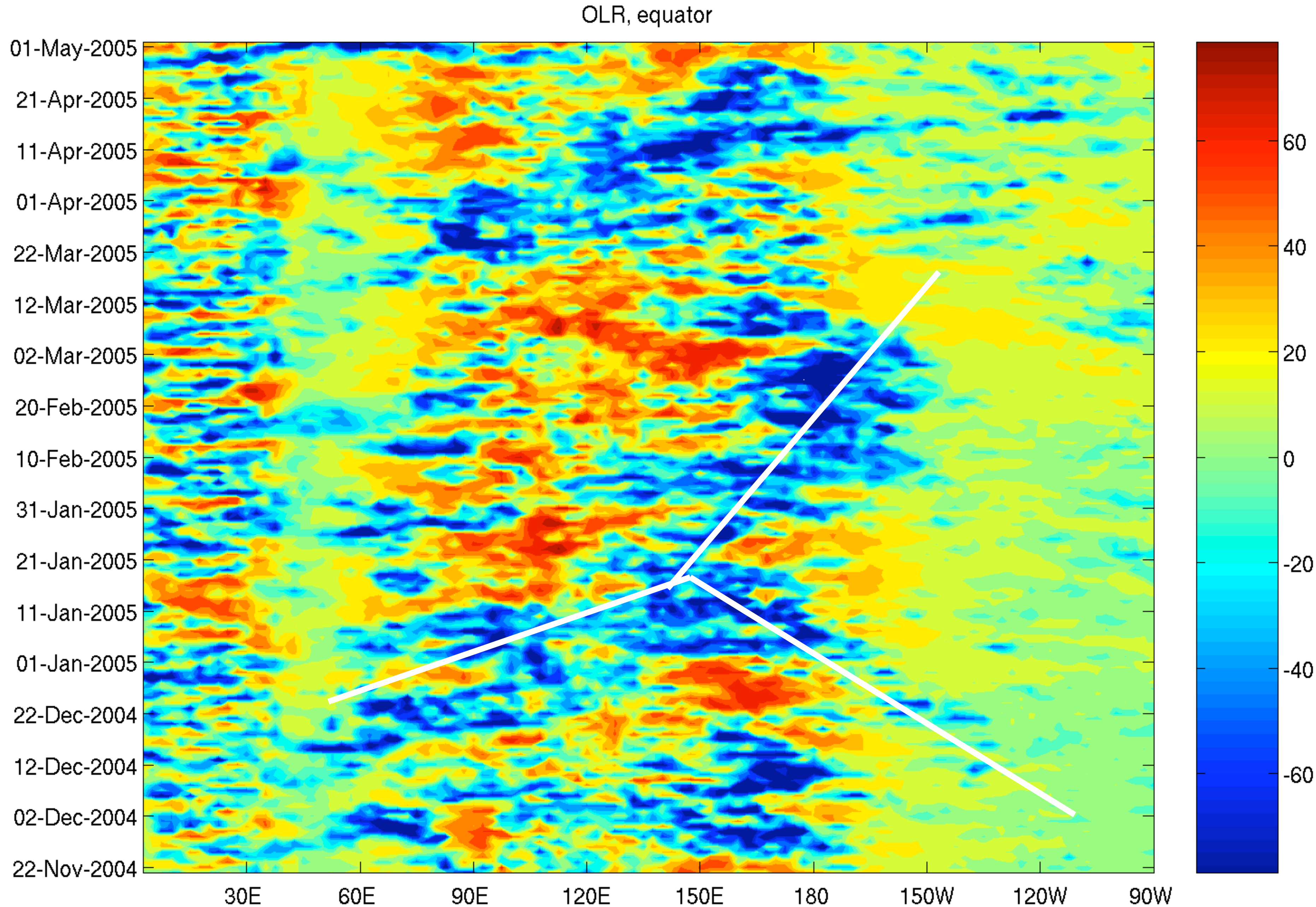

a. 20-100 Day Dynamic Height Anomaly and Total SST, 140W
cm
10
8
6
4
2
0
-2
-4
-6
-8
-10
30C
28C
26C
07-May-2002
16-Jun-2002
26-Jul-2002
04-Sep-2002

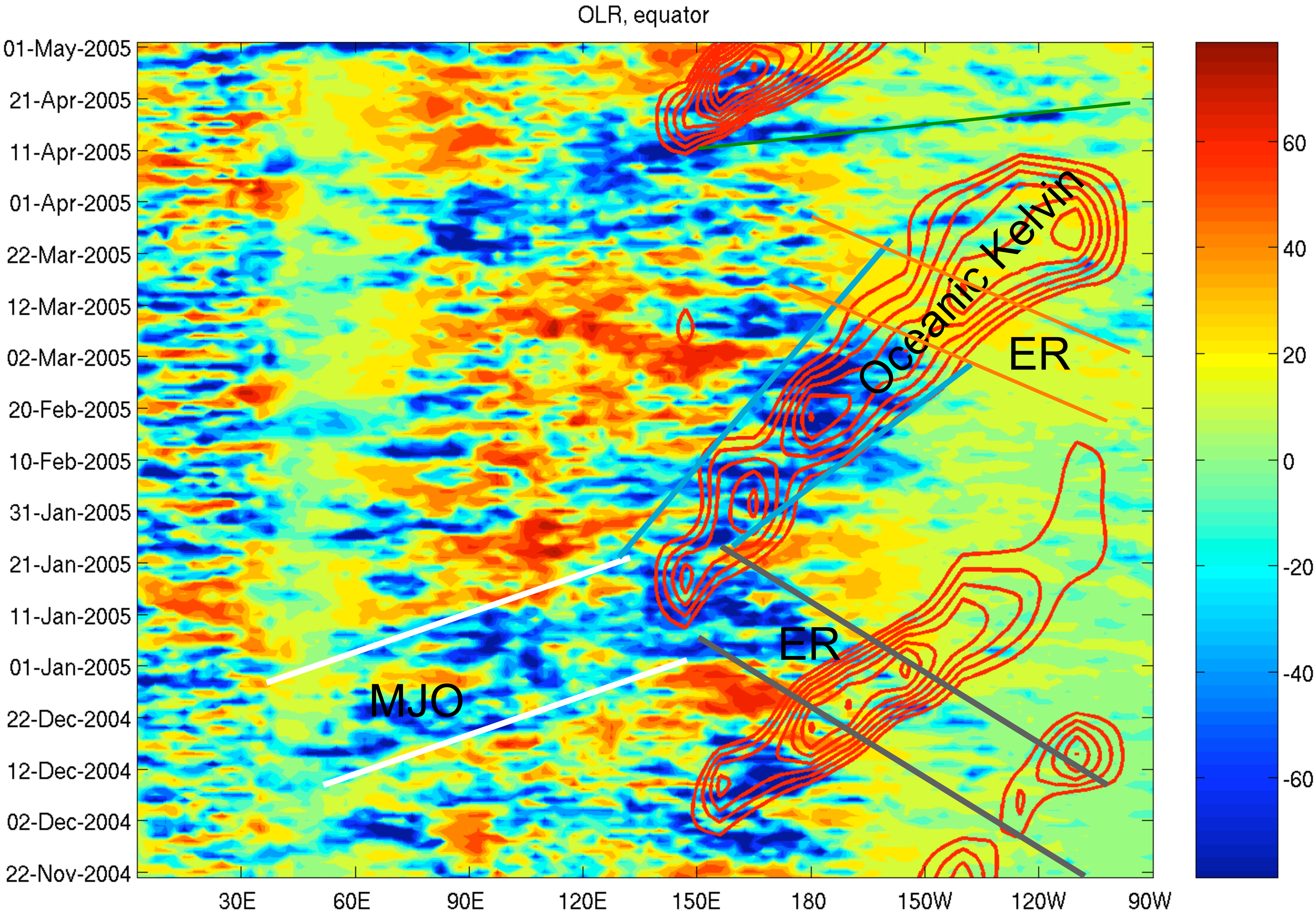


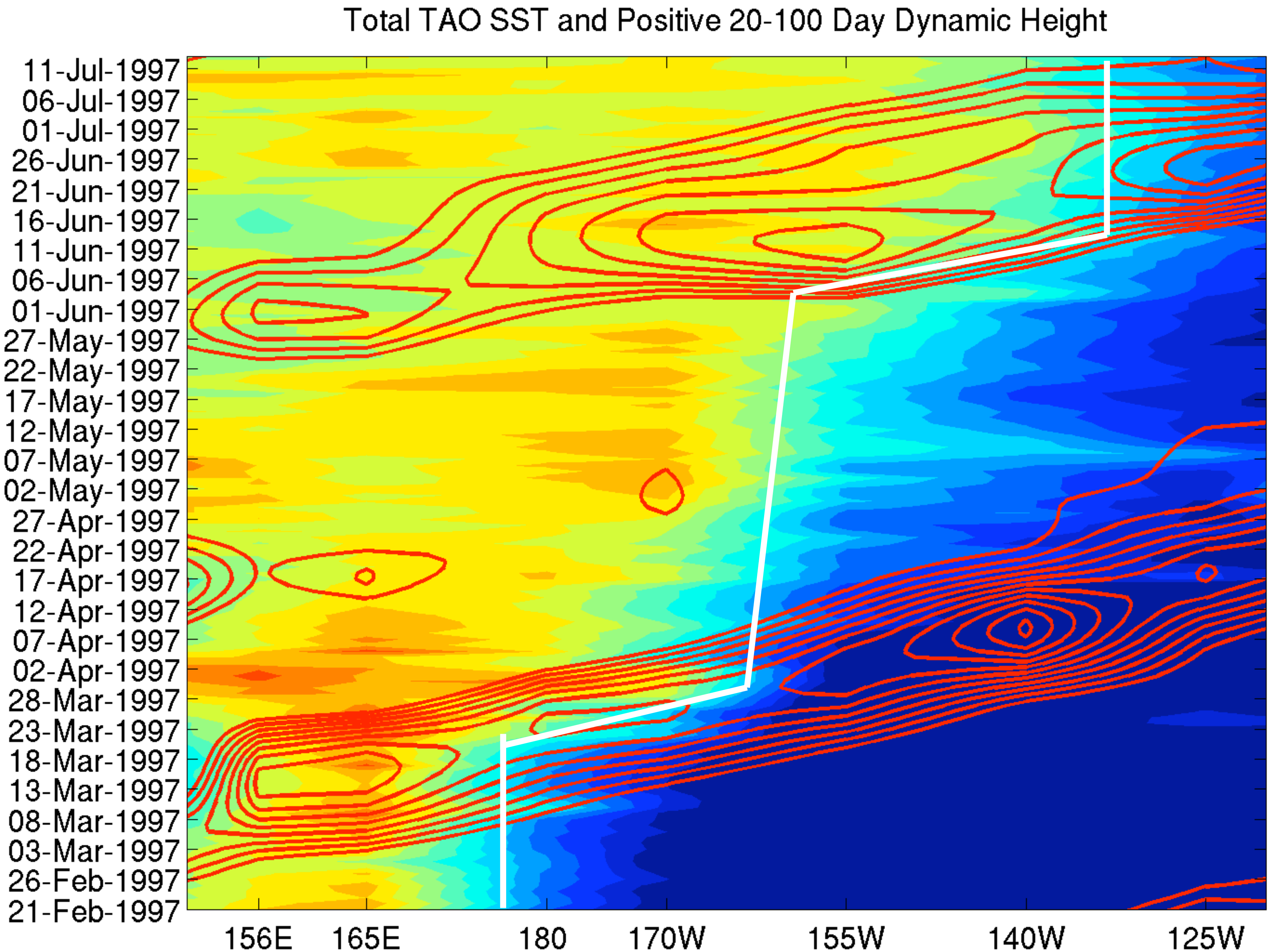
a. 20-100 Day Dynamic Height Anomaly and Total SST, 140W
cm
10
8
6
4
2
0
-2
-4
-6
-8
-10
30C
28C
26C
b. 20-100 Day Band Filtered Zonal Current Anomaly
Depth (m)
50
100
150
200
250
60
40
20
0
-20
-40
-60
07-May-2002
16-Jun-2002
26-Jul-2002
04-Sep-2002



Equatorial OLR Anomaly and Positive 20-100 Day Dynamic Height
27-Sep-1997
17-Sep-1997
07-Sep-1997
28-Aug-1997
18-Aug-1997
08-Aug-1997
29-Jul-1997
19-Jul-1997
09-Jul-1997
29-Jun-1997
19-Jun-1997
50E
75E
100E
130E
147E
165E
180
170W
155W
140W
125W
110W
80
60
40
20
0
-20
-40
-60
-80


OLR, equator
01-May-2005
21-Apr-2005
11-Apr-2005
01-Apr-2005
22-Mar-2005
12-Mar-2005
02-Mar-2005
20-Feb-2005
10-Feb-2005
31-Jan-2005
21-Jan-2005
11-Jan-2005
01-Jan-2005
22-Dec-2004
12-Dec-2004
02-Dec-2004
22-Nov-2004
30E
60E
90E
120E
150E
180
150W
120W
90W
60
40
20
0
-20
-40
-60


OLR, equator
01-May-2005
21-Apr-2005
11-Apr-2005
01-Apr-2005
22-Mar-2005
12-Mar-2005
02-Mar-2005
20-Feb-2005
10-Feb-2005
31-Jan-2005
21-Jan-2005
11-Jan-2005
01-Jan-2005
22-Dec-2004
12-Dec-2004
02-Dec-2004
22-Nov-2004
30E
60E
90E
120E
150E
180
150W
120W
90W
Oceanic Kelvin
ER
ER
MJO
60
40
20
0
-20
-40
-60

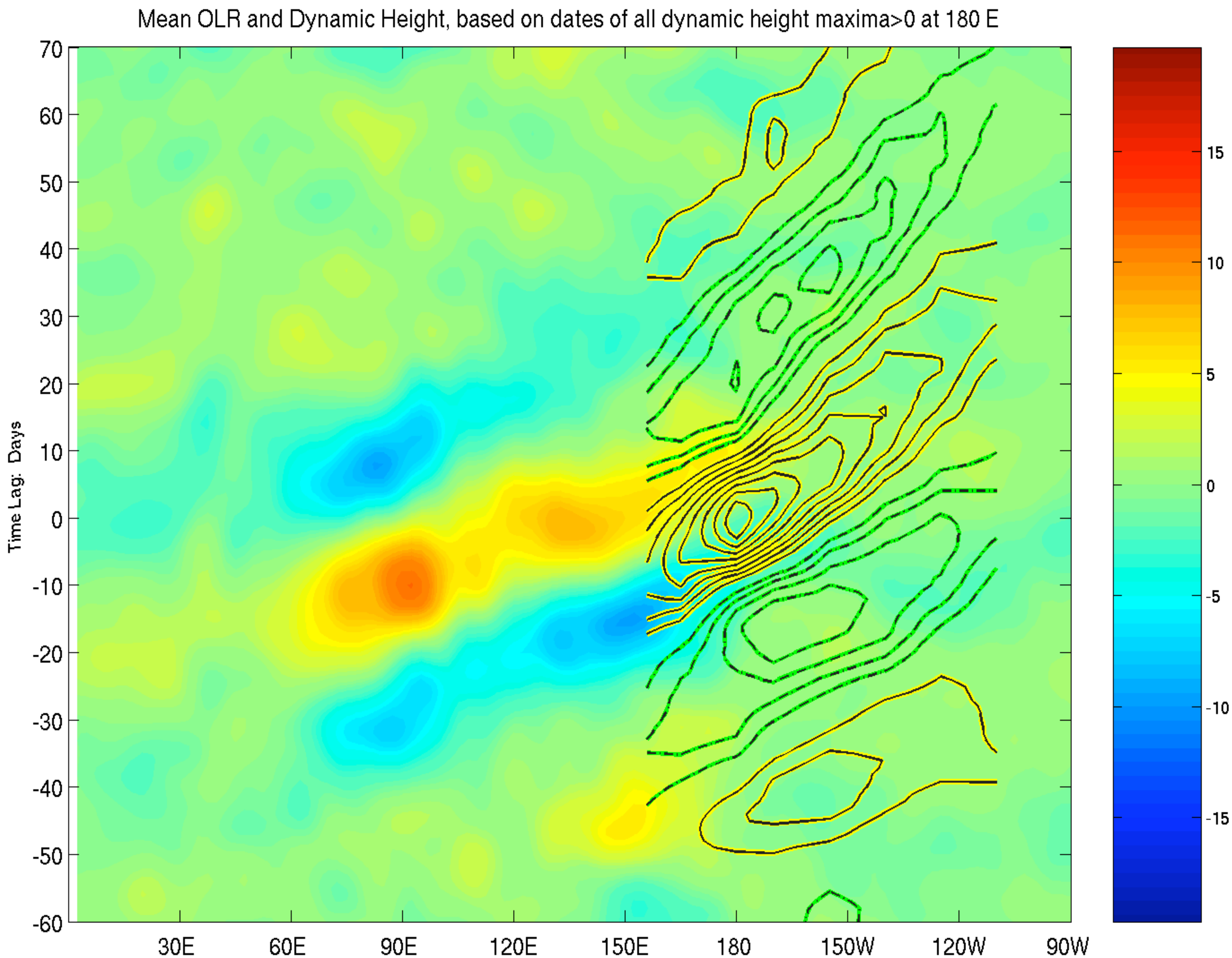

Total TAO SST and Positive 20-100 Day Dynamic Height
11-Jul-1997
06-Jul-1997
01-Jul-1997
26-Jun-1997
21-Jun-1997
16-Jun-1997
11-Jun-1997
06-Jun-1997
01-Jun-1997
27-May-1997
22-May-1997
17-May-1997
12-May-1997
07-May-1997
02-May-1997
27-Apr-1997
22-Apr-1997
17-Apr-1997
12-Apr-1997
07-Apr-1997
02-Apr-1997
28-Mar-1997
23-Mar-1997
18-Mar-1997
13-Mar-1997
08-Mar-1997
03-Mar-1997
26-Feb-1997
21-Feb-1997
156E
165E
180
170W
155W
140W
125W

How General is the Pattern?

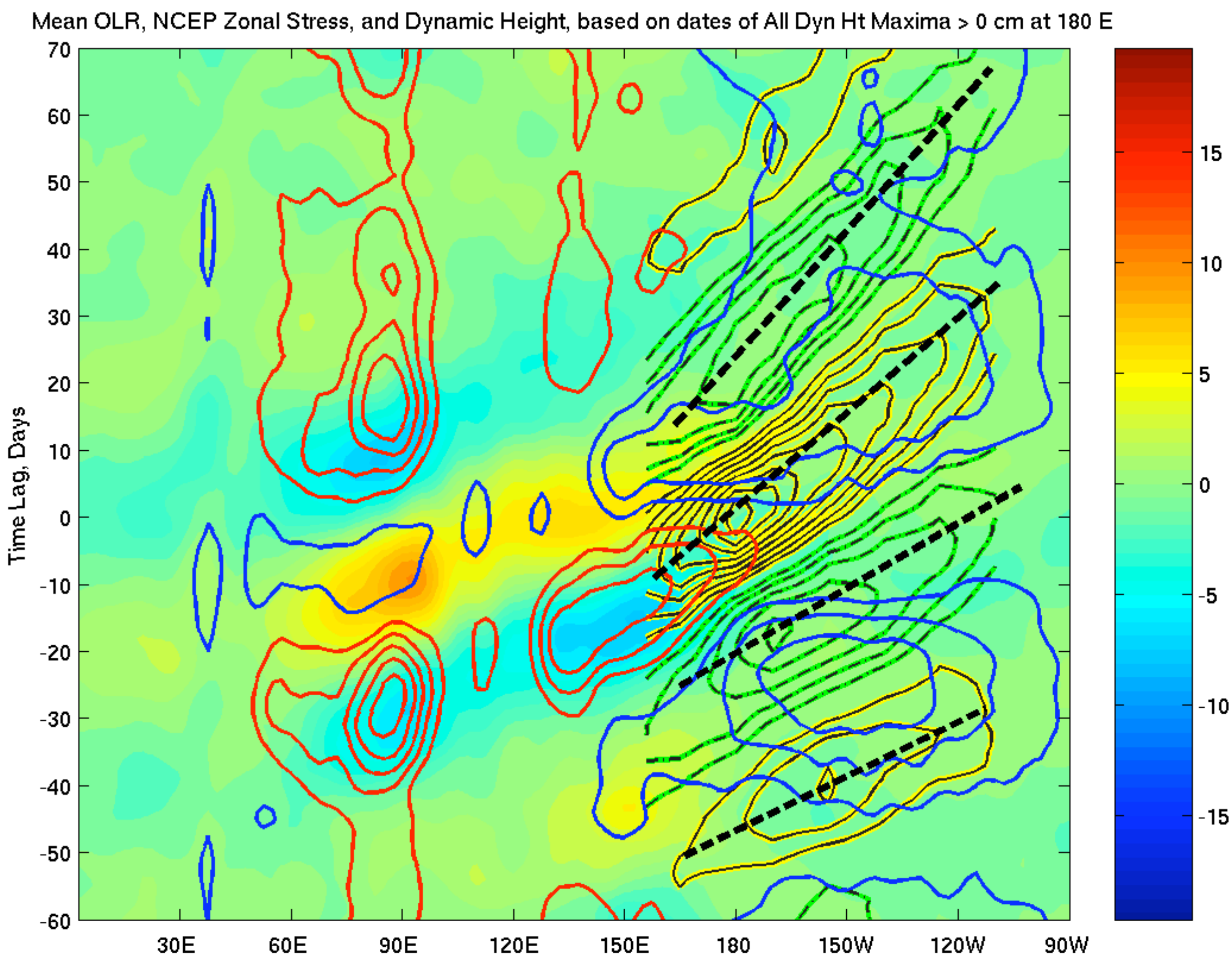
- Apply a variety of composite techniques
  - Composite average
  - Regression

Composite Average

- Find dates of all Kelvin wave crests at the dateline
- Average data fields over those dates and lags
  - The set of dates may subset to selected background states



Mean OLR and Dynamic Height, based on dates of all dynamic height maxima>0 at 180 E
Time Lag: Days
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
30E
60E
90E
120E
150E
180
150W
120W
90W
15
10
5
0
-5
-10
-15

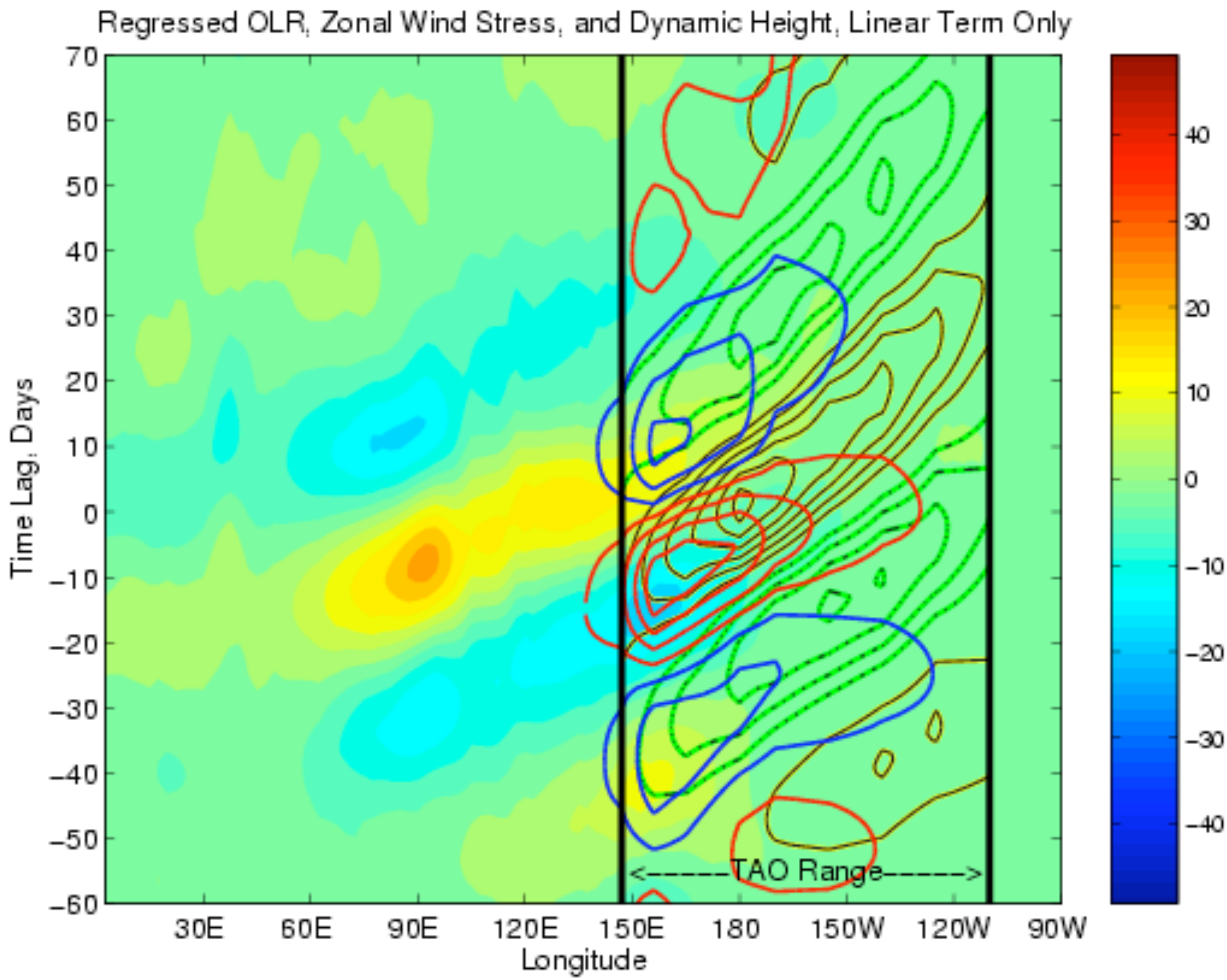


Mean OLR, NCEP Zonal Stress, and Dynamic Height, based on dates of All Dyn Ht Maxima > 0 cm at 180 E
Time Lag, Days
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
30E
60E
90E
120E
150E
180
150W
120W
90W
15
10
5
0
-5
-10
-15

Linear Regression

- Regress OLR, dynamic height, and wind stress onto Kelvin wave index at lag
  - $y=a_1x+a_2$

- Substitute time series for y and let x=time index of Kelvin waves at dateline, solve, and substitute



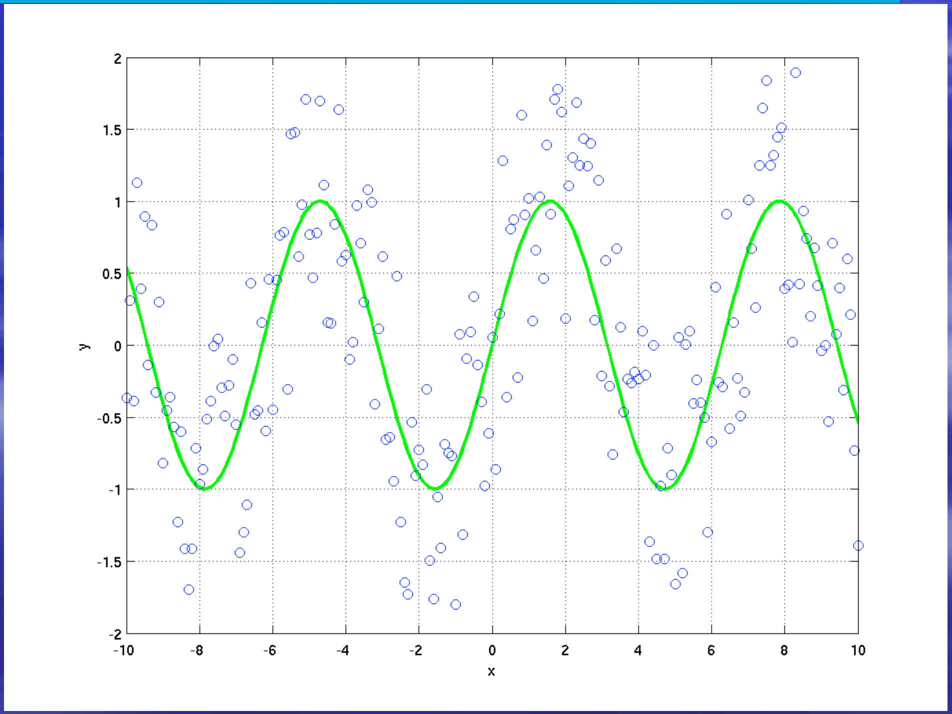
Regressed OLR, Zonal Wind Stress, and Dynamic Height, Linear Term Only
Time Lag, Days
70
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
30E
60E
90E
120E
150E
180
150W
120W
90W
Longitude
<------TAO Range------>
40
30
20
10
0
−10
−20
−30
−40

Power Series Regression

- Fits a polynomial to a scatterplot

$$y = a_1 + a_2 x + a_3 x^2 + a_4 x^3 \ldots$$

- Useful for diagnosing relationships between waves of different shapes and frequencies



Cross-Product Regression

- Diagnoses Modulation
- Let k=Kelvin wave index
- Let e=ENSO index

- y=…+ake+…

MJO/Kelvin Wave/ENSO Combined Regression Approach

$$y = a_0 + a_1\mathrm{e} + a_2\dot{\mathrm{e}} + a_3 k + a_4 k^2 +$$

$$a_5 k^3 + a_6 k^4 + a_7 \mathrm{e} \bullet k + a_8 \dot{\mathrm{e}} \bullet k$$

$$+ a_{13}(\dot{\mathrm{e}} k^2) + a_{14}(\dot{\mathrm{e}} k^3) + \varepsilon$$

MJO/Kelvin Wave/ENSO Combined Regression Approach

$$y = a_0 + a_1 \mathrm{e} + a_2 \dot{\mathrm{e}} + a_3 k + a_4 k^2 +$$

$$a_5 k^3 + a_6 k^4 + a_7 \mathrm{e} \bullet k + a_8 \dot{\mathrm{e}} \bullet k$$

$$+ a_{13}(\dot{\mathrm{e}} k^2) + a_{14}(\dot{\mathrm{e}} k^3) + \varepsilon$$

MJO/Kelvin Wave/ENSO Combined Regression Approach

$$y = a_0 + a_1\text{e} + a_2\dot{\text{e}} + a_3 k + a_4 k^2 +$$

$$a_5 k^3 + a_6 k^4 + a_7\text{e} \bullet k + a_8\dot{\text{e}} \bullet k$$

$$+ a_{13}(\dot{\text{e}}k^2) + a_{14}(\dot{\text{e}}k^3) + \varepsilon$$

MJO/Kelvin Wave/ENSO Combined Regression Approach

$$y = a_0 + a_1 \mathrm{e} + a_2 \dot{\mathrm{e}} + a_3 k + a_4 k^2 + a_5 k^3 + a_6 k^4 + a_7 \mathrm{e} \bullet k + a_8 \dot{\mathrm{e}} \bullet k + a_{13}(\dot{\mathrm{e}} k^2) + a_{14}(\dot{\mathrm{e}} k^3) + \varepsilon$$

MJO/Kelvin Wave/ENSO Combined Regression Approach

$$y = a_0 + a_1 e + a_2 \dot{e} + a_3 k + a_4 k^2 +$$

$$a_5 k^3 + a_6 k^4 + a_7 e \bullet k + a_8 \dot{e} \bullet k$$

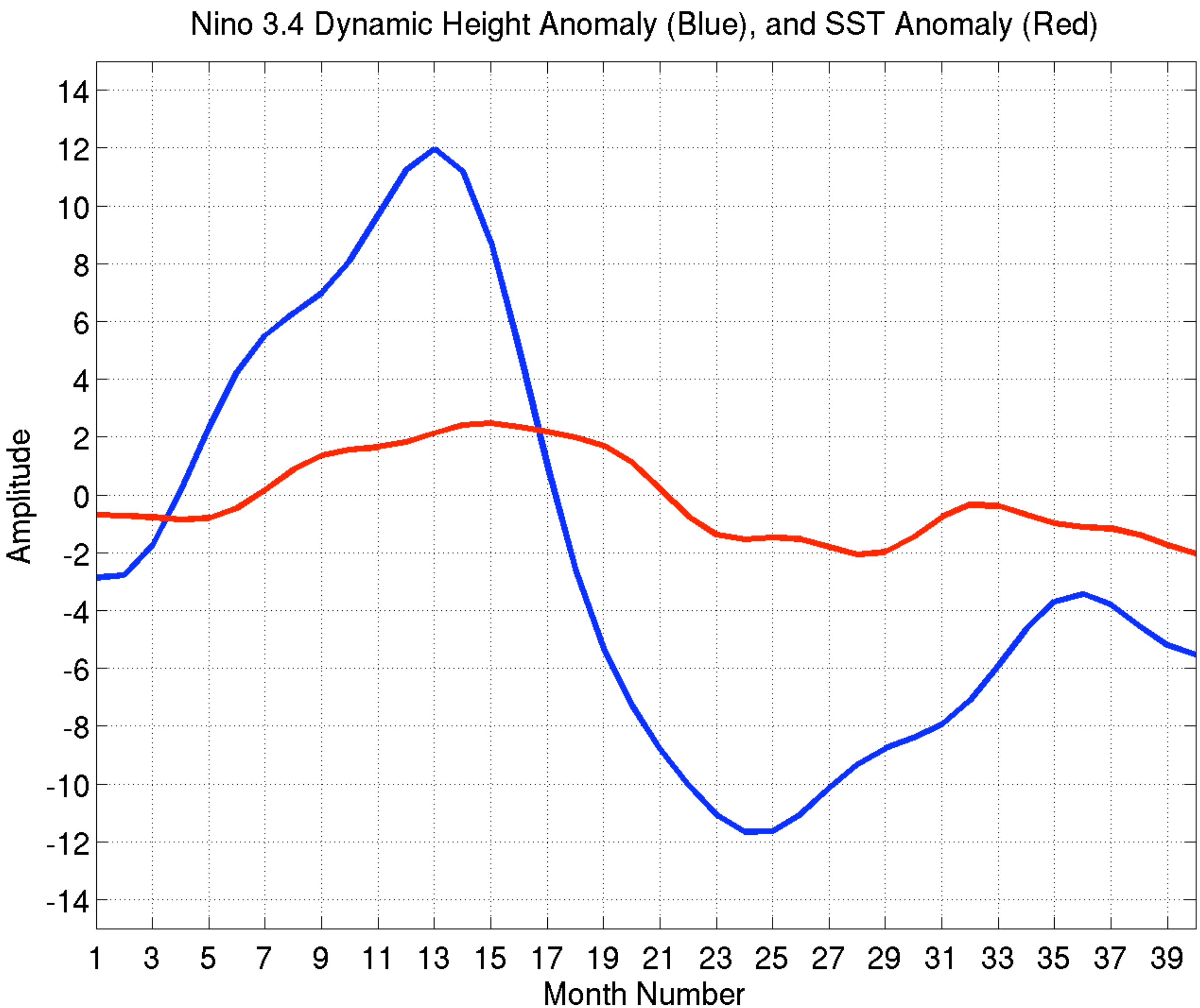
$$+ a_{13}(\dot{e} k^2) + a_{14}(\dot{e} k^3) + \varepsilon$$

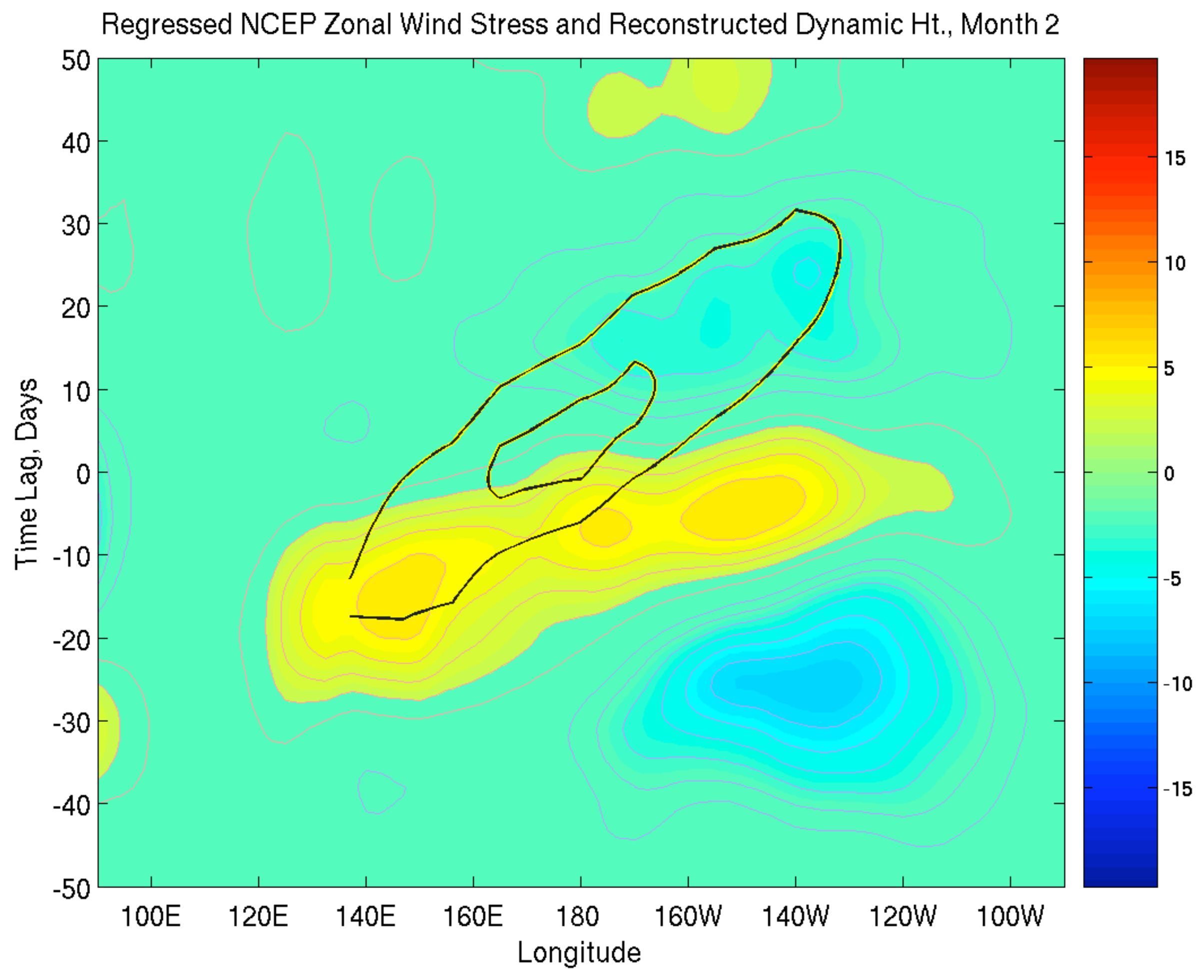
MJO/Kelvin Wave/ENSO Combined Regression Approach

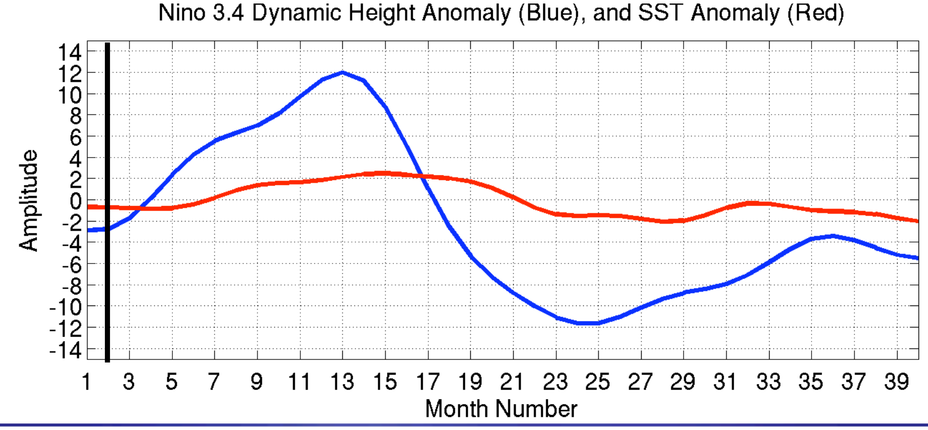
$$y = a_0 + a_1 e + a_2 \dot{e} + a_3 k + a_4 k^2 +$$

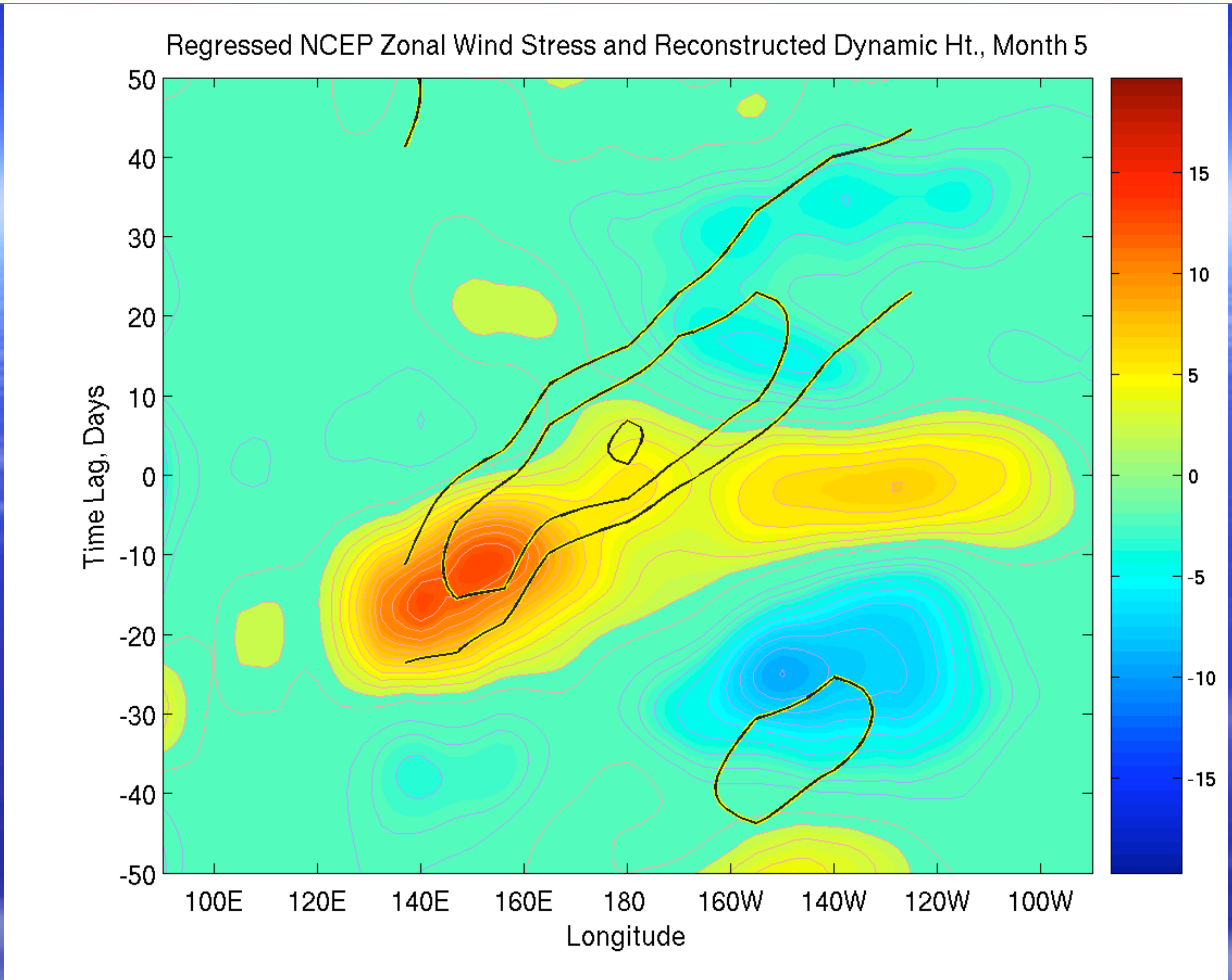
$$a_5 k^3 + a_6 k^4 + a_7 e \bullet k + a_8 \dot{e} \bullet k$$

$$+ a_{13}(\dot{e}k^2) + a_{14}(\dot{e}k^3) + \varepsilon$$

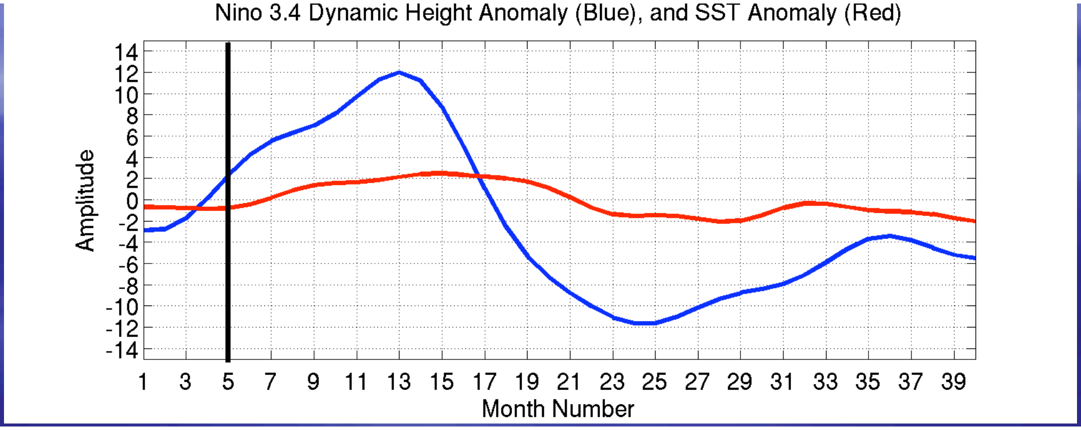

Nino 3.4 Dynamic Height Anomaly (Blue), and SST Anomaly (Red)
Amplitude
Month Number
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39


Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 2
Time Lag, Days
50
40
30
20
10
0
-10
-20
-30
-40
-50
100E
120E
140E
160E
180
160W
140W
120W
100W
Longitude
15
10
5
0
-5
-10
-15

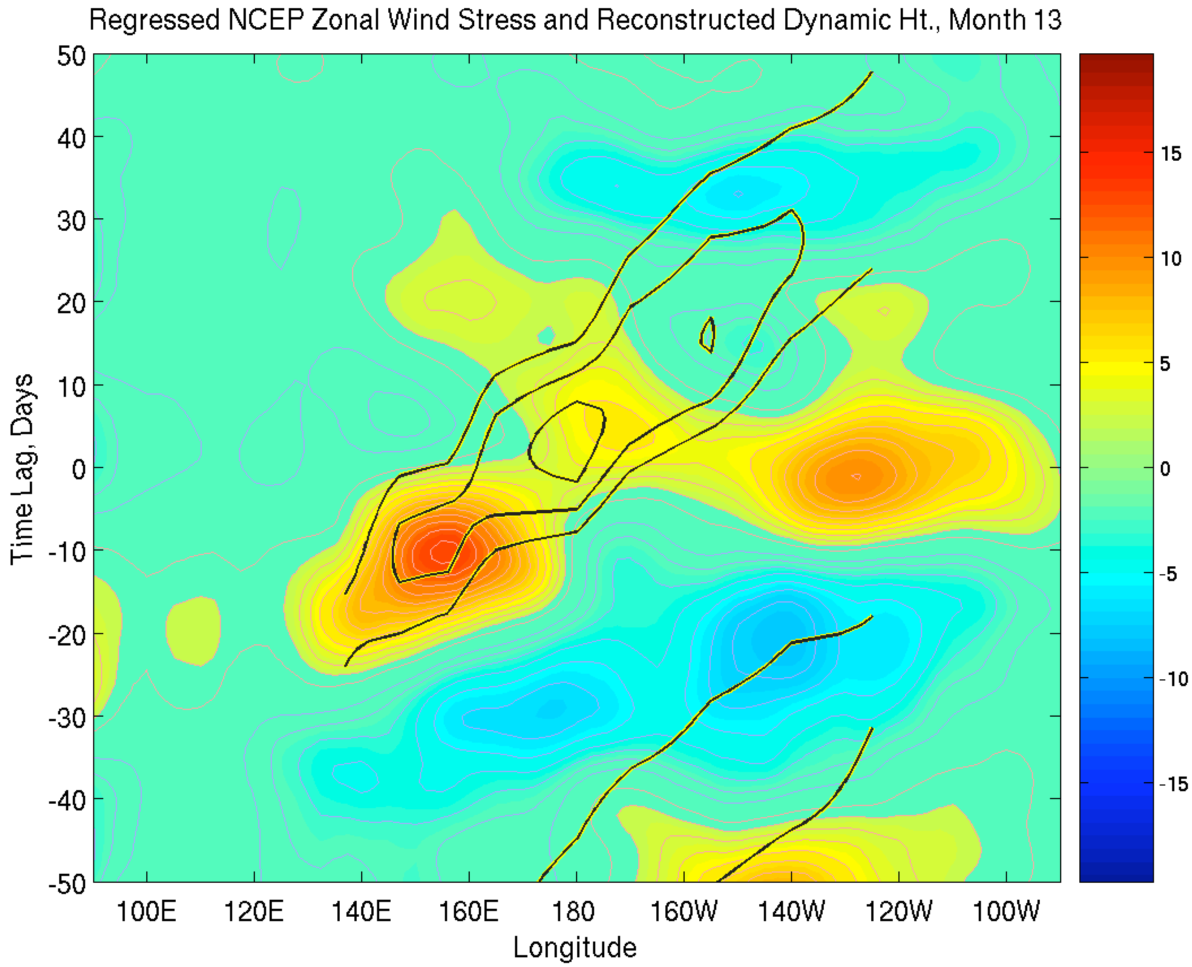

Nino 3.4 Dynamic Height Anomaly (Blue), and SST Anomaly (Red)
Amplitude
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
Month Number

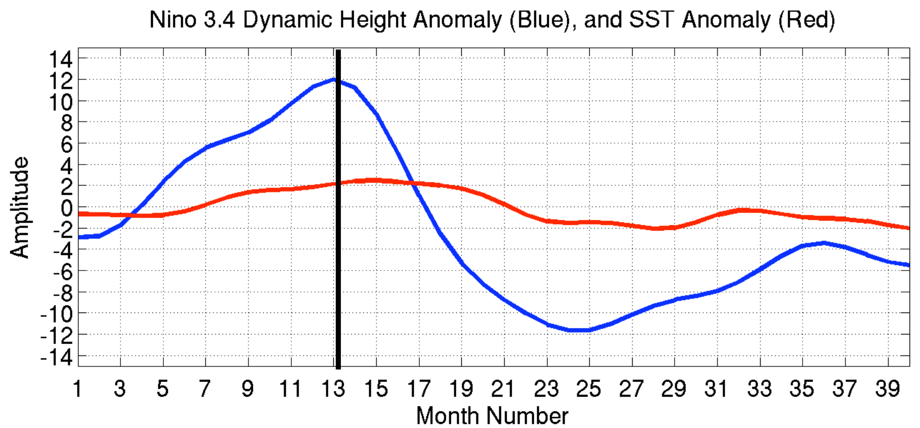


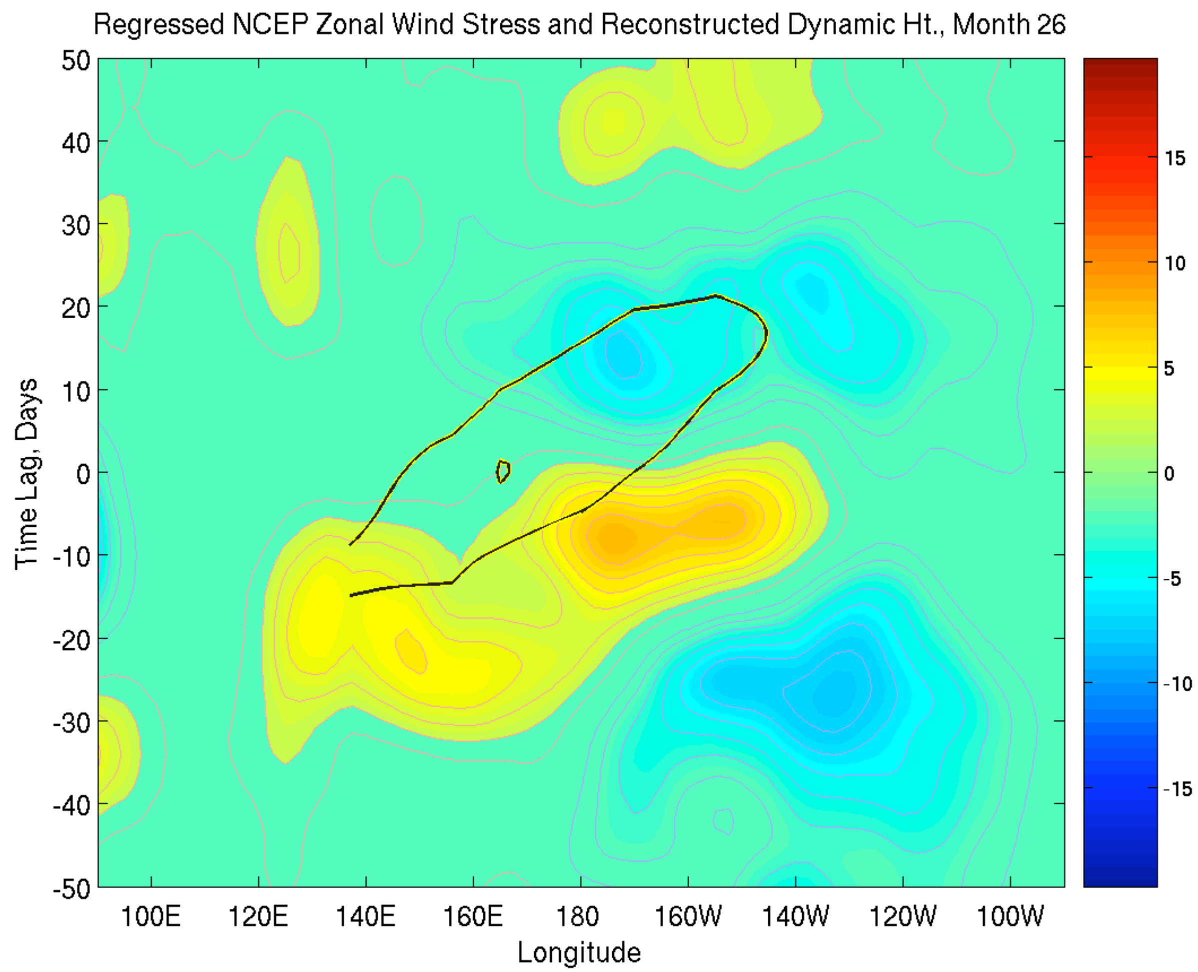
Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 5
Time Lag, Days
50
40
30
20
10
0
-10
-20
-30
-40
-50
100E 120E 140E 160E 180 160W 140W 120W 100W
Longitude
15
10
5
0
-5
-10
-15



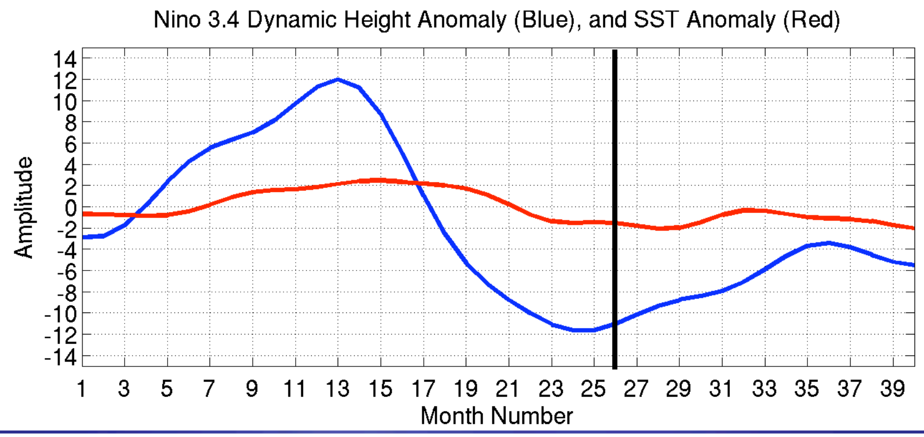
Nino 3.4 Dynamic Height Anomaly (Blue), and SST Anomaly (Red)
Amplitude
14 12 10 8 6 4 2 0 -2 -4 -6 -8 -10 -12 -14
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39
Month Number


Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 13
Time Lag, Days
50
40
30
20
10
0
-10
-20
-30
-40
-50
100E
120E
140E
160E
180
160W
140W
120W
100W
Longitude
15
10
5
0
-5
-10
-15

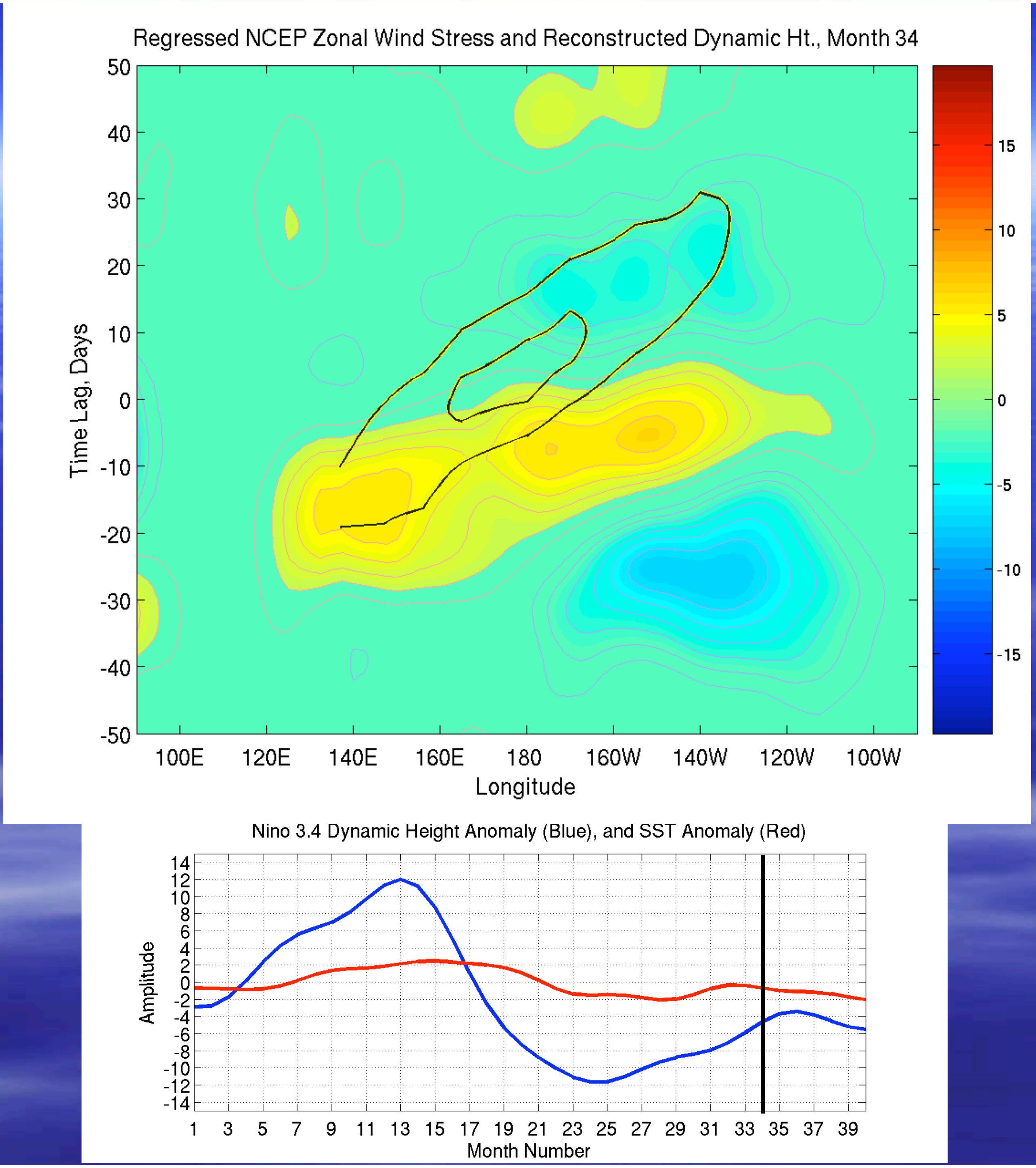

Nino 3.4 Dynamic Height Anomaly (Blue), and SST Anomaly (Red)
Amplitude
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
Month Number



Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 26
Time Lag, Days
Longitude
100E
120E
140E
160E
180
160W
140W
120W
100W



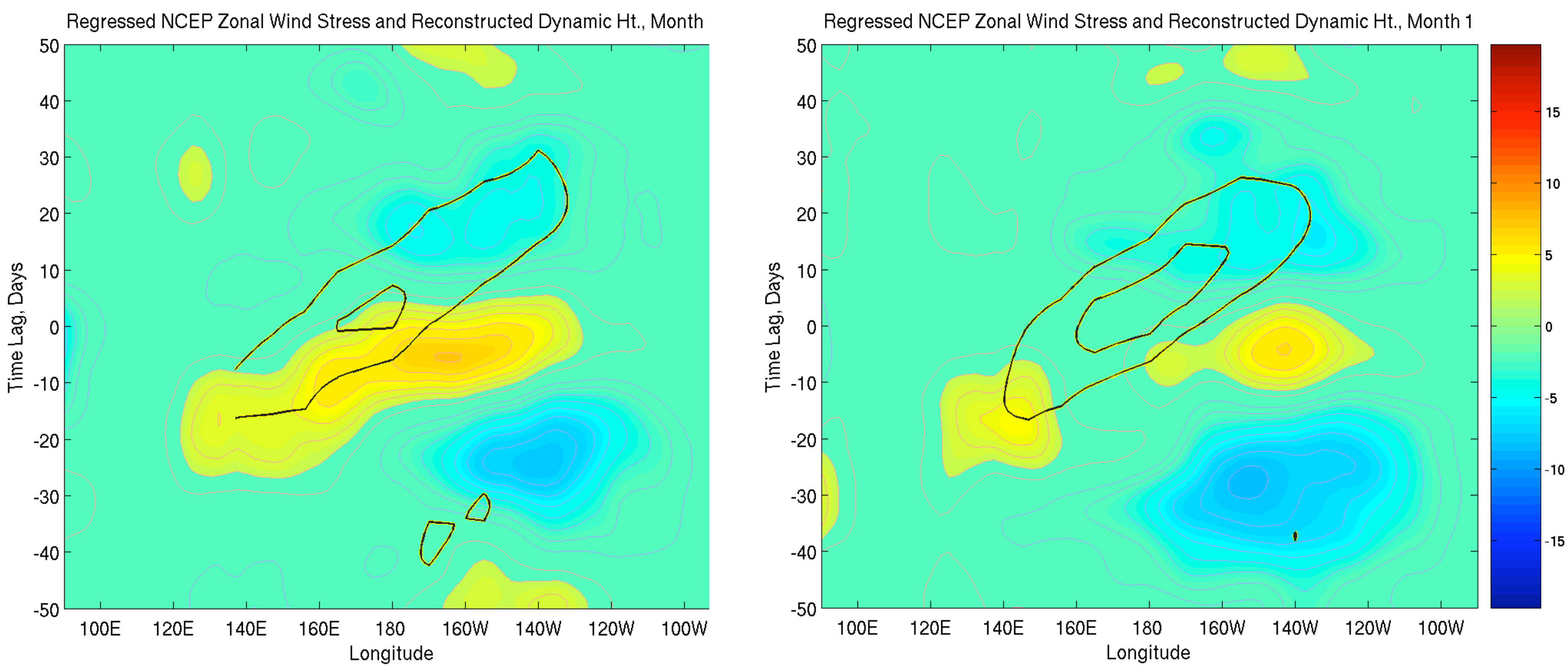
Nino 3.4 Dynamic Height Anomaly (Blue), and SST Anomaly (Red)
Amplitude
Month Number

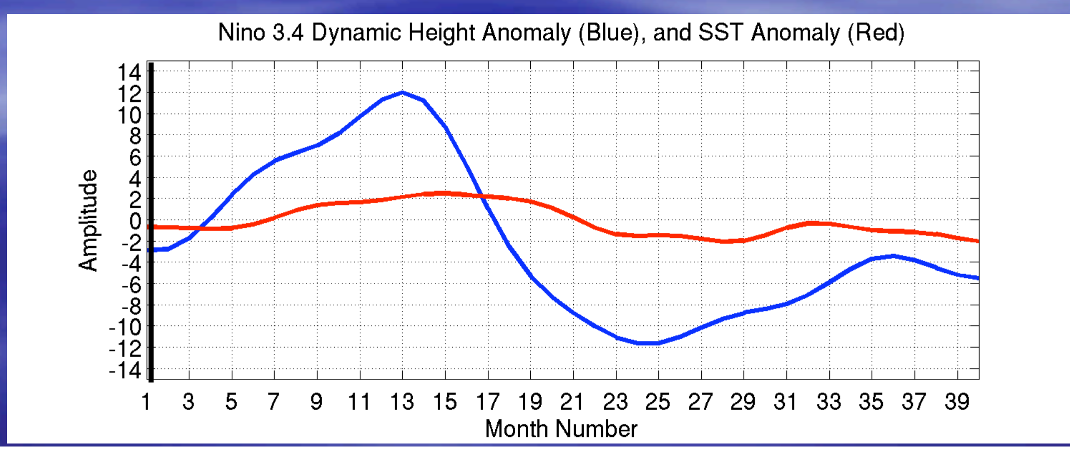


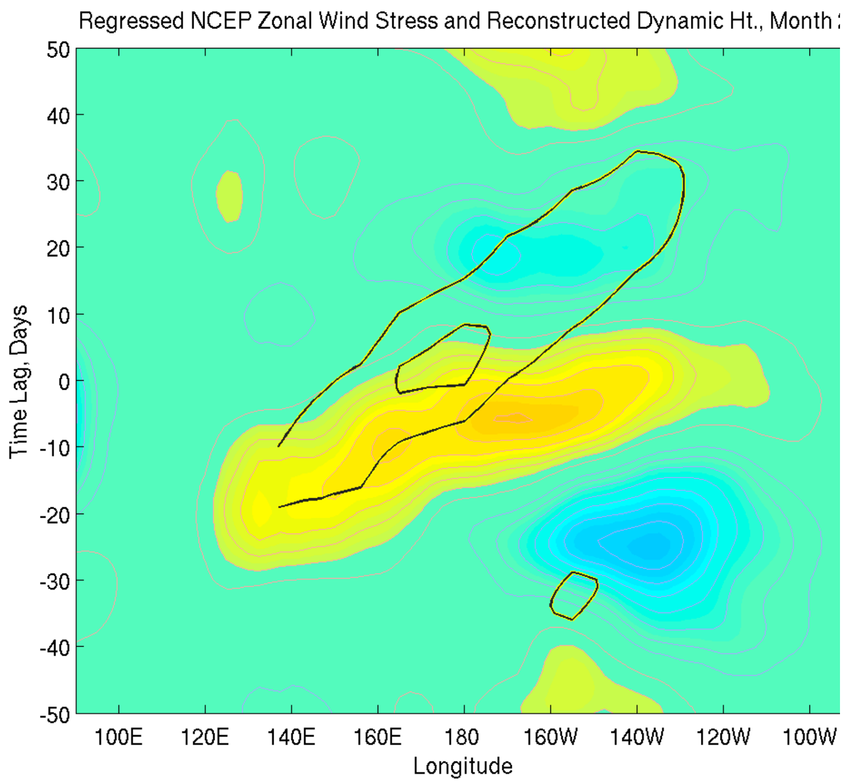
Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 34
Time Lag, Days
Longitude
100E 120E 140E 160E 180 160W 140W 120W 100W
Nino 3.4 Dynamic Height Anomaly (Blue), and SST Anomaly (Red)
Amplitude
Month Number

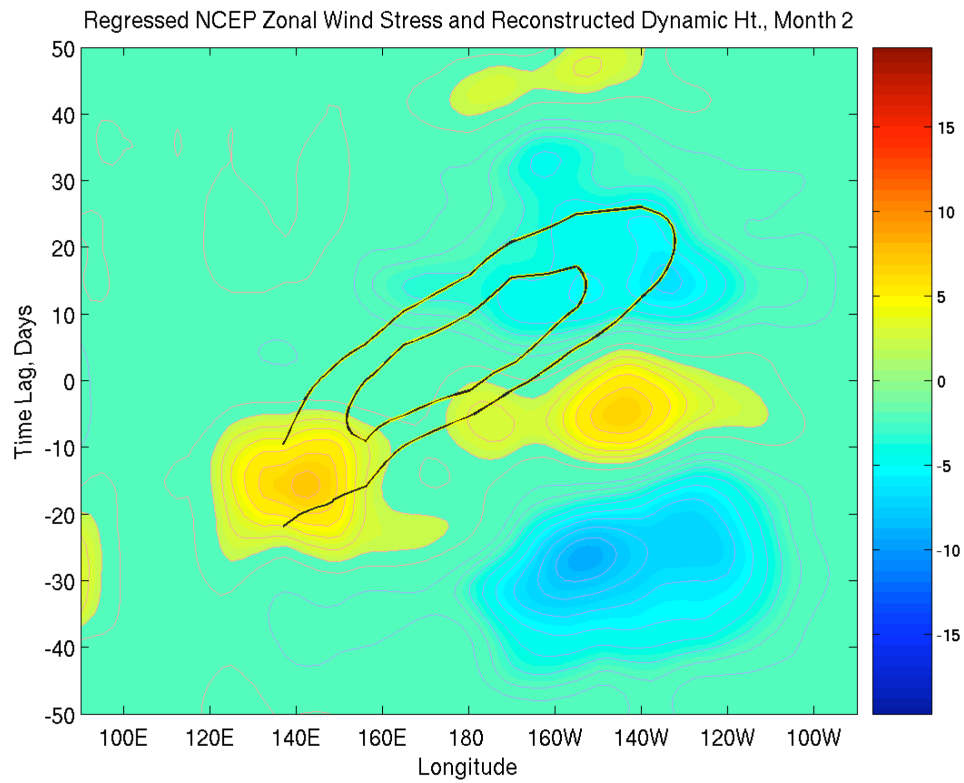
Has the Pattern Changed with the Climate?

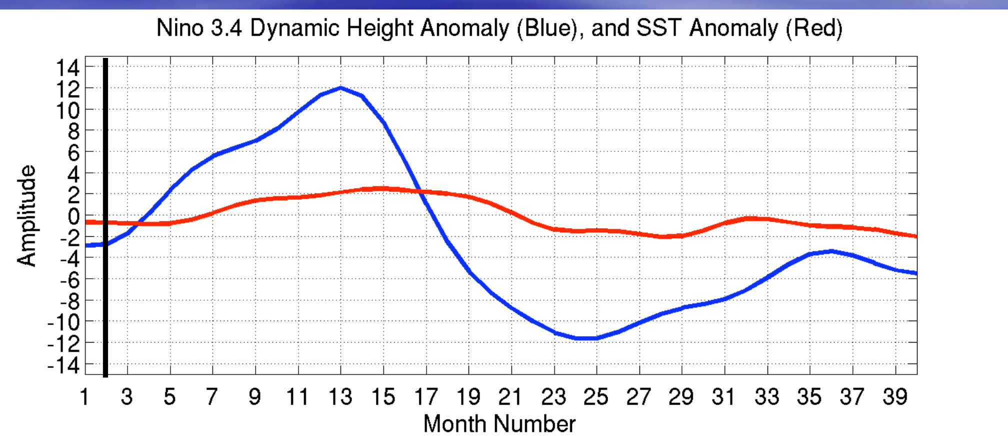
- Apply same regression model and interannual pattern
- Train model 1988-2002 and 1974-1987 periods

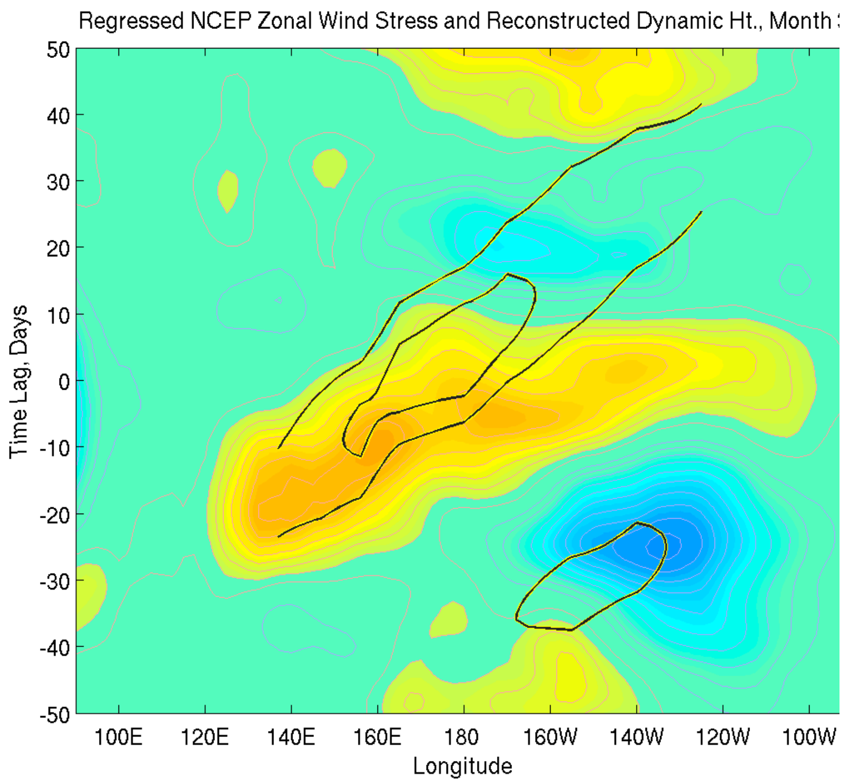

Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month
Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 1
Time Lag, Days
Longitude
50
40
30
20
10
0
-10
-20
-30
-40
-50
100E
120E
140E
160E
180
160W
140W
120W
100W
15
10
5
0
-5
-10
-15

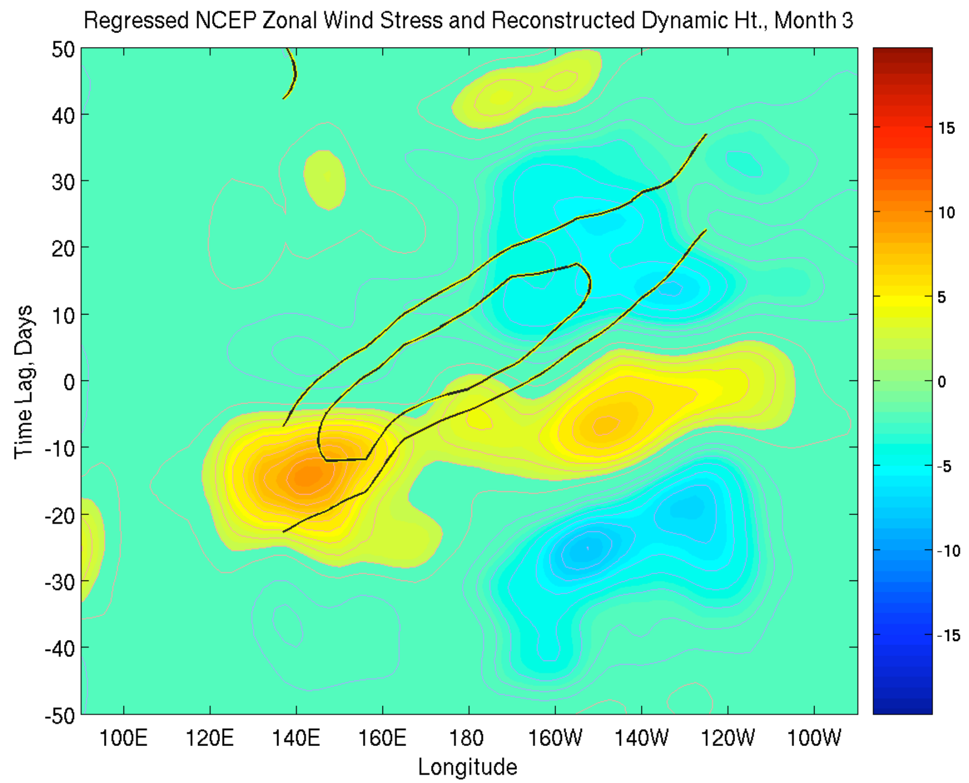

Nino 3.4 Dynamic Height Anomaly (Blue), and SST Anomaly (Red)
Amplitude
Month Number
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39

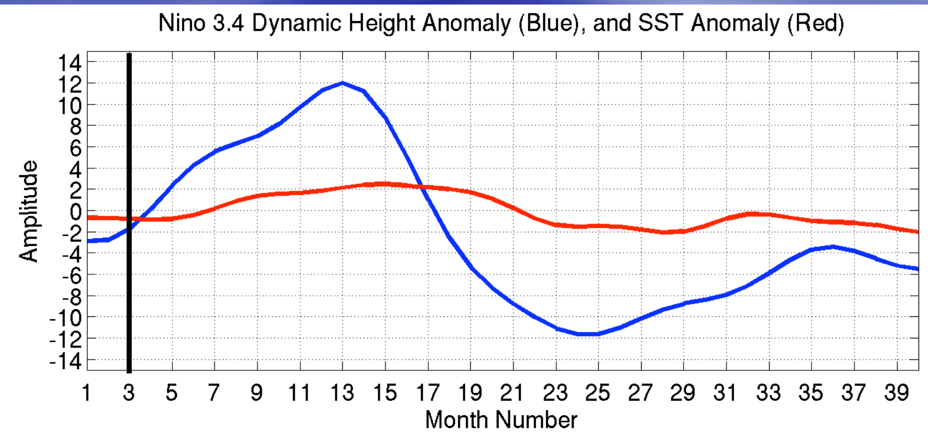

Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month
Time Lag, Days
50 40 30 20 10 0 -10 -20 -30 -40 -50
100E 120E 140E 160E 180 160W 140W 120W 100W
Longitude

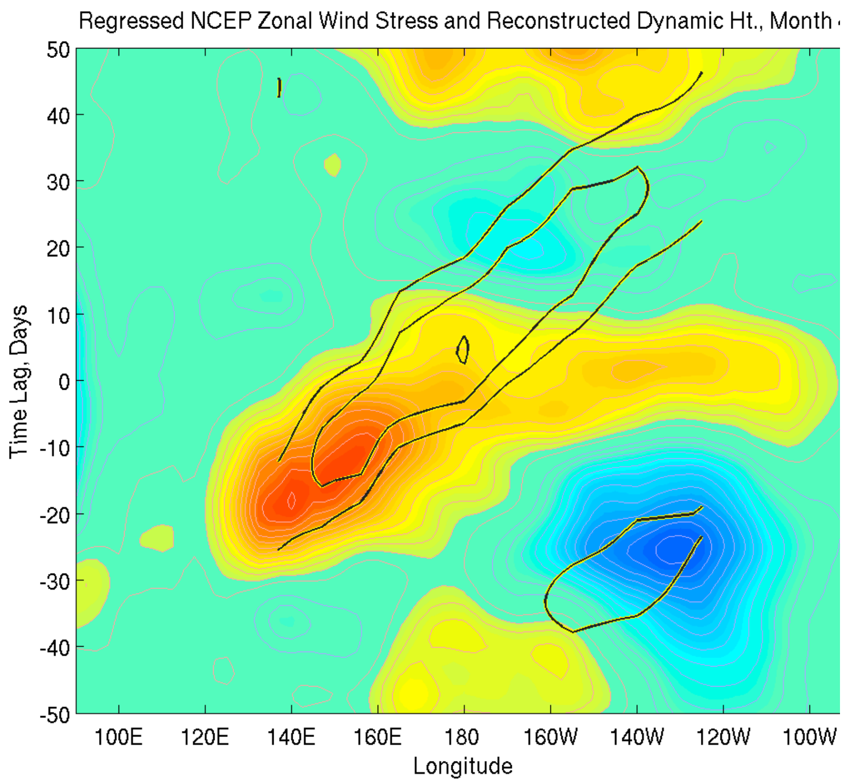

Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 2
Time Lag, Days
50 40 30 20 10 0 -10 -20 -30 -40 -50
100E 120E 140E 160E 180 160W 140W 120W 100W
Longitude
15 10 5 0 -5 -10 -15

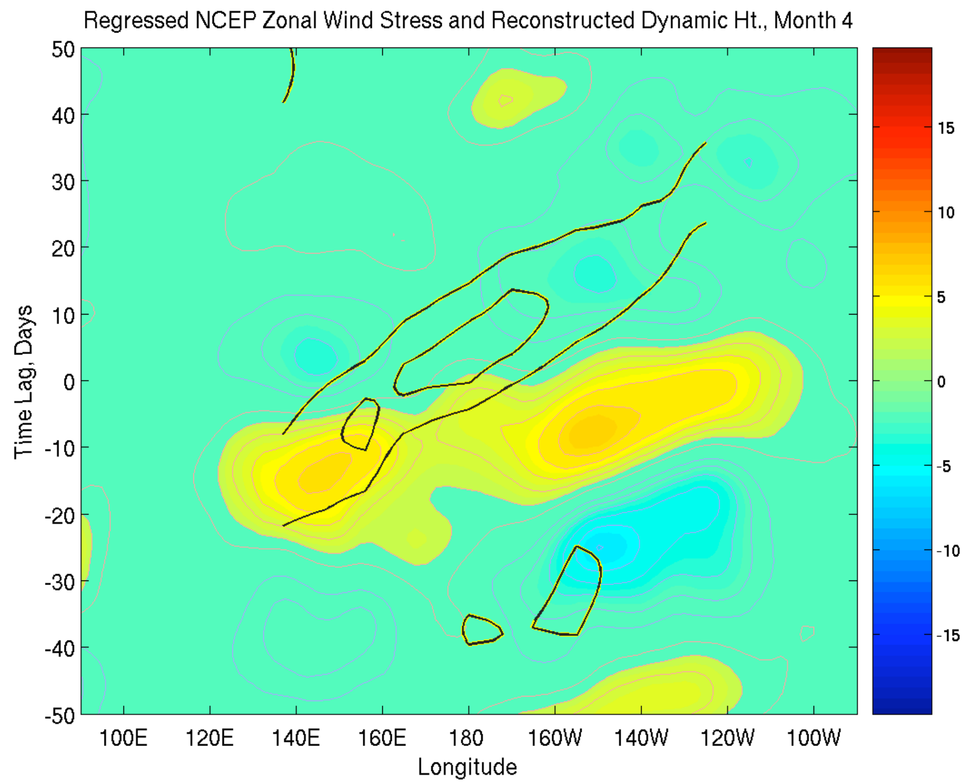

Nino 3.4 Dynamic Height Anomaly (Blue), and SST Anomaly (Red)
Amplitude
14 12 10 8 6 4 2 0 -2 -4 -6 -8 -10 -12 -14
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39
Month Number

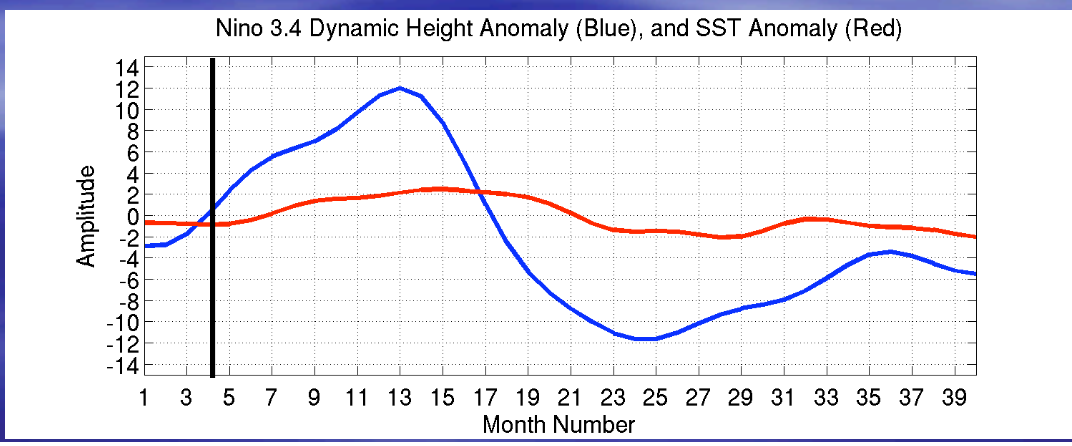

Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 3
Time Lag, Days
Longitude
50
40
30
20
10
0
-10
-20
-30
-40
-50
100E
120E
140E
160E
180
160W
140W
120W
100W

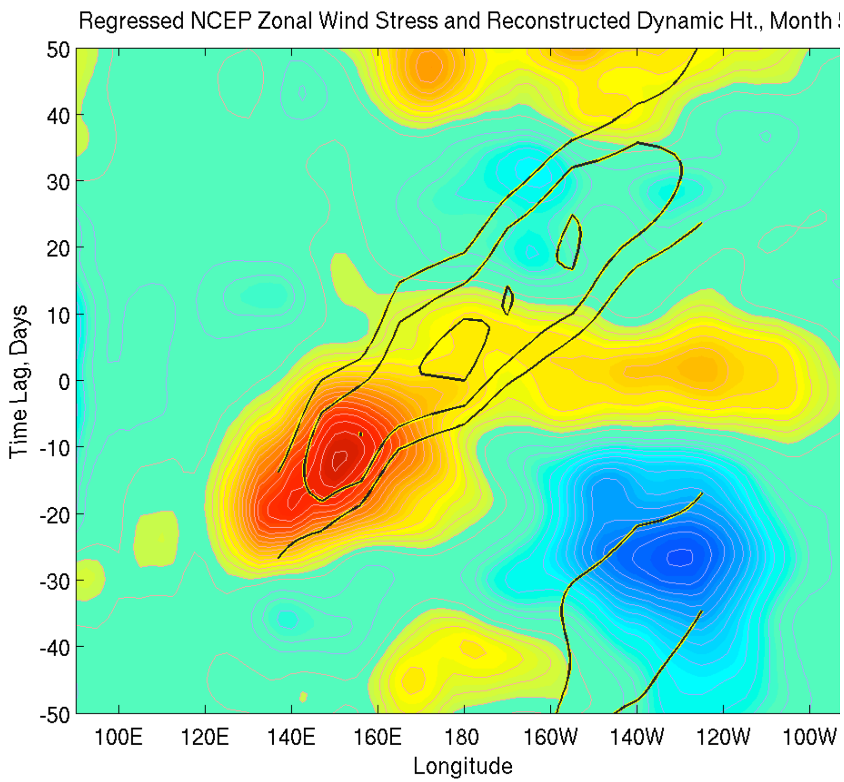

Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 3
Time Lag, Days
Longitude
50
40
30
20
10
0
-10
-20
-30
-40
-50
100E
120E
140E
160E
180
160W
140W
120W
100W
15
10
5
0
-5
-10
-15

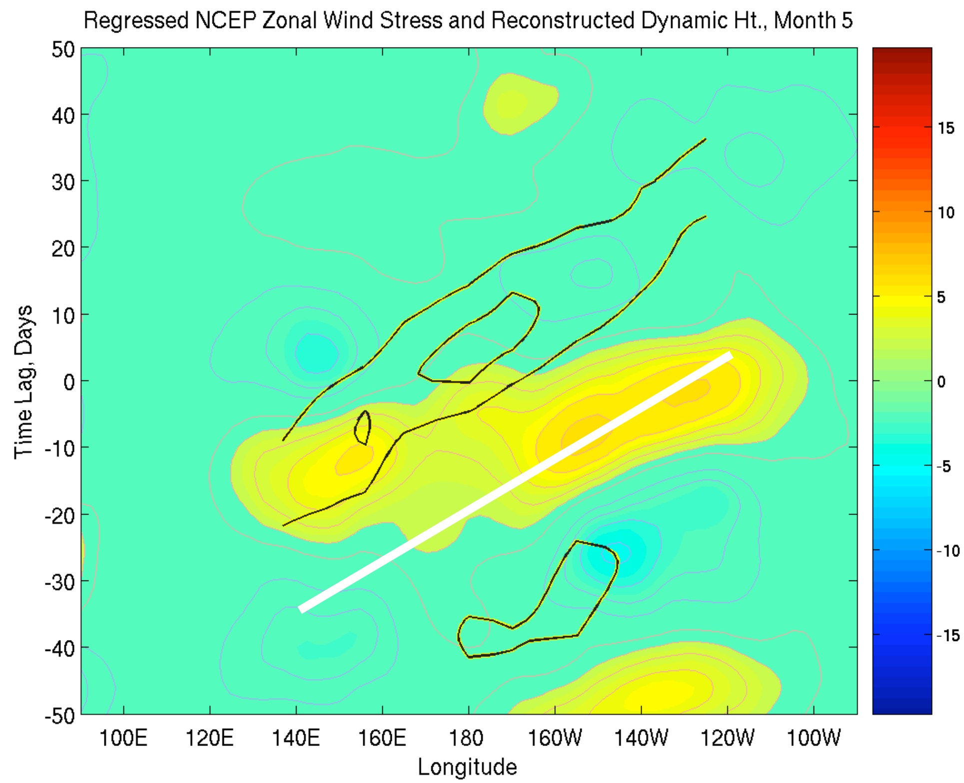

Nino 3.4 Dynamic Height Anomaly (Blue), and SST Anomaly (Red)
Amplitude
Month Number
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39

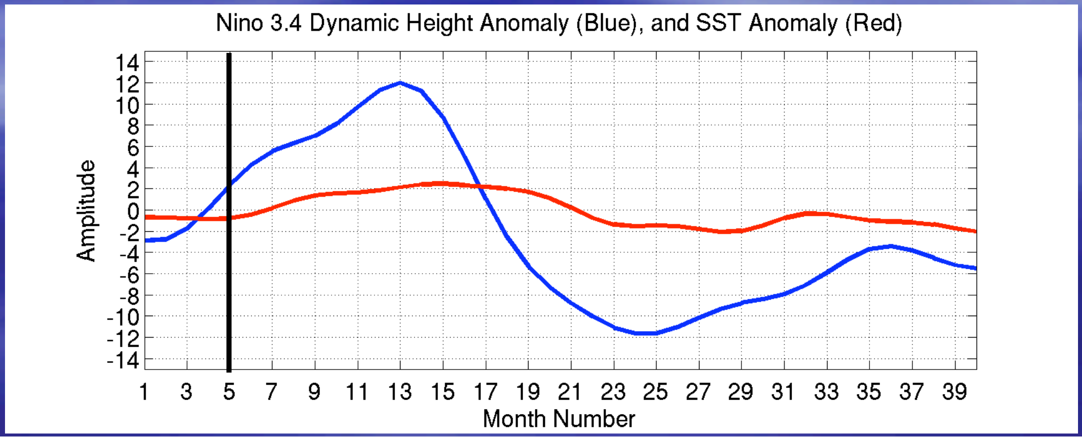

Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 4
Time Lag, Days
Longitude
50
40
30
20
10
0
-10
-20
-30
-40
-50
100E
120E
140E
160E
180
160W
140W
120W
100W


Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 4
Time Lag, Days
Longitude
50
40
30
20
10
0
-10
-20
-30
-40
-50
100E
120E
140E
160E
180
160W
140W
120W
100W
15
10
5
0
-5
-10
-15


Nino 3.4 Dynamic Height Anomaly (Blue), and SST Anomaly (Red)
Amplitude
Month Number
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39

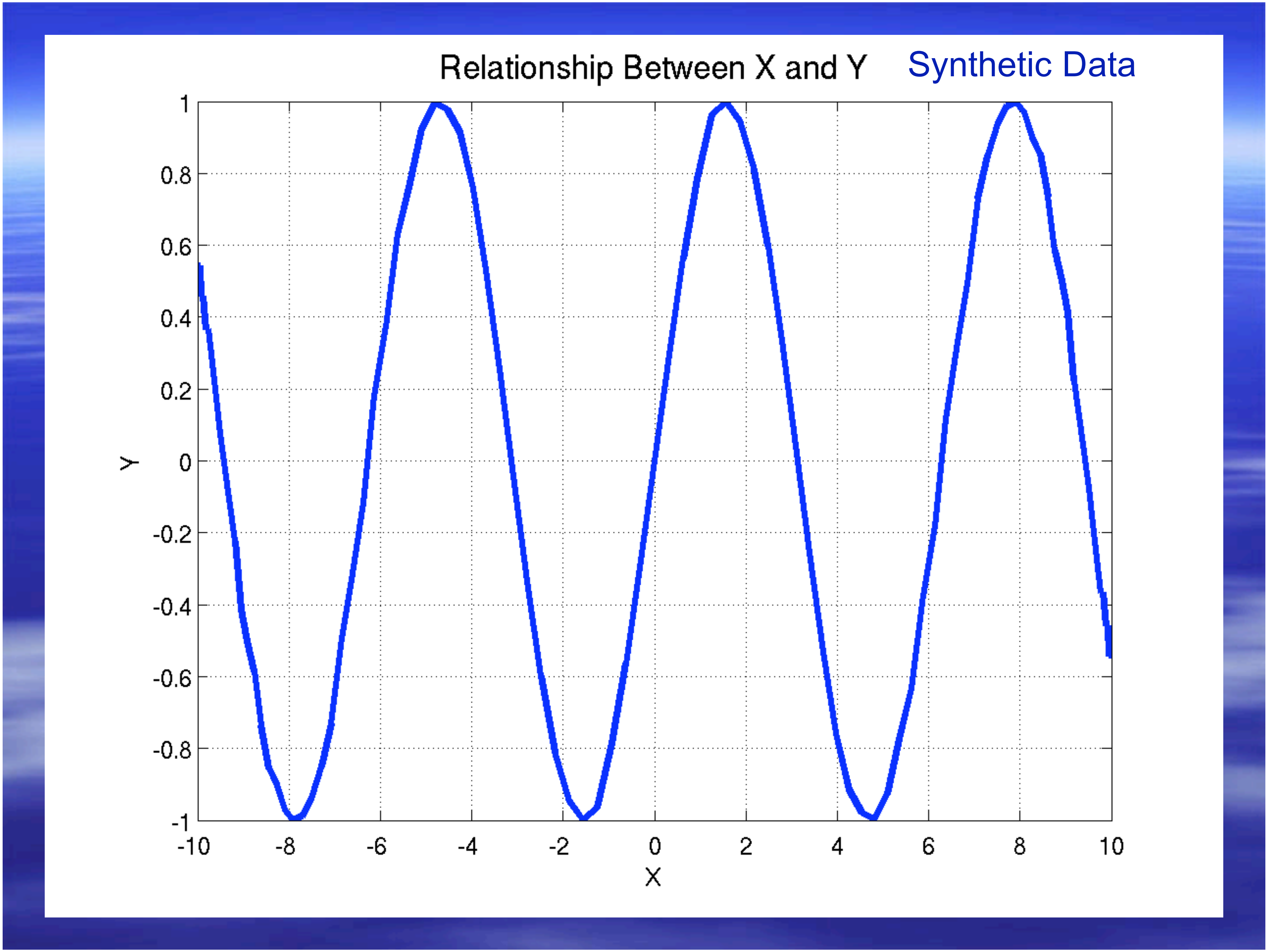

Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month
Time Lag, Days
50
40
30
20
10
0
-10
-20
-30
-40
-50
100E 120E 140E 160E 180 160W 140W 120W 100W
Longitude

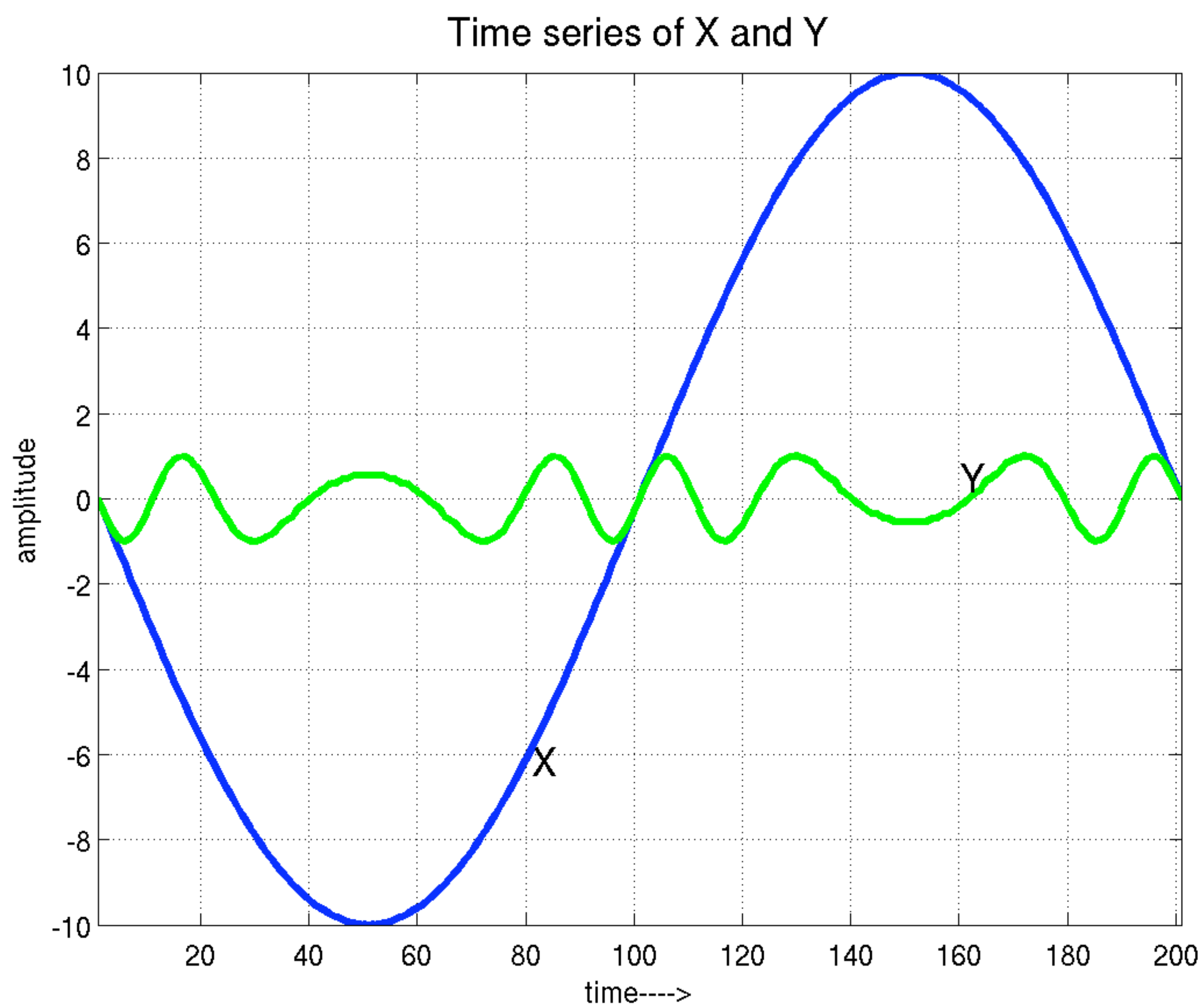

Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 5
Time Lag, Days
50
40
30
20
10
0
-10
-20
-30
-40
-50
100E 120E 140E 160E 180 160W 140W 120W 100W
Longitude
15
10
5
0
-5
-10
-15

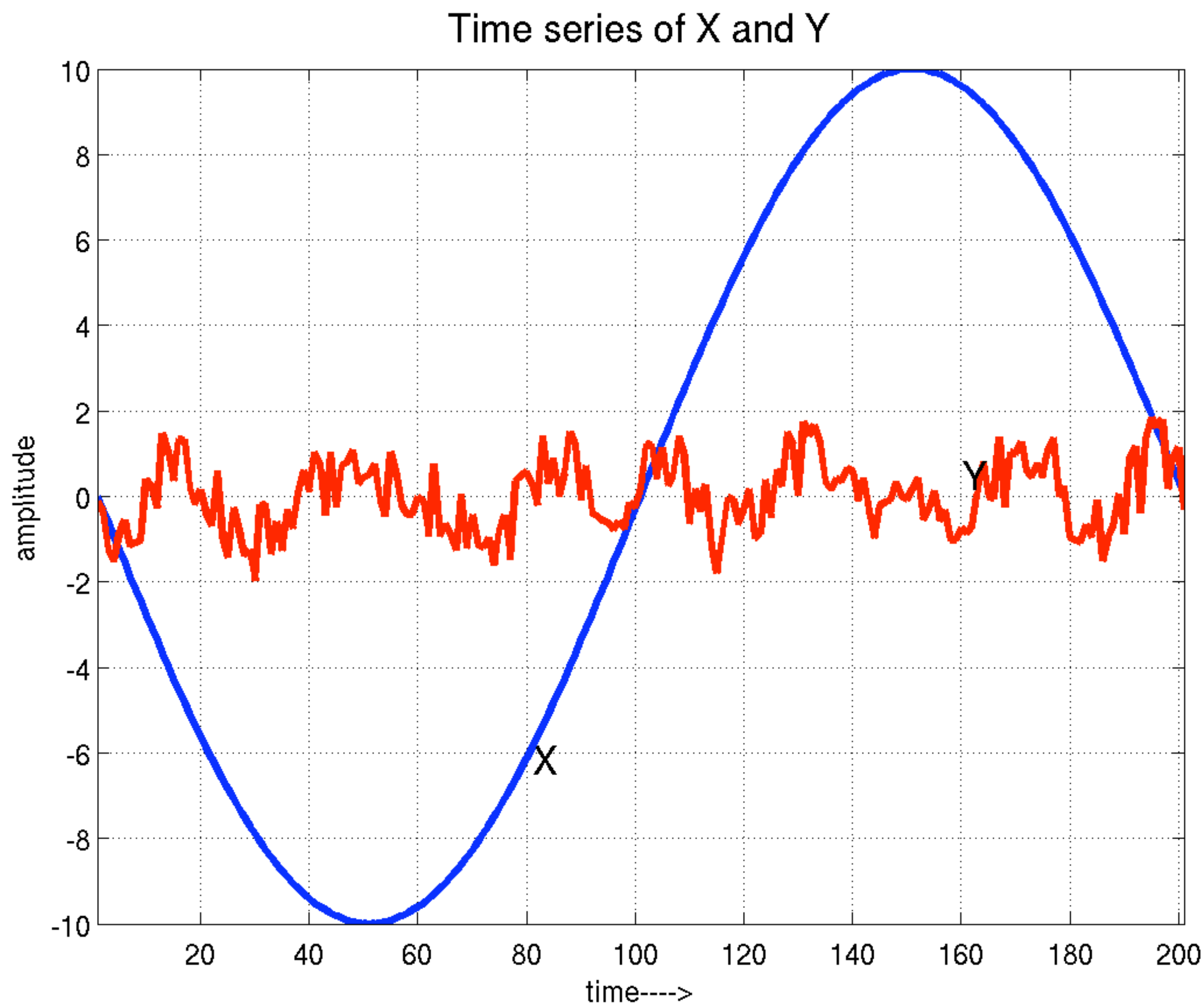

Nino 3.4 Dynamic Height Anomaly (Blue), and SST Anomaly (Red)
Amplitude
14 12 10 8 6 4 2 0 -2 -4 -6 -8 -10 -12 -14
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39
Month Number

Conclusions

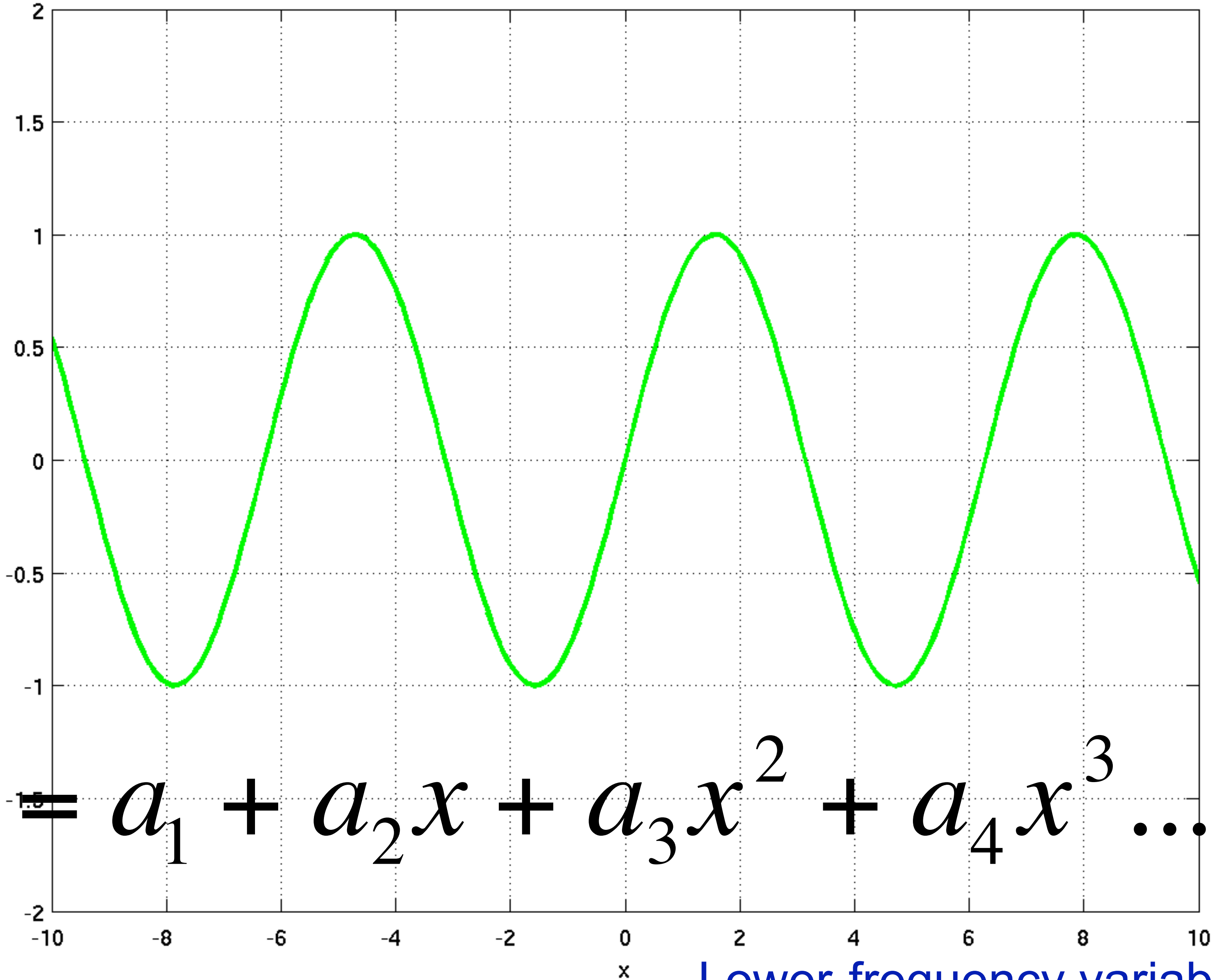
- Intraseasonal wind stress triggers Kelvin waves in the ocean
- The forcing sometimes couples to Kelvin waves
- The waves sometimes continue to amplify, cross the basin, and subsequently raise East Pacific SST
- Trade surges develop along and to the east of the crests of other Kelvin waves, attenuating the waves and upwelling cold water across the east


Relationship Between X and Y
Synthetic Data
Y
X
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-10
-8
-6
-4
-2
0
2
4
6
8
10


Time series of X and Y
10
8
6
4
2
0
-2
-4
-6
-8
-10
amplitude
20
40
60
80
100
120
140
160
180
200
time---->
X
Y


Time series of X and Y
amplitude
time---->
X
Y
10
8
6
4
2
0
-2
-4
-6
-8
-10
20
40
60
80
100
120
140
160
180
200

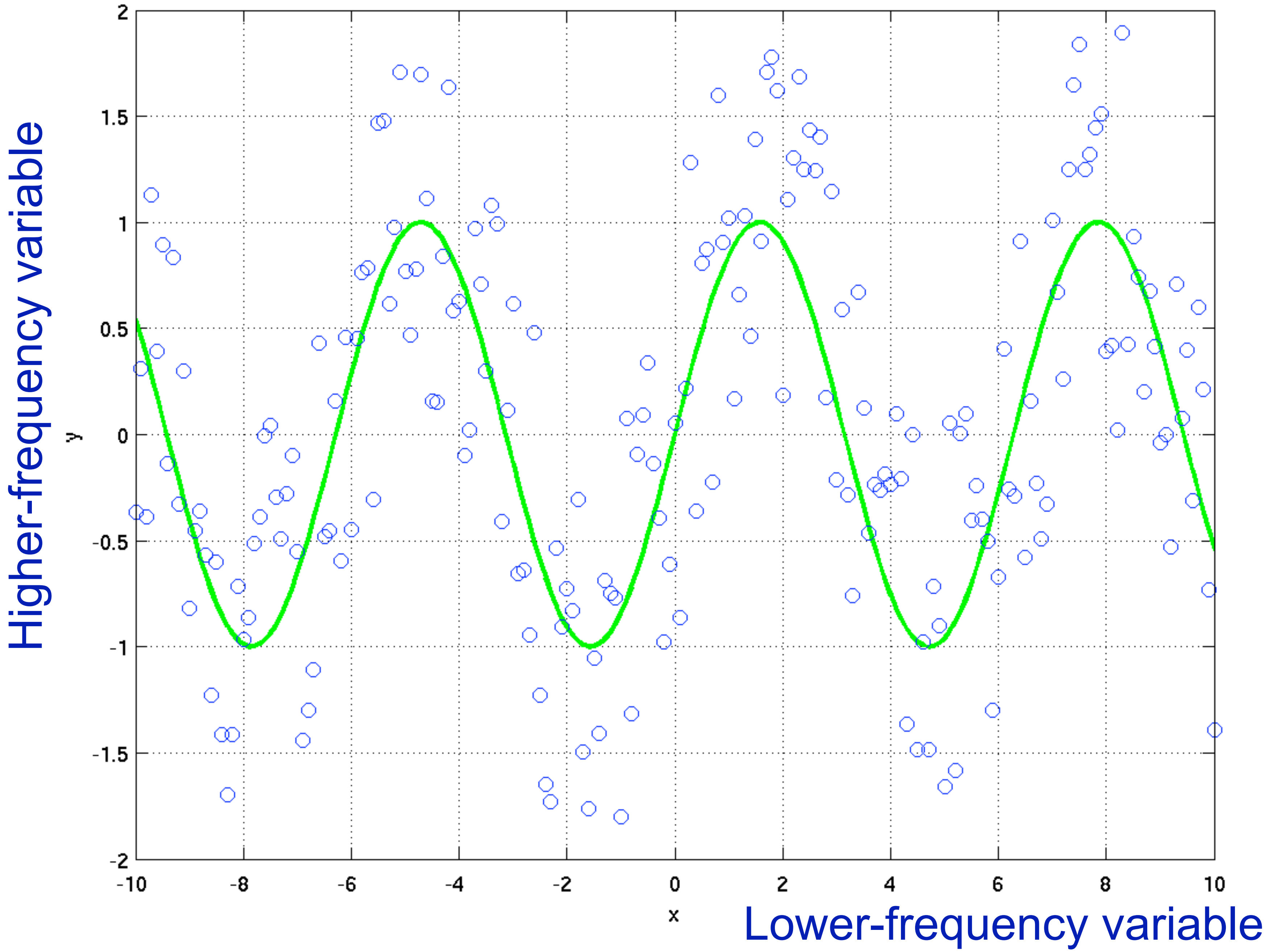
How can polynomial regression solve the problem?



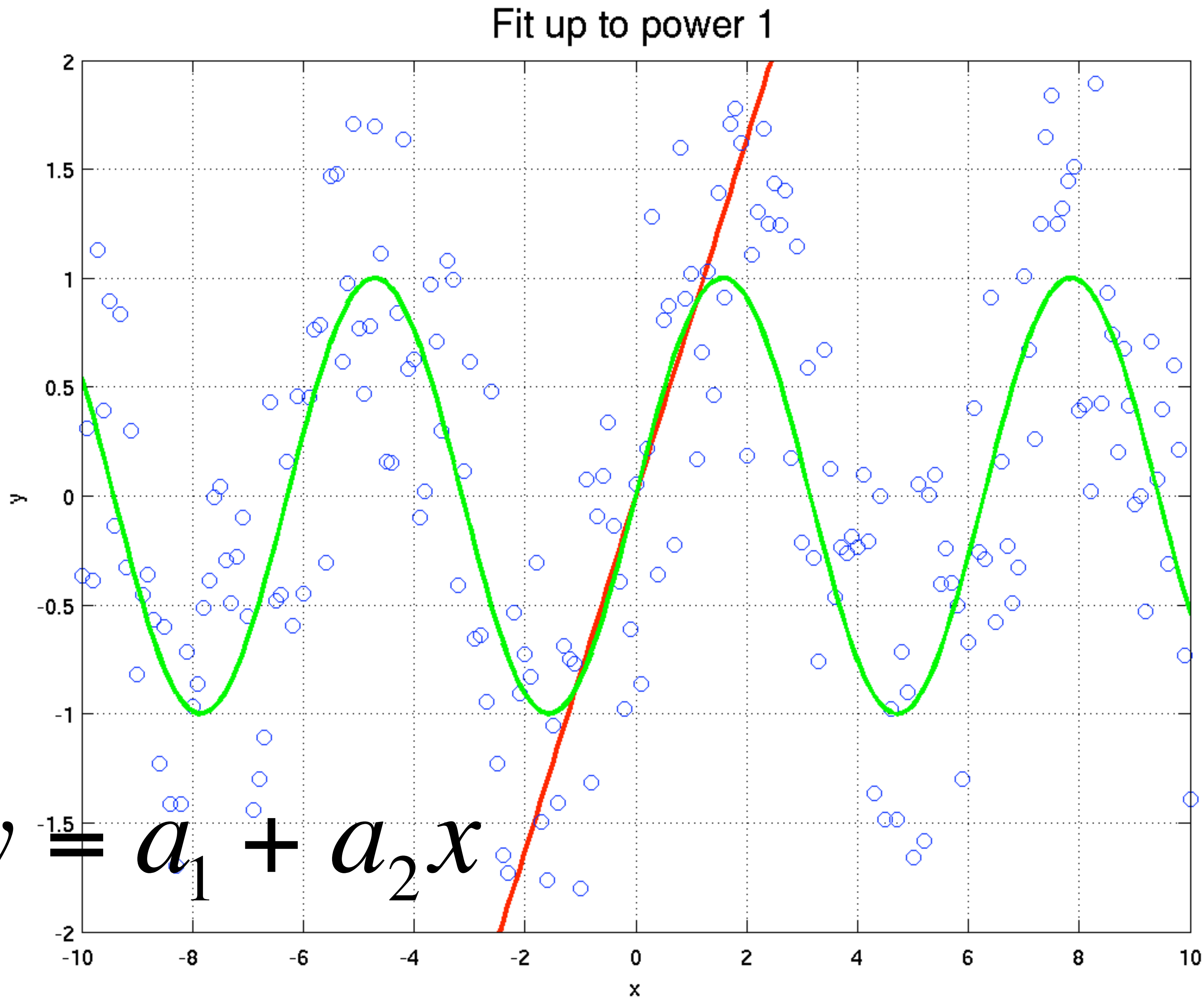
Higher-frequency variable

Lower-frequency variable

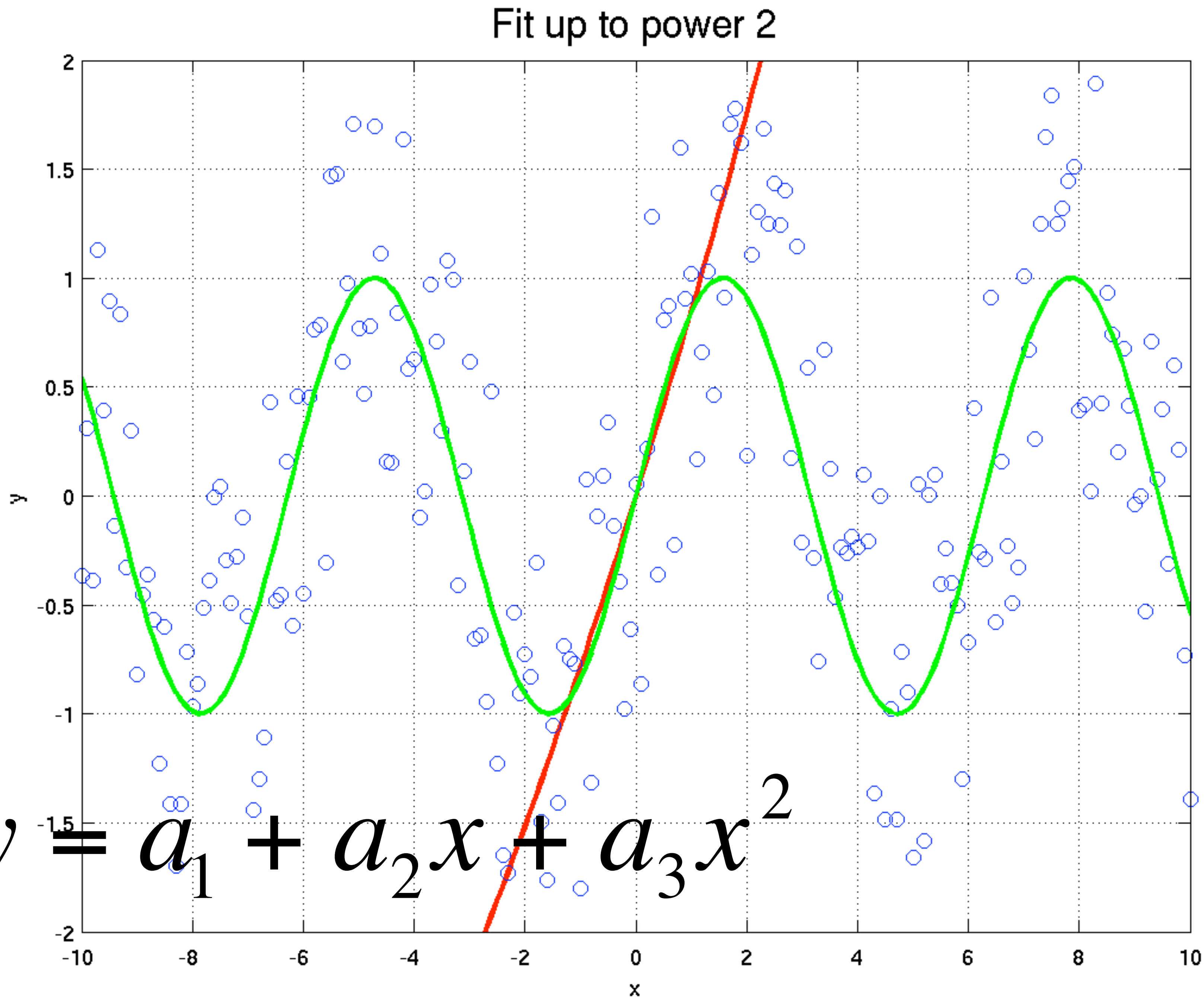
$$y = a_1 + a_2 x + a_3 x^2 + a_4 x^3 \ldots$$



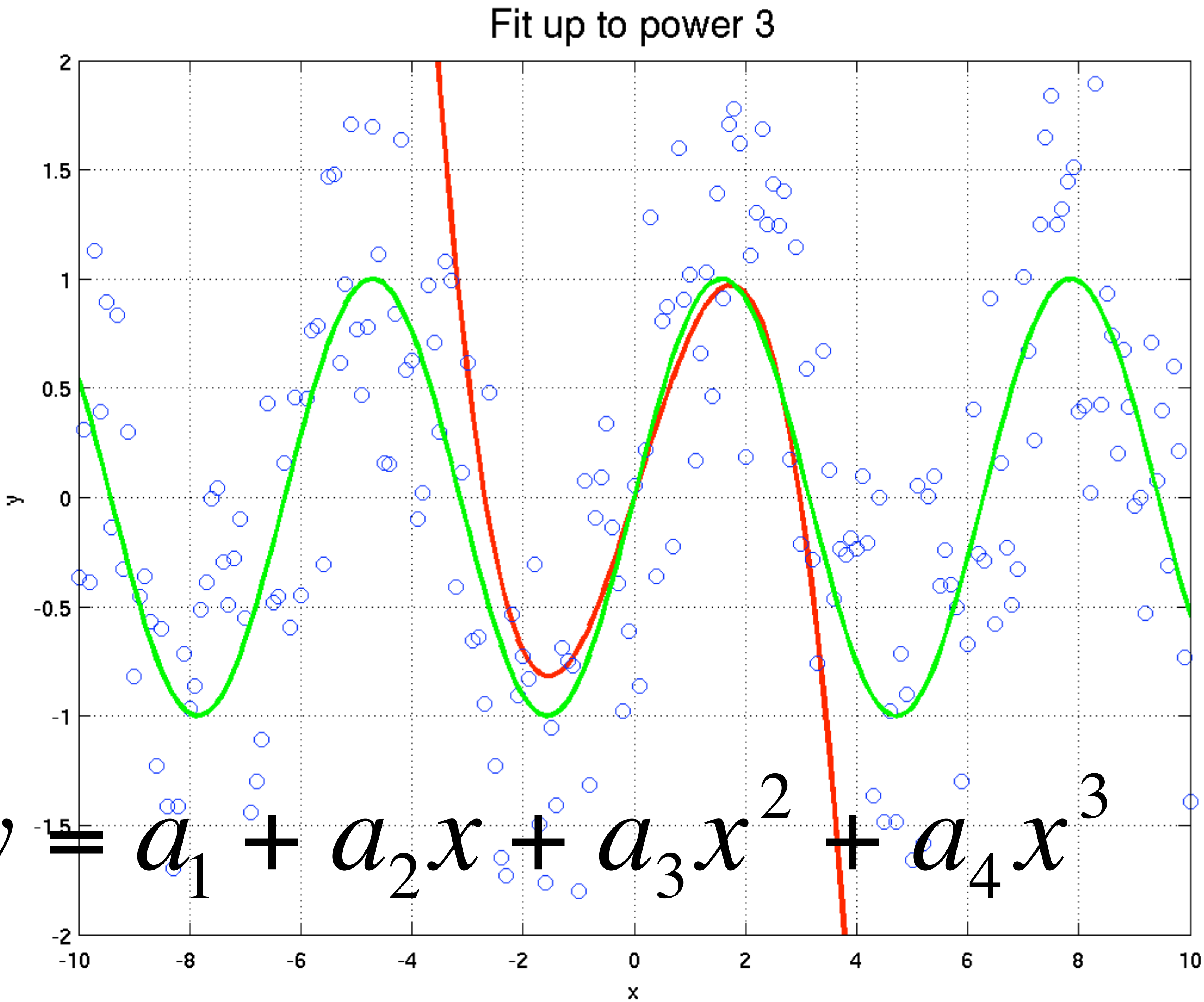
Higher-frequency variable
Lower-frequency variable
y
x
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-10
-8
-6
-4
-2
0
2
4
6
8
10



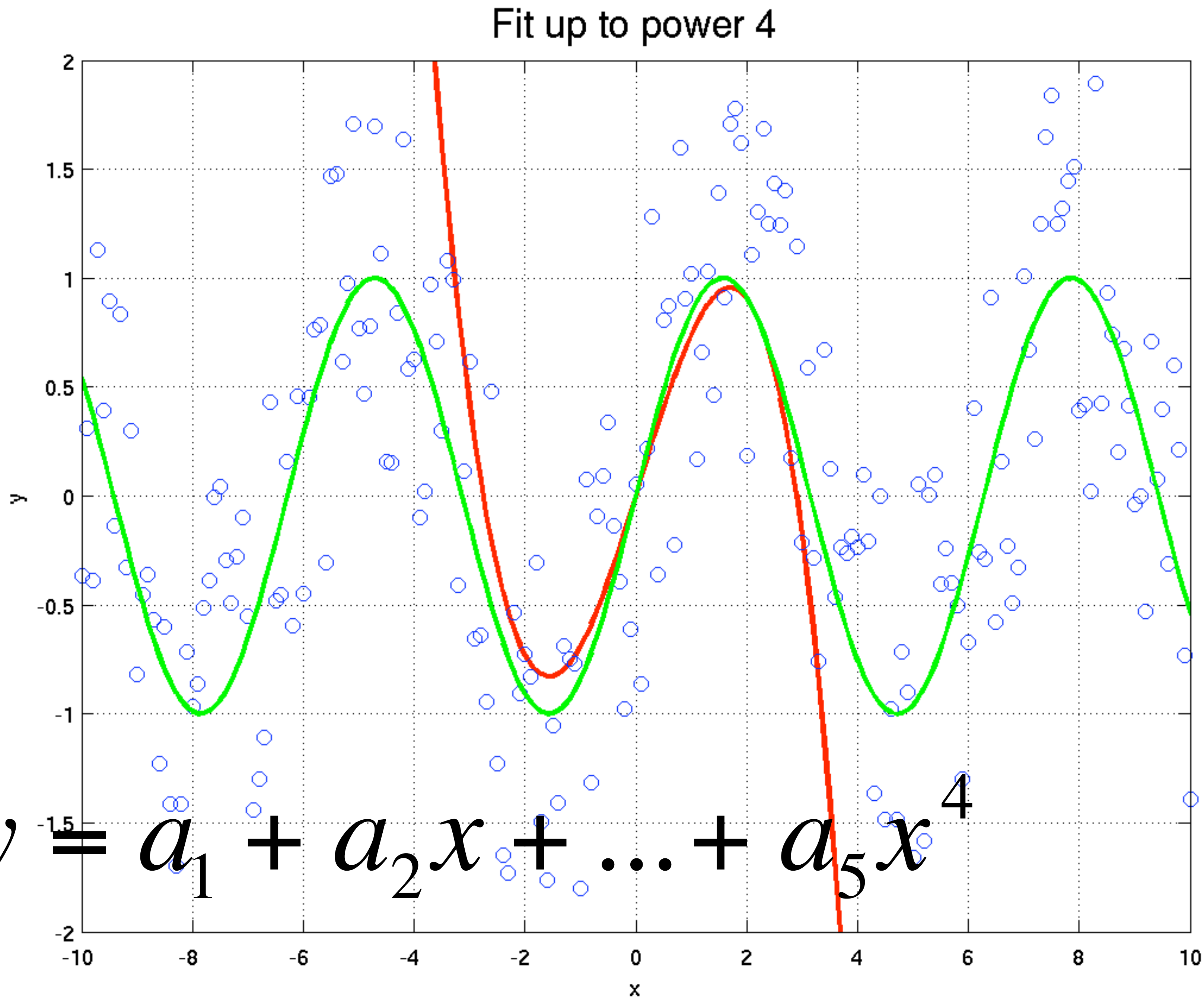
$$y = a_1 + a_2 x$$



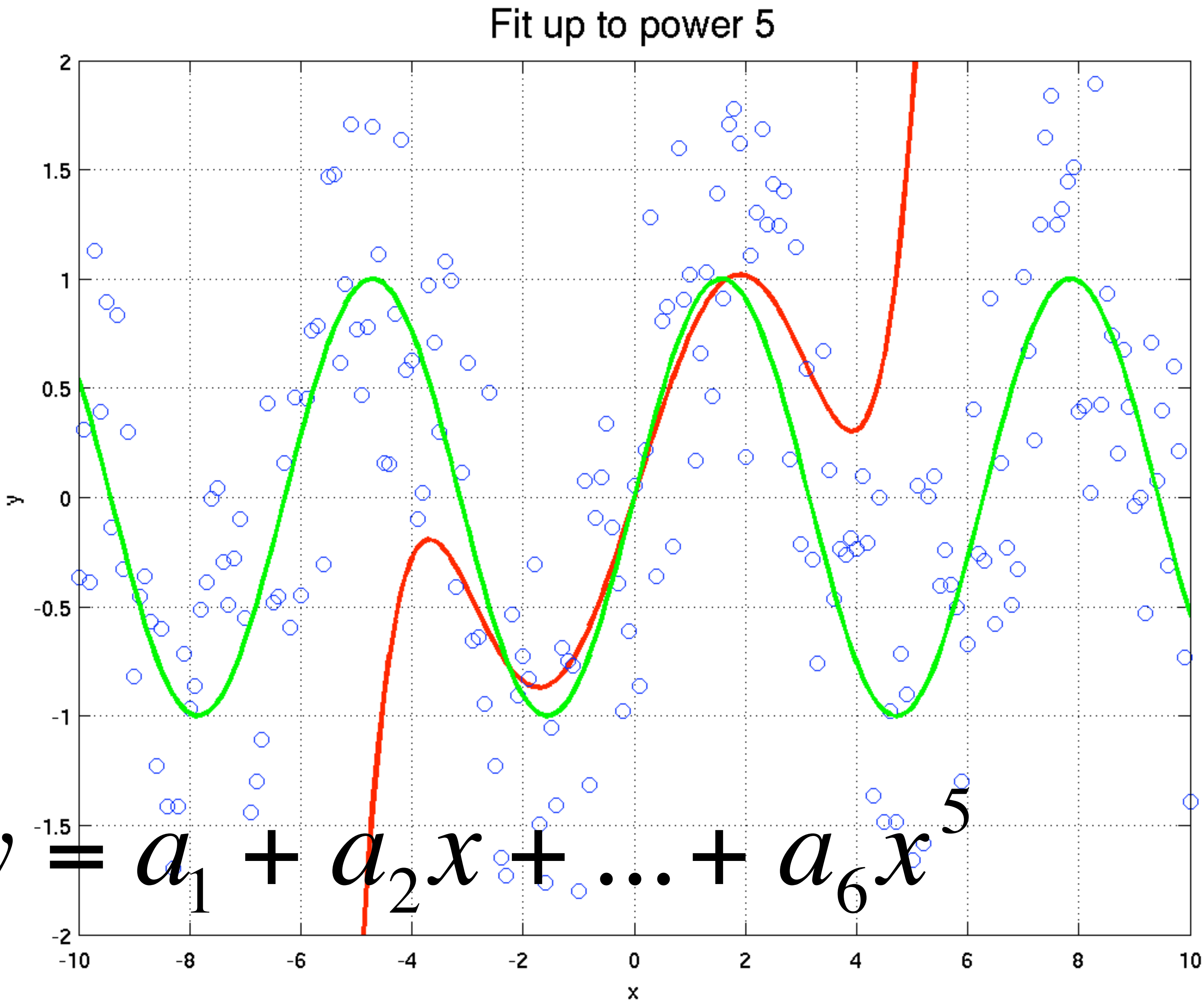
$$y = a_1 + a_2 x + a_3 x^2$$



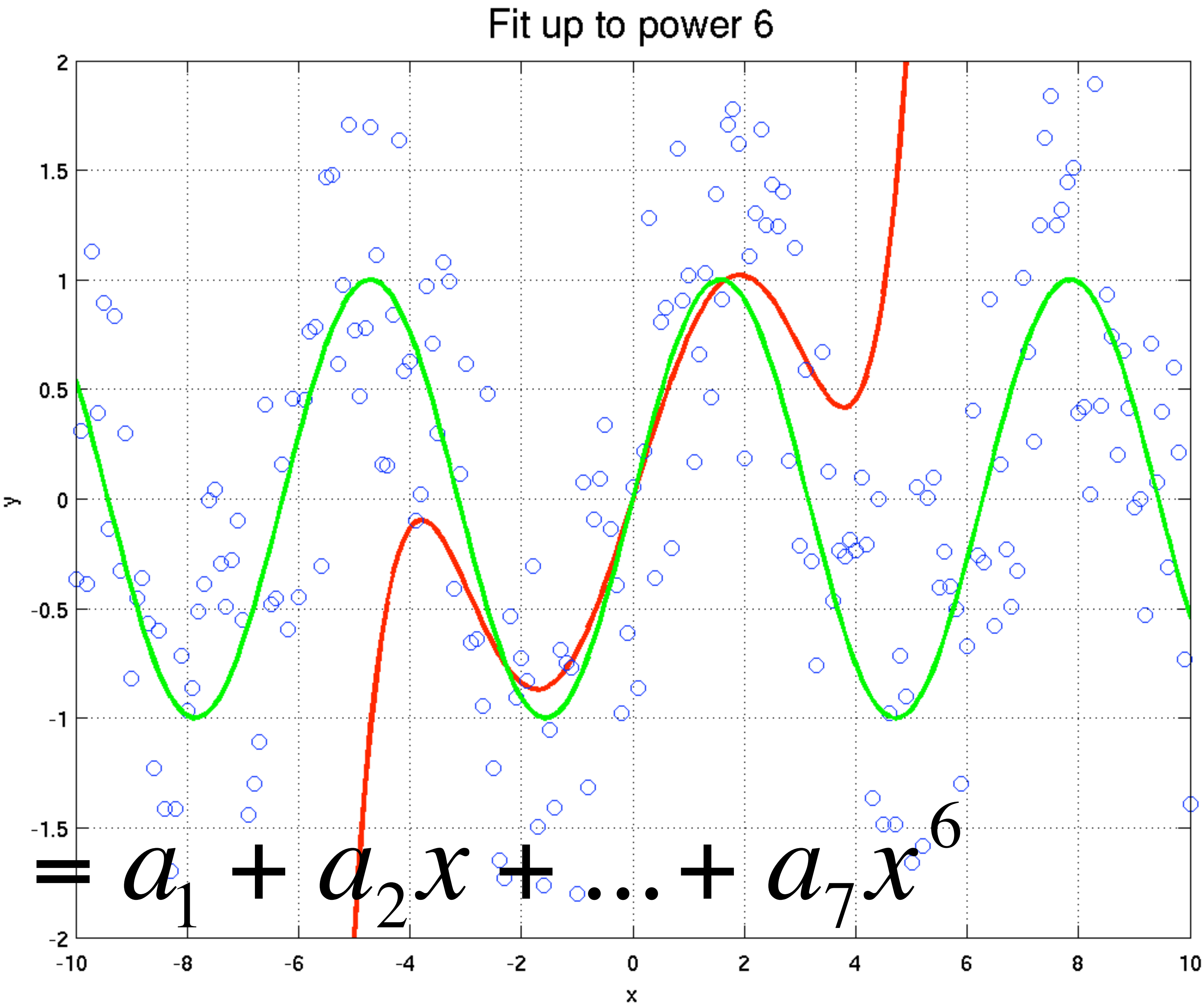
$$y = a_1 + a_2 x + a_3 x^2 + a_4 x^3$$



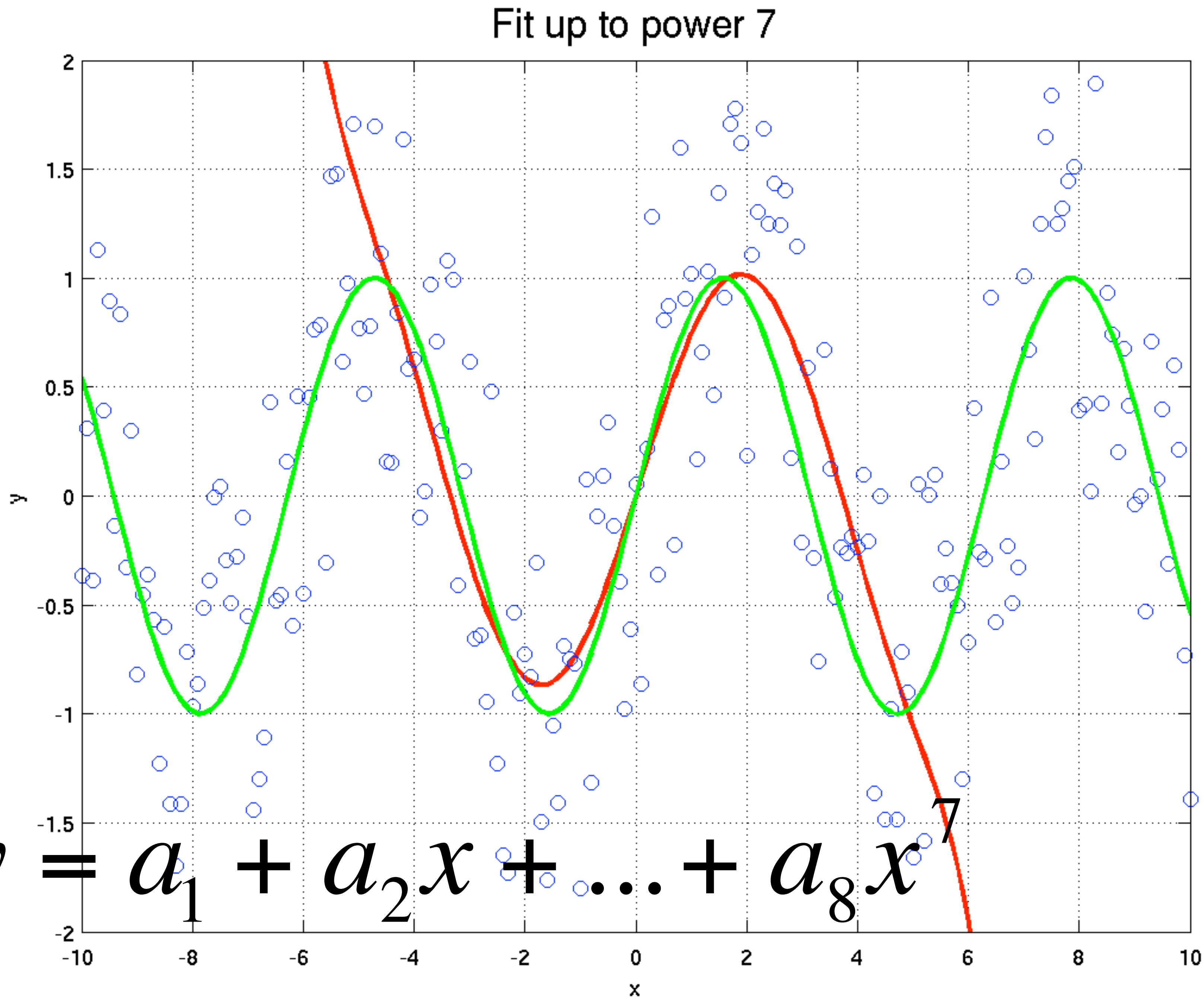
$$y = a_1 + a_2 x + \ldots + a_5 x^4$$



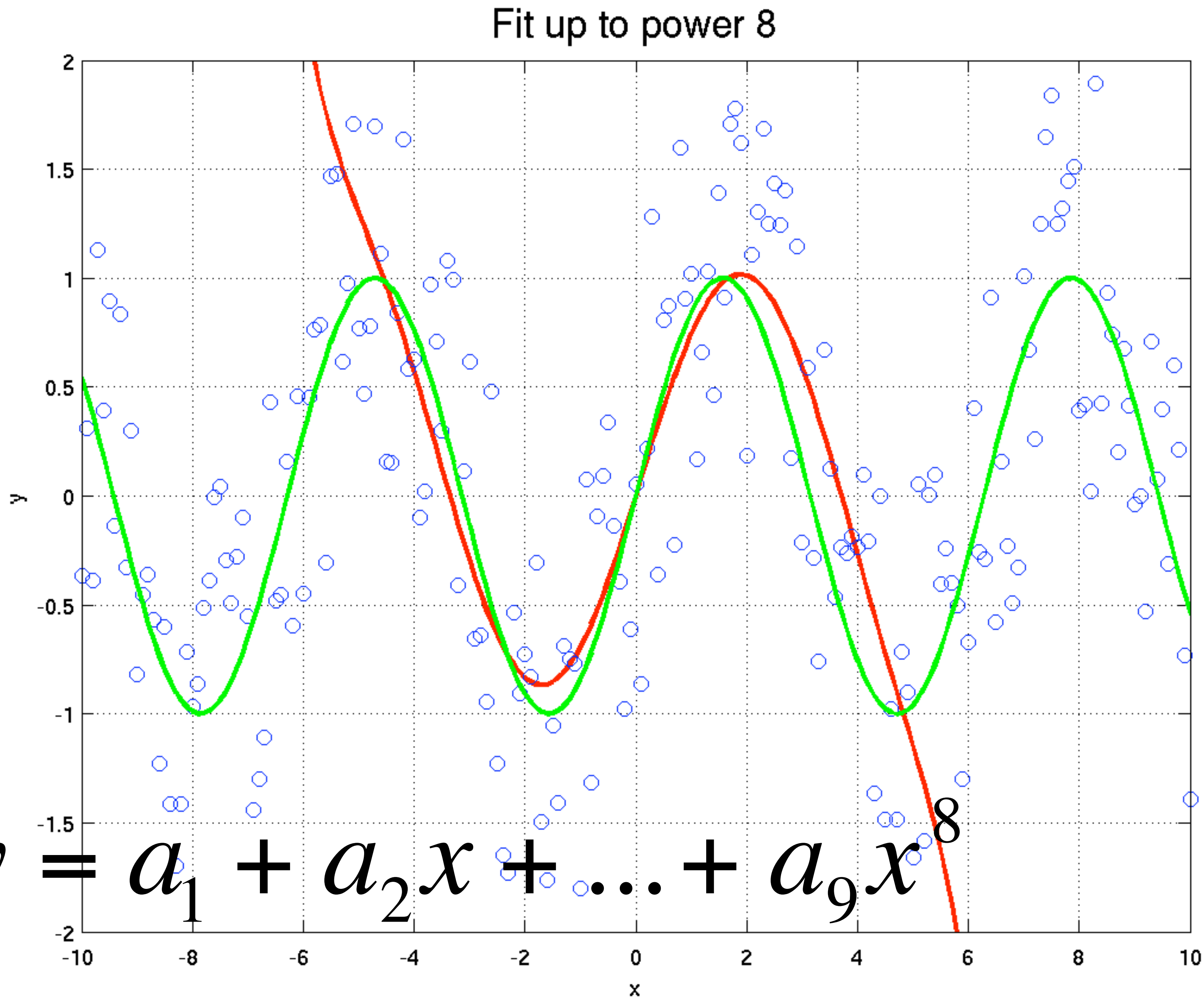
$$y = a_1 + a_2 x + \ldots + a_6 x^5$$



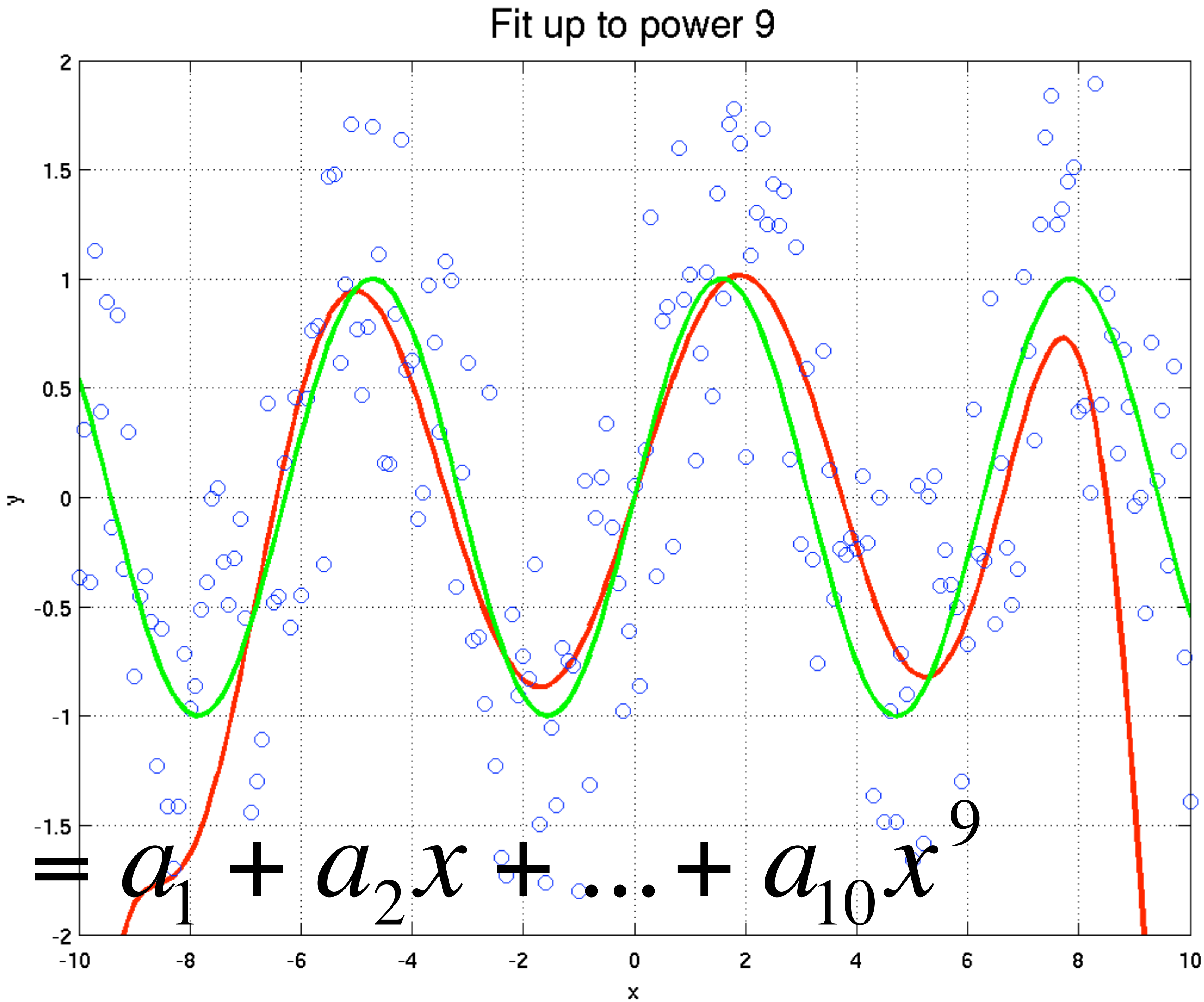
$$y = a_1 + a_2 x + \ldots + a_7 x^6$$



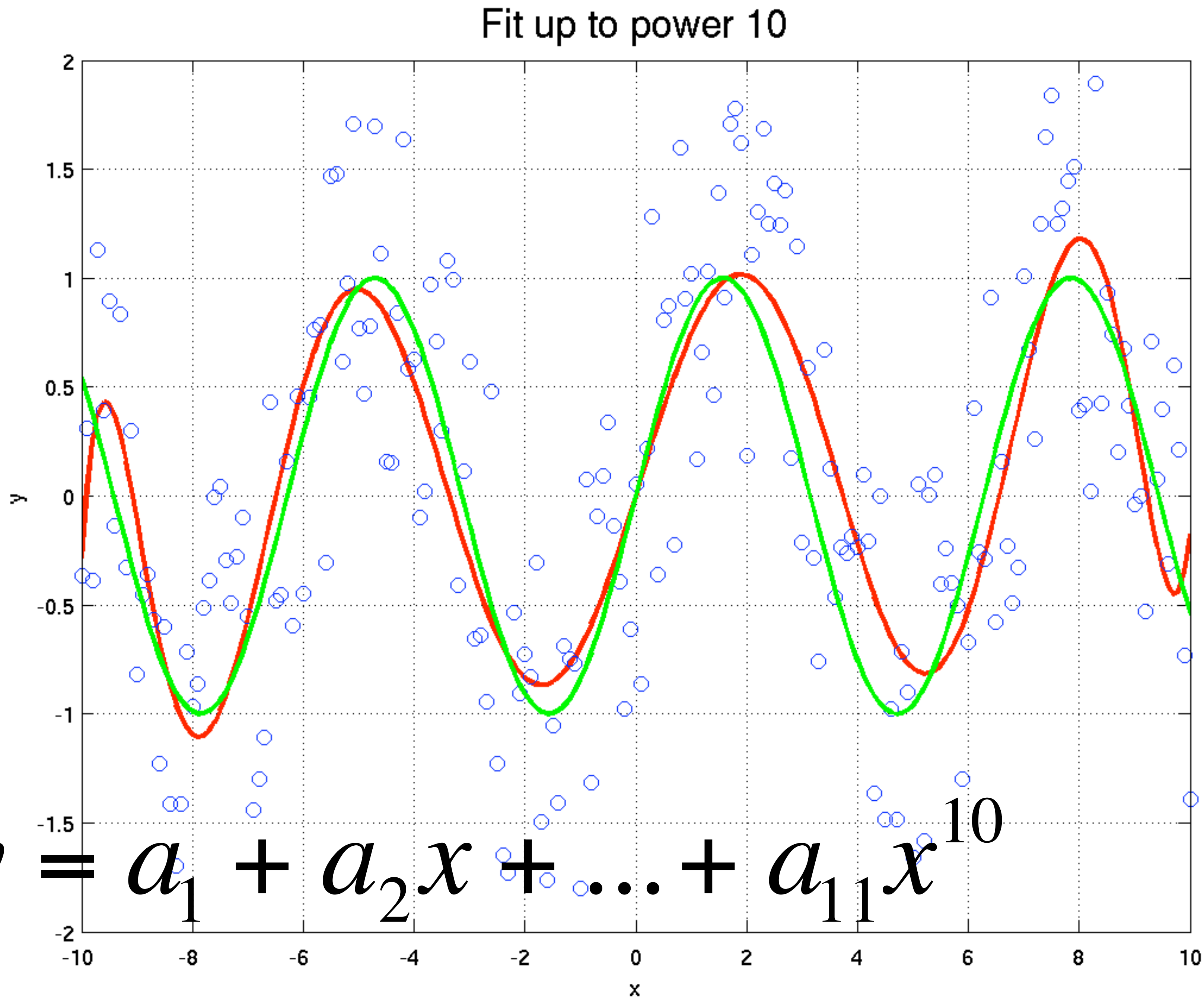
$$y = a_1 + a_2 x + \ldots + a_8 x^7$$



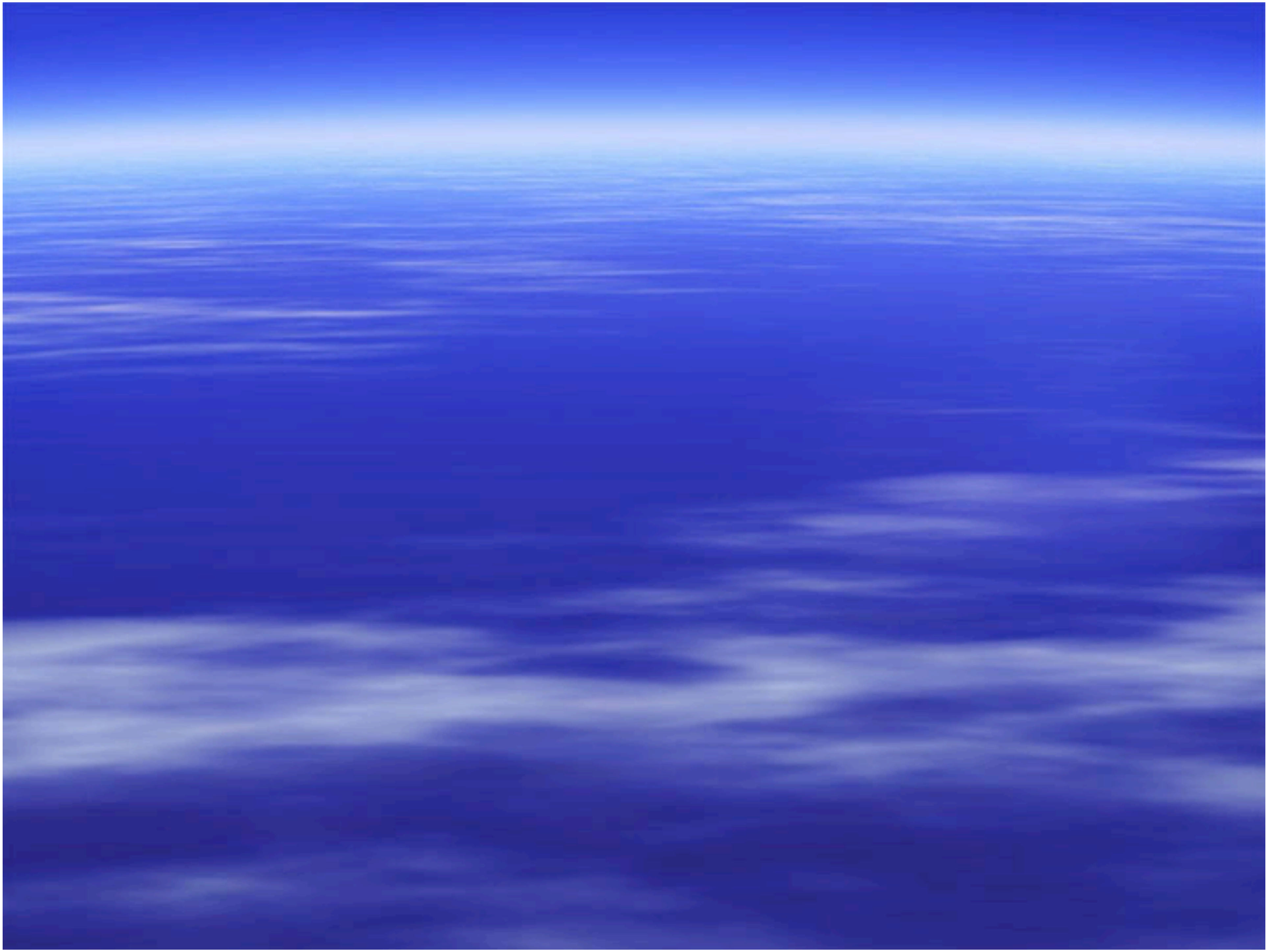
$$y = a_1 + a_2 x + \ldots + a_9 x^8$$



$$y = a_1 + a_2 x + \ldots + a_{10} x^9$$



$$y = a_1 + a_2 x + \ldots + a_{11} x^{10}$$

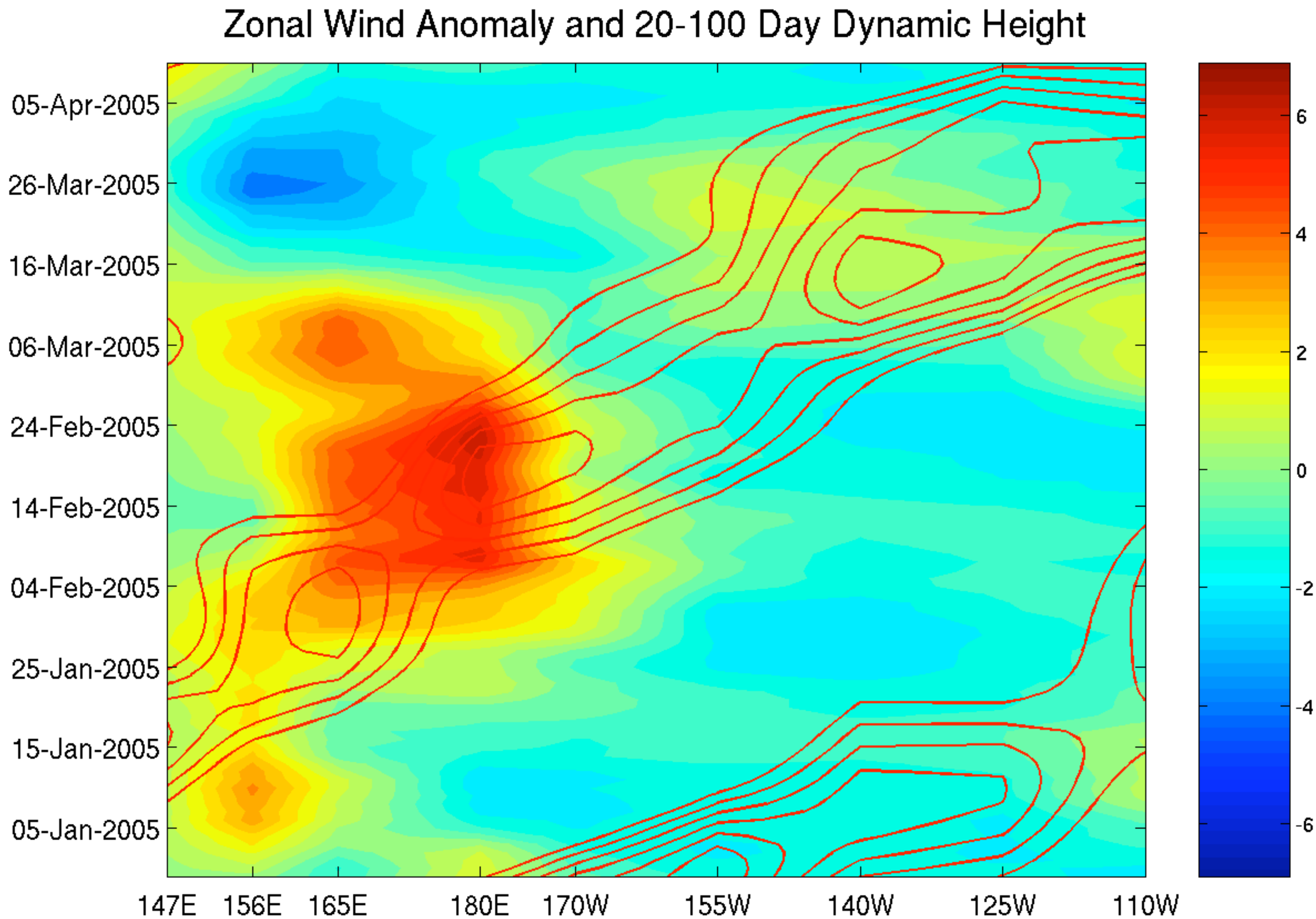


MJO/Kelvin Wave/ENSO Combined Regression Approach

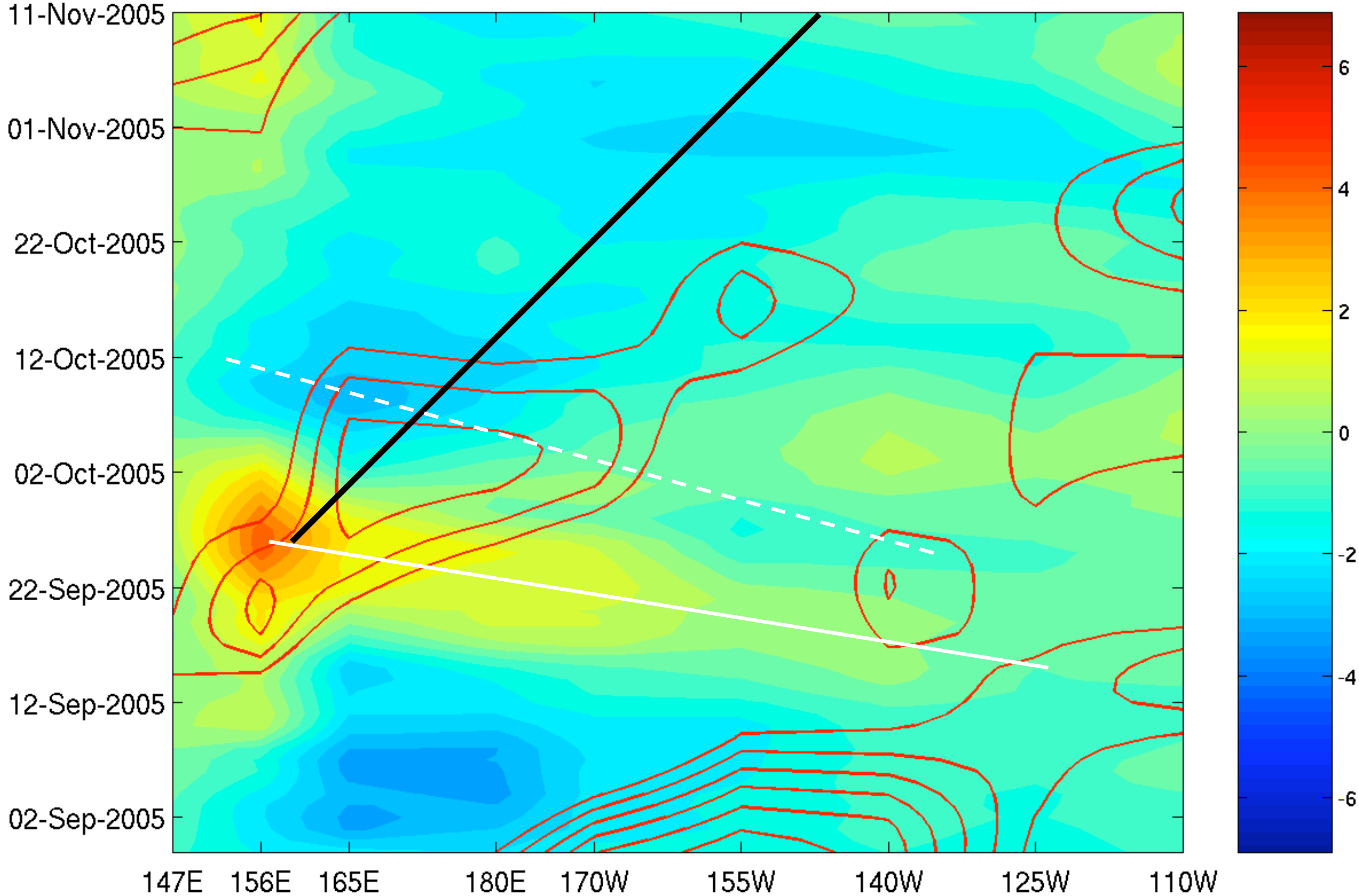
$$y = a_0 + a_1 e + a_2 \dot{e} + a_3 k + a_4 k^2 +$$

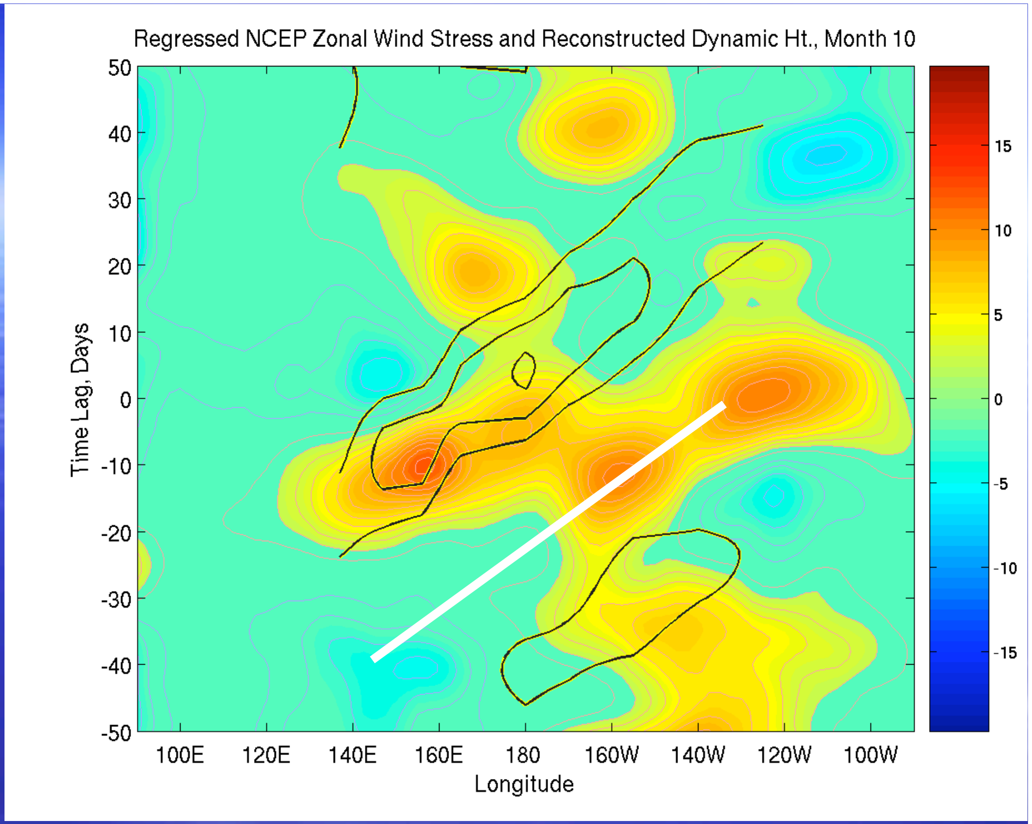
$$a_5 k^3 + a_6 k^4 + a_7 e \bullet k + a_8 \dot{e} \bullet k$$

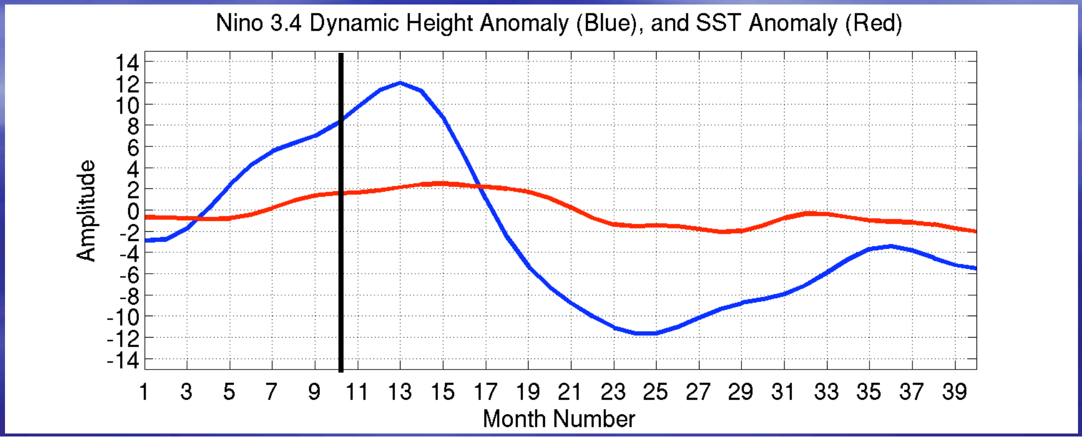
$$+ a_{13}(\dot{e} k^2) + a_{14}(\dot{e} k^3) + \varepsilon$$


Zonal Wind Anomaly and 20-100 Day Dynamic Height
05-Apr-2005
26-Mar-2005
16-Mar-2005
06-Mar-2005
24-Feb-2005
14-Feb-2005
04-Feb-2005
25-Jan-2005
15-Jan-2005
05-Jan-2005
147E
156E
165E
180E
170W
155W
140W
125W
110W
6
4
2
0
-2
-4
-6

Zonal Wind Anomaly and 20-100 Day Dynamic Height




Regressed NCEP Zonal Wind Stress and Reconstructed Dynamic Ht., Month 10
Time Lag, Days
Longitude
100E 120E 140E 160E 180 160W 140W 120W 100W
50 40 30 20 10 0 -10 -20 -30 -40 -50
15 10 5 0 -5 -10 -15


Nino 3.4 Dynamic Height Anomaly (Blue), and SST Anomaly (Red)
Amplitude
Month Number
14 12 10 8 6 4 2 0 -2 -4 -6 -8 -10 -12 -14
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39