A biweekly mode in the equatorial Indian Ocean

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IOM, 1 Dec 2004

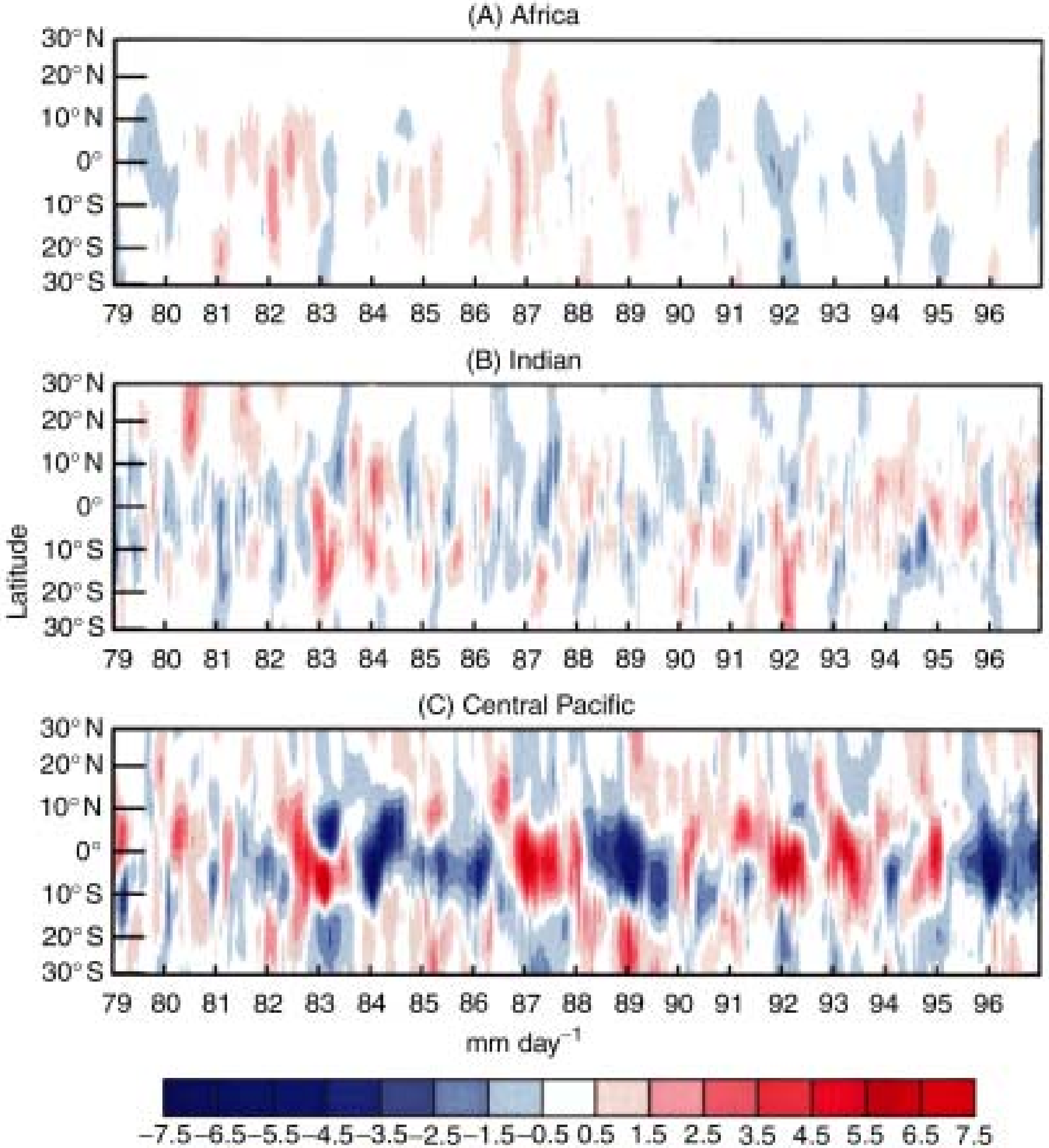
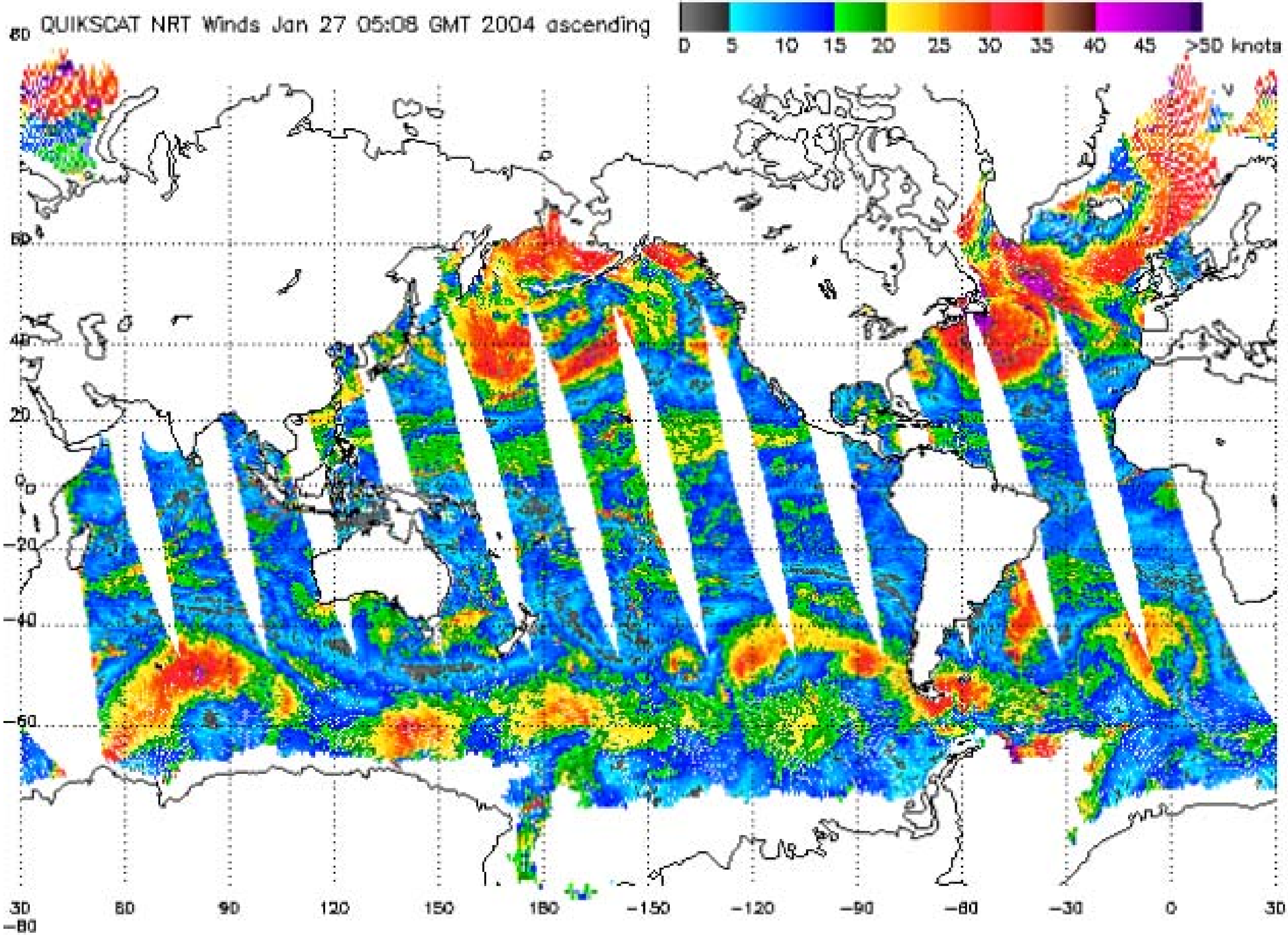
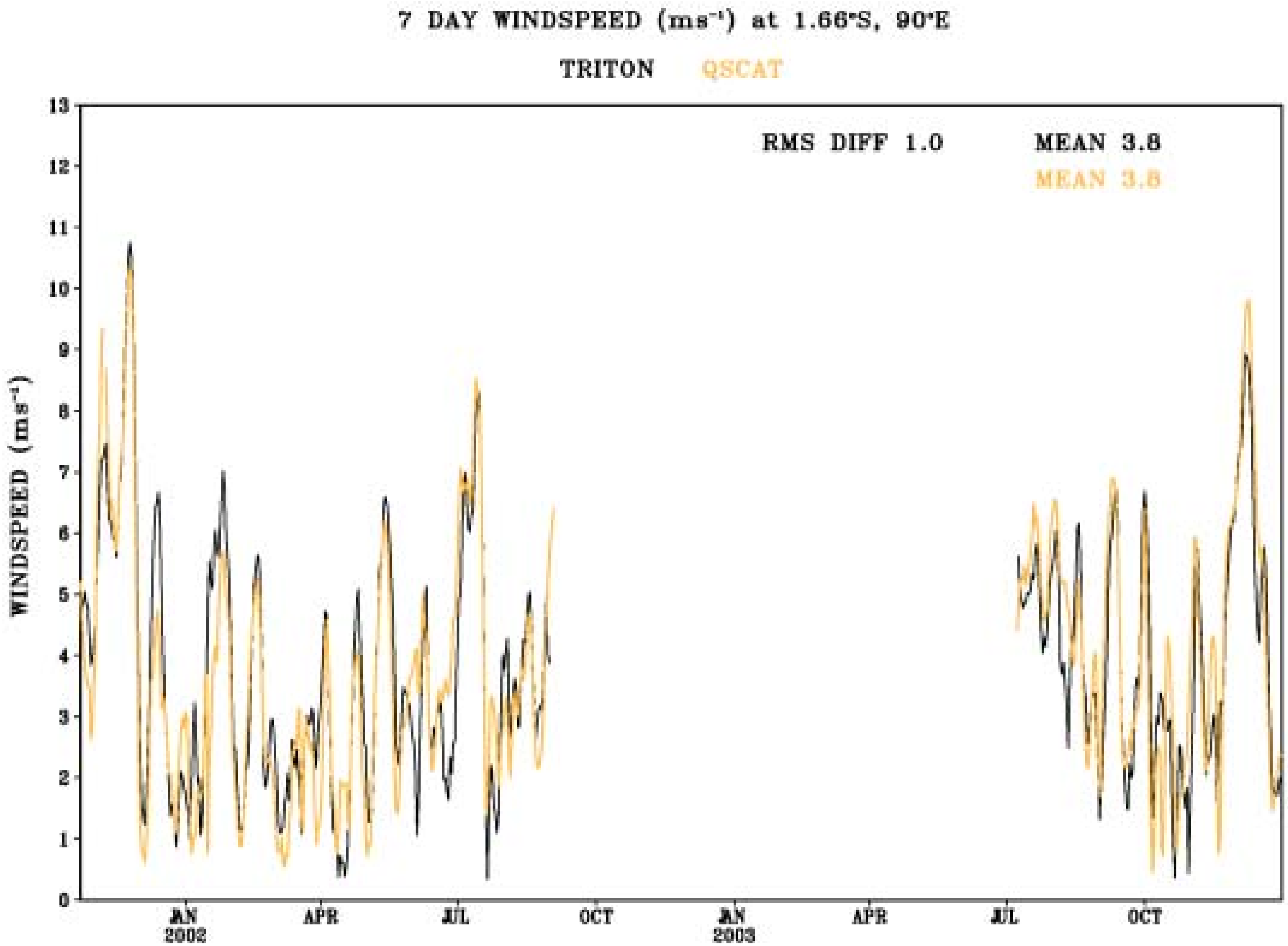


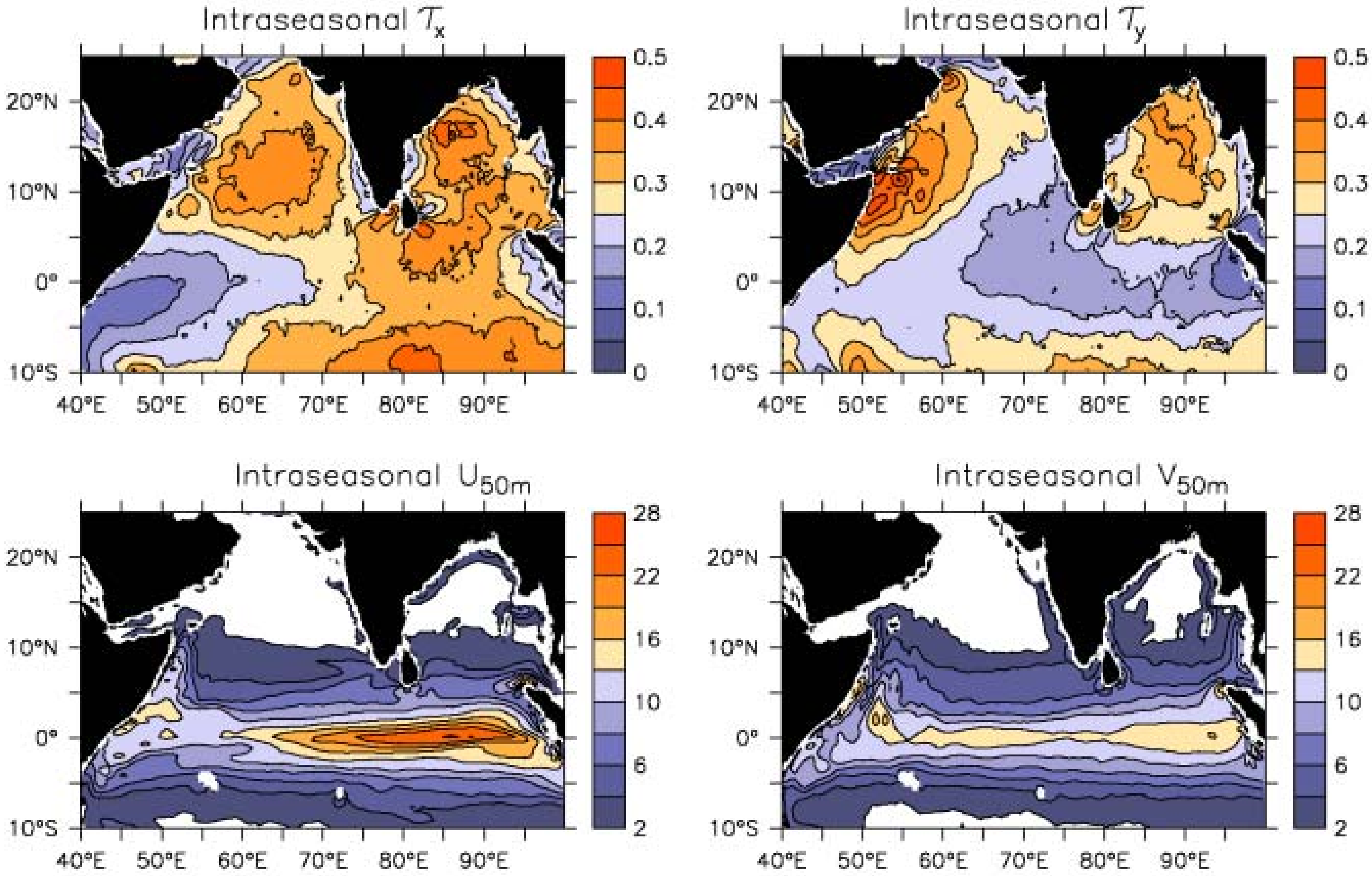
Figure 9 Time–latitude diagrams of the anomalies in rainfall associated with the ITCZ zonally averaged over three different longitude sectors: (A) Africa, 10–40° E; (B) Indian, 60–100° E; and (C) central Pacific, 160° E–160° W. Departures are computed from the mean annual cycles shown in **Figure 8**. (*Source*: National Oceanographic and Atmospheric Administration's (NOAA) Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP).)


QUIKSCAT NRT Winds Jan 27 05:08 GMT 2004 ascending
0 5 10 15 20 25 30 35 40 45 >50 knots
80
60
40
20
0
-20
-40
-60
-80
30 60 90 120 150 180 -150 -120 -90 -60 -30 0 30



7 DAY WINDSPEED (ms⁻¹) at 1.66°S, 90°E
TRITON
QSCAT
RMS DIFF 1.0
MEAN 3.8
MEAN 3.8
WINDSPEED (ms⁻¹)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
JAN 2002
APR
JUL
OCT
JAN 2003
APR
JUL
OCT

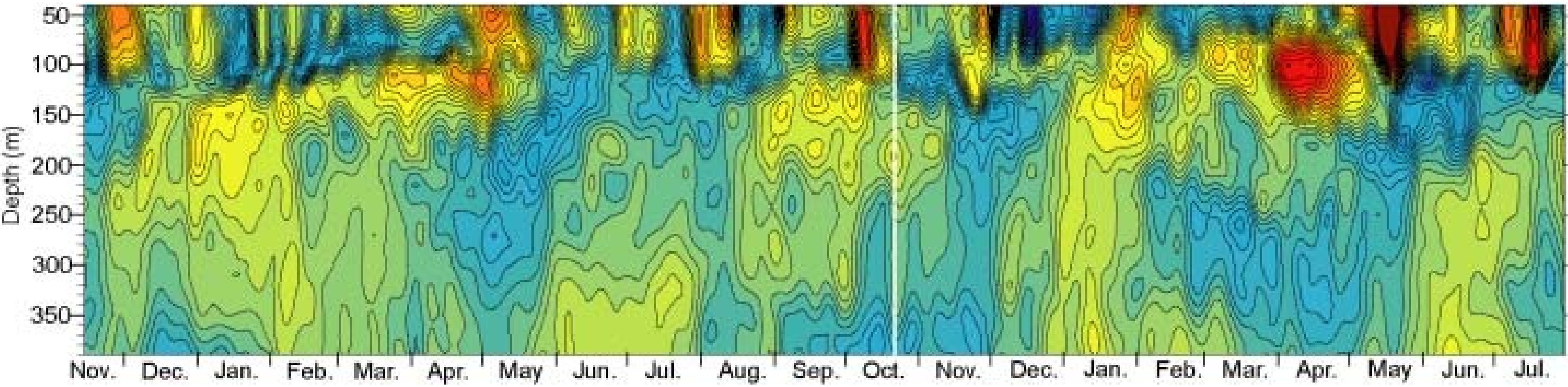
Kuroda, 2000



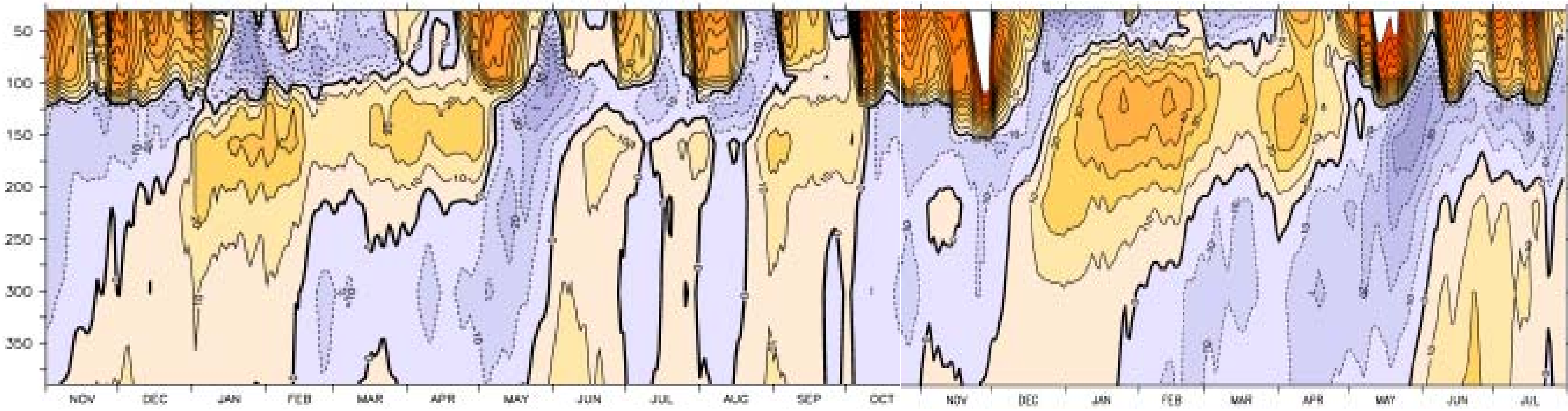
10-60 day current is strong in the equatorial waveguide; it is mostly wind forced

ZONAL VELOCITY 0° 90°E

OBS (MASUMOTO, 2004)



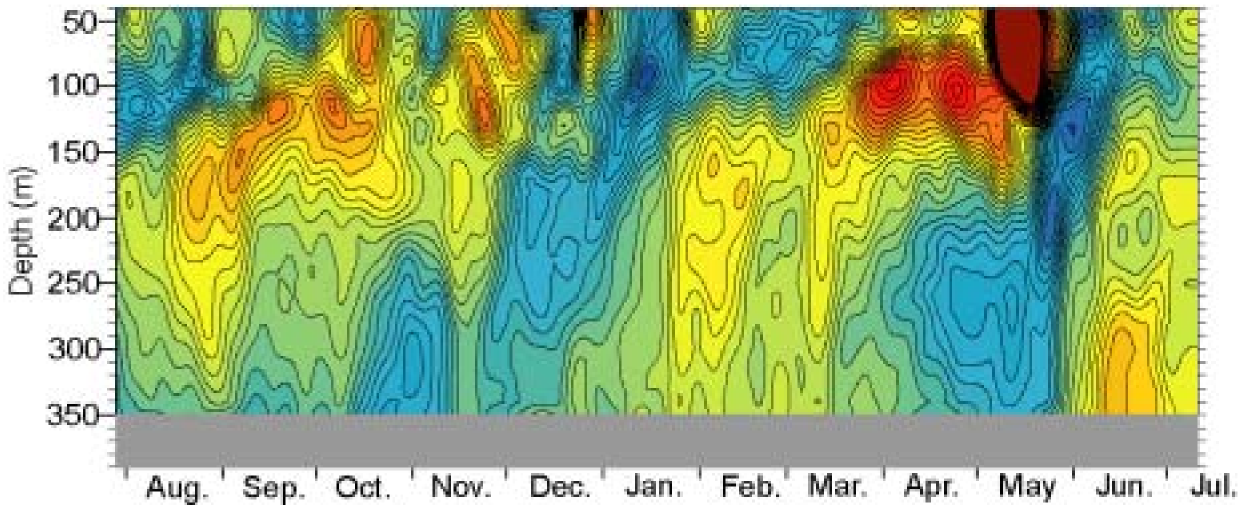
MODEL



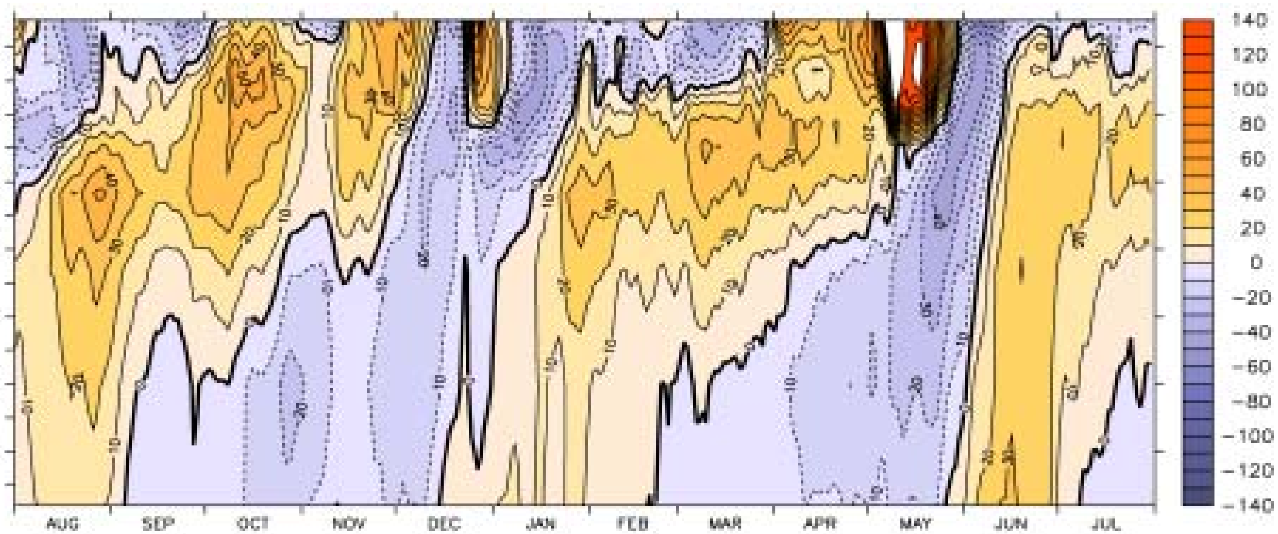
2001 **2002**

ZONAL VELOCITY 0° 90°E

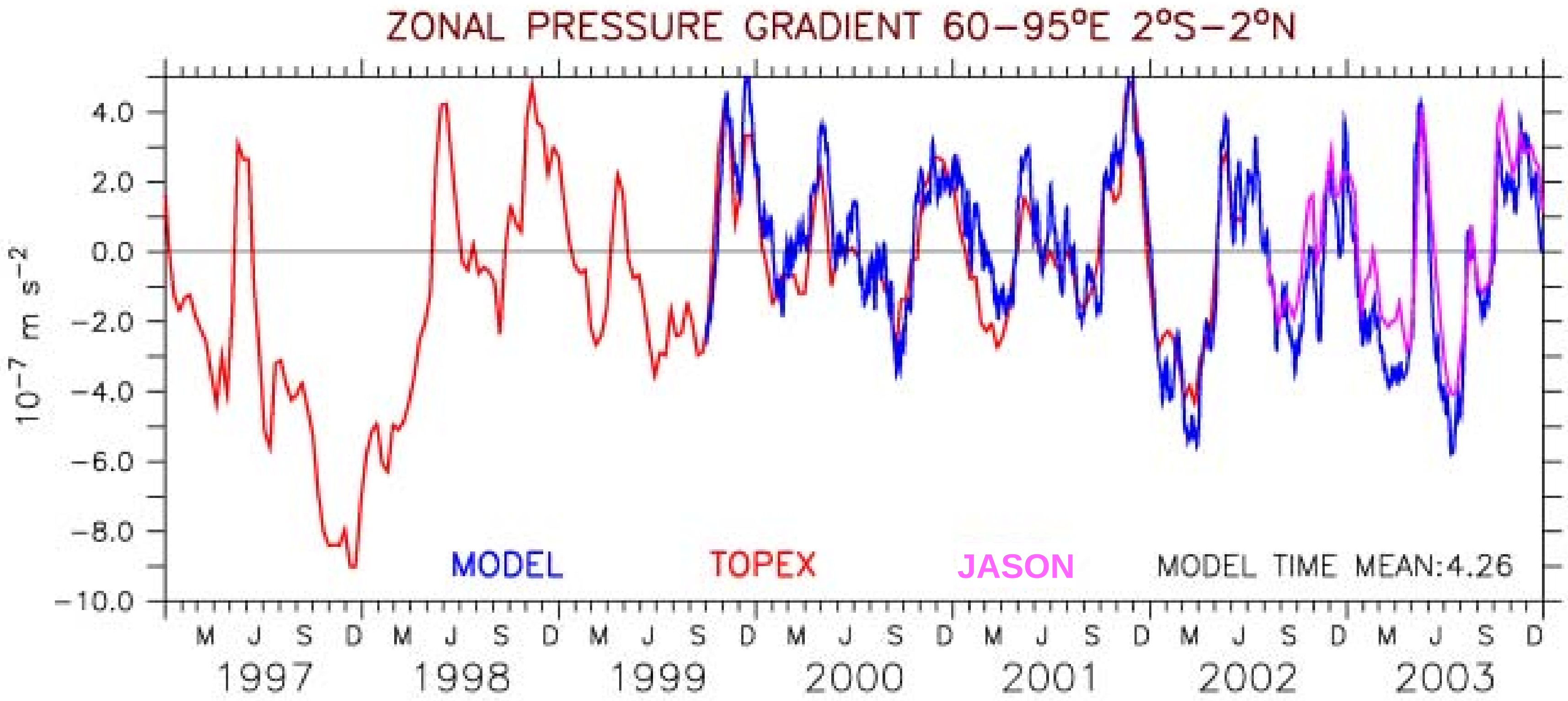
OBS

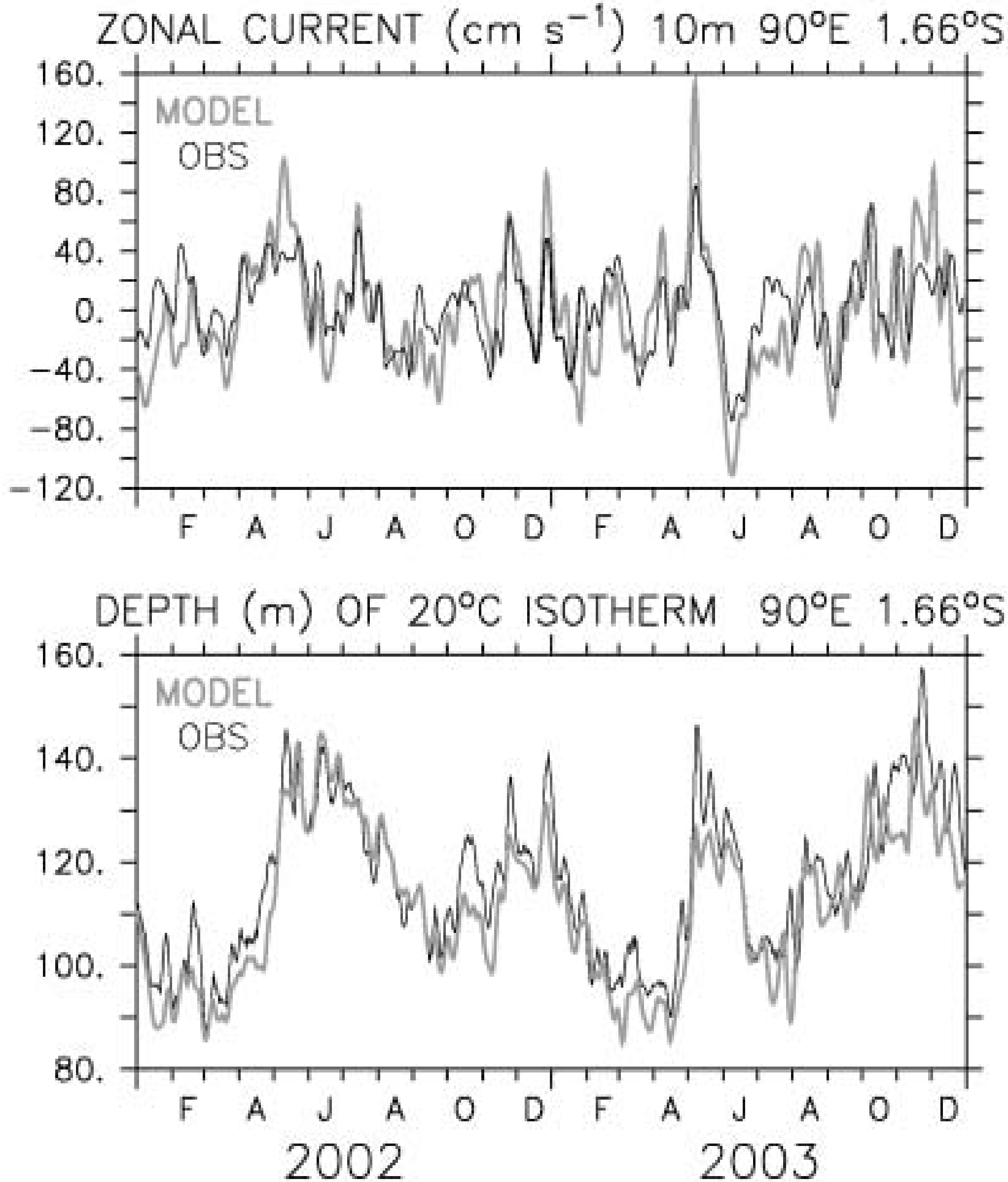


MODEL

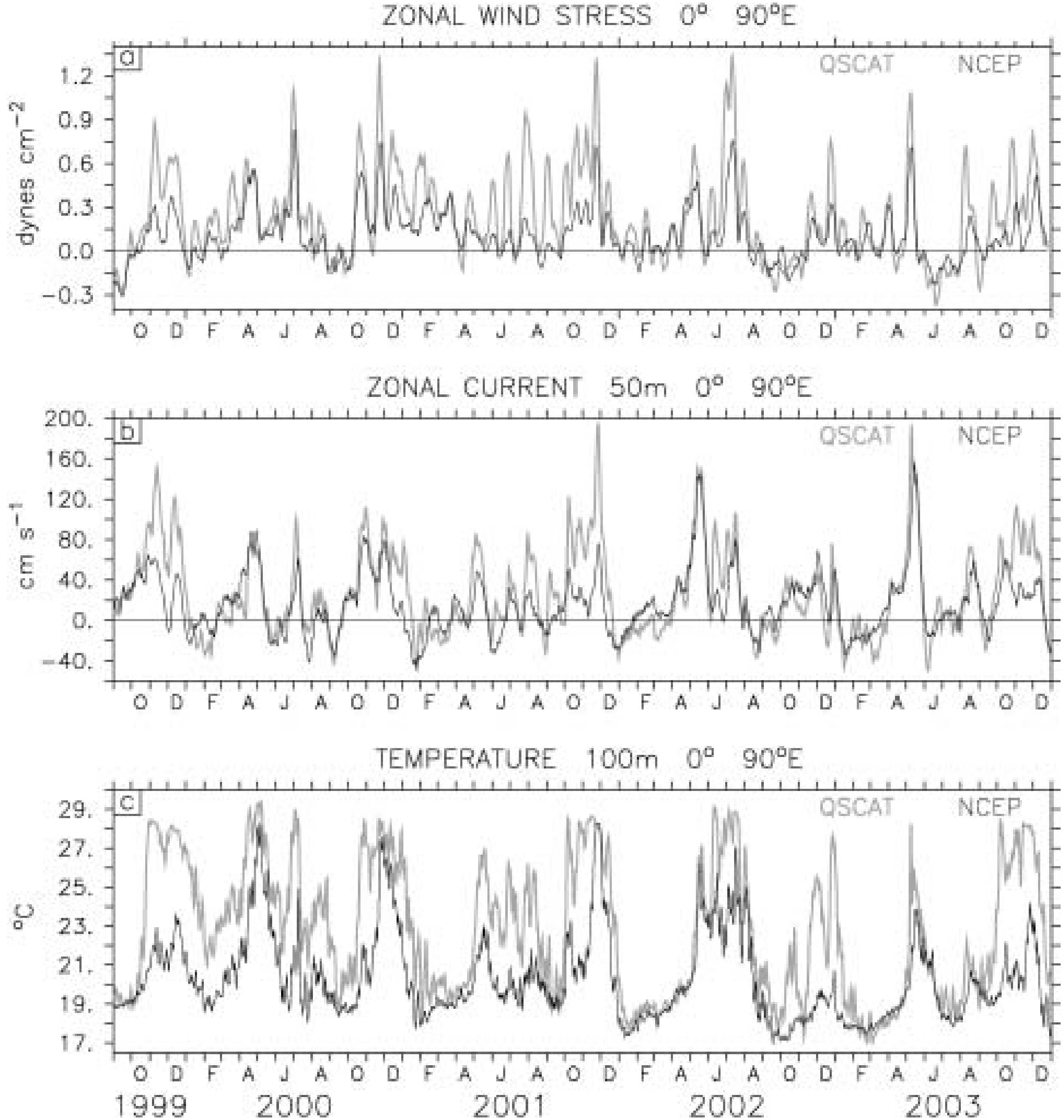


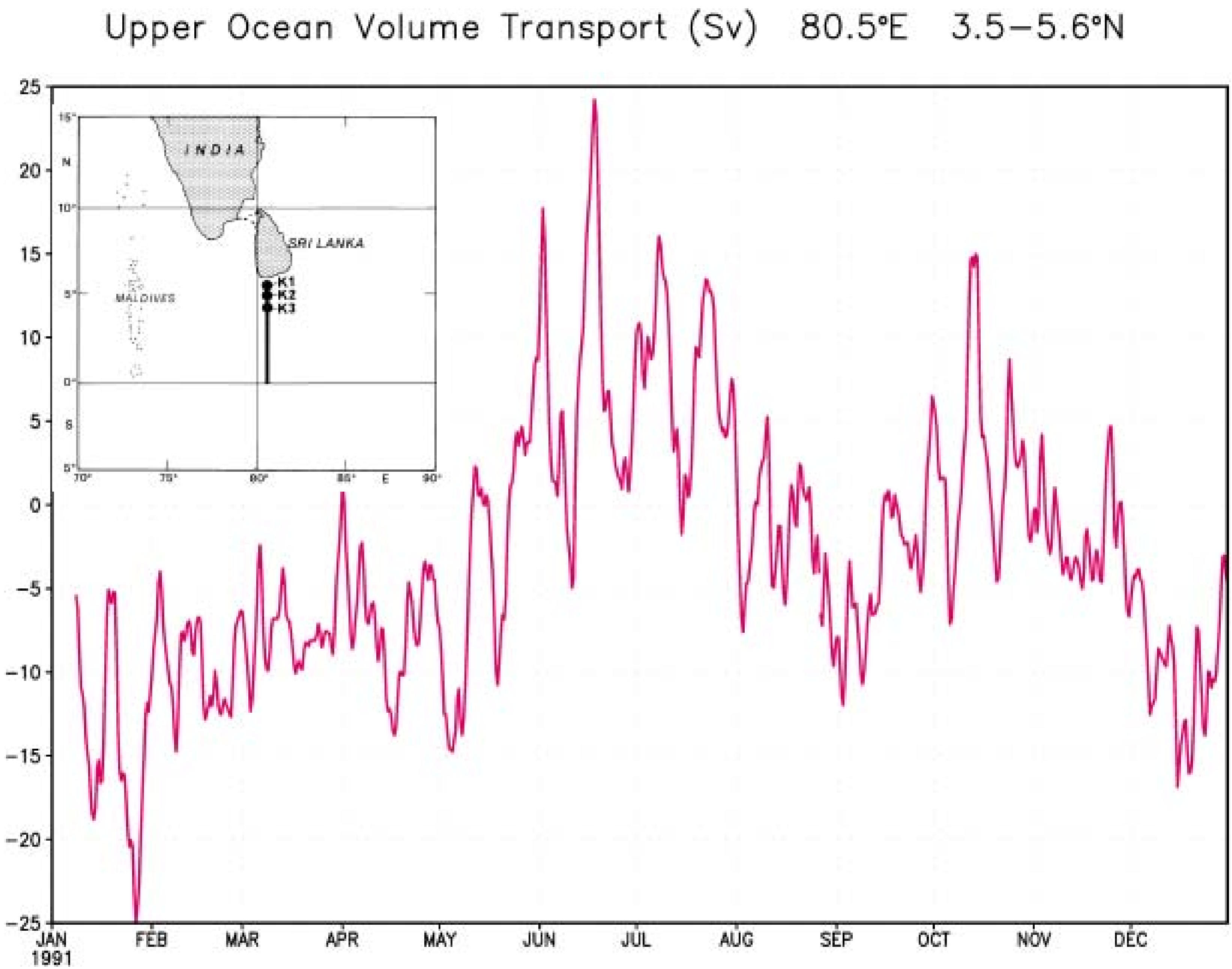
2002 **2003**


ZONAL PRESSURE GRADIENT 60−95°E 2°S−2°N
10^{-7} m s^{-2}
4.0
2.0
0.0
−2.0
−4.0
−6.0
−8.0
−10.0
MODEL
TOPEX
JASON
MODEL TIME MEAN:4.26
M J S D M J S D M J S D M J S D M J S D M J S D M J S D
1997
1998
1999
2000
2001
2002
2003

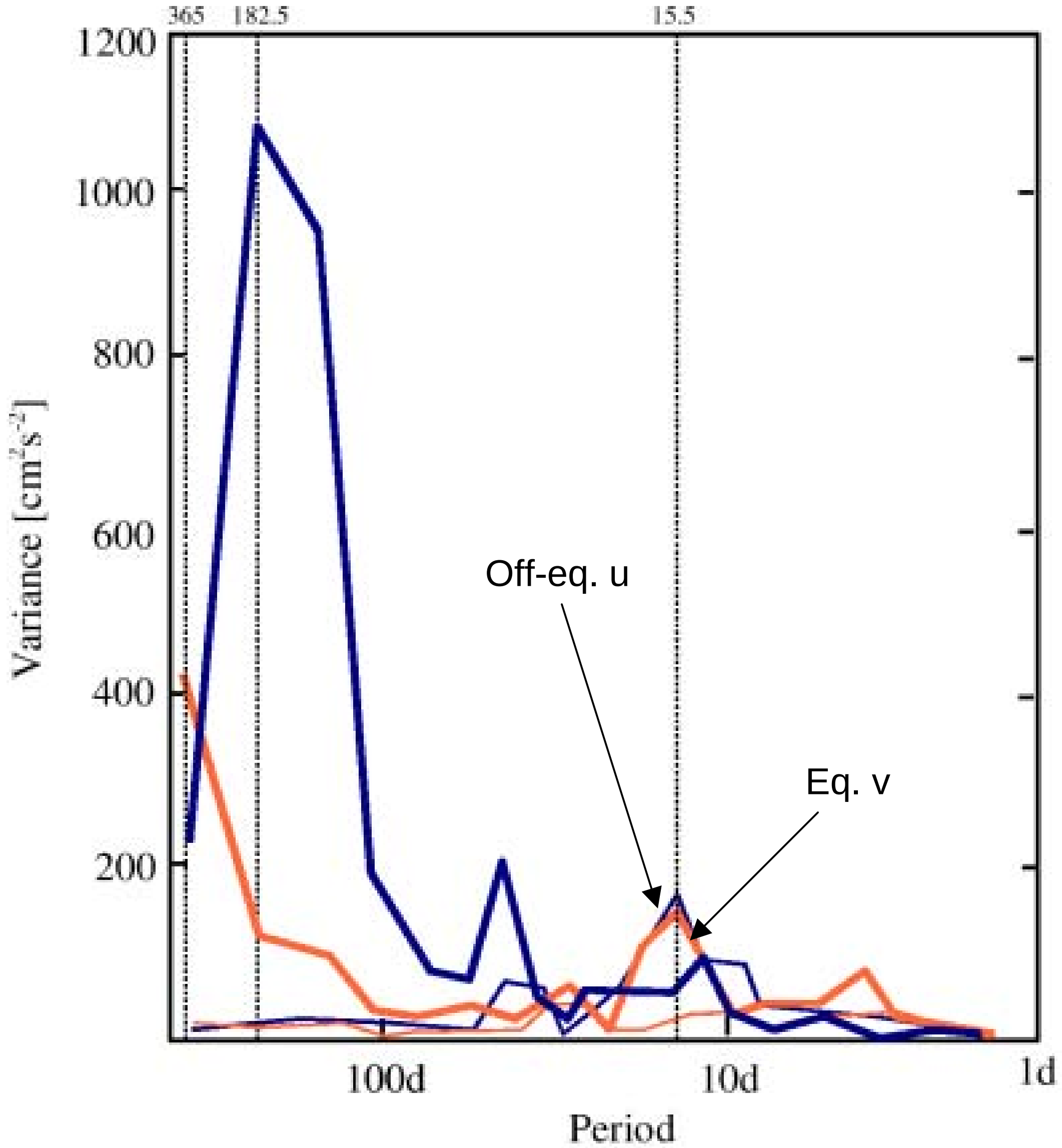

ZONAL CURRENT (cm s⁻¹) 10m 90°E 1.66°S
MODEL
OBS
160.
120.
80.
40.
0.
−40.
−80.
−120.
F A J A O D F A J A O D
DEPTH (m) OF 20°C ISOTHERM 90°E 1.66°S
MODEL
OBS
160.
140.
120.
100.
80.
F A J A O D F A J A O D
2002
2003

Kuroda 2000

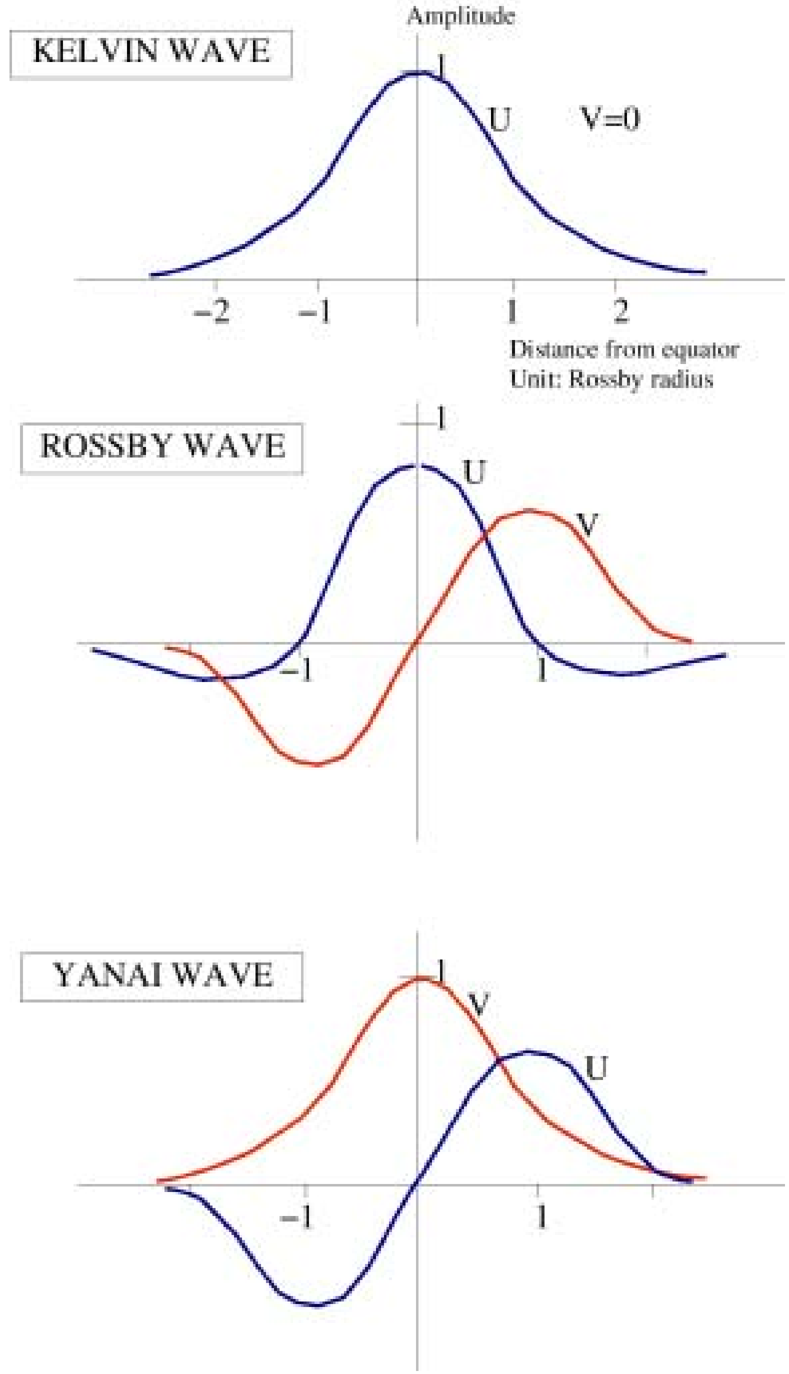

ZONAL WIND STRESS 0° 90°E
a
QSCAT
NCEP
dynes cm^{-2}
1.2
0.9
0.6
0.3
0.0
-0.3
O D F A J A O D F A J A O D F A J A O D F A J A O D
ZONAL CURRENT 50m 0° 90°E
b
QSCAT
NCEP
cm s^{-1}
200.
160.
120.
80.
40.
0.
-40.
O D F A J A O D F A J A O D F A J A O D F A J A O D
TEMPERATURE 100m 0° 90°E
c
QSCAT
NCEP
°C
29.
27.
25.
23.
21.
19.
17.
O D F A J A O D F A J A O D F A J A O D F A J A O D
1999
2000
2001
2002
2003



Schott et al., 1994, JGR

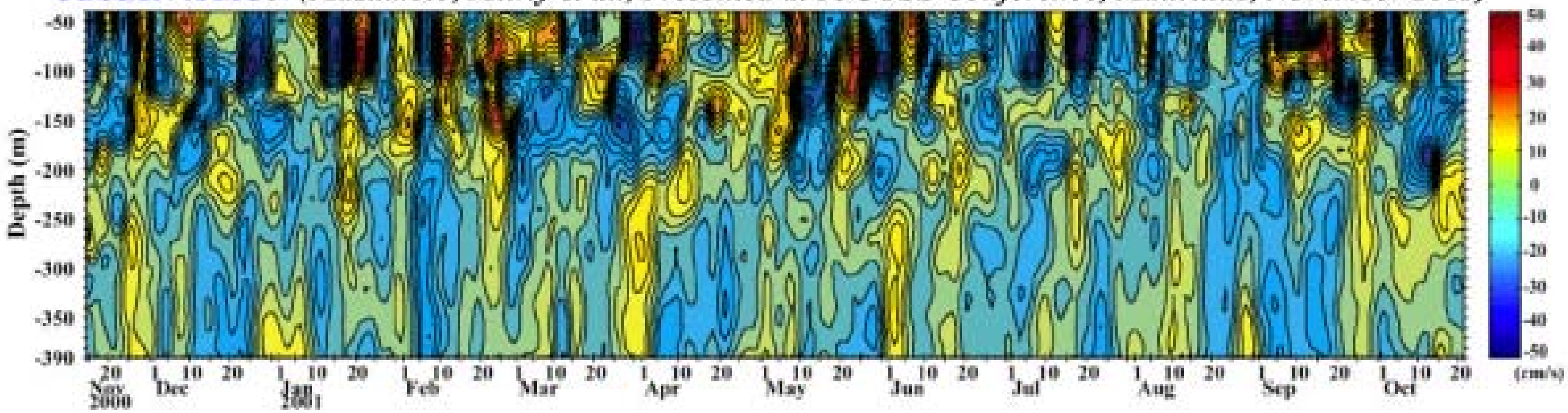


Reppin et al., 1996; Schott & McCreary, 2001

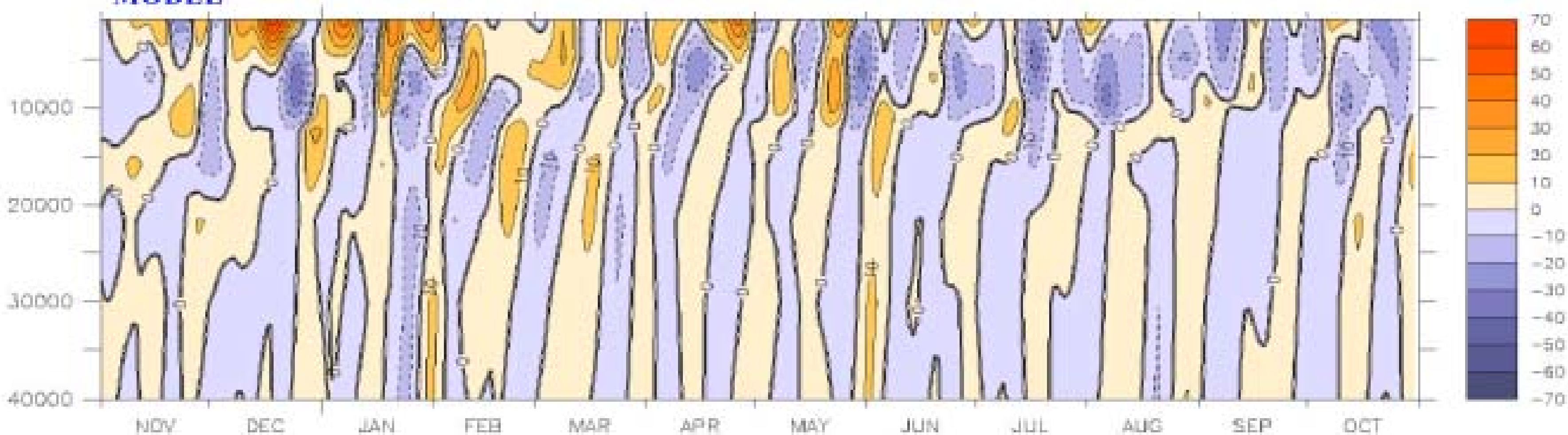

Amplitude
KELVIN WAVE
1
U
V=0
−2
−1
1
2
Distance from equator
Unit: Rossby radius
ROSSBY WAVE
1
U
V
−1
1
YANAI WAVE
1
V
U
−1
1

MERIDIONAL VELOCITY (cm s^{-1}) 90°E EQUATOR

OBSERVATION *(Masumoto, Murty et al., Presented at IOGOSS Conference, Mauritius, November 2002)*

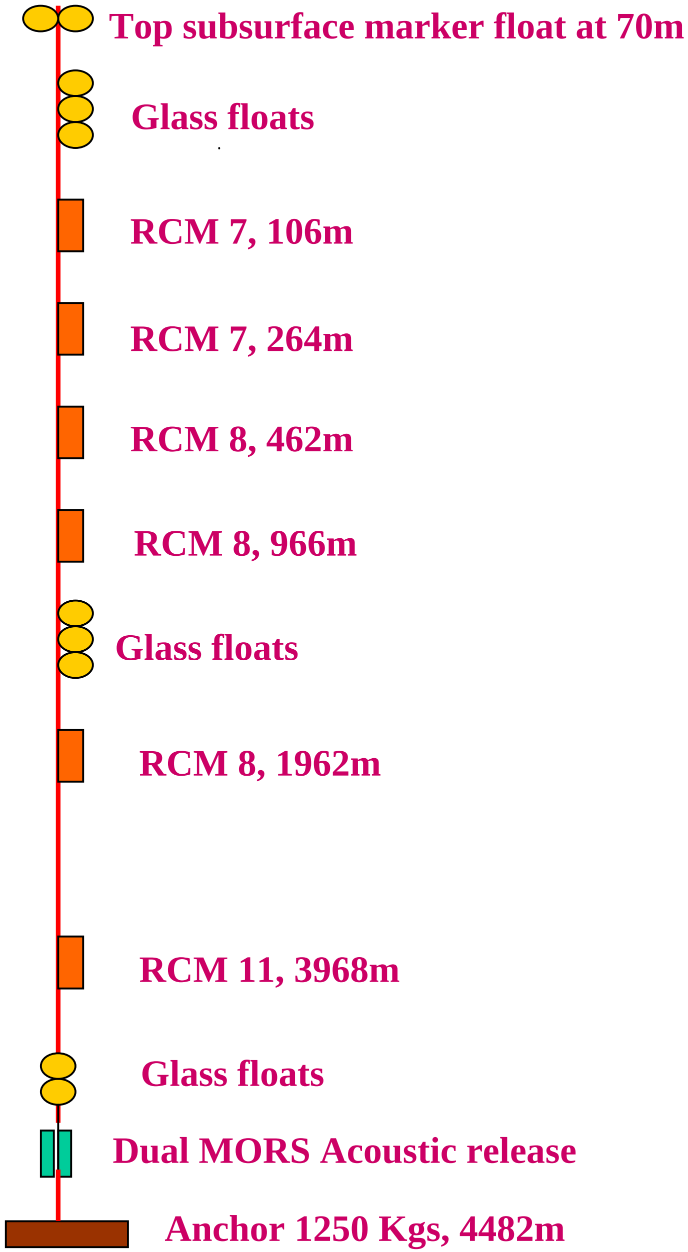


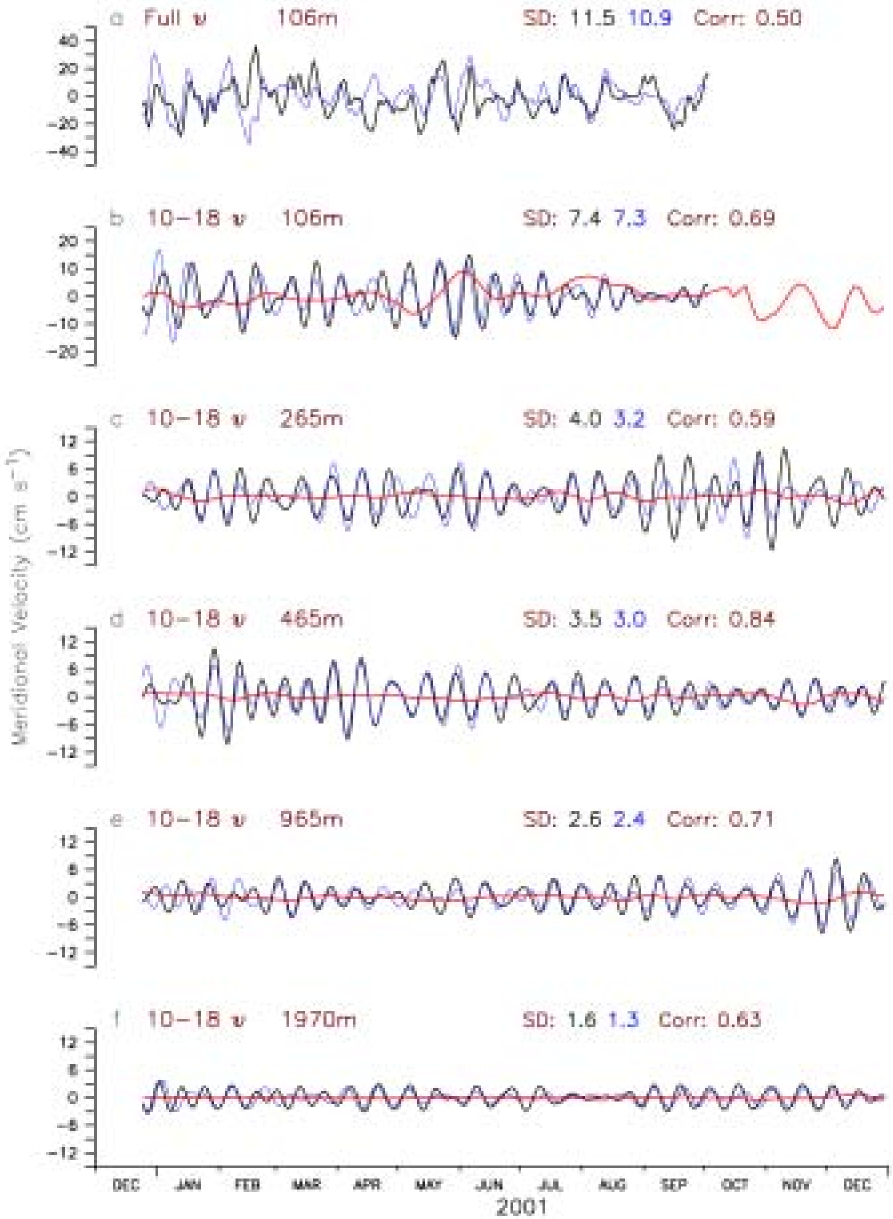
MODEL

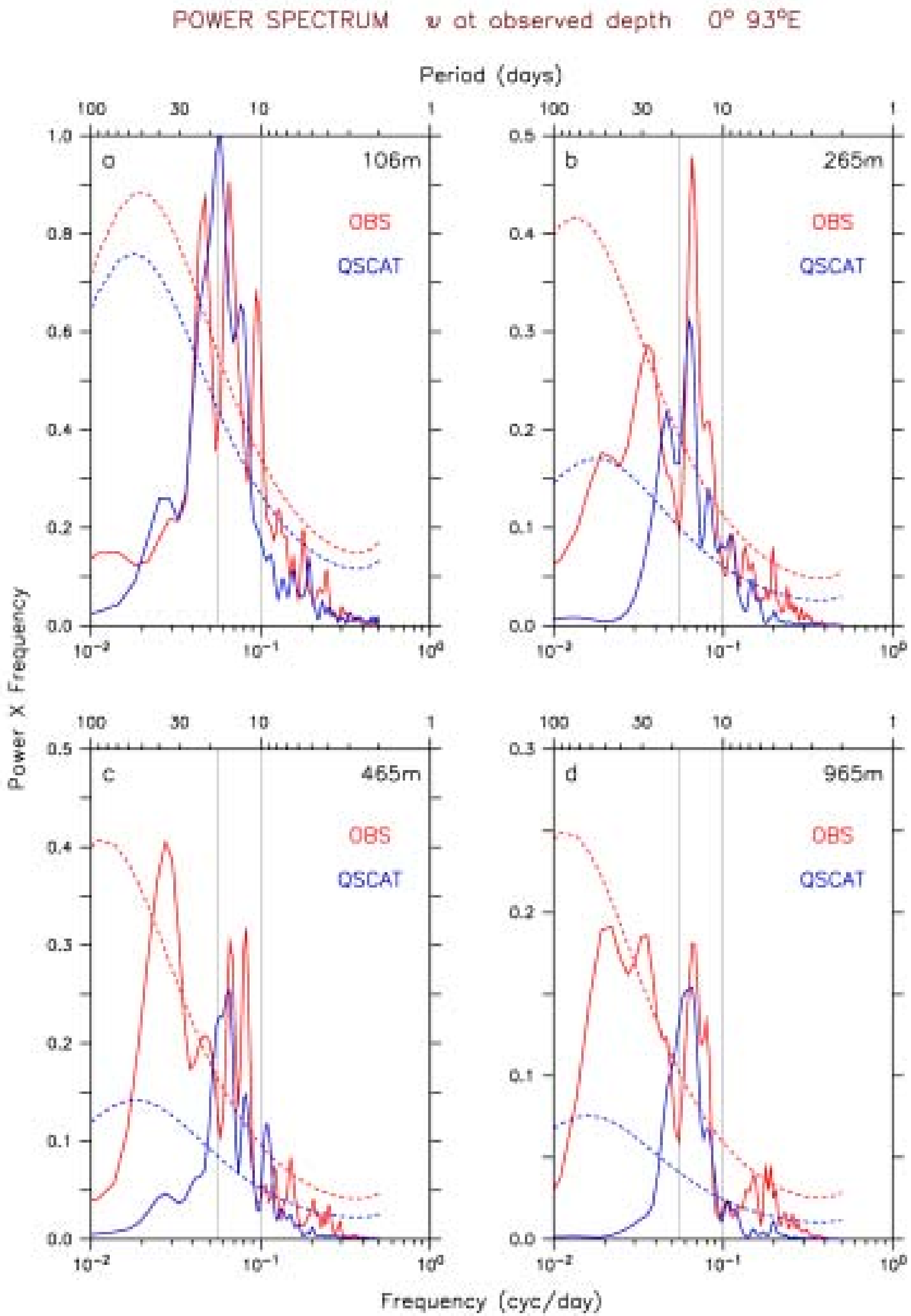


v variability: mainly 14-day Yanai waves at all depths + 30-60 day ?? below ~150m

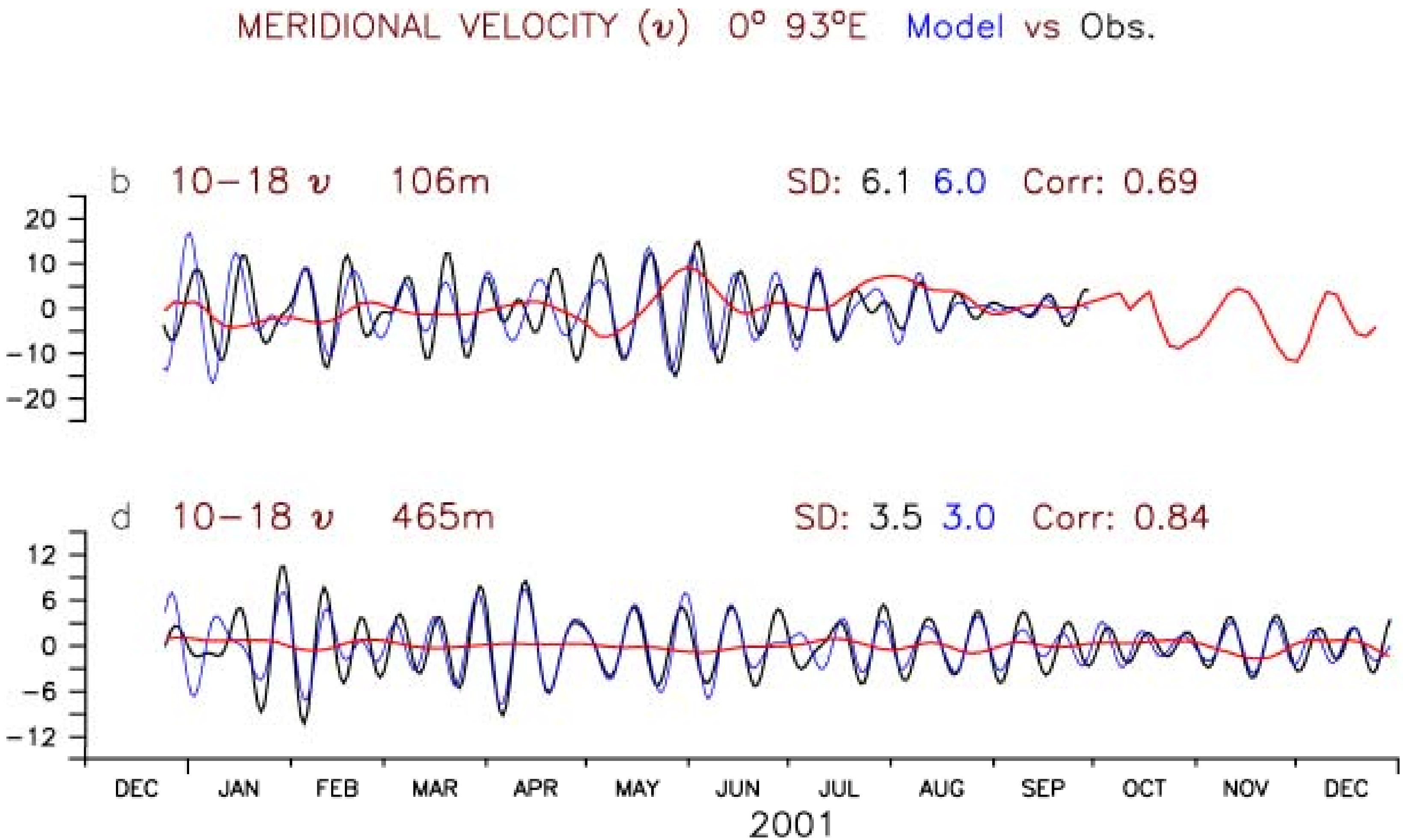
93°E NIO Obs and Model







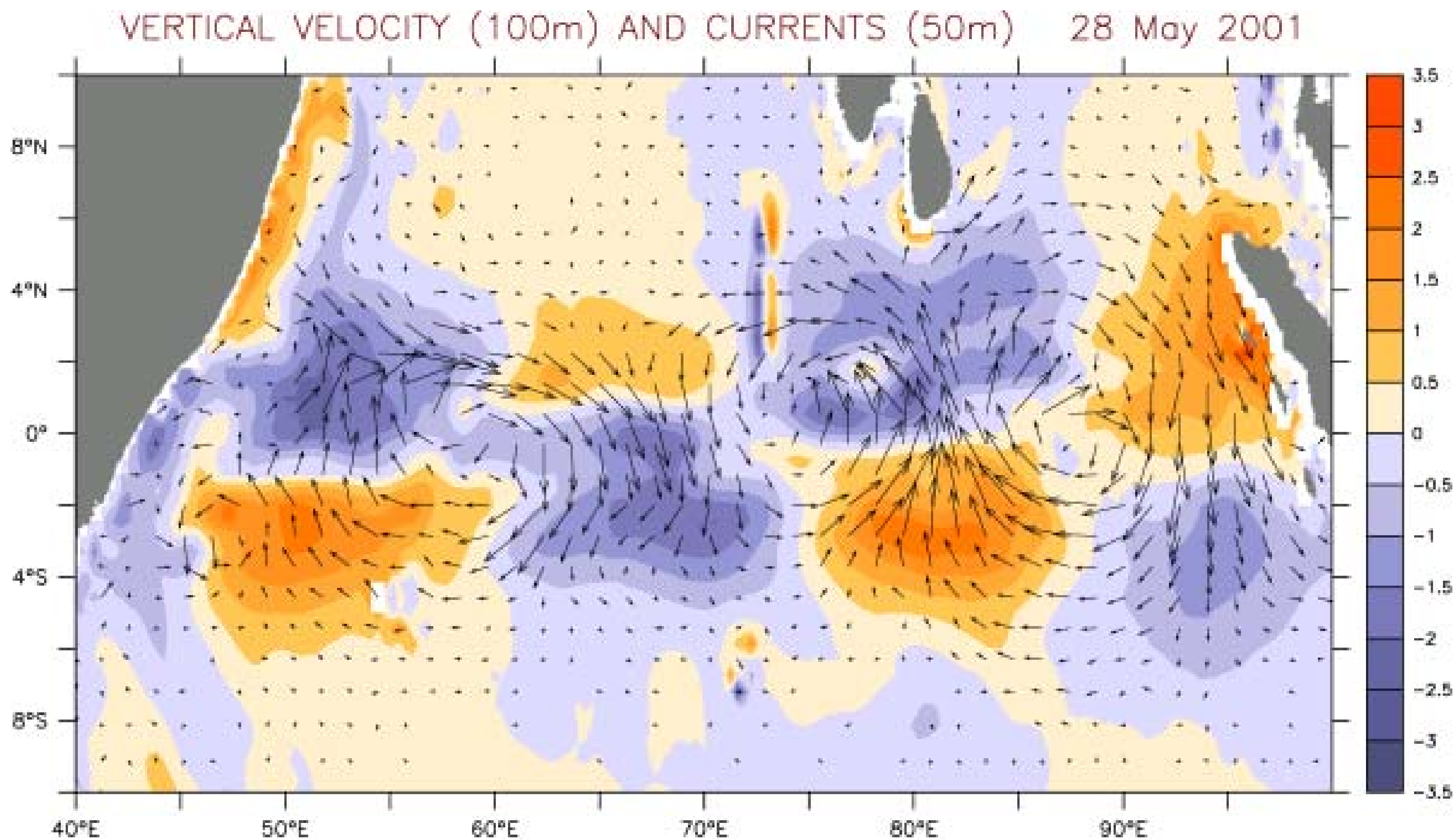
POWER SPECTRUM v at observed depth 0° 93°E
Period (days)
Power X Frequency
Frequency (cyc/day)
a
106m
b
265m
c
465m
d
965m
OBS
QSCAT


MERIDIONAL VELOCITY (v) 0° 93°E Model vs Obs.
b 10–18 v 106m
SD: 6.1 6.0 Corr: 0.69
20
10
0
−10
−20
d 10–18 v 465m
SD: 3.5 3.0 Corr: 0.84
12
6
0
−6
−12
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
2001

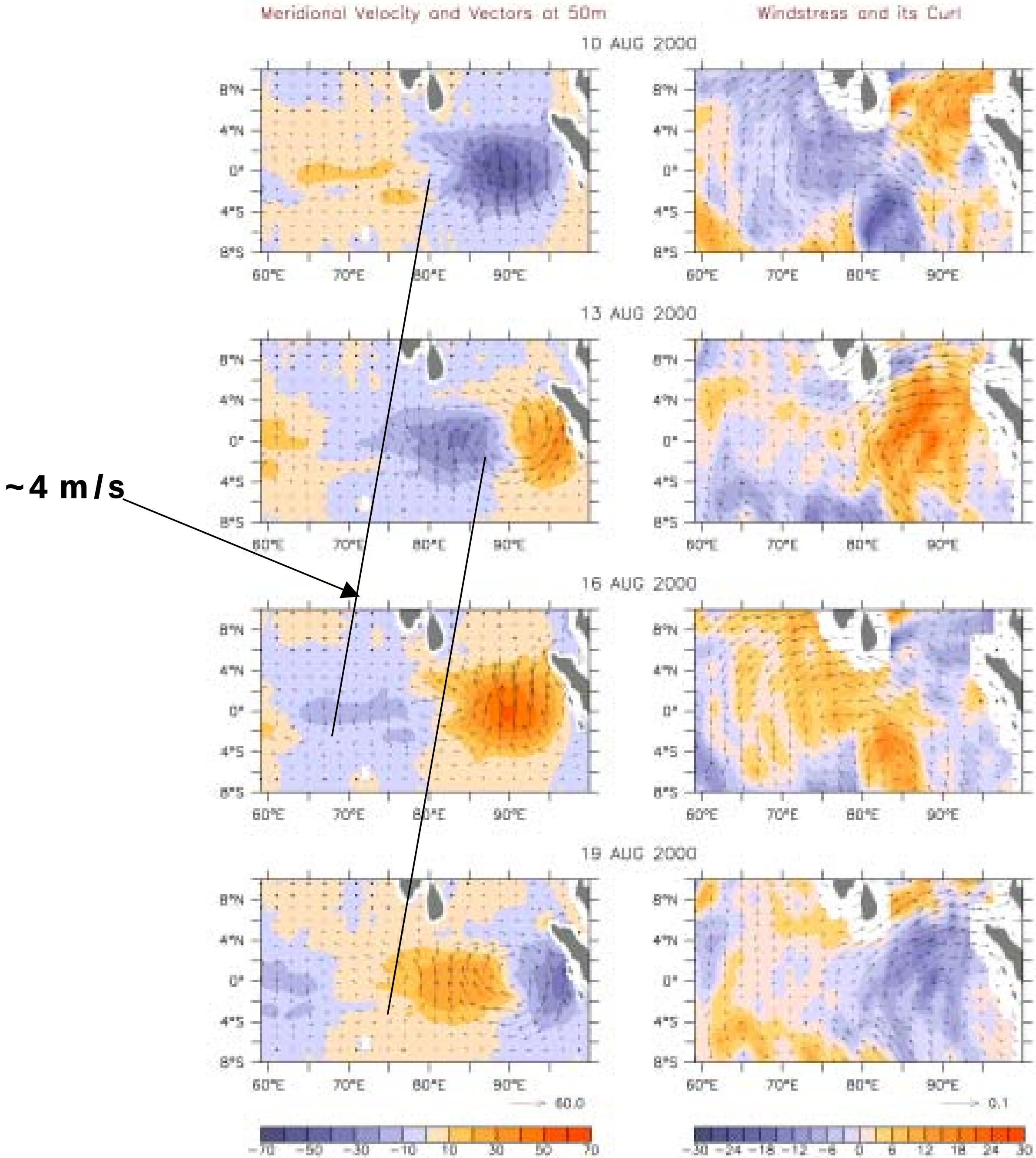
From NIO Observations

Period	Zonal wavelength (km)
10 Jan – 7 Feb 2001	3400
2 Mar – 22 Mar 2001	6100
1 Jun – 5 Jul 2001	2100
25 Jul – 30 Aug 2001	3100
5 Sep 2001 – 15 Oct 2001	3100

a. 93°E		b. 83°E	
Period	Vertical wavelength (m)	Period	Vertical wavelength (m)
30 Aug-27 Sep	4700	25 Feb-20 Mar	3200
2 Nov-27 Nov	1400	10 Oct-3 Nov	3200

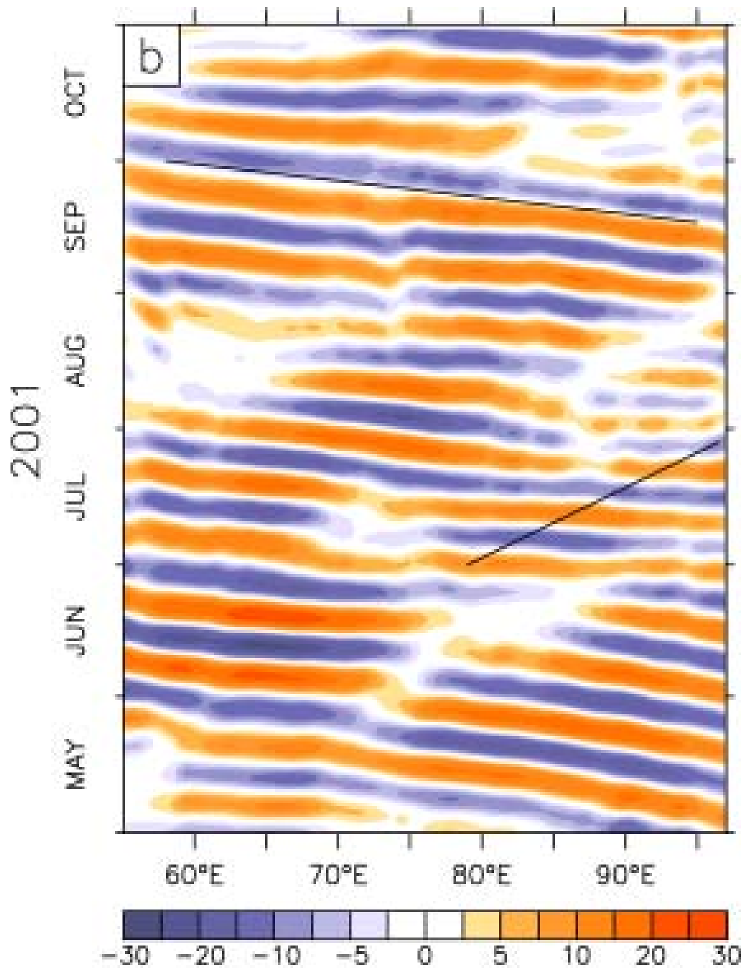

VERTICAL VELOCITY (100m) AND CURRENTS (50m) 28 May 2001
8°N
4°N
0°
4°S
8°S
40°E
50°E
60°E
70°E
80°E
90°E
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5

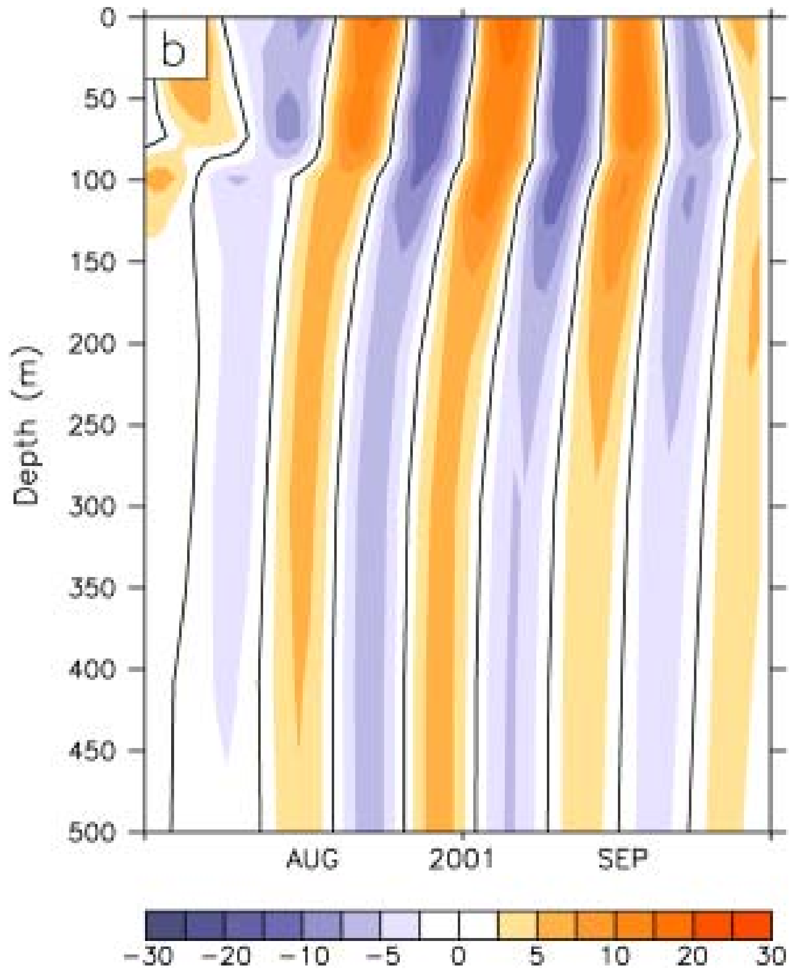
~3,300 km

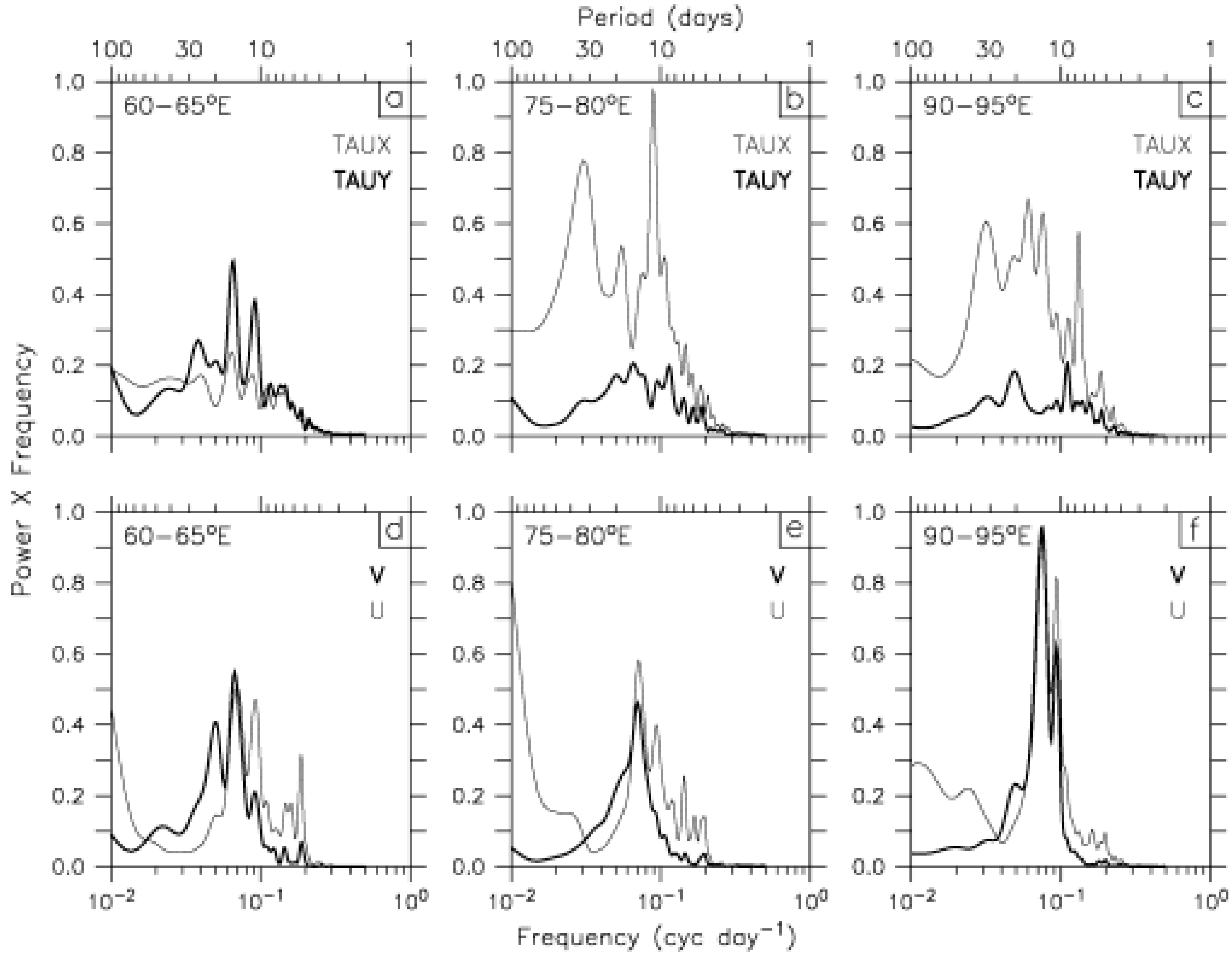


Meridional Velocity and Vectors at 50m
Windstress and its Curl
10 AUG 2000
13 AUG 2000
16 AUG 2000
19 AUG 2000
~4 m/s

10-18 day Model v 1ºS-1ºN

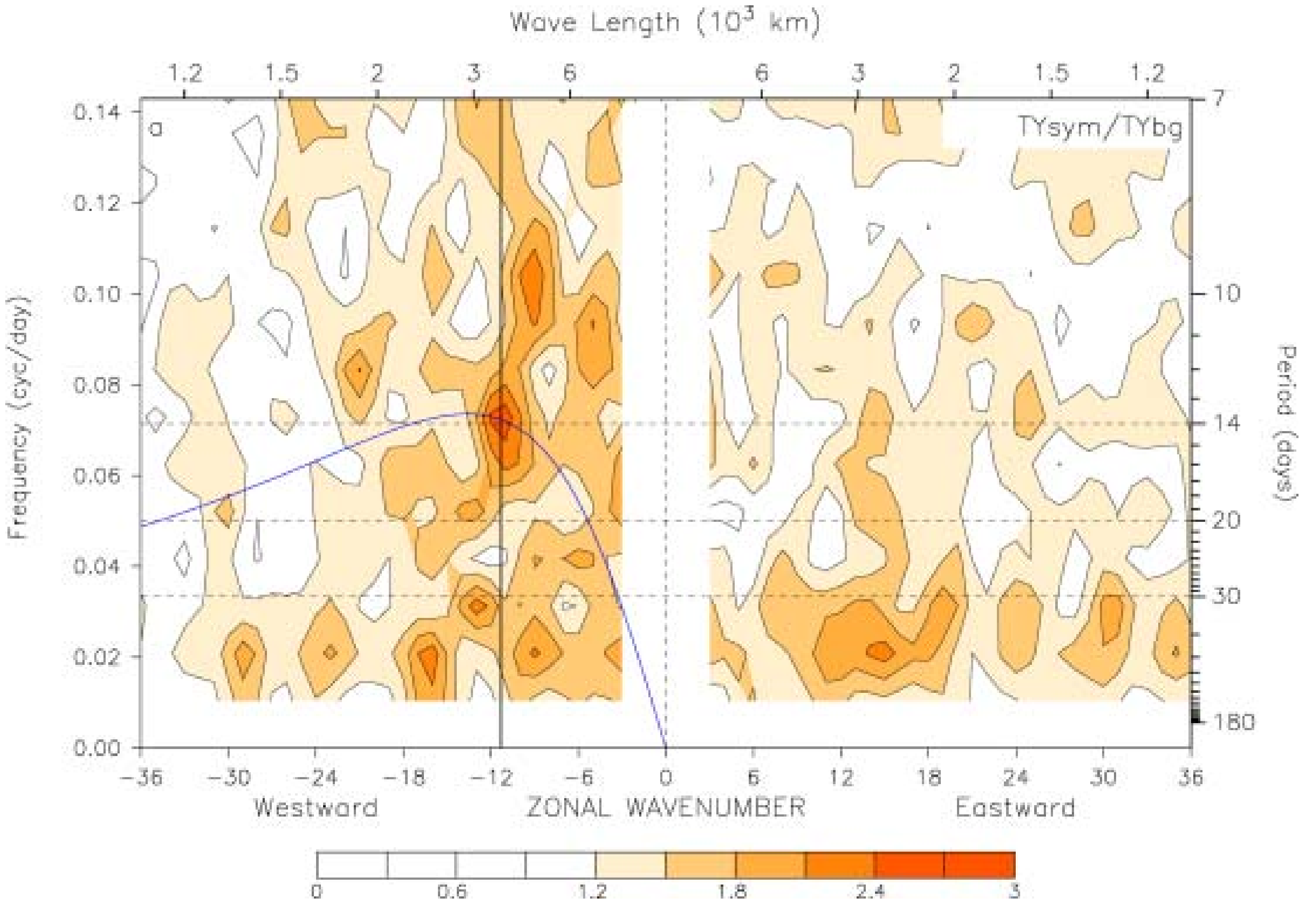


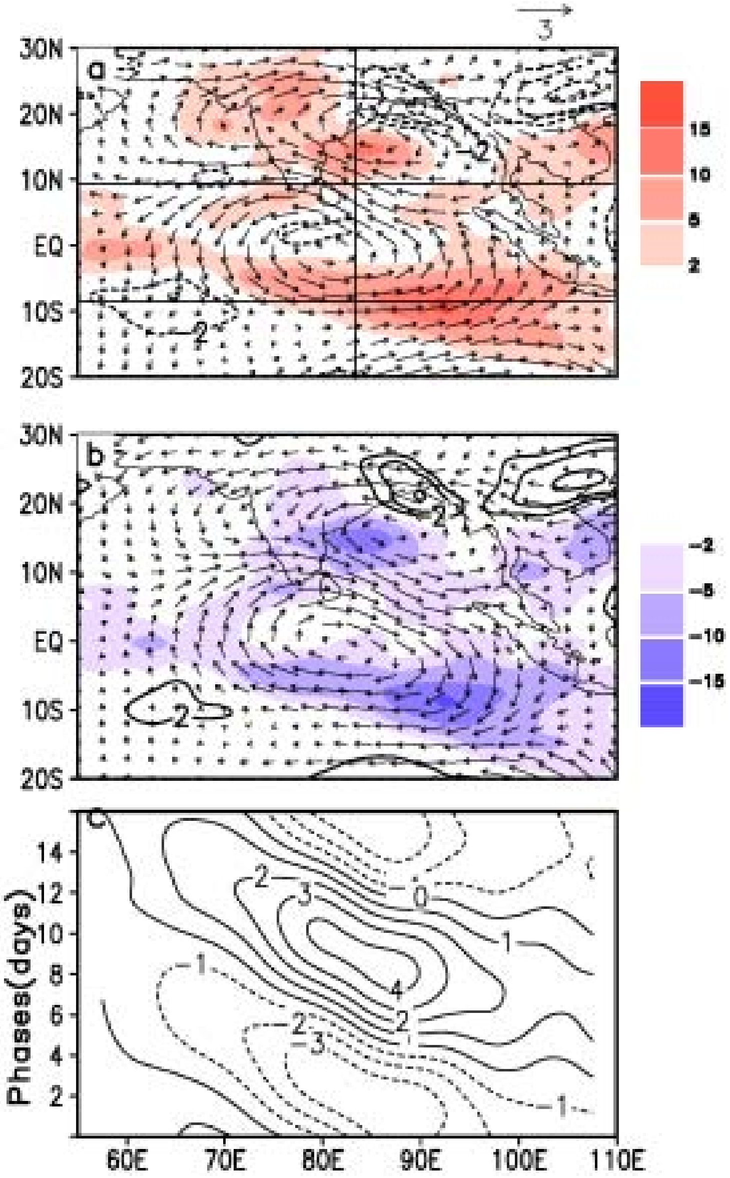




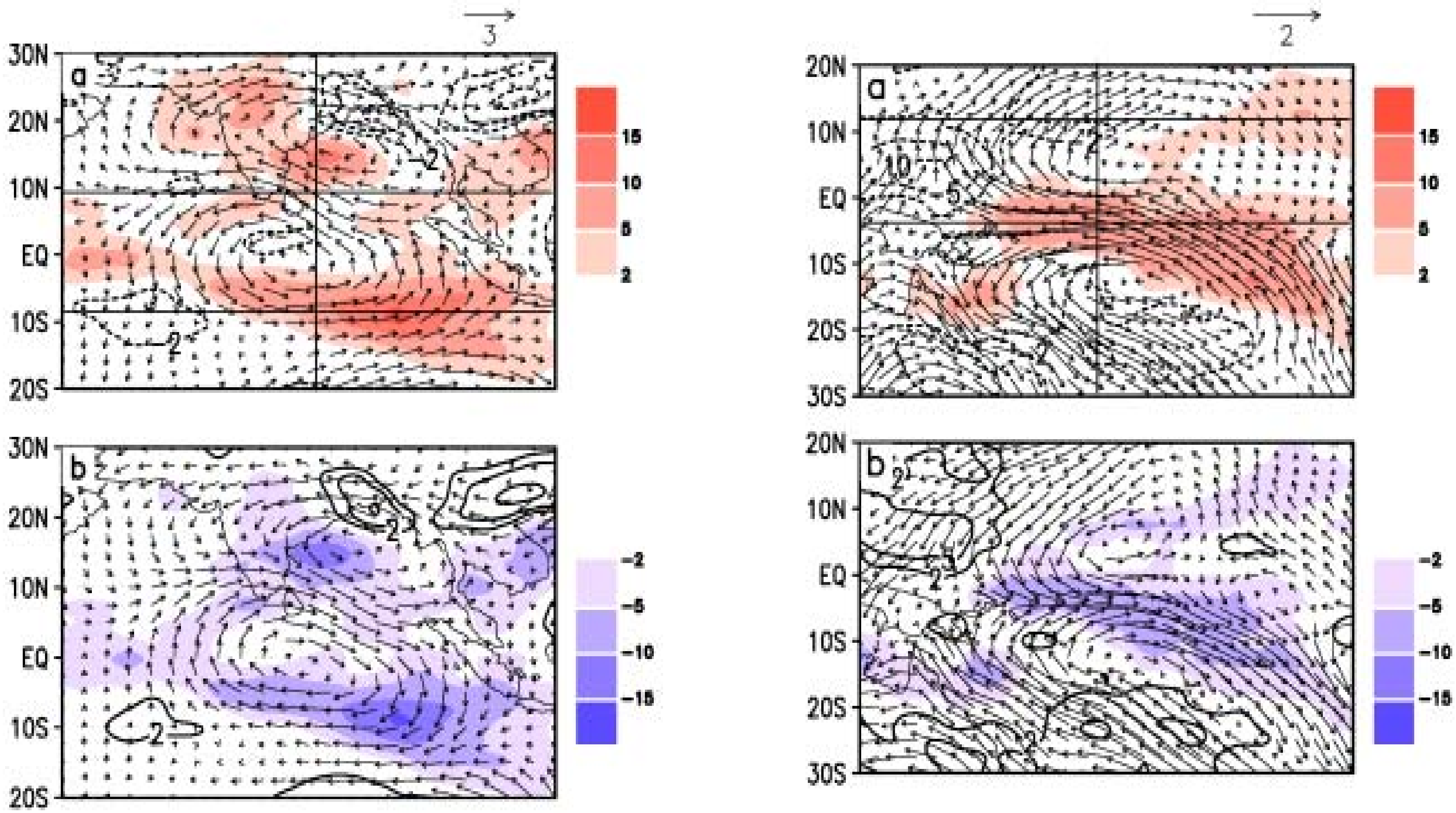
Period (days)
100
30
10
1
1.0
0.8
0.6
0.4
0.2
0.0
60–65°E
a
TAUX
TAUY
75–80°E
b
90–95°E
c
60–65°E
d
V
U
75–80°E
e
90–95°E
f
Power X Frequency
10^{-2}
10^{-1}
10^{0}
Frequency (cyc day^{-1})

SPACE-TIME SPECTRUM τ_y



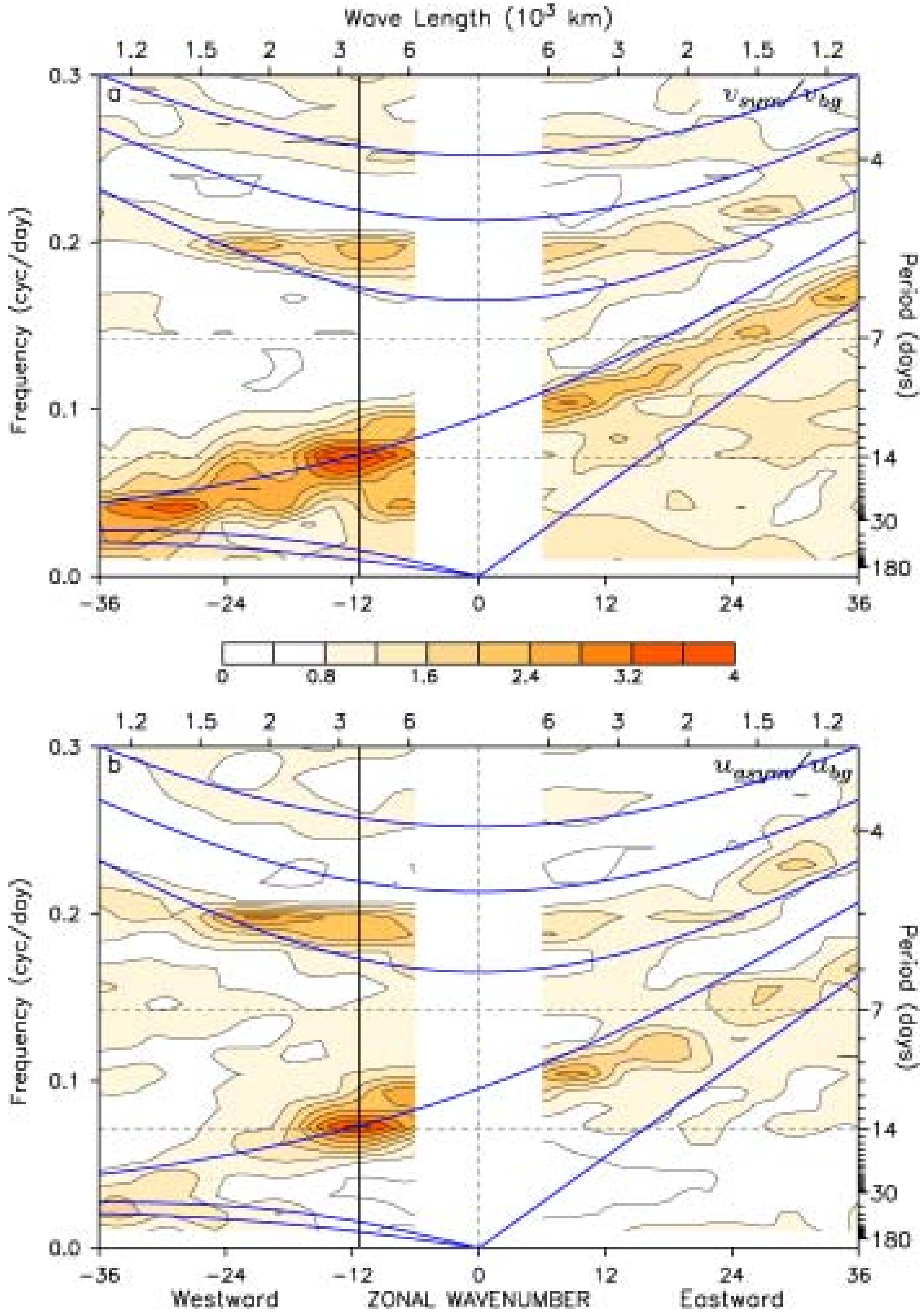


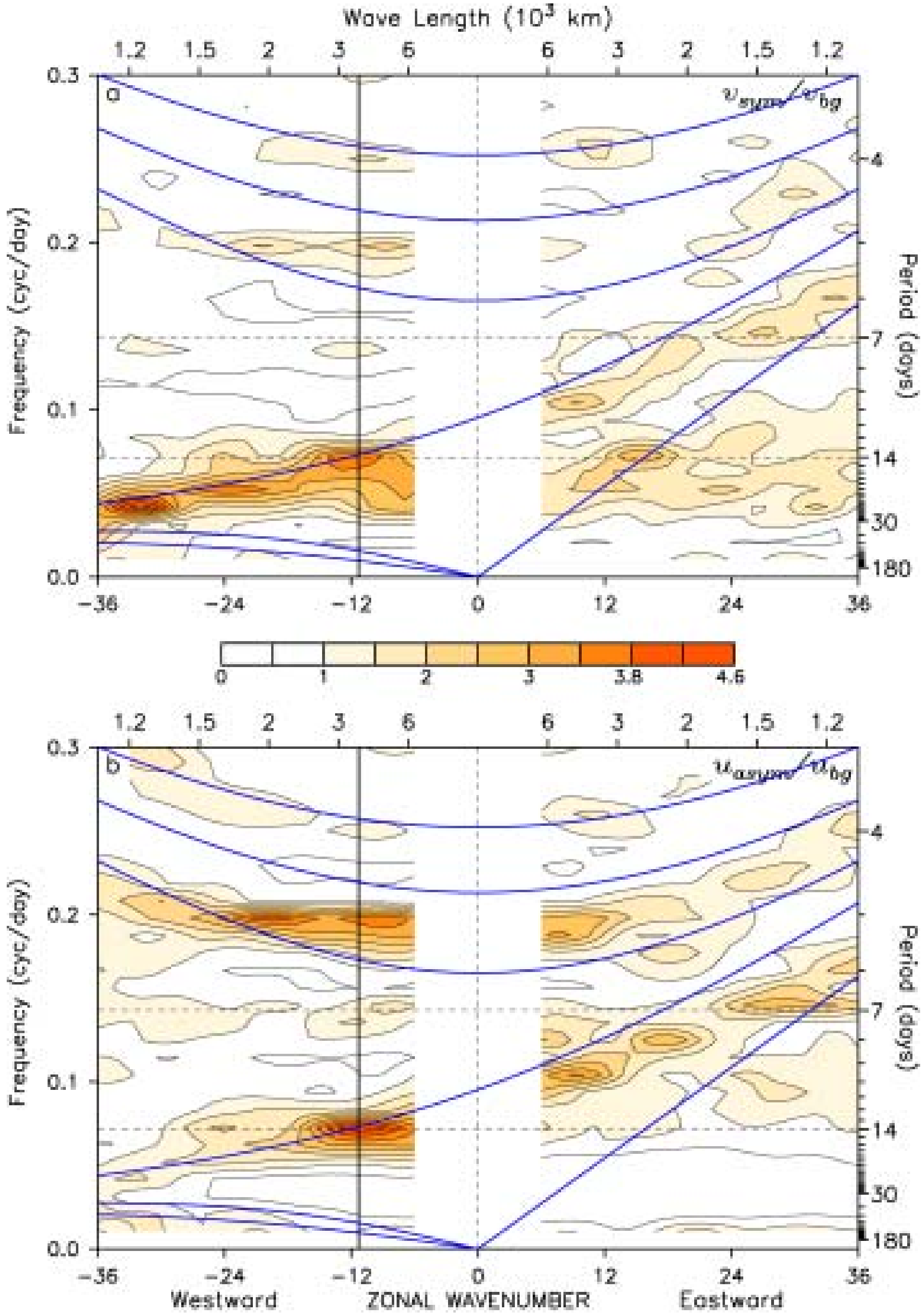
QBO: **Chatterjee & Goswami, 2004 QJRMS**


3
2
30N
20N
10N
EQ
10S
20S
30S
a
b
15
10
5
2
-2
-5
-10
-15

SPACE-TIME SPECTRUM

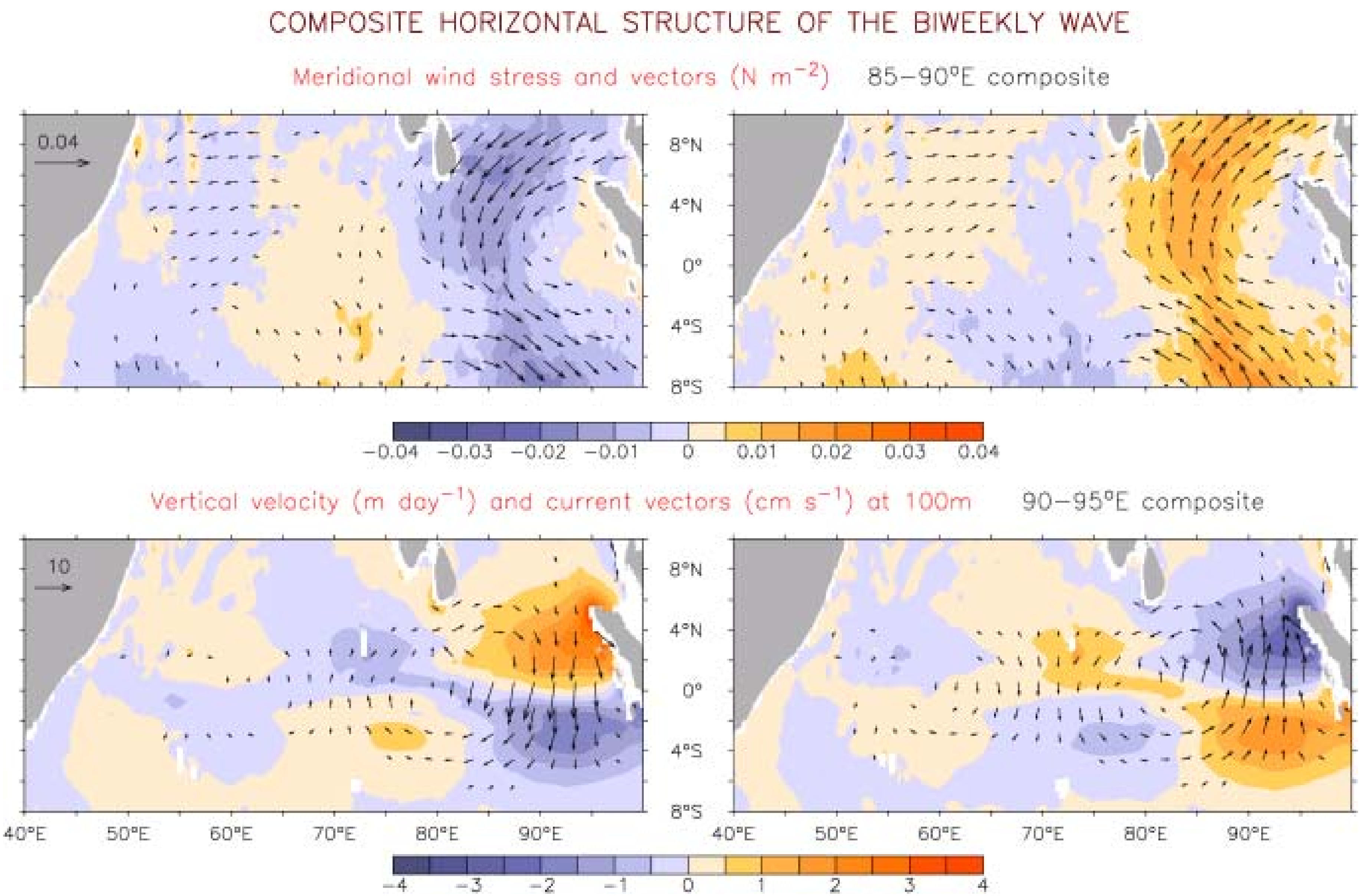
v 50m



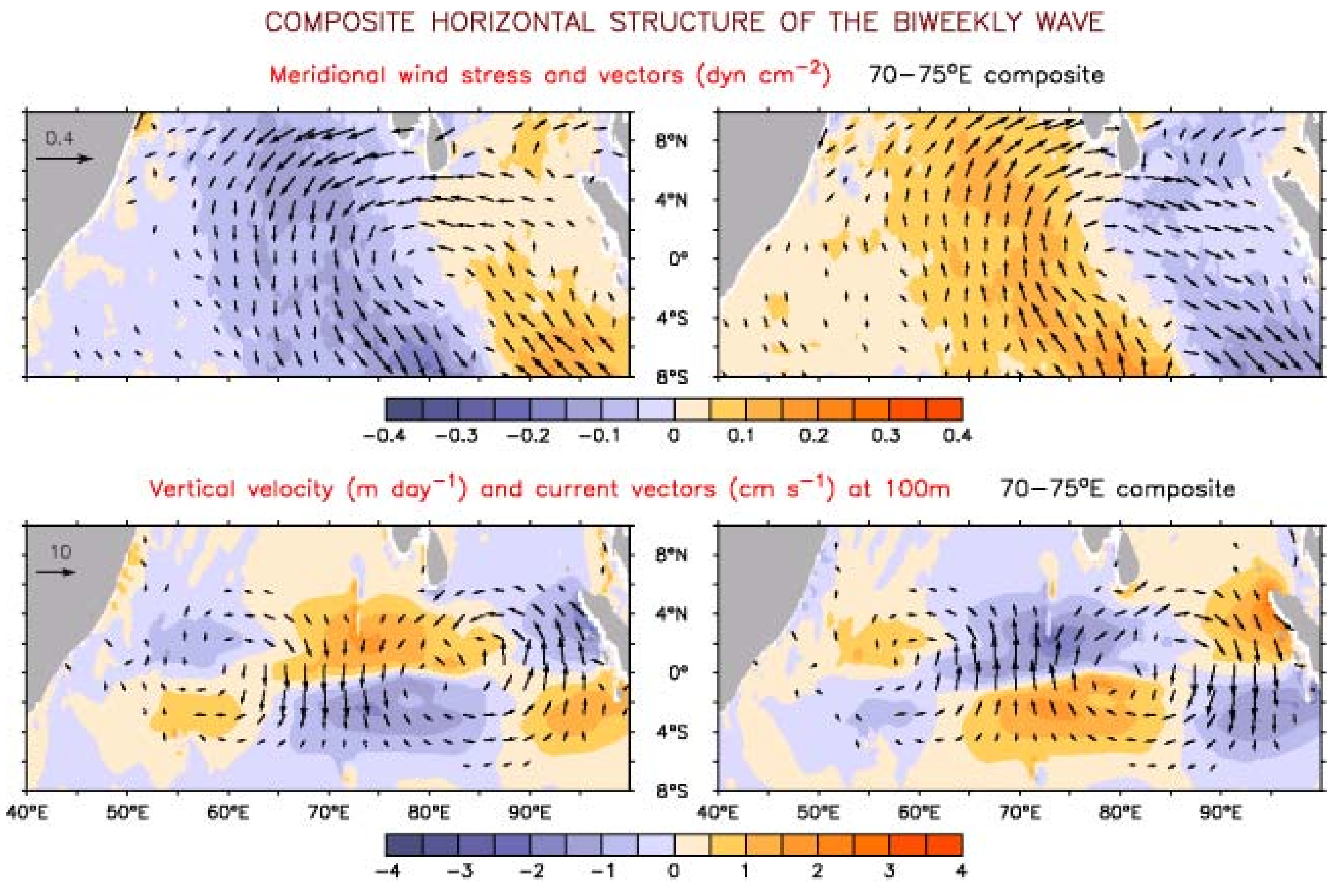


SPACE-TIME SPECTRUM

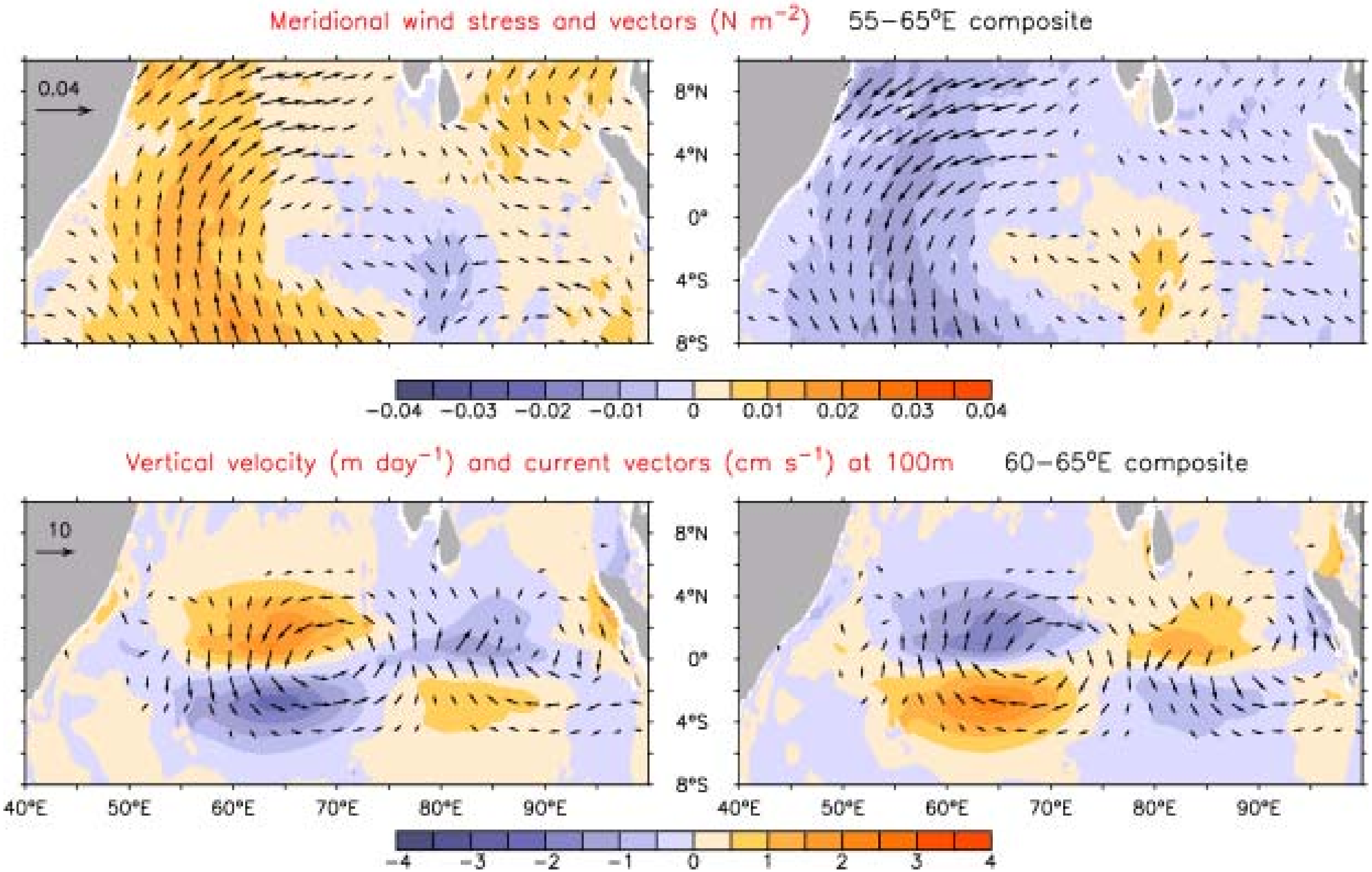
v 500m



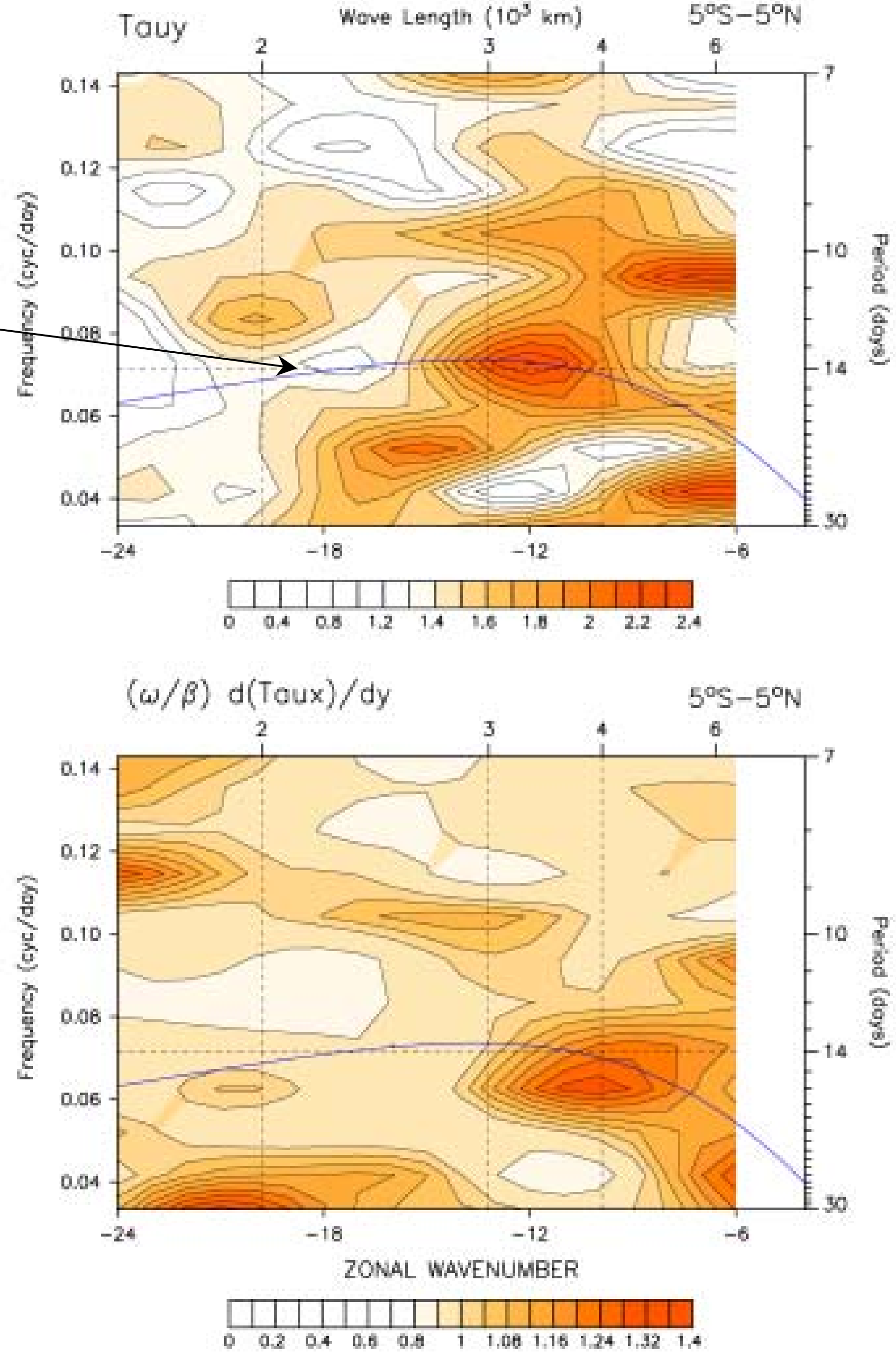
COMPOSITE HORIZONTAL STRUCTURE OF THE BIWEEKLY WAVE
Meridional wind stress and vectors (N m−2)
85−90°E composite
0.04
8°N
4°N
0°
4°S
8°S
−0.04
−0.03
−0.02
−0.01
0
0.01
0.02
0.03
0.04
Vertical velocity (m day−1) and current vectors (cm s−1) at 100m
90−95°E composite
10
40°E
50°E
60°E
70°E
80°E
90°E
−4
−3
−2
−1
0
1
2
3
4


COMPOSITE HORIZONTAL STRUCTURE OF THE BIWEEKLY WAVE
Meridional wind stress and vectors (dyn cm⁻²) 70–75°E composite
0.4
8°N
4°N
0°
4°S
8°S
−0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4
Vertical velocity (m day⁻¹) and current vectors (cm s⁻¹) at 100m 70–75°E composite
10
40°E 50°E 60°E 70°E 80°E 90°E
−4 −3 −2 −1 0 1 2 3 4

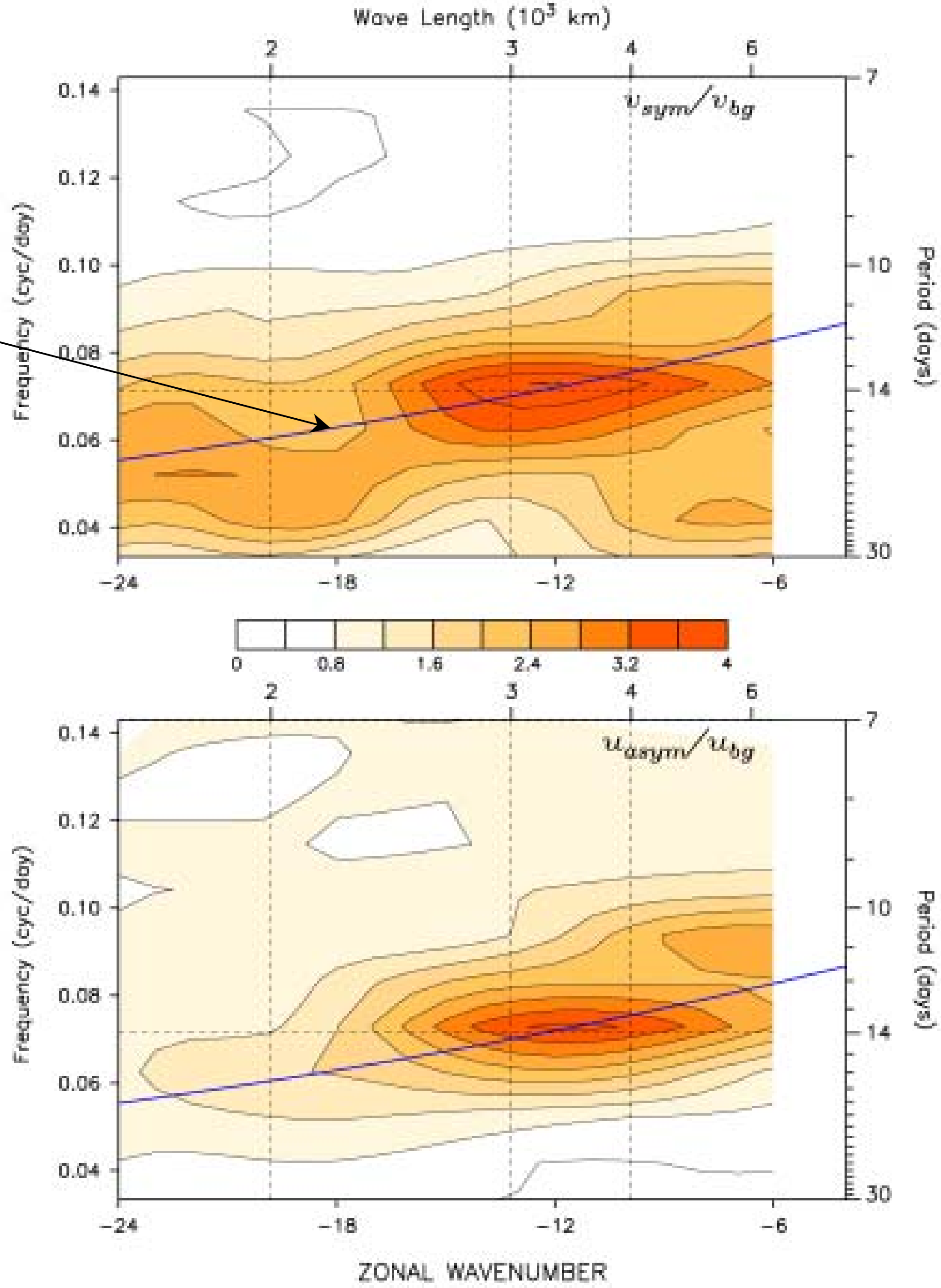
COMPOSITE HORIZONTAL STRUCTURE OF THE BIWEEKLY WAVE

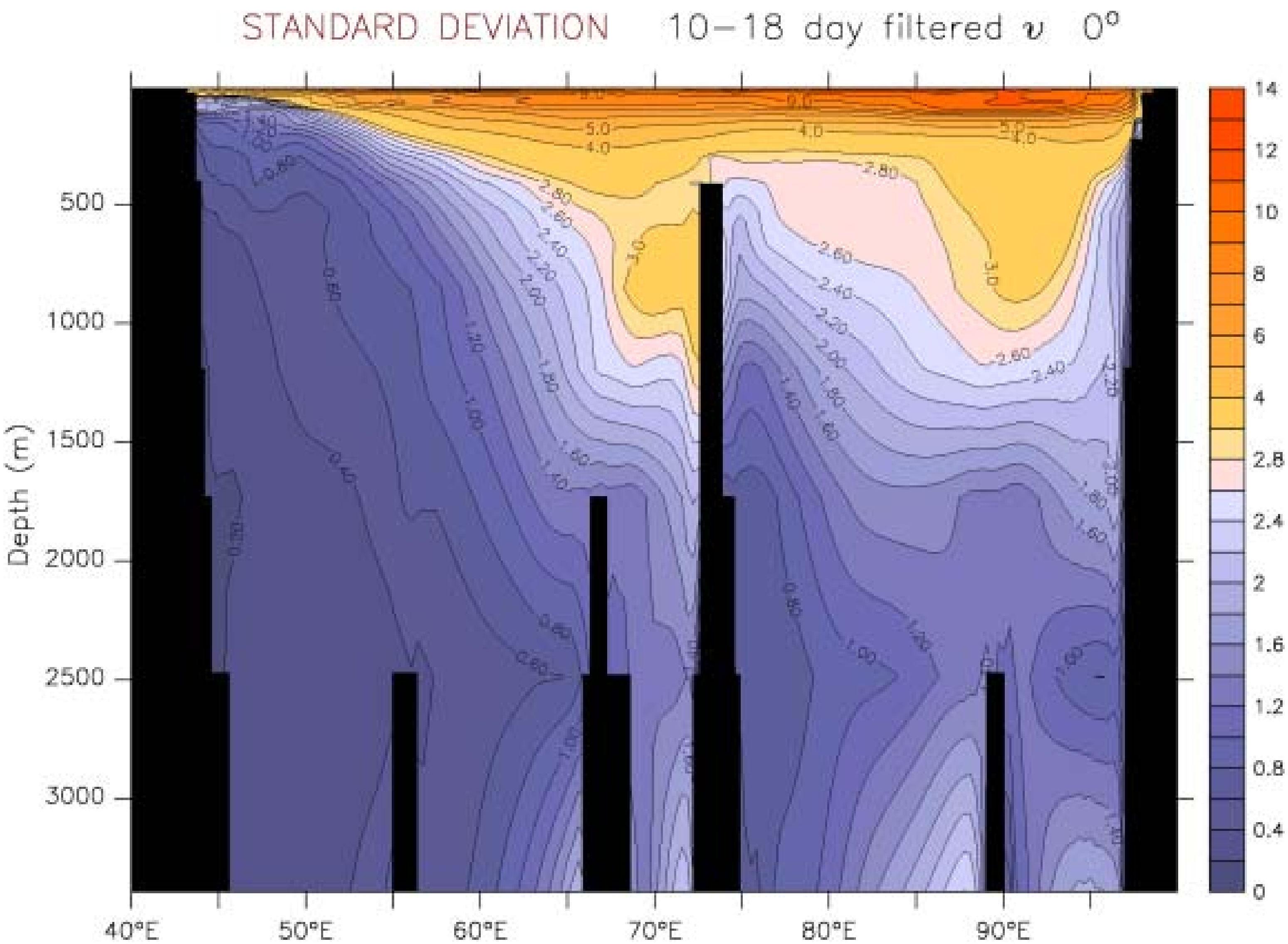


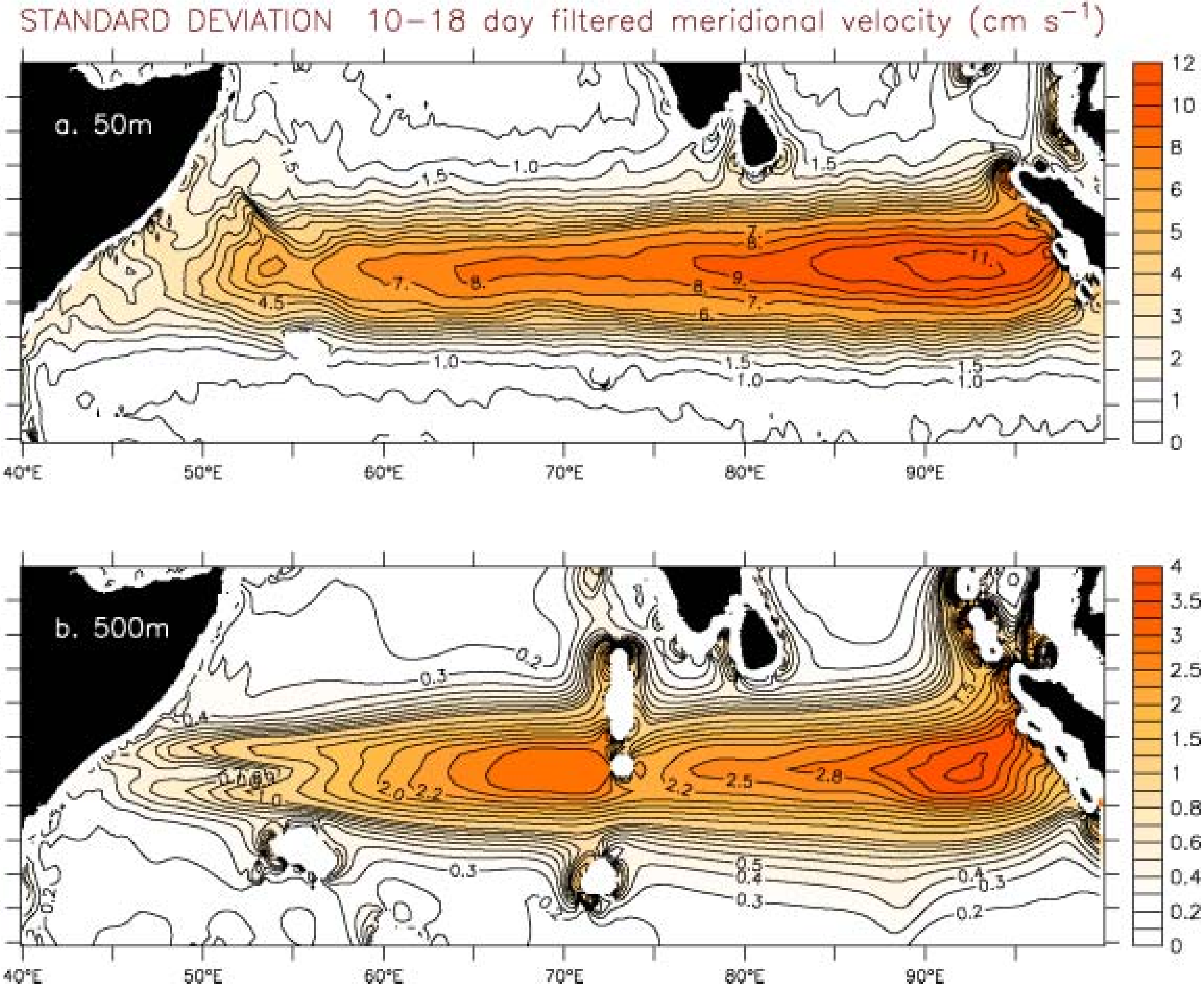
Rossby wave dispersion curve c=15 ms^{-1}

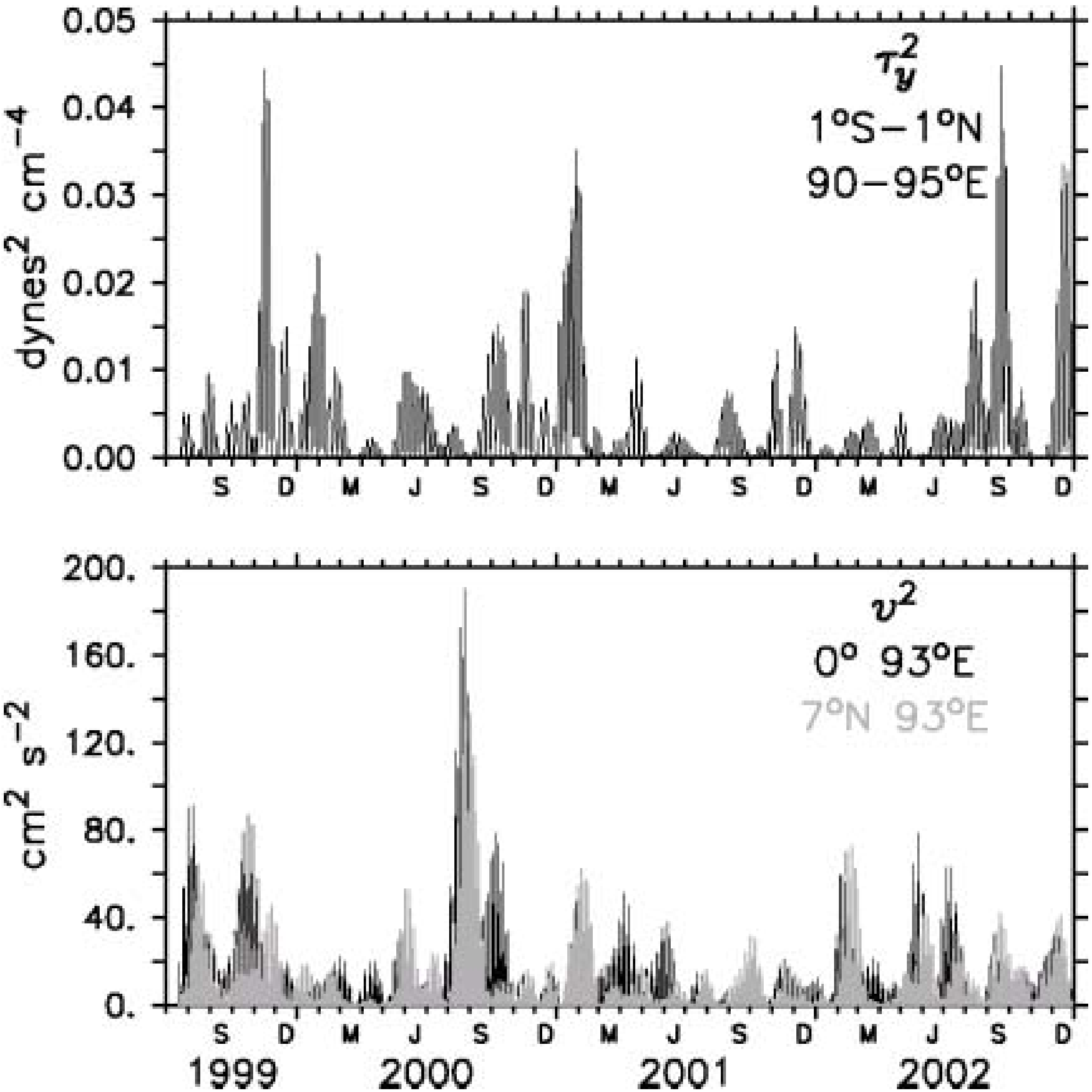


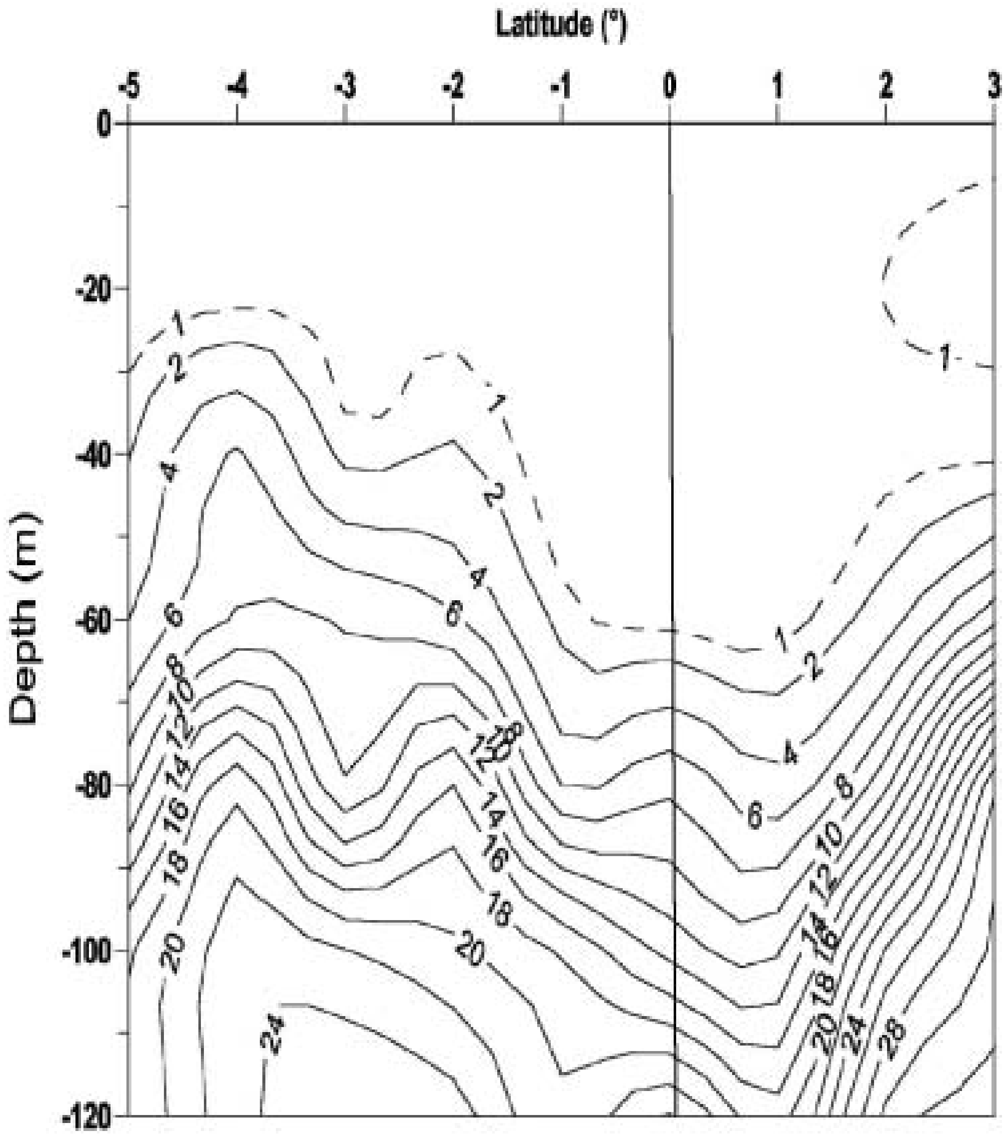
Yanai wave dispersion curve $c = 2.1\ ms^{-1}$




STANDARD DEVIATION 10-18 day filtered v 0°
Depth (m)
500
1000
1500
2000
2500
3000
40°E
50°E
60°E
70°E
80°E
90°E
14
12
10
8
6
4
2.8
2.4
2
1.6
1.2
0.8
0.4
0

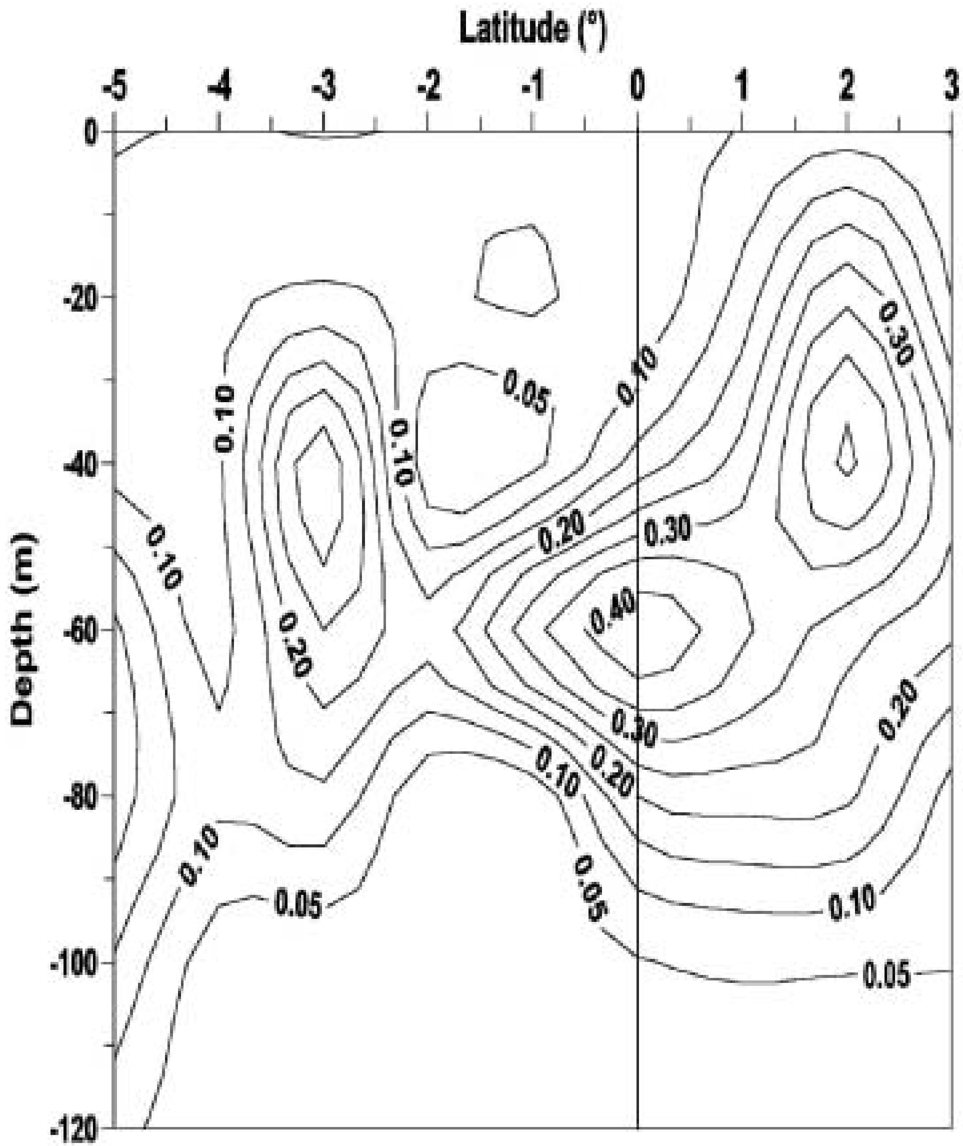

STANDARD DEVIATION 10–18 day filtered meridional velocity (cm s^{-1})
a. 50m
b. 500m
8°N
4°N
0°
4°S
8°S
40°E
50°E
60°E
70°E
80°E
90°E


0.05
0.04
0.03
0.02
0.01
0.00
dynes^2 cm^{-4}
τ_y^2
1°S−1°N
90−95°E
S D M J S D M J S D M J S D
200.
160.
120.
80.
40.
0.
cm^2 s^{-2}
v^2
0° 93°E
7°N 93°E
S D M J S D M J S D M J S D
1999
2000
2001
2002

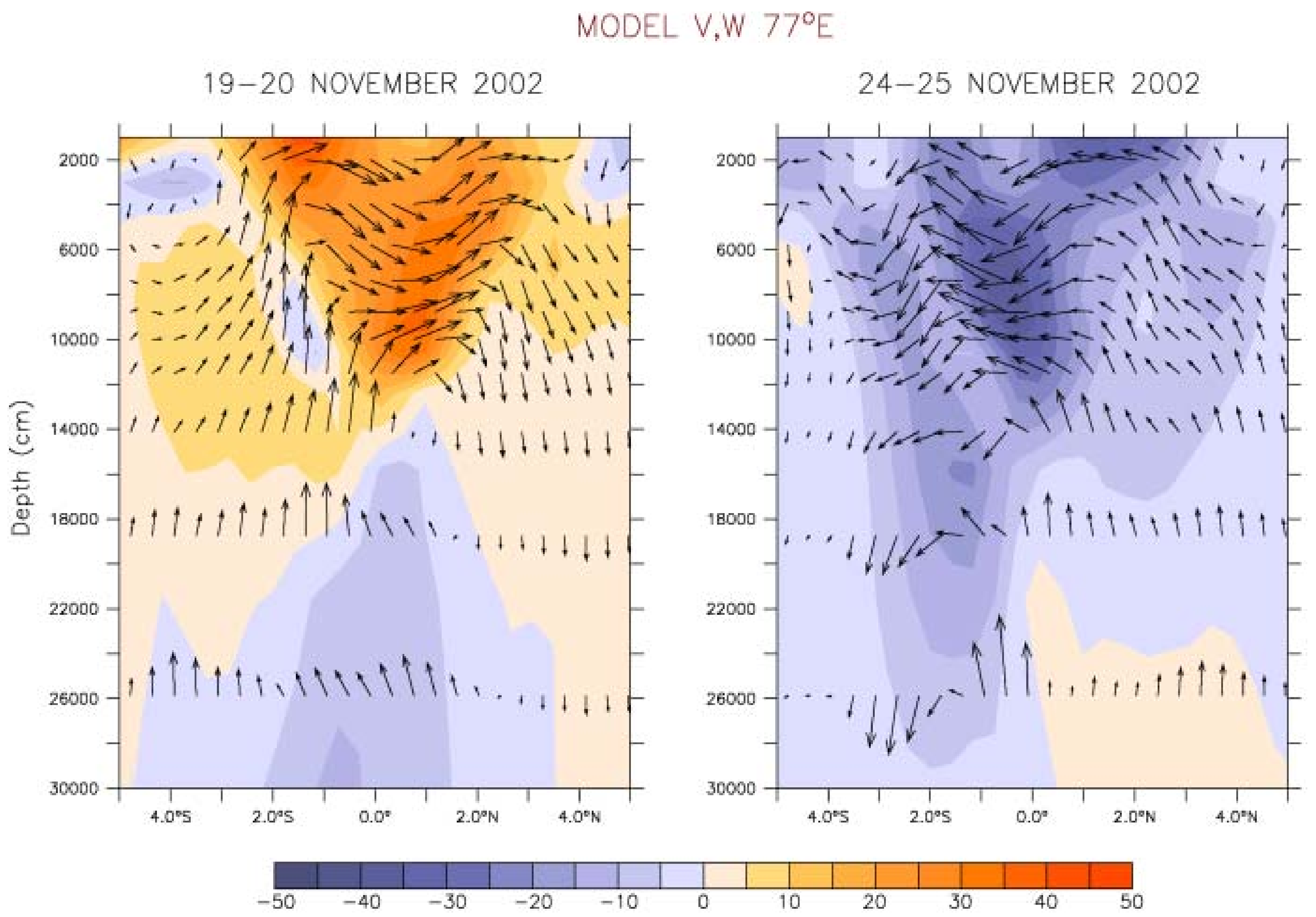


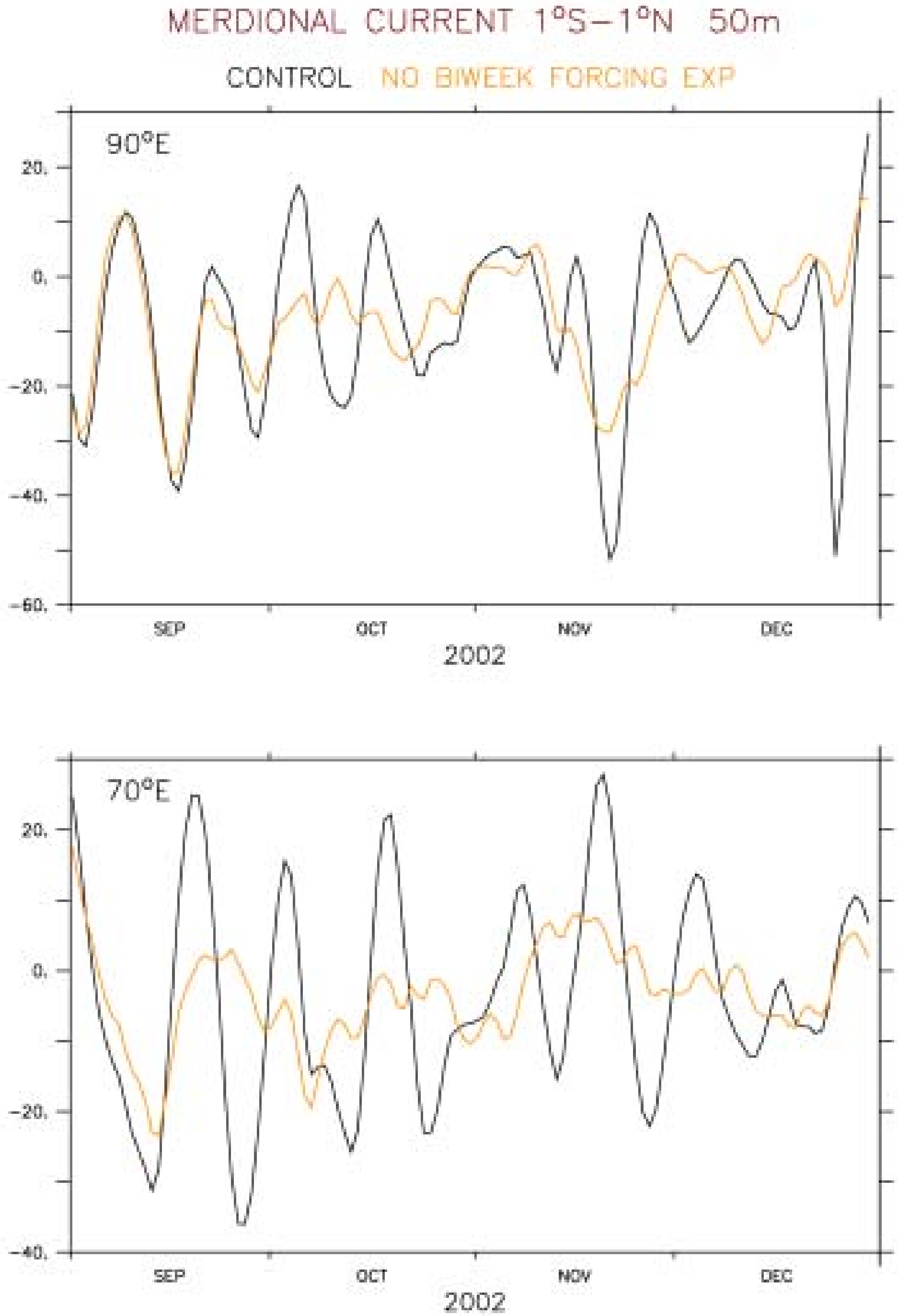
Distribution of Nitrate (micro mole) along 77°E section in the equatorial Indian Ocean during 19-25 Nov. 2002

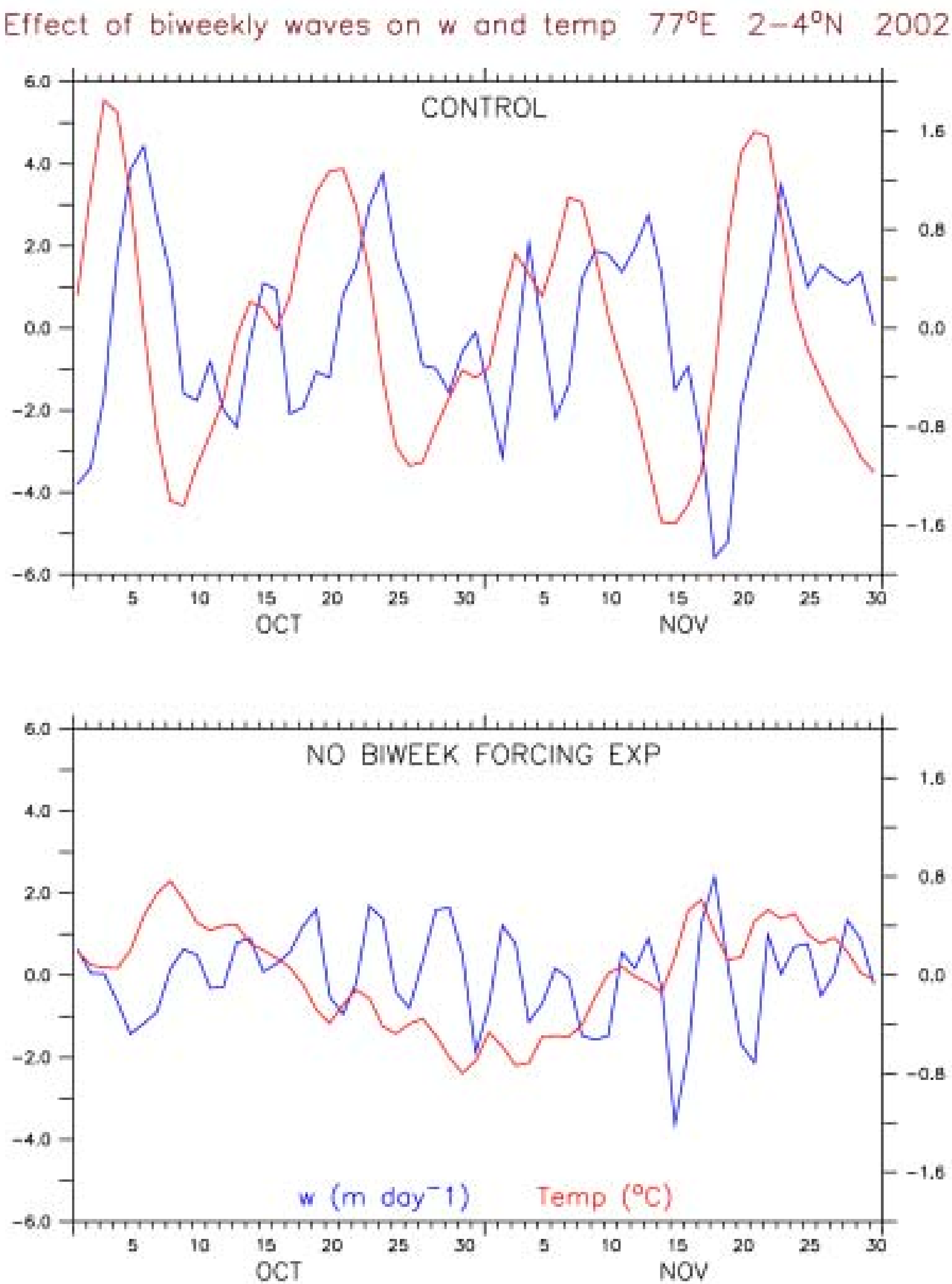
VSN Murty NIO

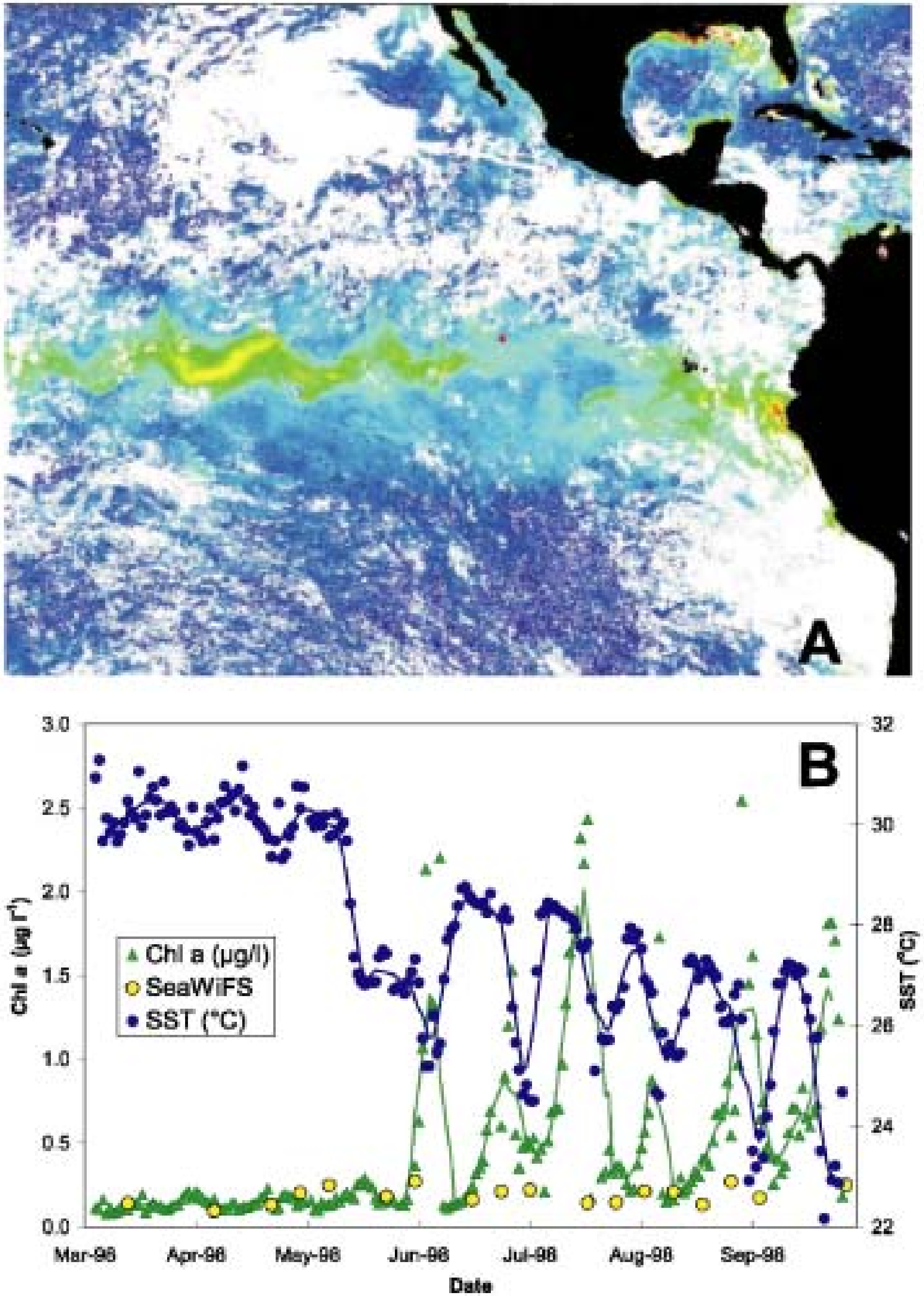


Distribution of chlorophyll a (micro gram/litre) along 77°E section in the equatorial Indian Ocean during 19-25 Nov. 2002


MODEL V,W 77°E
19–20 NOVEMBER 2002
24–25 NOVEMBER 2002
Depth (cm)
2000
6000
10000
14000
18000
22000
26000
30000
4.0°S
2.0°S
0.0°
2.0°N
4.0°N
−50
−40
−30
−20
−10
0
10
20
30
40
50


MERDIONAL CURRENT 1°S−1°N 50m
CONTROL NO BIWEEK FORCING EXP
90°E
20.
0.
-20.
-40.
-60.
SEP
OCT
NOV
DEC
2002
70°E
20.
0.
-20.
-40.
SEP
OCT
NOV
DEC
2002


Effect of biweekly waves on w and temp 77°E 2-4°N 2002
CONTROL
NO BIWEEK FORCING EXP
w (m day⁻1) Temp (°C)
OCT
NOV

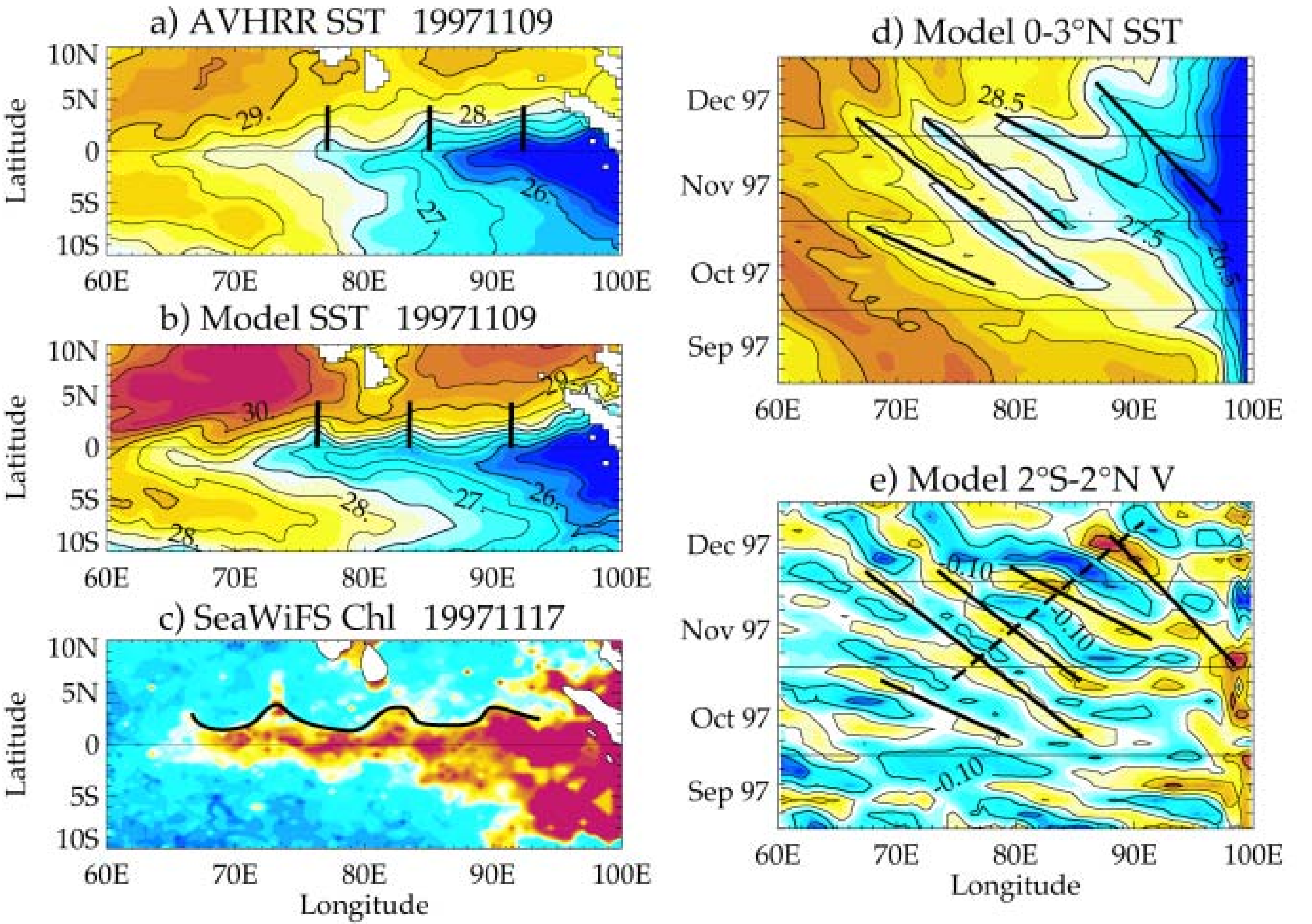


Chavez et al., 1999

CONCLUSIONS

- **Accurate winds give good model currents – currents are deterministic away from the western boundary.**
- **Observed currents have distinct biweekly variability. The model simulates this, but not the 30-60 day v variability.**
- **The biweekly mode is a westward propagating Yanai wave with ~14 day period and 3000-4500 km wavelength, resonantly forced by the atmospheric quasi-biweekly mode.**
- **The biweekly wave is associated with intermittent, off-equator upwelling/downwelling (1-8 metres per day) throughout the year.**
- **Upwelling followed by mixing is an irreversible process. The biweekly mode might influence subsurface temperature and biology.**

Subseasonal variability might influence seasonal and longer time scale changes in Indian Ocean currents, SST and Climate


a) AVHRR SST 19971109
b) Model SST 19971109
c) SeaWiFS Chl 19971117
d) Model 0-3°N SST
e) Model 2°S-2°N V
Latitude
Longitude
10N
5N
0
5S
10S
60E
70E
80E
90E
100E
29.
28.
27.
26.
30.
28.5
27.5
26.5
-0.10
Dec 97
Nov 97
Oct 97
Sep 97

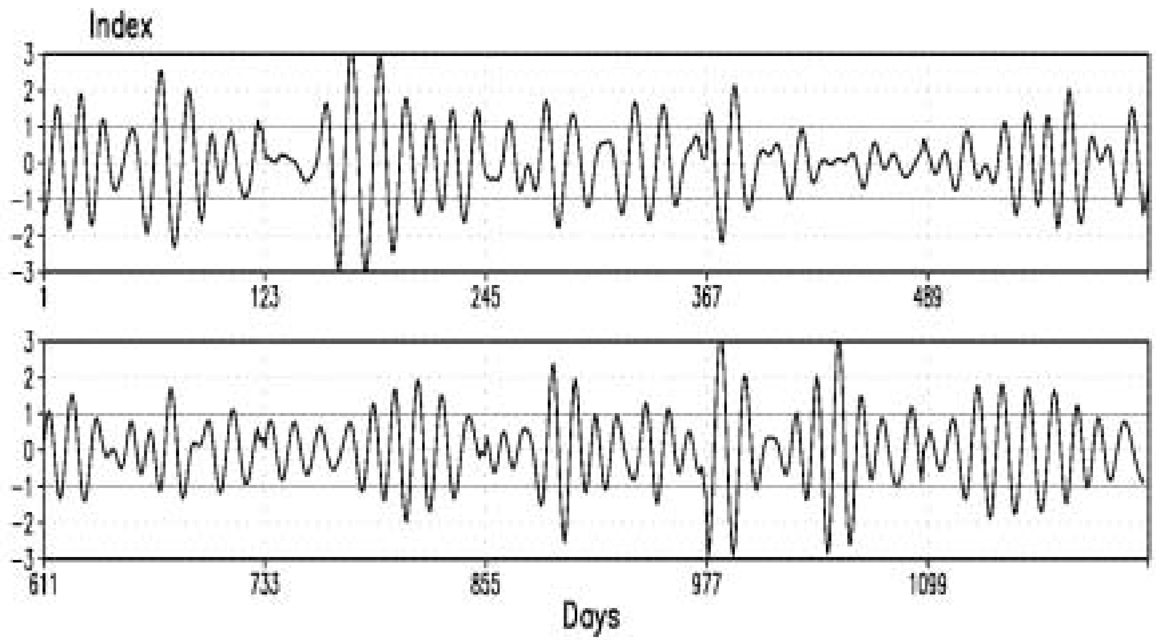
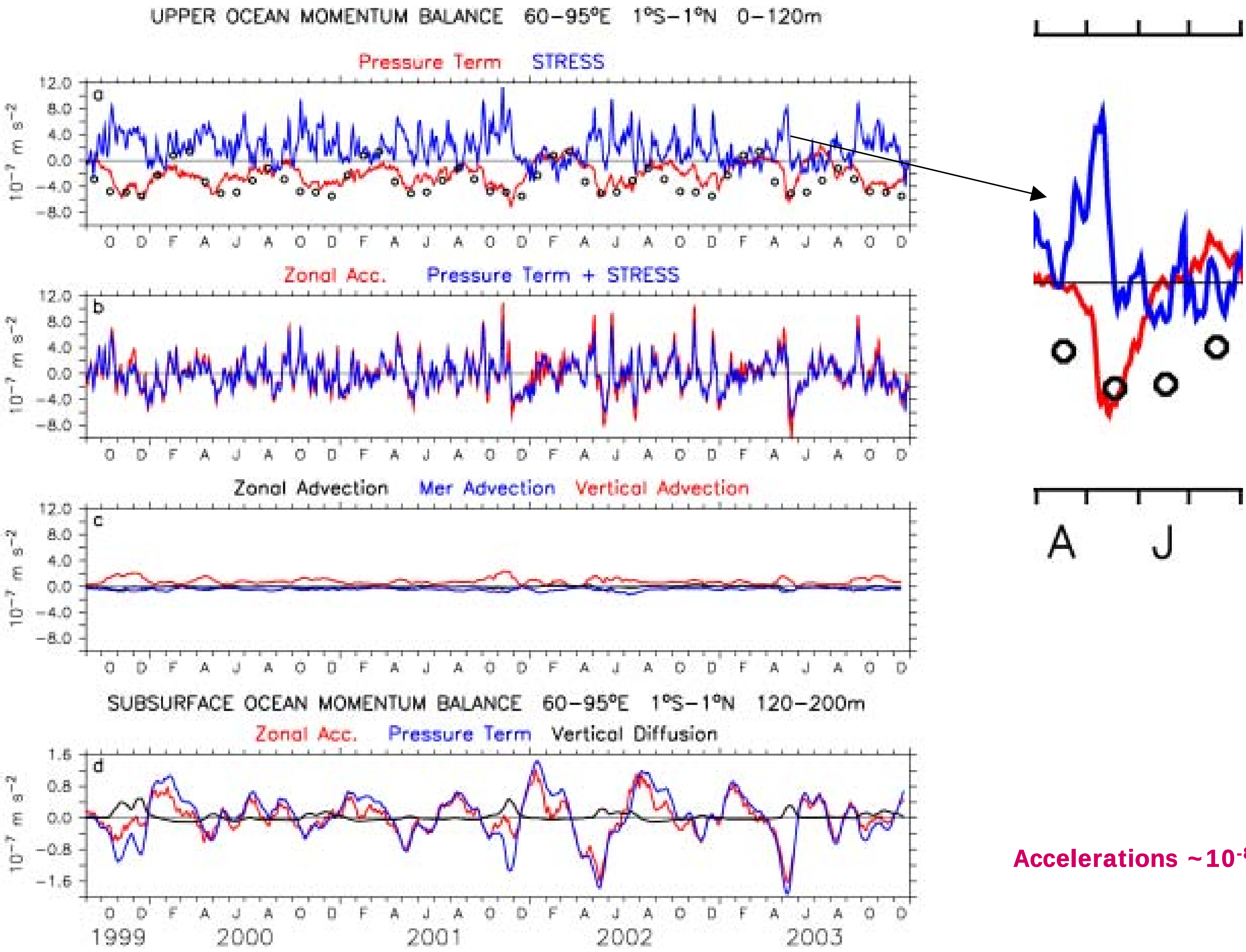
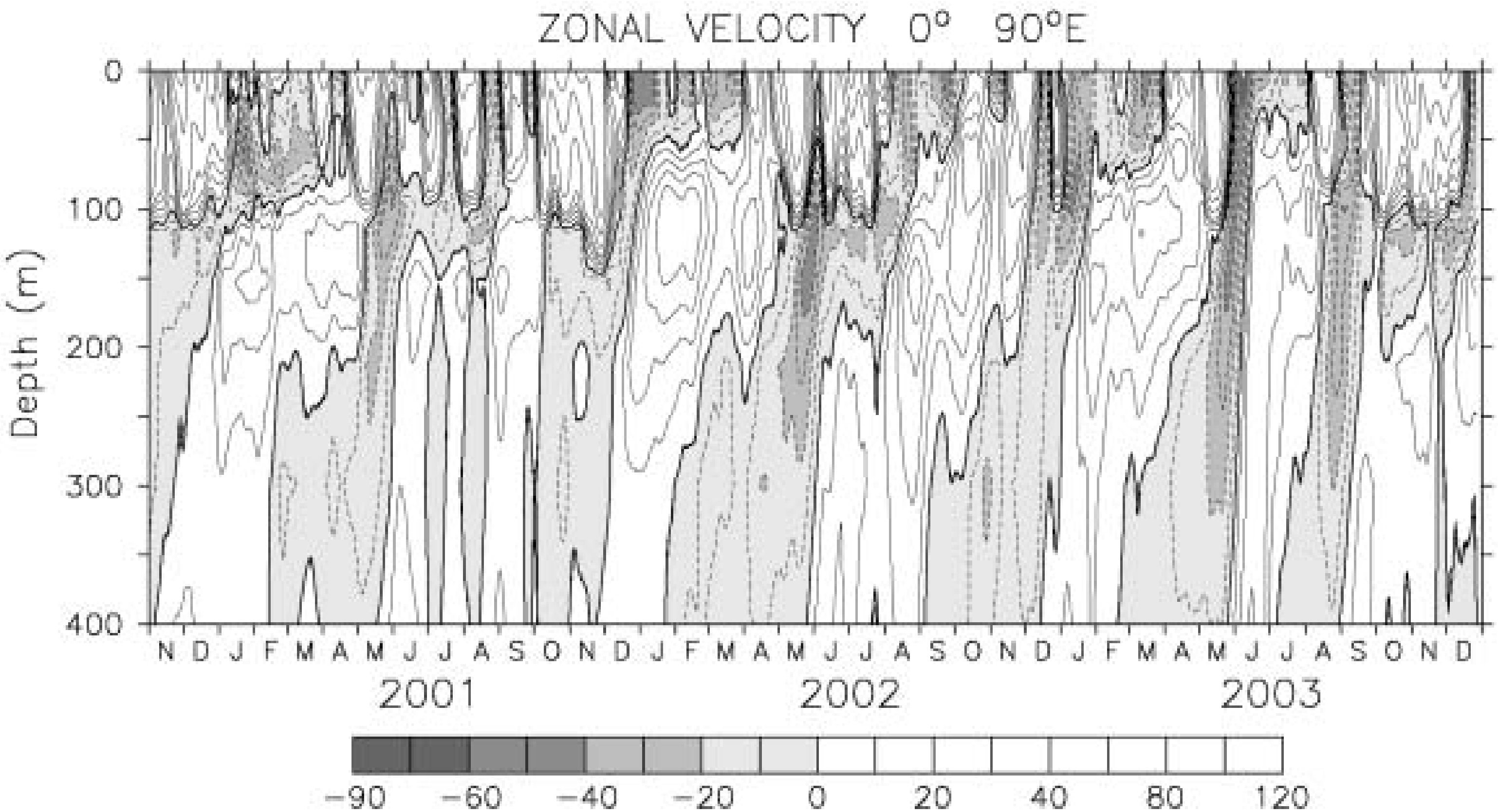


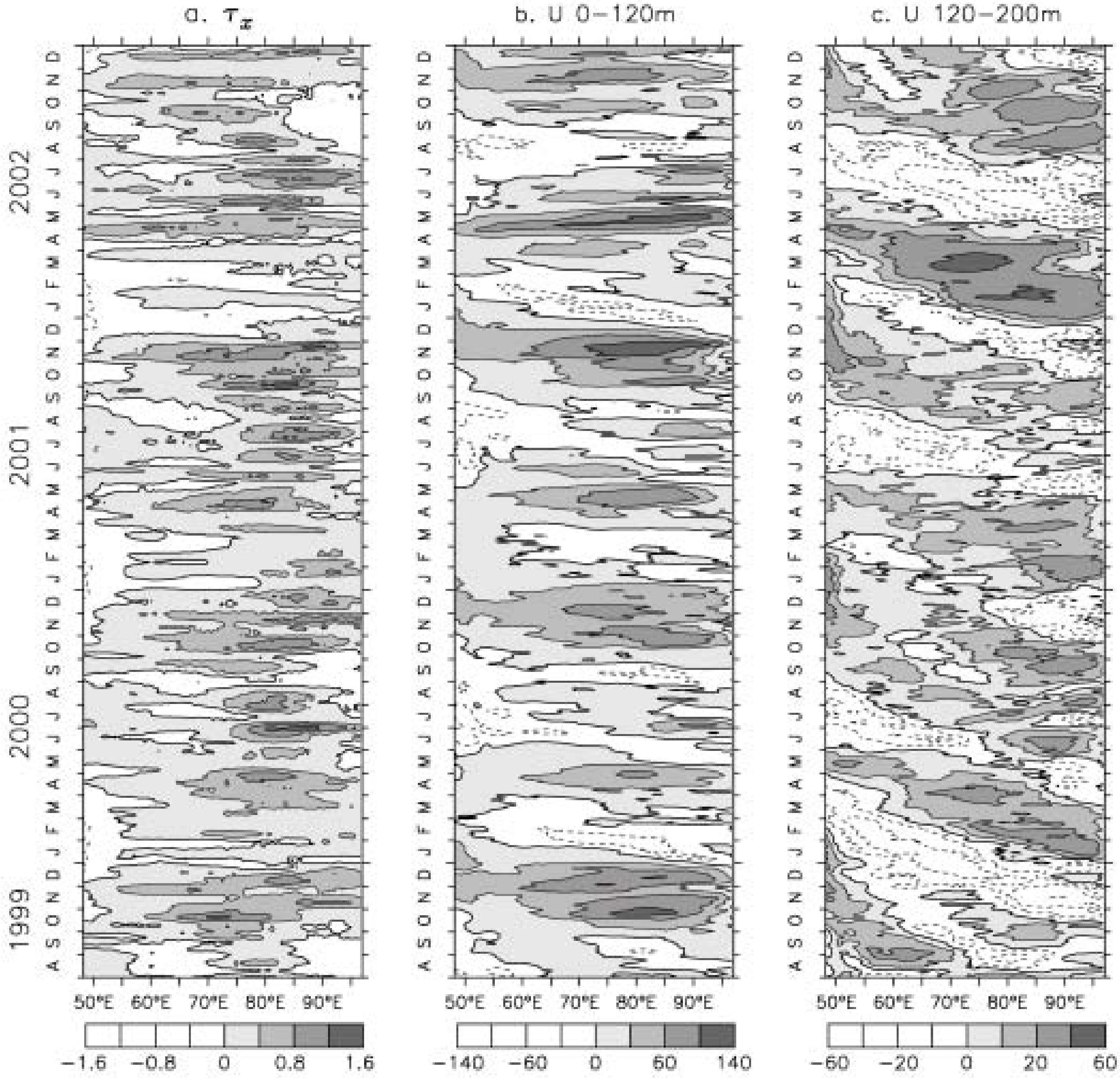
Figure 2: QBM index derived from the first two PC's of combined EOF of 10-20 day filtered zonal and meridional winds at 850 hPa and OLR for 10 years normalized by its own standard deviation.



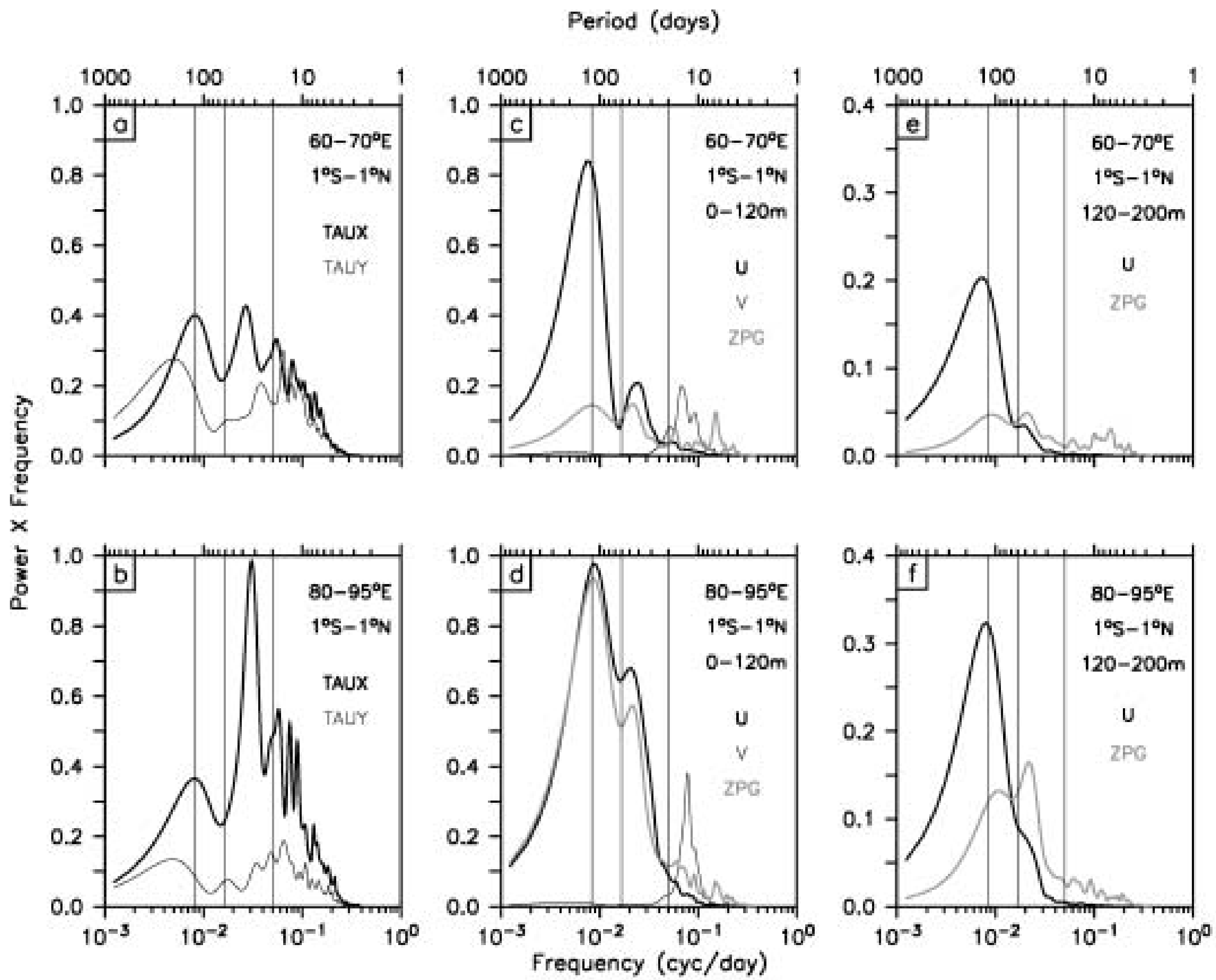
Accelerations ~10^{-8} g

u variability: Eq. Jets + Rossby & Kelvin waves from boundaries

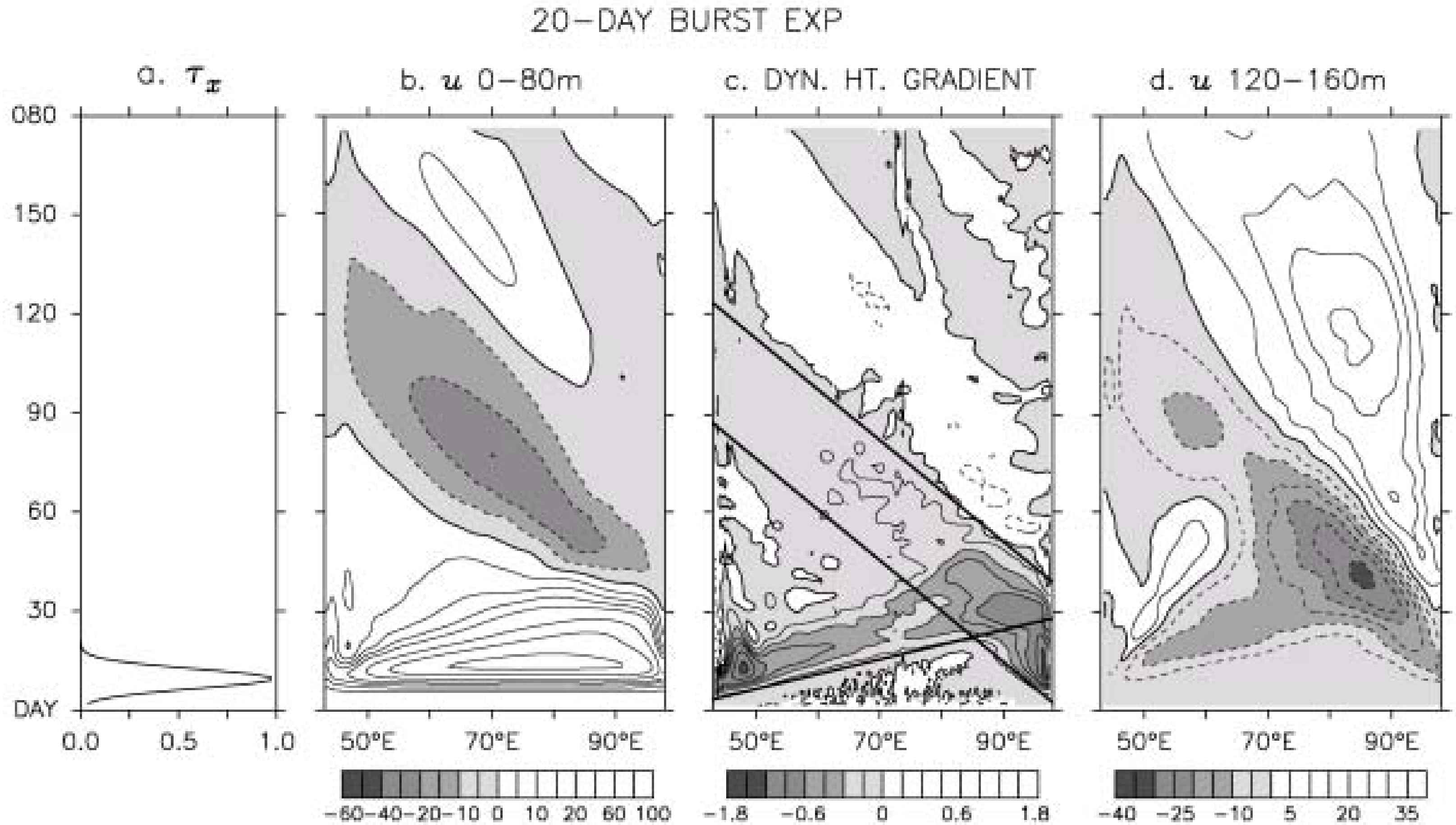

ZONAL VELOCITY 0° 90°E
Depth (m)
0
100
200
300
400
N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
2001
2002
2003
−90 −60 −40 −20 0 20 40 80 120



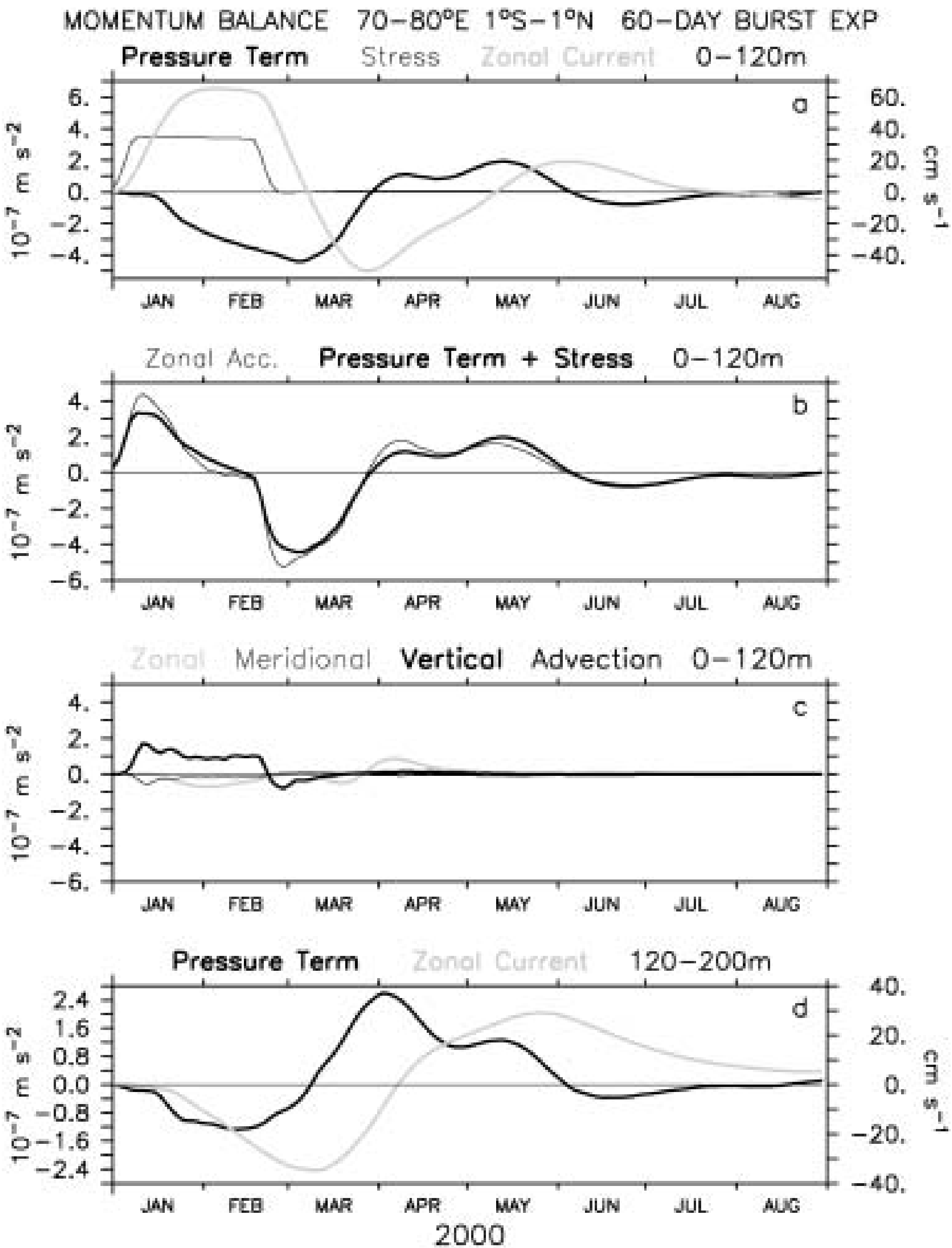
a. τ_x
b. U 0–120m
c. U 120–200m
1999
2000
2001
2002
A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
50°E 60°E 70°E 80°E 90°E
−1.6 −0.8 0 0.8 1.6
−140 −60 0 60 140
−60 −20 0 20 60



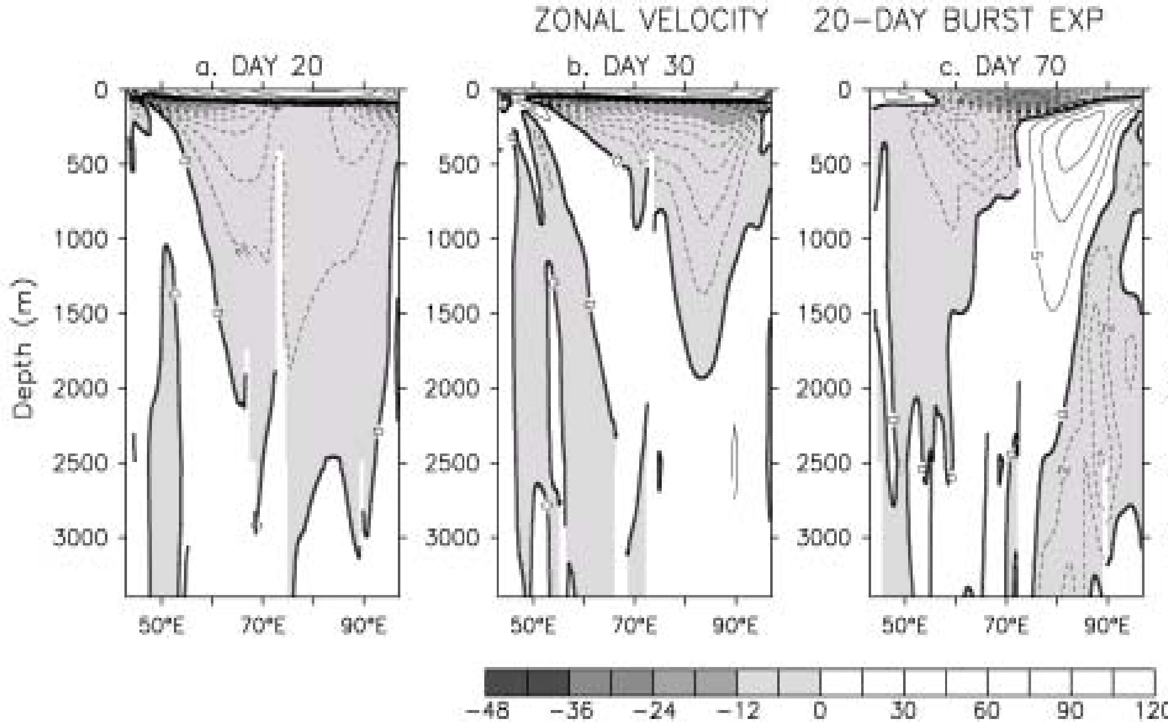
Period (days)
Power X Frequency
Frequency (cyc/day)
a
60–70°E
1°S–1°N
TAUX
TAUY
b
80–95°E
1°S–1°N
TAUX
TAUY
c
60–70°E
1°S–1°N
0–120m
U
V
ZPG
d
80–95°E
1°S–1°N
0–120m
U
V
ZPG
e
60–70°E
1°S–1°N
120–200m
U
ZPG
f
80–95°E
1°S–1°N
120–200m
U
ZPG



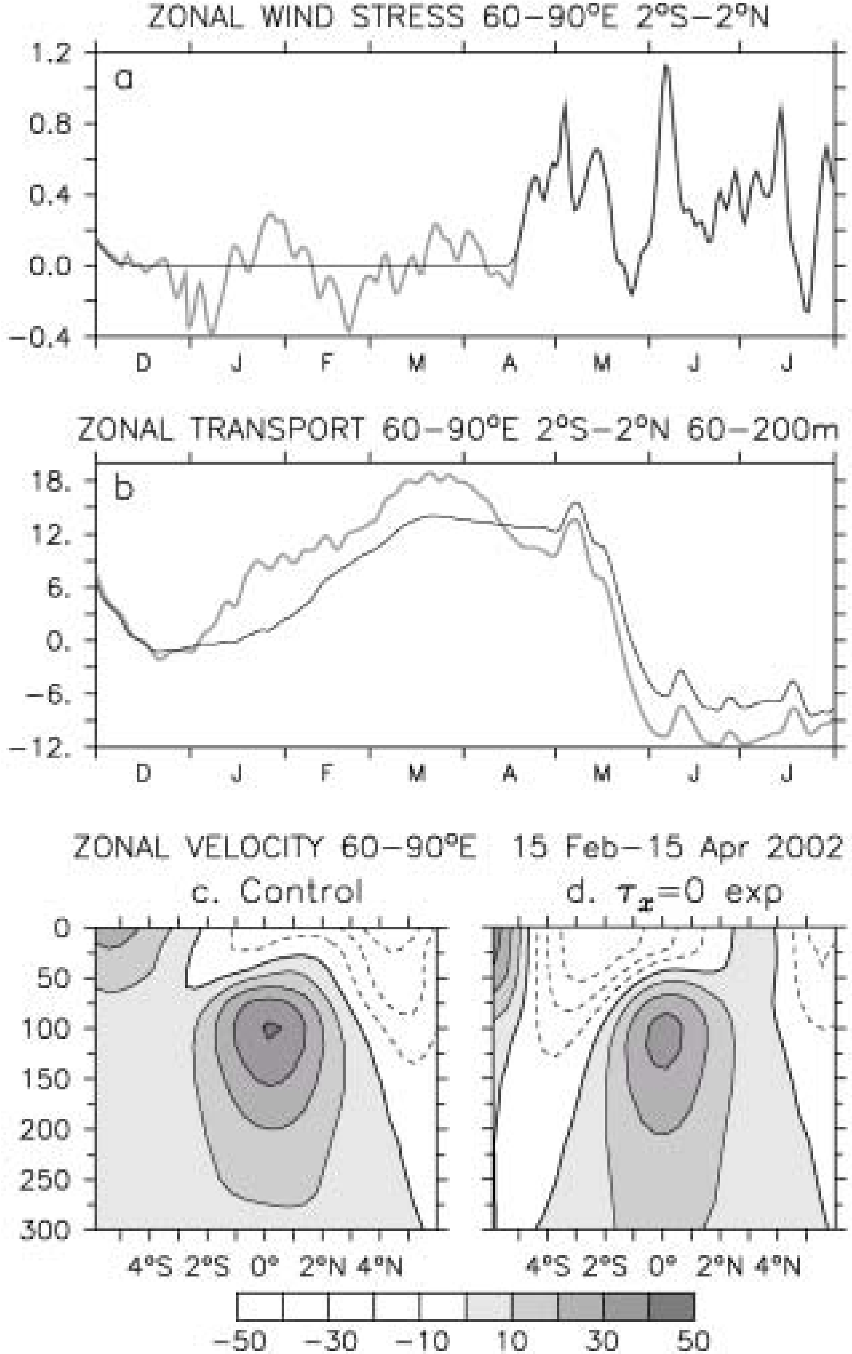
20-DAY BURST EXP
a. τ_x
b. u 0-80m
c. DYN. HT. GRADIENT
d. u 120-160m
080
150
120
90
60
30
DAY
0.0 0.5 1.0
50°E 70°E 90°E
-60 -40 -20 -10 0 10 20 60 100
-1.8 -0.6 0 0.6 1.8
-40 -25 -10 5 20 35



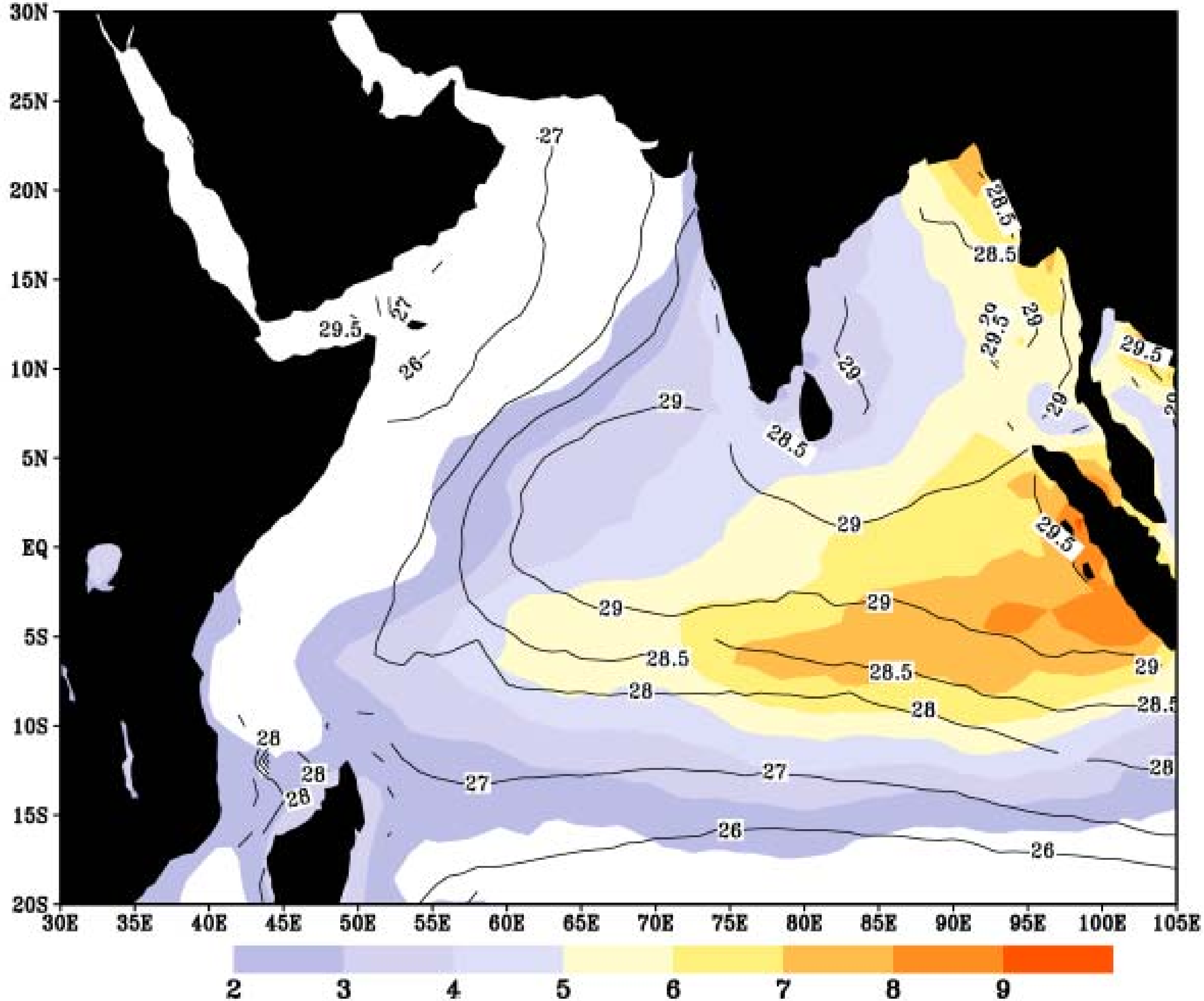
MOMENTUM BALANCE 70-80°E 1°S-1°N 60-DAY BURST EXP
Pressure Term Stress Zonal Current 0-120m
a
6. 4. 2. 0. -2. -4.
60. 40. 20. 0. -20. -40.
10^{-7} m s^{-2}
cm s^{-1}
JAN FEB MAR APR MAY JUN JUL AUG
Zonal Acc. Pressure Term + Stress 0-120m
b
4. 2. 0. -2. -4. -6.
10^{-7} m s^{-2}
JAN FEB MAR APR MAY JUN JUL AUG
Zonal Meridional Vertical Advection 0-120m
c
4. 2. 0. -2. -4. -6.
10^{-7} m s^{-2}
JAN FEB MAR APR MAY JUN JUL AUG
Pressure Term Zonal Current 120-200m
d
2.4 1.6 0.8 0.0 -0.8 -1.6 -2.4
40. 20. 0. -20. -40.
10^{-7} m s^{-2}
cm s^{-1}
JAN FEB MAR APR MAY JUN JUL AUG
2000



ZONAL VELOCITY 20-DAY BURST EXP
a. DAY 20
b. DAY 30
c. DAY 70
d. DAY 110
Depth (m)
0
500
1000
1500
2000
2500
3000
50°E
70°E
90°E
-48
-36
-24
-12
0
30
60
90
120

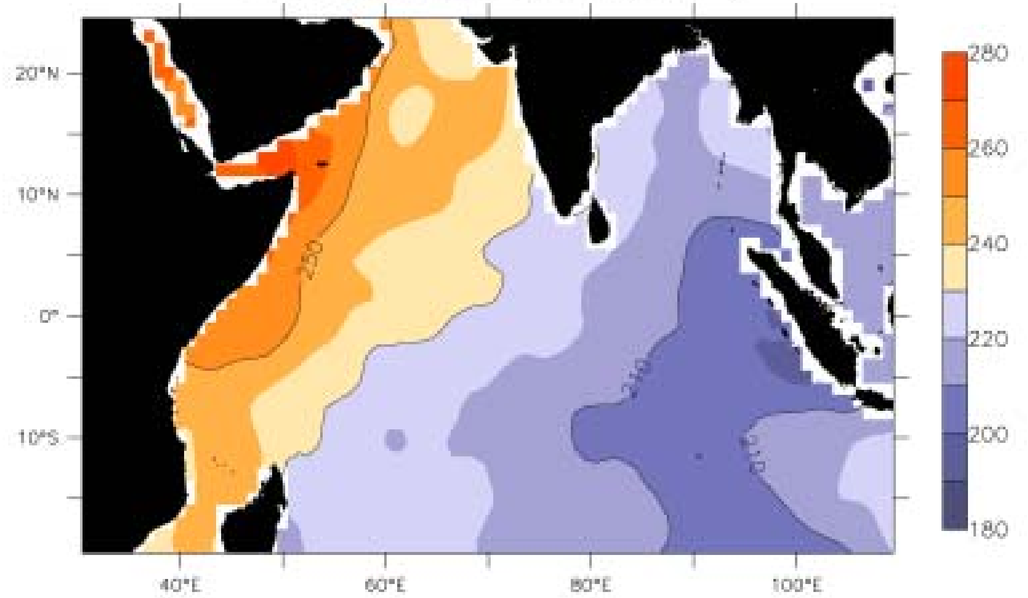

ZONAL WIND STRESS 60–90°E 2°S–2°N
a
ZONAL TRANSPORT 60–90°E 2°S–2°N 60–200m
b
ZONAL VELOCITY 60–90°E 15 Feb–15 Apr 2002
c. Control
d. τ_x=0 exp
D J F M A M J J
4°S 2°S 0° 2°N 4°N
−50 −30 −10 10 30 50

GPCP RAIN ($mm day^{-1}$), TMI SST (°C)

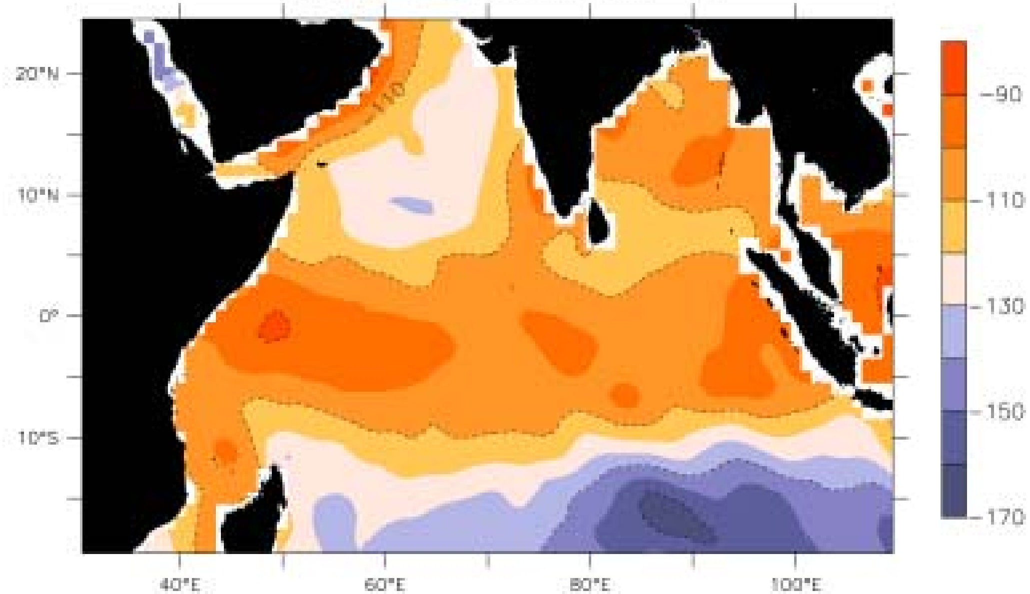


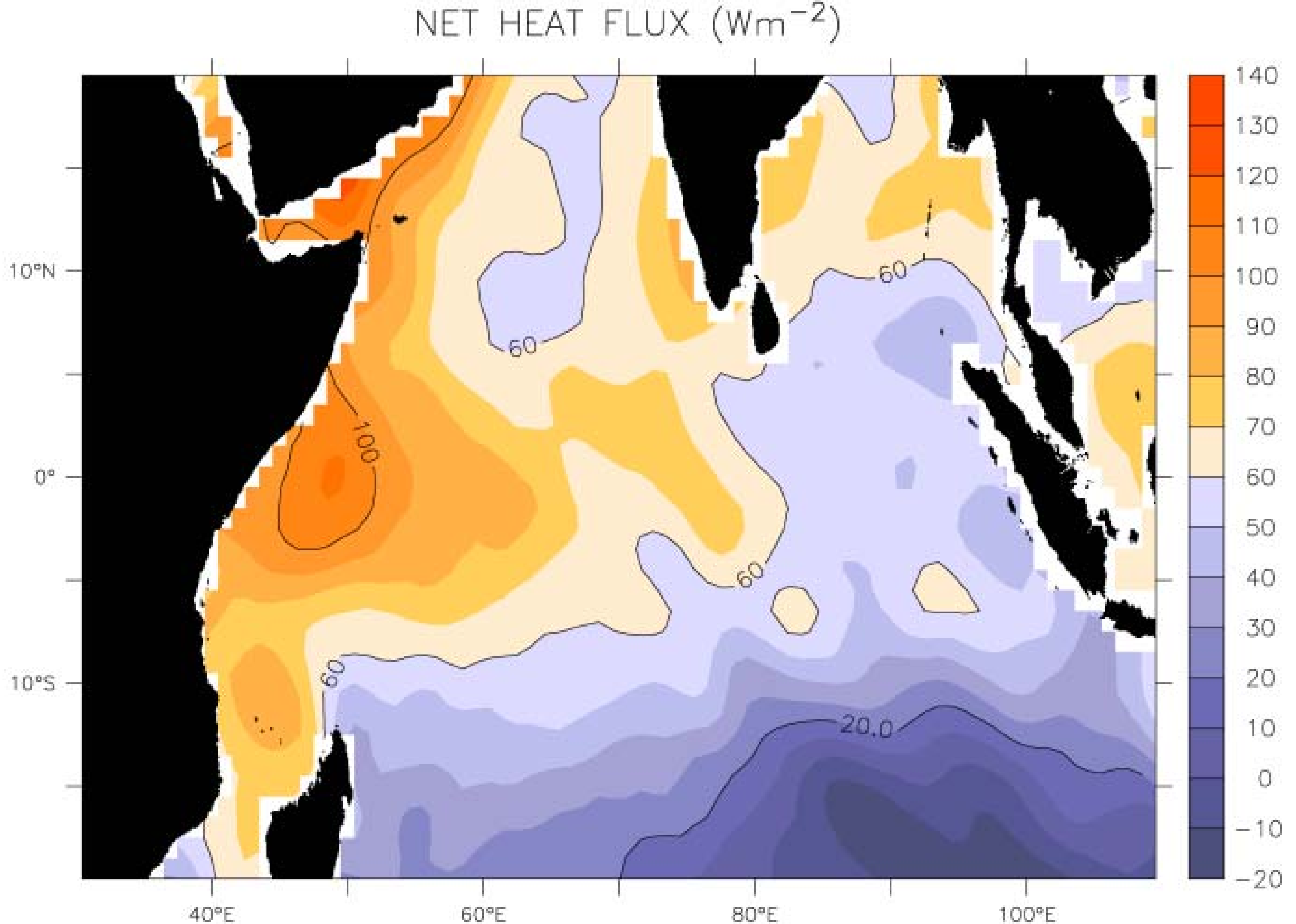
SOC FLUXES

SHORTWAVE RADIATION (Wm^{-2})

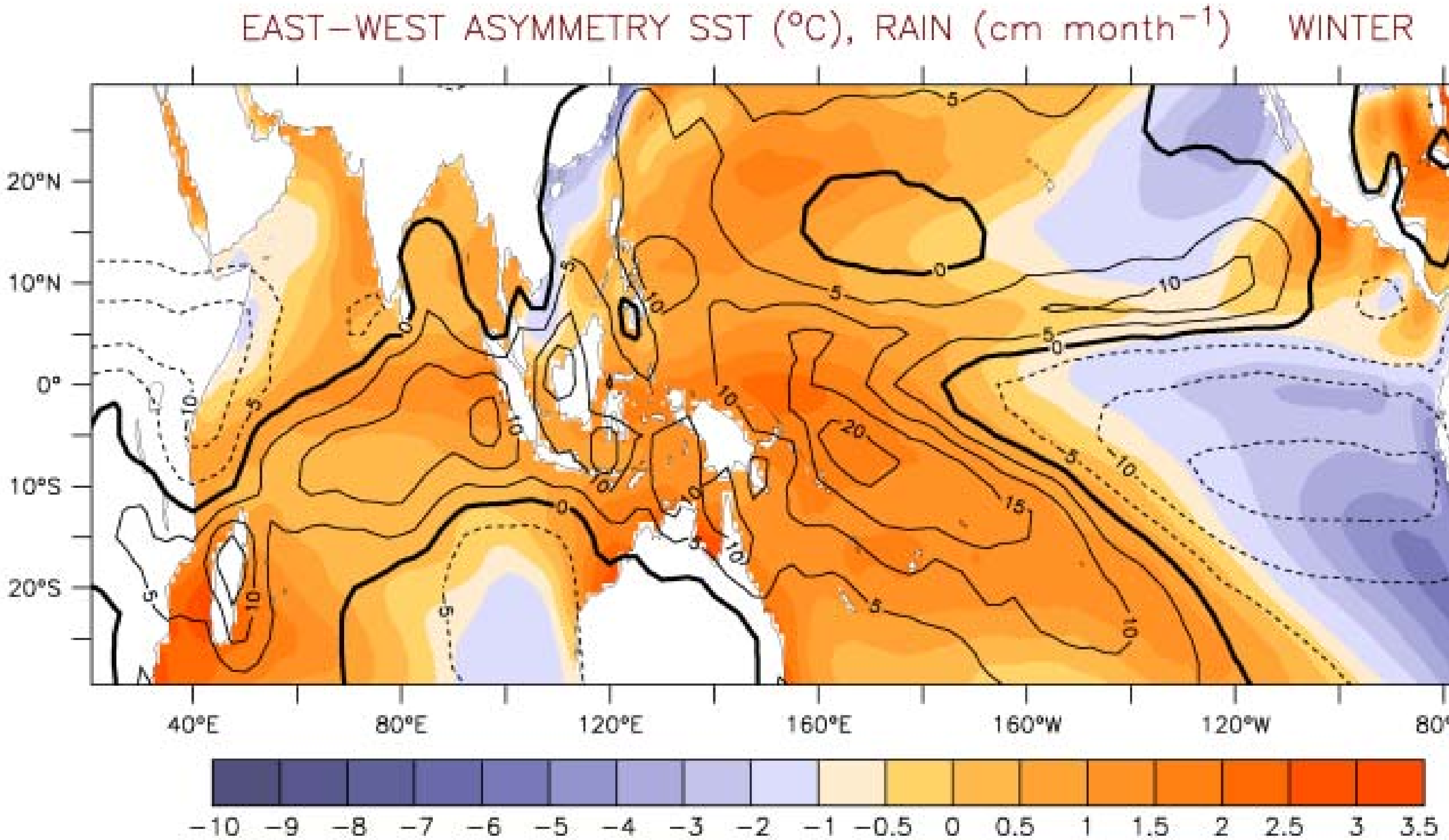


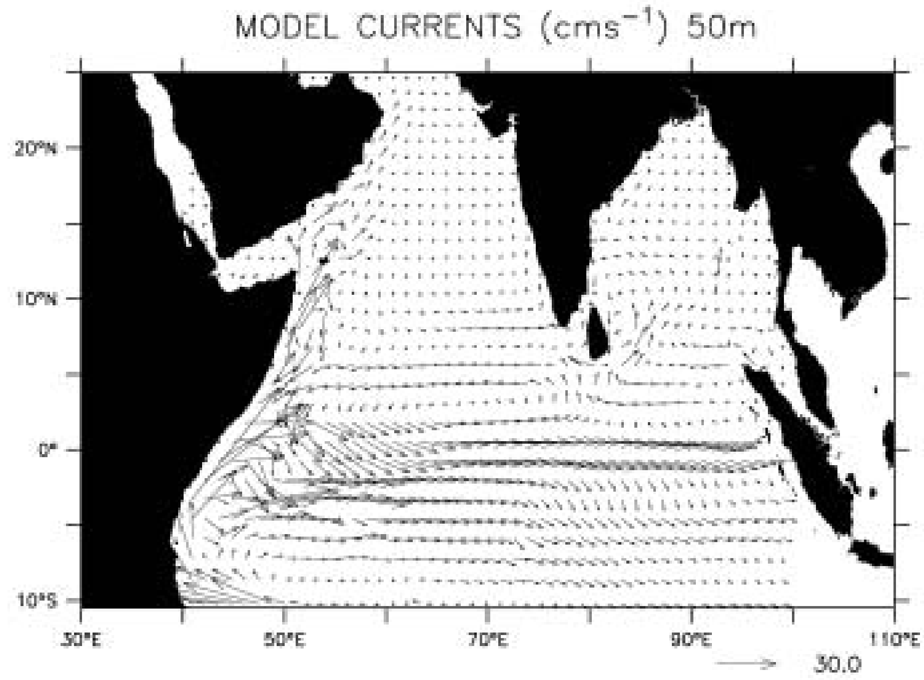
LATENT HEAT FLUX (Wm^{-2})



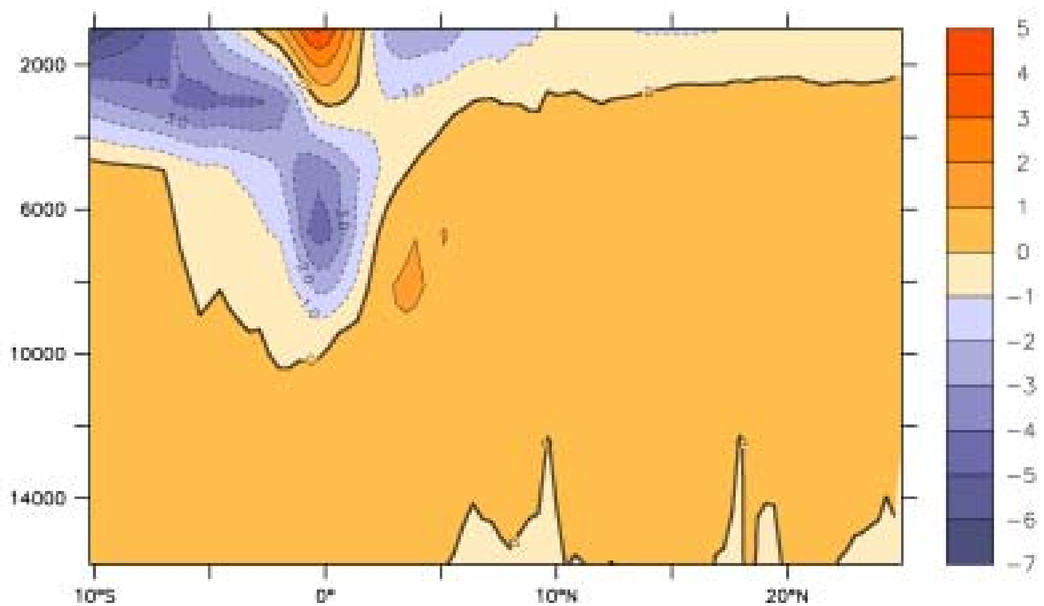


NET HEAT FLUX (Wm^{-2})
10°N
0°
10°S
40°E
60°E
80°E
100°E
60
100
20.0
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20


EAST–WEST ASYMMETRY SST (°C), RAIN (cm month^{-1}) WINTER
20°N
10°N
0°
10°S
20°S
40°E
80°E
120°E
160°E
160°W
120°W
80°W
−10 −9 −8 −7 −6 −5 −4 −3 −2 −1 −0.5 0 0.5 1 1.5 2 2.5 3 3.5



Meridional Current (cm/s)



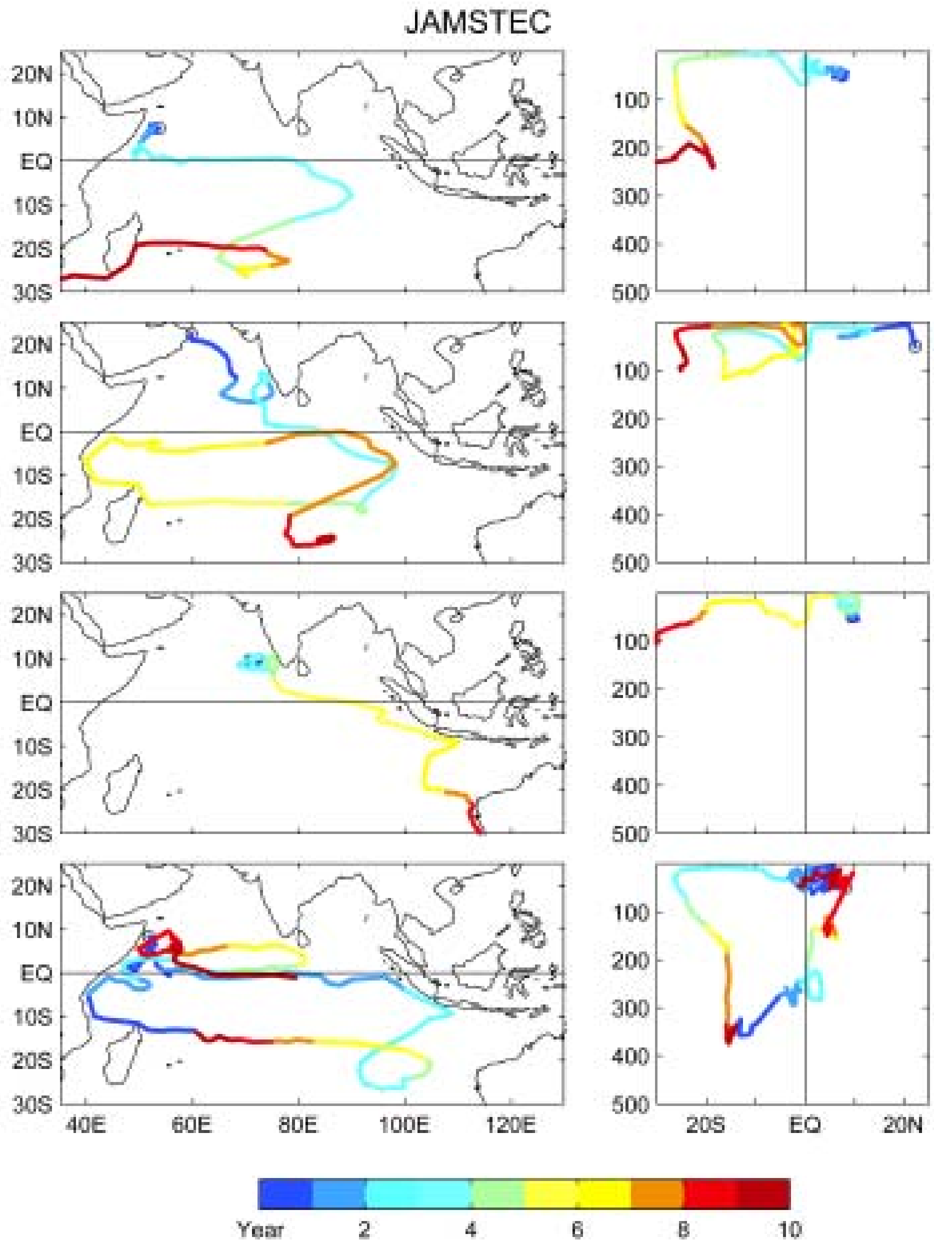
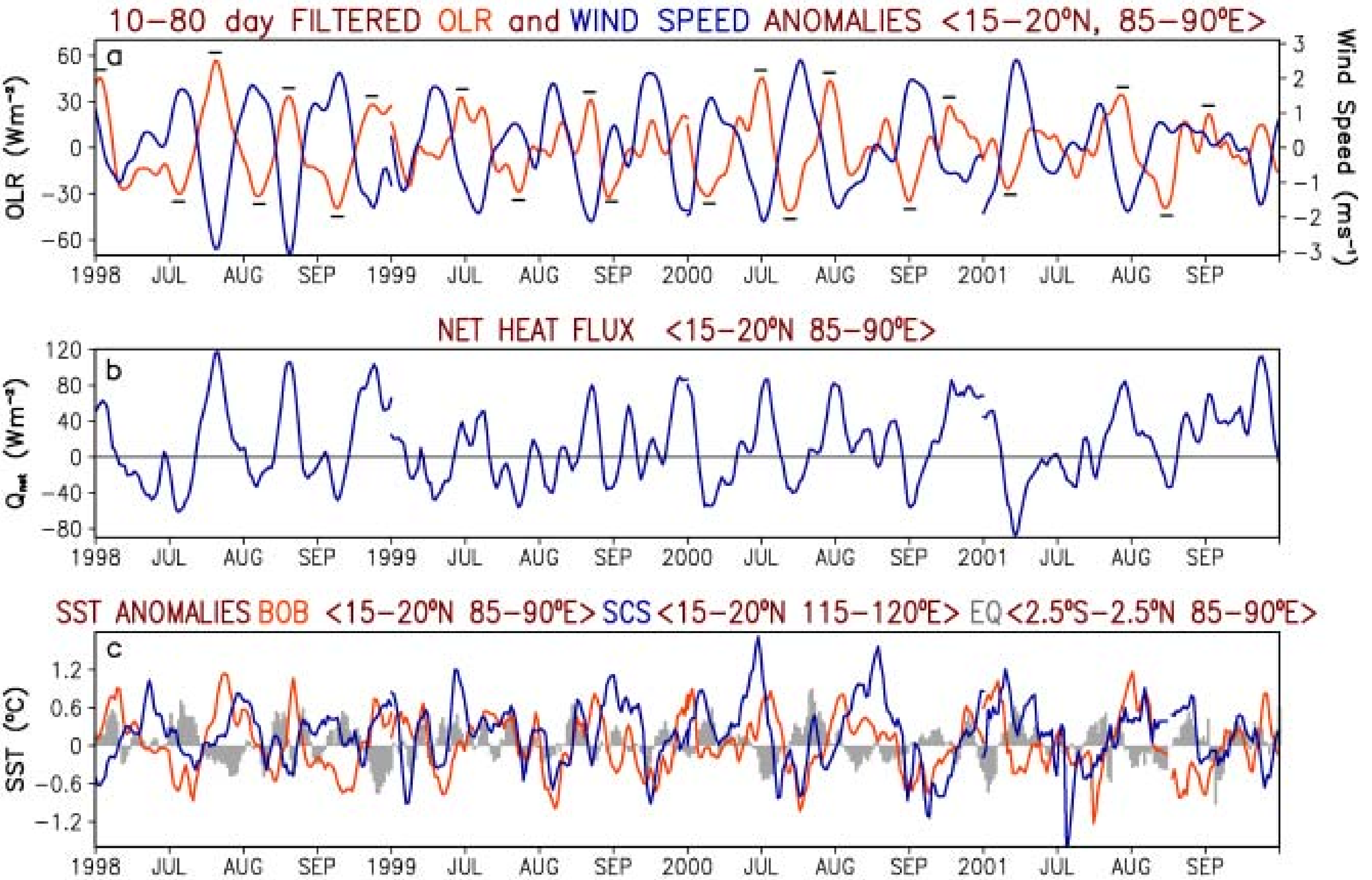
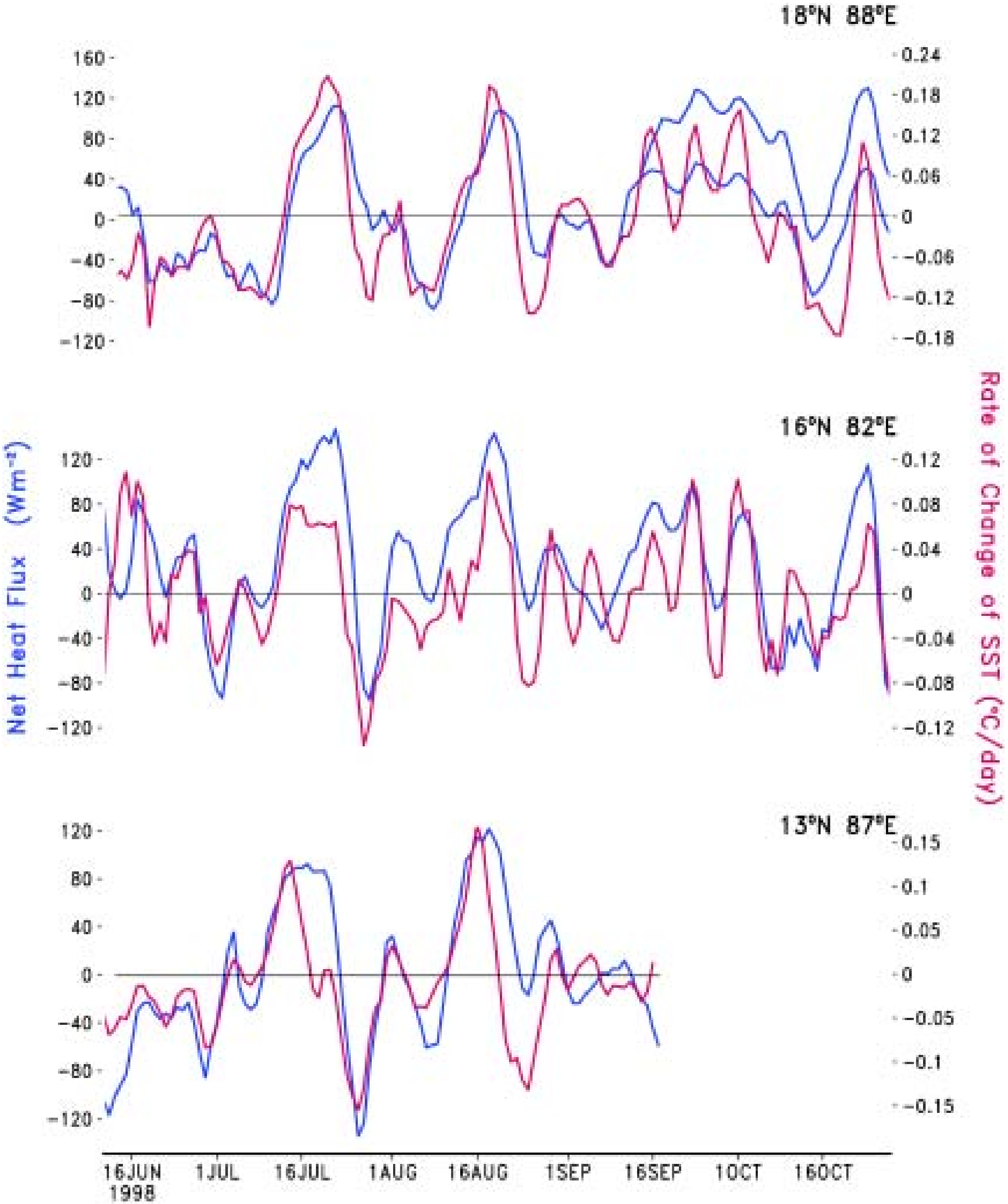


Figure 7: Four drifter trajectories tracked forwards in time using the annual-mean velocity field of the JAMSTEC solution, showing x-y and y-z views in corresponding left and right panels. The trajectories illustrate types of commonly occurring pathways. Color indicates the time in years since the release of the drifter and colors repeat after 10 years.



10-80 day FILTERED OLR and WIND SPEED ANOMALIES <15-20ºN, 85-90ºE>
a
OLR (Wm⁻²)
Wind Speed (ms⁻¹)
60 30 0 -30 -60
3 2 1 0 -1 -2 -3
1998 JUL AUG SEP 1999 JUL AUG SEP 2000 JUL AUG SEP 2001 JUL AUG SEP
NET HEAT FLUX <15-20ºN 85-90ºE>
b
Qnet (Wm⁻²)
120 80 40 0 -40 -80
1998 JUL AUG SEP 1999 JUL AUG SEP 2000 JUL AUG SEP 2001 JUL AUG SEP
SST ANOMALIES BOB <15-20ºN 85-90ºE> SCS <15-20ºN 115-120ºE> EQ <2.5ºS-2.5ºN 85-90ºE>
c
SST (ºC)
1.2 0.6 0 -0.6 -1.2
1998 JUL AUG SEP 1999 JUL AUG SEP 2000 JUL AUG SEP 2001 JUL AUG SEP


18°N 88°E
16°N 82°E
13°N 87°E
Net Heat Flux (Wm⁻²)
Rate of Change of SST (°C/day)
16JUN
1998
1JUL
16JUL
1AUG
16AUG
1SEP
16SEP
1OCT
16OCT

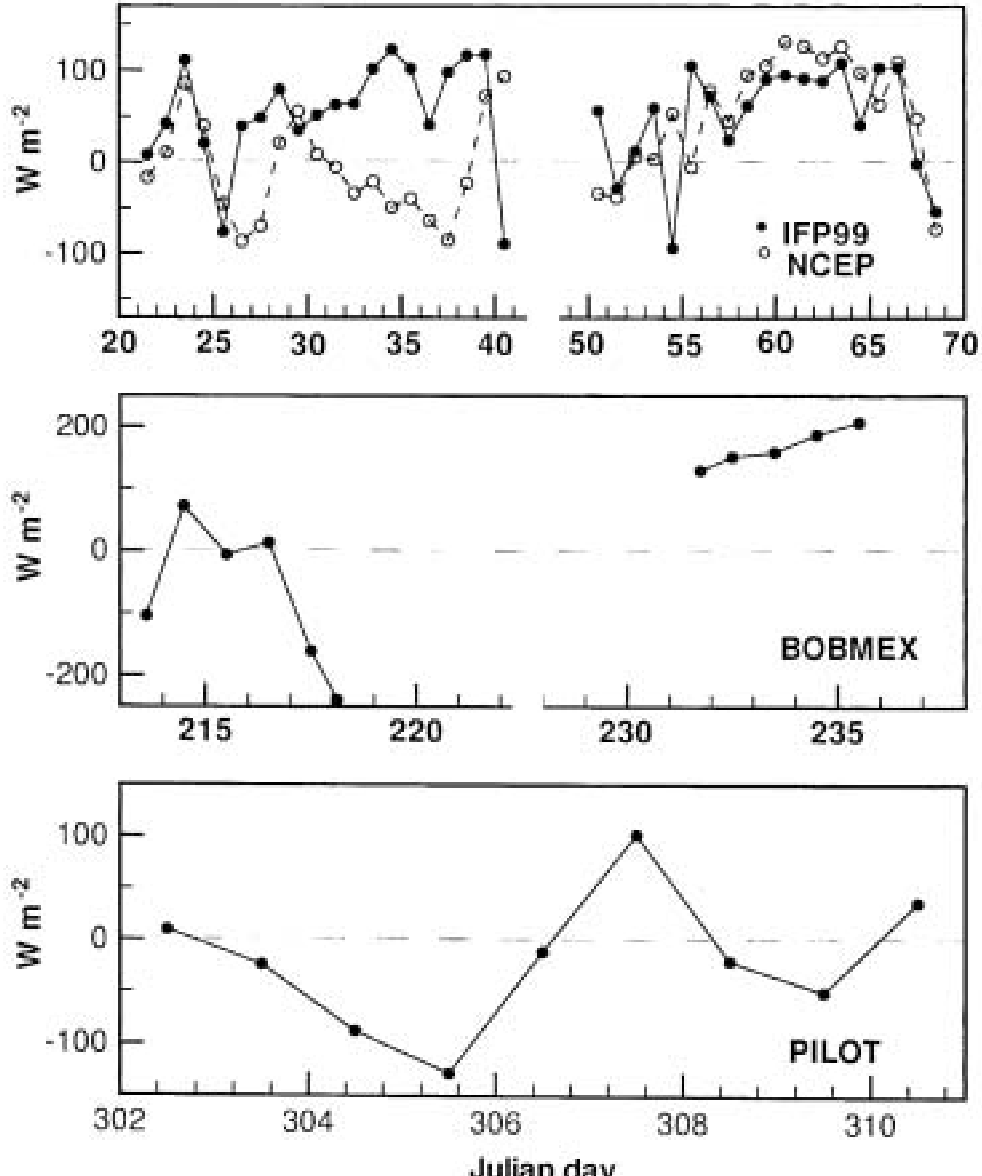
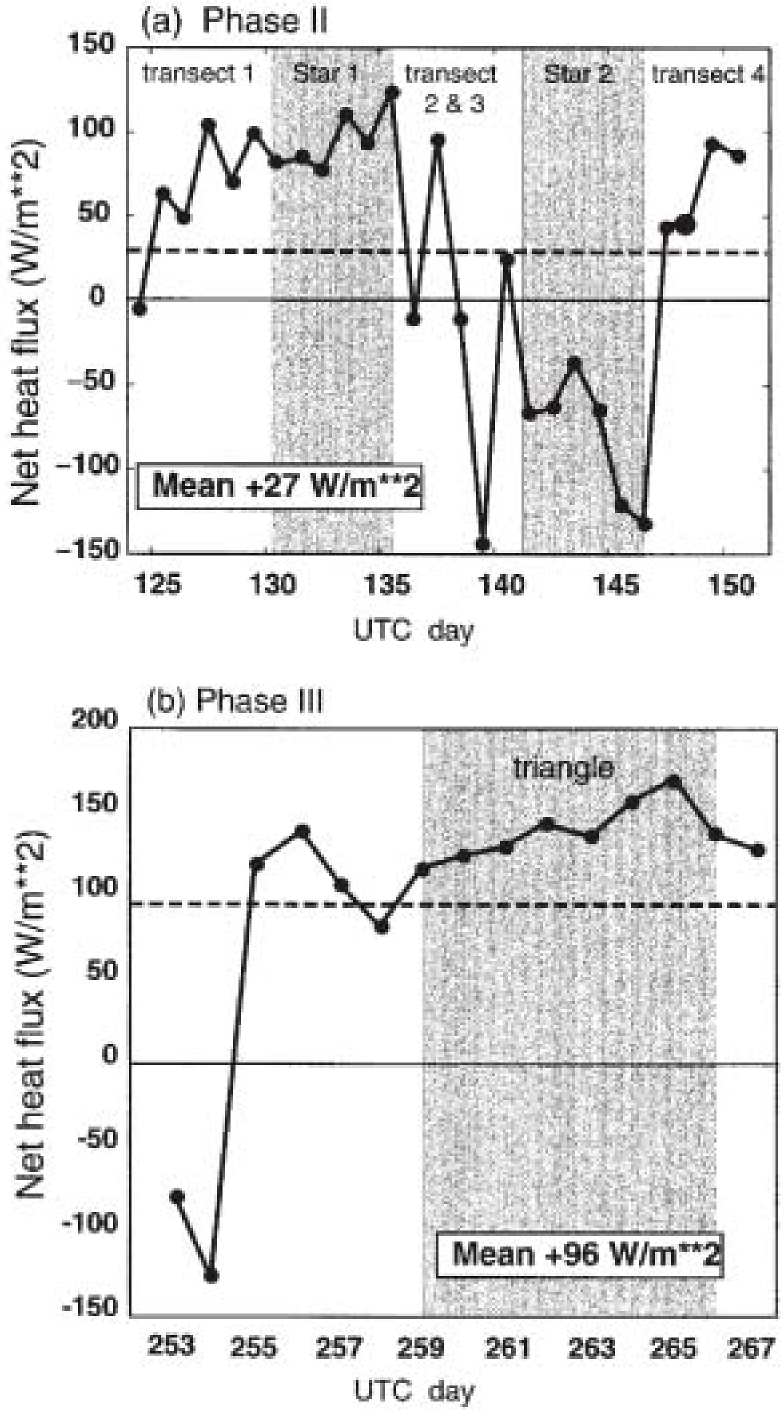
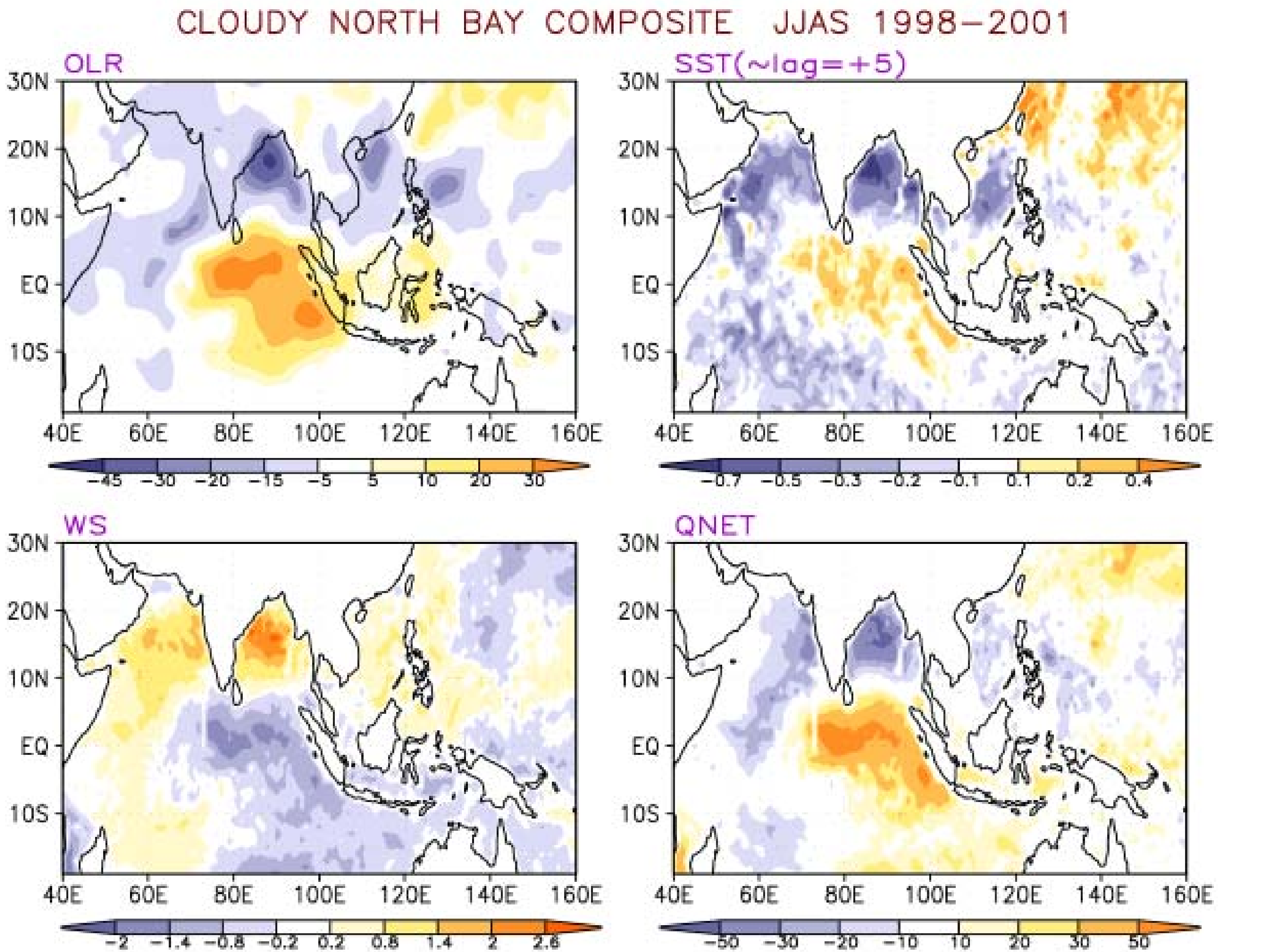
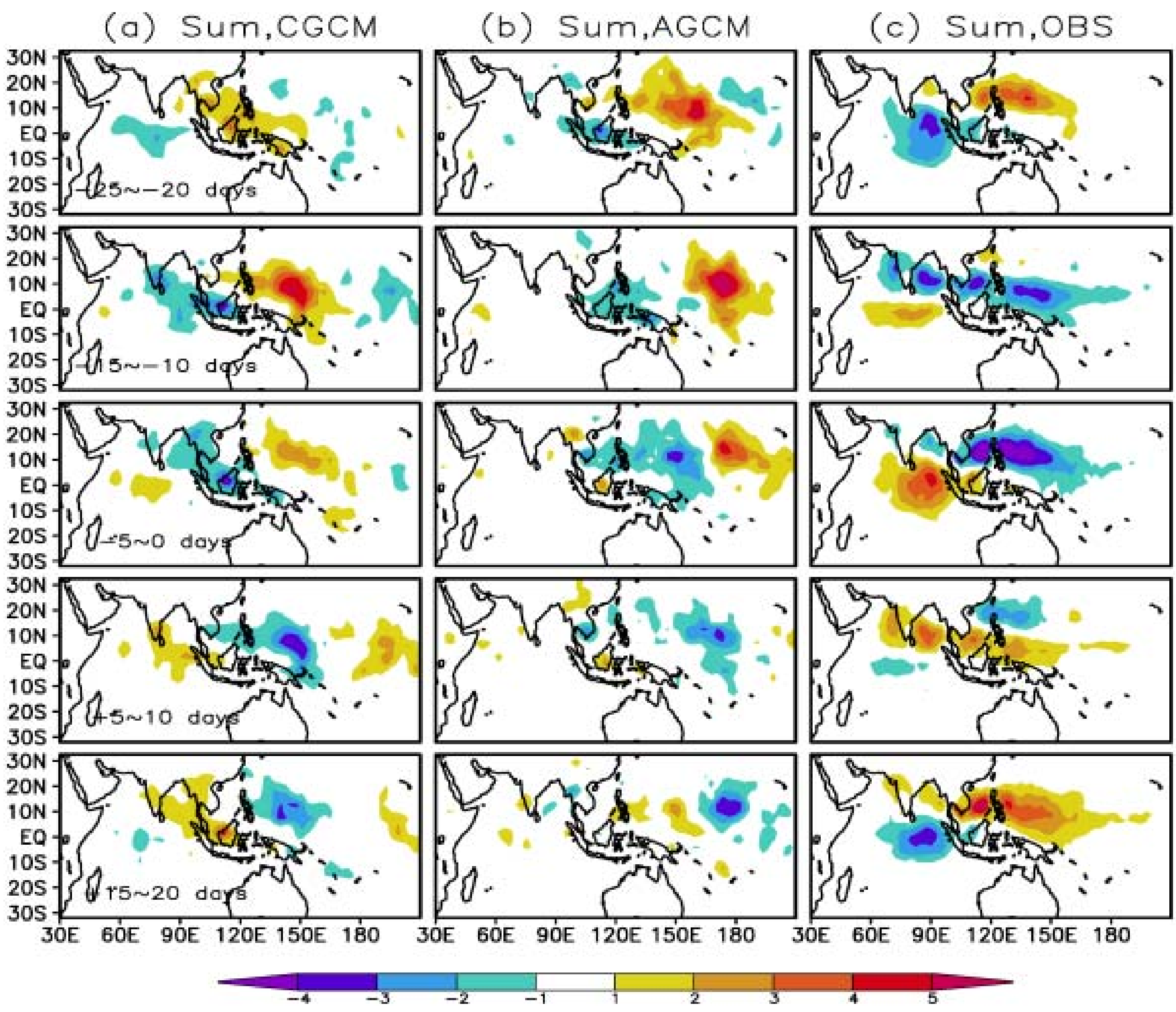


FIG. 3. Variation of daily net heat flux for (top) IFP99, (middle) BOBMEX, and (bottom) PILOT. Also shown in (top) is NCEP reanalysis net heat flux.

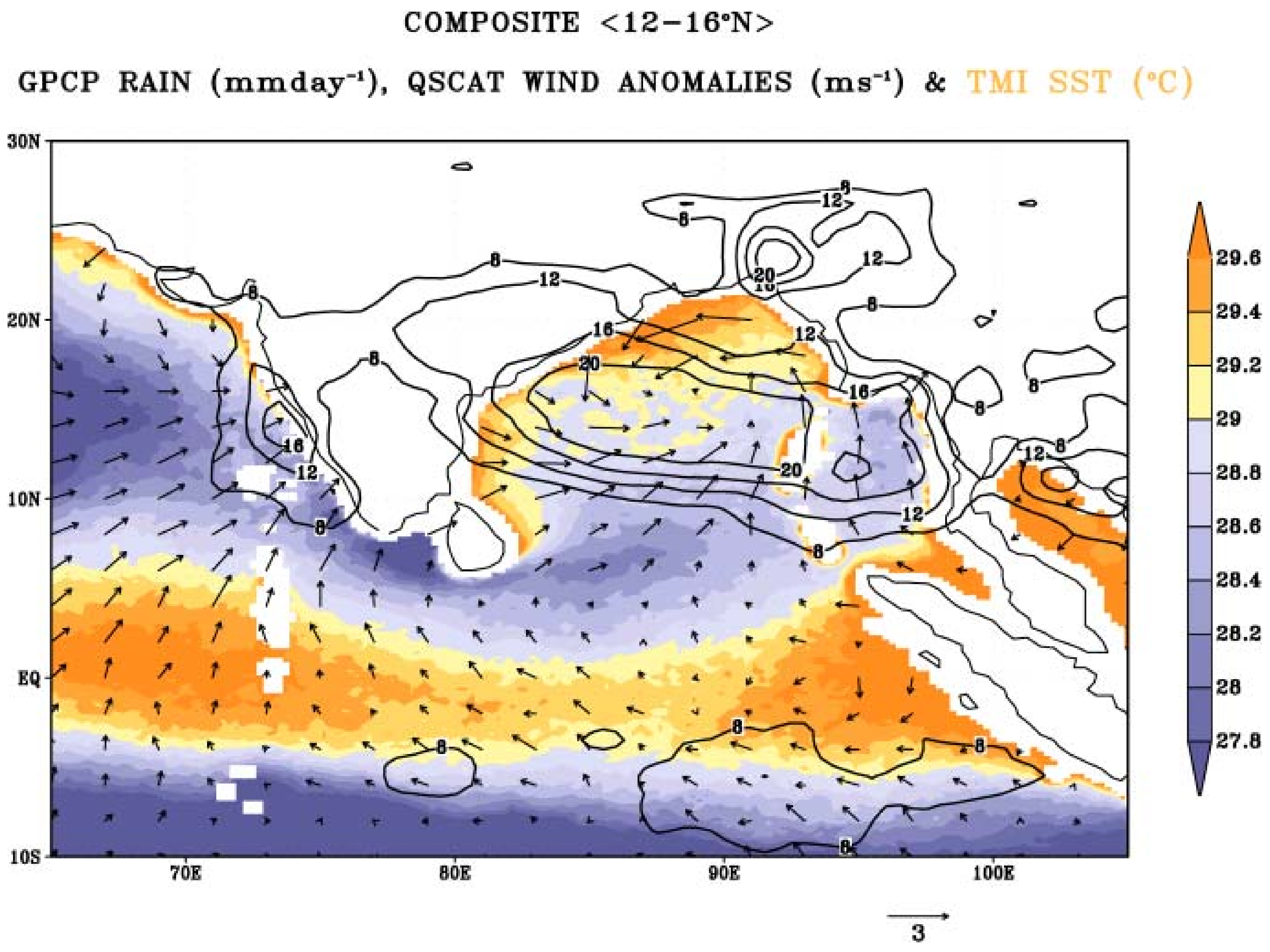
JASMINE


(a) Phase II
transect 1
Star 1
transect 2 & 3
Star 2
transect 4
Net heat flux (W/m**2)
Mean +27 W/m**2
150
100
50
0
-50
-100
-150
125
130
135
140
145
150
UTC day
(b) Phase III
triangle
Net heat flux (W/m**2)
Mean +96 W/m**2
200
150
100
50
0
-50
-100
-150
253
255
257
259
261
263
265
267
UTC day

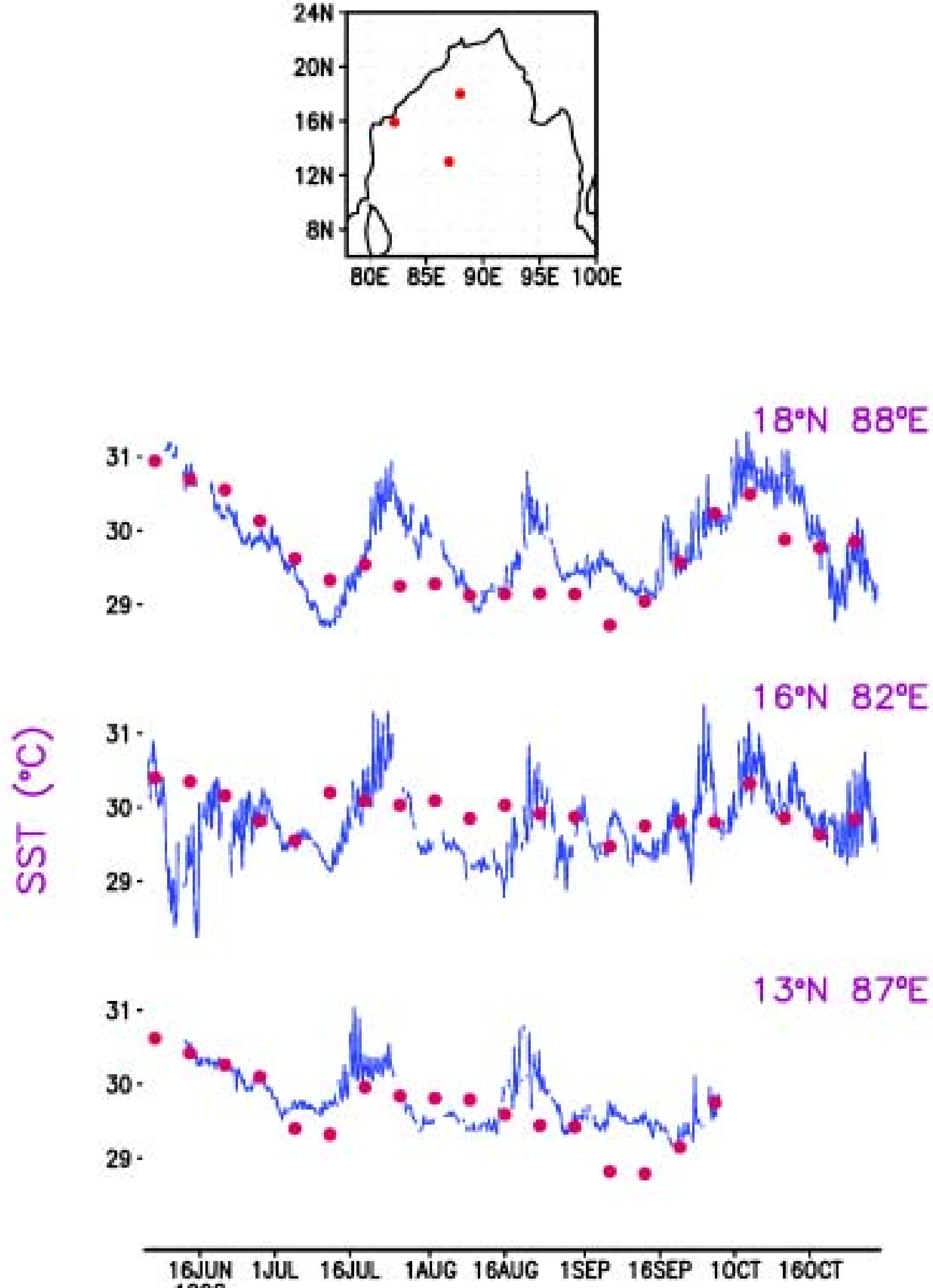

CLOUDY NORTH BAY COMPOSITE JJAS 1998-2001
OLR
SST(~lag=+5)
WS
QNET
30N
20N
10N
EQ
10S
40E
60E
80E
100E
120E
140E
160E
-45 -30 -20 -15 -5 5 10 20 30
-0.7 -0.5 -0.3 -0.2 -0.1 0.1 0.2 0.4
-2 -1.4 -0.8 -0.2 0.2 0.8 1.4 2 2.6
-50 -30 -20 -10 10 20 30 50

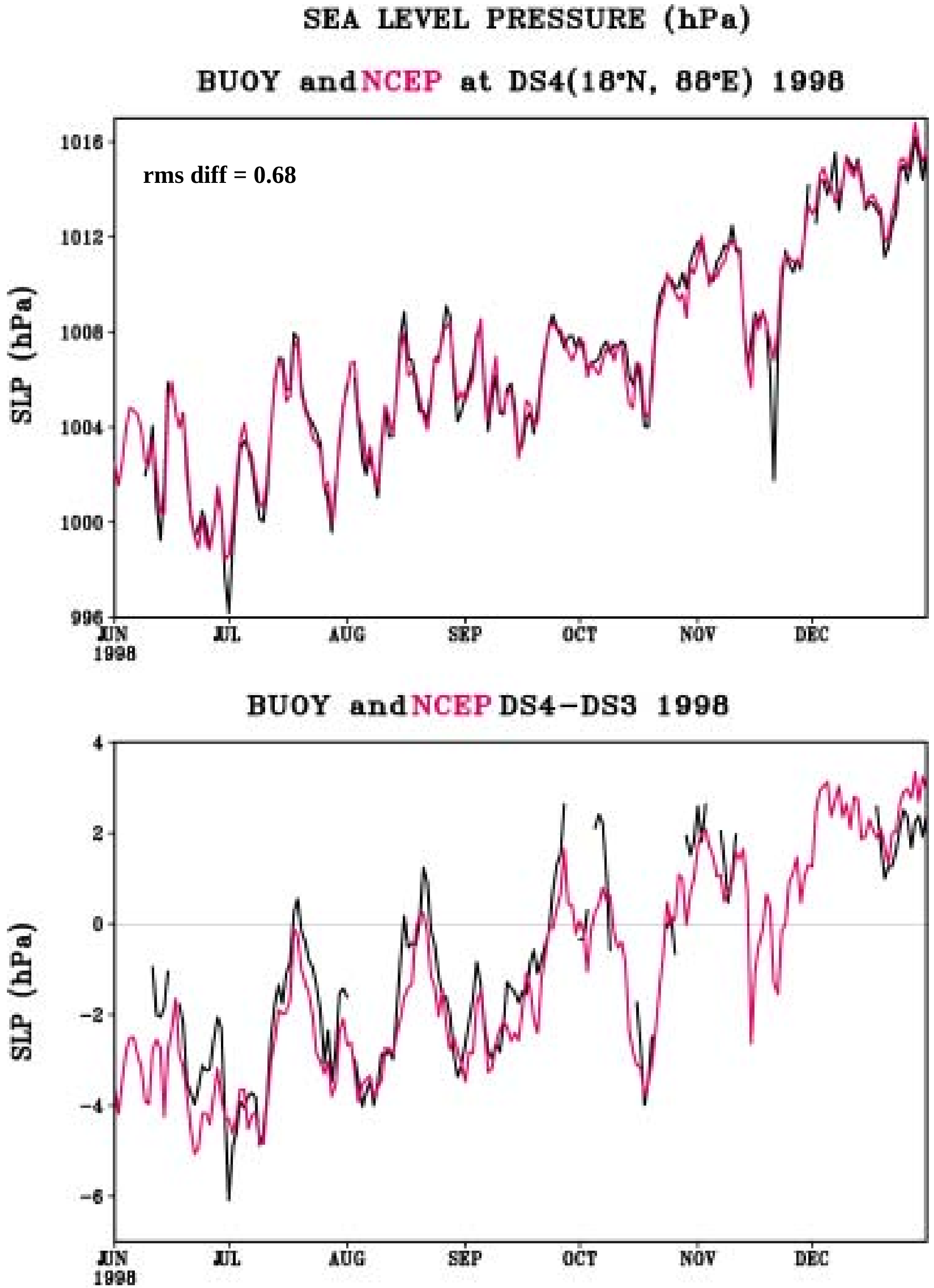


(a) Sum,CGCM
(b) Sum,AGCM
(c) Sum,OBS
−25~−20 days
−15~−10 days
−5~0 days
+5~10 days
+15~20 days
30N
20N
10N
EQ
10S
20S
30S
30E
60E
90E
120E
150E
180
−4
−3
−2
−1
1
2
3
4
5



COMPOSITE <12-16°N>
GPCP RAIN (mmday⁻¹), QSCAT WIND ANOMALIES (ms⁻¹) & TMI SST (°C)
30N
20N
10N
EQ
10S
70E
80E
90E
100E
29.6
29.4
29.2
29
28.8
28.6
28.4
28.2
28
27.8
3


24N
20N
16N
12N
8N
80E
85E
90E
95E
100E
18°N 88°E
16°N 82°E
13°N 87°E
SST (°C)
31
30
29
16JUN
1998
1JUL
16JUL
1AUG
16AUG
1SEP
16SEP
1OCT
16OCT



SEA LEVEL PRESSURE (hPa)
BUOY and NCEP at DS4(18°N, 88°E) 1998
rms diff = 0.68
SLP (hPa)
1016
1012
1008
1004
1000
996
JUN 1998
JUL
AUG
SEP
OCT
NOV
DEC
BUOY and NCEP DS4-DS3 1998
SLP (hPa)
4
2
0
-2
-4
-6
JUN 1998
JUL
AUG
SEP
OCT
NOV
DEC

MODEL BASIC EQUATIONS

$$u_t = -\nabla \cdot (u\,\mathbf{u}) + v\left(f + \frac{u \tan\phi}{a}\right) - \left(\frac{1}{a\,\rho_\circ \cdot \cos\phi}\right) p_\lambda + (\kappa_m u_z)_z + F^u$$

$$v_t = -\nabla \cdot (v\,\mathbf{u}) - u\left(f + \frac{u \tan\phi}{a}\right) - \left(\frac{1}{a\,\rho_\circ}\right) p_\phi + (\kappa_m v_z)_z + F^v$$

$$w_z = -\nabla_h \cdot \mathbf{u}_h$$

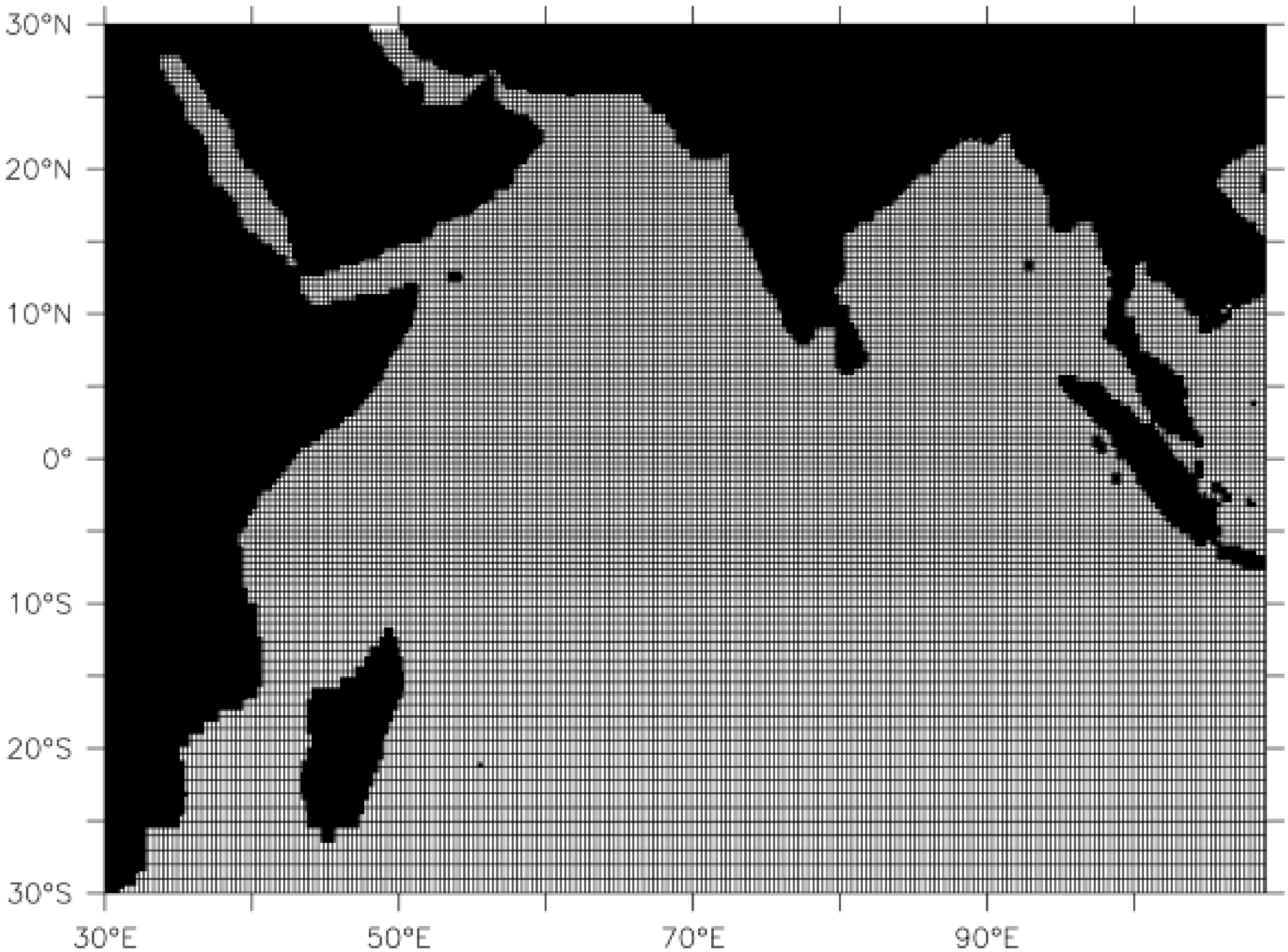
$$p_z = -\rho\, g$$

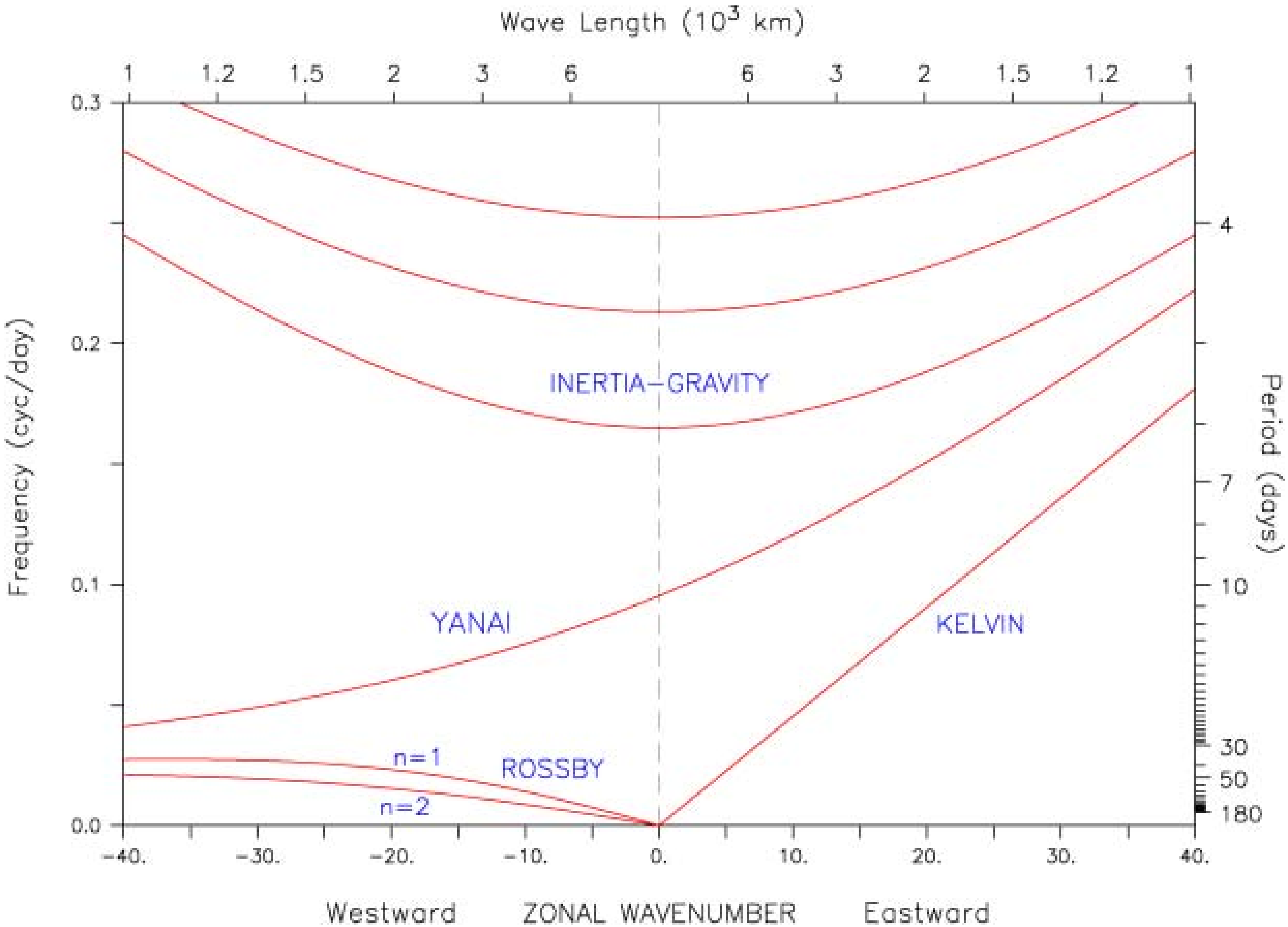
$$\theta_t = -\nabla \cdot [\mathbf{u}\,\theta + \mathbf{F}(\theta)]$$

$$s_t = -\nabla \cdot [\mathbf{u}\,s + \mathbf{F}(s)]$$

$$\rho = \rho(\theta, s, z).$$

MODEL DOMAIN AND GRID




Wave Length (10^3 km)
1
1.2
1.5
2
3
6
6
3
2
1.5
1.2
1
0.3
0.2
0.1
0.0
Frequency (cyc/day)
INERTIA−GRAVITY
YANAI
KELVIN
n=1
ROSSBY
n=2
4
7
10
30
50
180
Period (days)
-40.
-30.
-20.
-10.
0.
10.
20.
30.
40.
Westward
ZONAL WAVENUMBER
Eastward

CONCLUSIONS

- **Climate in our region is made of 10-60 day intraseasonal events**

- **These climate events probably involve air-sea-land interaction**

- **Intraseasonal events are likely to be predictable 15-25 days ahead (*Waliser*, *Goswami*, *Webster*, *Hendon*, *Wheeler* …)**

- **Understanding of intraseasonal air-sea-land interaction will improve in the next few years**