

**Dynamics of intraseasonal sea level and thermocline variability in the  
equatorial Atlantic during 2002-2003**

Weiqing Han

Department of Atmospheric and Oceanic Sciences, University of Colorado,

UCB 311, Boulder, Colorado 80309; whan@enso.colorado.edu; Tel: 303-735-3079

Peter J. Webster

School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta,  
Georgia

Jia-Lin Lin

Department of Geography, the Ohio State University, Columbus, Ohio

W. T. Liu

JPL, California Institute of Technology, Pasadena, California

Rong Fu

School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta,  
Georgia

Dongliang Yuan

Institute of Oceanology, Chinese Academy of Sciences, Qingdao, P.R. China

Aixue Hu

National Center for Atmospheric Research, Boulder, Colorado

## **Abstract**

Satellite and in situ observations in the equatorial Atlantic Ocean during 2002-2003 show dominant spectral peaks at 40-60 days and secondary peaks at 10-40 days in sea level and thermocline within the intraseasonal period band (10-80 days). A detailed investigation of the dynamics of the intraseasonal variations is carried out using an ocean general circulation model, namely, the Hybrid Coordinate Ocean Model (HYCOM). Two parallel experiments are performed in the tropical Atlantic Ocean basin for the period of 2000-2003: one is forced by daily QuikSCAT winds together with other forcing fields, and the other is forced by the low-passed 80-day version of the above fields. To help to understand the role played by the wind-driven equatorial waves, a linear continuously stratified ocean model is also used.

Within  $3^{\circ}\text{S}$ - $3^{\circ}\text{N}$  of the equatorial region, the strong 40-60-day sea surface height anomaly (SSHA) and thermocline variability result mainly from the first and second baroclinic modes equatorial Kelvin waves that are forced by intraseasonal zonal winds, with the second baroclinic mode playing a more important role. Sharp 40-50-day peaks of zonal and meridional winds appear in both the QuikSCAT and PIRATA (Pilot Research Moored Array in the Tropical Atlantic) data for the period of 2002-2003, and they are especially strong in 2002. Zonal wind anomaly in the western-central equatorial basin for the period of 2000-2006 is significantly correlated with SSHA across the equatorial basin, with simultaneous/lag correlation ranging from -0.62 to 0.74 above 95% significance. Away from the equator ( $3^{\circ}\text{N}$ - $5^{\circ}\text{N}$ ), however, sea level and thermocline variations in the 40-60-day band are caused largely by tropical instability waves (TIWs).

On 10-40-day timescales and west of  $10^{\circ}\text{W}$ , spectral power of sea level and thermocline appears to be dominated by TIWs within  $5^{\circ}\text{S}$ - $5^{\circ}\text{N}$  of the equatorial region. The wind driven circulation, however, also provides a significant contribution. Interestingly, east of  $10^{\circ}\text{W}$  SSHA and thermocline variations at 10-40-day periods result almost entirely from wind-driven equatorial waves. During boreal spring of 2002 when TIWs are weak, Kelvin waves dominate the SSHA across the equatorial basin ( $2^{\circ}\text{S}$ - $2^{\circ}\text{N}$ ). The observed quasi-biweekly Yanai waves are excited mainly by the quasi-biweekly meridional winds, and they contribute significantly to the SSHA and thermocline variations in  $1^{\circ}$ - $5^{\circ}\text{N}$  and  $1^{\circ}$ - $5^{\circ}\text{S}$  regions.

## 1. Introduction

Observations in the equatorial Atlantic Ocean show large-amplitude intraseasonal (defined as the 10-80-day period band) variations in zonal and meridional currents and sea level across the equatorial basin (e.g., Dueing et al. 1975; Weisberg et al. 1979; Weisberg and Horigan 1981; Weisberg 1984; Weisberg and Colin 1986; Houghton and Colin 1987; Katz 1987, 1997; Legeckis and Reverdin 1987; Weisberg and Wingartner 1988; Musman 1989, 1992; Luther and Johnson 1990; Contreras 2002; Caltabiano et al. 2005; Giarolla et al. 2005; Grodsky et al. 2005; Kessler 2005 for a review; Brandt et al. 2006; Bunge et al. 2006, 2007; Lyman et al. 2007). Spectral peaks of currents in 10-40-day and 40-60-day period bands have been identified by these observations.

On 10-40-day timescales, both wind-driven equatorial waves and tropical instability waves (TIWs) have been observed. Energetic oscillations near 14-day period have been observed in the equatorial Atlantic basin. Garzoli (1987) showed a significant coherence at 14-16-day periods between the observed zonal wind stress and ocean surface dynamic height near 28°W, and found that the maximum amplitude of the 14-day signal occurred at 3°N. Houghton and Colin (1987) found near 15-day oscillations in observed meridional currents and sea surface temperature (SST) in the Gulf of Guinea during 1984. They suggested that these oscillations are the second baroclinic mode Yanai waves forced by local meridional winds and contribute significantly to the heat divergence and SST variability. Bunge et al. (2006, 2007) detected near 14-day meridional currents during spring 2002, and speculated that they might be wind-driven first baroclinic mode Yanai

waves. The 14-day oscillations have also been observed at depth on the continental slope off the Angola coast (Vangriesheim et al. 2005). Katz (1987) analyzed inverted echo sounder records and showed dominant Kelvin wave signals at 10-40-day periods along the equator from 34°W to 1°W, and suggested that they are the first baroclinic mode Kelvin waves driven by zonal wind stress in the mid-basin.

Also on 10-40-day timescales, TIWs are suggested to attain their maximum power (e.g., Lyman et al. 2007). The TIWs are often generated during boreal summer and may exist throughout May-January (e.g., Jochum et al. 2004). They have wavelengths of 600-1200km (e.g., Legeckis 1977; Miller et al. 1985; Legeckis and Reverdin 1987; Perigaud 1990; Steger and Carton 1991; McPhaden 1996) and westward phase speed of 20-50 cm s<sup>-1</sup> (e.g., Weisberg and Colin 1986; Malarde et al. 1987; Weisberg and Weingartner 1988; Musman 1989, 1992; Katz 1997; Kennan and Flament 2000), and are strongest in the central basin - away from the eastern or western boundary (Richardson and Philander 1987). Data analysis, theoretical and modeling studies suggest that the TIWs result mainly from barotropic instabilities of the mean zonal currents (Philander 1976, 1978; Weisberg and Weingartner 1988; McCreary and Yu 1992; Qiao and Weisberg 1995; Jochum et al. 2004; Johnson and Proehl 2004). Baroclinic (Cox 1980; Hansen and Paul 1984; Luther and Johnson 1990; Baturin and Niiler 1997; Masina et al. 1999; Grodsky et al. 2005), frontal (Yu et al. 1995) and Kelvin-Helmholtz instabilities (Proehl 1996) also contribute.

Few observational studies have shown distinct spectral peaks at 40-60-day periods in near surface zonal currents. Katz (1997) used two hundred days of data from five inverted echo sounders deployed along the equatorial Atlantic during 1983-84 and showed a sharp spectral peak of energy density near 54-day periods. The near 54-day variability has eastward phase propagation, and is thought to be the first baroclinic mode Kelvin wave driven by the zonal winds in the western equatorial basin. Brandt et al. (2006) analyzed data from 11 cross-equatorial ship sections taken at 23°W-29°W during 1999-2005 and data from moored Acoustic Doppler Current Profilers (ADCP) at 23°W on the equator during February 2004-May 2005, and found significant spectral peaks at 35-60 days in zonal surface currents. The 35-60-day peaks did not possess a meridional current component (their Fig. 4a), indicating that TIWs may not be the sole cause for the variability.

While extensive modeling and theoretical studies on TIWs exist, the role intraseasonal winds play in generating oceanic variability in the equatorial Atlantic remains unclear. Although wind-driven equatorial Kelvin and Yanai waves have been identified in observations (Garzoli 1987; Houghton and Colin 1987; Katz 1987, 1997; Bunge et al. 2006, 2007), modeling studies that investigate the detailed dynamics have not yet been done. Hence, a thorough and comprehensive investigation on the relative roles of wind-driven equatorial waves and TIWs in causing intraseasonal variability is needed. There is ample evidence of high amplitude intraseasonal wind and rainfall variability in the equatorial Atlantic Ocean. Grodsky and Carton (2001), Janicot and Sultan (2001) and Thorncroft et al. (2003) all indicate that the West African monsoon can significantly

affect the equatorial Atlantic Ocean. There is some evidence that Amazon convection can influence winds in western Atlantic basin (Wang and Fu 2007). Furthermore, the Madden-Julian Oscillation (MJO, Madden and Julian 1971, 1972) from the Indian-Pacific Ocean may propagate into the Atlantic to affect the winds there (Foltz and McPhaden 2004). In summary, it can be expected that intraseasonal wind variability may have a strong influence on oceanic variability.

The overall goal of this paper is to provide a detailed understanding of the role played by intraseasonal winds in causing intraseasonal variability in the equatorial Atlantic Ocean, focusing in particular on the response of sea level and thermocline depth. In addition, the relative importance of wind-forced waves verses TIWs is also addressed. A two-pronged approach towards the solution of this problem is adopted using analysis of data and a series of model experiments. First, available satellite data together with in situ observations are analyzed to document the intraseasonal variability. Second, an ocean general circulation model, the HYbrid Coordinate Ocean Model (HYCOM) is used as a primary tool to investigate the mechanisms. A linear model (LM) is also used to help understand the role of the wind-driven equatorial waves.

## **2. Data and Models**

### **2.1. Data**

Data from the Pilot Research Moored Array in the Tropical Atlantic (PIRATA; Servain et al. 1998) and satellite remotely sensed observations for the period of interest, 2001-2003,

are used to document intraseasonal variability. The PIRATA data analyzed in this paper are depths of 20° isotherms (D20) and surface winds at several locations along the equator, ADCP currents at (23°W, 0°N), which were measured at 0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1000 and 1100m depths, and SST. The satellite data include sea surface height anomalies (SSHA), which are from a merged product of Topex/Poseidon, Jason 1, and European Research Satellite altimeter produced by the French Archiving, Validation, and Interpolation of Satellite Oceanographic Data (AVISO) project using the mapping method of Ducet et al. (2000). The SSHA data are interpolated onto a global grid of 1/3° resolution, archived weekly and computed relative to a 7-year mean from January 1993 to December 1999. In addition, daily QuikSCAT winds and 3-day-mean SST from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (Wentz et al. 2000) for the period of interest are also examined. Although we focus on 2001-2003, winds and SSHA for the entire period of July 1999-January 2007 will also be analyzed.

## **2.2 The Ocean models**

### **2.2.1 HYCOM**

The HYCOM is documented in detail in Bleck (2002) and Halliwell (1998, 2004). For the current study, it is configured to the tropical Atlantic Ocean 30°S-40°N, with a horizontal resolution of 0.5° x 0.5° and realistic bottom topography with 5°x5° smoothing. This resolution can reasonably resolve the scale of the TIWs (Cox 1980), which have typical wavelengths of 600-1200km. Vertically, 22 sigma-layers are chosen with a fine resolution in the upper ocean to better resolve the vertical structures of upper ocean

currents, temperature, mixed layer, and thermocline. Reference pressure sigma-0 is adopted, because we focus on upper ocean processes. The nonlocal K-profile parameterization (KPP) is used for the boundary layer mixing scheme (Large et al. 1994, 1997). The diapycnal mixing coefficient is set to  $(1 \times 10^{-7} \text{ m}^2 \text{ s}^{-2})/N$  where  $N$  is the buoyancy frequency. Isopycnal diffusivity and viscosity values are formulated as  $u_d \Delta x$  where  $\Delta x$  is the local horizontal mesh size and  $u_d$  is  $0.03 \text{ m s}^{-1}$  for momentum and  $0.015 \text{ m s}^{-1}$  for temperature and salinity. In regions of large shear, isopycnal viscosity is set proportional to the product of mesh-size squared and total deformation (Bleck 2002), and the proportionality factor used here is 0.1. Solar shortwave radiation penetration is included with Jerlov water type IA (Jerlov 1976).

Along the continental boundaries, no-slip boundary conditions are applied. Near the southern and northern boundaries, sponge layers of  $5^\circ$  ( $30^\circ\text{S}$ - $25^\circ\text{S}$  and  $35^\circ\text{N}$ - $40^\circ\text{N}$ ) are applied to relax the model temperature and salinity to the Levitus and Boyer (1994) and Levitus et al. (1994) climatologies. Similar versions of HYCOM have been used in the tropical Indian Ocean for studying intraseasonal-to-interannual variability (e.g., Han et al. 2004; Han 2005; Yuan and Han 2006).

Daily QuikSCAT winds (Tang and Liu 1996), net short wave and long wave radiative fluxes from the International Satellite Cloud Climatology Project flux data (ISCCP-FD; Zhang et al. 2004), and NCEP/NCAR reanalysis (Kalnay et al. 1996) air temperature and specific humidity are used as surface forcing fields for HYCOM. Precipitation is from the Climate Prediction Center Merged Analysis of Precipitation (CMAP) pentad data (Xie

and Arkin 1996), which is interpolated to daily resolution before forcing the model. Daily QuikSCAT wind stress is calculated from wind speeds using a drag coefficient of 0.0015. These choices are made based on the best available datasets for the period of interest (see Han et al. 2007).

Two versions of the forcing fields are utilized: daily mean, which includes intraseasonal variations, and lowpassed version of the daily field using a Lanczos digital filter (Duchon 1979) with a half-power period at 80 days, which excludes intraseasonal variations. The model is spun up from a state of rest for 20 years using COADS monthly mean climatological fields. Based on the results of year 20, HYCOM is integrated forward in time using the daily and lowpassed 80-day forcing fields of 2000-2003 (see section 2.2.3), a period when all the above forcing fields and PIRATA data (current, D20 and SST) are available. Considering that the first two years results may contain transient effects induced by switching on of the forcing from monthly climatology to daily fields, we use the results of 2001-2003 to obtain the band-pass filtered fields (see section 3) and focus on analyzing the solutions for 2002-2003.

### **2.2.2 The LM**

The linear continuously stratified ocean model is described in detail in McCreary (1980, 1985), and it has been applied to several Indian Ocean studies (e.g., McCreary et al. 1996; Han et al. 2004; Han 2005). Here, it is set up for the tropical Atlantic Ocean. The equations of motion are linearized about a state of rest with a realistic background stratification calculated from the Levitus temperature and salinity averaged over 10°S-

10°N (Levitus and Boyer 1994; Levitus et al. 1994). The ocean bottom is assumed to be flat. With these restrictions, solutions can be represented as expansions in the vertical normal modes of the system, with the total solution being the sum of all modes. In this paper, unless specified otherwise the first 25 baroclinic modes are used and solutions are well converged (not shown). Table 1 lists the characteristic speeds  $c_n$  for the first four baroclinic modes estimated from buoyancy frequency  $N_b$  calculated from the Levitus data, together with other useful values. The wind coupling coefficient for mode  $\mathcal{N}$  ( $\mathcal{N}=1,2,3,\dots$ ),  $D_n = 1 / \int_H^0 \psi_n^2(z) dz$ , indicates the efficiency of wind projection onto each mode. Here,  $H=4000$  m is the ocean depth,  $\psi_n(z)$  is the eigen function for  $\mathcal{N}$  th baroclinic mode and is estimated from  $N_b$  (for detailed derivation see McCreary 1980, 1985). Apparently, winds most effectively project onto the second baroclinic mode. The Laplacian mixing on momentum is included with a coefficient of  $5 \times 10^7 \text{ cm}^2 \text{ s}^{-1}$ . Vertical mixing coefficient is  $\nu = A/N_b^2$ , where  $A = 1.3 \times 10^{-4} \text{ cm}^2 \text{ s}^{-3}$ .

The model basin, grid points and continental boundary conditions are the same as those of the HYCOM, except that the LM does not have bottom topography. Closed boundaries are used at the northern and southern boundaries and a damper on zonal currents is applied within 5° of the boundaries to damp the currents toward zero, in order to reduce the spurious coastal Kelvin waves caused by the artificial boundaries. This is basically consistent with the sponge layer of HYCOM for the same regions. As with HYCOM, the LM is first spun up for 20 years using the monthly climatology of COADS wind stress forcing. Restarting from year 20, the model is integrated forward for the period of 2000-2003 forced by the daily QuikSCAT wind stress.

### **2.2.3 Experiments**

Two HYCOM experiments are performed. Experiment HYCOM main run (MR) is forced by the unfiltered daily forcing fields. Intraseasonal variability in the MR results from both intraseasonal atmospheric forcing and TIWs. To assess the role played by TIWs, HYCOM is also forced by the low-passed 80-day fields, which purposely exclude intraseasonal atmospheric forcing and, thus, wind-forced oceanic intraseasonal variability. This experiment is referred to as “HYCOM experiment run” (EXP). To understand the role of wind-driven equatorial waves, the LM, which excludes TIWs, is forced by the unfiltered daily wind stress fields and it is referred to as LM MR. To estimate the effects of zonal versus meridional wind stress on equatorial waves, in LM EXP1 the LM is forced by zonal wind stress only. Note that winds over the equatorial Atlantic can also be affected by the feedback from the TIWs (Xie et al. 1998; Liu et al. 2000; Chelton et al. 2001; Gentemann et al. 2001; Hashizume et al. 2001; Caltabiano et al. 2005). To exclude this effect, in LM EXP2 the LM is forced by winds with a spatial filter of 12° running average in the zonal direction within 8°S-8°N, which works well for removing the TIW signals (Hashizume et al. 2001). These experiments are summarized in Table 2.

## **3. Results**

We first analyze available observations to document intraseasonal variability in the equatorial Atlantic Ocean, and compare HYCOM MR solution with the observations to verify the model performance (section 3.1). Next, we examine the hierarchy of HYCOM

and LM solutions to gain an understanding of the dynamics of the 40-60-day and 10-40-day variability of sea level and thermocline (sections 3.2 and 3.3). In both sections, we address the roles of wind-forced waves and TIWs in generating the observed variability. Finally, in section 3.4 we estimate the effects of winds associated with the TIWs.

### **3.1 Observed and simulated intraseasonal variability**

Figs 1a-c show variance spectra of AVISO weekly SSHA along the equator for 2002-2003, 2002, and 2003, respectively. Interestingly, sea level variability shows strong spectral peaks at 40-60 days across most of the equatorial basin, and dominates in magnitude the 10-40-day variability that contains the TIWs (Fig 1a). The dominance of 40-60-day SSHA is most apparent in 2002, when the 40-60-day SSHA amplitude is particularly strong and spatially coherent while the 10-40-day variability is especially weak (Fig. 1b). In 2003, SSHA has significant power at both 10-40-day and 40-60-day periods, and the strength and dominant periods of SSHA vary with longitudinal locations (Fig. 1c). The dominance of 40-60-day SSHA in 2002, and the significant power of SSHA at both periods in 2003, are reasonably simulated in HYCOM MR solution (Figs 1d-1f). Overall though, the model spectral peaks are weaker than those of observations.

Consistent with the sea level observations, D20 obtained from PIRATA data during 2002-2003 shows a sharp 40-50-day spectral peak at both 35°W and 23°W on the equator (Figs 2a-b), with significance exceeding 95% at both locations. Time series of 10-80-day band-pass filtered D20 shows that intraseasonal fluctuations of the thermocline vary between -15m and 13m at 23°W during the 20-month date period. This variation is large

compared to the shallow, mean thermocline depth of 78m obtained from PIRATA data at the same location for the same period of time. HYCOM is able to reproduce the dominant 40-60-day peaks (Figs 2a-b, dotted lines), but their power is much weaker than the observations. The weak amplitudes of HYCOM intraseasonal SSHA and D20 (Figs 1 and 2) may result from the deeper mean thermocline, which would be less sensitive to the surface forcing. The mean D20 from HYCOM MR is 123m at 23°W during the 20-month PIRATA data period, 45 m deeper than that of the PIRATA D20.

The 40-60-day peak is also present in the PIRATA near-surface zonal current at (23°W, 0°N), and no corresponding peak exists in meridional current (Figs 3a-b). This may suggest the equatorial symmetric property of the 40-60 day variability, which will be discussed in section 3.2. Basically, HYCOM produced the spectral peaks of zonal currents at both 10-40-day and 40-60-day period bands, and peaks of meridional currents at 10-40-day period range, although significant model-data differences exist especially at the 10-40-day periods when TIWs are strong (Fig. 3). To quantify how well the TIWs are simulated, we calculate the HYCOM MR perturbation kinetic energy (PKE; see Weisberg and Weingartner 1988 for definition) during 2002-2003 at the same location and depths as those of Weisberg and Weingartner (1988). The TIWs reach their maximum energy in summer with an energy peak of 1300 erg cm<sup>-3</sup> at 10m and 635 erg cm<sup>-3</sup> at 75m in HYCOM MR (not shown), comparing to 1600 erg cm<sup>-3</sup> at 10m and 600 erg cm<sup>-3</sup> at 75m in Weisberg and Weingartner (1988; their Fig. 6). The peak energy in HYCOM is weaker than the observations at the surface and somewhat stronger at depth, indicating that more energy is mixed downward in HYCOM. The model PKE has a

weaker, secondary peak during fall, a feature that was also observed by Weisberg and Weingartner (1988; see also Jochum et al. 2004).

To quantify further the variations of sea level along the equator on intraseasonal timescales, Fig. 4 shows the band-pass filtered SSHA and D20 averaged over  $2^{\circ}\text{S}$ - $2^{\circ}\text{N}$  from AVISO observations and model solutions in 2002. Since AVISO data have weekly resolution, the periods for the Lanczos band-pass filter are chosen to be 14-80 days. The observed SSHA appears to be dominated by near 45-day oscillations for most of the year (Fig. 4a). An exception is during June-August, when the SSHA patterns are complicated by the westward-propagating, higher-frequency variability. The dominance of the 40-50-day oscillations and the occurrence of strong higher frequency variability in summer are reasonably simulated by HYCOM MR (Fig. 4b).

Note that HYCOM produces weaker SSHA, D20 and somewhat weaker TIW PKE near the surface than the observations. The quantitative differences between data and model at a specific location may result partly from the influence of TIWs, the deeper D20 in HYCOM, and errors in the model and forcing fields. Nevertheless, HYCOM is able to reasonably simulate the observed intraseasonal peaks of sea level, thermocline depth and the TIWs, and is thus a useful tool for the identification of major processes that cause intraseasonal variability.

## **3.2 Dynamics of the 40-60 day variability**

### **3.2.1. 2002-2003**

It is interesting to note that the strong 40-50-day SSHA shown in Fig. 4a is reproduced by the LM solution (Fig. 4c), which demonstrates the deterministic role played by wind-driven equatorial wave dynamics. During spring and early summer, intraseasonal SSHA and D20 exhibit an-eastward phase propagation (the dark solid lines in Fig. 4) with a speed of approximately  $174 \text{ cm s}^{-1}$ , which is between that of the first and second baroclinic modes of the equatorial Kelvin waves (see Table 1). The westward propagating, higher-frequency variability during summer results mainly from the TIWs (Fig. 4d), which are strong in northern summer. Variations of D20 basically mirror the SSHA (compare Figs 4e and 4b). When SSHA is high, thermocline deepens.

Fig. 5 plots the variance spectra of SSHA averaged over  $2^{\circ}\text{S}$ - $2^{\circ}\text{N}$  from HYCOM MR, HYCOM EXP and LM solutions for 2002-2003. The 40-50-day variances extend across the equatorial Atlantic basin in both the HYCOM MR and LM solutions (Figs 5a and 5c), but disappear in HYCOM EXP run (Fig. 5b). This demonstrates that the 40-60-day especially the 40-50-day SSHA is forced by intraseasonal winds rather than induced by TIWs. Indeed, both the zonal and meridional wind stresses from QuikSCAT data exhibit strong 40-60-day periodicity especially at 40-50-day in the equatorial Atlantic (Figs 6a-6b). The 40-50-day peaks are also present in the zonal wind stress of the NCEP/NCAR reanalysis data. However, the maximum power in the reanalysis product is in the western basin and is much weaker than the variance found in QuikSCAT wind in the central ocean (c.f. Figs 6a and 6c). Moreover, no spectral peaks appear in NCEP meridional wind stress at 40-50-day periods in the central basin (Fig 6d). Consistent with the QuikSCAT winds (solid curves of Fig. 7), PIRATA data also show largest spectral peaks at 40-50-

day periods in zonal and meridional wind stress at  $35^{\circ}\text{W}$  and  $23^{\circ}\text{W}$  of the equator during 2002-2003 (dashed curves).

To examine the spatial structure of the 40-50-day sea level oscillations, the 40-60-day band-pass filtered SSHA for a case of spring 2002 is plotted in Fig. 8. This is a time when the 40-50-day variation dominates the intraseasonal SSHA (Fig. 4). Within the  $3^{\circ}\text{S}$ - $3^{\circ}\text{N}$  equatorial region, the observed SSHAs are dominated by wind-driven equatorial wave dynamics (Figs 8a-i), and TIWs appear to play a minor role (Figs 8j-l). The LM solution (Figs 8g-i) exhibits equatorial Kelvin wave structure in the central and eastern basin, which is symmetric about the equator with decreasing amplitudes towards the poles. The wavelength is approximately  $60^{\circ}$  (Fig. 8i), which is between the first and second baroclinic mode Kelvin waves' lengths ( $80^{\circ}$  and  $46^{\circ}$  at 45-day period; Table 1). Note that the TIWs generally project their energy on Yanai and Rossby waves (Cox 1980), which have weak sea level amplitudes at the equator (Yuan 2005). In addition, the strong spectral peaks of TIWs generally occur at 10-40-day periods (see section 1) rather than at 40-60-day periods. All of these may contribute to the dominance of 40-60-day Kelvin waves, which obtain their maximum amplitudes on the equator. Away from the equator at  $3^{\circ}\text{N}$ - $5^{\circ}\text{N}$ , SSHA is dominated by the TIWs even at the 40-60-day periods (Figs 8j-l).

In the western equatorial basin, the LM SSHA shows the first meridional mode Rossby wave structure, with double maximum amplitudes off the equator and relative minimum on the equator (Figs 8g-i). The double maxima off the equator appear to be traceable in the AVISO data (Figs 8a-c), although the structures are complicated by the presence of

TIWs at 3°N-5°N. The 40-60-day oscillations during fall have also been analyzed, producing results similar to those shown in Fig. 8.

Further inspection of the LM solutions suggest that the 40-60-day SSHA near the equator results mainly from the first two baroclinic modes contribution with mode 2 possessing larger amplitudes than mode 1 (not shown). This is because mode 2 is more effectively excited by winds, with a wind coupling coefficient of 2.6 times of mode 1 (Table 1). Note that mode 3 is not effectively excited even though its wind-coupling coefficient is larger than that for mode 1. This is because amplitudes of Kelvin waves also depend on the spatial structure of forcing winds. Assume the ocean is forced by a stationary zonal wind stress  $\tau^x$ . The amplitudes of Kelvin or Rossby waves are proportional to the zonal integral of the product of the wind and the wave structure,  $\int \tau^x e^{-ikx} dx$ , where  $k$  is the wavenumber of Kelvin or Rossby waves. The amplitude thus depends on the parameter  $kL$ , where in this case  $L$  represents the zonal scale of the wind. If  $kL \geq 1$ , then  $e^{-ikx}$  oscillates within the region of the wind, producing an oscillating integral; when  $kL \ll 1$ ,  $e^{-ikx} \approx 1$  and the amplitude achieves its maximum possible value. The length of Kelvin wave associated with mode 1 is much longer than that of mode 3 (Table 1). Mode 1 is therefore more efficiently excited by the large-scale wind. Additionally, vertical mixing acts more strongly on the higher order modes (McCreary 1980, 1985), and this also tends to reduce their amplitudes.

The strong 40-60-day westerly wind anomaly in the western-central basin causes equatorial convergence, raises sea level (Figs 9a-c). The high SSHA signals propagate

eastward as equatorial Kelvin waves (Figs 9b-c). The importance of zonal wind stress in forcing Kelvin waves is quantified by Fig. 9d (compare with Fig. 9c). Interestingly, the complex spatial pattern of winds appears to enhance the wave response. For example, in early March westerly winds along the equator excite mode 1 and mode 2 Kelvin waves that are associated with positive SSHA (Figs 9a-c). In late March when the positive SSHA propagates to the eastern boundary, significant westerly winds appear over 10°W-10°E, which enhance the Kelvin wave amplitudes in the region especially for the first baroclinic mode. Figs 9a-b seems to show that zonal winds move eastward with oceanic Kelvin waves in the central-eastern basin during January-June. The enhanced Kelvin wave response to the eastward propagating wind had been discussed by Hendon et al. (1998) for the Pacific and Han et al. (2001) for the Indian Ocean. It is not obvious, however, whether the winds in the western basin are actually propagating to the east or winds in the eastern and western basins originated from different atmospheric systems. During summer and especially fall, winds are weaker and the “propagation” feature disappears. The 40-60-day winds (Fig. 9a) also coincide with the observed intraseasonal SSHA, which is dominated by 40-60-day oscillations (Fig. 4a).

Given that the 40-60-day SSHA basically shows a symmetric Kelvin wave structure (Fig. 8), Rossby waves especially anti-symmetric Rossby waves are not excited effectively, even though strong spectral peaks exist in the meridional winds at this period band (Fig. 6b). This is because propagating Rossby waves are available only for the first baroclinic mode (Fig. 10), which is weakly coupled to the forcing winds (Table 1). The second baroclinic mode Rossby waves only exist at periods longer than 45 days, and their

wavelengths are too short ( $12^\circ$  at 50-day period; Table 1) to be excited efficiently by the large-scale winds.

The variance spectra of TRMM SST during 2002-2003 also exhibit 40-60 day spectral peaks (Fig. 11a). This is consistent with the strong 40-60-day peaks of winds and D20. Time series of SST from TRMM and PIRATA data at ( $10^\circ\text{W}$ ,  $0^\circ\text{N}$ ), a location where 40-60-day SST has strong power, shows significant intraseasonal SST variations (Fig. 11b). The near 45-day oscillations of SST can be identified visually for the periods of January-April of 2002 and June-August of 2003, during which SST can vary as much as  $2^\circ\text{C}$ - $4^\circ\text{C}$ . For example, at the beginning of April 2002, SST cools to  $27^\circ\text{C}$  whereas by the end of the month it warms to  $31^\circ\text{C}$ . Strong cooling at the end of July 2003 drops the SST to  $22.5^\circ\text{C}$  whilst warming in late August increases the SST to  $26^\circ\text{C}$ . There is a strong correspondence between the SST measurements from PIRATA and estimates from the TRMM. Detailed examination on the relative importance of surface heat fluxes versus oceanic processes, including thermocline variability and mixed layer physics, in determining intraseasonal SST variability is beyond the scope of this paper, but it will be an essential part of our future research.

### **3.2.2. 1999-2006**

Fig. 12 shows the variance spectra of QuikSCAT wind stress and AVISO SSHA based on a 7-year record of 2000-2006. Both zonal and meridional winds have significant power for the entire 10-60-day periods, and there are relative spectral peaks at 40-50 days in the central basin (Figs 12a-b). The SSHA spectra (Fig. 12c), however, have much stronger peaks at 40-50 days than they are at 10-40-day TIW periods in the central basin. Fig. 13

shows correlation maps between 40-60-day zonal wind stress averaged over (35°W-10°W, 2°S-2°N), a region where  $\tau^x$  has a relative peak at 40-50 days (Fig. 12a), and SSHA at every grid point within 5°S-5°N. Daily QuikSCAT winds and weekly AVISO SSHA for the period of August 1 1999 – January 3 2007 are used to obtain the 40-60-day filtered fields. To remove the end point effects of the filter, data during February 2000-June 2006 are used to calculate the correlation in Figs 13a-b. Simultaneous correlation between  $\tau^x$  and SSHA shows a positive correlation west of 20°W and negative correlation east of 20°W with a strongest correlation of -0.62 (Fig. 13a). When SSHA lags the wind by 15 days, the correlation is positive in the central-eastern basin (Fig. 13b) with the maximum coefficient of 0.74 above 95% significance. The east-west out of phase correlation indicates eastward propagation of oceanic Kelvin waves, as shown in Fig. 9. The  $\tau^x$ -SSHA correlation is especially strong during 2002, with coefficients ranging from -0.96 to 0.91 above 90% significance for simultaneous and lag correlations (Figs. 13c-d). The strong correlation between winds and SSHA demonstrates the important role played by winds in causing 40-60-day variability of sea level and thermocline in general and especially for 2002.

### **3.3 The 10-40-day variability**

In contrast to the 40-60-day SSHA that is dominated by the equatorially symmetric Kelvin waves within the 3°S-3°N equatorial belt, variations on 10-40-day timescales consist of both symmetric and anti-symmetric components. In addition, TIWs have their maximum spectral peaks at the 10-40-day period band (e.g., Lyman et al. 2007).

Along the equator, the symmetric component (averaged over  $2^{\circ}\text{S}$ - $2^{\circ}\text{N}$ ) of 10-40-day SSHA results largely from TIWs in the region west of  $10^{\circ}\text{W}$  (Fig. 5), with a maximum spectral peak occurring near the 30-day period. The wind-driven sea level variability, however, also appears to have considerable contributions (compare Figs 5a-c). East of  $10^{\circ}\text{W}$ , the 10-40-day SSHA power is relatively weak, and it is forced by the 10-40-day wind possessing significant power at these periods (Fig. 6). The dominance of wind forcing in the eastern equatorial basin is also illustrated in Figure 14. Interestingly, during January-May of 2002 when the TIWs are relatively weak, wind forcing appears to dominate TIWs across the equatorial basin. Variations of D20 mirror those of SSHA (Figs 14c-d). During June-December, both TIWs (Fig 14b) and wind forcing (Fig 14a) are important in the region west of  $10^{\circ}\text{W}$  (compare 14a-c).

Off the equator at  $2^{\circ}\text{N}$ - $5^{\circ}\text{N}$ , variability of sea level and thermocline in the eastern basin is still dominated by wind forcing (Fig. 15). West of  $10^{\circ}\text{W}$ , TIWs, which have westward phase propagation, play a dominant role during summer (compare Figs 15a-d). During spring and winter, both wind forcing and TIWs contribute. A similar situation holds near  $2^{\circ}\text{S}$ - $5^{\circ}\text{S}$  (not shown). Interestingly, the LM solution shows large SSHA associated with quasi-biweekly Yanai waves during spring 2002, which are anti-symmetric about the equator and have an eastward group velocity (March-May of Fig 15a). This is consistent with the observational analysis of Bunge et al. (2006, 2007). By interacting with the TIWs, the Yanai waves complicate the sea level and thermocline variability (Figs 15a-e). The Yanai waves appear to originate from the central-western basin and result mainly from the 2<sup>nd</sup> baroclinic mode response (not shown). They are forced primarily by the

meridional wind stress  $\tau^y$  (Fig. 15b), although wind stress curl associated with  $\tau^x$  also contributes to their formation (seen by the difference between Figs 15a and 15b). Indeed, both  $\tau^x$  and  $\tau^y$  have relative spectral peaks at quasi-biweekly period. These peaks, however, do not seem to be stronger than the winds at 20-40-day and 40-60-day periods (Fig 6).

Why do the Yanai waves favor the biweekly period? At this relatively high frequency, the only available anti-symmetric waves possible are Yanai waves, which have a small wavenumber and thus long wavelength (Fig. 10, Table 1). Therefore, the Yanai waves are excited effectively by the basin-scale winds. Quasi-biweekly Yanai waves are also present in the equatorial Indian Ocean, and they dominate the meridional current variability there (Masumoto et al. 2005; Miyama et al. 2006). At 40-60-day periods, Yanai waves are also available and higher order baroclinic modes have longer wavelengths (not shown). These modes can also be excited by large-scale  $\tau^y$  and  $\partial\tau^x/\partial y$  in an inviscid ocean (Miyama et al. 2006). These modes, however, are strongly damped by vertical mixing and thus contribute weakly to the total solution (Miyama et al. 2006).

The spatial structures of SSHA associated with the Yanai waves are shown in Fig. 16 (right column). The SSHA attains its maximum amplitudes near 2-3°S and 2-3°N and oscillates at a period of approximately 2 weeks. The SSHA at the equator (Fig. 16g) results from equatorial Kelvin waves, as discussed above. The influence of Yanai waves on SSHA is seen clearly in HYCOM MR (Figs 16a-c). However, there are significant differences between the LM and HYCOM solutions due to the presence of TIWs and the

nonlinearity of HYCOM. Note that TIWs have large amplitudes at 2°N-5°N and 2°S-5°S (Figs 16d-f), and the associated SSHAs are symmetric about the equator in phase, consistent with the satellite observations (Chelton and Schlax 1996; Chelton et al. 2000; Lyman et al. 2005).

Correlation maps between 10-40-day QuikSCAT  $\tau^x$  averaged over central and western basin (45°W-10°W, 2°S-2°N) and 10-40-day AVISO SSHA in the equatorial basin show a maximum coefficient of  $\sim 0.2$  for the period of 2000-2006 and  $\sim 0.5$  for 2002 (not shown). Correlations between  $\tau^y$  and SSHA have similar amplitudes. Note, however, that to a large degree, the weaker wind-SSHA correlation on 10-40-day timescales may result from the interference between the forced waves and the strong TIWs. Even though intraseasonal winds have significant influence, the correlation can be weak due to the TIWs interference.

### **3.4. Effects of TIW winds**

Because TIWs can feedback to the atmosphere to induce wind changes (Xie et al. 1998; Liu et al. 2000; Chelton et al. 2001; Hashizume et al. 2001; Caltabiano et al. 2005), intraseasonal winds that force the ocean models include the TIW effect. Comparison of solutions from LM MR and LM EXP2 shows that neither the 40-60-day nor the 10-40-day SSHA is apparently altered by the TIW winds (not shown). The most visible contribution from the TIWs appears to occur during summer and fall in the central-western basin, where the TIWs are strong and their winds cause small-spatial scale SSHA with westward phase propagation. Consequently, TIW winds do not seem to

“overestimate” the wind-forced variability on intraseasonal timescales. Rather, they cause small-scale variability that appears to propagate westward with the TIWs.

#### **4. Summary and Discussion**

In this paper, dominant spectral peaks within the intraseasonal window at 40-60 days are identified in sea level and thermocline depth along the Atlantic equator during the period of 2002-2003 (Figs 1 and 2). The peaks are especially strong and spatially coherent at 40-50 days during 2002, and are far stronger than the variance in the 10-40-day band associated with the TIWs within 3°S-3°N equatorial region. The 10-80-day bandpass filtered D20 varies from -15m to 13m at 23°W during 2002-2003 period of interest (Fig. 2c). These amplitudes are large comparing to the PIRATA mean D20 of 78m. The results of diagnostic and modeling studies are presented to determine the relative role of wind driven waves and TIWs in producing the observed intraseasonal variability in the equatorial Atlantic Ocean. The OGCM, HYCOM, is able to simulate the observed intraseasonal variability of SSHA, D20 and currents (Figs 1-5) and produce reasonable perturbation kinetic energy associated with the TIWs (section 3.1).

The SSHA from both AVISO observations and model solutions shows equatorial Kelvin wave structure and eastward phase propagation (Figs. 8 and 4), demonstrating that the 40-60-day variability results from equatorial Kelvin waves driven by intraseasonal winds (Fig. 5). The QuikSCAT winds peak at 40-60-day especially at 40-50-day periods in both zonal and meridional components across the equatorial basin (Fig. 6), and these peaks are

also present in the PIRATA wind data (Fig. 7). The LM solution suggests further that the 40-60-day Kelvin waves are mainly forced by the zonal wind component and are dominated by the first two baroclinic modes, with the second mode playing a more important role (Fig. 9; Table 1). Sea level and D20 variations associated with the 40-60-day Kelvin waves have much larger amplitudes than the TIWs in 3°S-3°N belt (Fig. 8) and dominate the 10-40-day variability along the equator (Figs. 1 and 2). Spectra of QuikSCAT zonal and meridional wind stress and AVISO SSHA for a 7-year period during 2000-2006 also show relative peaks at 40-60 days (Fig. 12), and zonal wind stress in the central-western equatorial basin is significantly correlated with the SSHA in the equatorial region (Fig. 13), suggesting the importance of winds in driving the 40-60-day variability of SSHA and D20 in general. Away from the equator at 3-5°N and 3-5°S where TIWs are strong, 40-60-day variability has comparable power with the 10-40-day variability, and the TIWs appear to dominate the wind-driven SSHA and thermocline variations at 40-60-day periods (Fig. 8).

Consistent with the sea level and thermocline depth variations, there are also 40-60-day spectral peaks in SST along the equator (Fig. 11) and corresponding SST changes by 2-4°C during March-April 2002 and June-August 2003. During boreal spring, mean SST is near 29°C and the ITCZ is very close to the equator (Xie and Carton 2004). At such a high SST, a 2-4°C change of temperature may have large impact on ITCZ convection.

On 10-40-day timescales, both SSHA and D20 are influenced by Kelvin waves, Yanai waves and TIWs. West of 10°W, spectral power of SSHA during 2002-2003 is

contributed significantly from TIWs along the equator (Fig. 5); SSHA and D20 are dominated by the TIWs at 2°N-5°N and 2°S-5°S during northern summer (Fig. 15). Wind-driven equatorial waves, however, also have significant contributions (Figs. 5, 15 and 16). East of 10°W, sea level and thermocline variability is caused almost entirely by wind-driven equatorial waves within 5°S-5°N of the equatorial ocean (Figs. 5, 14, 15, 16). Along the equator, during boreal spring of 2002 when TIWs are weak, wind-forced equatorial Kelvin waves are the major cause for the SSHA and D20 variability even in the central and western basin (west of 10°W; Fig. 14). In addition, Yanai waves are strongly excited by winds especially the meridional winds at quasi-biweekly periods during spring of 2002 (Figs. 15-16), which have strong influence on the SSHA and D20 in the equatorial Atlantic basin.

A Key result from this study is that intraseasonal variability in the equatorial Atlantic Ocean is not always dominated by the TIWs. Rather, the wind-driven equatorial waves play a crucial role. There are a number of immediate questions that come to mind. For example, from where do the strong 40-50-day and 10-40-day surface forcing winds emerge? Are they associated with the MJO that is generated in the tropical Indian and western Pacific Oceans (Foltz and McPhaden 2004), or do they originate from the Amazon convection as suggested by Wang and Fu (2007)? Are the quasi-biweekly winds that force the strong oceanic Yanai waves related to the quasi-biweekly winds of the West African monsoon (Grodky and Carton 2001; Janicot and Sultan 2001)? It is the winds associated with the ISOs that produce large amplitude variability in sea level and thermocline depth. Winds from the TIWs feedback only generate weak SSHA with small

spatial scale in the central-western basin during summer and fall (section 3.4). How does the oceanic variability affect the ITCZ convection? How do the atmospheric ISOs affect the Atlantic “El Nino”? These are important questions that need to be addressed in future research.

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### **Figure captions**

Fig. 1. a) Variance spectra of SSHA along the equator (averaged over 2°S-2°N) based on AVISO weekly satellite observations for the period of 2002-2003; b) Same as a) except for 2002; c) Same as a) except for 2003; d), e) and f) are the same as a), b) and c), respectively, except for the SSHA spectra calculated from the daily HYCOM MR solution. Dashed lines show 95% significance levels. Units:  $\text{cm}^2$ .

Fig. 2. a) Variance spectra of 20°C isotherm depth (D20) at (35°W, 0°N) from PIRATA data (solid) and HYCOM MR (dashed), based on the period of 2002-2003; the corresponding dash-dotted lines represent 95% significance levels. Note that seasonal cycle is removed before the spectral analysis is performed. b) Same as a) except for (23°W, 0°N) based on the overlapping model/data period of 01/01/2002-08/24/2003. c) The 10-80 day band-pass filtered D20 at (23°W, 0°N) from PIRATA data (solid) and from HYCOM MR (dashed). The 20 months data (January 2002 – August 2003) are used for the filter but only the period of April 2002 – April 2003 is shown to exclude the end point effects of the filter.

Fig. 3. a) Variance spectra of zonal current at 30m depth based on the daily records during 12/14/2001-12/20/2002 at (23°W, 0°N) from the PIRATA data (dark) and HYCOM MR solution (gray). Seasonal cycle is removed before the spectral analysis is performed. The dashed curves show 95% significance level. The 40-60-day peak did not exceed 95% significance due to the short data record, but it did exceed 85% significance level (not shown). b) Same as a) except for meridional current. Units:  $\text{cm}^2 \text{s}^{-2}$ .

Fig. 4. Longitude-time plot of 14-80 day band-passed SSHA along the equator (2°S-2°N average) during 2002 from a) weekly AVISO observations; b) daily HYCOM MR solution; c) daily LM MR solution; d) daily HYCOM EXP solution, which isolates the TIWs; e) Same as b) except for HYCOM MR D20. AVISO and model data of 2001-2003 are used for the filter. Units: cm for SSHA and m for D20.

Fig. 5. a) Variance spectra of SSHA along the equator (2°S-2°N average) based on daily HYCOM MR solution for the period of 2002-2003; b) same as a) except for HYCOM EXP; c) Same as a) except for LM MR solution. Dashed contours represent 95% significance level.

Fig. 6. Variance spectra of surface wind stress along the Atlantic equator (5°S-5°N average) based on daily winds of 2002-2003. a) QuikSCAT zonal wind stress,  $\tau^x$ ; b) QuikSCAT meridional wind stress,  $\tau^y$ ; c) NCEP  $\tau^x$ ; d) NCEP  $\tau^y$ . As the QuikSCAT wind stress, NCEP wind stress is calculated from 10 m U and V winds using a drag coefficient of 0.0015.

Fig. 7. a) Variance spectra of  $\tau^x$  at (35°W, 0°N) from daily QuikSCAT (solid) and PIRATA (dashed) data for the period of 2002-2003. The dash-dotted line is the 90% significance curve for the QuikSCAT data. The seasonal cycle is removed before performing the spectral analysis. b) Same as a) but for  $\tau^y$ ; c) Same as a) but for (23°W, 0°N); d) Same as c) but for  $\tau^y$ . The 1°S-1°N averaged values are shown for QuikSCAT winds.

Fig. 8. a) The 40-60 day band-passed AVISO weekly SSHA in the equatorial Atlantic basin during spring, day 50 of 2002; b) and c) are the same as a) except for day 71 and day 92; d)-f): Same as a)-c) except for SSHA from HYCOM MR solution; g)-i): Same as a)-c) except form SSHA from the wind-driven, LM MR solution; j)-l): Same as a)-c)

except for SSHA from HYCOM EXP, which excludes intraseasonal forcing and represents the effects of TIWs.

Fig. 9. a) Longitude-time plot of 40-60-day filtered QuikSCAT zonal wind stress along the equatorial Atlantic (5°S-5°N average) during 2002. Positive values are shaded and negative ones are contoured (dashed lines), with an interval of .03 dyn cm<sup>-2</sup>. b) Same as a) except for 2°S-2°N averaged 40-60-day SSHA from mode 1 of the LM MR solution. Positive values are shaded and negative ones are contoured, with an interval of .2 cm. c) Same as b) except for mode 2. d) Same as c) except for mode 2 of the LM EXP1, which is forced by zonal wind stress only.

Fig. 10. Dispersion relations for equatorial Kelvin, Rossby and Yanai waves for the first 3 baroclinic modes of the LM.

Fig. 11. a) Variance spectra of SST averaged over 2°S-2°N of the Atlantic equator from 3-day-mean TRMM data for the period of 2002-2003. Dashed contours show 90% significance level. b) Time series of TRMM and PIRATA SST at (10°W, 0°N) during 2002-2003. Note that continuous PIRATA SST is available only in 2003 at this location.

Fig. 12. a) Variance spectra of QuikSCAT zonal wind stress,  $\tau^x$ , averaged over 5°S-5°N based on a 7-year period of 2000-2006. b) Same as a) except for meridional wind stress,  $\tau^y$ . c) Variance spectra of AVISO SSHA averaged over 2°S-2°N based on the period of 2000-2006.

Fig. 13. a) Simultaneous correlation map between time series of 40-60-day bandpass filtered QuikSCAT zonal wind stress averaged over (35°W-10°W, 2°S-2°N) and 40-60-day AVISO SSHA in the equatorial Atlantic basin for the period of 2000-2006. Positive values are shaded and negative ones are contoured in dashed lines, with an interval of 0.2. Zero contour is suppressed. Correlation coefficients in regions within the thick solid gray lines exceed 95% significance. b) Same as a) except for SSHA lags the wind by 15 days. c) Same as a) except for 2002. For this case the thick solid gray lines represent 90% significance. d) Same as c) except that SSHA lags the wind by 15 days.

Fig. 14. a) Longitude-time plot of 10-40-day band-passed SSHA averaged over 2°S-2°N from the LM MR solution for 2002; b) Same as a) except for HYCOM EXP run; c) Same as a) except for HYCOM MR; d) Same as a) except for HYCOM MR D20.

Fig. 15. a) Longitude-time plot of 10-40-day band-passed SSHA averaged over 2°N-5°N from the LM MR solution for 2002; b) Same as a) except for LM (MR-EXP1), which isolates  $\tau^y$  forcing; c) Same as a) except for HYCOM EXP run; d) Same as a) except for HYCOM MR; e) Same as d) except for HYCOM MR D20.

Fig. 16. a) The 10-40 day band-passed HYCOM MR SSHA in the equatorial Atlantic basin during spring, day 71 of 2002; b) and c) are the same as a) except for day 78 and day 85; d)-f) Same as a)-c) except for SSHA from HYCOM EXP; g)-i) Same as a)-c) except for SSHA from LM MR solution.

Table 1. Parameters for the LM:  $C_n$  is the characteristic speed of baroclinic mode  $n$  ( $n=1,2,3,4$ );  $D_n$  is the wind-coupling coefficient for mode  $n$ , and the larger the  $D_n$ , the stronger the mode is excited by winds;  $L_k$  is Kelvin wavelength at 45-day period (here we use  $1^\circ=111\text{km}$ );  $L_r$  is the first meridional mode Rossby wavelength at 50-day (values outside the parentheses) and 45-day (values within the parentheses) periods;  $L_{mrg}$  is the mixed Rossby-gravity wavelength at  $T=15$  days (outside parentheses) and 28 days (within the parentheses).

Parameter	Mode 1	Mode 2	Mode 3	Mode 4
$C_n$ (cm s <sup>-1</sup> )	227	132	86	62
$D_n$ (m <sup>-1</sup> )	3.5x10 <sup>-3</sup>	9.2x10 <sup>-3</sup>	4.1x10 <sup>-3</sup>	2.4x10 <sup>-3</sup>
$L_k$ (°) T=45 days	80	46	30	22
$L_r$ (°) T=50(45) day	26(22)	12(NO)	NO	NO
$L_{mrg}$ (°) T=15(28) day	22(7.4)	55(8.3)	62(10.0)	18(12.2)

Table 2: A suite of HYCOM and LM experiments performed for the period of 2000-2003. See text for more detailed description.

Experiment	Forcing	Description
HYCOM MR	Daily	Complete
HYCOM EXP	Lowpassed 80-day	Remove intraseasonal forcing
LM MR	Daily wind stress	Total wind stress

LM EXP1	Daily zonal wind stress	Zonal wind stress only
LM EXP2	Daily wind stress with a 12° zonal filter within 8°S-8°N.	Remove the winds caused by TIWs

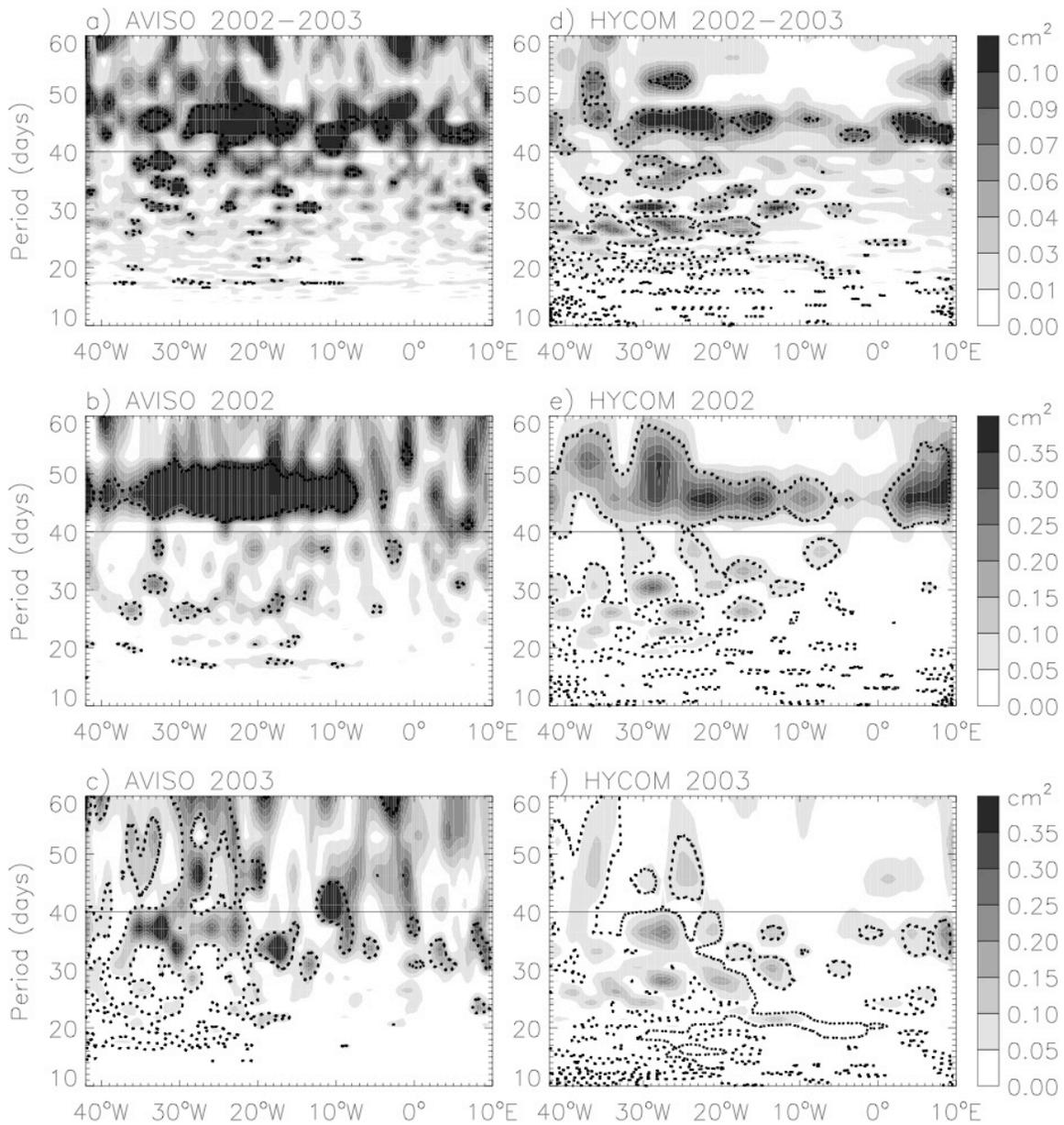


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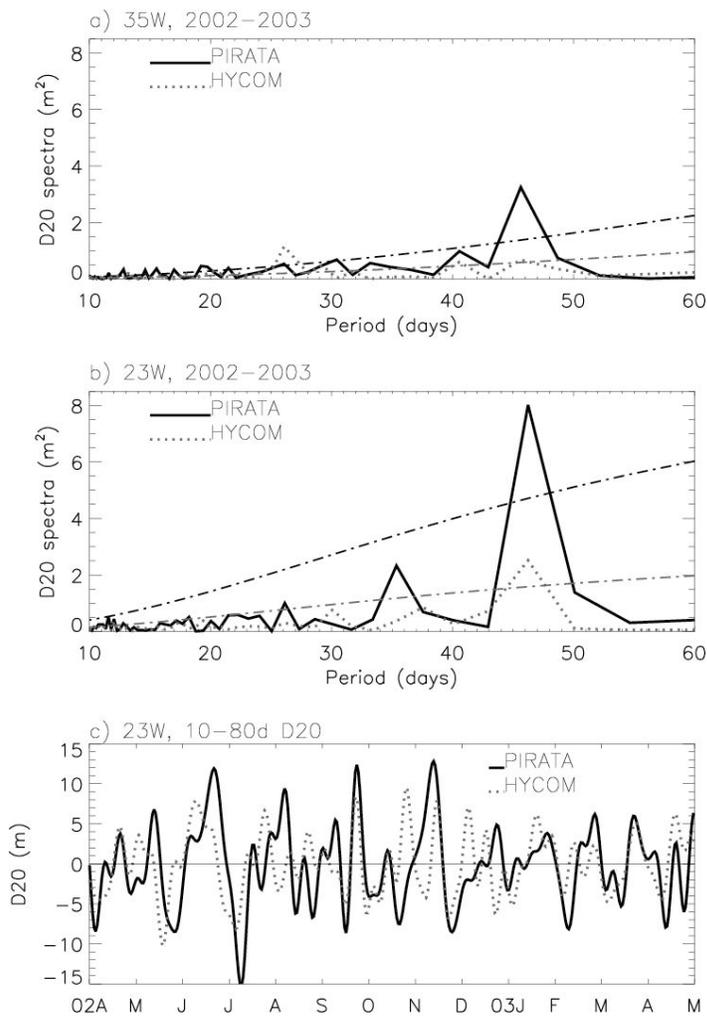


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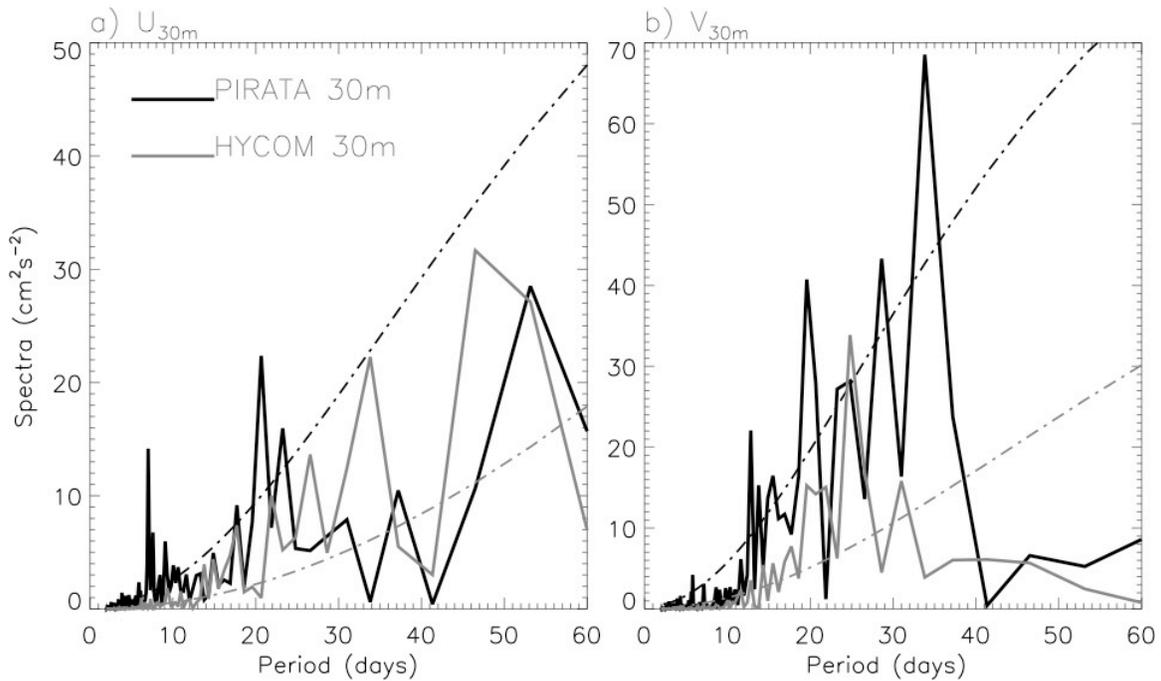


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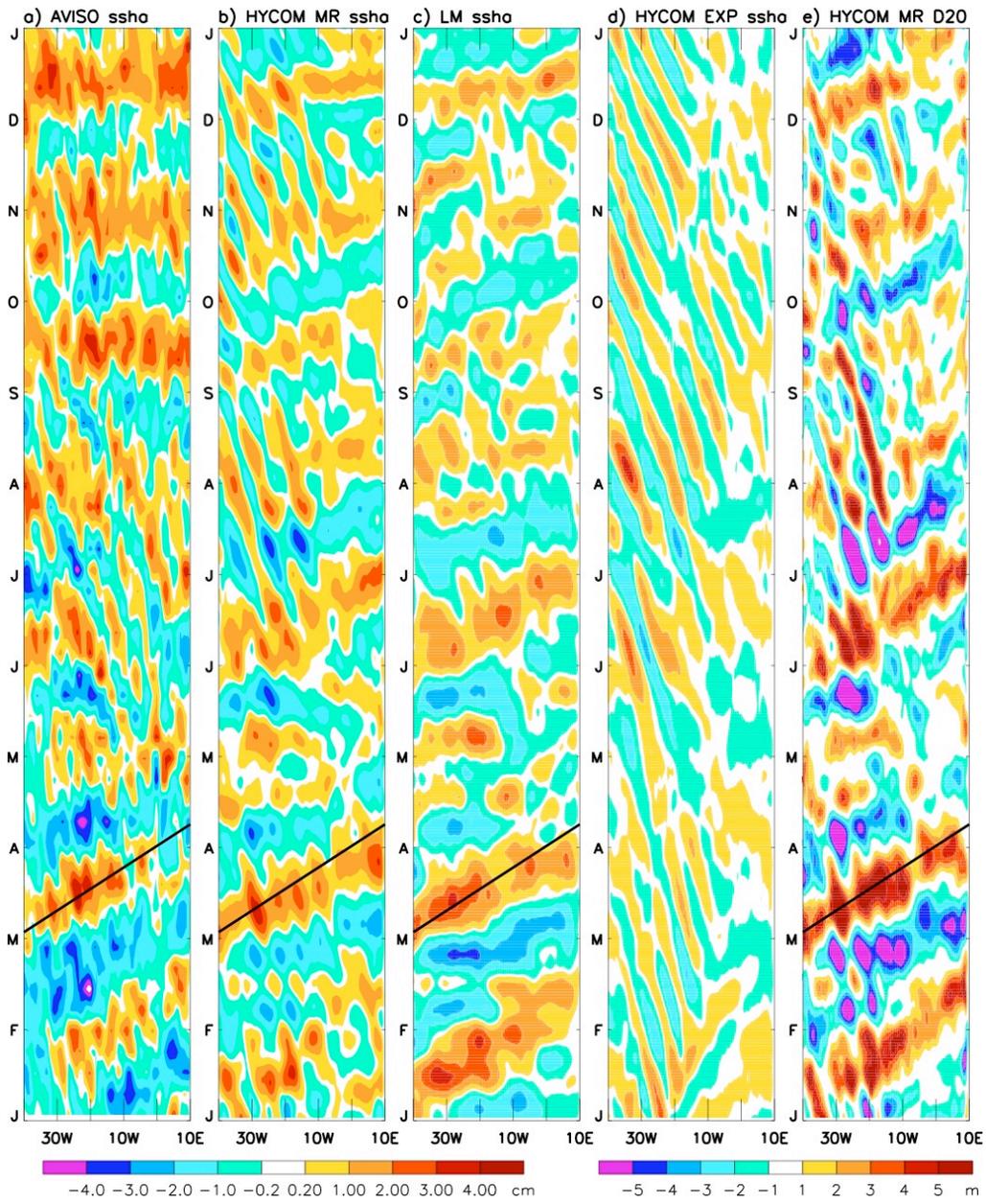


Fig. 4. Longitude-time plot of 14-80 day band-passed SSHA along the equator ( $2^{\circ}\text{S}$ - $2^{\circ}\text{N}$  average) during 2002 from a) weekly AVISO observations; b) daily HYCOM MR solution; c) daily LM MR solution; d) daily HYCOM EXP solution, which isolates the TIWs; e) The same as b) except for HYCOM MR D20. AVISO and model data of 2001-2003 are used for the filter. Units: cm for SSHA and m for D20.

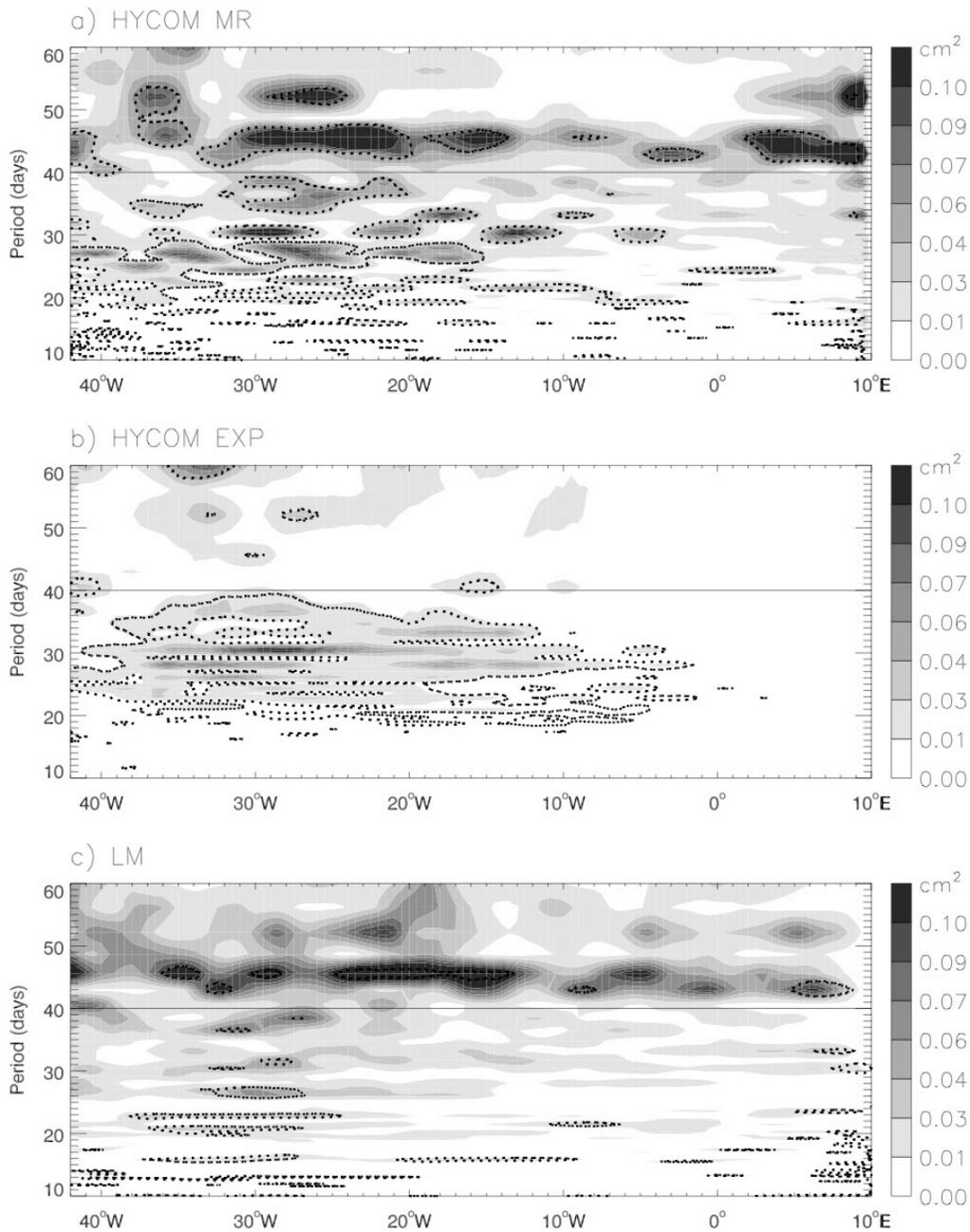


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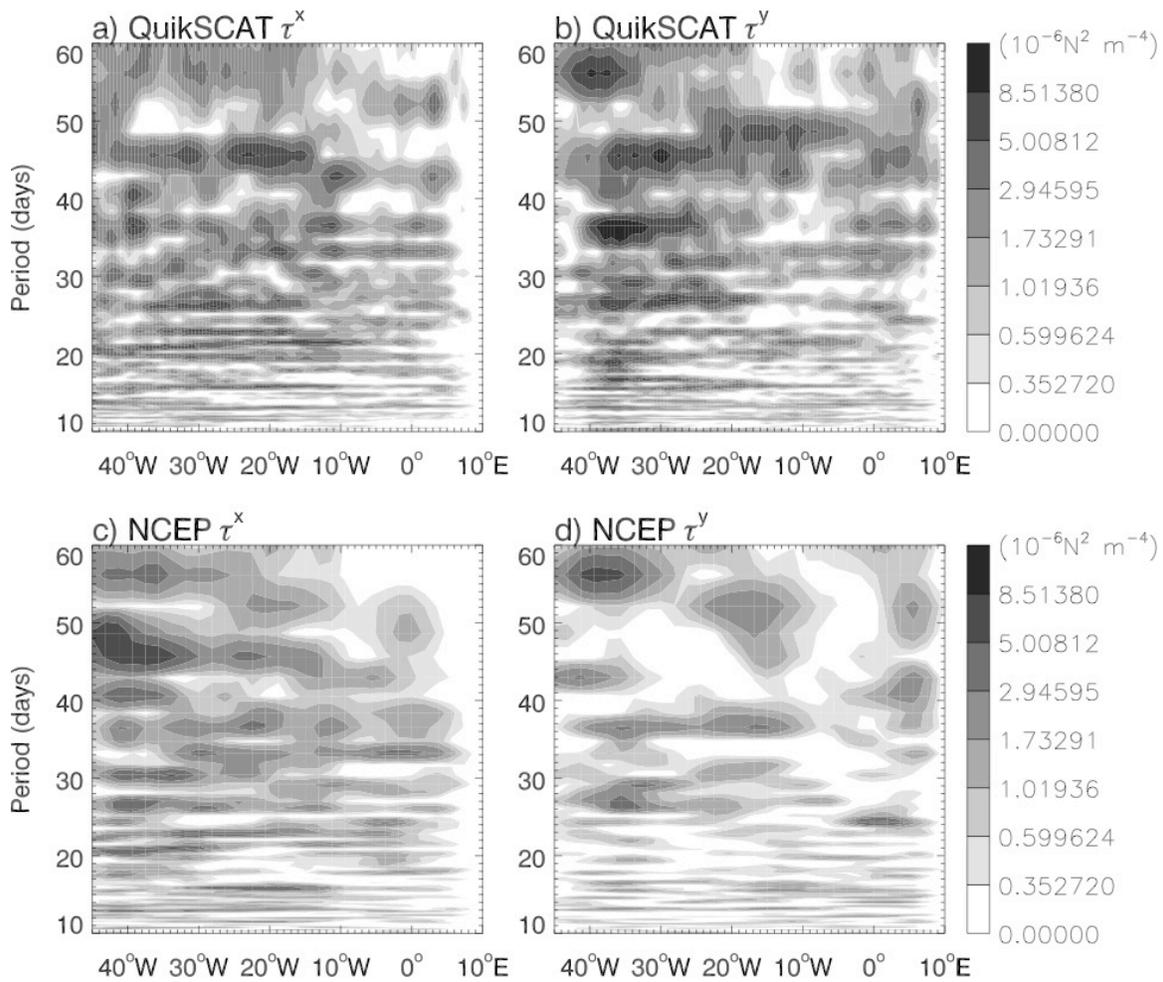


Fig. 6. Variance spectra of surface wind stress along the Atlantic equator ( $5^{\circ}\text{S}$ - $5^{\circ}\text{N}$  average) based on daily winds of 2002-2003. a) QuikSCAT zonal wind stress,  $\tau^x$ ; b) QuikSCAT meridional wind stress,  $\tau^y$ ; c) NCEP  $\tau^x$ ; d) NCEP  $\tau^y$ . As the QuikSCAT wind stress, NCEP wind stress is calculated from 10 m U and V winds using a drag coefficient of 0.0015.

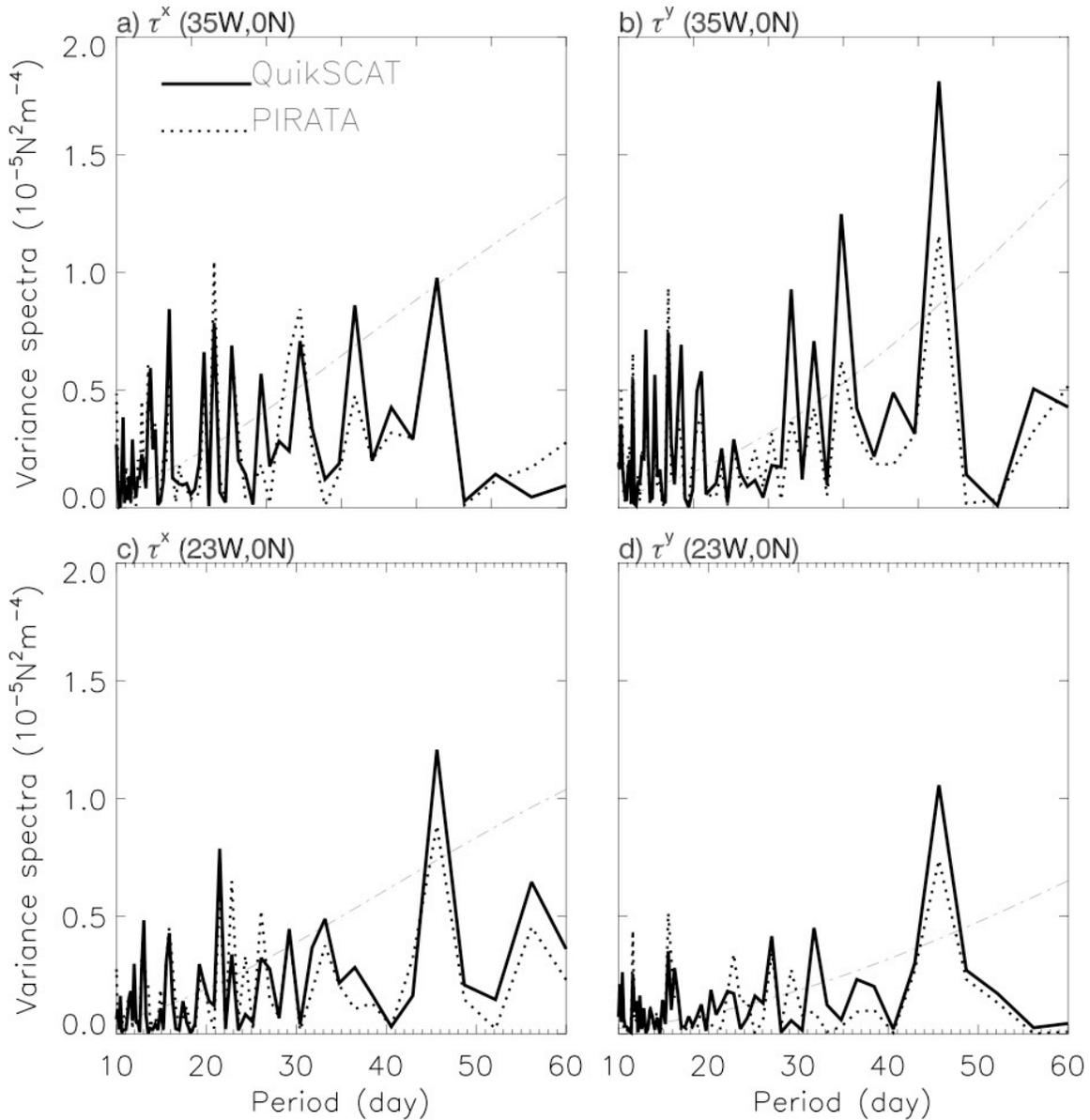


Fig. 7. a) Variance spectra of  $\tau^x$  at ( $35^\circ\text{W}$ ,  $0^\circ\text{N}$ ) from daily QuikSCAT (solid) and PIRATA (dashed) data for the period of 2002-2003. The dash-dotted line is the 90% significance curve for the QuikSCAT data. The seasonal cycle is removed before performing the spectral analysis. b) Same as a) but for  $\tau^y$ ; c) Same as a) but for ( $23^\circ\text{W}$ ,  $0^\circ\text{N}$ ); d) Same as c) but for  $\tau^y$ . The  $1^\circ\text{S}$ - $1^\circ\text{N}$  averaged values are shown for QuikSCAT winds.

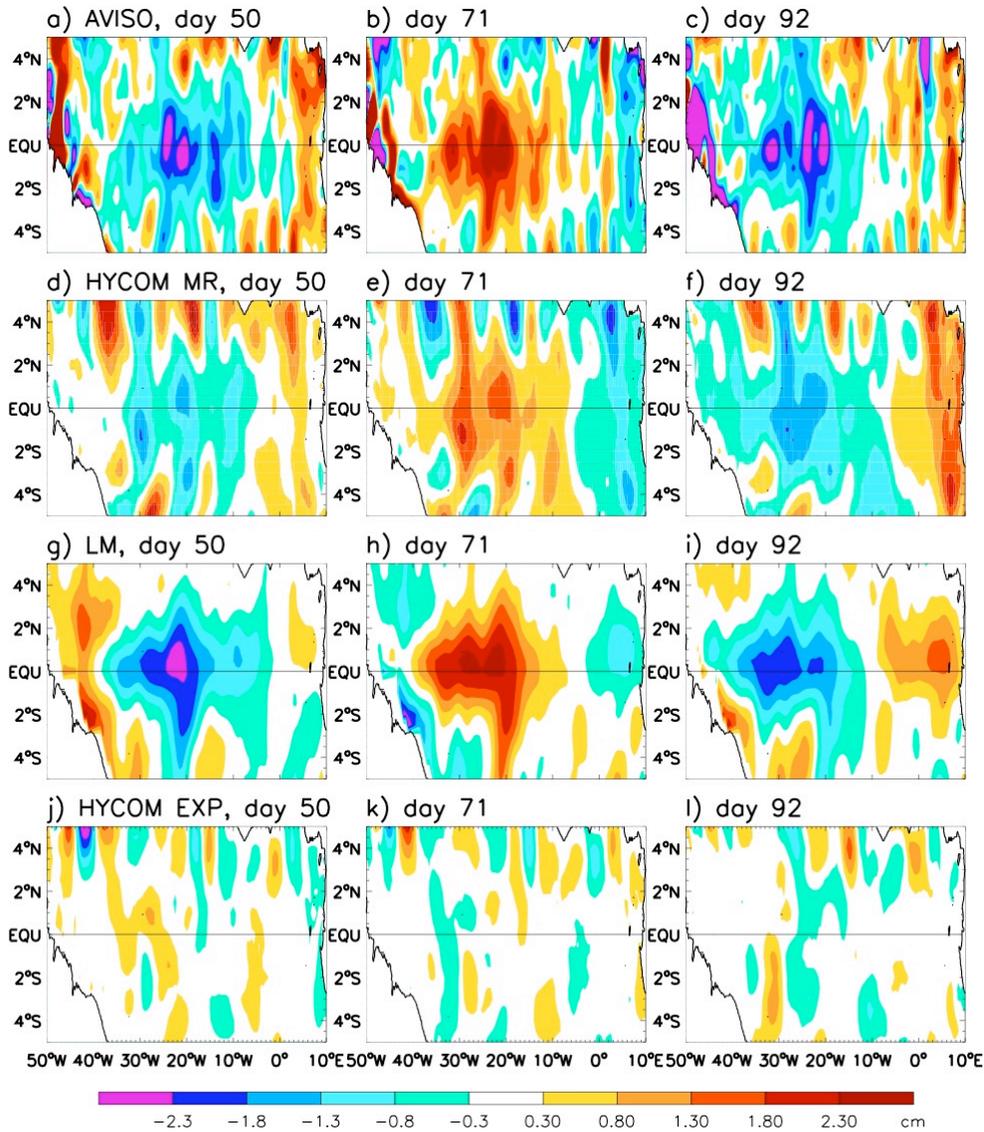


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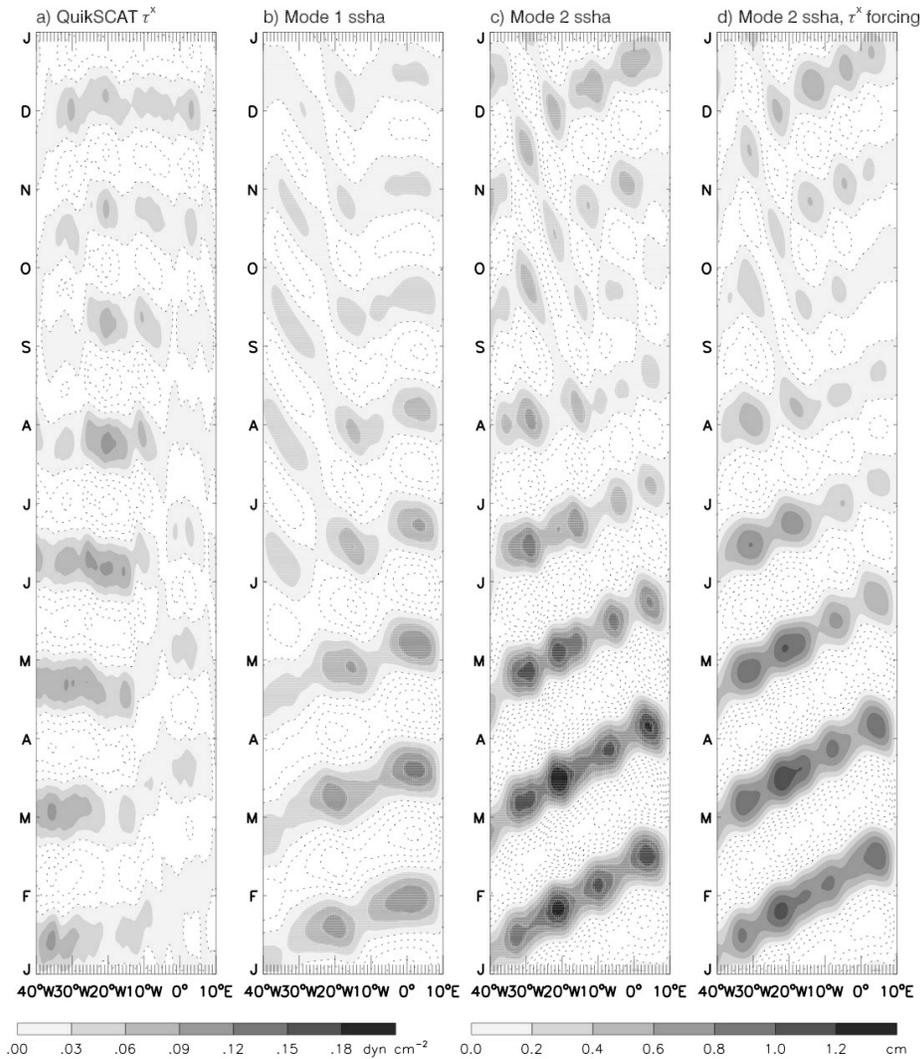


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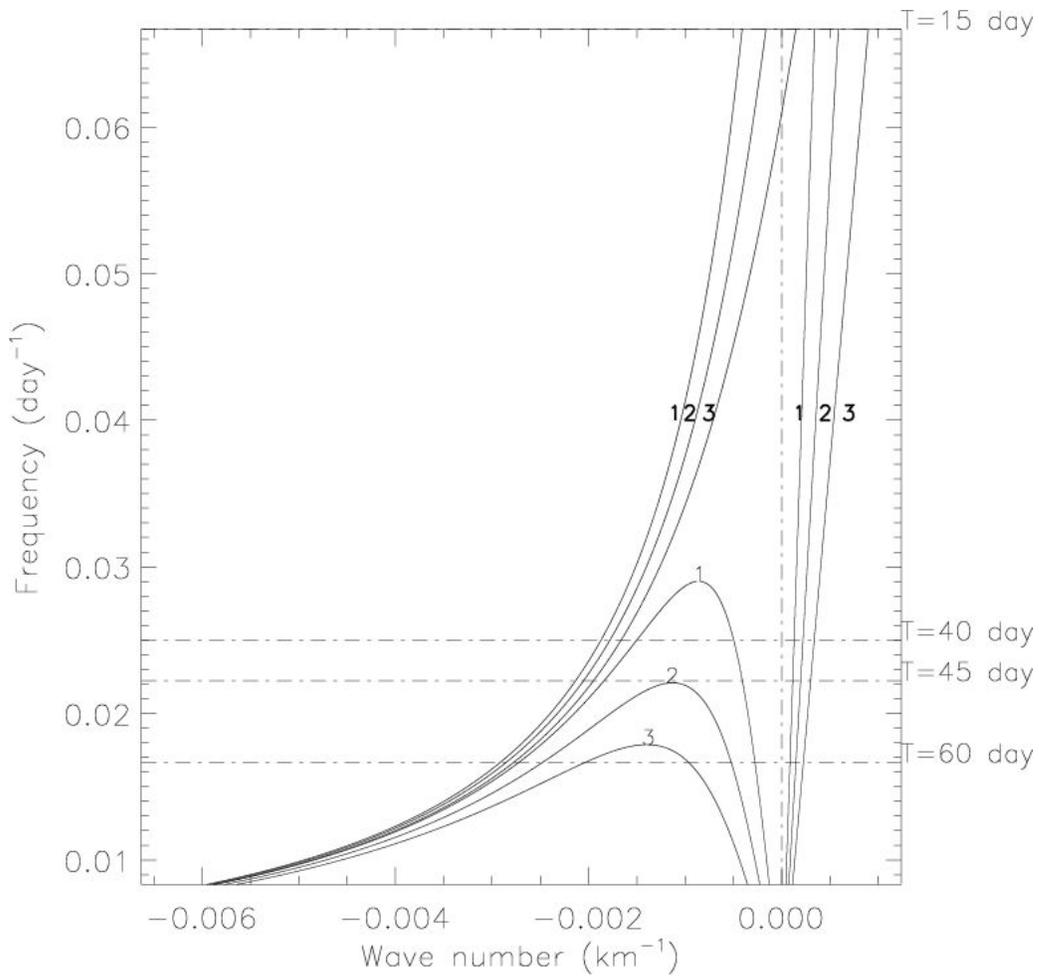


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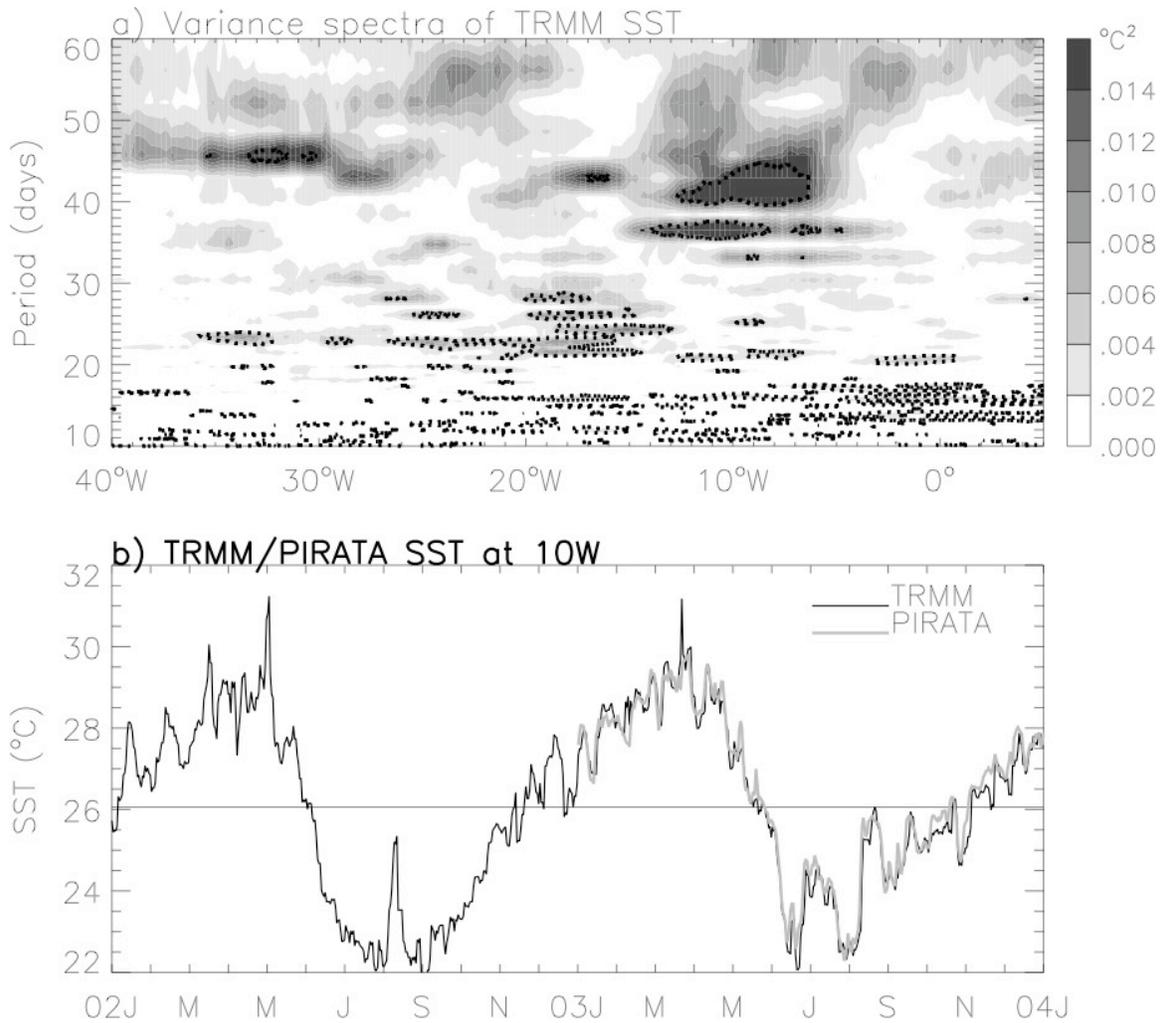


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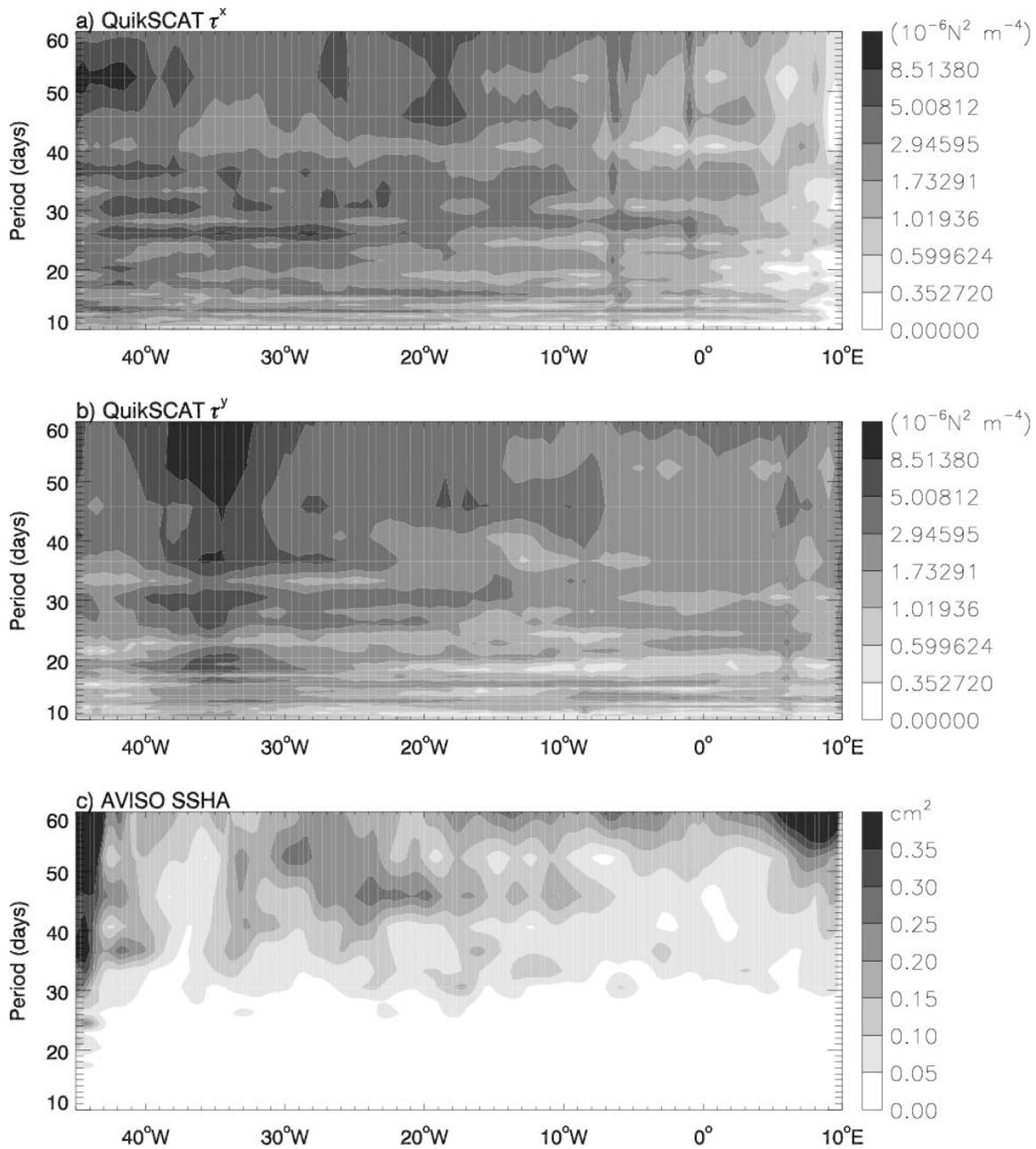


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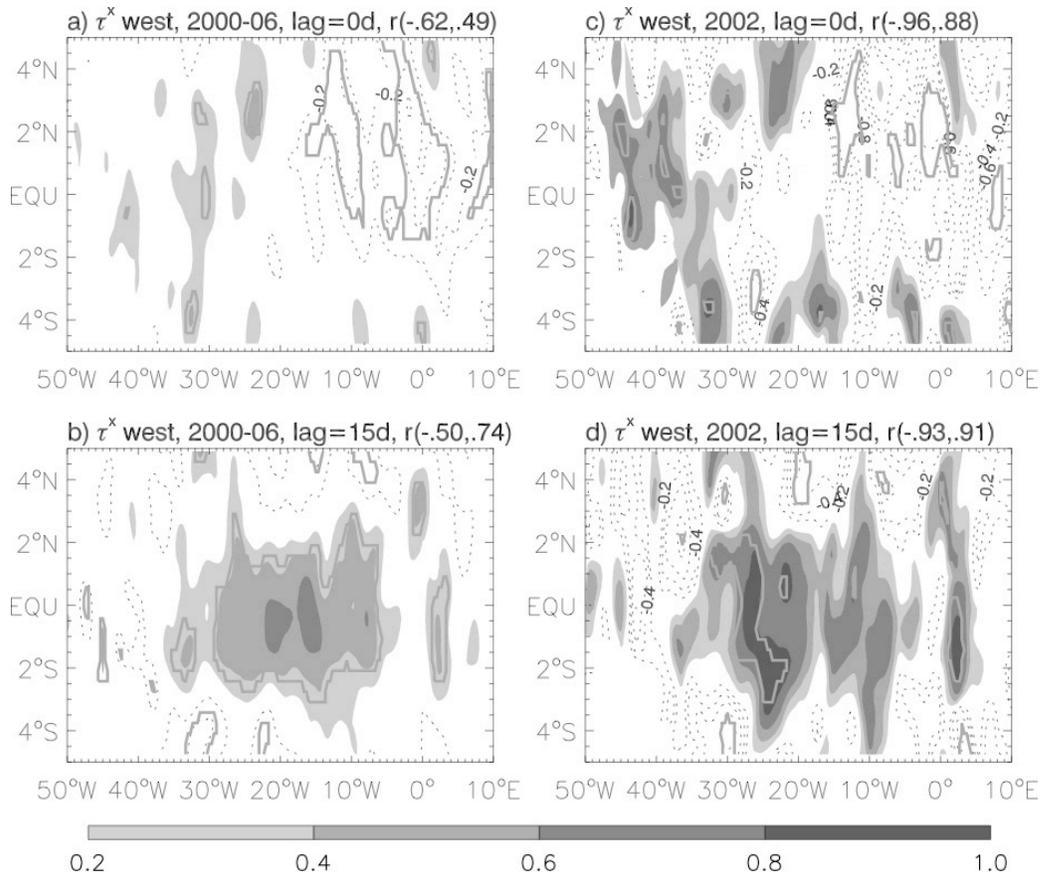


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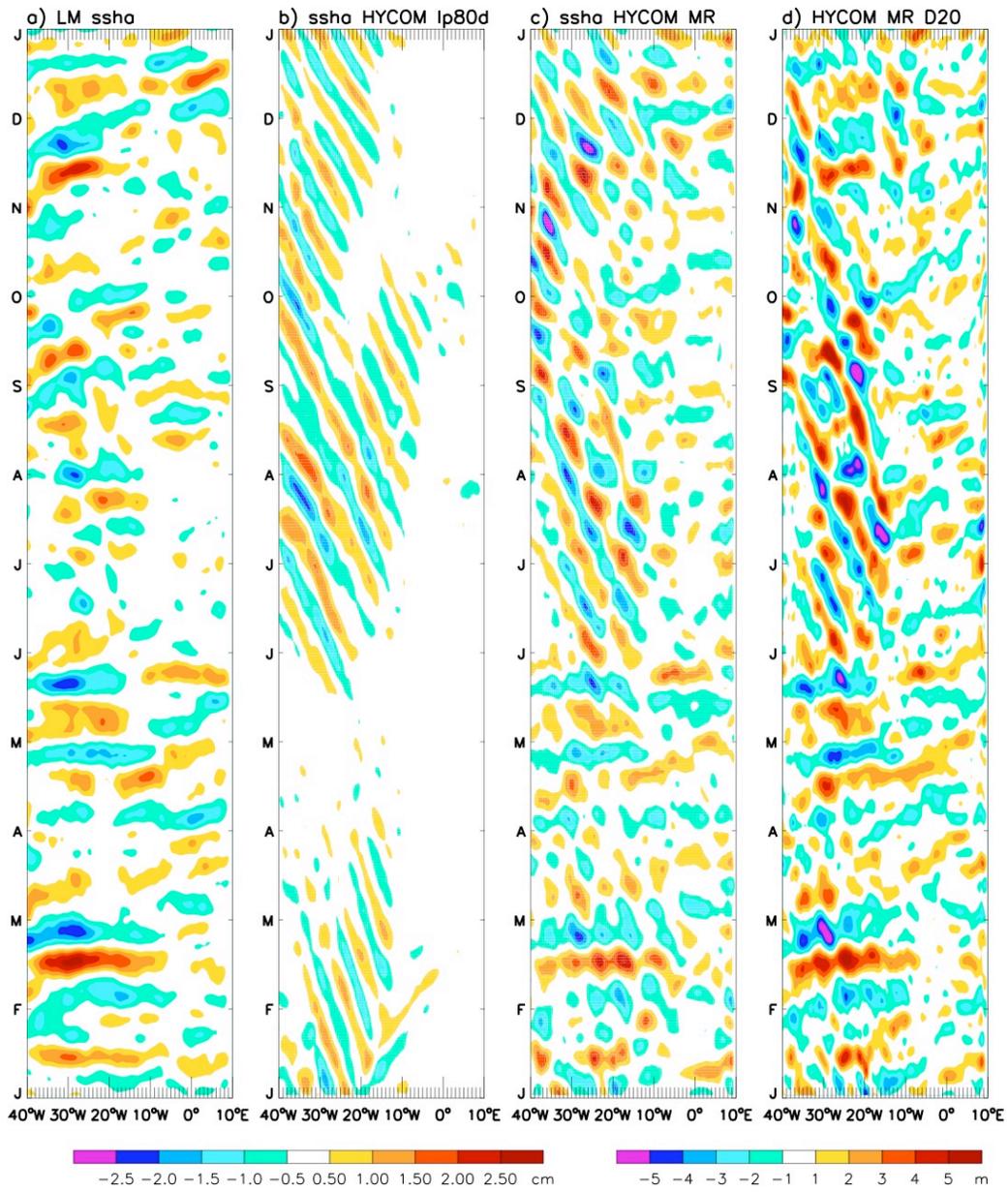


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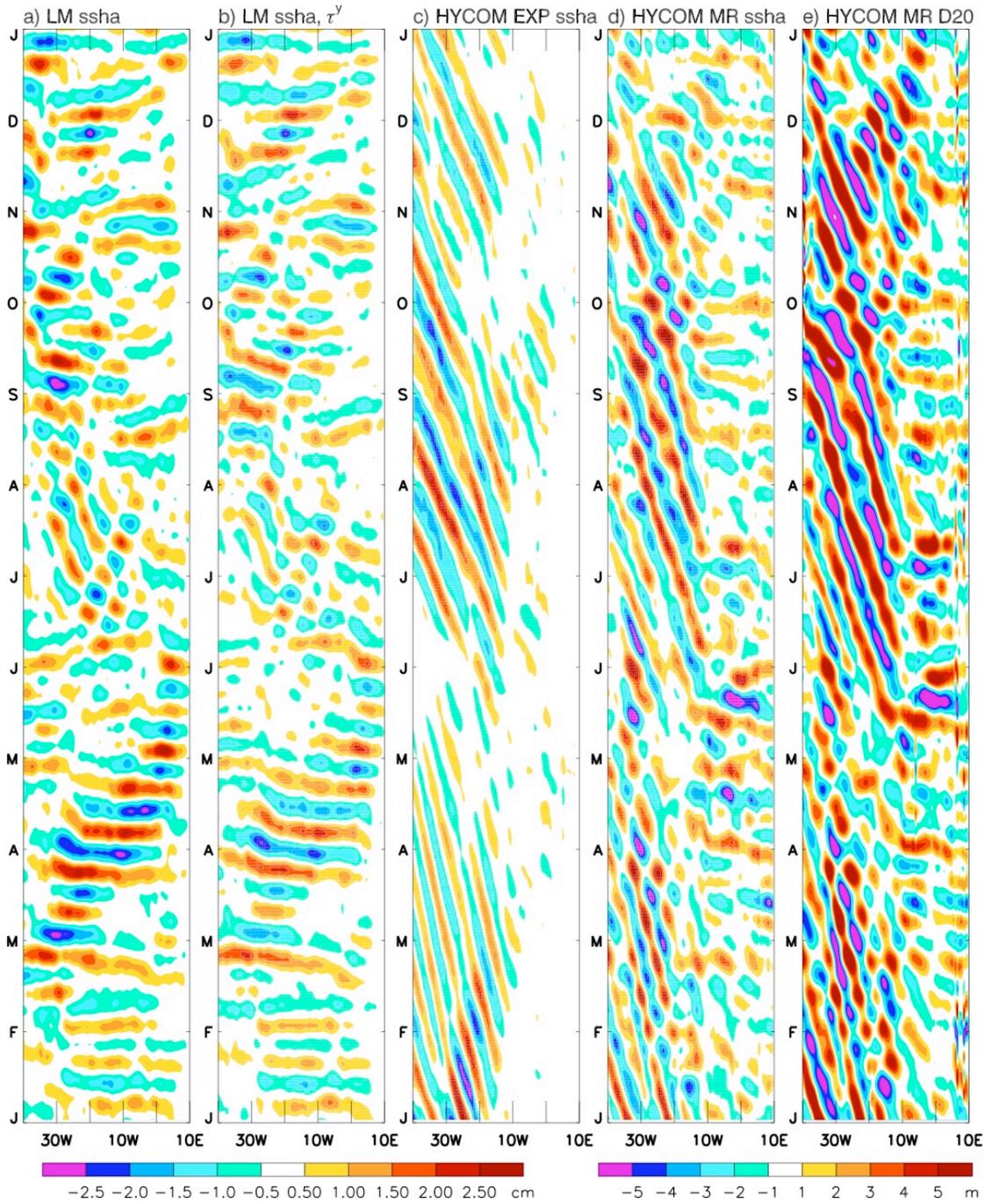


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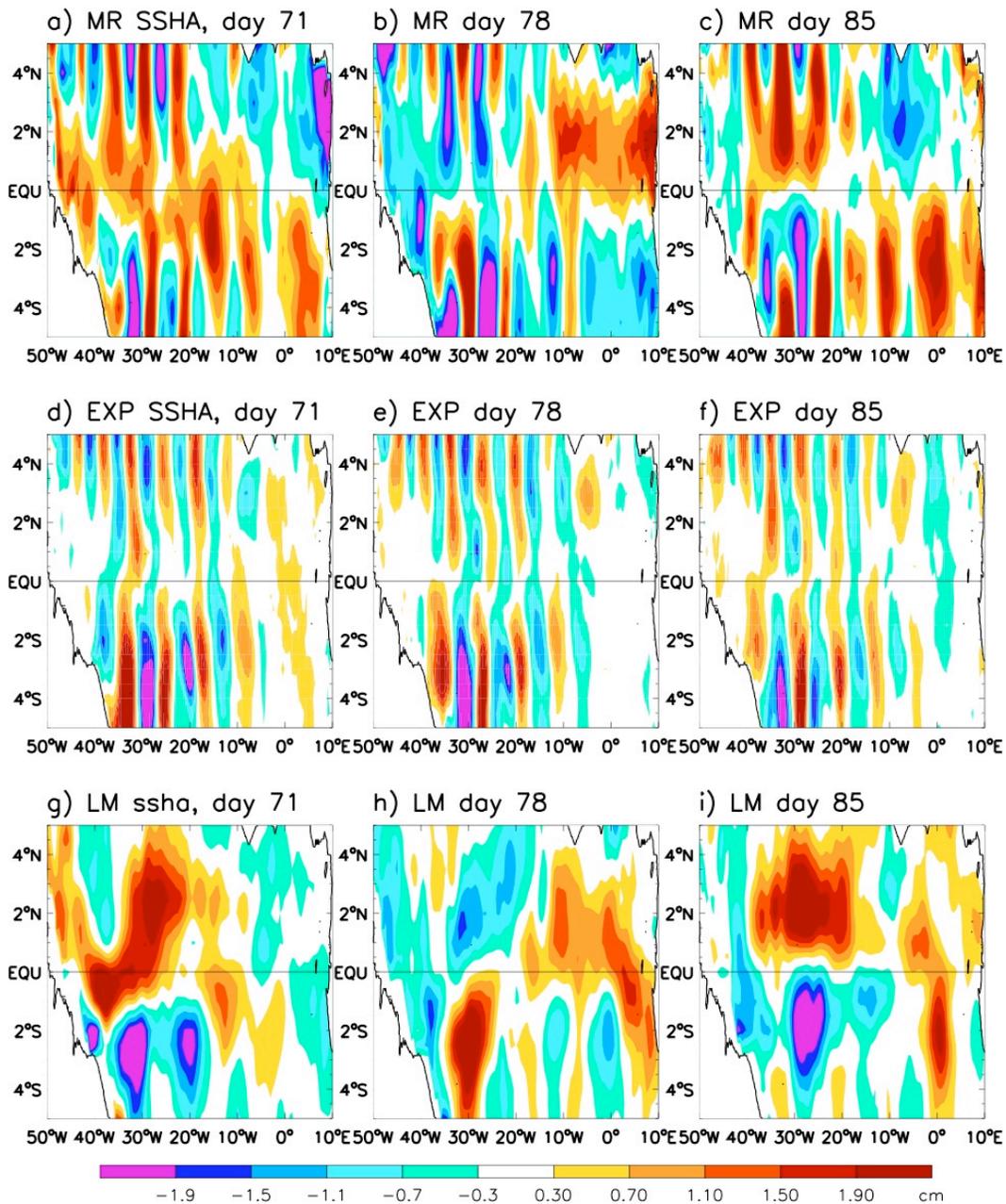


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