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Origin of intraseasonal variability of circulation in the tropical central Indian Ocean

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Abstract. Observed upper ocean currents south of Sri Lanka exhibit large, irregular fluctuations with periods of days to weeks. An ocean model driven by daily surface winds is able to reproduce the observed fluctuations. We find from model experiments that low frequency (30-50 day) intraseasonal variability (ISV) arises when Rossby waves radiated from the eastern boundary are amplified by hydrodynamic instability in the eastern and central Indian Ocean. High frequency (10-15 day) ISV is forced directly by ISV of the wind field in the eastern Indian Ocean. In spite of the contribution from instability, the ocean circulation south of Sri Lanka is a deterministic response to wind forcing.

Introduction

Historical time series of currents from the western equatorial Indian Ocean have shown prominent intraseasonal fluctuations with 20-30 day and 40-60 day periods [*Knox*, 1976; *Luyten*, 1982] superposed on the annual and semiannual signals. Many observed features of the ISV in this region have been successfully simulated by ocean models forced at the surface by climatological monthly mean wind stress, which has little power at intraseasonal time scales [*Kindle and Thompson*, 1989; *Jensen*, 1993]. These modelling studies have demonstrated that ISV of ocean currents arise from instability of the western boundary circulation. On the other hand, surface winds over the tropical Indian Ocean have large ISV with periods of days to several weeks [*Rao et al.*, 1993]. Daily surface winds from the National Centers for Environmental Prediction/National Center for Atmospheric Research (hereafter NCEP) reanalysis [*Kalnay et al.*, 1996] have prominent ISV with 10-20 day and 30-60 day periods, particularly in the central and northeastern Indian Ocean [*Goswami et al.*, 1998]. Can ISV of wind drive ISV of ocean currents in this region, or is oceanic ISV mainly the result of hydrodynamic instabilities, as in the west? Recent measurements from moored instruments along 80.5°E south of the island of Sri Lanka [*Schott et al.*, 1994; *Reppin et al.*, 1999] have revealed striking ISV in upper ocean currents. The time series of zonal currents between 3.75°-6°N from January 1991 to February 1992 contain large irregular oscillations with periods of a few days to 50 days, superposed on the seasonal cycle [*Schott et al.*, 1994]. Here we use an ocean general circulation model to show that although low frequency ISV of the observed ocean currents in 1991 is caused by instability in the northeast Indian Ocean, the apparently disorderly ocean ISV is a deterministic response to the ISV of the wind field.

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Model set-up

We use the Modular Ocean Model [*Pacanowski*, 1996] set up for the Indian Ocean basin between 30°S-30°N and 30°E-110°E, with horizontal resolution of 1/3° by 1/3° north of 5°S. There are 19 levels in the vertical, six of which are in the top 100 metres. Horizontal eddy diffusivity and viscosity are 500 m^2s^{-1}. Vertical mixing is based on the scheme of Pacanowski and Philander [*Pacanowski*, 1996]. Ocean bottom topography is based on the 1/12° by 1/12° resolution data from the U.S. National Geophysical Data Center. Surface temperature and salinity fields are relaxed to the observed annual cycle from the climatological data of Levitus [*Levitus*, 1982]. The model ocean is driven at the surface by daily wind stress created from the NCEP daily wind field at 10 metre height with a constant drag coefficient of 0.0013. A comparison with surface winds from three moored met-ocean buoys in the Bay of Bengal from late 1997 and 1998 shows that NCEP wind is somewhat weak, particularly during short lived episodes of high winds. However, NCEP daily wind reproduces faithfully all ISV on time scales from a few days to months [*Sengupta et al.*, 1999]. This may be because it assimilates, on average, over 10 ship wind observations a month in each 2.5° box over the Bay of Bengal, as well as surface pressure reports.

Model runs

Harmonic analysis was used to isolate the seasonal cycle (periods of 90 days or more) of the NCEP daily wind stress for each year, from the higher frequency variations. Thus

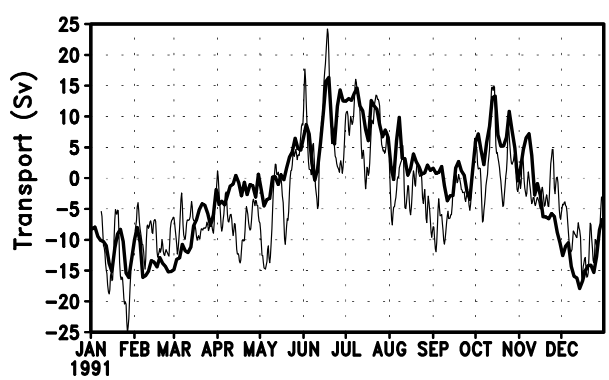

Figure 1. Transport in Sverdrup (1Sv = 10^6 m^3 s^{-1}) in the upper 300m across a section along 80.5°E south of Sri Lanka from the observations (thin line) and the *control run* of the model (bold line). The section extends from 3°45′N to 5°52′N in the transport calculations of *Schott et al.*[1994], and from 3.5°N to 5.6°N in the model transport calculations.

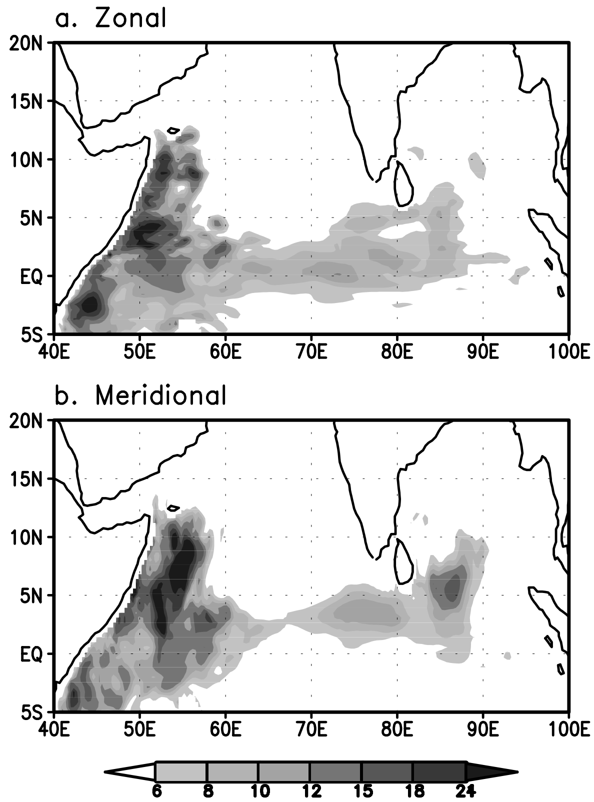

Figure 2. Standard deviation (cm s^{-1}) of (a) zonal and (b) meridional anomaly current at 50m depth between 1 June and 31 December 1991 from the *seasonal* run.

the seasonal wind stress has no ISV while the intraseasonal wind stress contains only the ISV of the full field. We carried out three experiments with the ocean model to bring out the origin of ISV of upper ocean currents. The *control run* is a five year integration of the model forced by daily wind stress from 1 January 1987 to 31 December 1991. The initial conditions are zero flow and observed January mean temperature and salinity fields [*Levitus*, 1982]. The *seasonal run* uses the seasonal wind stress, starting with ocean fields of 30 October 1990 from the *control run* as initial conditions. The *intraseasonal run* is designed to isolate the effects of ISV of the wind stress field on upper ocean circulation. This is a two year integration of the model forced by intraseasonal wind stress, beginning 1 January 1990. The initial conditions are horizontally uniform temperature and salinity profiles, corresponding to the annual mean vertical profiles averaged over the Bay of Bengal [*Levitus*, 1982], and zero flow. Therefore in this run, horizontal density gradients and currents associated with these density gradients develop purely as a result of forcing by the ISV of wind stress. We use results for the year 1991 from all three model experiments.

Comparison with observations

The observed volume transport in the upper 300 metres across an array of moored current meters south of Sri Lanka [*Schott et al.*, 1994], and the corresponding transport from the *control run* of the model are shown in Figure 1. The generally westward flow in winter is associated with the Northeast Monsoon Current and the eastward flow in summer with the Southwest Monsoon Current (SMC) [*Hastenrath and Greischar*, 1991]. It is important to note that the intraseasonal fluctuations in the model transport are in phase with the larger of the observed fluctuations. The amplitudes are generally smaller in the model. Comparison with vertical profiles of observed currents shows that model upper ocean currents are systematically weak, perhaps due to limitations in model horizontal or vertical mixing. The *control run* also reproduces the observed circulation off the east coast of India in March and December 1991 [*Shetye et al.,* 1993, 1996], including the more prominent eddies with lateral scales of a few hundred kilometers (not shown).

Intraseasonal variability of the circulation

We find that oceanic ISV is generated in the *seasonal* and *intraseasonal runs* as well as the *control run.* To isolate that part of the ISV which is generated by instability of the large scale circulation, we remove the seasonal cycle (periods 90 days or greater) from the *seasonal run* model currents. The standard deviation of the resulting *anomaly currents* in the period June-November 1991 (Figure 2) shows that there are two regions of instability, where oceanic ISV is generated in the absence of an intraseasonal signal in the wind stress.

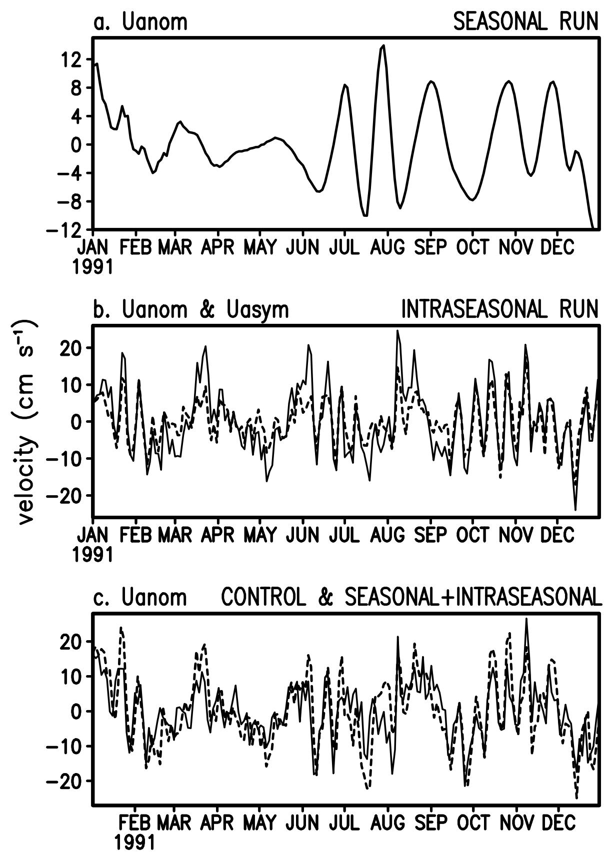

Figure 3. Anomaly zonal current at 50 metres along 80.5°E averaged between 3.5°N and 5.6°N (a) from the *seasonal* run, (b) from the *intraseasonal* run (solid), and its antisymmetric part (dashed); (c) from the *control* run (solid), and the sum of the *seasonal* and *intraseasonal* runs (dashed). All units are cm s^{-1}.

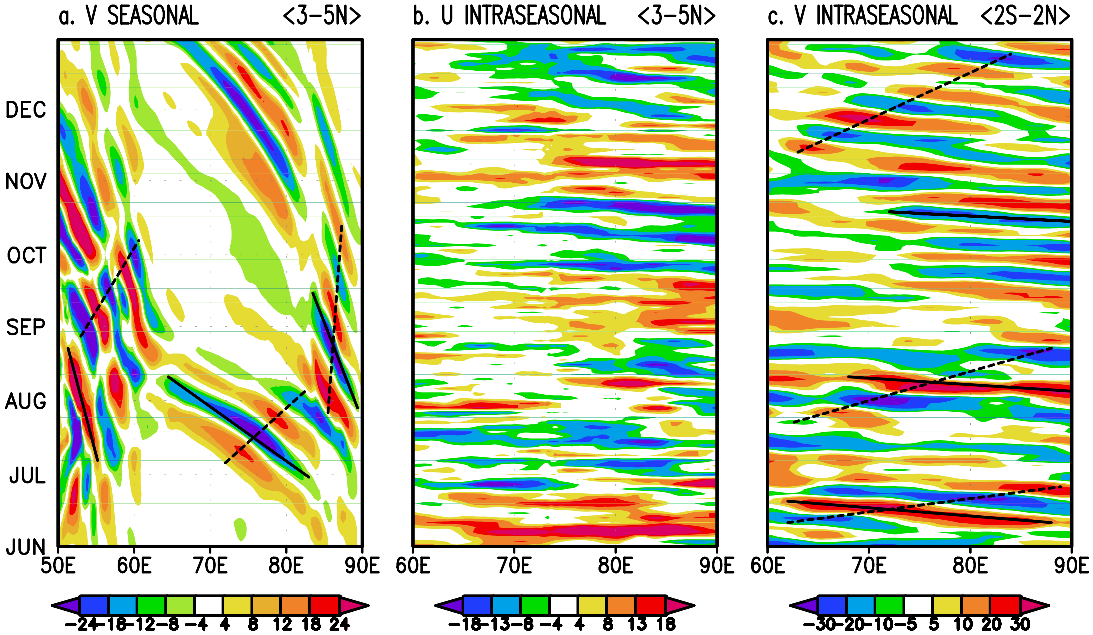

Figure 4. (a) Time-longitude plots of (a) anomaly meridional current averaged between 3°N and 5°N from the *seasonal* run, (b) 3°N-5°N averaged zonal current from the *intraseasonal* run, (c) same as (b) but for 2°S-2°N averaged meridional current. Units are cm s^{-1}. The solid and dashed lines indicate the phase and group propagation of the oscillations.

They are located in the western Indian Ocean and in the equatorial ocean east and south of Sri Lanka. For brevity we refer to these as the western and eastern regions of instability. The northward gradient of potential vorticity changes sign at several places in the upper 150 metres, confirming that necessary conditions for instability are satisfied in these regions. The eastern region of instability lies to the north of 2°S and east of 75°E. We shall show below that instabilities in the western Indian Ocean do not contribute to the ISV south of Sri Lanka.

Figure 3a shows anomaly currents from the *seasonal run* south of Sri Lanka; the 30-50 day fluctuations arise from instability in the eastern region. The instability is the result of interaction of eastward mean flow with Rossby waves radiated from the eastern boundary, as in the nonlinear experiments of *Greatbatch* [1985] with idealised winds, and the simulation of *Vinayachandran and Yamagata* [1998]. In the *seasonal run*, Rossby waves are generated when downwelling equatorial Kelvin waves of April-May and September-October 1991 (the spring and fall eastward equatorial jets, [*McCreary et al.*, 1993]) meet the eastern boundary, and by Ekman pumping in the southeastern Bay of Bengal. When these Rossby waves encounter the eastward SMC that lies north of the equator, or the fall equatorial jet, a series of vortices is generated that move west and influence the flow south of Sri Lanka from June to November. The vortices are most intense between 2°S and 6°N. They do not have the simple structure of first or second meridional mode free linear Rossby waves, and their westward movement is faster. The high frequency ISV from the *intraseasonal run* is predominantly due to 12-15 day period mixed Rossby-Gravity (MRG) waves with basin scale zonal wavelengths, westward phase speed of about 4 m s^{-1} and eastward group speed of about 1 m s^{-1}. The meridional current (V) associated with these waves is symmetric about the equator while the zonal current (U) is antisymmetric (Figure 3b). They do not arise from instability, but appear to be directly forced by intraseasonal winds in the eastern equatorial ocean, where the wind ISV has a sharply peaked 10-15 day component that propagates west at about 4 m s^{-1}. The large intraseasonal signal in late May-early June marks the onset of the SMC, forced by low latitude Ekman pumping north of the equator as the summer monsoon winds abruptly strengthen. In spite of the contribution from instability, Figure 3c shows that the (anomaly) current from the *control run* is nearly equal to the sum of (anomaly) currents from the *seasonal run* and the *intraseasonal run* - we call this feature *quasilinearity*.

In the *control run* and the *seasonal run*, packets of MRG waves with monthly and bimonthly period radiate towards the central equatorial Indian Ocean from the western instability region, as in previous modelling studies [*Kindle and Thompson*, 1989; *Jensen*, 1993]. However, these waves have slow eastward group speed, and do not contribute significantly to the oceanic ISV south of Sri Lanka. At 80.5°E, the low frequency ISV comes from the eastern instability region (Figure 4a). Figures 4b and 4c illustrate that high frequency ISV from the *intraseasonal run* comes from westward propagating 12-15 day MRG waves generated in the eastern Indian Ocean. The meridional averaging used in Figure 4c highlights the symmetric meridional current associated with this mode. The zonal current field has a 60-day modulation that arises from the presence of a similar signal in the intraseasonal wind stress. Note also the abrupt onset of the SMC in June.

Schott et al.[1994] propose that ISV of summer transport south of Sri Lanka is due to coastal Kelvin waves in the Bay of Bengal generated by fluctuation of the large scale monsoon winds. We do not find evidence for this mechanism in the model. However, coastal waves associated with ISV east of Sri Lanka do produce episodes of westward flow at 80.5°E in summer.

Conclusions

We have shown that the origin of ISV in the central and eastern tropical Indian Ocean involves Rossby wave radiation from the eastern boundary and their amplification by instability, as well as direct forcing by winds. Instability in the ocean can generate variability whose evolution cannot be predicted far into the future even if the surface forcing is known [*Philander*, 1990]. Nevertheless, the *control run* reproduces (the phase of) the intraseasonal fluctuations in the 1991 observations. Further, although *quasilinearity* is not valid in the western instability region, it holds over most of the east Indian Ocean, including the western boundary of the Bay of Bengal. It appears that the rapidly changing structure of the mean flows in this region, and the quick dispersal of energy caps the growth of unstable disturbances, making the system predictable.

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