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Inference of vertical motion in the equatorial Indian Ocean using satellite data

Monsoon onset
Mixed layer slope
Zonal windstress
Equatorial vertical motion
Satellite data

Début de la mousson
Pente de la couche de mélange
Contrainte de vent zonale
Mouvement vertical équatorial
Données satellitaires

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ABSTRACT

Vertical motion in the equatorial Indian Ocean in the form of vertical displacements of the thermocline is studied during the Monex-79 summer monsoon season. These displacements are associated with the jet-like surface response of the equatorial ocean to zonal windstress reversal at the time of the onset of the monsoon. The surface windstress distribution and variations are obtained indirectly from GOES geosynchronous satellite low-cloud motion winds by utilizing suitable collateral data. The sea-surface-temperature field from the TIROS-N satellite is also examined.

A more complete experiment involving INSAT, NOAA, microwave satellites, *in situ* data, numerical models and a biological component is proposed, conveniently entitled EQUatorial INdian Ocean eXperiment (EQUINOX), signifying the response to seasonal transitions.

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RÉSUMÉ

Effets d'un mouvement vertical dans l'Océan Indien équatorial déduits de données satellitaires

Un mouvement vertical, sous la forme de déplacements verticaux de la thermocline dans l'Océan Indien équatorial, a été étudié lors de la campagne de la mousson d'été Monex-79. Ces déplacements sont associés à la réponse en surface, sous forme de jet, de l'océan équatorial au renversement de la contrainte zonale du vent, au début de la mousson. La répartition et les variations de la contrainte en surface du vent sont obtenues indirectement, en utilisant les données du satellite géostationnaire GOES. Le champ de température de surface est examiné à l'aide des données du satellite TIROS-N.

Une expérience plus complète, tenant compte des données *in situ*, de INSAT/NOAA, satellite à micro-ondes, de modèles numériques et des composants biologiques est proposée et appelée EQUatorial INdian Ocean eXperiment (EQUINOX), c'est-à-dire réponse aux changements saisonniers.

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INTRODUCTION

Seasonal reversal of the atmospheric winds has a significant influence on the circulation in the Indian Ocean. The general surface wind-pattern during the south-west monsoon is not conducive to equatorial upwelling. However the rapid event-like onset of the westerlies generates a jet of surface current in the equatorial wave guide (Wyrtki, 1973 ; O'Brien, Hurlburt, 1974) and a reversal of the undercurrent also takes place (Luyten, 1981) ; theses changes are expected to be accompanied by marked vertical displacements of the thermocline, as shown by a non-linear numerical model (O'Brien, Hurlburt, 1974). Analysis of Gan island data has indicated the importance of dynamically-induced vertical motion of the thermocline (the mixing due to entrainment being generally negligible), and a coherence of the mixed layer depth (MLD) with the zonal wind around a 40-day period has been detected (McPhaden, 1982). This suggests that vertical motion may be inferred in terms of thermocline depression/rise if the zonal wind-stress is known. In view of the rapid and integral nature of this response, the stress field must be determined over the whole belt, and on a short (~ weekly) time scale. The integral nature of the response is discussed at some length in Weisberg (1984) and references cited therein ; essentially, each segment of the equatorial belt may be seen as generating its own eastward-propagating Kelvin wave or Yoshida jet as a response to the local zonal windstress impulse ; these disturbances then accumulate at the eastern end of the belt.

The only practical means of observing the oceanic wind-stress field synoptically and frequently is through satellite sources. Wylie and Hinton (1984) and Simon and Desai (1986) have discussed the extension of geosynchronous satellite winds to the surface in the Indian Ocean. In the present paper, GOES low-cloud winds have been utilized to deduce the evolution of the zonal wind-stress field over the equatorial Indian Ocean during Monex-79 ; this evolution is examined in relation to the variations of MLD and sea-surface-temperature (SST). The MLD is estimated from research ships' TEmperature-SAlinity-Current (TESAC) profiles, whereas the SST field is obtained from the TIROS-N satellite.

In addition to the preliminary corroboration of the above idea of inferring the vertical motion, a suggestion for some further experimentation is advanced.

DATA AND METHODOLOGY

The following daily data during Monex-79 (May-July) were used :
1) GOES satellite low-cloud (900 mbar) winds, FGGE/ECMWF objectively analysed wind field, and research ships' surface observations from 5.5°S to 5.5°N and 40 to 90°E ; and 2) research ships' TESAC data and TIROS-N SST and atmospheric water vapour data in two belts (5°S to 5°N and 5-15°N) from 45 to 95°E.

The ECMWF 2-deg.-grid analysed field was used to estimate the average 1 000-850 mbar windshear in each of 20 boxes of interest of size 6 × 5° (Fig. 1) in each of nine 10-day periods, *viz.* May 1-10 to July 21-30, 1979. The shear depends on meteorological conditions such as low-level thermal stability, wind-speed, advection etc. Grid size and the averaging duration were chosen to optimise between the criteria of " homogeneity " and " statistical significance " of the data sets. The shear parameters were : the veering angle and the ratio of the magnitude of the vector wind-difference (1 000-850 mbar) to the 850 mbar wind speed. The acuteness/obtuseness of the angle between the wind-difference vector and the 1 000 mbar wind was noted (as an alias-removal parameter). These shear parameters were then reduced to 900 mbar *via* simple interpolation and applied to individual satellite cloud-vectors (at 900 mbar) to estimate the " surface " (1 000 mbar) winds, which were then averaged over the 6°/5° latitude/longitude grids (Fig. 1) for periods of 10 days. This procedure permitted optimal use of the large " regional " satellite wind data-base together with " global " objective analysis fields derived from all sources of data ; *i.e.* maximal weight was given to the local satellite winds, whereas the analysed global fields were only used to obtain auxiliary information on the wind-shear parameters. Details may be found in a recent related paper (Simon, Desai, 1986). The surface stress was obtained from surface wind using ships' air-density *via* a simple parameterization scheme (Saunders, 1976). The TIROS-N SST was corrected for a water vapour dependent bias as suggested in an inter-comparison study (Pathak, 1982). Ships' TESAC reports were processed to estimate MLD. No standard method exists in the literature for the estimation of MLD. Ostapoff and Worthem (1974) defined MLD as the depth at which the temperature is lower by 1° than the temperature at a 10-m depth. Another method is to define MLD by the temperature gradient. Sometimes the gradient check is satisfied very close to the surface, yielding unduly small MLD. Hence in the present method the depth at which the temperature is one degree less than that at 10 m is first estimated. Then from this point the gradient is checked towards the surface until it is less than 0.08°/m, and the MLD

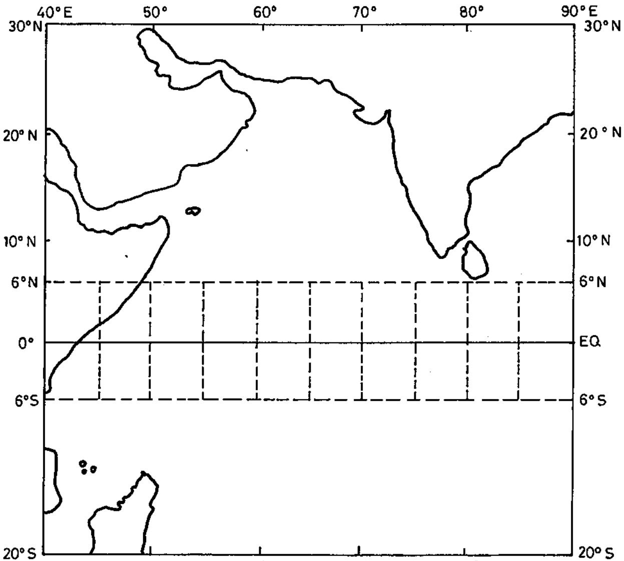


Figure 1

Grids used for wind extrapolation.

is estimated as the mean depth of the last layer with temperature gradient greater than 0.08°/m. If the first layer fails the check, then the mean of the first checked level and the next deeper level is taken as the MLD. Weekly MLD histories in 5 × 10° boxes were developed in both the belts mentioned above, from which the vertical velocities were estimated using simple linear interpolation in space and time to estimate the missing data. Along the equatorial belt (5°S to 5°N), the FGGE/Monex-79 ships' observations are indeed confined largely to the longitude range 45-70°E in weeks 1 to 5 (May 1 to June 4), and to the range 65-95°E in weeks 8 and 9 (June 19 to July 2) whereas in weeks 6 and 7 (June 5 to 18) and in week 10 and onwards, there are scant observations which do not permit longitudinal extrapolation, except at the central sector (65-70°E).

RESULTS AND DISCUSSIONS

The satellite wind reduction to the sea surface was initially validated using ships' surface observations. Based on over 2 400 comparison points the RMS difference was found to be 2 m/s in speed and 35° in direction. The corresponding error margin in the surface stress component determination is estimated to be about 50 % (this reduces to about 40 % if the slight shear in the layer from 1 000 mbar to the sea-surface is accounted for).

The shear parameter results showed a greater impact of the monsoon onset — and a greater subsequent steadiness — in the western segments than in the east, reflecting the characteristics of the Somali low-level jet.

The wind-stress histories do show a marked monsoon onset signal. Typical histories for two boxes in the Arabian Sea and two in the Bay of Bengal are shown in Figure 2. The eastward stress in the southern hemisphere between July 10 and 30 in the 85-90°E grid relates to a cyclonic (clockwise) system that developed just south of that location. The average stress in the equatorial belt is eastward after about June 1. The equatorial belt wind reversal thus occurred about two weeks before the onset of the south-west monsoon over peninsular India (marked in Fig. 2 and 3). This official " onset " is defined in terms of rains over the southern tip of India and the low-level wind direction at that location.

As mentioned earlier, the MLD histories are not available for all periods at all locations due to the limited coverage of ships' observations. However the available data clearly indicate a deepening after onset

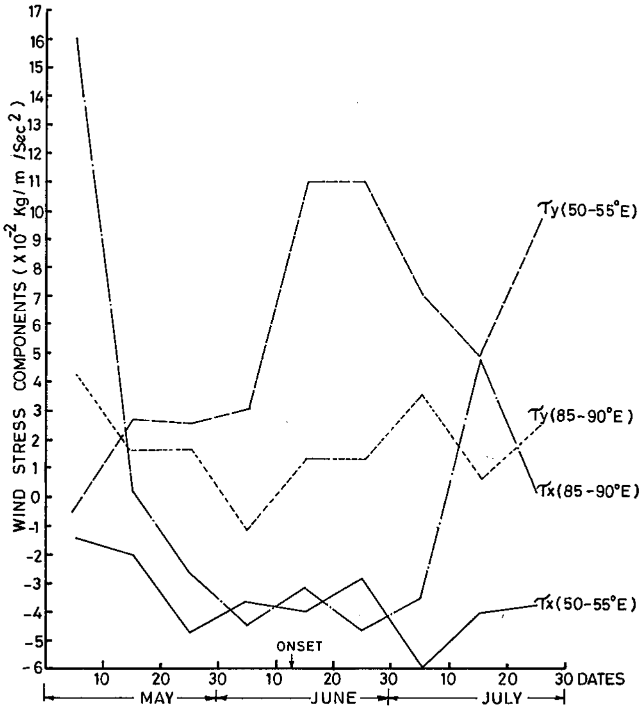


Figure 2 *b*

Typical satellite surface wind stress at the Equator (S.H. : 0-6°S ; 10-day averages).

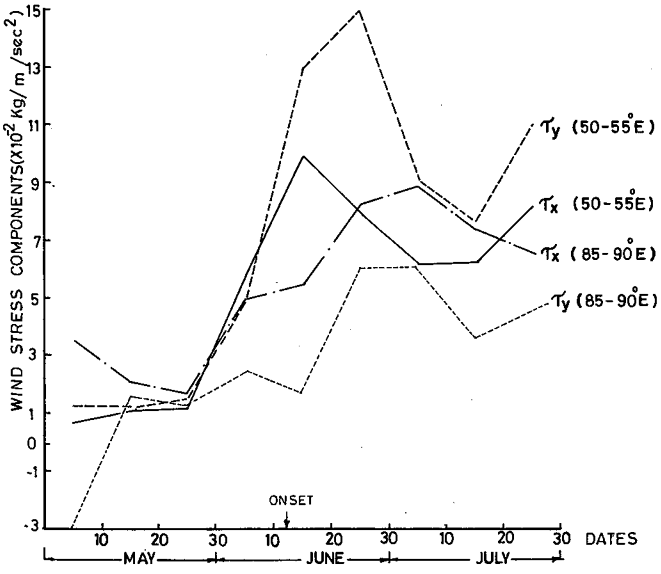


Figure 2 *a*

Typical satellite surface wind stress at the Equator (N.H. : 0-6°N ; 10-day averages).

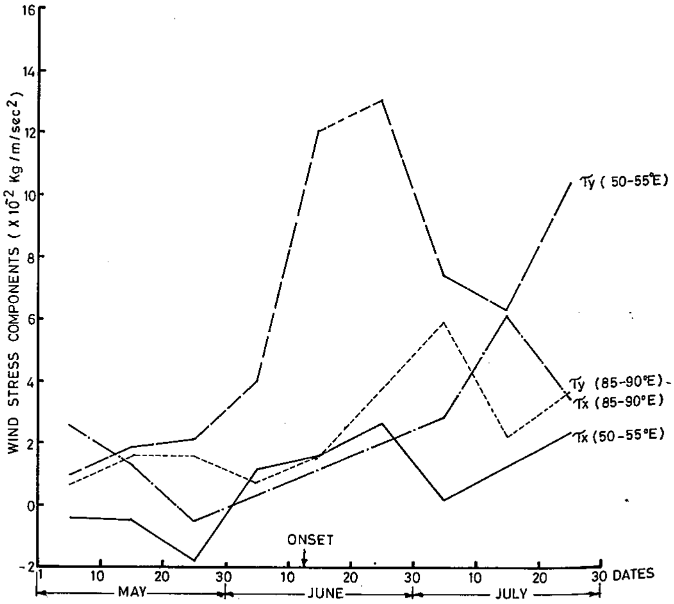


Figure 2 *c*

Satellite surface wind stress (equatorial belt : 6°N-6°S).

in the central, and still more so in the eastern segments, whereas at the western end upwelling and mixed-layer shallowing are seen. Thus the zonal slope of the thermocline at the Equator reverses (downslope from west to east) after the onset. This is in conformity with the integral (eastward cumulative) property of the oceanic response mentioned earlier. The response is fairly rapid (at a time scale of the order of a week to a month). Vertical displacement histories at 3 typical locations are shown in Figure 3 ; the corresponding vertical velocity estimates are also indicated. In the 8th to 9th weeks the MLD trend is arrested somewhat ; this could be the result of a reflected Rossby wave at the eastern boundary.

Deepening is less marked at the off-equator belt (5-15°N, figure not shown). This is attributed to the absence of a waveguide and to the blocking effect of the Laccadive/Maldive isle chain and of the Indian peninsula. Wind-stress-curl induced upwellings occur in this region, which also weaken the deepening process.

Quantitative verification of the extent of thermocline deepening would require a full model and better data coverage. Even an order-of-magnitude check on the balance of wind stress with hydrostatic pressure force across the basin (*e.g.* in the 9th week) could not be carried out due to the lack of ships' data in the western segments at that time. However, at least the qualitative features of the MLD response conform to the expectations as discussed above.

The SST field (Fig. 4) initially shows a cooling in the Somali Zone — more as a coastal upwelling effect — but later this spreads eastward, consistent with the horizontal advection implied by the equatorial response to the zonal wind-stress discussed above. Equatorial upwelling is not indicated (no central equatorial SST minimum is noticed). The comparable eastward spread of cooling in the 5-15°N belt may be related to the separation of the Somali current from the African horn.

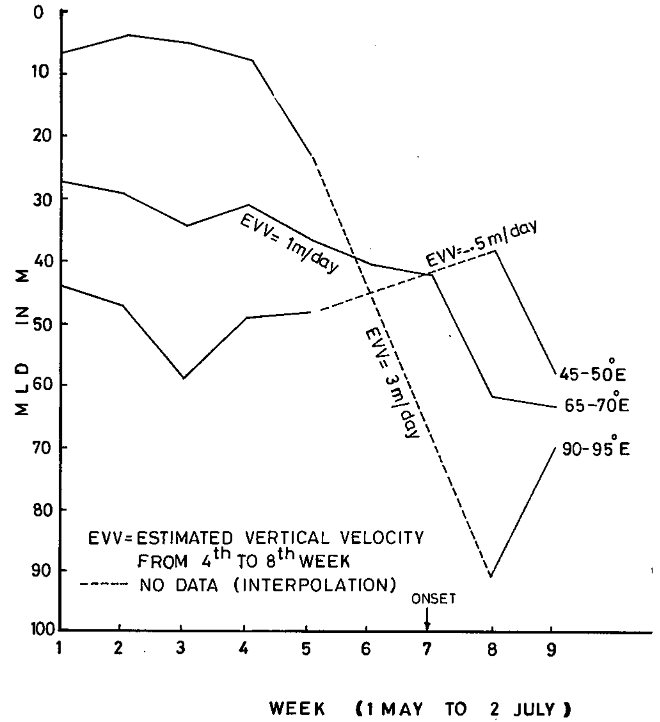
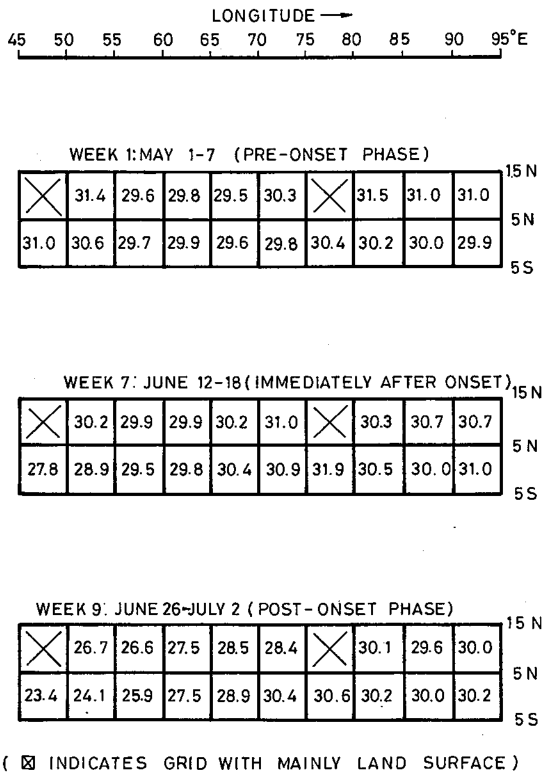


Figure 3

History of MLD variations in 3 longitude grids : latitude belt 5°S to 5°N.



WEEK 1: MAY 1-7 (PRE-ONSET PHASE)

☒	31.4	29.6	29.8	29.5	30.3	☒	31.5	31.0	31.0
31.0	30.6	29.7	29.9	29.6	29.8	30.4	30.2	30.0	29.9

WEEK 7: JUNE 12-18 (IMMEDIATELY AFTER ONSET)

☒	30.2	29.9	29.9	30.2	31.0	☒	30.3	30.7	30.7
27.8	28.9	29.5	29.8	30.4	30.9	31.9	30.5	30.0	31.0

WEEK 9: JUNE 26-JULY 2 (POST-ONSET PHASE)

☒	26.7	26.6	27.5	28.5	28.4	☒	30.1	29.6	30.0
23.4	24.1	25.9	27.5	28.9	30.4	30.6	30.2	30.0	30.2

Figure 4

TIROS-N sea-surface temperatures (°C) over 2 Indian Ocean belts in 3 weeks before, at and after South-West monsoon onset.

The thermocline slope reversal should be accompanied by an eastward surface current jet (Bruce, 1987). Ship and buoy drift currents near Gan in 1979 do indeed show high eastward values from about mid-May to mid-June with a peak around May 31 (Reverdin, Cane, 1984 ; Fig. 2 *b*). Recently Luther and O'Brien (1985) have reported results of a nonlinear reduced gravity model of the seasonal circulation in the Arabian Sea forced by observed climatological winds (monthly mean ships' data — the Global Marine Sums set). They find an eastward surface current in the equatorial belt in late April and early May. Inasmuch as the year 1979 had a delayed monsoon compared to climatology, the time shift of about 3 weeks found herein is not unreasonable, and since it is of the order of a month, it is considered significant even on the monthly time-scale at which Luther and O'Brien have studied the response. Reverdin (pers. comm.) also finds an equatorial surface current maximum in the Indian Ocean in late May to mid-June 1979 in the sector 50-70°E (although in the sector 70-90°E the maximum is found 2-4 weeks earlier). His analysis refers to data within 2° of the Equator (ours extends to 5°).

Based on theoretical literature and previous observations, it may be concluded that the vertical motion in the equatorial Indian Ocean, as reported herein, constitutes a general seasonal response to the monsoonal wind reversal, although the specific date of occurrence of these events may vary from year to year.

SUGGESTED EXPERIMENT

With the above preliminary background, a detailed experiment on the response of the equatorial Indian Ocean to the monsoon wind reversals (at its onset and withdrawal) can be conceived ; it could be named EQUINOX (for EQUatorial INdian Ocean eXperiment) signifying the response to seasonal transitions. The observations should include satellite data such as INSAT and ERS-1 surface wind-stress, ERS-1 and TOPEX sea surface topography, NOAA and ERS-1 sea surface temperature, and satellite tracked buoys for surface currents. *In situ* data including ships' XBTs (Expendable Bathy-Thermographs), inverted echo-sounders as used in the FOCAL/SEQUAL project (Katz, 1984), current meters to monitor the surface and the undercurrent, and tidal gauges are also needed. Further, biological measurements could be made to investigate whether the reported lower plant nutrient level of the Bay of Bengal compared to that of the Arabian Sea (*e.g.* Jhingran, 1983) is related to the eastern mixed-layer deepening. The numerical experiment should focus on the ocean-atmosphere interaction at the 40-day mode of monsoon oscillation (Krishnamurti, Gadgil, 1985). Some of the observations overlap with those of the TOGA experiment.

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