layered structures (designated laminated terrain), a vast system of canyons and channels, and a persistent residual south polar cap thought to be composed of water ice (*9*). It is an exciting prospect that the origin of some of these features may be linked to periodic climatic changes associated with the oscillating obliquity. No complete understanding of the history and behavior of volatiles on Mars is possible until this effect is taken into account (*10*).

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An Equatorial Jet in the Indian Ocean

Abstract. *At the surface of the Indian Ocean along the equator a narrow, jet-like current flows eastward at high speed during both transition periods between the two monsoons. The formation of the jet is accompanied by thermocline uplifting at the western origin of the jet and by sinking at its eastern terminus. This demonstrates that a time-variable current can have profound effects in changing the mass structure in the ocean.*

A narrow, high-speed surface jet flows along the equator from west to east across the entire Indian Ocean during the transition periods between the two monsoon seasons. This jet is apparent in the monthly maps of surface currents published by the hydrographic offices of several countries (*1–3*), but as yet it has not been reported in the literature. This is probably because emphasis has been placed mostly on contrasting the circulation at the time of full development of the two monsoons.

The extent of this equatorial jet is most strikingly seen in a plot of the resulting current vectors for all the 1-degree squares in which speed exceeds 20 miles per day (43 cm/sec) (Fig. 1). The jet appears in April and May, and again in September and October, at which times the countercurrent shifts from one hemisphere to the other. This jet also coincides with the occurrence of strong westerly winds along the equator (*2–4*), which leads to the conclusion that the jet is driven by the wind. The jet is narrow—about 500 km wide—and is symmetrical to the equator. It is strongest between 60°E and 90°E, where surface speeds often exceed 30 miles per day (64 cm/sec), and maximum values of 100 miles per day (215 cm/sec) have been reported (*2*).

The only direct current measurements available from which conclusions about the depth of this jet may be

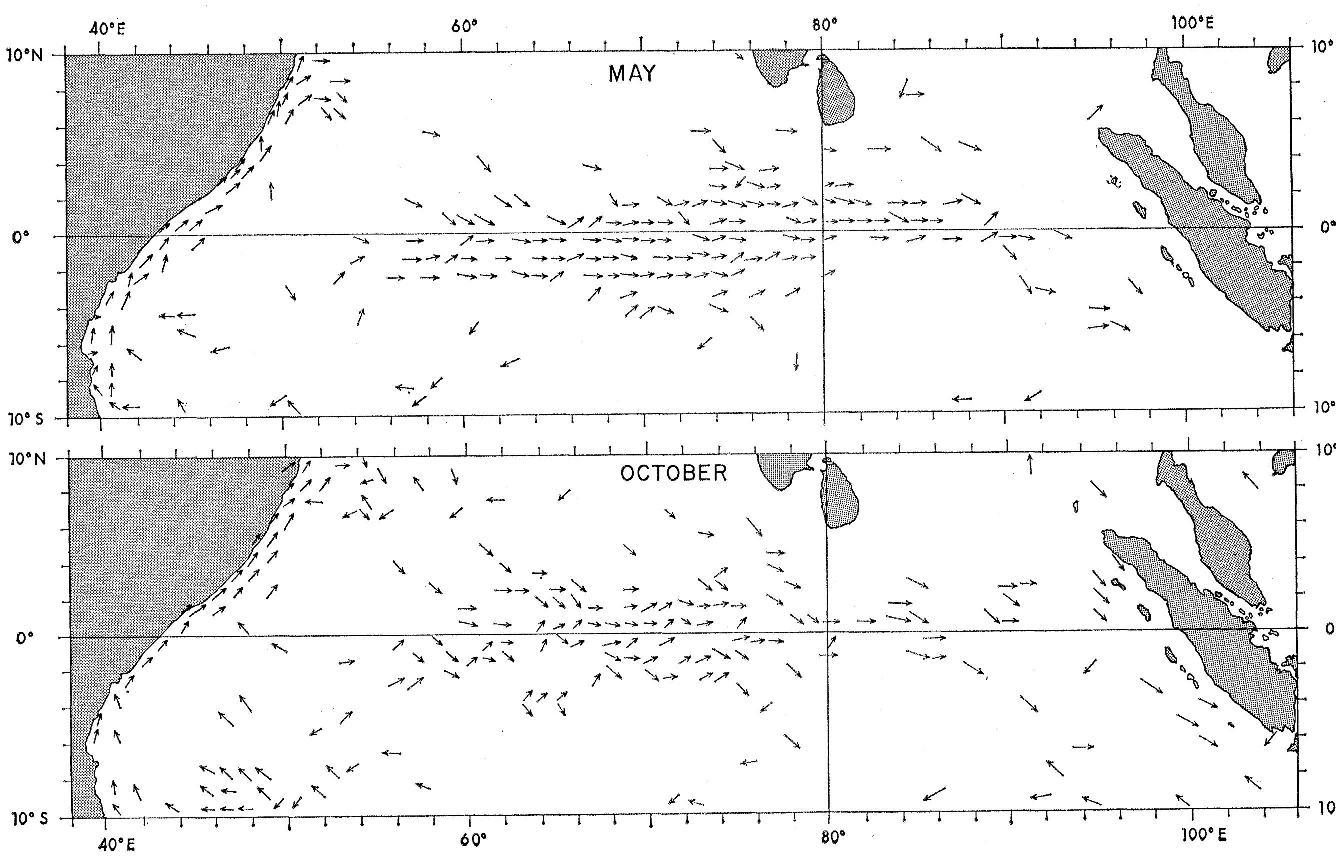

Fig. 1. The equatorial jet in the Indian Ocean in May and October shown by surface current vectors for all 1-degree squares where the speed exceeds 20 miles per day (43 cm/sec), according to data in (*1*).

drawn are those made in May 1963 by Taft and Knauss (*5*) along 53°E at the far western origin of the jet. These measurements indicate a surface flow at the equator of more than 50 cm/sec, which decreases rapidly to a depth of 80 m and reverses direction below 120 m. The flow is strongest at the equator and decreases to about half its surface speed at 2°N and 2°S.

This strong equatorial jet profoundly influences the water structure at its western origin and eastern terminus by removing water from the west and accumulating it in the east; this is reflected in changes in the thickness of the surface layer. Figure 2 shows the mean depth of the 20°C isothermal surface off Africa and off Sumatra, according to (*6*). The two curves display exactly opposite seasonal variations. In April and May, and again in October and November, the 20°C isotherm rises off Africa and, concomitantly, the warm surface layer becomes thicker off Sumatra. This implies that the equatorial jet is insufficently supplied by lateral inflow and must draw additional water from the region off Africa by raising the thermocline. At the same time, water accumulates off Sumatra and depresses the thermocline because horizontal flow is not dispersing the water fast enough.

To estimate the amount of water associated with the rising and falling of the thermocline, I computed the changes in the volume of water above the 20°C isotherm. The equatorial region between 5°N and 5°S was divided into a western part from the coast of Africa to 65°E and an eastern part from 80°E to Sumatra; each area comprises about 2.8×10^{12} m^2. The mean depth of the 20°C isotherm, representing the thickness of the warm surface layer, is plotted in Fig. 2 for both areas, and a smooth curve is drawn through the bimonthly means. It shows that the variation of the volume of warm water in the two areas is completely opposite. From these mean depths the change in volume between bimonthly periods has been calculated and is expressed in million cubic meters per second in the same figure. The curves demonstrate that in April and May the jet is fed at its western origin at a rate of 13×10^6 m^3/sec through the rise of the thermocline alone. Simultaneously, water is accumulated off Sumatra at a rate of 16×10^6 m^3/sec. If the jet is 500 km wide and has an average speed of 75 cm/sec in a layer 60 m thick, there is a transport

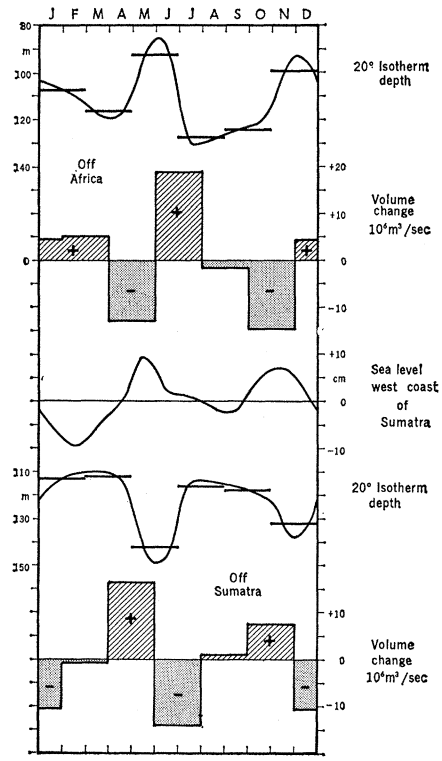

Fig. 2. Displacements of the 20°C isotherm off Africa and off Sumatra associated with the equatorial jet in May and October, and change of volume of the warm surface layer in million cubic meters per second. The horizontal bars give the mean depth of the 20°C isotherm for bimonthly periods (*6*); the blocks give the volume change between successive bimonthly periods. The average monthly sea level at Sumatra's west coast is according to (*8*).

of 22.5×10^6 m^3/sec, of which more than half is supplied by the rise of the thermocline off Africa. The weaker eastward flow on both sides of the jet is not included in this estimate. In June the area off Africa is filled again with warm surface water by the south equatorial current, and in July and August by water recirculating from the Arabian Sea along the equator to the west. The accumulation of water off Sumatra in April and May depresses the 20°C isotherm to more than 140 m over a wide area, taking up more than half of the flow of the jet. This water disperses slowly during the following 2 months, when the thermocline rises again to its normal level.

A similar but somewhat weaker jet is developed in October and November. It is supplied in the west by thermocline uplifting at a rate of 14×10^6 m^3/sec, because much of the water turning north from the south equatorial current still flows into the Somali current and not into the equatorial jet. The accumulation of water off Sumatra is much smaller during this period—only 7.5×10^6 m^3/sec—because the monsoon gyre still possesses sufficient momentum, and water from the jet is diverted rather rapidly into the south equatorial current. In December and January the situation equalizes again, when water returns west in the north and south equatorial currents.

Summarizing, one may say that during each transition season between the monsoons the west winds blowing along the equator cause a surface jet to develop. The jet is narrow because (i) Ekman transports are convergent at the equator (*7*) and (ii) the conservation of vorticity forces an eastward flow to concentrate along the equator. Since the current builds up quickly, it is insufficiently supplied with water in its source region and causes an uplift of the thermocline. At its eastern end the jet accumulates water, and depresses the thermocline, because the accumulated water cannot disperse sufficiently fast. When the winds cease to blow, the disturbances equalize through westward flow in the north and south equatorial currents during the respective seasons. It is noteworthy that the deformation of the thermocline by a modest, but measurable, amount over a large region can contribute substantially to the supply of a strong ocean current, and that time-variable currents can have a profound effect in changing the mass structure in the ocean.

There seems to be no direct connection between these two jets and the equatorial undercurrent; the jets are driven by the wind and the flow is in the surface layer, whereas the undercurrent is driven by a pressure gradient and flows within the thermocline. Moreover, the jets develop during the two transition periods, whereas the undercurrent is associated with the northeast monsoon season, when surface flow along the equator is westward.

The surface currents seem to respond rather rapidly to the westerly winds; no phase delay can be determined from the data available. The buildup of the jets is probably completed in a week once the winds have started to blow consistently. More interesting, however, is the response of the mass structure. The changes in the thickness of the warm layer off Sumatra are directly reflected in changes of sea level along the coast. The seasonal variation of monthly mean sea level averaged from the records of three stations along the west coast of Sumatra

(8) is also represented in Fig. 2, and demonstrates the response of sea level to both the accumulation of warm water and the wind stress. During the 2 months when the west winds blow, a slope of the sea surface of about 20 cm over a distance of 5000 km from west to east is generated; this is shown in the maps of dynamic topography in the Indian Ocean atlas (6). The rise of sea level along the coast of Sumatra is also documented by the observed sea level in Fig. 2. By the end of the 2-month period this slope essentially balances the wind stress. The wind stress τ and surface slope along the equator are related by the expression

$$\tau = \frac{\rho g D \Delta h}{L}$$

where $\Delta h = 20$ cm is the difference in sea level over the distance $L = 5000$ km, $D = 120$ m is the thickness of the upper layer below which the horizontal pressure gradient is assumed compensated, ρ is the water density, and g is the gravitational constant. With these values a wind stress of 0.5 dyne cm^{-2} results, which agrees with the observed strength of the west winds. Consequently, at the end of 2 months sufficient water has piled up off Sumatra to cause a surface slope which balances the wind stress and leads to a decrease in the strength of the current and to geostrophic flow away from the equator.

The following conclusions can be drawn from this investigation:

1) West winds over the equator during the transition periods between the two monsoon seasons cause the rapid development of a narrow jet at the equator.

2) This jet is the only ocean surface current that flows eastward at the equator.

3) The current develops within a very short time.

4) Uplifting of the thermocline at its western origin and sinking at its eastern terminus accompany the jet.

5) Thermocline upwelling can supply the water transport of a time-dependent current.

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Cadmium: Mode of Occurrence in Illinois Coals

Abstract. *The cadmium content of 23 Illinois coals ranges from less than 0.3 to 28 parts per million. The higher cadmium contents are found in coals that also have a relatively high zinc content. Cadmium occurs in these coals in solid solution, replacing zinc in the mineral sphalerite (ZnS). The ratios of zinc to cadmium in sphalerites are similar to the ratios of zinc to cadmium in the whole coals from which the sphalerites were separated.*

The investigation of Cd in coal has not kept pace with the studies of many other trace elements in coal. We are aware of only three references to Cd in coal and coal ash published prior to 1969 (1). During the past 4 years additional analyses have been reported (2–6). In the only study designed to investigate coals systematically, Swanson (4) analyzed 71 coal samples and found that 61 had a Cd content below detectable limits, which for the analytical method used was approximately 0.5 part per million (ppm) in a 1.0-g sample of coal ash.

Five of the seven recent publications that mentioned Cd in coal listed the results of individual analyses of coal samples (4–6), and the highest amount of Cd in coal reported was 0.7 ppm (5). The other two publications did not list the results of individual analyses of coal samples but gave Cd ranges of 2 to 100 ppm in the coal ash (2) and 1 to 2 ppm in the coal (3).

In a current investigation of the potentially volatile trace elements in coals being conducted at the Illinois State Geological Survey (7), relatively high Cd and Zn concentrations have been

Table 1. The Cd and Zn analyses of Illinois coals.

Analysis number	Zn (ppm)		Cd (ppm)		Zn : Cd ratio	
	HTA	LTA	HTA	LTA	HTA	LTA
			Herrin (No. 6)			
C-16030	1760	1610	3.6	3.2	490 : 1	500 : 1
C-14970	15	24	≤ 0.3	≤ 0.4		
C-16317	1670	2660	17.0*	28.0†	98 : 1	95 : 1
C-12062		3100		19.0‡		160 : 1
C-15117	41	121	0.5	1.2	82 : 1	100 : 1
C-15456	59	178	≤ 0.3	≤ 0.4		
C-13895	68	30	< 0.3	< 0.5		
C-15231		297		1.1		270 : 1
C-14684	39	31	< 0.2	< 0.3		
C-13464	41	31	0.5	0.5	82 : 1	62 : 1
C-14721	221	294	1.4	1.8	160 : 1	160 : 1
C-16139		86		0.9		96 : 1
C-12831		24		≤ 0.4		
C-15038		102		0.8		130 : 1
			Springfield-Harrisburg (No. 5)			
C-16264	182	166	3.1§	2.7‖	58 : 1	61 : 1
C-14796	97	64	0.5	≤ 0.3	190 : 1	
C-15384	34	34	≤ 0.3	≤ 0.4		
C-12495		18		≤0.6		
C-14774		885		7.1		120 : 1
C-17001	171	184	1.8	1.2	95 : 1	150 : 1
			Summum (No. 4)			
C-15331	54	54	0.7	0.7	77 : 1	77 : 1
			Colchester (No. 2)			
C-15566		213		0.9		240 : 1
			DeKoven			
C-15944		189		≤ 0.4		

* 18 ppm by ASV. † 29 ppm by ASV; 21 ppm by NAA. ‡ 17 ppm by NAA; 28 ppm by ASV. § 3.0 ppm by ASV. ‖ 2.4 ppm by ASV.