INTEREST OF TRAJECTORIES DEDUCED FROM CLOUDS AND WATER VAPOUR MOTIONS OVER THE INDIAN OCEAN ON METEOSAT 5 IMAGES

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ABSTRACT

Trajectories of air parcels are regaining interest, specially for the study of transports of different constituents (water vapour, pollutants, radioactive elements,...) at different levels of the atmosphere. Generally, direct or retro-trajectories are derived from model analyses or simulations. This approach is very efficient in regions where the models assimilate a large number of data, as it allows to retrieve 3D-trajectories. But in areas with few conventional measurements, where only partial satellite data are assimilated, one can doubt of the result of such an approach. The possibilities and usefulness of deriving trajectories directly from the cloud motions is therefore examined here.

In the Tropics, where analyses of operational models are less performing, due to the lack of meteorological stations, trajectories may be very useful in several applications: One of them is the outflow from the anvil of cumulonimbi of Mesoscale Convective Complexes. Trajectories, in particular in the water vapour channel, are very suggestive of the outflow of water vapour. Trajectories done with the visible channel on low clouds of the trade winds area or of the monsoon systems are also useful for following the horizontal transport of pollutants and water vapour in the boundary layer. This approach will be specially applied in the frame of the INDOEX programme, in comparison with other in-situ measurements.

Finally, it appears also that the trajectory approach of cloud motions can help to improve the “ cloud wind ” determination : the time consistency is tested on longer periods than in the usual wind producing procedures.

1. INTRODUCTION

The concept of trajectory is commonly used to characterise the motion of air parcels containing specific constituents (water vapour, pollutants, radioactive elements...) as well as large atmospheric structures (cyclones...). Generally 3-dimensional trajectories are derived from model analyses or forecasts, but in areas with few conventional measurements, the representativity of such trajectories can be questioned. The need of a better understanding of the meteorology in such an area, the Indian Ocean, and in particular the influence of pollutants originating from the Indian subcontinent is at the origin of the INDOEX project (foreseen to take place at the beginning of 1999). For this purpose, the Meteosat 5 satellite has been displaced over the Indian Ocean, with its subsatellite point located at 0°N, 63°E, and provides complementary information to the operational Insat satellite, located further east above the equator. Part 2 of this paper presents cloud and water vapour motion winds (CMWs hereafter) computed from Meteosat 5 images in 4 selected areas in or around the Indian Ocean. In part 3, trajectories show the persistence and motion of clouds and water vapour structures during several hours. Finally, the potential of trajectories to improve cloud motion winds is pointed out in part 4.

2. REGIONAL STUDIES OF CLOUD MOTION WINDS OVER THE INDIAN OCEAN

A set of Meteosat 5 cloud motion winds produced by EUMETSAT (Schmetz et al., 1993),(Rattenborg and Holmlund, 1996) and covering the month of July 1998 has been used in this study. CMWs are computed from 32 x 32 pixels target windows (or segments) over a grid with neighbouring grid points separated by 32 pixels. In the available area, covering a large part of the Indian Ocean (approximately between 35°S and 35°N ; 30 and 120°E), 4 areas have been selected for statistical comparisons:

- The "North India" area (15 - 25°N ; 70 - 90°E) covers the north of the Indian peninsula and is mainly under the influence of the summer monsoon.
- The "South India" area (5 - 15°N ; 70 - 90°E).
- The "Somalian coast" area (0 - 10°N; 50 - 60°E) covers an area mainly over the ocean where the Somalian jet associated to the monsoon is the strongest.
- The "Central Indian Ocean" area (30 - 20°S ; 60 - 80°E) corresponds generally to the northern part of an anticyclone. All CMW s underwent automatic quality control (AQC) tests. In this chapter, results are presented only for those CMW s who successfully passed these tests. Figure 1 is an example of a CMW field in the IR channel (2 July 1998,0430 UTC) and shows the selected areas.

Pressure level in colour :

$P < 300$ hPa

$300 \leq P < 500$ hPa

$500 \leq P < 700$ hPa

$700 \leq P < 850$ hPa

$P \geq 850$ hPa

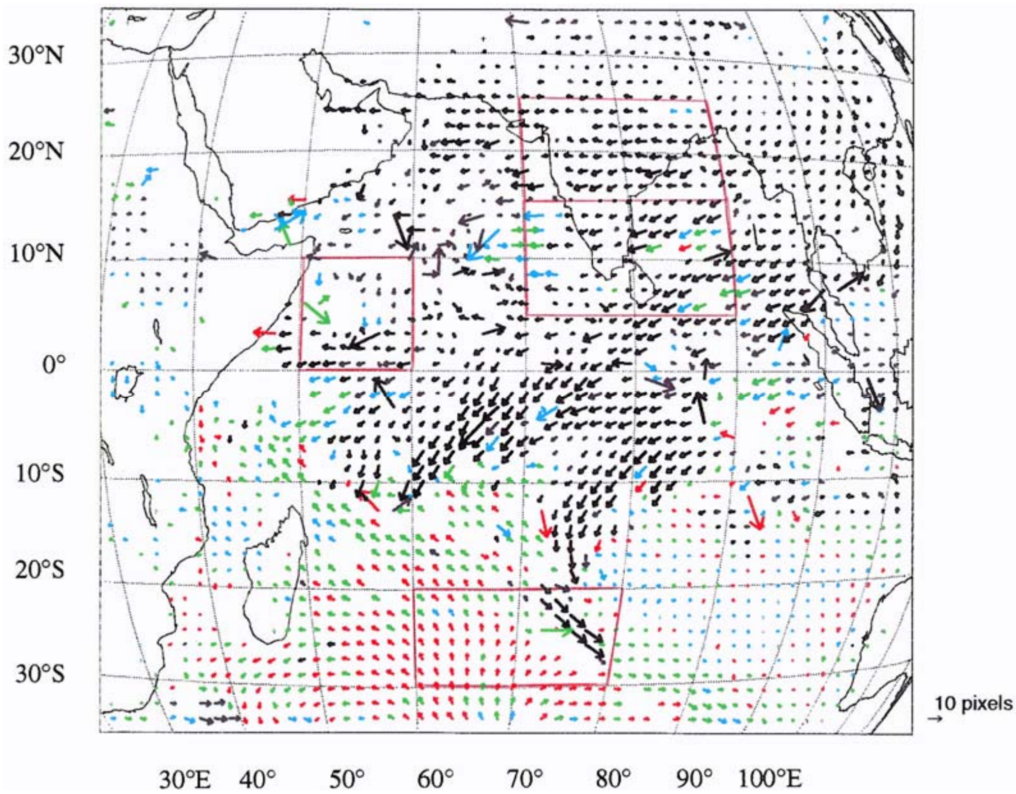

Figure 1 : all IR cloud motion winds (2 July 1998,0430 UTC)

2.1 Frequency of cloud motion winds in July 1998

Table 1 lists the frequency of the automatic quality controlled CMWs compared to all potential vectors (a CMW can theoretically be computed every 1.5 hour at each grid point). For the visible (VIS) channel, only CMWs produced during daytime, i.e. between 0300 and 1330 UTC are considered.

For the "North" and "South India" areas, CMWs in the water vapour absorption (WV) channel are more numerous than in the two other channels. This is mainly the result of the motion of numerous high level clouds, which are better tracked in the WV channel. Very few low level CMWs (and none over land) have been measured. Minor differences in percentage are observed between both areas, except for VIS vectors, due to the presence of low level monsoon winds over the sea. In the "Somalian coast" area, the smaller percentage of WV vectors and the larger percentage of VIS vectors is mainly due to a better tracking of the monsoon flow and the relative scarcity of high level clouds. Compared to the two Indian areas, the relatively high rate of VIS and IR CMWs in the "Central Indian Ocean" area reflect the dominant low level circulation in / around the anticyclone located around 35°S.

	North India	South India	Somalian Coast	Central Indian Ocean
VIS (daytime)	**0.7**	**1.5**	**6.5**	**27.1**
IR	**15.0**	**16.1**	**13.5**	**47.8**
WV	**33.3**	**33.3**	**26.8**	**3.1**

Table 1 : percentage of automatic quality controlled CMWs.

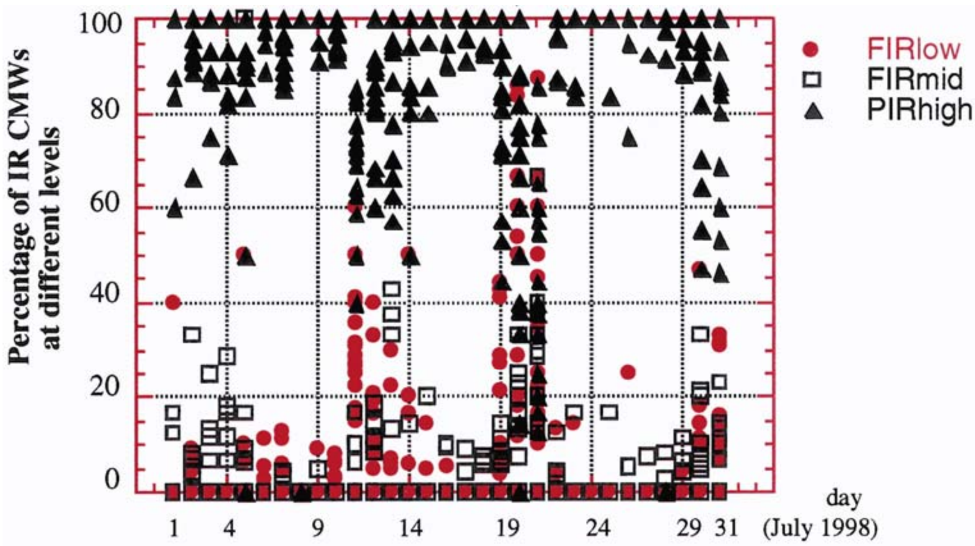

Figure 2 : frequency of CMWs at low, medium and high level for the "South India" area

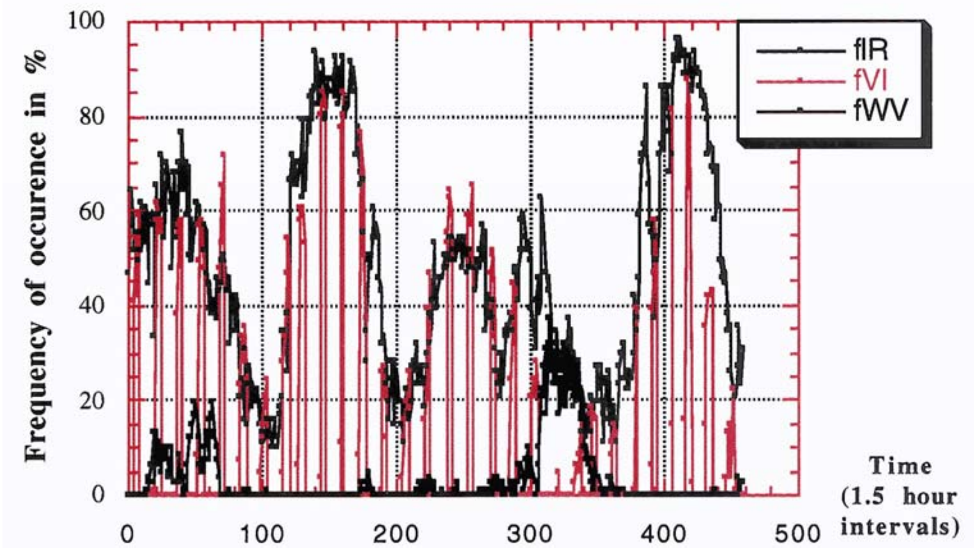

Figure 3 : percentage of CMWs (for all possible grid points) in the "Central Indian Ocean" area

2.2 Daily evolution of the number of cloud motion winds

Time series of the proportion of CMW s as a function of pressure level can give an indication of the evolution the meteorological situation. Figure 2 shows the evolution of the proportion of high (P < 440 hPa), medium (440 ≤ P < 680 hPa) and low level (P ≥ 680 hPa) CMWs in the IR channel on a daily basis, with 16 CMW fields per day, over "South India". It appears that the dominant situation corresponds to the presence of high level clouds. In several occasions (around July 12th, 20th and 31st), the proportion of high level winds decreases whereas more low level winds can be observed ; this probably corresponds to monsoon breaks over India.

On figure 3, percentages of (AQC) CMWs are represented on a 1.5 hourly basis in the "Central Indian Ocean" area for all three channels. This area is dominated by low level stratocumulus clouds, explaining the high percentages of VIS and IR CMWs. The diurnal cycle, clearly observed in the VIS channel, is superimposed to a 7 day period observed in both VIS and IR channels. High level clouds are minor elements, except between July 20 and 22 and, at a lesser extent, at the beginning of the month (2 to 5 July).

3. CLOUD & WATER VAPOUR TRAJECTORIES OVER THE INDIAN OCEAN

3.1 Construction of trajectories

The method used to construct trajectories is an extension of the computation of cloud motion winds to a series of images. The principle as well as practical details of the method have been presented in previous wind workshops (Szantai and Desbois, 1993 ; Szantai et al., 1996). In the first case, trajectories have been computed from a series of images on 2 July 1998, starting at 0430 UTC (this corresponds to 8:42 h local time at the subsatellite point) in all three channels. Trajectories in the IR and WV channels have been limited to a maximal duration of 19 hours; in the VIS channel, the maximal duration is limited by the daytime to 8.5 hours. Trajectories lasting less than 1.5 hours have been removed. On trajectories in the IR and WV channels (fig. 5, 6 and 8), the crude height assignment, based on the average of brightness temperature of the coldest pixels, is sufficient to discriminate high level clouds (in black and dark blue), medium level clouds or WV structures (in green) and low level and/or semi-transparent thin (high level) clouds (both in red or pink).

3.2 Trajectories on 2 July 1998

On the IR image (fig. 4) at the starting time of the trajectories (0430 UTC), large convective cloud clusters can be observed over the ocean close to the equator. Convective clouds associated to the monsoonal circulation are present over the Indian peninsula as well as over south-east Asia. Medium level clouds cover a large part of the Arabian Sea. A low level anticyclone in the central Indian Ocean is made visible by numerous stratocumulus clouds.

a) IR trajectories (0430 - 2330 UTC)

Trajectories form several groups which reflect the main high and low level atmospheric circulation over and around the Indian Ocean. On figure 5, numerous low level trajectories show the counterclockwise rotation of stratocumulus around the central Indian Ocean anticyclone. Other low level trajectories, located at the north-east of Madagascar, reveal the south-easterly monsoon flow towards the equator (between 20°S and 0°N). The following high level motions can also be observed on groups of trajectories:

- the clockwise rotation around a high altitude anticyclone located over the Tibetan plateau; this is in agreement with the climatological circulation observed in this area in July (Grotjahn, 1993).
- the tropical easterly jet circulation in the upper troposphere is located south of the Himalayas and throughout the north hemisphere summer monsoon region; trajectories make it visible from the north of the Indian peninsula to the north-east of the Arabian peninsula.
- the high level return current of the monsoon flow from the northern to the southern hemisphere starts from the Gulf of Bengal (south-westward motion), crosses the equator and takes a southward and then south-eastward direction.

b) WV trajectories

Trajectories in the WV channel give an improved visualisation of the high level circulation, compared to their IR counterparts (fig. 6) and are in good agreement with the upper level circulation indicated in climatological studies (Grotjahn, 1993) :

- trajectories of high level clouds are more numerous and have a longer duration in the easterly tropical jet area over the Arabian Sea, the south of the Arabian peninsula and Red Sea. The jet appears to split in two parts: in the northern part, trajectories have an east / north-eastward motion over north Arabia and the Gulf of Oman whereas in the southern branch (over the south of the Red Sea) trajectories show a westward (slightly south-westward) motion. Trajectories of the northern branch end at the border of a subsidence area (observed on WV images at ≈ 30°N ; 40 - 65°E).

- in the southern hemisphere, the trajectories showing a south / south-eastward motion have generally a longer duration and penetrate further south. The increase of brightness temperature can be explained by the dissipation of high level clouds or WV structures, possibly due to the subsidence and associated drying at the edge of the wide subsidence area located west of Australia (≈ 25°S ; 85 to 120°E). The arrival of high level clouds from the north-west into the "Central Indian Ocean" area of chapter 3, revealed by trajectories, explains the increase in the frequency of occurrence of WV CMWs observed on figure 3.
Close to the central Indian Ocean (35 - 30°S ; 60 - 75°E), a few medium level trajectories show a slightly divergent motion, different from the motion indicated by the IR trajectories associated to the motion of low level stratocumulus clouds. The divergent motion on top of an isolated convective cloud cluster can be observed from a group of trajectories around a vectorless area (≈ 5°N ; 60-75°E).

c) VIS trajectories (0430 - 1300 UTC)

Trajectories in the VIS channel (fig. 7) have been computed from full resolution images (with solar angle correction) on the same grid as IR and WV trajectories (thus only one correlation window out of 4 is used to start the trajectory computation, the number of pixels - 32 x 32 - being the same). VIS trajectories are of similar quality to their IR counterparts (but generally of shorter duration because of daytime) in the anticyclonic area of the central Indian Ocean. But the VIS channel is particularly useful to show the motion of low level clouds associated to the monsoon flow : the south-easterly trade winds in the southern hemisphere (25 to 5°S) take a southerly course when they cross the equator and then a south-westerly course in the vicinity of the Somalian coast. A few westerly trajectories can even be observed close to the west Indian coast. In other areas (over the Gulf of Bengal, the north of the Indian peninsula and Iran), groups of trajectories are mainly indicators of high level cloud motions, but trajectories are less numerous than in the corresponding groups in the IR channel.

3.3 **Trajectories on 20 July 1998** (not represented)

The divergent motion on top of convective cloud clusters can again be observed on several groups of trajectories (west of the Indian coast : ≈ 15°N ; 70°E, and west of Sumatra: 5°S ; 100°E). Otherwise, the observation of the satellite images and trajectory charts show several differences of cloud cover and atmospheric motions on 20 July when compared to the 2 July situation (fig. 9 : WV trajectories):
- Convective cloud clusters and high level clouds are more numerous around or just at the south of the equator.
- Few high level clouds are present over the south of India; this probably corresponds to a monsoon break. Trajectories are short in this region.
- The north-westerly / westerly motion of clouds around 20°S, between 55 and 90°E, is partly visible on WV trajectories (southern edge of the cloud band) and clearly shown by IR trajectories. Such a motion was not observed on the 2 July trajectory fields.

4. COMPARISON OF CLOUD MOTION WINDS WITH TRAJECTORY BEGINNINGS

The goal of this chapter is to show that trajectories constructed from satellite images (not assimilated into models nowadays) provide complementary information to CMWs and could potentially improve analyses. For this purpose, automatic quality controlled CMWs, with a precise height assignment, are compared to the first vector of exactly collocated trajectories (same grid). In this study, limited to latitudes between 35°S and 35°N, with CMWs computed and trajectories starting on 2 July, at 0430 UTC, the proportion of existing and correct vectors and trajectories, compared to all the grid points of the studied area (i.e. where a CMW can be computed and a trajectory can be started), has been determined. Table 2 shows that correct (AQC) CMWs are less numerous than (quality controlled) trajectories, which in turn are in smaller number than all existing CMWs.

% / channel	Correct trajectories	All existing CMWs	AQControlled CMWs
WV	44	52	19
IR	50	71	19
VIS	29	15	9

Table 2 : percentage of cloud motion winds and trajectories, compared to the number of grid points.

From a CMW perspective, each grid point can be classified into one of the 3 classes : good quality vector (AQC successful), bad quality vector or no vector. From a trajectory perspective, each grid point is also classified into 2 classes (trajectory present or absent). Table 3 compares the proportion of grid points common to classes of both systems. It appears that the proportion of common correct CMWs and trajectories is relatively small, less than 20 % (in red). The trajectories beginning where CMWs are bad or absent form a larger percentage and potentially contain useful information for assimilation (in green). The case "trajectory present - CMW bad or absent" can be explained by the appearance or by an important modification of the tracked cloud. For example, if a cloud appears on the second image of a triplet, the temporal symmetry check (between the 2 resulting cloud motion vectors) probably associate a bad quality indicator to the CMW, whereas the trajectory may be able to track the cloud if it is stable and lives on.

CMW	correct	bad	absent	correct	bad	absent
Trajectory beginning	present	present	present	absent	absent	absent
WV	**17**	**15**	**11**	**3**	**17**	**36**
IR	**16**	**27**	**7**	**3**	**25**	**22**
VIS	**7**	**2**	**19**	**2**	**4**	**66**

Table 3 : % of common CMW and trajectory classes (compared to the total number of grid ponts).

5. CONCLUSION AND PROSPECTS

This study shows that trajectories are good indicators of the general circulation of clouds and water vapour structures over the Indian Ocean and the southern part of Asia. The three channels of Meteosat bring complementary information : the motion of high level clouds, which are predominant in the Intertropical Convergence Zone and over south-east Asia, is highlighted by WV and IR trajectories, whereas the monsoon flow and the motion around the anticyclone in the central Indian Ocean is better represented by VIS (and at a lesser extent IR) trajectories. The divergent motion on top of convective cloud clusters is also well visualised by trajectories in the IR and WV channels.

Trajectories constitute a complementary information to quality controlled cloud motion winds and could improve the quality of analyses. But for this purpose, complementary studies have to be undertaken, with a more precise height assignment of trajectory vectors.

During the INDOEX experiment, planned for the beginning of 1999, trajectories obtained from satellite images could provide useful information about the transport of pollutants, and could be compared with balloon and model trajectories.

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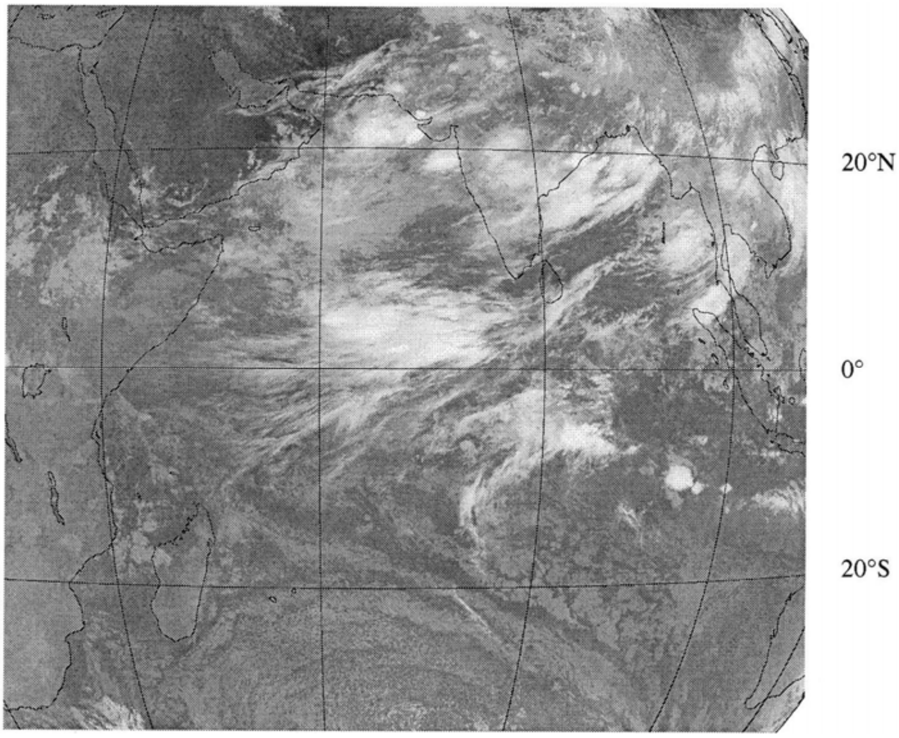
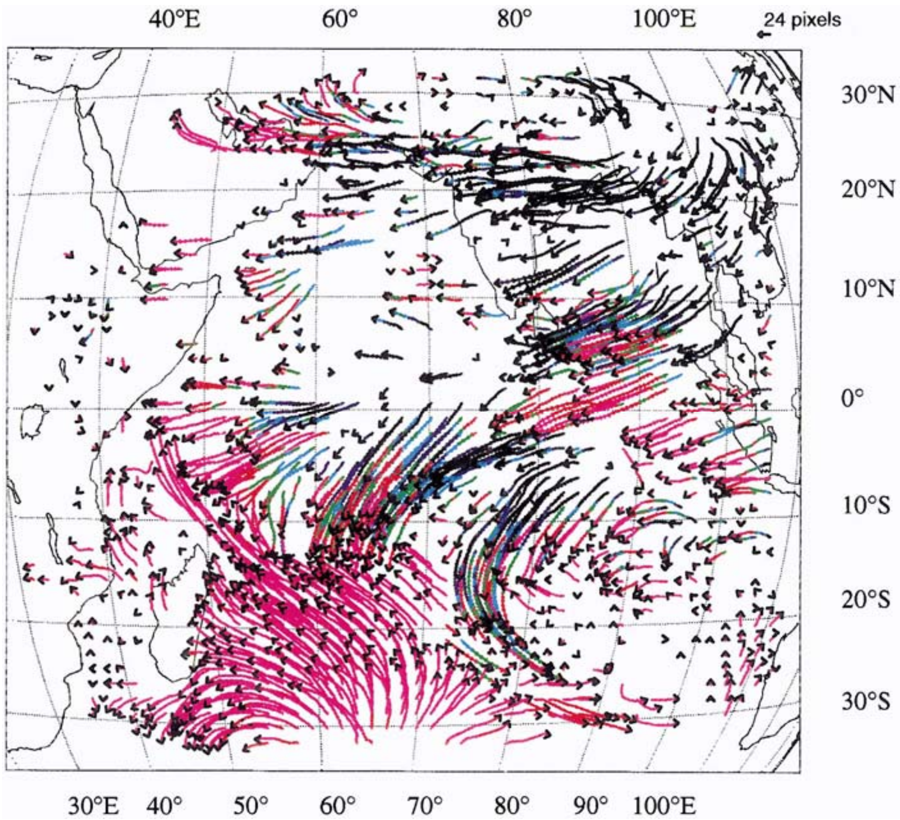


Figure 4 :
IR image,
2 July 1998,
0430 UTC



Colors of vectors function of brightness temperature :

Tb < 233 K

233 ≤ Tb < 243 K

243 ≤ Tb < 253 K

253 ≤ Tb < 263 K

263 ≤ Tb < 273 K

Tb ≥ 273 K

Figure 5 :
IR trajectories,
2 July 1998
0430 - 2330 UTC

Colors of vectors function of brightness temperature :

Tb < 233 K

233 ≤ Tb < 243 K

243 ≤ Tb < 253 K

253 ≤ Tb < 263 K

263 ≤ Tb < 273 K

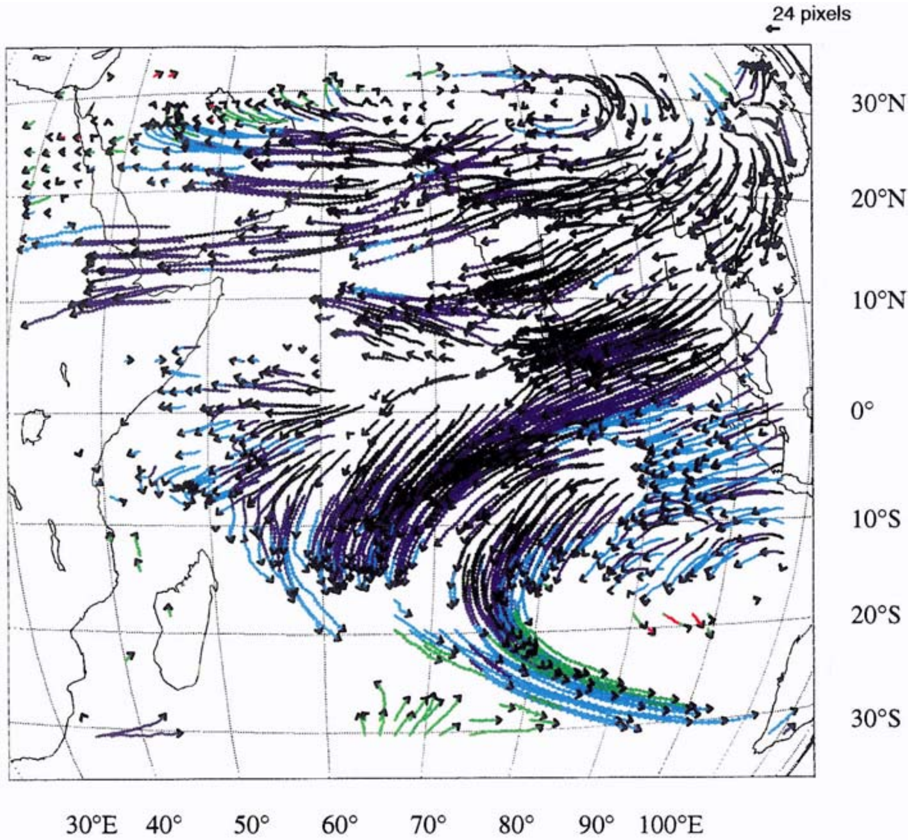


Figure 6 :
WV trajectories,
2 July 1998
0430 - 2330 UTC

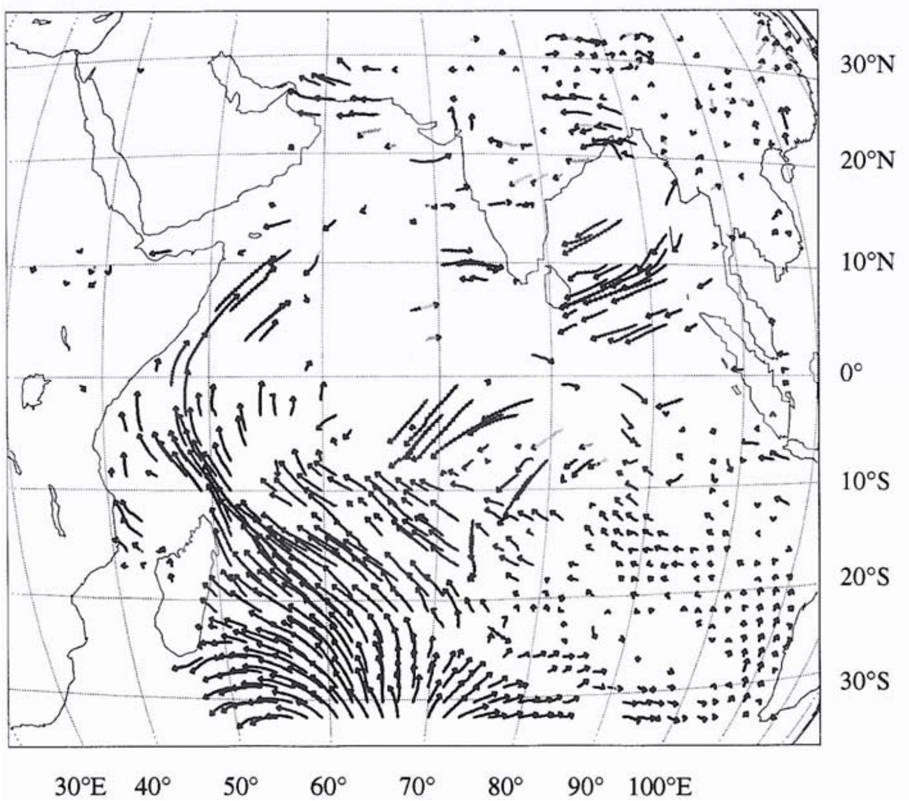


Figure 7 :
VIS trajectories,
2 July 1998
0430 - 1300 UTC