Evolution of Tropical Plumes in VAS Water Vapor Imagery

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ABSTRACT

Tropical plumes are common tropical synoptic disturbances marked by continuous upper tropospheric cloud bands extending out of the ITCZ into midlatitudes. Thirty-five tropical plumes over the northeast Pacific are composited in GOES VAS water vapor imagery at four time periods throughout their evolution, from a precursor stage 48 h before they fulfill an objective plume definition until they mature 24 h after this definition stage. A "quiescent" composite is constructed for 35 days in which no synoptic activity is occurring. Composites of outgoing longwave radiation data are constructed using the same days, for comparison.

Precursor signals are identified in the vapor imagery before clouds develop: a moist midlatitude trough, a synoptic scale wave in the moisture/cloud field along the ITCZ, and an anomalously dry intervening subtropical high, all appearing in an anomalously dry tropical environment. This pattern is contrasted with the synoptically quiescent composite, a nearly zonally symmetric pattern in vapor imagery, with a convectively active ITCZ, flanked by a linearly shaped subtropical high; the quiescent tropics are generally moist. The plume evolves as a stationary, tropical, dry/moist dipole, separated by an exceptionally strong cloud/moisture gradient. All features within individual composites and most variations from stage to stage are statistically robust. Tropical plume evolution is accompanied by a systematic drying of the tropical eastern Pacific atmosphere before development, and moistening and increased cloudiness with development. The precursor pattern is used as a forecasting tool applied to an independent set of vapor imagery; 65% of 29 plumes were forecast correctly by position and time of evolution. Forecasting errors were systematic.

1. Introduction

Tropical plumes are defined as common tropical synoptic events by McGuirk et al. (1987, 1988; hereafter referred to as MT1 and MT2, respectively). Most simply, tropical plumes are bands of near continuous upper tropospheric clouds, at least 2000 km in length, extending across 15°N. MT1 demonstrated that this simple geometric definition allowed classification and synthesis of a large collection of northeastern Pacific weather systems which link the tropics and midlatitudes. These systems exist throughout the northern and southern tropics, although the definition developed in MT1 has been applied only to Pacific systems. Thepenier and Cruette (1981) and additional references in MT1 and MT2 document occurrence of plumes throughout the tropics. Approximately ten plumes develop over the northeastern Pacific Ocean every cool season month. Almost every plume develops out of the ITCZ or rapidly becomes associated with it. McGuirk et al. (1989), MT1, and MT2 describe many details of tropical plume structure and several observational problems currently restricting more accurate description. Plumes' tropical interaction has been examined by Sadler (1967), and their midlatitude extensions by Thepenier and Cruette (1981). Lin and Mock (1986) depicted composite cloud imagery and analyzed vertical motion associated with tropical plumes (tropical intrusions, in their terminology). Although their analysis places the maximum upward vertical motion at about 18°N in mature plumes, the active plume convection in most plumes is associated more commonly with the ITCZ between 7° and 12°N, at the southwestern edge of the plume. MT1 and MT2 suggest that plumes provide the major synoptic scale interaction between the Pacific tropics and northern midlatitudes; northward transports during plume evolution can exceed climatological and zonal means by nearly an order of magnitude; these magnitudes, coupled with the frequency of plume development, suggest that plumes constitute a large component of the Pacific general circulation. Alternatively, when zonal mean ITCZ convection becomes activated, as in late northern summer or El Niño periods, tropical plume activity is curtailed severely. Unfortunately, accurate objective analysis of deep tropical synoptic features is limited severely by both a lack of conventional observations and limitations in forecast model initializations (Heckley 1985). Although satellite observations have increased over the last decade, accurate synoptic analysis in the tropics, particularly over the eastern Pacific, is problematic.

A number of quality satellite products are currently

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in use for both synoptic diagnosis and objective analysis. Satellite data ingested into objective analysis systems are limited to sounding retrievals from polar orbiters (including vapor channels at the ECMWF, but not at the National Meteorological Center) and cloud drift winds from geostationary satellites. Although sounding data from geostationary satellites have been available for nearly a decade, they are not used in these operational analyses. The power of these observations in synoptic diagnoses have been demonstrated, at least for midlatitudes by MT2, McGuirk et al. (1989), Peterson et al. (1984), Poc et al. (1980) and others. These studies demonstrate that quantitative information can be extracted and that the most important information usually is associated with the horizontal synoptic pattern.

This paper analyzes the synoptic scale tropical plume using only satellite data, primarily 6.7 μm water vapor channel imagery from GOES West, but also gridded outgoing longwave radiation (OLR) data within the 10.5–12.5 μm band. The purposes are to describe the evolution of plumes, examine their precursor signals, compare their horizontal moisture patterns with nonplume climatology, and assess their predictability based solely on satellite imagery. Two key questions are addressed: To what extent are these systems tropical or extratropical? How much information about plumes can be derived from vapor imagery? The data and analysis techniques are described in section 2; results are presented in the subsequent two sections. Discussion and conclusions appear in section 5.

2. Data and analysis

a. Observations

The data used to prepare the composites were extracted from full disk vapor images (6.7 μm band) available from the geostationary VAS [VISSR (visible and infrared spin-scan radiometer) atmospheric sounder] instrument. There are many interpretations of vapor imagery, ranging from estimating column precipitable water and vertical moisture distribution, to inferring midtropospheric winds from tracking "moisture features." The 6.7 μm vapor channel is highly sensitive to liquid water and vapor. Regardless of climatological vapor channel weighting functions, the vapor channel signal is determined almost completely by the first few millimeters of equivalent precipitable water that the satellite "sees," looking downward. Climatologically, this level of peak contribution lies around 400 to 500 mb in cloud free atmospheres. In individual observations, the level of maximum signal may range from 100 mb (in tropical cirrus or moisture streaks) to 800 mb (in extremely dry atmospheres). (See Blackwell 1987, for quantitative interpretation over the tropical Pacific.) In cloudy regions, many of which appear in the current dataset, the upwelling radiance approaches that estimated by the blackbody temperature near cloud top, with no information from below penetrating through the clouds to the satellite. The important feature of the vapor images in this study is the horizontal pattern variation of the cloud and vapor signal, whatever its ultimate atmospheric source. Specific cloud content or vertical distribution of moisture is not inferred from the vapor images, although in some cases, inferences are drawn from comparison between vapor images and contemporaneous infrared cloud images. In this paper, vapor channel radiances are assumed to measure some combination of vapor, liquid water and ice sensed by the satellite; this aggregate will be termed "moisture."

The VAS vapor images were gridded on a triangular grid, formed by dividing 5° latitude/longitude boxes by the southwest–northeast diagonal, to emphasize the geometry of tropical plumes. The effective resolution is thus just under 400 km. The 16-shade unenhanced gray scale was reduced to four integer values from white (cold, moist, cloudy), given a value of 1, to black (cloud-free and dry), given a value of 4. Regions assigned a value of 2 were covered generally by thin middle or upper tropospheric cloud, and regions of 3 were generally cloud free, but apparently containing significant detectable vapor. In composites that were formed, an approximate cloud/no cloud boundary was determined, from post analysis, to be approximately 2.6. These generalizations were reached by comparison of many vapor images and infrared cloud images. The reduction to four integer values was chosen both because of imagery interpretation uncertainty described above, and also to minimize any subjectivity in the analysis and subsequent interpretation. Each vapor image analyzed was registered to an objectively defined "origin point," as described below; each triangular area was assigned a number from 1 to 4 based on comparison of the average brightness within the triangle with the gray scale printed with the image.

b. Plume climatology

All tropical plumes from October 1983 through April 1984, for which complete data were available, were selected from the plume climatology prepared by MT1; this climatology was based on infrared satellite imagery. The southwestern edge of the cloud boundary was selected as an "origin point"; this term is selected for convenience in locating individual events and does not imply specific physics of initiation. Thirty-five plumes were selected and are listed in Table 1 along with their "origin points" and the time (within ±3 h) at which they first met the definition of a tropical plume (that is, a continuous mid and upper level cloud band, at least 2000 km long, which crosses 15°N). These 35 images were composited, as described below, into a mean vapor image referred to as the "definition time" composite.

Three other sets of imagery, 35 images each, also were composited to describe the plume evolution by

TABLE 1. Cases selected for the tropical plume composite.

Definition		Grid origin	
Date (1983/84)	Time (UTC)	(°N)	(°W)
25 Oct	1115	9	168
4 Nov	2315	9	123
15 Nov	1115	10	150
18 Nov	2315	11	177
22 Nov	0515	8	140
25 Nov	0515	10	130
27 Nov	1615	8	163
1 Dec	1116	10	130
14 Dec	1115	7	163
17 Dec	1616	8	158
24 Dec	2316	10	180
1 Jan	2316	8	127
3 Jan	0515	6	150
7 Jan	2316	5	156
18 Jan	0515	13	136
21 Jan	2316	12	128
22 Jan	2316	7	148
26 Jan	1115	5	157
2 Feb	0515	6	140
9 Feb	0515	7	157
17 Feb	0516	10	120
17 Feb	2316	0	158
22 Feb	1115	7	153
3 Mar	1115	6	128
8 Mar	0515	6	125
11 Mar	1115	12	120
16 Mar	1615	4	140
25 Mar	1615	6	130
1 Apr	1115	8	160
6 Apr	0515	5	140
10 Apr	1115	5	168
10 Apr	1115	5	135
16 Apr	0515	13	140
24 Apr	0515	7	123
28 Apr	1615	8	140

backing up 24 and 48 h before each definition time image and stepping ahead of each definition image 24 h. The resulting four composite sets consist of "precursor" (−48 h), "initiating" (−24 h), "definition" (0 h), and "mature" (+24 h) phases of tropical plumes. A fifth composite was constructed from 35 images in which tropical plumes were not present or commencing development. Selection of these events was actually the more difficult task, since MT1 concluded that plumes meeting the stated definition exist over the north eastern Pacific nearly 80% of the time during normal cool seasons. Plumes continue to meet the definition for 2.5 to 4 d, and multiple occurrences are common. The only restriction placed on these "no-plume" images was that no two would be selected from the same day; consecutive "no-plume" days were selected only four times. This composite is termed the "quiescent" composite. It represents a nonplume climatology and, as such, does not represent a normal wintertime climatology; it represents conditions that exist only about 20% of the time.

The labels, while implying specific stages of physical development, are only qualitatively correct. For example, we do not imply by the labeling that the first detectable signal of a tropical plume appears 48 h before the plume develops sufficiently to meet the definition. In fact, coherent plume signals might exist even several days before the precursor stage. We do show, however, that by 48 h before the system meets the definition, there already are indicators of the plume's development present in vapor imagery.

Each image of the four plume composites was moved, or registered, to a common origin point. This point is the latitude and longitude of the southwesternmost point of the middle and high cloud boundary of the plume as determined from infrared cloud imagery at definition time. This point is defined as the origin point in relative latitude and longitude. Its mean position is approximately 7°N and represents the approximate local position of the ITCZ as determined from convective clouds in infrared cloud imagery. The images of the quiescent composite were registered meridionally, so that 0° relative latitude is the latitude of the local ITCZ. The images were not shifted zonally since there is an absence of synoptic systems; that is, no zonal reference exists.

3. Imagery composites

a. Plume composites

Figure 1 depicts a typical tropical plume, but one not incorporated into the composite climatology. It reached definition stage somewhat before 12 UTC 14 December 1983. Both the precursor and definition images are shown in unenhanced infrared (cloud) imagery (Figs. 1a,c) and in vapor imagery (Figs. 1b,d). Caution must be used in ascribing quantitative interpretation to these images, because the gray scale varies shading from image to image; Fig. 1d is significantly and systematically whiter than Fig. 1b. The developing plume first exceeded 2000 km in length and crossed 15°N out of the ITCZ near 150°W. MT2 describes many of the features typical of these systems. The broad moist and cloudy area extending northward out of the ITCZ, the sharp moisture/cloud gradient on the north and west side of the plume, and the midlatitude trough north of Hawaii typify plumes. The ITCZ moisture distribution and the distance of the midlatitude trough from the tropical plume origin at 8°N, 152°W (about 2000 km) is typical (Fig. 1b). This case is compared with the composite below.

OLR and vapor imagery composites of quiescent events, Fig. 2, are described first to provide a comparison for the composites of tropical plumes. If a gridpoint area was cloud free and dry for all 35 images of the composite, its value in the vapor image composite would be 4. Similarly, if the gridpoint was covered with high cloud in all 35 images, its value would be 1. The range in Fig. 2a runs from 3.1 in the middle of the

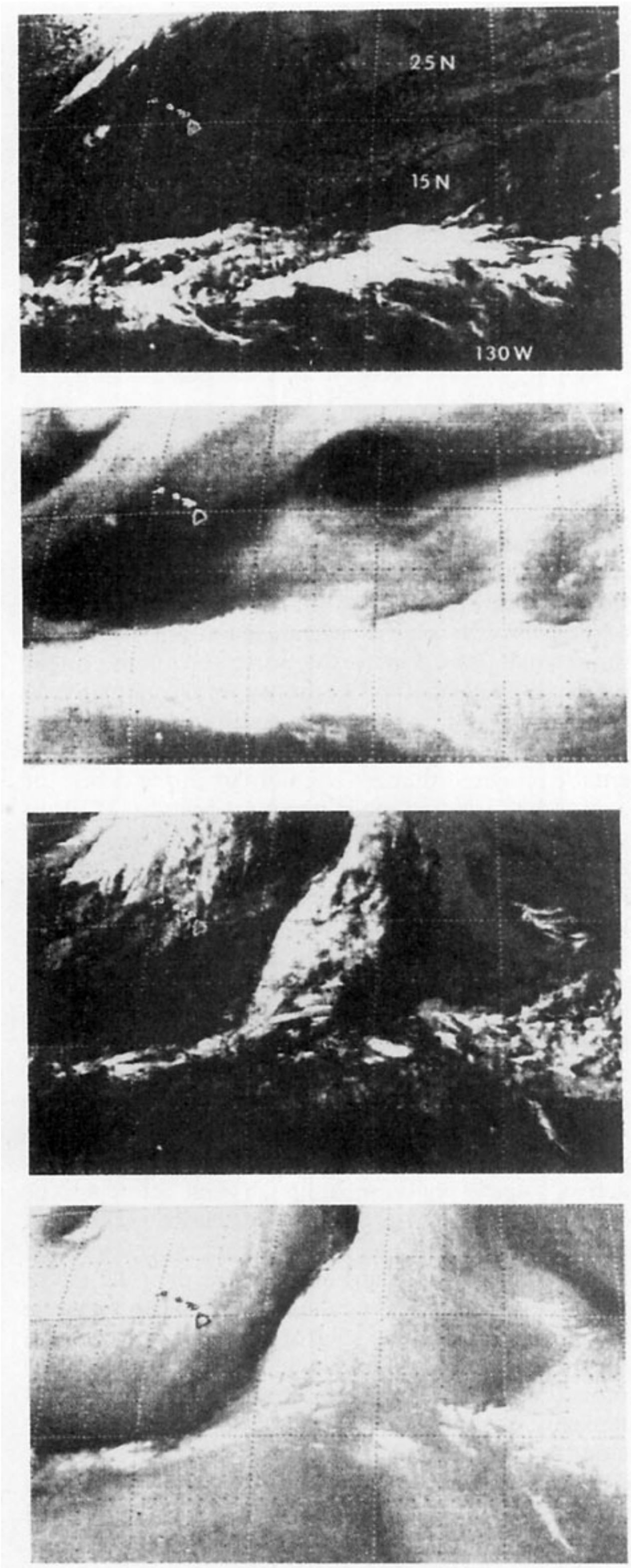

FIG. 1. GOES VAS imagery for precursor (a,b) and definition (c,d) stages of a tropical plume reaching definition stage on 1200 UTC 13 December 1983; (a) and (c) are infrared (cloud) images; (b) and (d) are vapor images. Gray scales are not consistent between images.

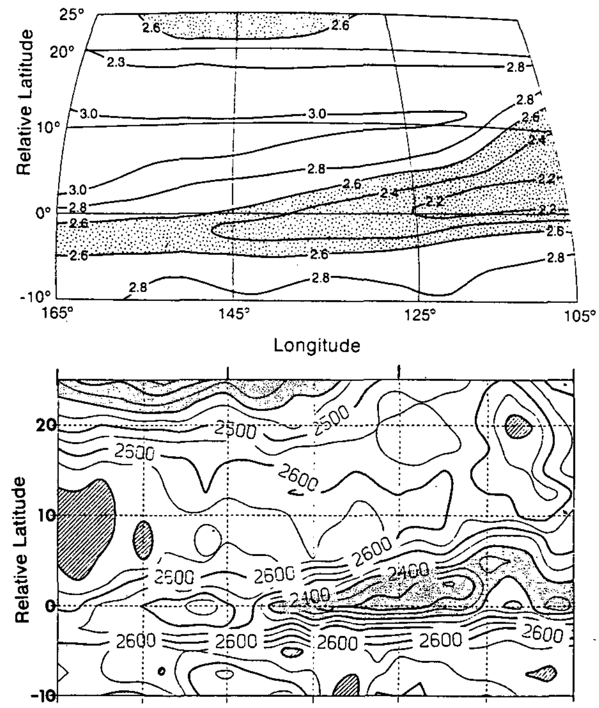

FIG. 2. Thirty-five day "quiescent" composite when no tropical plumes are active or about to develop in the eastern Pacific; 0° relative latitude corresponds to the latitude of the ITCZ. (a) VAS vapor image composite. Units are nondimensional, ranging from 1.0 (wettest) to 4.0 (driest) with values less than 2.6 stippled. (b) OLR composite. Units in 0.1 W m^{-2}, with cloudy areas stippled (less than 2400) and clear areas hatched (greater than 2700).

subtropical high to a value of 2.2 in the ITCZ between 125°W and South America. Composited OLR varies between about 225 and 275 W m^{-2}. The correspondence between vapor image and OLR composites is good. Patterns in both datasets are nearly zonal, with a slight poleward shift of the moist and cloudy axes only over the extreme eastern Pacific. The subtropical high is more a zonal, dry and cloud free axis (except possibly very low level clouds) than a high pressure "cell." A minor moisture maximum along the northern boundary centered at 145°W indicates the mean location of the mid-Pacific trough. Although these patterns are somewhat different than the expected climatology (at least in OLR), they resemble the mean wintertime OLR map for 1983/84 closely; this winter experienced anomalously active east Pacific convection. The outstanding feature of the quiescent composite is the absence of significant variation in the zonal direction. Even the long term climatology is more structured than this 35 image composite. The configuration of the quiescent subtropical high is different than both climatology and the 1983/84 winter mean; the high in the quiescent composite extends at least 30° to 40° longitude farther east than the 1983/84 winter mean or the climate mean positions.

Figure 3 depicts the evolution of tropical plumes in vapor image composites. The OLR precursor composite (constructed from the same dates as that in Fig. 3a) is shown as Fig. 4; the OLR definition composite is not shown but is nearly identical in pattern to that shown by Lin and Mock (1986). Four significant extrema appear in the vapor image precursor composite, 48 h *before* the plume reaches definition stage. The moist zone 3000 km to the northwest of the origin point is associated with the expected midlatitude trough. The dry region to the south of this trough is the subtropical high, both much stronger and differently configured than its counterpart in the quiescent composite. The two moist regions along the ITCZ are separated zonally by about 4000 km. Comparison of the vapor image and OLR (Fig. 4) precursor composites with the quiescent composites (Fig. 2) shows that the ITCZ and the subtropical high are less moist and less cloudy just before a tropical plume develops than when no significant synoptic activity is occurring (by 0.2–0.4 units in the vapor composites). The only place experiencing moister conditions than in the quiescent composite is a small region near and to the southwest of the plume origin. To the extent that the composite represents all plumes and the quiescent composite represents nonplume conditions, a moist, synoptically inactive, tropical region must first dry out before a tropical plume develops; as the plume develops, the tropical region rapidly moistens. The extrema observed in the vapor composite are not observed in the OLR composite (Fig. 4). OLR is not highly sensitive to moisture fluctuations within the subtropical high where clouds other than stratus and trade-wind cumulus are uncommon. The moist features on the ITCZ are associated typically with moisture variation, and not convective cloud variation, which would be detected by OLR. Thus elements of the vapor image precursor are clearly vapor and not cloud variations detectable in infrared cloud imagery.

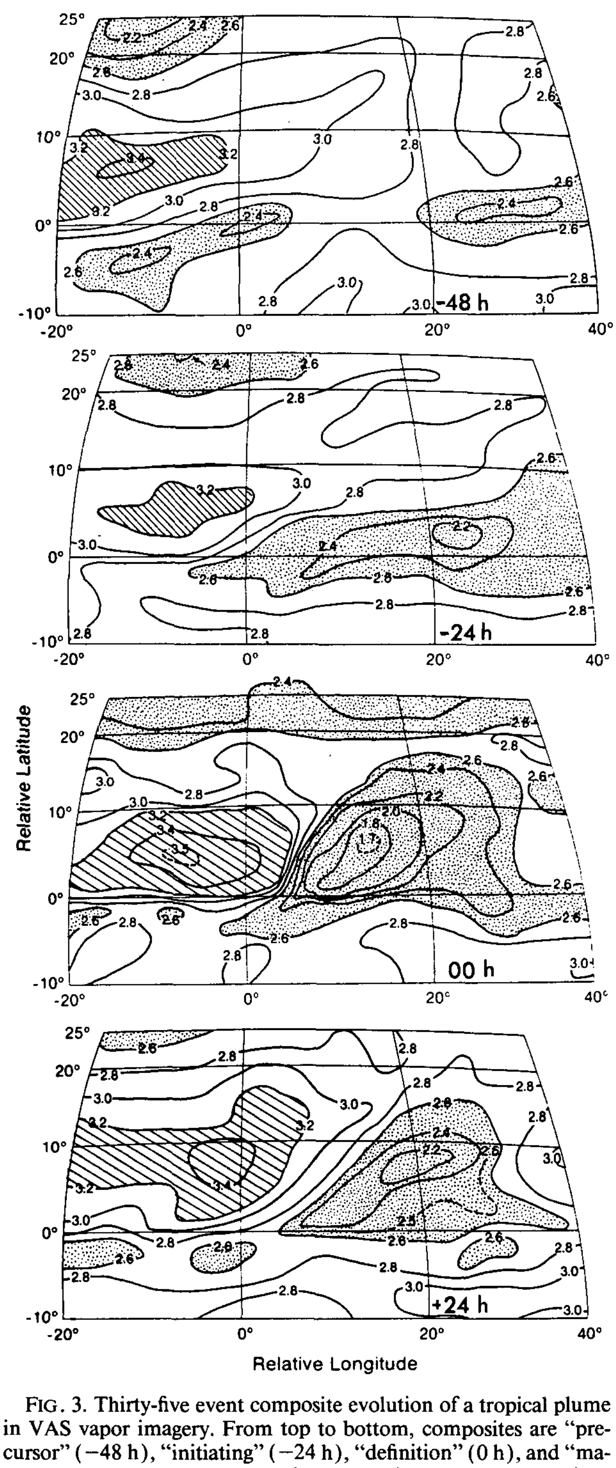

FIG. 3. Thirty-five event composite evolution of a tropical plume in VAS vapor imagery. From top to bottom, composites are "precursor" (−48 h), "initiating" (−24 h), "definition" (0 h), and "mature" (+24 h). Units and shading as in Fig. 2a, with dry regions (greater than 3.2) hatched. Origin, in relative latitude and longitude, is the tropical plume origin (see text).

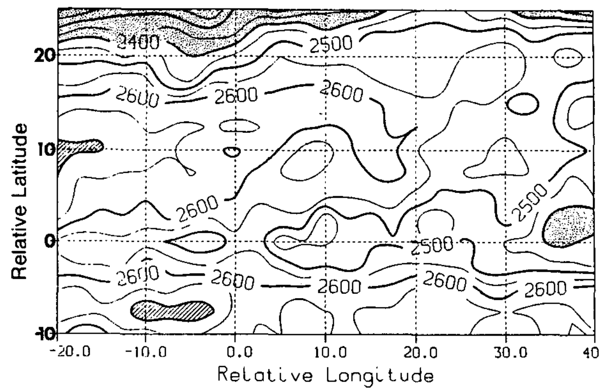

FIG. 4. Thirty-five event "precursor" composite in OLR data. Units and shading as in Fig. 2b. Origin, in relative latitude and longitude, is the tropical plume origin.

The initiating composite (24 h before definition) actually possesses a less definitive signature than the precursor composite. The midlatitude trough is weaker and the pattern is spread out. The subtropical high is slightly moister although it has expanded eastward and southward. The ITCZ from west of the plume origin point to over 4000 km to the east has moistened significantly and broadened meridionally. The last two features lead to the formation of a strong moisture gradient along the flank of the region that will soon be the tropical plume. The comparison between the initiating and quiescent composites shows them to be curiously similar, except for the location of the ITCZ moist maximum and the eastward extent of the subtropical high. Because of the averaging procedure, the quiescent moistness is known to be centered east of 110°W; MT1 demonstrated that plumes seldom develop here. The moist maximum in the initiating composite is centered about 125°W.

The definition composite is dominated by a moist–dry dipole located about 6° north of the origin–ITCZ latitude (approximately 13°N true latitude). The subtropical high is drier than both the precursor and the quiescent subtropical high. The moist maximum along the plume represents a continuous axis from near the equator just east of the origin point to over 3000 km northeastward; the OLR minimum in this region (not shown) is about 225 W m^{-2}, with values less than 230 W m^{-2} restricted to east of the origin region and south of 10°N. The midlatitude trough is no longer well defined, although the variation of moisture values along the northern boundary of the figure is marginally significant statistically (at the 95% level, as described in section 3b). The moisture gradient separating the nodes of the moist dipole is extreme (the shift from moist to dry occurs in one grid interval). The sharp edge of the moist boundary on the northern flank of plume in Fig. 1d is thus verified as a typical feature, one that is not averaged out when synthesized over many events. A secondary wavy shape appears in the moist region of the plume along the ITCZ; a wavy moist axis extends along the ITCZ some 4000 km east of the plume origin. This feature was first identified by Stockton (1986) in cloud imagery of a weak tropical plume which developed in May 1979.

Features of the mature composite, 24 h later, are similar to those of the definition composite. The amplitudes are weaker, particularly the moisture maximum and the moisture gradient to its west. The moisture dipole has moved north several 100 km and east about 600 km. The ITCZ south of the subtropical high has moistened. On the average, tropical plumes fail to meet the plume definition about 36 h after the mature composite: MT1 demonstrated that plumes last typically about 2.6 d.

Comparison of individual cases against the composites reveals that the four extrema described in the precursor composite are present in most individual images (between 80% and 90% of the time). Occasionally one is weak or missing; for example, one of the precursor features in Fig. 1b is weak (the separation of the western ITCZ moist maximum from the eastern maximum). Thus, the two well-defined moisture maxima are not obvious. The cloud image (Fig. 1a), which usually does not identify this feature, does depict two ITCZ areas of enhanced cloudiness. The dry region southwest of Hawaii is obvious as is the moist region associated with a midlatitude trough north of Hawaii. The cloud imagery does not delineate the dry area of the subtropical high. The definition vapor image (Fig. 1d), whose gray scale is different than that in Fig. 1b, depicts the moist dipole south and east of Hawaii. The moisture gradient to the northwest of the tropical plume is typically extreme, due in part to the intense dryness along the immediate flank of the plume. The plume is oriented somewhat more meridionally than the axis of the composite plume. The initiating image (not shown) depicts two moist maxima along the evolving plume, one located just southeast of Hawaii, between 15° and 20°N, the other north of 25°N; the separation is even stronger in the cloud imagery, implying the existence of two disturbances associated with this tropical plume: one tropical, and the other extratropical. Thus, the features of the example plume, although somewhat different from the composite plume, exemplify typical plume behavior.

b. Plume statistics

The robustness of the plume composite is demonstrated by the variance plots for three of the composite times in Fig. 5. Differences in pattern amplitudes of 0.2 exceed the 95% confidence level with respect to random data, if the composite variance is less than approximately 0.4; larger variance requires a proportionately larger amplitude difference for statistical confidence. The variance pattern for the quiescent case is nearly featureless, with a weak maximum of variability along and to the south of the subtropical high, and a weak minimum within the east Pacific ITCZ. This maximum in variance is caused by transient northward movements of the ITCZ in the central Pacific; the variance minimum is associated with the persistence of the east Pacific convection in the region where MT1 found minimal plume occurrence. Given the small variance values, there is less than one chance in twenty that the quiescent pattern occurring in Fig. 2 would occur randomly.

The variance structure of the precursor and definition composites (the middle and bottom of Fig. 5) lead to similar conclusions about these patterns: Strong ITCZ variability south of the subtropical high in the central Pacific and more persistence in the eastern portion of the ITCZ and within the subtropical high. The largest variances appear on the margins of the extrema described in Fig. 3. Thus, the existence of the maxima are most certain; variance is associated more with variations in the positions of the extrema relative to the plume origin. The largest variances are associated with the definition composite and are aligned along the large moisture gradient between nodes of the moisture di-

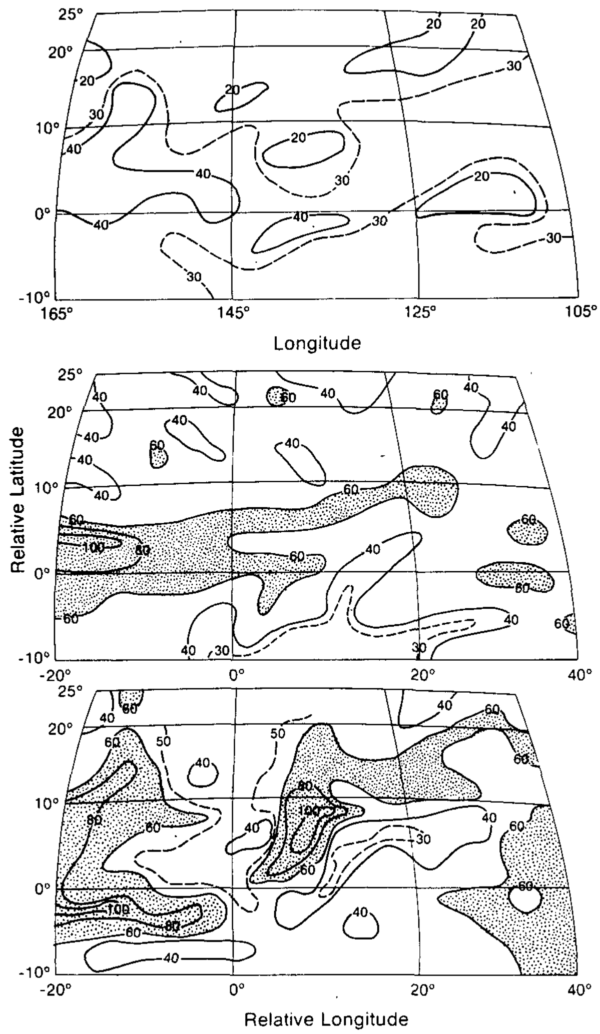

FIG. 5. Grid point variances of vapor imagery for quiescent (top), precursor (middle) and definition (bottom) composites. Units are multiplied by 100 with values greater than 60 shaded.

pole; this variance results from small positional changes of the gradient, noted in Fig. 1d.

The pattern differences between the plume composites and the quiescent composite are significant as well; that is, they are statistically unlikely to have occurred by chance. The figures are presented by Ulsh (1988). The principal features of the precursor composite are in excess of 0.4 different from the quiescent amplitudes. The initiation composite is significant in the moistening of the eastern ITCZ and the westward retreat of the subtropical high, although a number of features of this composite are similar to the quiescent composite. The definition and mature composite differences from the quiescent case are associated with the moist dipole, where differences exceed 1.0.

The three 24-h difference maps between the four plume composites, shown in Fig. 6, highlight the temporal evolution of plumes. The *pattern* of change from one composite time to the next in the tropics (south of 15° relative latitude) is nearly constant for all three maps; that is, the development in the composite plume is nearly stationary and restricted to tropical latitudes. The only meaningful change in the subtropics occurs between the initiating and definition stages, when nearly the whole northern margin of the composite moistens, and then dries between the definition and mature stages. There is no consistent signal of the midlatitude trough that is associated with tropical plume development. Thus, even though all plumes are accompanied by this trough (it is one of the dominant signals in the precursor composite), its position and movement is not systematic with respect to the nearly stationary plume. In fact, MT1 noted that plumes normally terminate when the midlatitude trough moves so far east of the tropical origin point that the cloud band becomes discontinuous.

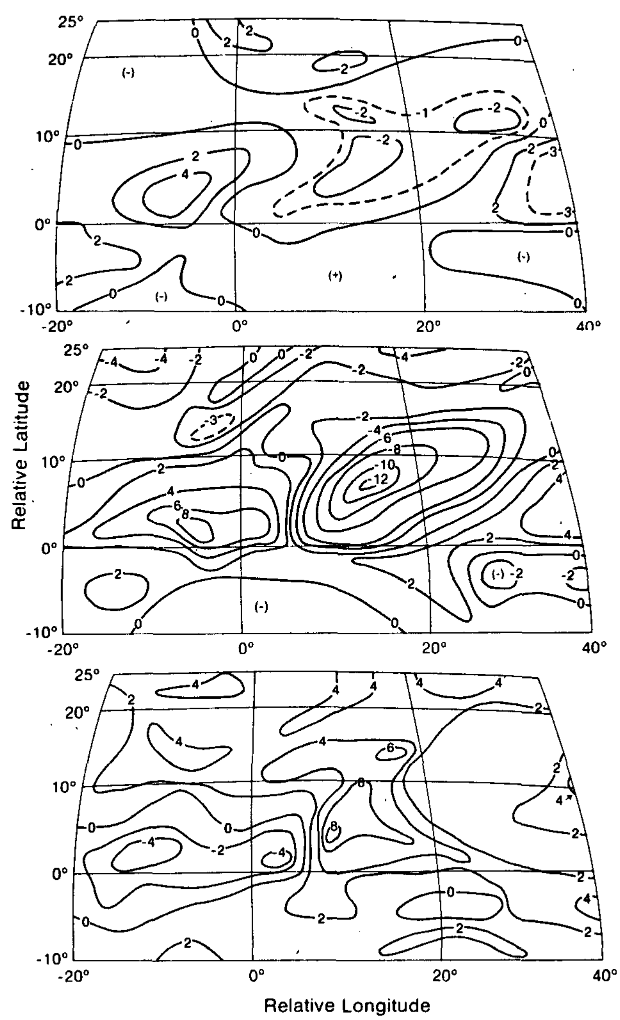

FIG. 6. Twenty-four hour difference maps (giving "vapor imagery tendency") for composites in Fig. 3: initiating—precursor (top); definition—initiating (middle); and mature—definition (bottom). Units are multiplied by 10.

4. Plume prediction

The precursor signal is sufficiently strong in vapor imagery to warrant a test on the predictability of tropical plumes from time periods before tropical cloud development occurs. A template was constructed of the patterns of the four extrema of the precursor composite; this template could be overlaid on individual vapor images. An undergraduate meteorology student was trained on images from the plume composite and then given an independent sample of images sequentially. The independent sample consisted of a continuous run of vapor images for the four month period November 1981 through February 1982; this collection contained 29 tropical plumes, a number unknown by the student forecaster. Predictions were made of plume origin by time and location. A successful forecast required the proper placement of the plume origin point (to within ±5° latitude and longitude, *and* ±12 h in time of occurrence). Table 2 summarizes the results. Nineteen of the events (65%) were predicted correctly. In addition there were seven overpredictions (predicted plumes that did not develop). Many of the forecast errors were systematic: The majority of overpredictions occurred over the extreme eastern Pacific, east of 120°W where plumes seldom develop. Most of the rest of the errors, overpredictions and underpredictions, occurred in complex synoptic situations where two or more synoptic features were present. A more sophisticated, but still simple, prediction scheme could be developed to improve the 65% success rate by not predicting plumes in climatologically atypical regions, and by withholding predictions in complex synoptic environments.

This simple prediction technique may not prove to be robust under more general conditions or more strict controls. However, it demonstrates that sufficient signals of nascent tropical plumes exist in satellite observations, even before the appearance of detectable clouds in infrared imagery, that forecast models could anticipate plume development. Problems that global numerical forecasting models have in describing plume evolution have been discussed in MT2 and by McGuirk et al. (1989).

TABLE 2. Summary of tropical plumes predicted from precursor composites.

Month	Observed plumes	Plume correctly predicted	Over-predicted events	Under-predicted plumes
Nov 81	6	4	4	2
Dec 81	7	4	1	3
Jan 82	11	7	1	4
Feb 82	5	4	1	1
Totals	29	19	7	10

5. Conclusions and discussion

The most general conclusion of this study is that the structure of individual tropical plumes is sufficiently repeatable and that the signals are sufficiently strong in vapor imagery, that statistically significant plume composites can be constructed. While the definition and mature stages of the plume development are similar to that constructed by Lin and Mock (1986) in cloud imagery (and repeated by the present authors), the composites herein describe evolution and more individual detail.

1) A well-defined plume precursor exists in vapor imagery, at least 36 h before the plume meets the definition criteria; these signals are often present before detectable clouds develop. The signal consists of a moist maximum of a midlatitude trough and two moist maxima on the ITCZ, separated by a well-defined, dry subtropical high cell. The eastern Pacific tropics, within and near the ITCZ, are *drier and less cloudy* than climatology at this time.

2) The tropical plume develops as a stationary tropical moist/cloudy dipole. Although the midlatitude trough to the northwest of the origin point on the ITCZ is a consistent and well-defined feature of the precursor stage, this trough is neither consistent nor well defined for the remainder of the plume evolution. A sharp moisture gradient exists along the northwest flank of the moisture maximum (which is the plume), separating moist and dry extrema.

3) Variability among plumes within the composites is low within the moist/dry extrema, and is only moderately large along the margins of these extrema; thus, the plume extrema are robust, with only moderate variations in location from event to event.

4) The precursor pattern and plume evolution are sufficiently strong and stable to demonstrate predictive skill, based solely on the vapor features of the precursor composite. Although skill is modest (65%), most forecast errors are associated with complex patterns or with regions where tropical plumes normally do not develop.

5) Finally, a composite of nonplume events results in the appearance of an anomalously strong zonally banded structure: Moister ITCZ and drier and zonally oriented subtropical high. This pattern is not similar to climatology. These anomalies are consistent with an anomalously active Hadley cell circulation. If such an active Hadley circulation exists, its rising branch would moisten and increase clouds within the ITCZ; its subsiding branch would dry the subtropics. Exactly such a pattern appears in the quiescent composite, with anomalies extending across the northeastern Pacific.

The composites reveal an important evolutionary cycle of tropical behavior over the northeastern Pacific. At times of weak synoptic activity, the eastern Pacific ITCZ is active convectively (more active than would be expected from climatology), and this activity is approximately zonally symmetric. This state is consistent with the observation in MT1 that an active ITCZ, as occurs during the summer season or during El Niño events, is associated with only weak tropical plume activity. During these periods of enhanced ITCZ, the tropical regions are more moist and cloudy than normal. Somewhat before tropical plume development, the tropical eastern Pacific atmosphere dries and becomes less cloudy, so that by precursor time the tropics are systematically dry with high OLR values. The subtropical high cell is exceptionally well developed and dry. The most likely cause for such an occurrence would be enhanced subsidence throughout the eastern Pacific. The tropical plume develops within this *dry* environment as *both* a midlatitude trough *and* synoptic scale anomalies along the ITCZ. The midlatitude trough is always present with tropical plume genesis; but, for the remaining life cycle of the plume, the trough does not exhibit consistent behavior. As the plume evolves, the ITCZ and the plume extension moisten rapidly, while the subtropical high becomes even drier, exhibiting the warmest brightness temperatures typically observed in the vapor channels over the Pacific Ocean (Blackwell 1987). This moist/dry dipole is most easily explained in terms of local synoptic scale overturning, with convection occurring somewhere in the southwestern portion of the tropical plume and subsidence occurring in the dry region of the vapor imagery to the northwest. Eventually, the plume activity dies out and the moistened atmosphere becomes more zonally symmetric, awaiting subsequent drying and plume development.

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