Assessment of the Aviation Weather Center Global Forecasts of Mesoscale Convective Systems*

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(Manuscript received 10 January 2003, in final form 18 November 2003)

ABSTRACT

This paper examines the precision of location and top height of mesoscale convective systems, as forecast by the Aviation Weather Center (AWC). The examination was motivated by the Mediterranean Israeli Dust Experiment (MEIDEX) on the space shuttle *Columbia,* aimed to image transient luminous events (TLEs), such as sprites, jets, and elves, from orbit. Mesoscale convective systems offer a high probability for the occurrence of TLEs above active thunderstorms. Because the operational methodology was planned around a 24-h cycle, there was a need for a global forecast of areas with a high probability of massive thunderstorms that are prone to exhibit TLE activity. The forecast was based on the high-level significant weather (SIGWX) maps, commonly used for civil aviation, provided by the AWC on the Internet. To estimate the operational skill of this forecast for successfully detecting clouds with a high probability for producing TLEs, predictions for selected dates were compared with satellite observations. The locations of 66 mesoscale cloud systems on Significant Weather Maps, produced for eight different dates in August 2001, were compared with satellite global IR images for these dates. Operational skill was determined as the percentage of observed cloud systems found within a 5° range in the regions that appeared on the forecast maps as having the potential to contain thunderclouds and was found to be 92%. No consistent error was found in location. The predicted size of the convective system was typically larger than the observed size. Cloud-top heights of 53 systems were examined on four dates in October–November 2001, using IR radiances converted to brightness temperatures. For each convective system, the coldest cloud-top temperature was converted to height, using the NCEP–NCAR reanalysis data for the respective location and time. The standard error in the forecast heights was 2516 m. Because the purpose was to get true alerts of potential TLE occurrences, operational forecast skill was defined as the percentage of forecasts that were accurate within 1000 m or higher than observed. The 1000-m tolerance was allowed because of inevitable uncertainties underlying this method of analysis. Operational skill was found to be only 43%. During the ''STS-107'' mission flown in January 2003, the forecasted areas of main convective centers were transmitted daily to the crew and helped them in pointing the cameras and targeting thunderstorms. This ensured the success of the MEIDEX sprite observations that recorded numerous events in many different geographical locations.

1. Introduction

Imaging transient luminous events (TLEs) from orbit was one of the objectives of the Mediterranean Israeli Dust Experiment (MEIDEX) on the space shuttle *Columbia.* Because the methodology of shuttle operations is usually planned around a 24-h cycle, there was a need for a global forecast of areas with a high probability of massive thunderstorms, where the chance of recording TLEs is enhanced. The forecast was to be based on the Aviation Weather Center (AWC) products.

a. Transient luminous events

TLE is the collective name given to a wide variety of optical emissions that occur in the upper atmosphere above active thunderstorms. Distinct classes and names were given to the various forms of TLE, all of which allude to their fleeting, unpredictable nature: trolls, pix-

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* This work was made possible by the devotion and enthusiasm of the seven astronauts of the space shuttle *Columbia* in mission STS-107, who gave their lives in the pursuit of scientific research from space.

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ies, embers, sprites, elves, and jets, to name but a few. Ever since sprites were serendipitously discovered by Franz et al. (1990), these very brief, colorful phenomena have been studied from the ground, balloons, aircraft (Sentman and Wescott 1993), the space shuttle (Boeck et al. 1998), and the International Space Station. The observations of blue jets (Wescott et al. 1995) and elves (Fukunishi et al. 1996) added more impetus to the study of these phenomena. There is a growing body of literature that covers the phenomenology and theory of TLE generation, and we refer the interested reader to recently published reviews (Rodger 1999; Lyons et al. 2000; Neubert 2003). Telescopic imaging (Gerken et al. 2000) and the use of high-speed imagers (Moudry et al. 2003) have greatly improved the knowledge of the fine structure of these emissions and their initiation and propagation mechanisms. Sprites are usually associated with intense positive cloud-to-ground lightning and are initiated at the height of 70–80 km, from which they propagate in visible tendrils downward and upward (Pasko et al. 1998). Elves occur higher up, around 90–95 km, and are a result of the interaction between the propagating electromagnetic pulse (EMP) from the lightning and the ionosphere (Inan et al. 1997).

The global occurrence rate of sprites is estimated at several per minute, and they are usually associated with extremely powerful ground flashes (Füllekrug and Price 2001). Sprites are expected to occur above intensive thunderstorms, especially in the Tropics and over the continental United States, in association with mesoscale convective complexes (MCCs; Boccippio et al. 1995). An MCC is a cluster of cumulonimbi with a collective diameter of hundreds of kilometers, which is widespread in tropical regions. The vast majority of sprites were observed in the summer within continental thunderstorms over the United States (Lyons et al. 2000) and Europe (Neubert et al. 2001), but lately they have been observed in winter storms in Japan (Takahashi et al. 2003) and over the Pacific Ocean (Su et al. 2002). TLE-producing thunderstorms in these cases differed from MCCs and often consisted of convective cells embedded in cold fronts associated with midlatitude cyclones.

b. *Sprite observations from the space shuttle*

The first images of TLEs from space were found in video footage obtained during the Mesoscale Lightning Experiment that was conducted in 1989–91 (Boeck et al. 1995). The space shuttle's cargo-bay cameras were used, which are standard low-light monochrome uncalibrated video cameras often operated for monitoring activities within the shuttle cargo bay. The flight controllers at the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) targeted the night limb and recorded lightning activity over the eclipse side of the earth, without any crew involvement. An analysis of hundreds of hours of video yielded only 17 events of vertical flashes that appeared to emanate from cloud tops toward the ionosphere (Boeck et al. 1995). These events were approximately geolocated by using stars and ground lights and were found to occur over Africa, South America, the United States, Australia, Borneo, and the Pacific Ocean.

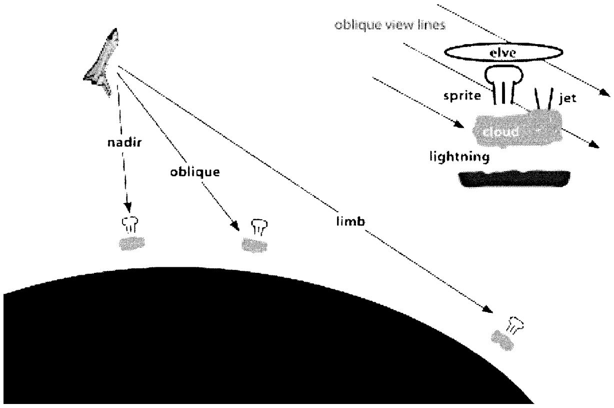

FIG. 1. Shuttle orientation during a sprite observation orbit.

The MEIDEX was conducted on the space shuttle *Columbia* in January 2003 during its last 16-day mission. The 39° inclination orbit passed over the earth's major thunderstorm regions. During the night side of 29 orbits, there were preplanned, targeted observations toward the earth limb above areas of active thunderstorms in an effort to image TLEs (Yair et al. 2003). Figure 1 shows the geometry of the observations. The MEIDEX offered a unique opportunity to conduct space-based observations using a calibrated, multispectral image-intensified camera, accompanied by an international ground campaign of observations of the electromagnetic radiation in the extremely low frequency (ELF)–very low frequency (VLF) range from sprite-inducing lightning.

Because the shuttle completed one revolution of the earth every 90 min and could observe any given target for only a few minutes, accurate forecasts of the geographical location of major storm centers were crucial. During the mission, the astronauts were asked to direct the cameras toward visible lightning activity centers. However, such manual real-time adjustment of the observation area was limited by the gimbal angle of the instrument, which was ±22° across track of the shuttle's vertical axis. In order to enhance the probability of success, a daily predetermined shuttle attitude maneuver was required for each orbit when an observation was scheduled.

In order to observe sprites from space and to photograph them effectively, the astronauts needed to have advance information on the location and intensity of cloud systems with a potential for producing TLEs. Areas of high convective activity were predicted, based on global aviation high-level significant weather (SIGWX) charts commonly used for civil aviation and disseminated on the Internet by the AWC of the U.S.

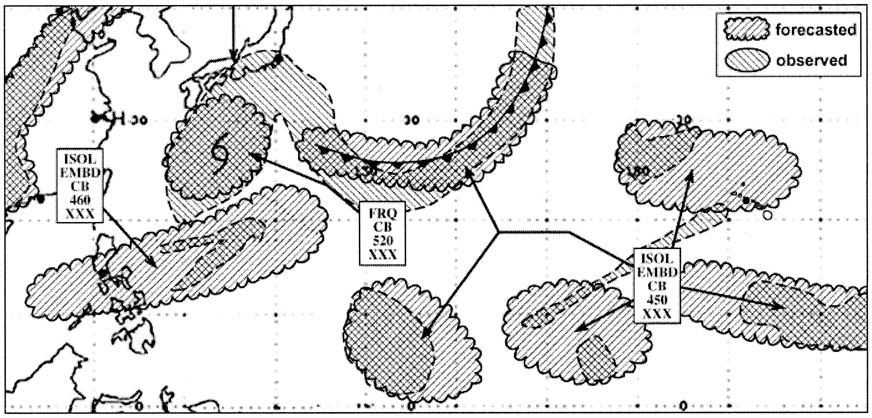

FIG. 2. An example of a verified significant map.

Department of Commerce, the National Oceanic and Atmospheric Administration (NOAA), and the National Centers for Environmental Prediction (NCEP; available online at http://aviationweather.gov/products/swh/). This type of map includes elements significant to aviation, such as regions of turbulence, icing, jet streams, and so on. The convective elements occurring in a specific region are denoted by symbols, together with annotations of the height of the cloud tops and the degree of expected convection intensity (e.g., severe, moderate). The forecast is prepared 24 h in advance and is valid for 6 h. The most preferred candidates for our space observations were mesoscale convective systems (MCSs), including squall lines.

Because these observations were to be predetermined on the basis of these forecasts, it was important to assess their accuracy. To this end we compared the location and top heights of the MCSs that were predicted for the area between 40°S and 40°N latitude with actual observed ones using satellite imagery. Section 2 describes the methodology used for the assessment, section 3 presents the results, and section 4 summarizes their implications for the ‘‘STS-107’’ mission, together with a brief description of the actual operational forecasting applied and some preliminary successful results of TLE observations.

2. Methodology

The examinations were divided into two parts. The first, in August 2001, involved the locations and existence of the MCSs, and the second, in October–November 2001, addressed the height of the cloud tops. In each assessment several series of SIGWX maps were compared with IR satellite imagery based on the network of meteorological geostationary satellites.

a. Location

Currently, forecasts of cloudiness are verified by comparison of cloud coverage, as derived from satellite images, with that forecast over grid boxes (e.g., Shaw et al. 2001). For our purposes we needed to verify the precision in locating specific objects, that is, MCSs, and so our approach differs from the common by being of Lagrangian nature. To determine the location of MCSs, satellite images were taken from the Naval Research Laboratory (NRL) Monterey (California) Tropical Images Web site (available online at http://www.nrlmry.navy.mil/sat-bin/tropics.cgi). Comparison was performed manually by superimposing observed cloud systems over those on the forecast maps (see, e.g., Fig. 2).

Two criteria were used for verification. The first was the existence of convective centers in the proximity of the regions marked in the forecast maps as having the potential for developing thunderclouds within a 5° range. This constitutes approximately 1/3 of the field of view of the Xybion camera, which was the main science instrument of the MEIDEX payload (this type of camera is often used in sprite field campaigns). When the above criterion was not fulfilled, the forecast was still regarded as successful if the observed cloud was located within a larger-scale cloud system, for example, along the intertropical convergence zone (ITCZ), or as a part of a cyclonic system that was correctly predicted. In any event, if the deviation was greater than 10°, the forecast was regarded as unsuccessful.

b. Height of cloud tops

To validate the height of cloud tops, we used Meteosat satellite imagery provided by the Deutsche Wetterdienst, in Offenbach, Germany, in which IR radiances are converted to temperatures and are color coded. For each convective element the coldest cloud-top temperature (corresponding to the pixel having the minimum radiance) was selected and converted to height. The conversion was based on a temperature profile extracted for the location and time for each cloud element from the NCEP–National Center for Atmospheric Research (NCAR) reanalysis Climate Data Assimilation System (CDAS)-1 archive (Kalnay et al. 1996; Kistler et al.

TABLE 1. Results of cloud location assessment.

Date	Region	MCS (clusters)		Squall lines		Operational skill
		Forecast	Observed	Forecast	Observed	
18 Aug 2001	Pacific	7	5	4	3	8/11
18 Aug 2001	Atlantic	6	6	2	1	7/8
19 Aug 2001	Pacific	4	4	5	4	8/9
19 Aug 2001	Atlantic	7	7	3	3	10/10
20 Aug 2001	Pacific	6	6	2	2	8/8
20 Aug 2001	Atlantic	3	3	3	3	6/6
21 Aug 2001	Pacific	6	6	1	1	7/7
21 Aug 2001	Atlantic	6	6	1	1	7/7
Total		45	43	21	18	92%

2001) with 2.5° × 2.5° and 6-h spatial and temporal resolutions, respectively. In cases in which the minimum temperatures were lower than the minimum in the profile (i.e., the tropopause), we assumed that the clouds penetrated the stratosphere because of inertia and that the temperatures at their tops, when crossing the tropopause, were identical to the surrounding air there. In such a case, we determined the top height as being the height of the tropopause plus an incremental height ΔH calculated by

$$\Delta H = \Delta T \Gamma_d, \tag{1}$$

where ΔT is the temperature difference between the tropopause and the cloud top and Γ_d is the dry lapse rate, which is a good approximation for the wet adiabatic lapse rate at temperatures lower than -50°C.

When converting radiance to cloud-top height, a number of errors may emerge, as specified below:

1) Errors related to the limited spatial distribution of the satellite imagery, on the order of 5 km (depending both on latitude and longitude), can occur. These errors may smooth the temperature distribution, resulting in an underestimation of the height of cloud tops.
2) A satellite image, by nature, is merely a snapshot of a longer-term dynamic atmospheric process. It, therefore, represents only one instant in the life cycle of the thundercloud (on the order of 1 h) and rarely coincides with the peak in lightning activity. Thus, one can expect that such an image will often miss the maximum vertical development, which is the stage most conducive to electrical activity (Williams et al. 1991). The resulting error is also an underestimation of cloud-top height.
3) Error in the transformation of radiance to temperature due to fluctuations in the emissivity of the cloud tops with respect to reference values can occur.
4) The tops of the convective clouds are normally cooler than the surrounding air (an effect that hinders their vertical development). Because the temperature–height conversion is based on the ambient profile, this may cause overestimation of the top height.

The different signs of the errors make the use of any correction factor for our calculated results fruitless.

3. Results

a. Location

During August 2001, 66 MCSs predicted on eight SIGWX maps were compared with those observed in satellite images for the same dates (see Table 1). No consistent error in the locations of the cloud systems was found. On the other hand, the area of the predicted systems was typically larger than that observed (e.g., Fig. 2). This is an inevitable consequence of the definition of the predicted system as a region with a *potential* for the development of comulunimbi and severe weather. Operational skill was determined as the percentage of successfully predicted cloud systems, based on the criteria specified above. The operational skill of the SIGWX maps was found to be 92%, suggesting that in the majority of the cases these maps correctly predicted the existence and location of thunderclouds. Only two systems that were found in the satellite images were not predicted. These storms were smaller than typical MCSs, and, hence, were probably not suitable candidates for sprite occurrence. (Such systems may, however, possess a significant threat for aviation.)

b. Top height

In October–November 2001, 53 predicted MCSs were examined. The detailed comparison is shown in Table 2. The average error was -1698 m; that is, the forecasted cloud tops were ~1700 m lower than those observed, on the average. The standard error in the height forecast HE was defined as

$$\mathrm{HE} = \left[\frac{1}{n}\sum_{i=1}^{n}(H_0 - H_f)^2\right]^{1/2}, \tag{2}$$

where H_0 and H_f are the observed and forecast heights, respectively, for n cases. Unsatisfactorily, HE was found to be 2516 m. Even when accepting a 1000-m error (considering the inevitable uncertainties underlying our method of analysis, as specified above), the percentage of successful forecasts was only 40%. Such inaccuracy needs to be taken into account for aviation safety.

Our purpose in using the aviation forecast was to have a true alert as to the possible occurrence of sprites.

TABLE 2. Results of cloud height assessment.

Lat (°)	Lon (°)	Date	Temperature (°C)	Predicted (m)	Observed (m)	Observed (actual) − predicted
−32	27	29 Oct 2001	−41	12 768	10 000	−2768
40	−105	29 Oct 2001	−47.5	10 336	10 500	164
35	148	29 Oct 2001	−55	12 160	12 300	140
−15	−35	29 Oct 2001	−59	11 248	13 300	2052
5	−57	29 Oct 2001	−63	13 680	13 850	170
10	−35	29 Oct 2001	−71	13 680	15 200	1520
−5	100	29 Oct 2001	−71.5	13 984	15 100	1116
15	−82	29 Oct 2001	−74	14 896	15 650	754
−10	−70	29 Oct 2001	−80	12 768	16 600	3832
10	−110	29 Oct 2001	−81	14 896	16 800	1904
−15	20	29 Oct 2001	−82.5	13 680	17 100	3420
0	25	29 Oct 2001	−87.5	13 680	18 650	4970
−32	165	30 Oct 2001	−45.5	10 640	9600	−1040
−22	125	30 Oct 2001	−51.5	12 160	12 400	240
10	−155	30 Oct 2001	−59.5	13 680	13 300	−380
35	−45	30 Oct 2001	−64	13 680	14 100	420
−20	−60	30 Oct 2001	−67	12 160	14 400	2240
10	−50	30 Oct 2001	−73	13 984	15 800	1816
15	−117	30 Oct 2001	−73	15 200	15 650	450
15	−72	30 Oct 2001	−74	14 592	15 300	708
10	−103	30 Oct 2001	−79	13 680	16 600	2920
−10	25	30 Oct 2001	−80.5	13 680	16 950	3270
0	120	30 Oct 2001	−82.5	13 680	16 300	2620
−5	−70	30 Oct 2001	−87	13 680	17 200	3520
−10	20	31 Oct 2001	−54	12 768	12 750	−18
20	−70	31 Oct 2001	−54	13 376	12 400	−976
−30	125	31 Oct 2001	−55	10 640	13 500	2860
30	160	31 Oct 2001	−55	10 944	12 400	1456
40	−40	31 Oct 2001	−59	12 160	12 400	240
30	−50	31 Oct 2001	−60	12 160	13 150	990
−30	30	31 Oct 2001	−63	11 552	15 300	3748
15	−50	31 Oct 2001	−66	13 984	14 000	16
5	−7	31 Oct 2001	−67	13 680	14 200	520
0	30	31 Oct 2001	−71	14 288	15 200	912
10	150	31 Oct 2001	−75	15 200	15 300	100
18	−84	31 Oct 2001	−76	14 592	15 800	1208
10	−120	31 Oct 2001	−81	14 592	16 600	2008
0	130	31 Oct 2001	−82.5	13 680	16 600	2920
0	−73	31 Oct 2001	−85	13 376	17 100	3724
35	12	4 Nov 2001	−61.5	12 768	12 600	−168
−12	−70	4 Nov 2001	−65	13 680	14 000	320
35	−50	4 Nov 2001	−65.5	12 160	18 500	6340
−35	30	4 Nov 2001	−67	11 248	18 900	7652
−20	20	4 Nov 2001	−71	12 160	15 300	3140
25	−40	4 Nov 2001	−71	13 984	15 200	1216
−25	−35	4 Nov 2001	−73	12 160	16 600	4440
9	−35	4 Nov 2001	−76.5	15 200	16 150	950
0	100	4 Nov 2001	−78	13 680	16 150	2470
0	150	4 Nov 2001	−78.5	13 984	16 150	2166
10	−150	4 Nov 2001	−79.5	14 592	16 800	2208
−10	−160	4 Nov 2001	−81	13 680	16 900	3220
20	−80	4 Nov 2001	−82	15 808	16 300	492
10	145	4 Nov 2001	−87	15 200	17 000	1800

Therefore, underestimating the cloud-top height was unacceptable for our needs because it may cause us to miss opportunities for observation from the shuttle. Füllekrug and Price (2001) found that a 1.6-km error corresponds to a drop in the correlation coefficient between the loading of the thunderclouds and sprite production from 0.75 to 0.65 over central Africa. Table 2 shows that 30 of the cloud systems were underestimated by more than 1000 m and two were overestimated by more than 1000 m, so that the operational skill can be regarded as 43%.

4. Summary

The forecast of MCS in SIGWX maps disseminated by the AWC was assessed in order to estimate its operational skill for successfully detecting clouds that have a high probability for yielding TLEs. The predicted cloud systems were compared with satellite observations for selected dates.

a. *Skill of the AWC forecasts*

Predicted locations of 66 cloud systems, on eight different dates, were compared with satellite IR images. The basic criterion for regarding a forecast as successful was the existence of a convective center within 5° of the region denoted as containing thunderclouds on the forecast map. When this criterion was not fulfilled, the forecast was still regarded as successful if the observed cloud was located within a larger-scale cloud system that was correctly predicted. If the deviation was greater than 10°, the forecast was regarded as unsuccessful. The operational skill was found to be 92%. No consistent error was found, and the size of the MCSs in the forecast was typically somewhat larger than the observed size.

The cloud-top heights of 53 storm systems were examined, using IR radiances that were converted to brightness temperatures and then to height, using NCEP–NCAR reanalysis data. The standard error in the forecast heights was found to be 2516 m. Because of the need for true alerts of possible sprite occurrences, the operational forecast skill was defined as the percentage of forecasts that were accurate within 1000 m of the observed height or overestimated. This discrepancy was allowed because of inevitable uncertainties underlying our method of analysis. Operational skill was found to be only 43%. Our calculated heights were compared with height derived by the same methodology but based on the Committee on Space Research (COSPAR) International Reference Atmosphere (IRA) 1986, which provides vertical profiles for each month, with a 5° latitudinal resolution. The cloud tops derived using the COSPAR data were lower by 517 m, on average. This indicates that in the 40°S–40°N latitudinal belt the isotherms are anomalously higher (hence, the upper air is anomalously warmer) in the vicinity of MCSs.

b. *Operational forecasting during the STS-107 mission*

Because of the MEIDEX orbital constraints (which primarily required daytime dust observations in the Atlantic and the Mediterranean regions), most of the nighttime observations were conducted in the southeast Pacific (Australia and Papua New Guinea), Africa, the southern Indian Ocean, and South America. Relevant inputs to the daily ‘‘execute packages’’ that were uplinked to the crew, including specific information on the active storms during a specific orbit, were derived as planned from the SIGWX maps.

We further deduced the necessary shuttle attitude maneuvers and camera gimbal changes from the (almost) real-time IR satellite images that were available on the Internet (online at http://www.bom.gov.au/weather/satellite/) and from the VLF lightning location network [from the Tropical Ocean and Global Atmosphere (TOGA) program; see online at http://ritz.otago.ac.nz/~sferix/TOGA_network.html] operated by the University of Otago in New Zealand. This ‘‘nowcasting’’ method allowed us to ask Mission Control for adjustments of the shuttle attitude, which were mostly granted (provided it was calculated no later than 4.5 h ahead of an observation, the time of three revolutions). In addition to an attitude change, the ground team performed preliminary camera pointing, increasing the likelihood of the Xybion field of view intercepting the main lightning activity regions, above which we expected to find TLEs. We instructed the astronauts to visually observe lightning activity (easily discernable from the shuttle) and to perform appropriate fine tuning of the camera pointing toward these regions. Contrary to remote-controlled or automatic robotic observations, the human factor played a significant and indispensable role in the real-time target acquisition, greatly enhancing the probability of capturing TLEs.

The fruitfulness of this approach was made clear in the first MEIDEX sprite observation during orbit 44 (0905:23.94 UTC 19 January). Mission Specialist D. Brown tracked a very active thunderstorm with continuous visible lightning activity located over the Pacific Ocean to the east of the Java–Fiji region. At the time of the event, the shuttle was located at 37.84°S, 150.08°W, with the center of the camera field of view pointed at azimuth 325°. The computed range of the storm center from the shuttle was 1635 km. A GOES satellite image showed a series of storm centers with cloud-top temperatures around −60°C [these are considered as having a higher probability for sprite formation (Füllekrug and Price 2001)].

An analysis of the video data (Fig. 3) showed an elf with the classical doughnut (ring) structure, above the top of the thunderstorm. Based on the viewing geometry, the calculated altitude of the central hole, reflecting the height of the plane of the elf above the ground, was found to be 88 ± 8 km. The unambiguous doughnut shape with the distinct hole in the center above the location of the causative ground stroke is in accordance with theory (Inan et al. 1997). Additional observations in subsequent orbits provided us with numerous successful observations of TLEs over Africa, South America, Australia, and the Atlantic and Pacific Oceans. These will be described in future publications.

It can be concluded that for the forecasting of potential regions of TLEs, the forecast accuracy of the AWC is only of limited use. It represents an indicator for predicting location but not for the potential for TLE occurrence. Thus, in order to meet our operational needs during the STS-107 mission, we considered any convective system appearing in the AWC significant maps whose top was at least 30 000 ft as a suitable candidate for TLE observations. This method proved to be successful in operationally predicting the major areas of convective activity. In the MEIDEX sprite campaign,

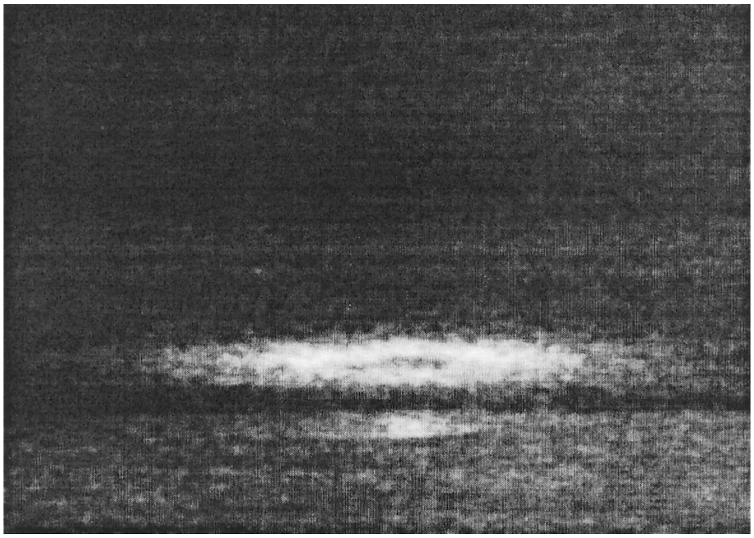

FIG. 3. Image of an elf recorded from the space shuttle *Columbia* on 19 January 2003, east of Fiji. The causative lightning is located below the central hole.

the *Columbia* astronauts succeeded in recording numerous TLEs over equatorial Africa, Australia, Brazil, and the Pacific Ocean.

Acknowledgments. The MEIDEX is a joint research of the Israeli Space Agency and NASA. We thank the Deutsche Wetterdienst, in Offenbach, Germany, for the satellite images. Forecast maps were used courtesy of the AWC. Figure 1 is courtesy of Stephen Clodman and Aaron Yeger.

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