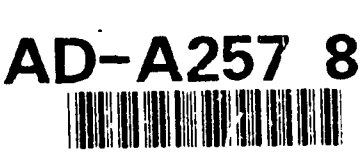

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

SURFACE METEOROLOGICAL PARAMETERS
OF
IDENTIFIED SHIP TRACKS

by

James Charles Pettigrew

September 1992

Advisor Philip A. Durkee

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Ships producing tracks in the atmosphere are identified and their surface meteorological parameters are specified. Thirteen case studies are presented with satellite imagery, synoptic discussion and surface meteorological parameters.

A composite "environment" is derived from reported surface meteorological parameters and is compared with climatological conditions of the region, showing that significant departures from normal conditions do not occur. No clear generation mechanism is suggested in a relationship between relative wind and separation distance of ship and ship track, indicating a complex relationship of generation mechanisms. Although a limited study, a firm foundation is now in place for further research into ship track genesis.

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Surface Meteorological Parameters of Identified Ship Tracks

by

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Lieutenant, United States Navy
B.S., Texas A&M University, 1984

Submitted in partial fulfillment of the
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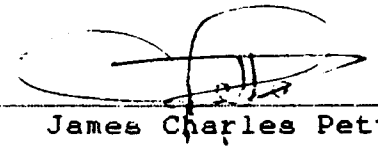
Author: 
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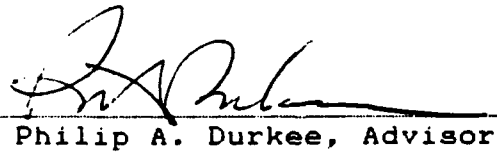
Approved by: 
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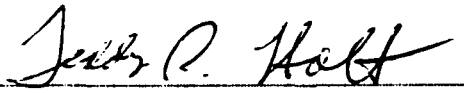
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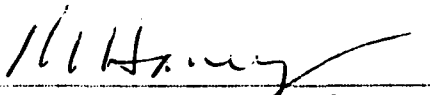
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ABSTRACT

Ships producing tracks in the atmosphere are identified and their surface meteorological parameters are specified. Thirteen case studies are presented with satellite imagery, synoptic discussion and surface meteorological parameters.

A composite "environment" is derived from reported surface meteorological parameters and is compared with climatological conditions of the region, showing that significant departures from normal conditions do not occur. No clear generation mechanism is suggested in a relationship between relative wind and separation distance of ship and ship track, indicating a complex relationship of generation mechanisms. Although a limited study, a firm foundation is now in place for further research into ship track genesis.

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Last, but certainly not least, my wife Tenise and son Joel were a daily inspiration to finish this thesis and proceed on. I love you both.

I. INTRODUCTION

Ship tracks were first observed by Conover in 1965. Conover (1966) presents background and possible explanations for observed "anomalous cloud lines". While cataloging synoptic weather in the vicinity of ship tracks, Conover found two ships that closely matched the position of observed cloud lines. He went on to identify the surface meteorological parameters of these two ships. Although the same surface meteorological parameters are reported on in this thesis, the approach is different. Instead of looking for weather reports in the area of a ship track, this thesis specifically identifies the platform generating the ship track and its surface meteorological parameters.

The intent of this thesis is to confirm ship and ship track coexistence and to identify the surface meteorological parameters in the presence of a ship track. To this end, thirteen case studies of surface weather reports from identified ship tracks are presented and evaluated.

There are many reasons to study the surface meteorological parameters of ship tracks. However, two stand out as significant. First, the effect of clouds in the earth's radiation budget is quite important. By further understanding the surface meteorological parameters that can alter cloud

radiative properties, radiation budget models would be better able to predict areas of increased reflectivity (Coakley et. al., 1987).

Secondly, and no less important, is the identification of key surface meteorological parameters which would lead to self-generation of ship tracks. This has obvious tactical implications, which will not be discussed in this thesis.

Coakley et al. (1987), shows that cloud condensation nuclei (CCN) from ship exhaust increases numbers of droplets and is consistent with a decrease in droplet size. Hindman (1990) also describes the contribution of both the ship's momentum wake (air wake) and plume dynamics in the perturbation of the marine boundary layer. Cook and Chaddock (1964) described wind tunnel tests that showed significant turbulence astern of an underway ship.

The resultant dip in droplet size yields an increase in reflectivity at 3.7 microns (channel 3 of the NOAA series satellites). The downward shift in droplet size and the increase in channel 3 reflectivity have been observed (Fig. 1) and is well documented (Twomey, 1977; Coakley et. al., 1987; King et. al., 1990). It is this change in channel 3 reflectivity that makes the ship track identifiable from the ambient background cloud.

Although ship tracks have been observed in many areas worldwide (Salvato, 1992), this thesis specifically studies ship tracks in the Pacific Ocean off the west coast of the

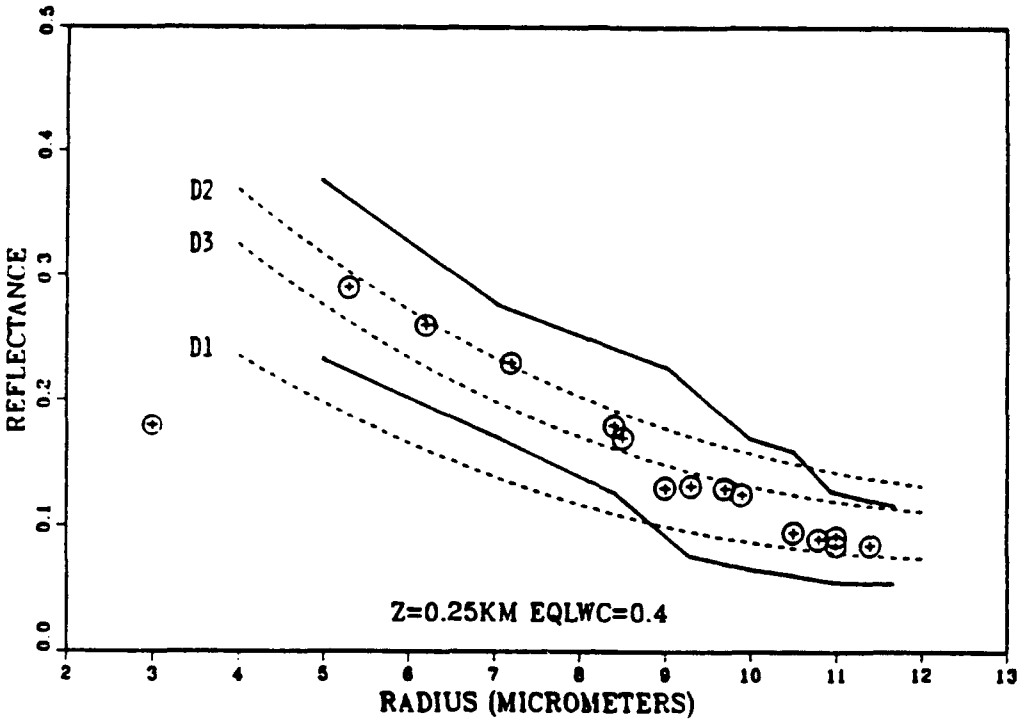

Fig. 1. Channel 3 reflectance vs. droplet size: (after Mineart, 1988)

United States. Ship tracks were objectively located in NOAA-9 and NOAA-10 AVHRR data. The period of study was 29 June-18 July 1987. By utilizing an archive of ship weather reports, which was obtained from Fleet Numerical Oceanography Center, ship tracks were matched to the position reported in their respective synoptic observations. These ship tracks were further identified by utilizing various shipping databases (Bluth, 1992).

Following a brief procedural discussion, thirteen cases will be presented. Each case study will include a synoptic overview of the eastern Pacific region, a listing of the pertinent surface meteorological parameters reported by the

ship, and a comparative discussion of the shiptrack's appearance in the image relative to the reported and derived parameters. Finally, conclusions and recommendations will be presented and will include parameter value ranges, possible errors, and distance difference statistics, as well as possible future research directions.

II. PROCEDURES

The procedure to identify the surface meteorological parameters of ship tracks involved two major steps. The first step was to objectively analyze satellite overpasses and locate ship tracks. The next step was establishing the identity of the ship by colocating the ship track with the position reported in a synoptic observation.

A. SATELLITE DATA

1. The Satellite

The satellite utilized was the NOAA series of polar orbiter, specifically NOAA-9 and NOAA-10. Both fly in a sun-synchronous orbit at an altitude of 525 miles. This configuration gives the possibility of coverage in the area of interest four times daily.

2. The Sensor

The NOAA satellites utilize the Advanced Very High Resolution Radiometer (AVHRR) to collect radiance data in five different wavebands (channels). The channels of interest for this thesis were channel 1 (visible, .58-.68 microns); and channel 3 (near infrared, 3.55-3.93 microns). The resolution of the AVHRR instrument is 1 km by 1 km at pass center.

3. Processing

Processing was performed at the U.S. Naval Postgraduate School's Interactive Digital Environmental Analysis (IDEA) Laboratory. Each case study was originally derived from an overpass of NOAA-9 or NOAA-10 AVHRR data. Each channel 3 overview was inspected visually to identify ship-tracks in the image. When a candidate ship track was found, a 512 km by 512 km subscene was generated. The final processing step was the "real mapping" of the ship track area (usually a 6 degree by 6 degree area centered on the ship track of interest). This real mapping placed the image on a mercator projection.

B. SURFACE METEOROLOGICAL DATA

Fleet Numerical Oceanography Center, Monterey, California (FNOC), maintains an active archive of ship synoptic weather reports. A subset of this archive was produced and utilized in the identification of ship tracks.

Once candidate ship tracks were located in each satellite overpass, the position reported by each ship in its synoptic report was utilized to find a platform that corresponded to the candidate ship track. The next step was to quality check the identification by matching the overpass ship track location with the extrapolated ship position. This was accomplished by utilizing its synoptic location along with its course and speed. Once the identity (call sign) was

determined then the following surface meteorological parameters could be identified for that ship track:

Total cloud cover in octas
Reported True Wind
Relative Wind
Reported Course and Speed
Sea Level Pressure in millibars
Air Temperature in Centigrade
Dewpoint Temperature in Centigrade
Water Temperature in Centigrade
Low Cloud Cover and Type

By utilizing the course and speed along with reported true wind, the relative wind (apparent wind) is found with a simple vector relation. Ship motion and winds are depicted on each image in the following manner:

--Direction of ship motion ➤

--True wind direction ➡

--Relative wind direction ⇨

The area that is most likely to contain errors within this analysis, are the meteorological observations. Merchant ships do not earn their money taking observations. Specifically, sea surface temperatures are normally injection temperatures taken anywhere from ten to thirty feet below the surface, depending on the draft of the ship. Also, air temperature and dewpoint are not measured with the scientific accuracy needed for a rigorous study. However, this "general" data will give a representative picture of the ship track environment. Also the positions reported at

synoptic times may not be highly accurate. However, this error is probably within 10 nautical miles of truth, and would not impact identification.

III. CASE STUDIES

As previously discussed, each ship track was objectively located in NOAA-9 and NOAA-10 overpasses. These candidate ship tracks were next compared with positions reported in synoptic condition reports. After a quality check was accomplished, identification of the ship track was complete and analysis of surface meteorological conditions can take place.

A. 3EMB4

The ship 3EMB4 was observed in an overpass of NOAA-10 at 1550Z (0850 local) on 30 June 1987 (Fig. 2). Fig. 3 shows synoptically, at this time an intensifying upper-level trough was located off of Oregon and California. The sub-tropical high was located near 150W, while its southern lobe extended to Baja. The high coupled with a strong thermal low inland, produced northwesterly winds throughout the area of interest (Kloesel, et al., 1988). The synoptic report by 3EMB4 at 1800Z (1100 local) showed the following surface meteorological parameters:

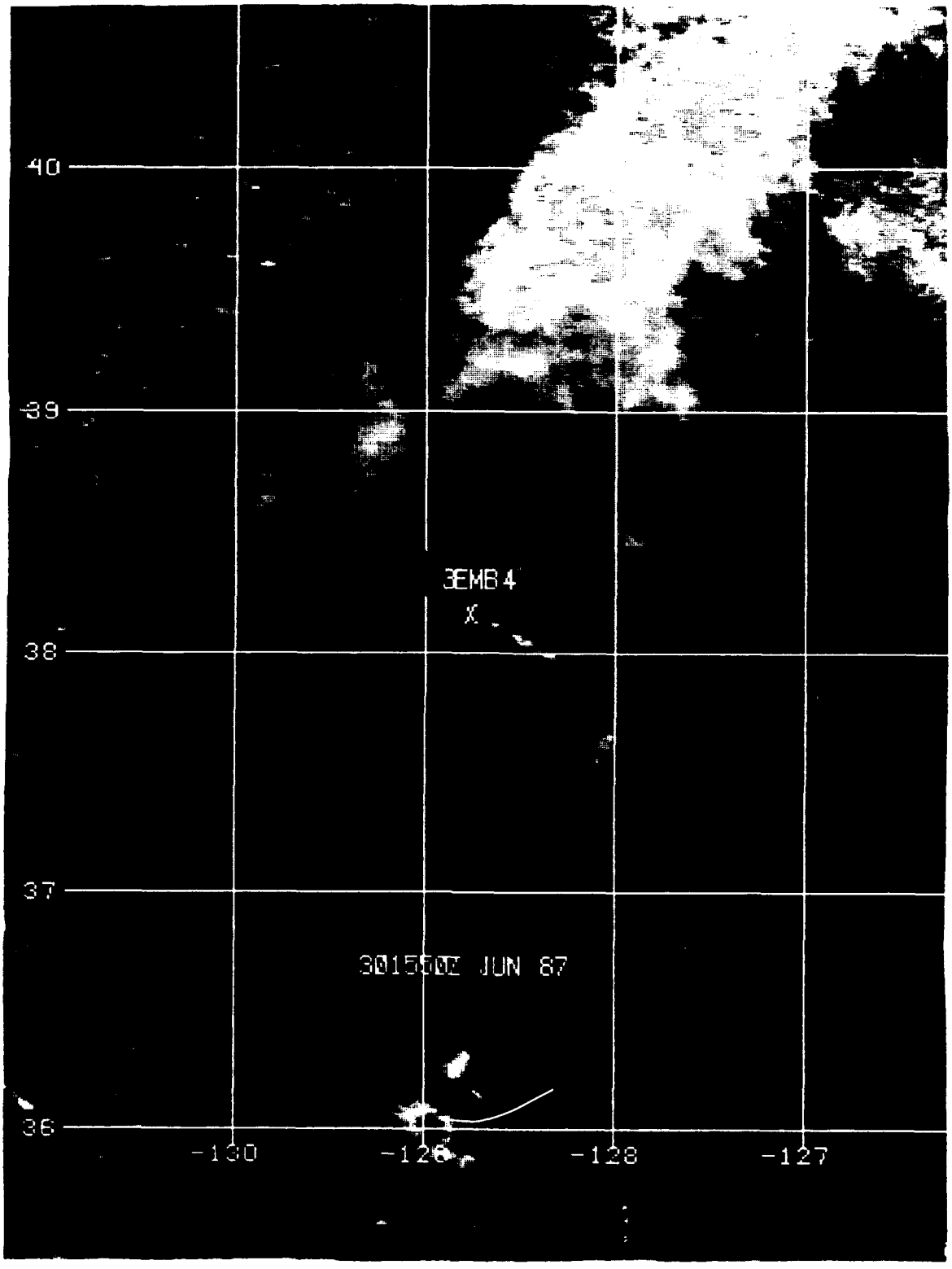

Fig. 2. Channel 3 imagery showing 3EMB4: 1550Z on 30 June 1987.

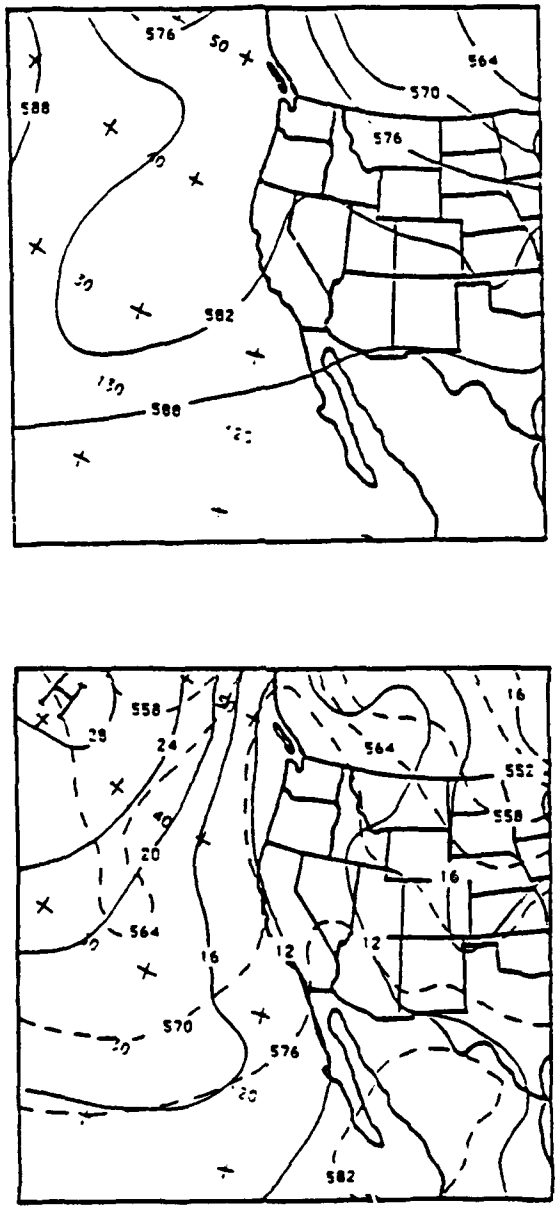

Fig. 3. 30 June 1987 12Z NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

8 octas total cover
True wind 330/8
Relative wind 5 deg stbd 25 kts
C/S 315/15
1014.7 mb
17C Ta
12C Td
21C Tw
8 octas St

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 2. Also the shiptrack is located in an area of stratus within the image, which is reported by the ship. The position of the ship track in this image is 38.17N 128.88W, while the position derived from 3EMB4's synoptic reports is 38.12N 129.02W. This difference in positions is approximately 8.92 nautical miles. The identity of 3EMB4 has yet to be determined from shipping databases.

B. 3ELT3

The ship 3ELT3 was observed in an overpass of NOAA-10 at 1513Z (0829 local) on 1 July 1987 (Fig. 4). Fig. 5 shows synoptically, at this time in response to the intensifying upper-level trough a small surface trough developed at 36N 130W. With the continued intensification of the inland thermal low strong northwest winds continued throughout the area of interest (Kloesel, et al., 1988). The synoptic report by 3ELT3 at 1800Z (1100 local) showed the following surface meteorological parameters:

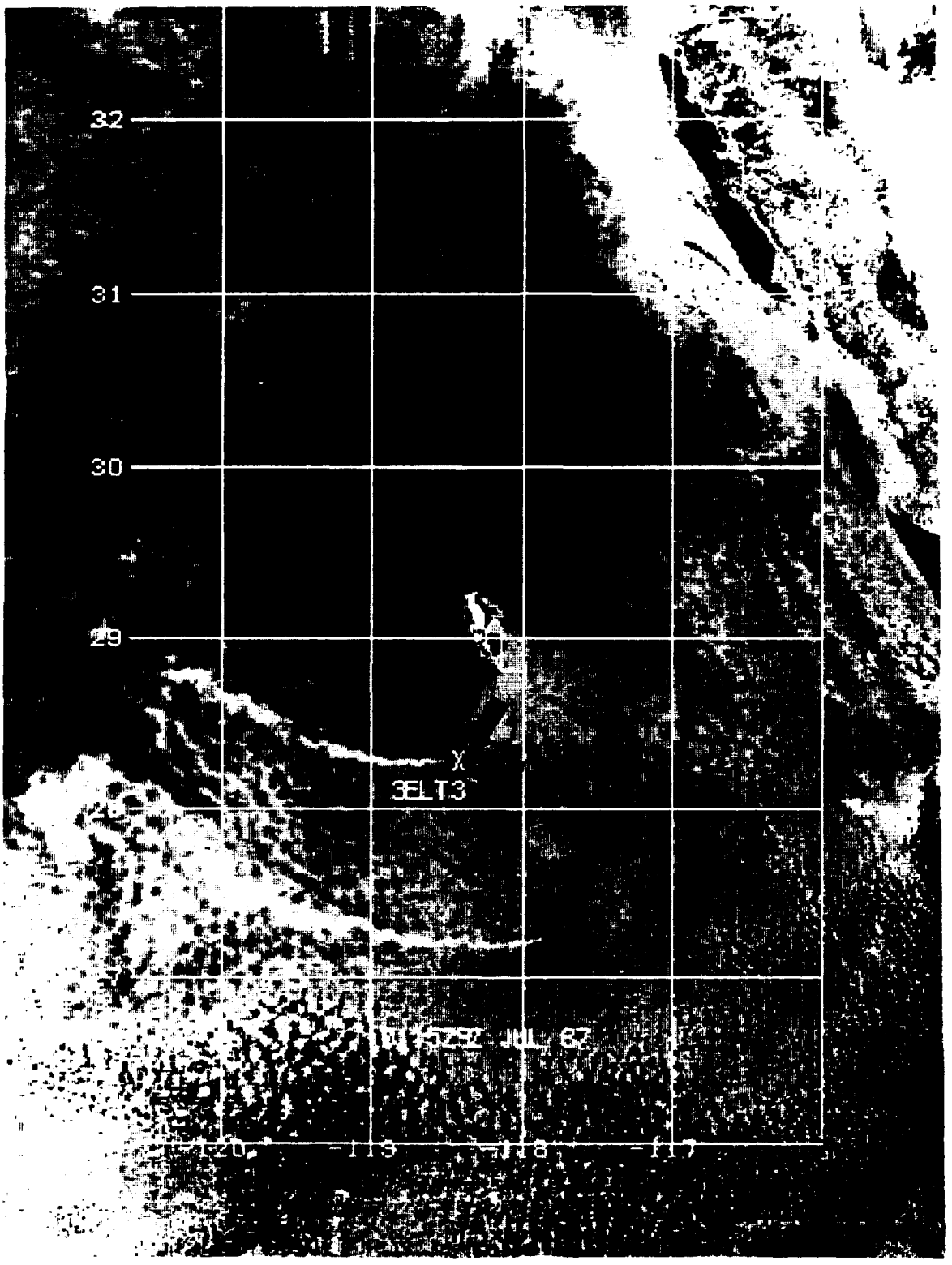

Fig. 4. Channel 3 imagery showing 3ELT3: 1529Z on 1 July 1987.

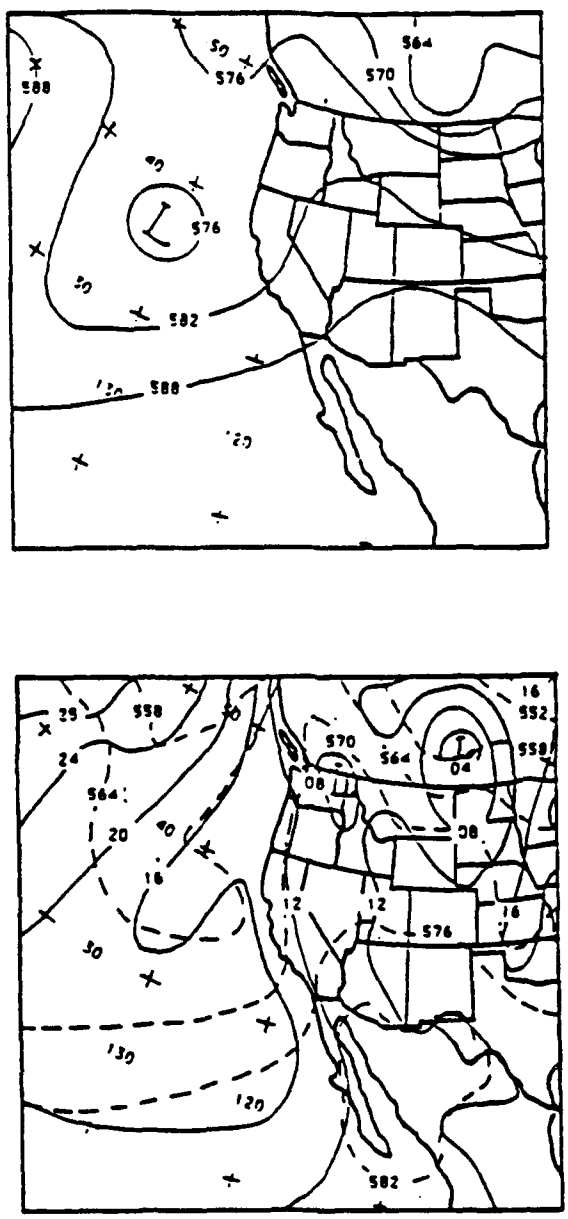

Fig 5. 1 July 1987 12Z NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

6 octas total cover
True wind 030/10
Relative wind 35 deg port 15 kts
C/S 135/15
1017.5 mb
20C Ta
16C Td
20C Tw
8 octas Sc

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 4. Also the shiptrack is located in an area of stratus within the image, which is reported by the ship. The position of the ship track in this image is 28.12N 118.49W, while the position derived from 3ELT3's synoptic reports is 27.95N 118.65W. This difference in positions is approximately 10.01 nautical miles. The identity of 3ELT3 has been determined to be the Merchant Vessel Diamond Highway. This vessel is a large roll-on roll-off (RORO) car carrier that is powered by diesel engines.

C. KSFK

The ship KSFK was observed in two successive overpasses. The first observation was in an overpass of NOAA-10 at 1647Z (0944 local) on 2 July 1987 (Fig. 6). Fig. 7 shows synoptically, at this time the small surface trough dissipated while the southern lobe of the subtropical high spread north. Winds became more northerly on this day (Kloesel, et al. 1988). The surface meteorological parameters reported

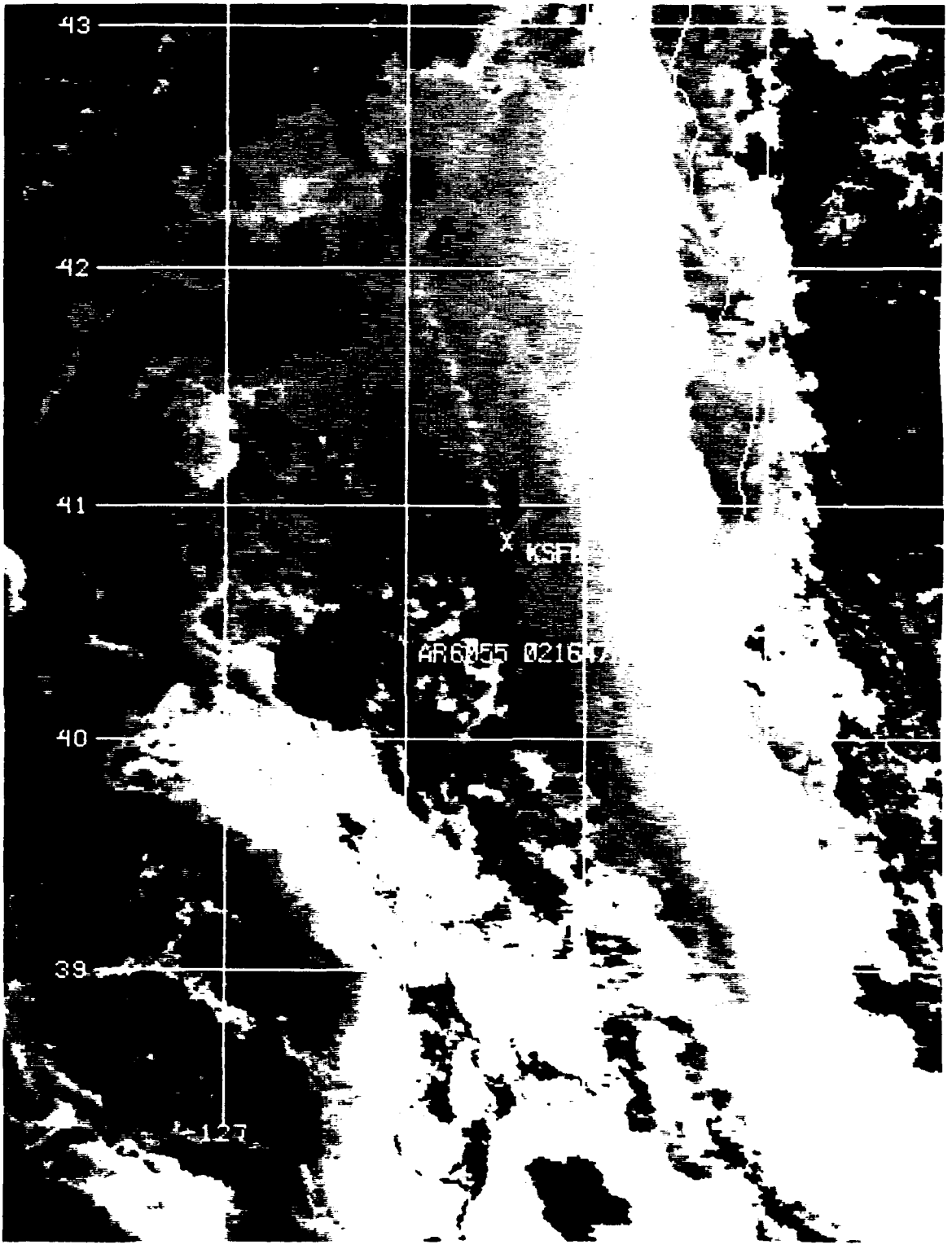

Fig. 6. Channel 3 Imagery showing KSFK: 1647Z on 2 July 1987.

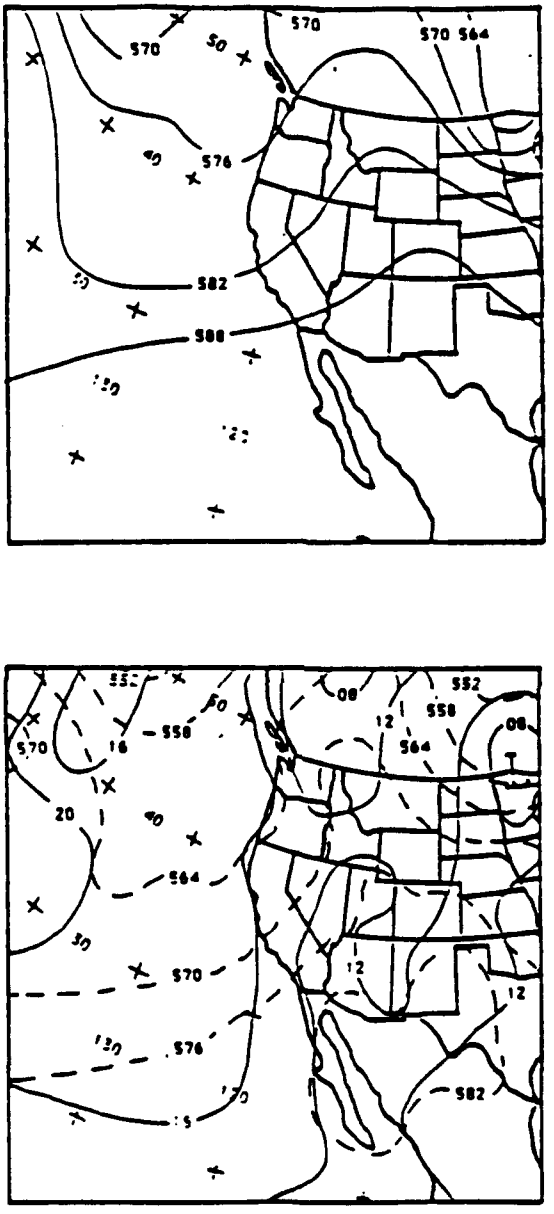

Fig. 7. 2 July 1987 122 NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

at 1700Z (1000 local) by a nearby (approximately 15 nautical miles) weather buoy where as follows:

True wind 350/5
Relative wind 10 deg port 10 kts
C/S 145/15
1018.1 mb
13C Ta
12C Tw

KSFK did not begin to send out synoptic reports until 1700Z (1000 local) 4 July 1987. Ship locations prior to this were obtained from shipping databases (Bluth, 1992). The direction of the ship track matches well with the relative wind direction and the analysis in fig. 6. The position of the ship track in this image is 40.79N 125.49W while the position derived from shipping databases is 40.73N 125.48W. This difference in positions is approximately 4.33 nautical miles.

The second observation of KSFK was in an overpass of NOAA-10 at 1604Z (0904 local) 4 July 1987 (Fig.8). Fig. 9 shows synoptically, the axis of the upper-level trough reaching the coast. The surface trough reached the coast of Oregon and Washington, while the subtropical high moved eastward. The continued intense thermal low over Mexico kept winds strong and northerly throughout the area of interest (Hoesel, et al., 1988). The synoptic report by KSFK at 1700Z (1000 local) showed the following surface meteorological parameters:

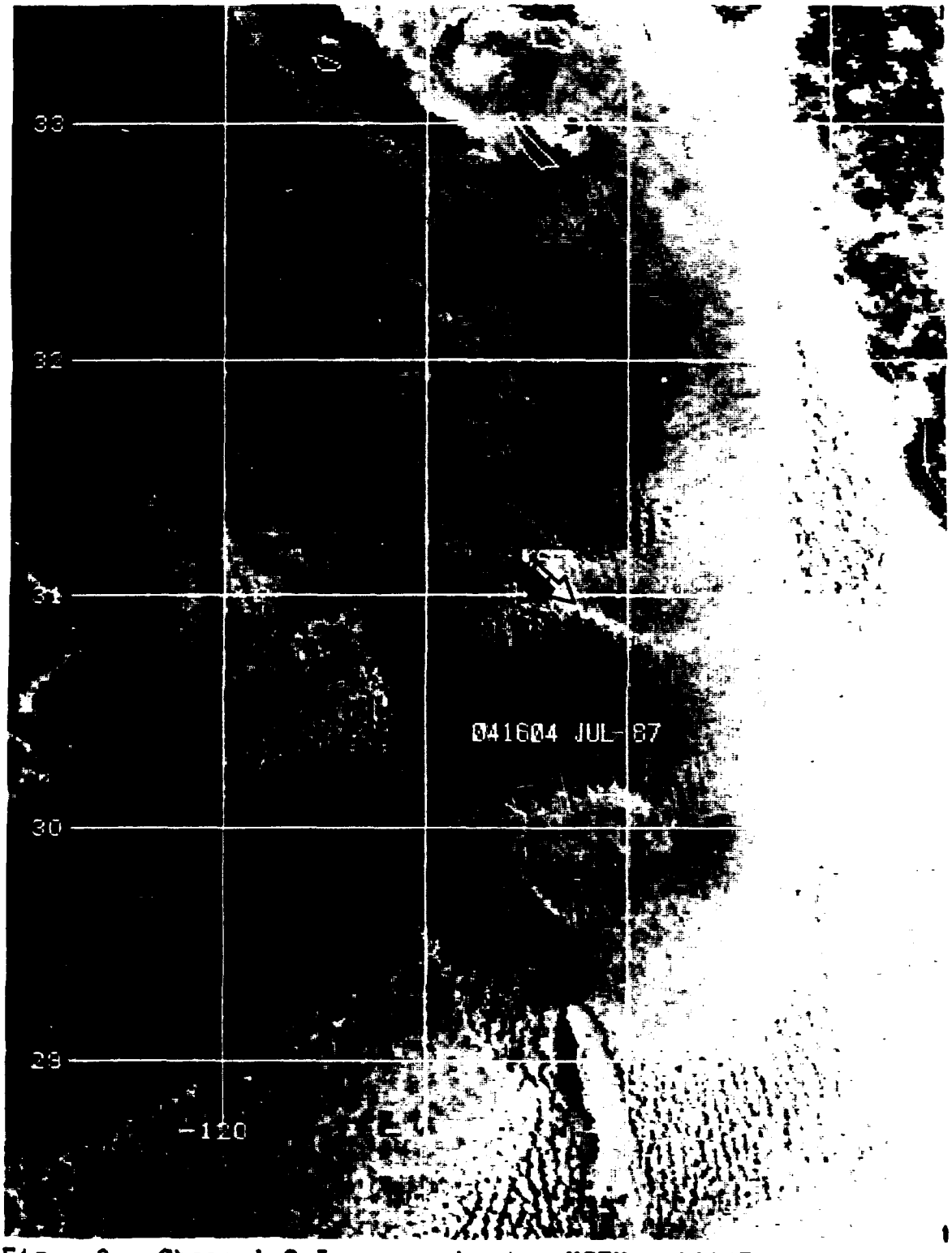

Fig. 8. Channel 3 Imagery showing KSFK: 1604Z on 4 July 1987.

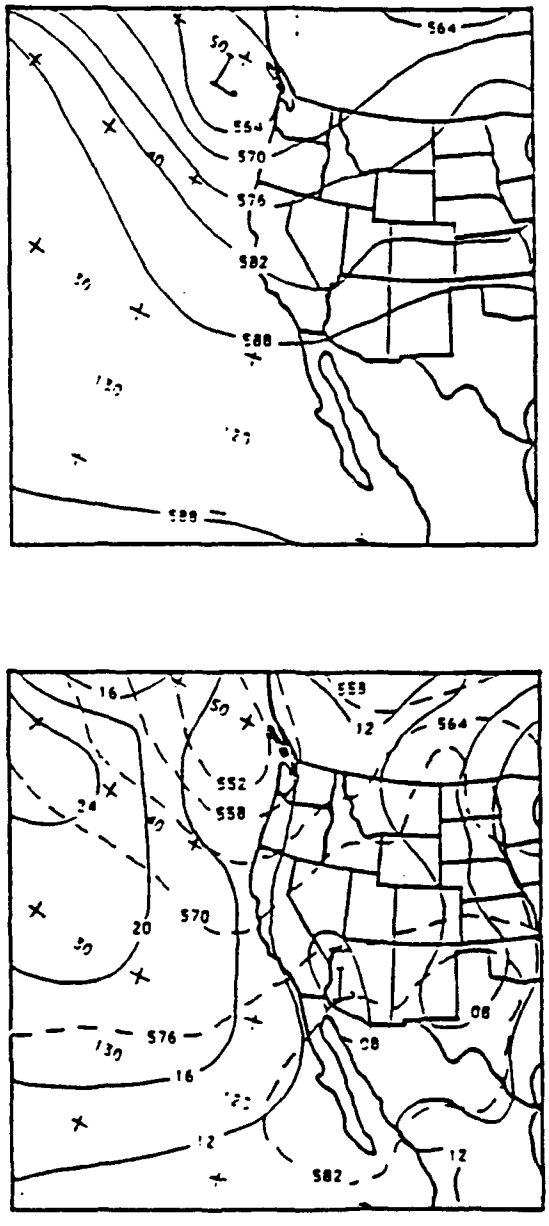

Fig. 9. 4 July 1987 12Z NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

7 octas total cover
True wind 320/15
Relative wind 0 kts
C/S 145/15
1016.9 mb
21C Ta
15C Td
17C Tw
7 octas St

The direction of the ship track matches well with the relative wind direction, in this case the ambient wind is blowing the ship track "ahead" of the ship (Fig. 8). Also the shiptrack is located in an area of stratus within the image, which is reported in by the ship. The position of the ship track in this image is 30.98N 118.39W while the position derived from KSFK's synoptic reports is 31.0N 118.48W. This difference in positions is approximately 5.53 nautical miles. The identity of KSFK has been determined to be the Merchant Vessel Keystone Canyon. This vessel is an oil tanker that uses geared steam turbine engines for propulsion.

D. NLVS

The ship NLVS was observed in an overpass of NOAA-10 at 1447Z (0947 local) on 2 July 1987 (Fig.10). Fig. 11 shows synoptically, at this time the small surface trough dissipated while the southern lobe of the subtropical high spread north. Winds became more northerly on this day (Kloesel, et al. 1988).

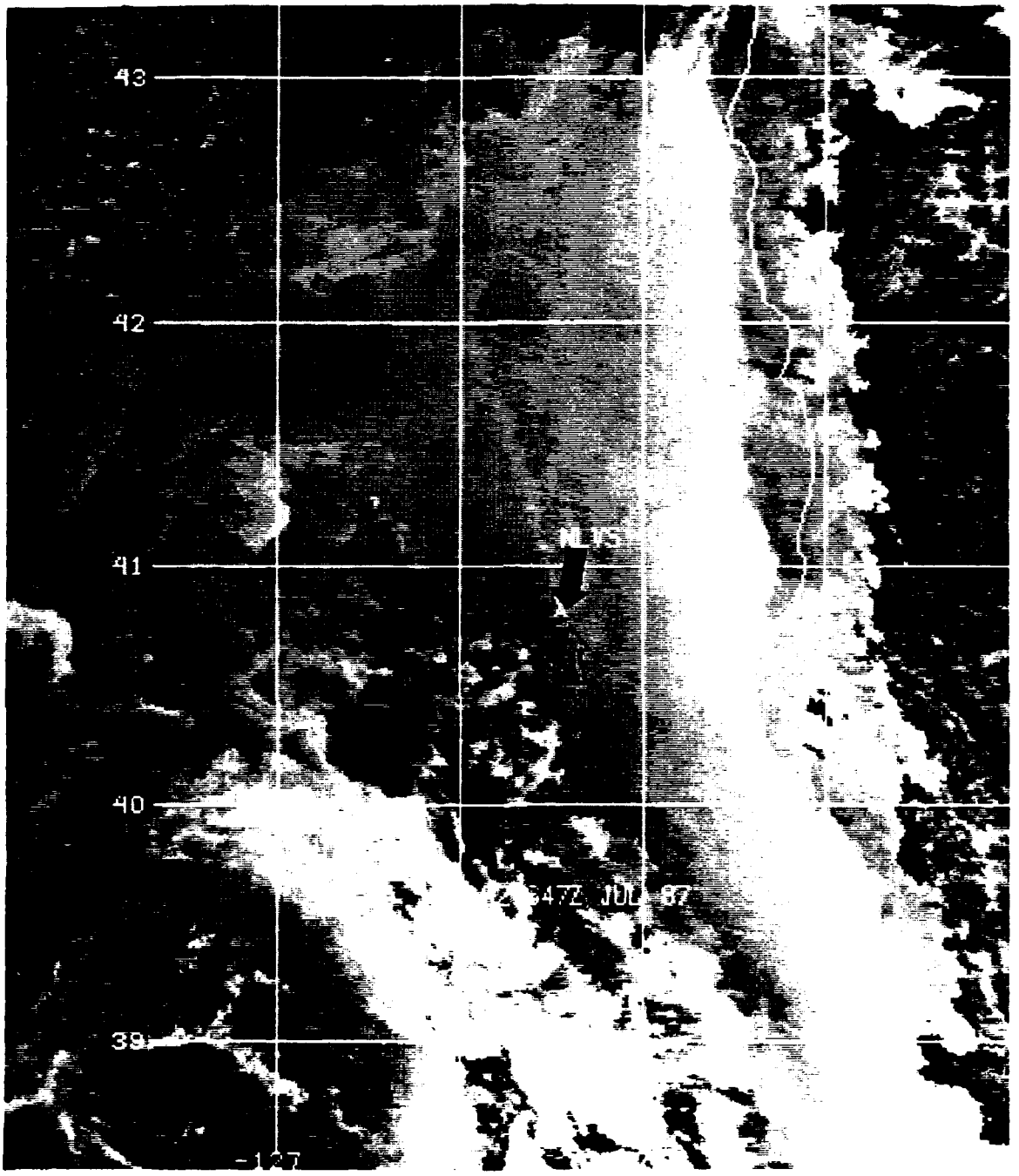

Fig. 10. Channel 3 Imagery showing NLVS: 1647Z on 2 July 1987.

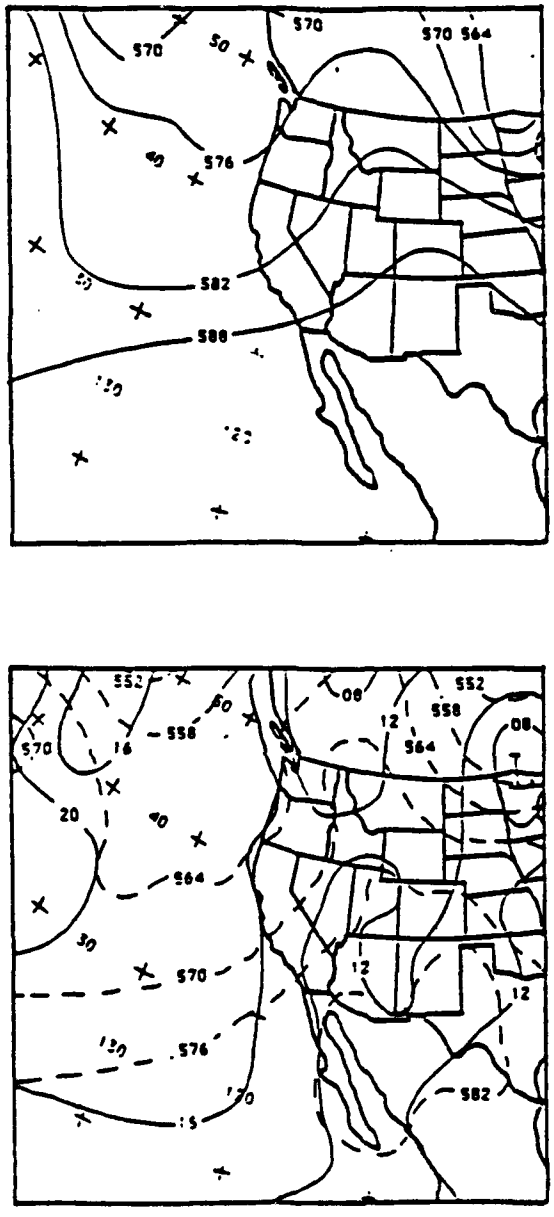

Fig. 11. 2 July 1987 122 NGM Analysis: 500mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

The synoptic report by NLVS at 1800Z (1000 local) showed the following surface meteorological parameters:

8 octas total cover
True wind 010/4
Relative wind 10 deg port 10 kts
C/S 180/15
1015.5 mb
14C Ta
No Td reported
14C Tw
8 octas low Cu

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 10. Also the shiptrack is located near an area of low cumulus within the image, which is reported by the ship. The position of the ship track in this image is 40.91N 125.48W while the position derived from NLVS's synoptic reports is 41.14N 125.50W. This difference in positions is approximately 13.85 nautical miles. The identity of NLVS is the Coast Guard Cutter Rush. This vessel utilizes both gas turbines and diesel engines for propulsion.

E. 3ERV

The ship 3ERV was observed in an overpass of NOAA-10 at 1800Z (0904 local) on 4 July 1987 (Fig. 12). Fig. 13 shows synoptically, the axis of the upper-level trough reached the coast. The surface trough reached the coast of Oregon and Washington, while the subtropical high moved eastward. The continued intense thermal low over Mexico kept winds strong

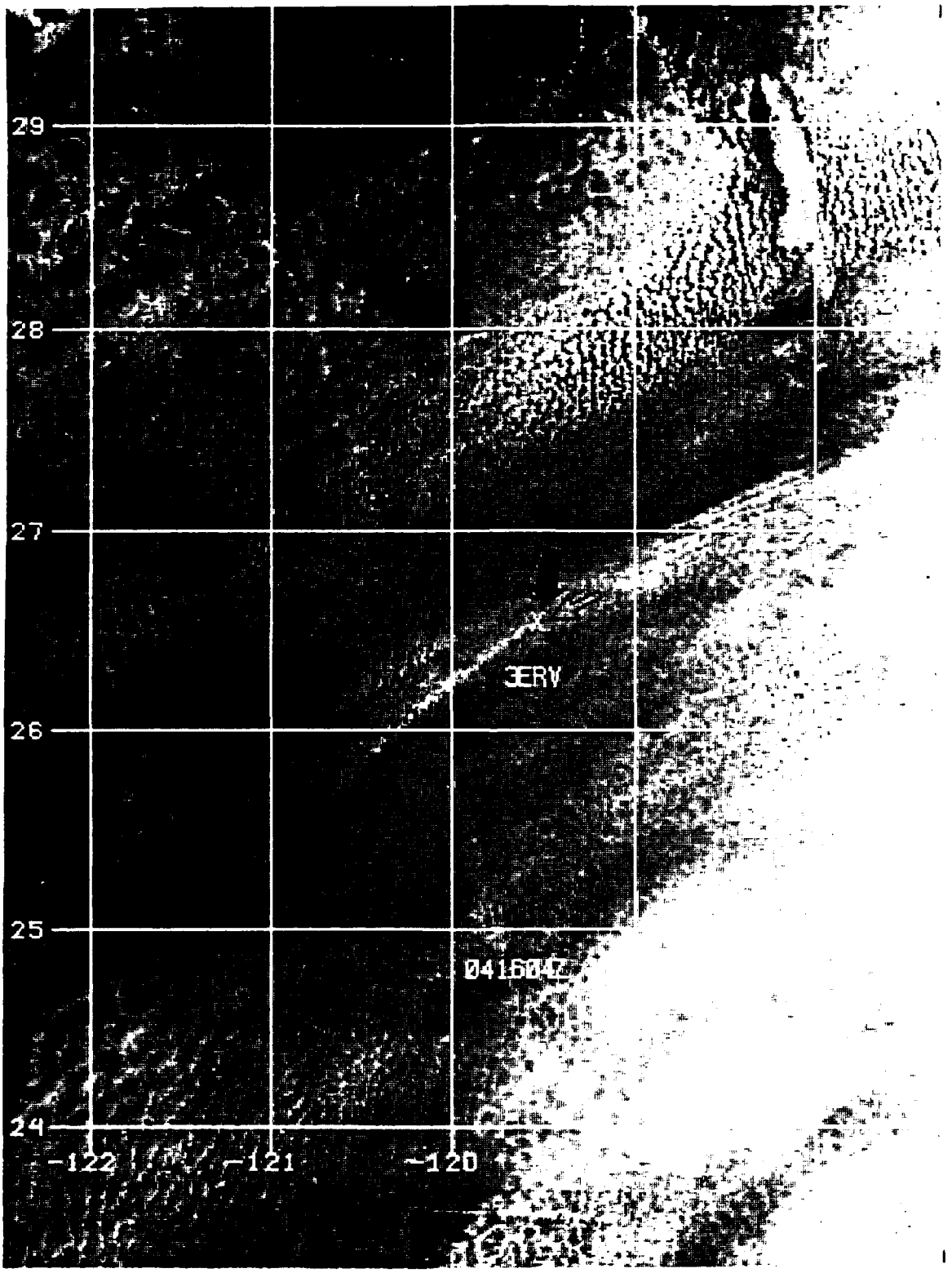

Fig. 12. Channel 3 Imagery showing 3ERV: 1604Z on 4 July 1987.

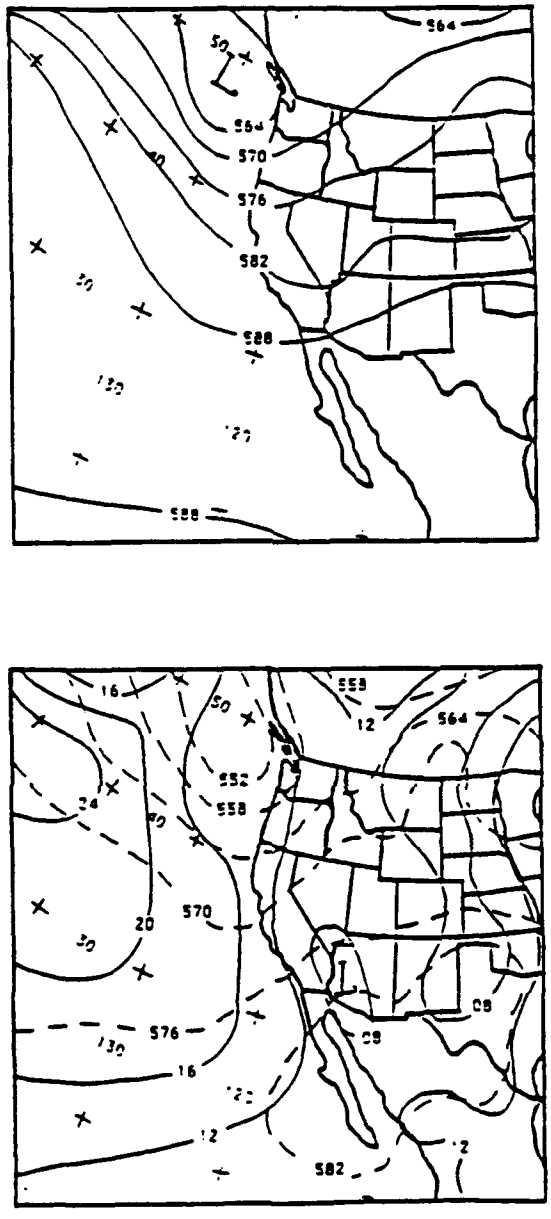

Fig. 13. 4 July 1987 12Z NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

and northerly throughout the area of interest (Kloessel, et al., 1988). The synoptic report by 3ERV at 1800Z (1100 local) showed the following surface meteorological parameters:

8 octas total cover
True wind 010/18
Relative wind 50 deg port 25 kts
C/S 120/19
1015.0 mb
20C Ta
16C Td
19C Tw
8 octas Sc

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 12. Also the shiptrack is located in an area of stratocumulus within the image, which is reported by the ship. The position of the ship track in this image is 26.61N 119.54W, while the position derived from 3ERV's synoptic reports is 26.57N 119.52W. This difference in positions is approximately 3.39 nautical miles. The identity of 3ERV is the Merchant Vessel Antonio. This vessel is a general dry cargo ship that utilizes direct drive oil engines for propulsion.

F. JKLQ

The ship JKLQ was observed in an overpass of NOAA-10 at 1839Z (0939 local) on 7 July 1987 (Fig. 14). Fig. 15 shows synoptically, zonal flow is observed at upper-levels, while the subtropical high maintains its position into Oregon and California. Winds continue to be strong and out of the

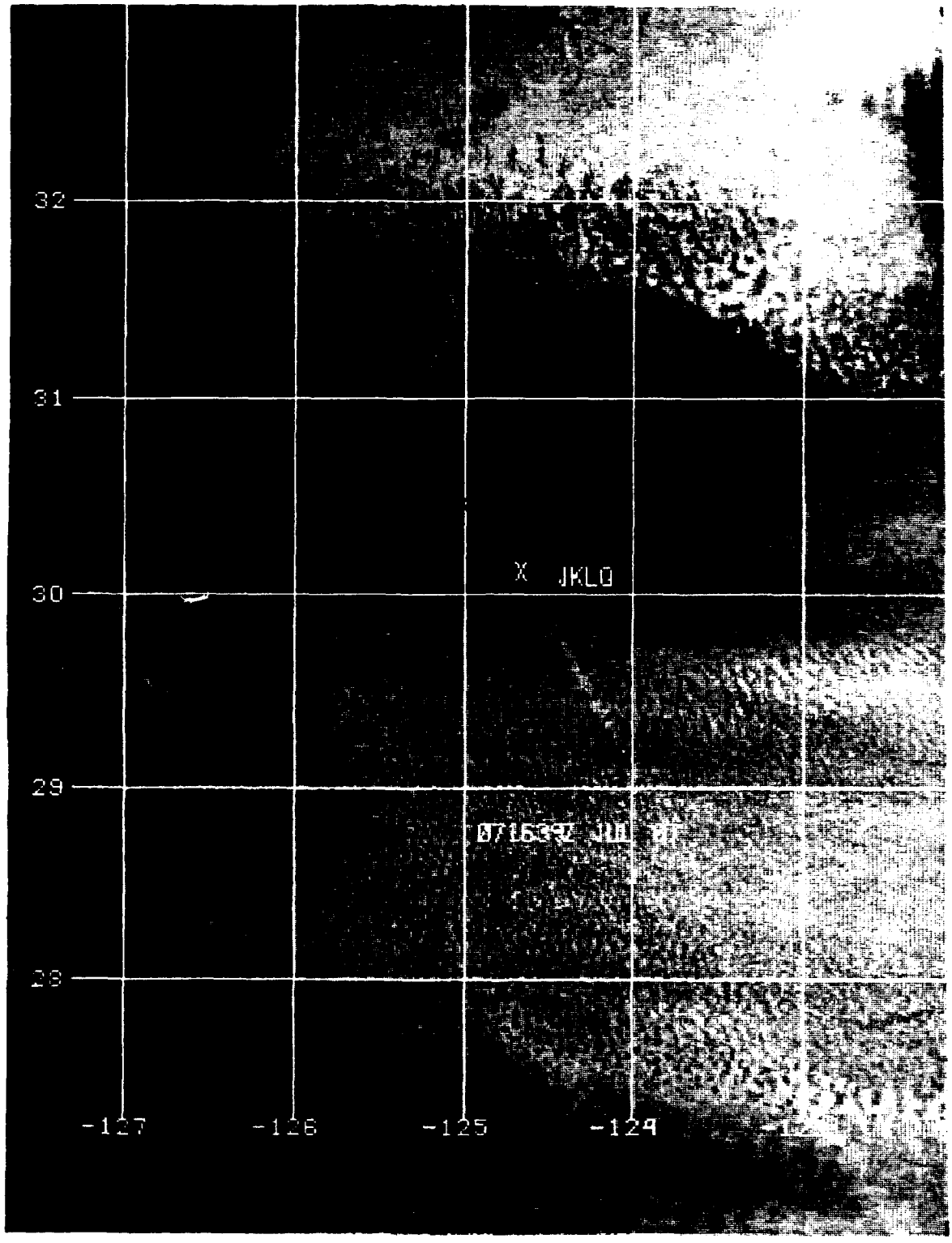

Fig. 14. Channel 3 Imagery showing JKLQ: 1639Z 7 July 1987.

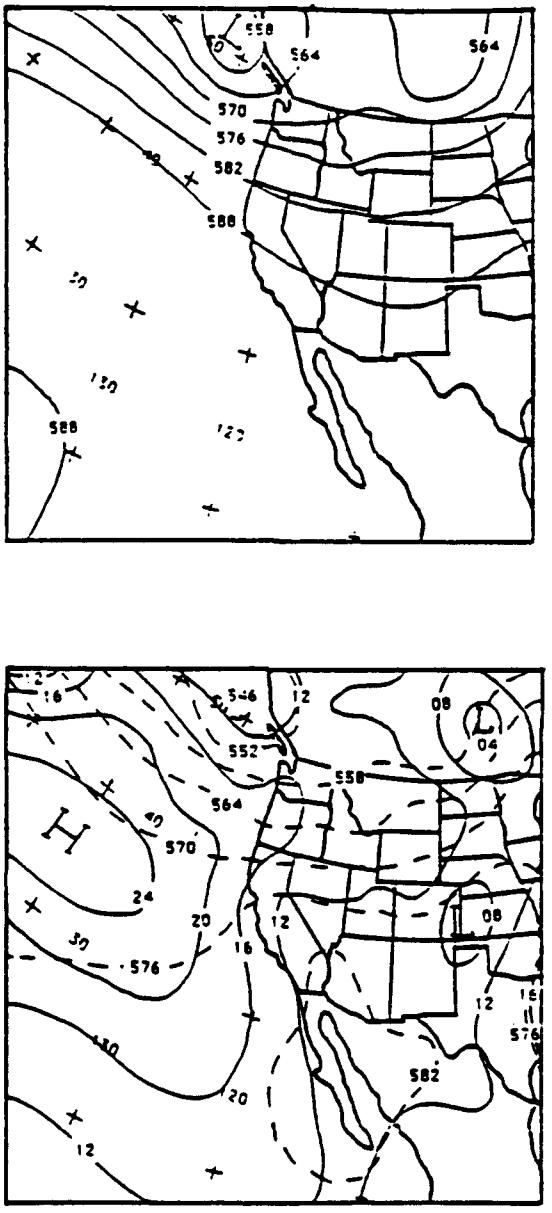

Fig. 15. 7 July 1987 122 NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

northwest (Kloesel, et al., 1988). The synoptic report by JKLQ at 1800Z (1100 local) showed the following surface meteorological parameters:

8 octas total cover
True wind 340/26
Relative wind 20 deg stbd 45 kts
C/S 300/21
1022.0 mb
17C Ta
16C Td
18C Tw
8 octas Sc

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 14. Also the shiptrack is located in an area of stratocumulus within the image, which is reported by the ship. The position of the ship track in this image is 30.11N 124.69W while the position derived from JKLQ's synoptic reports is 30.06N 124.69W. This difference in positions is approximately 3.00 nautical miles. The identity of JKLQ is the Merchant Vessel Michigan Highway, a RORO cargo/vehicle carrier. This vessel utilizes oil burning engines for propulsion.

G. 3EJI5

The ship 3EJI5 was observed in three successive overpasses. The first observation was in an overpass of NOAA-10 at 1639Z (0939 local) on 7 July 1987 (Fig. 16). Fig. 17 shows synoptically, zonal flow is observed at upper-levels, while the subtropical high maintains its position into Oregon and

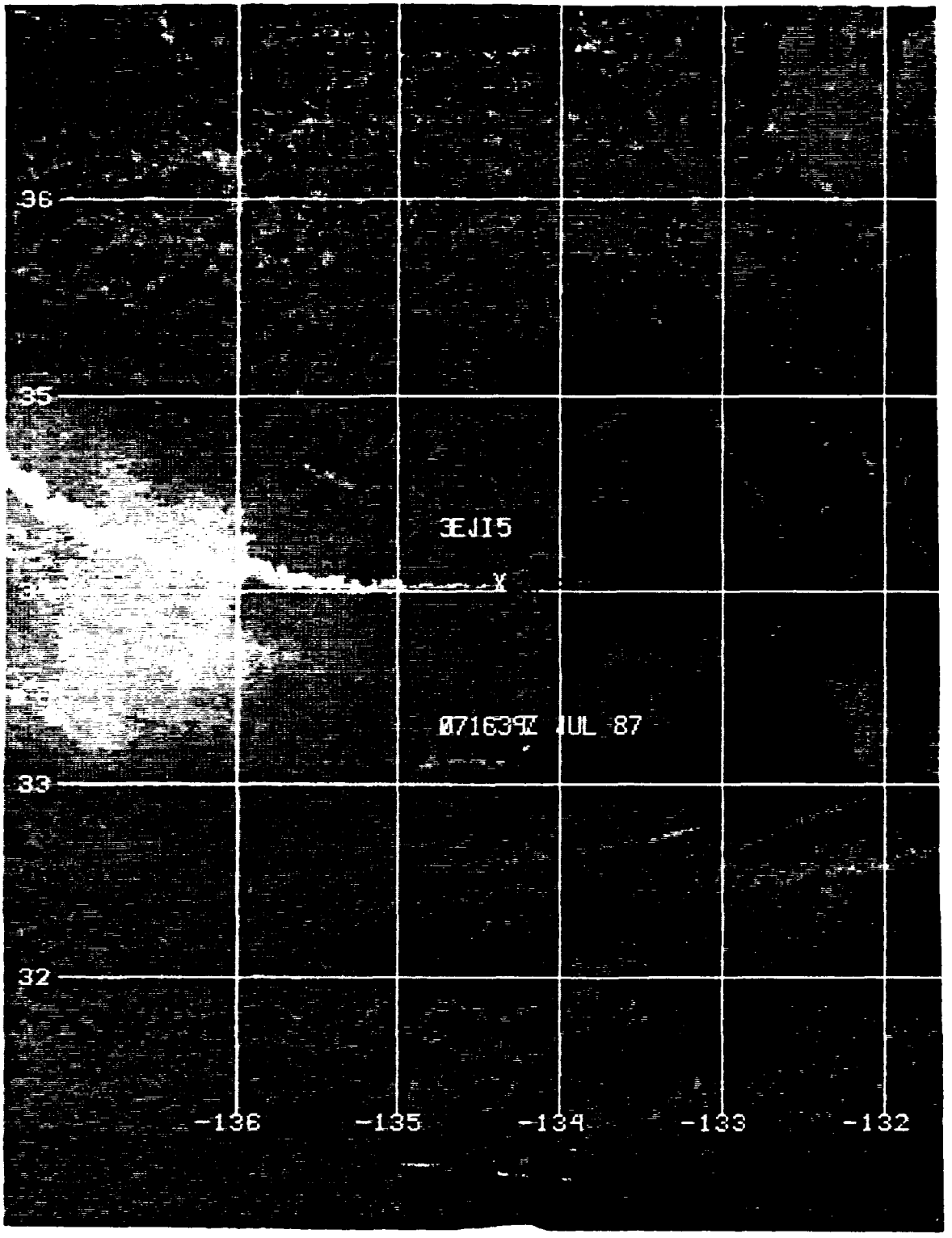

Fig. 16. Channel 3 Imagery showing 3EJI5: 1639Z on 7 July 1987.

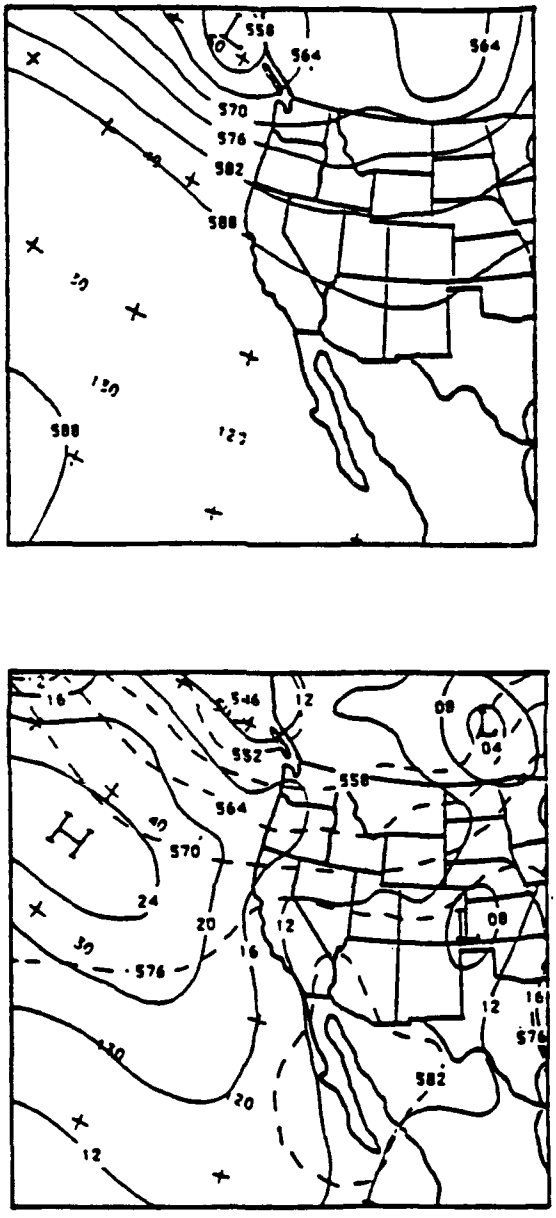

Fig. 17. 7 July 1987 122 NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

California. Winds continue to be strong and out of the northwest (Kloesel, et al., 1988). The synoptic report by 3EJI5 at 1800Z (1100 local) showed the following surface meteorological parameters:

6 octas total cover
True wind 030/5
Relative wind 10 deg port 50 kts
C/S 110/26
1026.0 mb
19C Ta
15C Td
18C Tw
6 octas Sc

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 16. Also the shiptrack is located in an area of stratocumulus within the image, which is reported by the ship. The position of the ship track in this image is 34.02N 134.41W while the position derived from 3EJI5's synoptic reports is 34.00N 134.35W. This difference in positions is approximately 3.79 nautical miles.

The second observation of 3EJI5 is in an overpass of NOAA-9 at 2237Z (1537 local) on 7 July 1987 (Figs. 18 and 19). The synoptic report by 3EJI5 at 0000Z (1700 local) showed the following surface meteorological parameters:

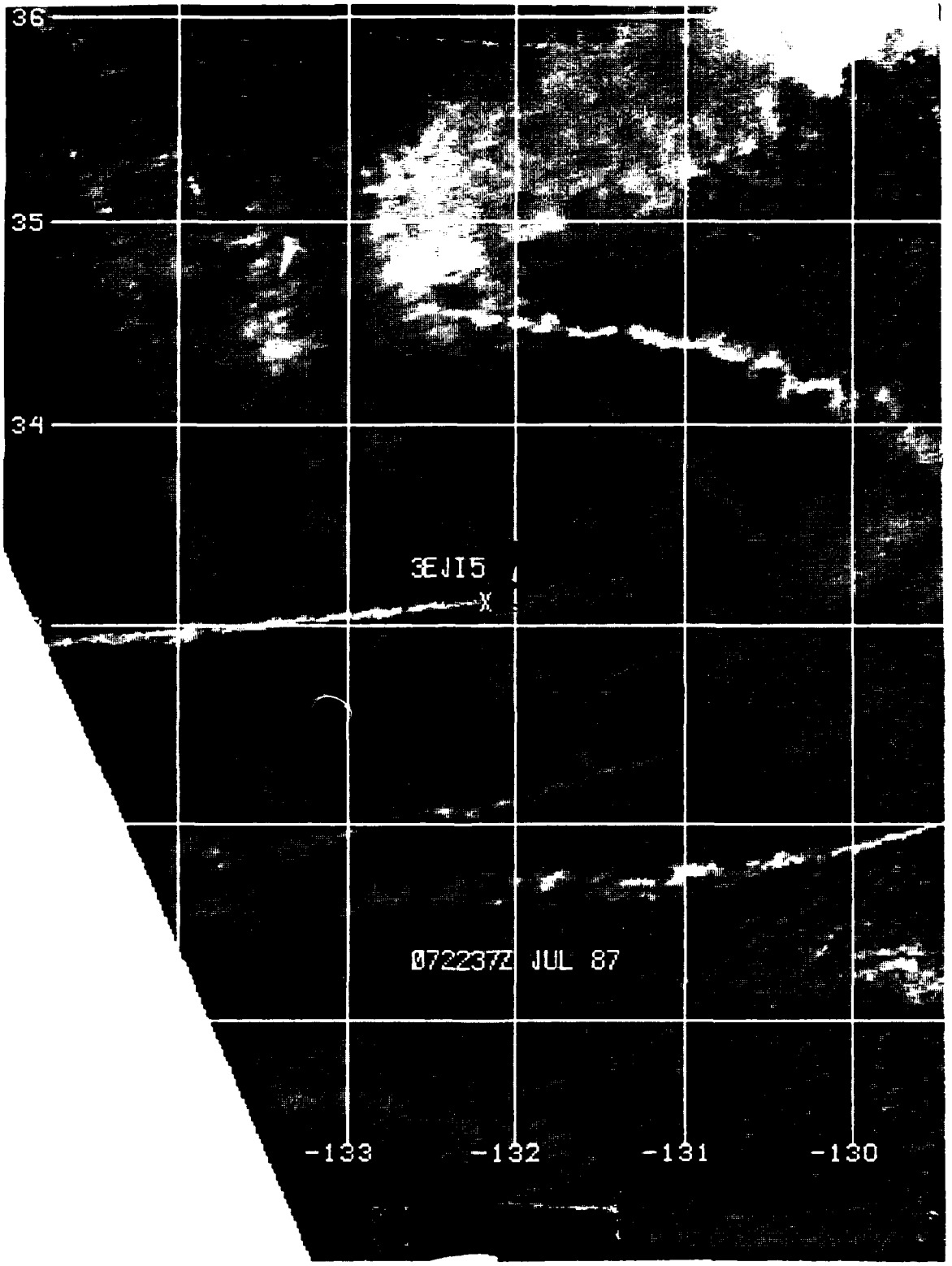

Fig. 18. **Channel 3 Imagery showing 3EJI5:** 2237Z on 7 July 1987.

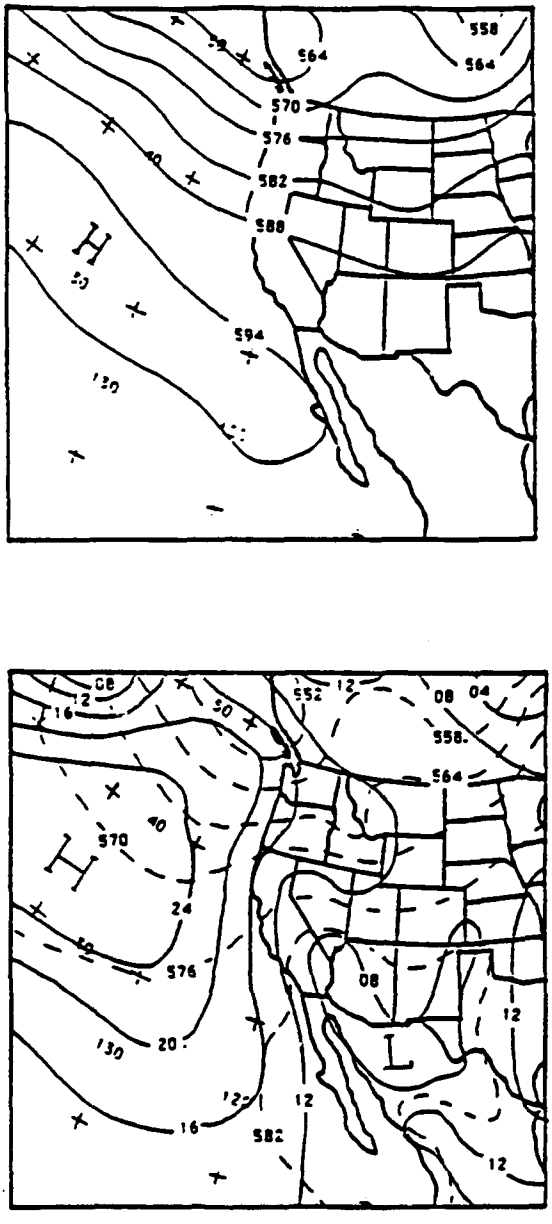

Fig. 19. 8 July 1987 00Z NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

6 octas total cover
True wind 030/11
Relative wind 20 deg port 30 kts
C/S 110/26
1024.5 mb
21C Ta
18C Td
18C Tw
6 octas Sc

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 18. Also the shiptrack is located in an area of stratocumulus within the image, which is reported by the ship. The position of the ship track in this image is 33.10N 132.18W, while the position derived from 3EJI5's synoptic reports is 33.11N 131.96W. This difference in positions is approximately 13.21 nautical miles.

The third observation of 3EJI5 is in an overpass of NOAA-10 at 1617Z (0917 local) on 8 July 1987 (Fig. 20). Fig. 21 shows synoptically, the zonal upper-air flow continues, while the subtropical high intensified into Oregon and Washington. The winds continue to be out of the north throughout the area (Kloesel, et al., 1988). The synoptic report by 3EJI5 at 1800Z (1100 local) showed the following surface meteorological parameters:

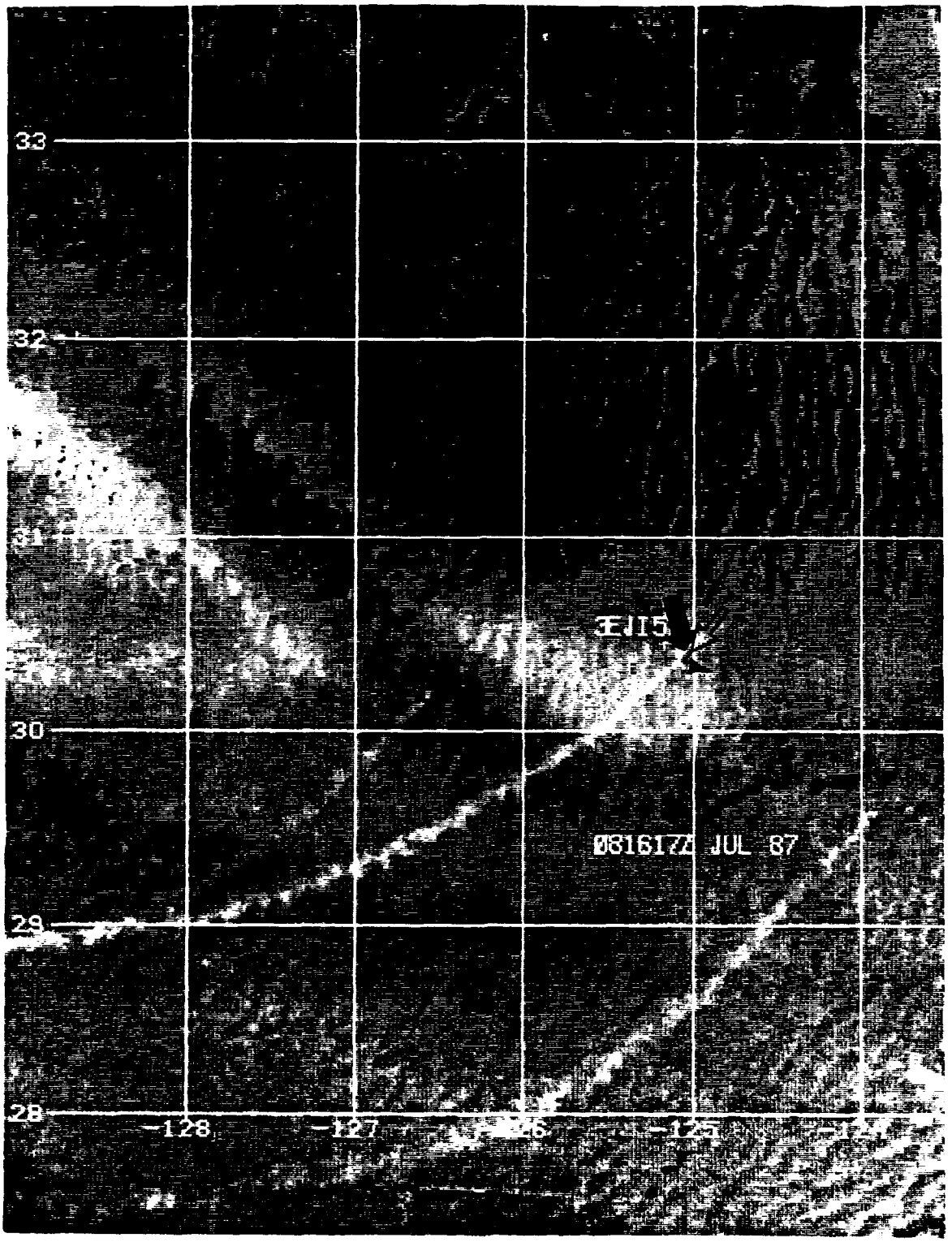

Fig. 20. Channel 3 Imagery showing 3EJI5: 1617Z 8 July 19`7.

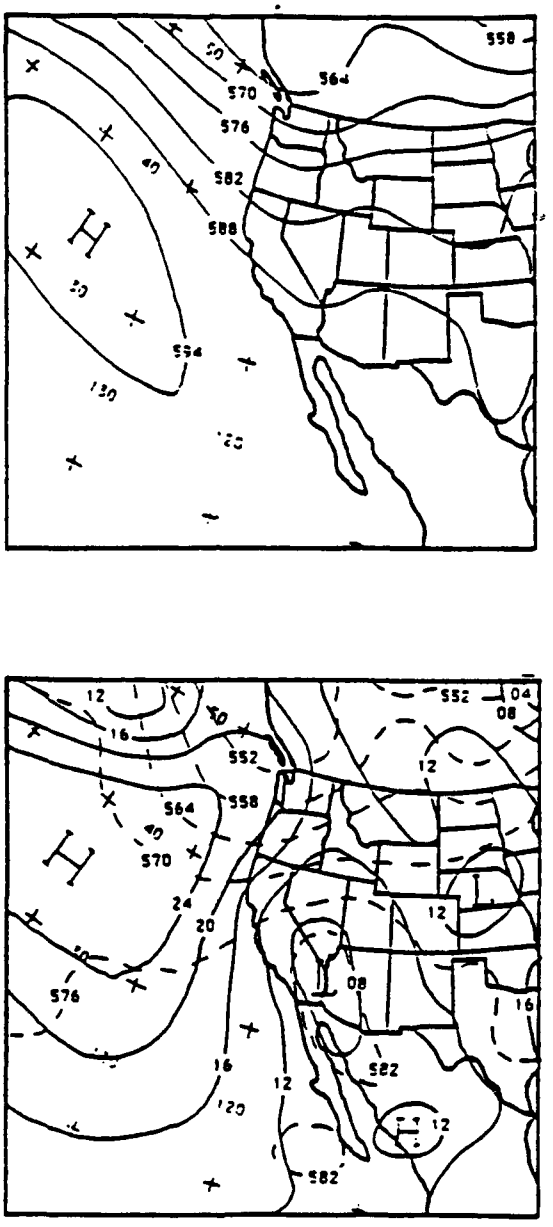

Fig. 21. 8 July 1987 12Z NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

8 octas total cover
True wind 350/21
Relative wind 50 deg port 25 kts
C/S 110/25
1019.5 mb
20C Ta
16C Td
19C Tw
8 octas Sc

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 20. Also the shiptrack is located in an area of stratocumulus within the image, which is reported by the ship. The position of the ship track in this image is 30.39N 125.11W, while the position derived from 3EJI5's synoptic reports is 30.35N 125.17W. This difference in positions is approximately 4.33 nautical miles. The identity of 3EJI5 has not yet been determined from shipping databases.

H. JDXS

The ship JDXS was observed in an overpass of NOAA-10 at 1534Z (0834 local) on 10 July 1987 (Fig. 22). Fig. 23 shows synoptically, the upper level was oriented with a ridge along 140W and a trough along 118W. The surface pressure gradient weakened slightly as the subtropical high shifted westward. Winds continued to be moderate and out of the north. (Kloesel, et al., 1988). The synoptic report by JDXS at 1800Z (1100 local) showed the following surface meteorological parameters:

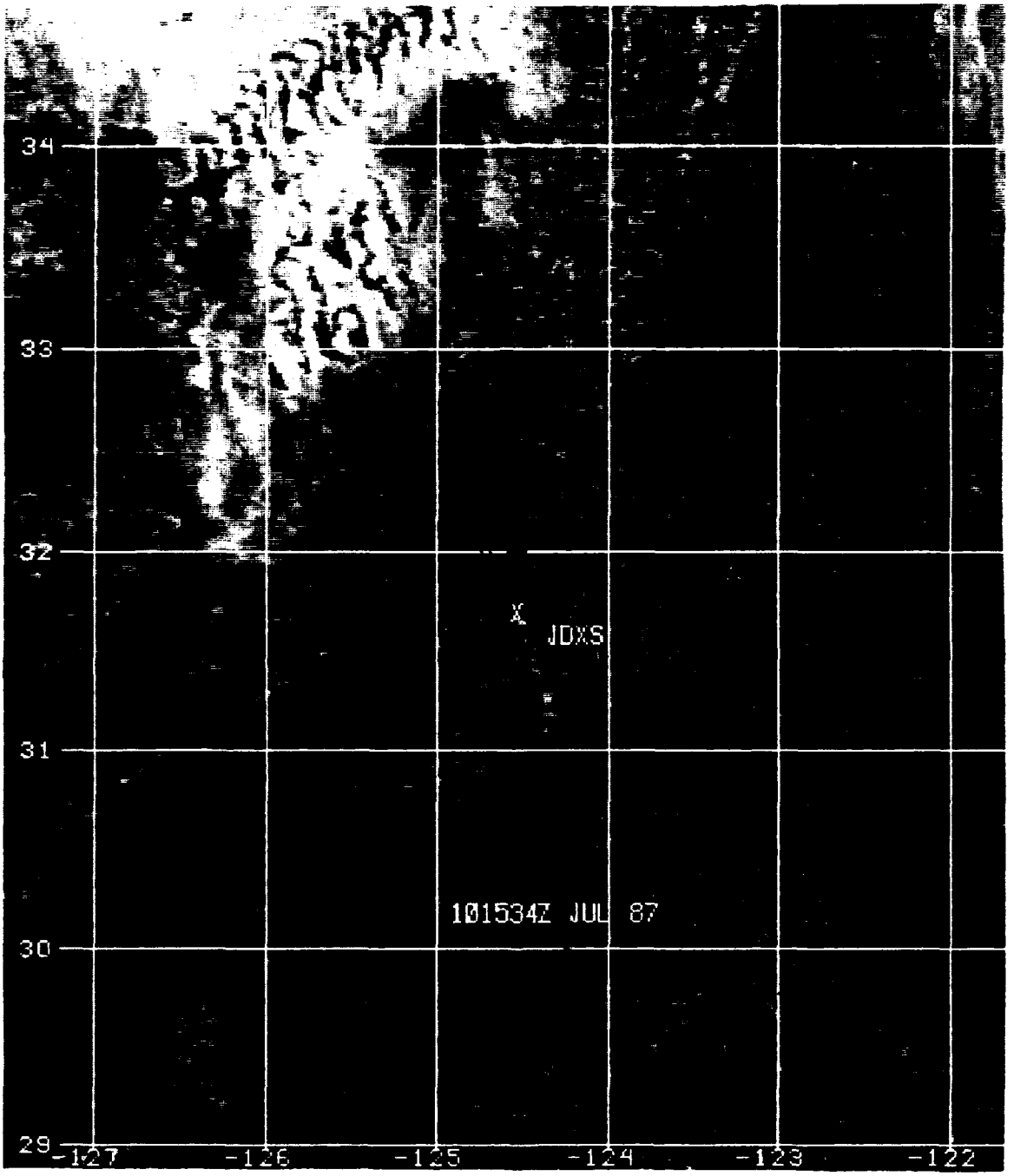

Fig. 22. Channel 3 Imagery showing JDXS: 1534Z 10 July 1987.

Fig. 23. 10 July 1987 12Z NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

8 octas total cover
True wind 000/20
Relative wind 25 deg stbd 35 kts
C/S 315/15
1014.2 mb
19C Ta
18C Td
No Tw reported
7 octas Sc

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 22. Also the shiptrack is located in an area of stratocumulus within the image, which is reported by the ship. The position of the ship track in this image is 31.73N 124.59W, while the position derived from JDXS' synoptic reports is 31.77N 124.87W. This difference in positions is approximately 16.97 nautical miles. The identity of JDXS is the Merchant Vessel Toyofuji 10, a RORO Car Carrier. This vessel utilizes a diesel engine for its propulsion.

I. 3EFS5

The ship 3EFS5 was observed in an overpass of NOAA-9 at 2347Z (1647 local) on 10 July 1987 (Fig. 24). Fig. 25 shows synoptically, the upper level was oriented with a ridge along 140W and a trough along 118W. The surface pressure gradient weakened slightly as the subtropical high shifted westward.

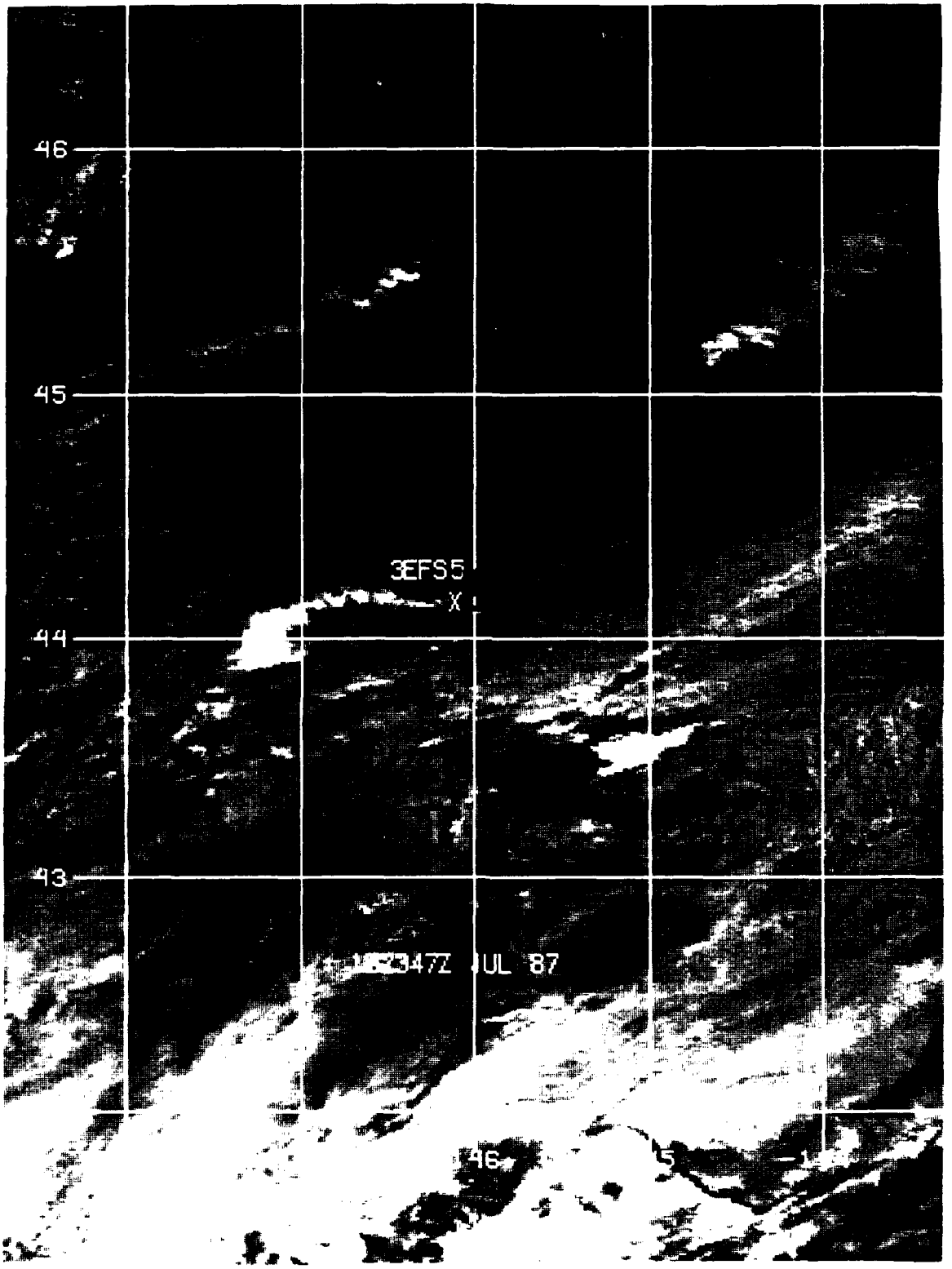

Fig. 24. Channel 3 Imagery showing 3EFS5: 2347Z on 10 July 1987.

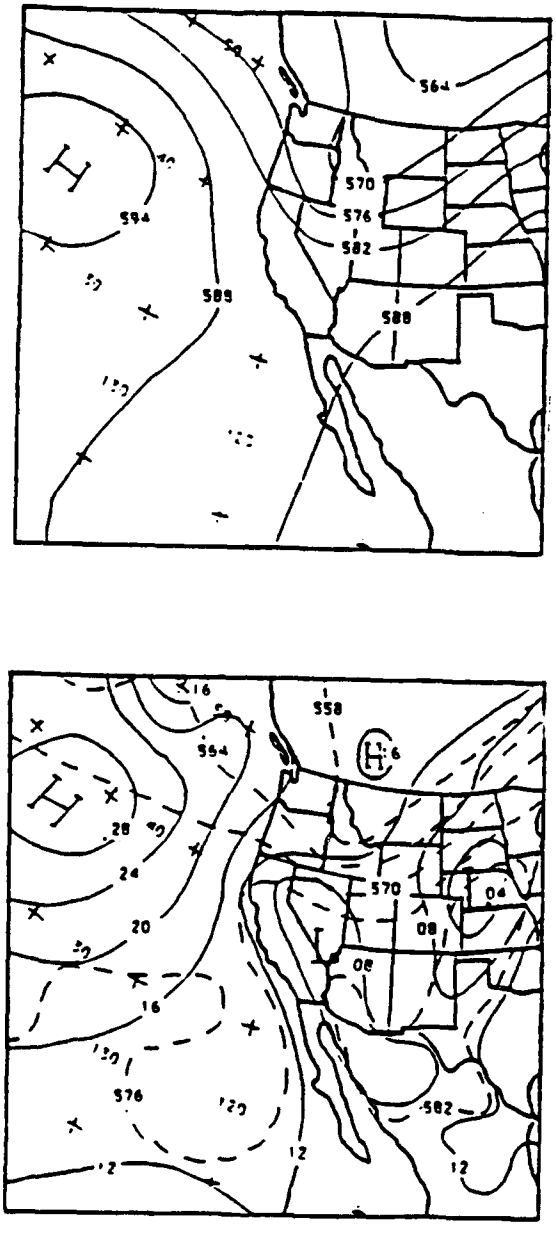

Fig. 25. 11 July 1987 00Z NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

Winds continued to be moderate and out of the north (Kloesel, et al., 1988). The synoptic report by 3EFS5 at 0000Z (1700 local) showed the following surface meteorological parameters:

8 octas total cover
True wind 050/9
Relative wind 10 deg port 35 kts
C/S 100/28
1025.6 mb
15C Ta
13C Td
14C Tw
7 octas Sc

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 24. Also the shiptrack is located in an area of stratocumulus within the image, which is reported by the ship. The position of the ship track in this image is 44.17N 146.14W, while the position derived from 3EFS5's synoptic reports is 44.12N 146.20W. This difference in positions is approximately 4.69 nautical miles. The identity of 3EFS5 has yet to be determined from shipping databases.

J. ELFZ8

The ship ELFZ8 was observed in an overpass of NOAA-9 at 2352Z (1635 local) on 11 July 1987 (Fig. 26). Fig. 27 shows synoptically, the upper level ridge began to move eastward. At the surface, the subtropical high remained stationary while the inland thermal low began to dissipate. This further reduced the offshore pressure gradient, with winds

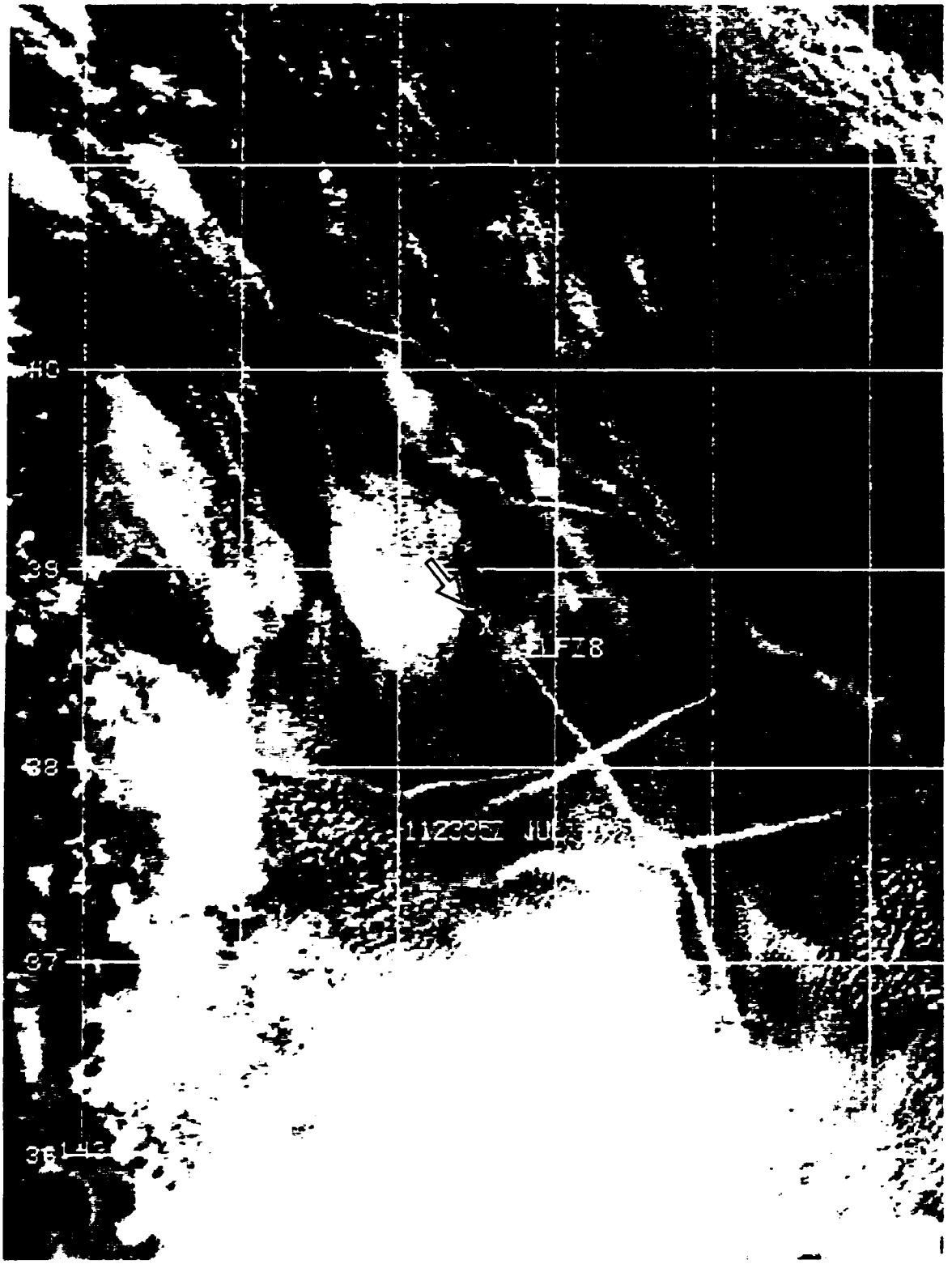

Fig. 26. Channel 3 Imagery showing ELFZ8: 2335Z on 11 July 1987.

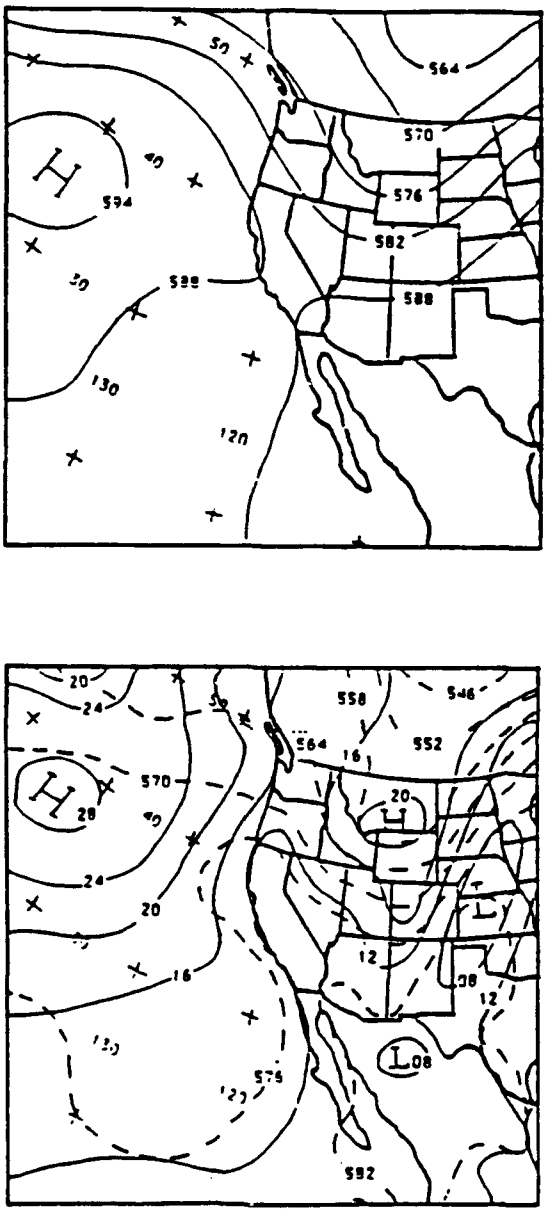

Fig. 27. 12 July 1987 00Z NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

light to moderate out of the northwest (Kloesel, et al., 1988). The synoptic report by ELFZ8 at 0000Z (1700 local) showed the following surface meteorological parameters:

8 octas total cover
True wind 340/18
Relative wind 30 deg stbd 40 kts
C/S 295/21
1028.0 mb
18C Ta
15C Td
No Tw reported
8 octas Sc

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 26. Also the shiptrack is located in an area of stratocumulus within the image, which is reported by the ship. The position of the ship track in this image is 38.76N 140.48W, while the position derived from ELFZ8's synoptic reports is 38.67N 140.44W. This difference in positions is approximately 5.91 nautical miles. The identity of ELFZ8 is the Merchant Vessel Nosac Skaukar, a RORO car carrrier. This vessel utilizes diesel engines for propulsion.

K. JKES

The ship JKES was observed in an overpass of NOAA-9 at 2352Z (1635 local) on 11 July 1987 (Fig. 28). The synoptic situation is discussed in section j and is shown in fig. 27.

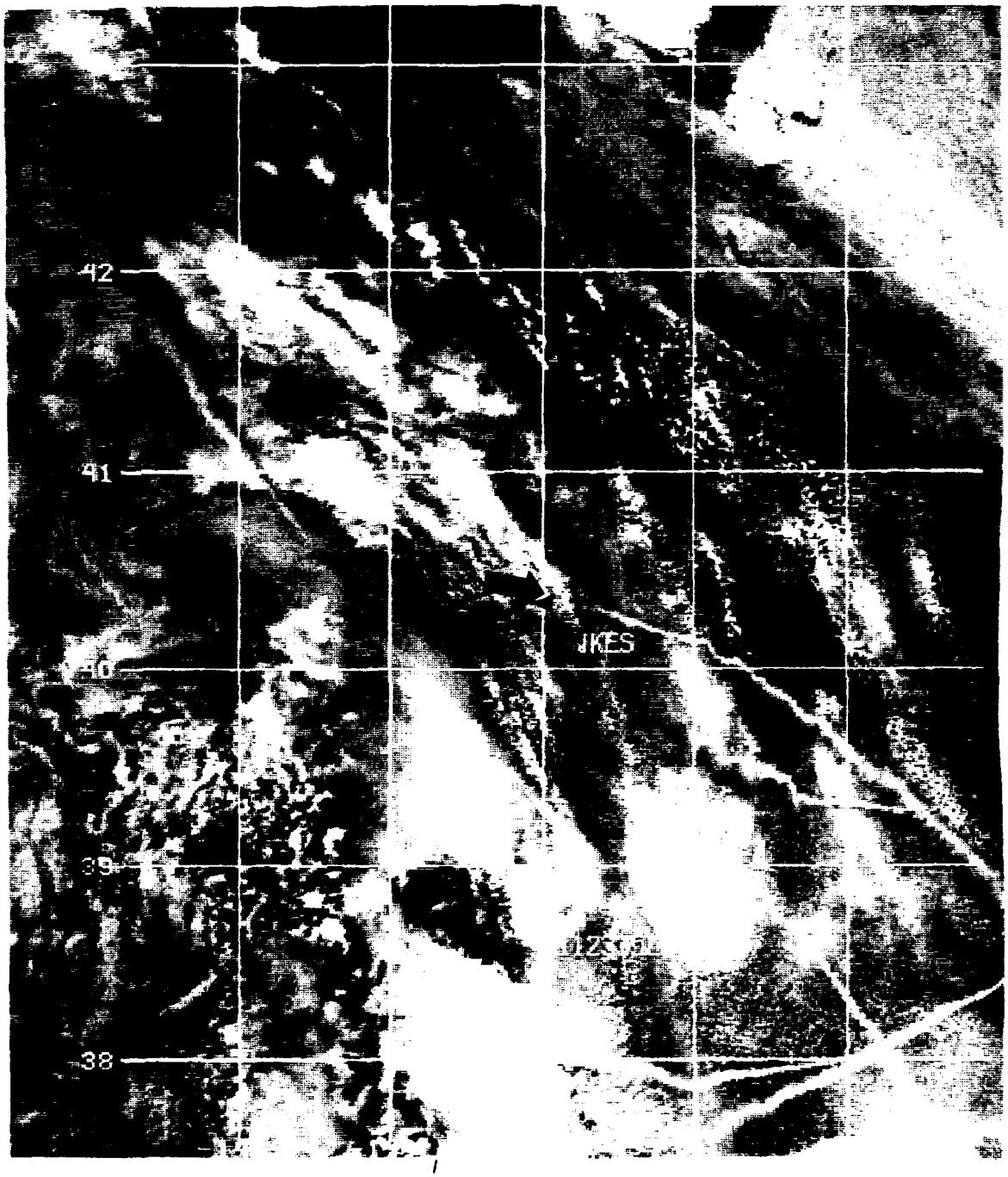

Fig. 28. Channel Imagery showing JKES: 2335Z on 11 July 1987.

The synoptic report by JKES at 0000Z (1700 local) showed the following surface meteorological parameters:

8 octas total cover
True wind 280/7
Relative wind 0 deg 35 kts
C/S 280/28
1028.2 mb
18C Ta
16C Td
15C Tw
No low cloud code reported

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 28. The position of the ship track in this image is 40.34N 141.94W, while the position derived from JKES' synoptic reports is 40.27N 141.91W. This difference in positions is approximately 4.57 nautical miles. The identity of JKES is the Merchant Vessel Mackinac Bridge. This vessel's type and propulsion are yet unidentified.

L. 3FOC

The ship 3FOC was observed in an overpass of NOAA-9 at 23352 (1635 local) on 11 July 1987 (Fig 29). The synoptic situation is discussed in section j and is shown in fig. 27.

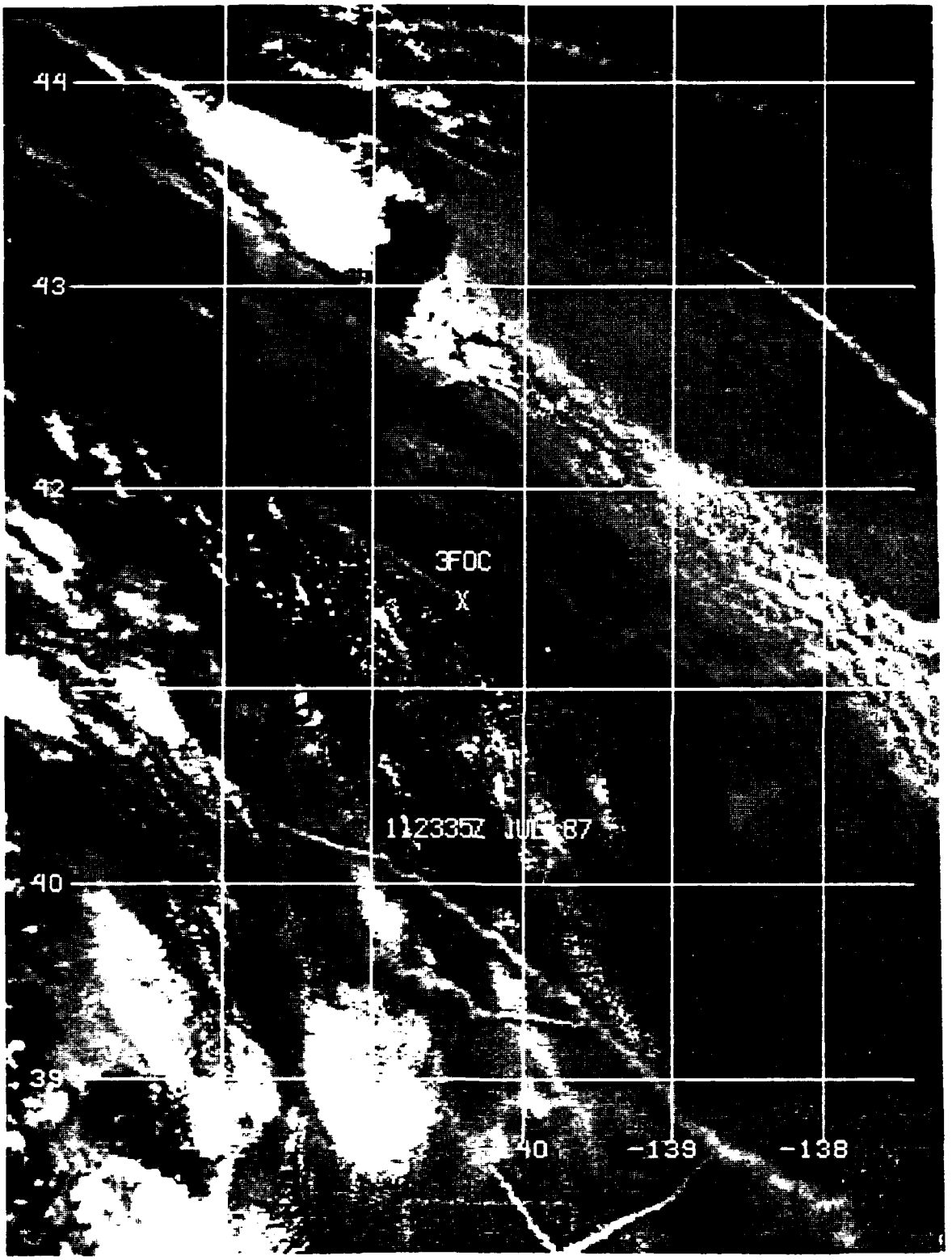

Fig. 29. Channel 3 Imagery showing 3FOC: 2335Z on 11 July 1987.

The synoptic report by 3FOC at 0000Z (1700 local) showed the following surface meteorological parameters:

8 octas total cover
True wind 200/3
Relative wind 5 deg stbd 30 kts
C/S 105/25
1027.0 mb
18C Ta
16C Td
16C Tw
8 octas St

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 29. Also the shiptrack is located in an area of stratus within the image, which is reported by the ship. The position of the ship track in this image is 41.48N 140.47W, while the position derived from 3FOC's synoptic reports is 41.33N 140.37W. This difference in positions is approximately 10.82 nautical miles. The identity of 3FOC is the Merchant Vessel Appolo Peak, a general dry cargo ship. This vessel utilizes direct drive oil burning engines for propulsion.

M. 9VOQ

The ship 9VOQ was observed in an overpass of NOAA-9 at 1335Z (1635 local) on 11 July 1987 (Fig. 30). The synoptic situation is discussed in section j and is shown in fig. 27.

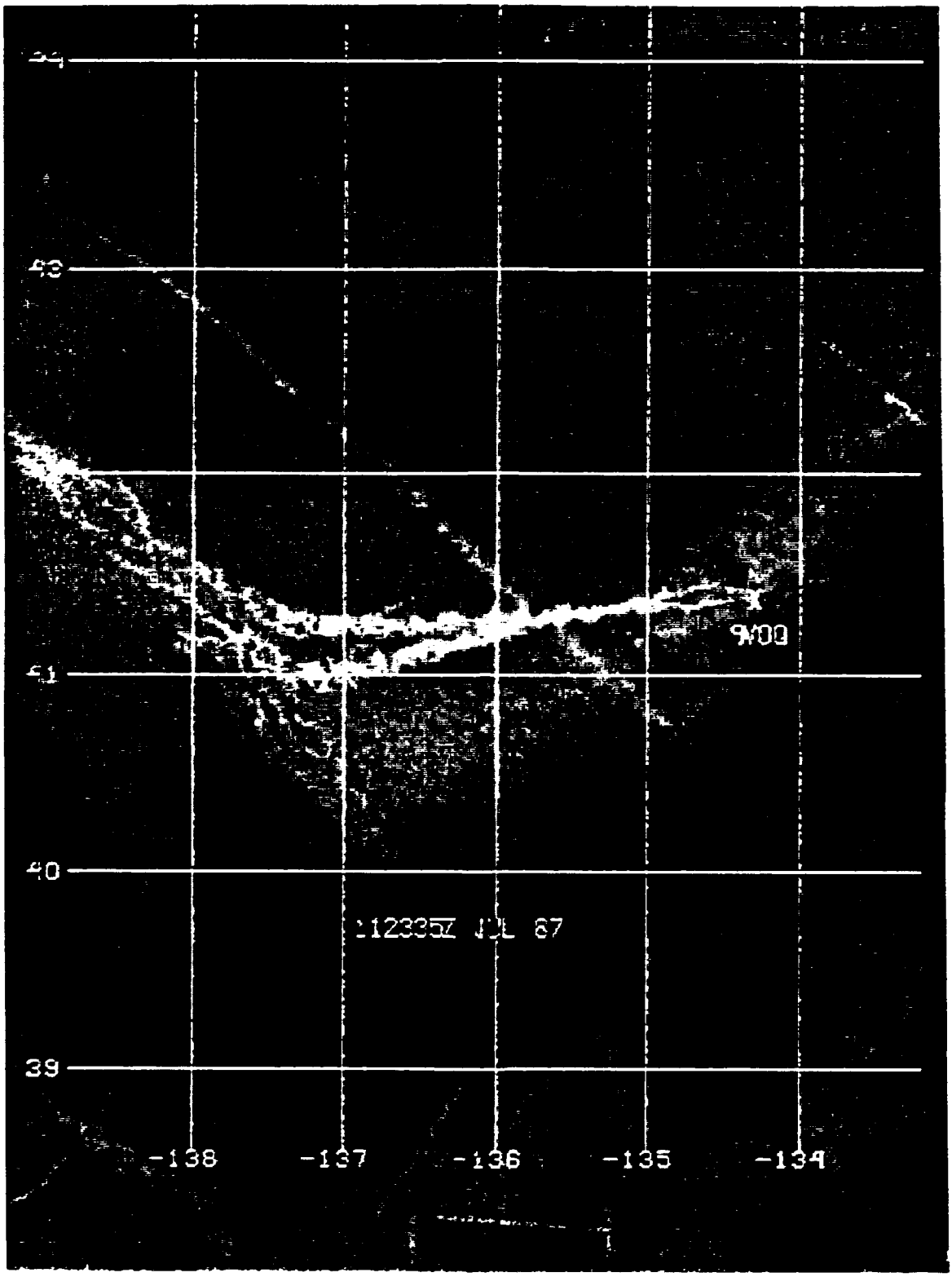

Fig. 30. Channel 3 Imagery showing 9V0Q: 2335Z on 11 July 1987.

The synoptic report by 9VOQ at 0000Z (1700 local) showed the following surface meteorological parameters:

8 octas total cover
True wind 320/17
Relative wind 30 deg port 20 kts
C/S 110/28
1028.7 mb
19C Ta
17C Td
No Tw reported
3 octas Sc

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 30. Also the shiptrack is located in an area of stratocumulus within the image, which is reported by the ship. The position of the ship track in this image is 41.39N 134.37W, while the position derive from 9VOQ's synoptic reports is 41.37N 134.38W. This difference in positions is approximately 1.34 nautical miles. The identity of 9VOQ is the Merchant Vessel Neptune Garnet, a container ship. This vessel utilizes direct drive oil burning engines for propulsion.

N. ELHB9

The ship ELHB9 was observed in two successive overpasses. The first observation was in an overpass of NOAA-10 at 1609Z (0909 local) on 13 July 1987 (Fig. 31). Fig. 32 shows synoptically, the upper level ridge has moved eastward over the Pacific Northwest. While at the surface the subtropical high has moved northwestward and the inland thermal low strengthened somewhat. Winds have increased and are still out of the northwest (Kloesel, et al., 1988). The synoptic

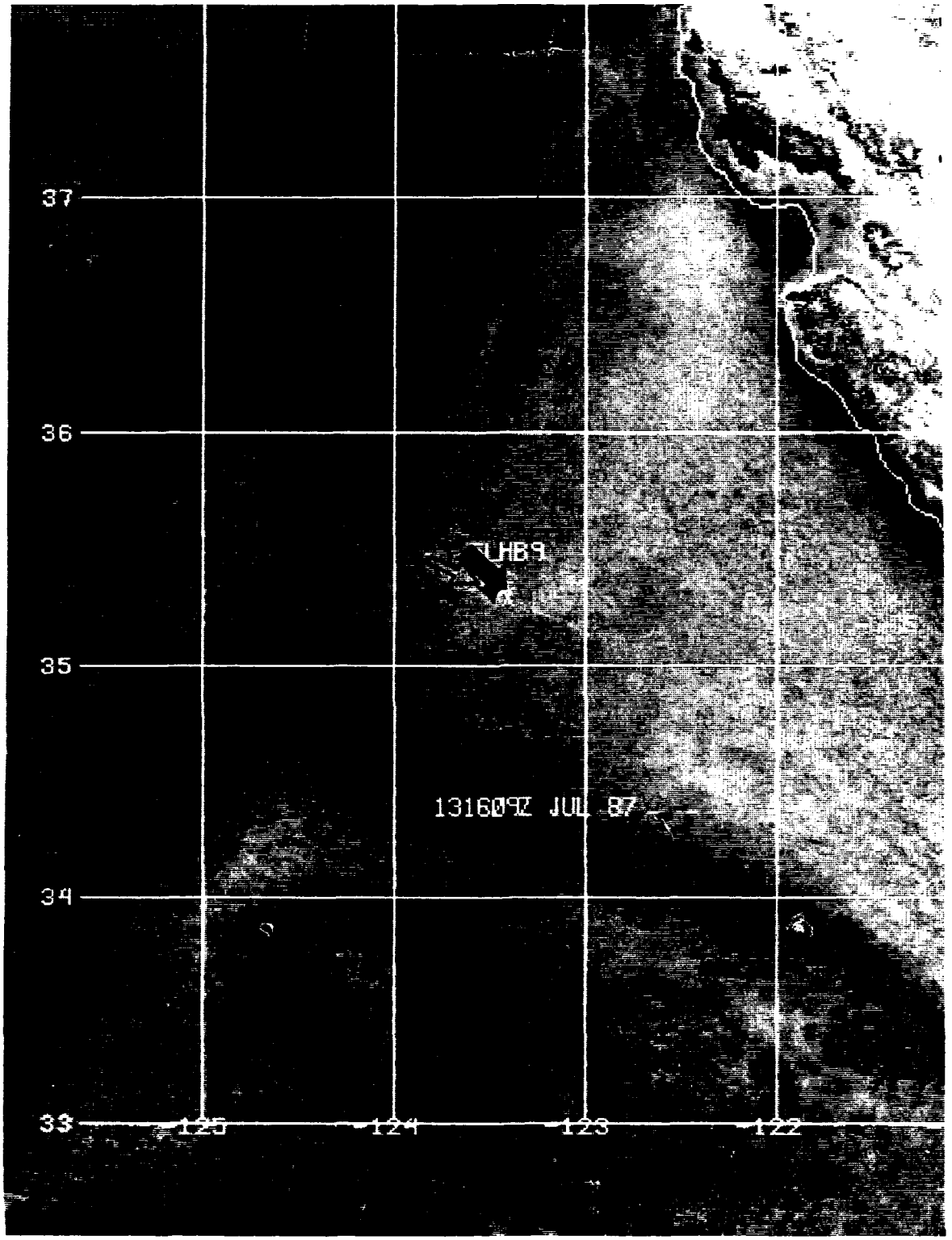

Fig. 31. Channel 3 Imagery showing ELHB9: 1609Z on 13 July 1987.

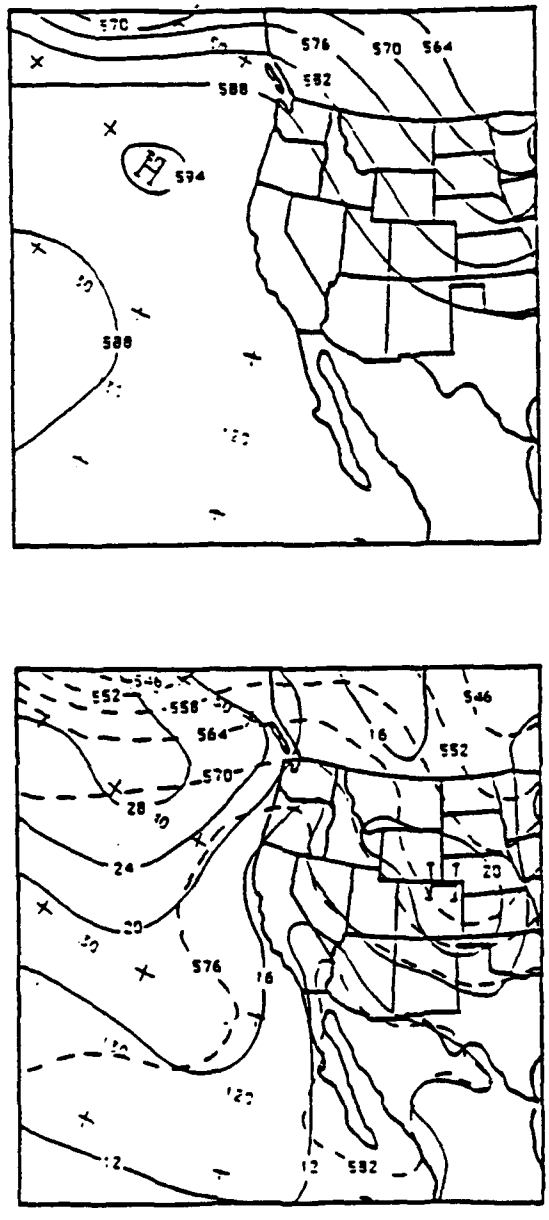

Fig. 32. 13 July 1987 12Z NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

report by ELHB9 at 1800Z (1100 local) showed the following surface meteorological parameters:

8 octas total cover
True wind 300/7
Relative wind 5 deg stbd 35 kts
S/C 290/25
1016.7 mb
16C Ta
14C Td
16C Tw
8 octas Sc

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 31. Also the shiptrack is located in an area of stratocumulus within the image, which is reported by the ship. The position of the ship track in this image is 35.28N 123.43W, while the position derived from ELHB9's synoptic reports is 35.14N 123.48W. This difference in positions is approximately 8.92 nautical miles.

The next observation of ELHB9 is in an overpass of NOAA-9 at 2303Z (1603 local) on 14 July 1987 (Fig. 32). Fig. 33 shows synoptically, the upper level ridge continues to move inland. At the surface, the subtropical high strengthens and moves eastward while the inland thermal low also increases in intensity. This coupling increases winds over the area of interest (Kloesel, et al., 1988). The synoptic report by ELHB9 at 0000Z (1700 local) showed the following surface meteorological parameters:

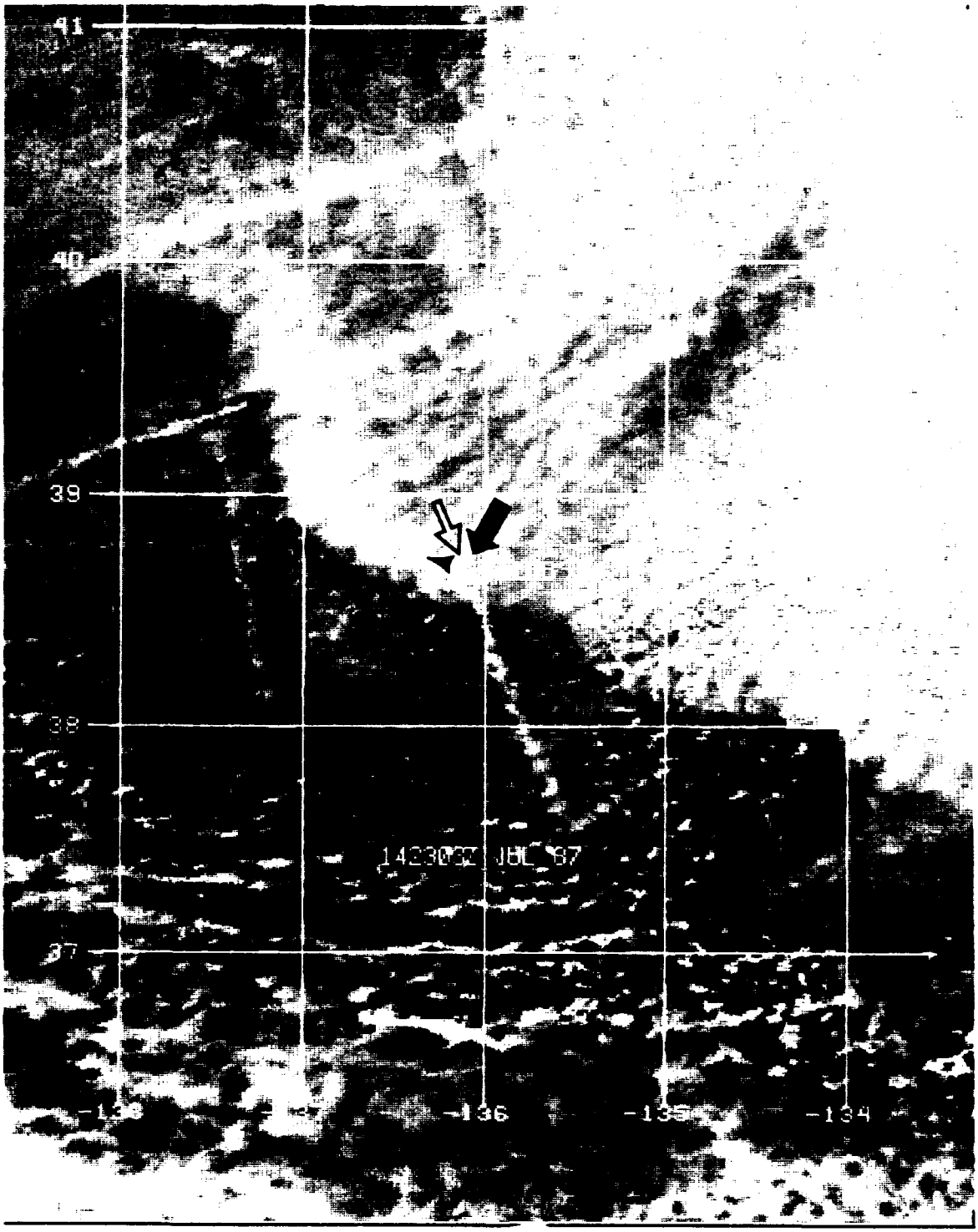

Fig. 32. Channel 3 Imagery showing ELHB9: 2303Z on 14 July 1987.

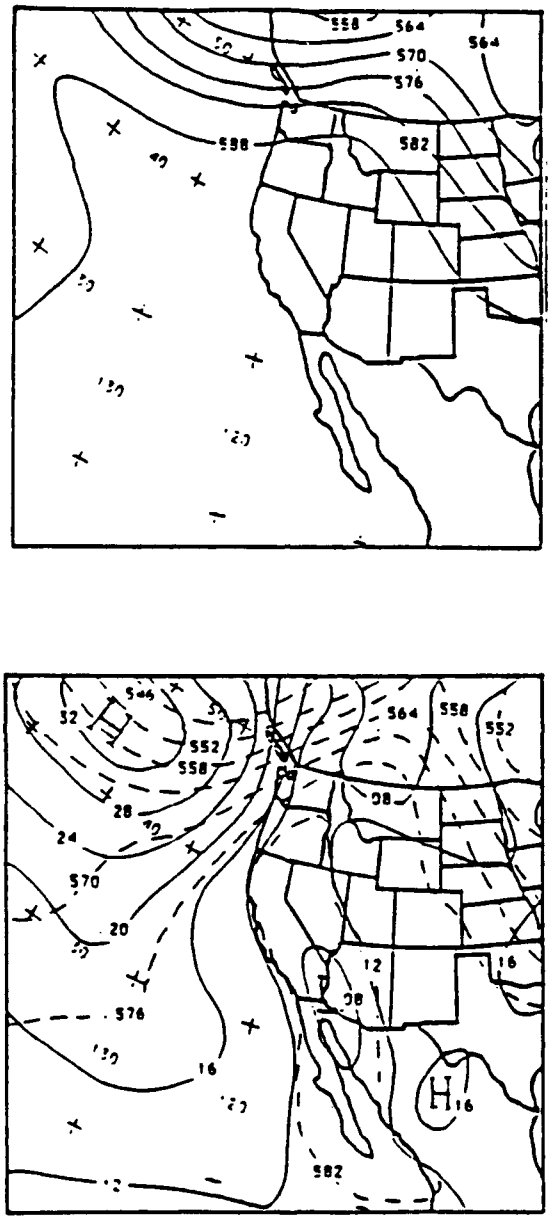

Fig. 33. 15 July 1987 00Z NGM Analysis: 500 mb heights (top) and surface pressure/1000-500 mb thickness (bottom).

6 octas total cover
True wind 030/25
Relative wind 50 deg stbd 30 kts
C/S 280/25
1025.2 mb
17C Ta
14C Td
18C Tw
6 octas Sc

The direction of the ship track matches well with the relative wind direction and the analysis in fig. 32. Also the shiptrack is located in an area of stratocumulus within the image, which is reported by the ship. The position of the ship track in this image is 38.71N 136.08W, while the position derived from ELHB9's synoptic reports is 38.73N 135.91W. This difference in positions is approximetely 10.27 nautical miles. The identity of ELHB9 is the Merchant Vessel Neptune Agate, a container ship. This vessel utilizes diesel engines for propulsion.

IV. ANALYSIS

Thirteen case studies were presented with discussions of synoptic patterns as well as local surface conditions. Table 1 summarizes this data, and also includes propulsion type and ship to ship track separation information. Also by observing the relation between relative wind and distance between ship and ship track (fig. 38), factors involved in generation of ship tracks should be able to be postulated. If advection of the CCN's was the driving force a positive relation between relative wind and ship to ship track separation would be shown (dashed line in fig. 34). Conversely, if the momentum (turbulence) wake astern of the ship were an important factor a negative relation should exist (solid line in fig. 34). Fig. 34 shows that neither of these situations clearly exist, and suggests that ship track generation is a complicated process that involves more than these two techniques alone. In addition, the steam and oil engine propelled ships had a smaller separation distance than did the diesel platforms (4.81 and 4.64 nm vice 11.66 nm). A possible hypothesis for this situation is that the plume dynamics and CCN concentrations are different for each propulsion class.

TABLE 1
Summary of Ship Track Parameters

CALL SIGN	DTG	RELATIVE WIND (KTS)	PROPULSION TYPE	SEPARATION DISTANCE (NM)	SYNOPTIC WINDS (KTS)
3EMB4	301550Z	5°stbd 25	unknown	8.92	330°/8
3ELT3	011529Z	35°port 15	diesel	14.01	030°/10
KSFK	021647Z	10°port 10	steam	4.33	350°/5
	041604Z	0° 0	steam	5.53	320°/15
NLVS	021647Z	10°port 10	diesel	13.85	010°/4
3ERV	041604Z	50°port 25	oil	3.39	010°/18
JKLQ	071639Z	20°port 45	oil	3.00	340°/26
3EJI5	071639Z	10°port 50	unknown	3.79	030°/5
	072237Z	20°port 30	unknown	13.21	030°/11
	081617Z	50°port 25	unknown	4.33	350°/21
JDXS	101534Z	25°stbd 35	diesel	16.97	000°/20
3EFS5	102347Z	10°port 35	unknown	4.69	050°/9
ELFZ8	112335Z	30°stbd 40	diesel	5.91	340°/18
JKES	112335Z	0° 35	unknown	4.57	280°/7
3FOC	112335Z	5°stbd 30	oil	10.82	200°/3
9VOQ	112335Z	30°port 20	oil	1.34	320°/17
ELHB9	131609Z	5°stbd 35	diesel	8.92	300°/7
	142303Z	50°stbd 30	diesel	10.27	030°/25

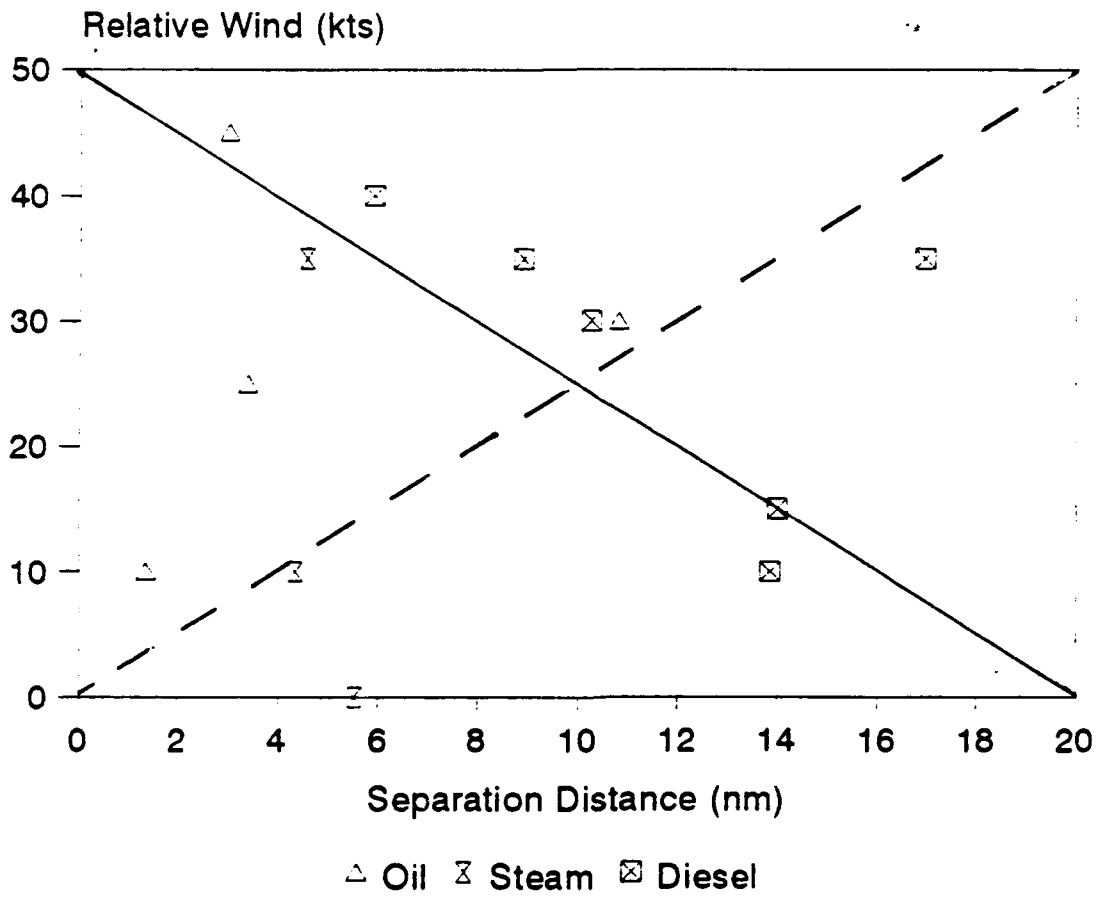

Fig. 34. Relative Wind versus Separation of ship from ship track: dashed line--advection effect
solid line--turbulent wake effect

Surface meteorological parameters were found to be the following composite:

7.9 octas total cover (6 - 8 octas)
True wind 13.5 kts (3 - 26 kts)
Relative wind 29 kts (0 - 50 kts)
1021.1 mb (1014.8 - 1027.2 mb)
18.9C Ta (21C - 13C)
17.6C Td (18C - 12C)
18.2C Tw (21C - 12C)
.8C Ta-Tw (-4C - 4C)
7.6 octas St/Sc (3 - 8 octas)

On the average, the ship track environment is characterized by high humidity, cool temperatures, low broken to overcast skies, a moderate wind, oceanic temperatures near the air temperature, and all located within a high pressure environment. This characteristic environment is not extraordinary when compared with climatological conditions during July in the north Pacific (Fett, et. al., 1979; Kloesel, et. al.,1988).

As mentioned in an earlier section, the area of greatest errors are in the specific measurements of air temperature, dewpoint, and sea surface temperature. Although, scientifically these errors can be significant, the data still portray a general picture of the composite ship track environment. Also, with only thirteen cases which occur throughout the majority of the eastern Pacific basin (24N-46N and 117W-148W) statistics are not reliable. A statistical separation does not seem to exist between the composite ship track

environment and the typical July eastern Pacific environment. Uncertainties in the data not withstanding, this result is consistent with the ubiquitous nature of observed ship tracks in the eastern North Pacific.

V. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this thesis was to confirm ship and ship track coexistence as well as to identify their surface meteorological parameters. Thirteen case studies were presented with discussions of synoptic patterns as well as local surface conditions. The primary result is that thirteen different ships were conclusively identified as origins of observed ship tracks.

No clear generation mechanism was seen in a comparison of relative wind and ship to ship track separation. This would indicate that the generation of ship tracks is a complicated process that involves many factors. Although, in this analysis steam and oil propulsion plants showed a smaller (4.61 nm and 4.64 nm) separation of ship to ship track than did diesel power plants (11.66 nm).

The general composite of the ship track environment does not show significant departures from normal conditions in the eastern Pacific basin during July. This is consistent with the fact that observed ship tracks are numerous in the region during July.

Future research into the ship track environment will take numerous avenues. Some priority areas should be:

--Ship track radiative characteristics and appearance versus ship type. This research should continue to enhance the database and enable real time classification from imagery.

--Craft of Opportunity (COO), should be employed to further define the environment in which ship tracks develop. Thirteen ships have been identified in this thesis as "generators", efforts should be made to ride these ships through favorable environments (the Keystone Canyon makes voyages between Valdez, AK and the Panama Canal) and accurately measure surface meteorological parameters to include air temperature, dewpoint, surface pressure, sea surface temperature, ten meter winds, and any others deemed relevant by future research. Also, since it is not well documented, studies of the turbulent boundary layer astern of the ship, and the characteristics of the exhaust plume would be critical. Exact (Global Position Satellites) position information would be important to the study of separation of ship from ship track .

--Ships, in the vicinity of ship tracks and elsewhere, which do not make ship tracks should be studied, beginning with an overview of the surface meteorological parameters, and eventually integrating with COO investigations. COO measurements can be made when there is no appar-

ent ship track in a satellite overpass. Then a scientifically accurate comparison can be accomplished between the ship track and no-ship track environments.

Ship tracks have now been positively associated with their generating platforms. A significant foundation is in place for future research into ship track genesis.

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