AD-A265 851

REPORT DOCUMENTATION PAGE

Form Approved OBM No. 0704-0188

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1. Agency Use Only *(Leave blank)*.	2. Report Date. February 1993	3. Report Type and Dates Covered. Final - Journal Article

4. Title and Subtitle.
The Kamishak Gap wind as depicted in DMSP OLS and SSM/I data

5. Funding Numbers.
Contract
Program Element No. 0603704N
Project No. X1596
Task No.
Accession No. DN658753
Work Unit No. 94411B

6. Author(s).
R. W. Fett

7. Performing Organization Name(s) and Address(es).
Naval Research Laboratory
Marine Meteorology Division
Monterey, CA 93943-5006

8. Performing Organization Report Number.
JA 441:044:91

9. Sponsoring/Monitoring Agency Name(s) and Address(es).
Space and Naval Warfare Systems Command (PMW-141)
Washington, DC 20361

10. Sponsoring/Monitoring Agency Report Number.
JA 441:044:91

11. Supplementary Notes.
Published in the International Journal of Remote Sensing.

12a. Distribution/Availability Statement.
Approved for public release; distribution is unlimited.

12b. Distribution Code.

13. Abstract *(Maximum 200 words)*.

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14. Subject Terms.
Satellite sensing, remote sensing, weather analysis

15. Number of Pages. 21

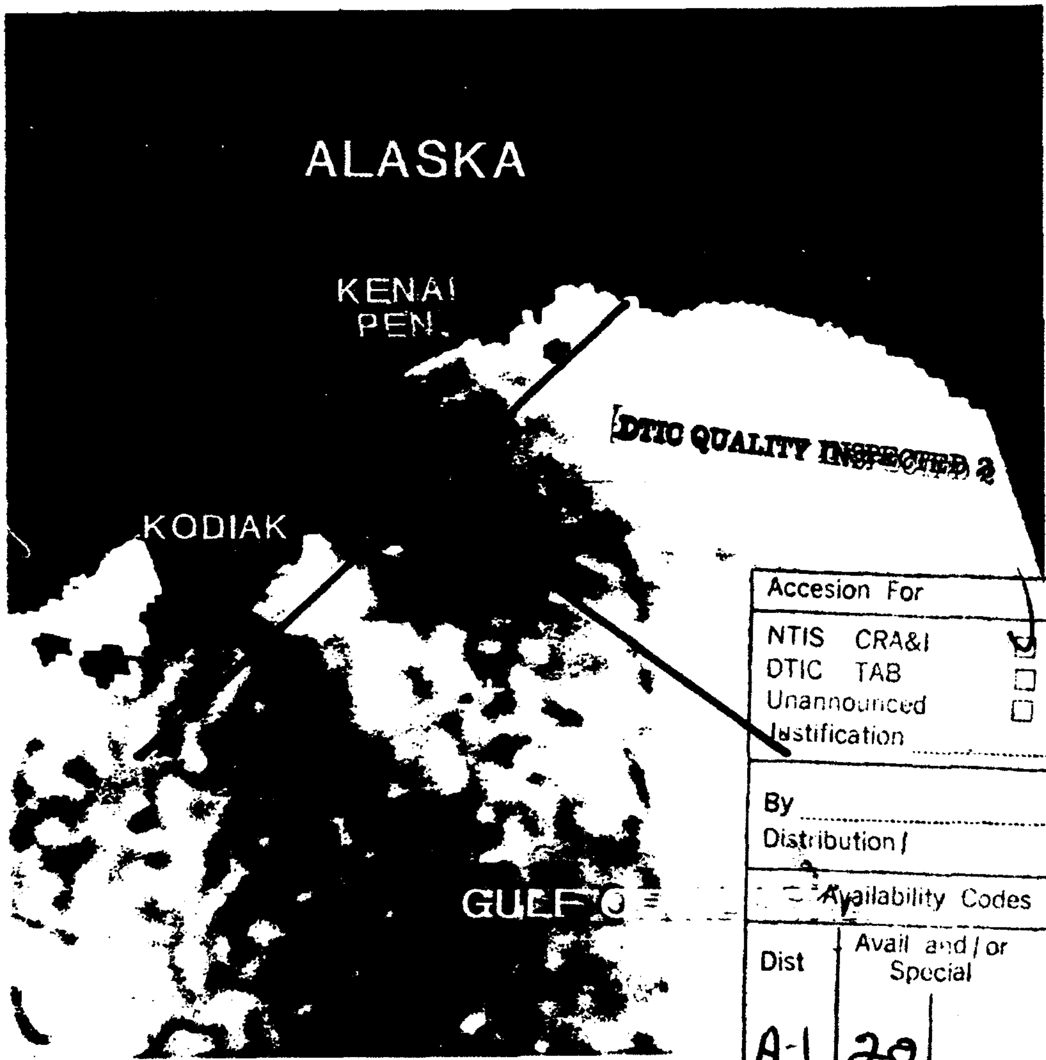
16. Price Code.

17. Security Classification of Report.	18. Security Classification of This Page.	19. Security Classification of Abstract.	20. Limitation of Abstract.
Unclassified	Unclassified	Unclassified	SAR

INTERNATIONAL JOURNAL OF

REMOTE SENSING

Volume 14 Number 3 February 1993



An official journal of the Remote Sensing Society

Taylor & Francis
London • Washington, DC

ISSN 0143-1161

INT. J. REMOTE SENSING, 1993, VOL. 14, NO. 3, 403-423

The Kamishak Gap wind as depicted in DMSP OLS and SSM/I data

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(Received 22 July 1991)

Abstract. DMSP visual and infrared Operational Line Scanner (OLS) data reveal several effects of a mountain gap wind generated by wind flow through the Kamishak Gap on the west side of Cook Inlet, Alaska. The existence of the wind can be inferred through one of three separate effects apparent in the data: (1) a roughened sea effect, appearing as a dark grey shade swath within a sunglint pattern; (2) an anomalous grey shade effect induced by sea spray and aerosols, and, (3) a multiple cloud line effect originating as a result of a moisture flux from the sea to the air in a high speed, cold air, coastal outbreak. The Special Sensor Microwave Imager (SSM/I) of the DMSP satellite provides another means to detect the Kamishak Gap wind due to the sensitivity of this sensor to changes in microwave emission of the sea surface as a result of sea spray and foam in high wind speed areas and to associated changes in integrated water vapour content (oceanic total precipitable water). Developed algorithms provide a methodology to quantify from a satellite perspective some of the characterisitics of such events.

1. Introduction

The Kamishak Gap is a mountain gap in the region between Lake Iliamna and Kamishak Bay near the south-west end of Cook Inlet, Alaska (figure 1(*a*)). Figure 1(*b*), in the inset region of figure 1(*a*), shows the orography of lower Cook Inlet. Mountains on either side, on the Alaska and Aleutian Range, rise to nearly 1000 m. Macklin *et al.* (1980) and Macklin *et al.* (1990) provide documentation of the existence and structure of the Kamishak wind utilizing weather observations from National Weather Service stations and an environmental buoy in the gap region in the former study, and through an instrumented research aircraft flight in the latter study. It was noted in their study of a particular event, that the Kamishak Gap wind was a cold low-level jet that extended over 200 km downstream from the coast, having a width of about 30 km, a depth of about 500 m, and a speed equal to that at the geostrophic level. An abrupt wind shift from N-W to N was noted on the N-E side of the jet. The jet tended to warm, widen, and deepen downstream, exhibiting a pronounced coriolis deflection. The jet was noted to accelerate on leaving the coast, with the strongest winds ($>20\,m\,s^{-1}$) in their example occurring on the south side of the jet's thermal axis at a height of 80 m and a distance of about 90 km downstream from the coast of Kamishak Bay. As might be expected in a cold Kamishak wind example, with the air temperature less than the water temperature, the potential temperature of the air and the specific humidity at low-levels increased in the downstream direction, resulting from the heat and moisture flux from the sea to the air.

The present study focuses on four separate Kamishak wind events as revealed by DMSP visible and infrared data. One of the studies also includes data from the

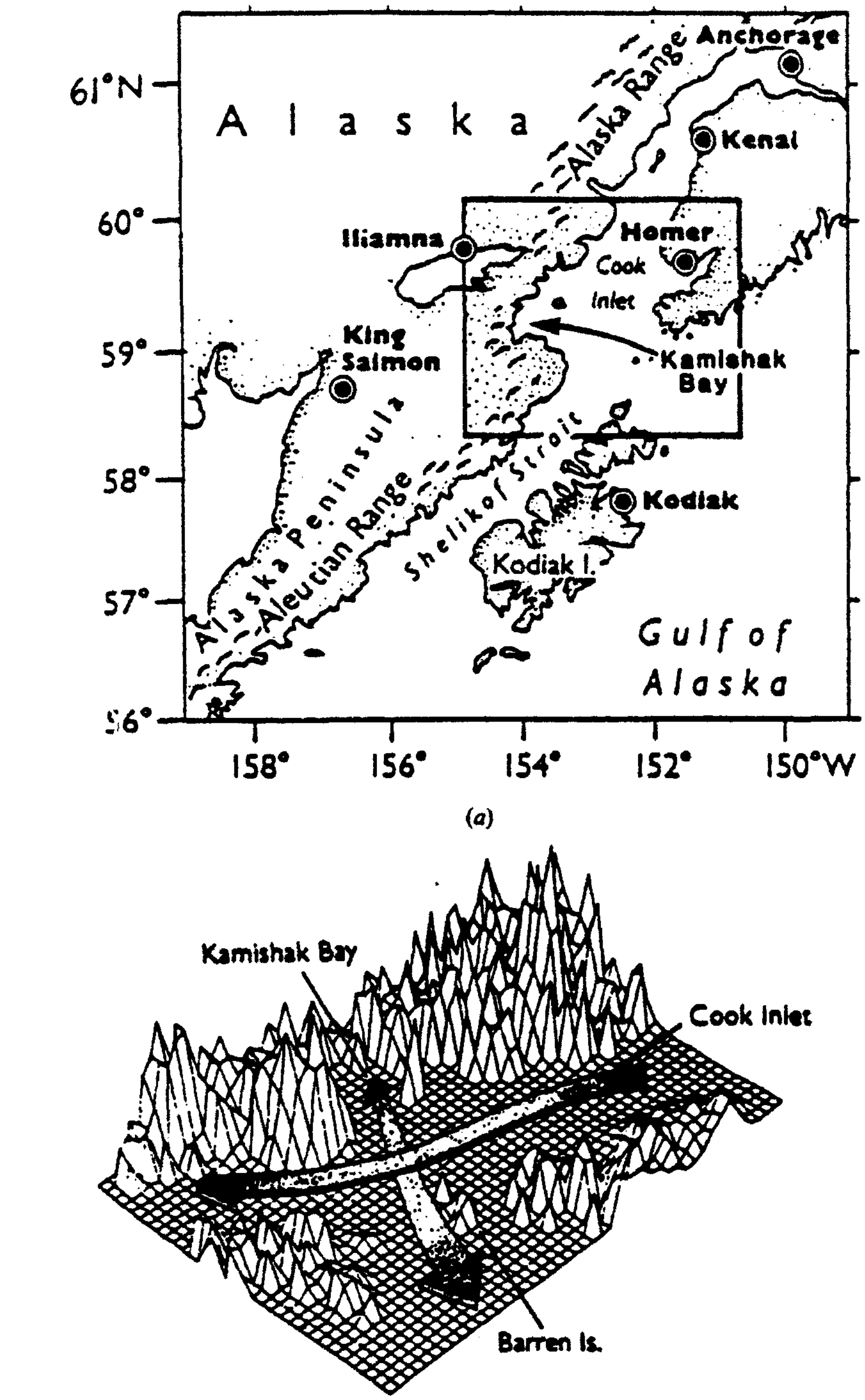


Figure 1. (*a*) Cook Inlet and the Kamishak Bay region. The Kamishak Gap runs from southeastern Iliamna Lake to Kamishak Gay. (*b*) Orography of lower Cook Inlet: grid spacing is about 6 km, the vertical scale is exaggerated 40-fold. Arrows denote orographic wind channels. (Courtesy Macklin, Bond, and Walker 1990)

Special Microwave Imager Sensor (SSM/I). The examples shown provide additional insights and quantitative detail concerning the physical dimensions of the phenomenon and variability of effects as sensed from space.

2. Kamishak wind in sunglint

The use of satellite visible imagery in detecting calm and rough sea state effects and island barrier effects has been described in several papers (Parmenter 1969, Strong *et al.* 1974), Fett and Rabe 1976, Fett and Burk 1981). Where seas are relatively calm, near the Primary Specular Point (PSP), the Sun's reflection appears very bright in satellite visible imagery. Any increase in sea state due to wind action on water diminishes the reflective effect, so that a strong, narrow, low-level jet in such a region is revealed as a darkened swath surrounded by more brilliant reflection. Aerosols or sea spray resulting from the strong wind act further to diminish the reflective power through scattering of incident and reflected light.

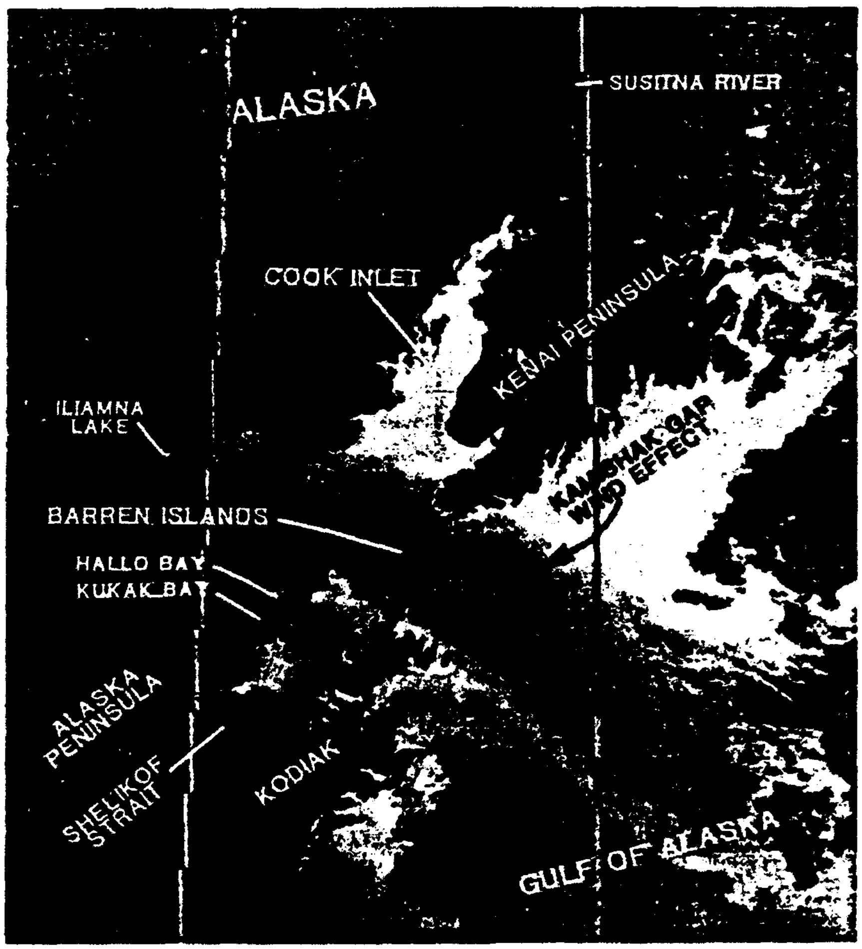


Figure 2. DMSP Visible light (LF) data. 16.30 UTC, 9 May 1990.

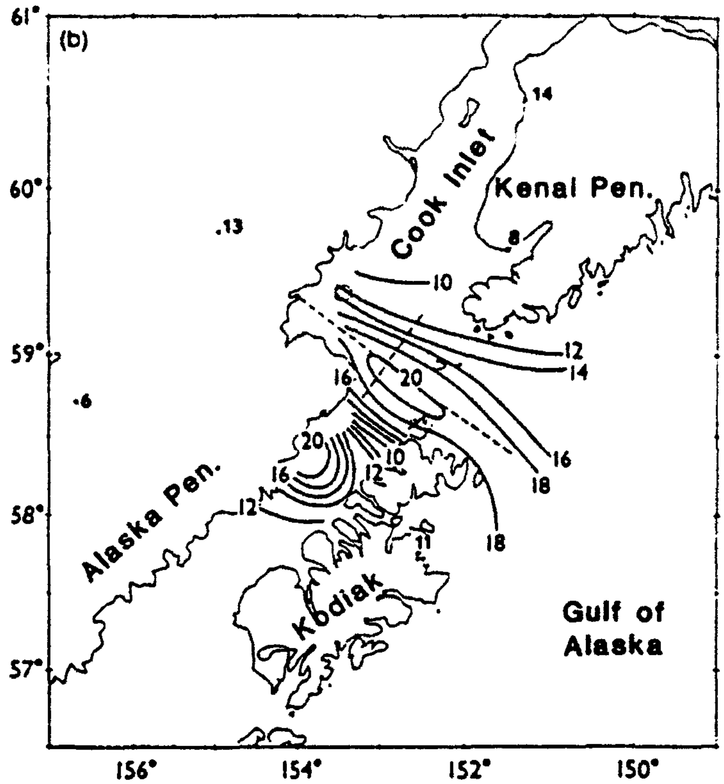


Figure 3. Isotachs of 10 m wind speed based on aircraft measured winds, 11 February 1982 (Courtesy Macklin *et al.* 1990)

Figure 2 is a DMSP high resolution visible image of such an effect extending south-east of the Kamishak Gap. Data were acquired on 9 May 1989 at 16.30 UTC. Visible data at 18.19 UTC (not shown) over the same area, when sunglint was not present, showed the region downstream from the gap to be clear of clouds and other grey shade effects. Roughened seas due to strong winds, therefore, appears to be a proper interpretation of this example. The data suggest relatively calm conditions in the northern portion of the Cook Inlet and south of the Kenai Peninsula. Restricted areas in the Shelikof Strait and in the lee of the Kodiak archipelago also show brilliant reflection, indicating near calm sea state conditions resulting from topographic blocking. The rough sea region crossing Kukak Bay and Hallo Bay indicates a gap wind effect from valley exits leading through low-lying terrain to King Salmon. Calmer seas are indicated on either side of this region. This conclusion is consistent with the isotach analysis based on aircraft measured winds on a different date (Kamishak wind study by Macklin *et al.* 1990) (figure 3). As noted by Macklin *et al.* This high wind speed area is in the lee of low terrain containing two valleys that also tend to promote a mountain gap wind effect. The grey shade tone over the two bays is nearly identical to that in the Kamishak Gap exit area. This compares well with the aircraft measured maximum winds at 10 m (figure 3) in the two areas which were also identical in the study by Macklin *et al.*

The Barren Islands, in the middle of the entrance to Cook Inlet (figure 2), have lee trails of reduced sea state extending over 100 km to the south-east. This implies very stable surface conditions, with the air temperature equal to or warmer than the sea surface temperature. The Fleet Numerical Oceanography Center (FNOC) sea surface temperature analysis for 19 May at 1200 UTC (figure 4) shows temperatures ranging from 4°–8°C in the northwestern Gulf of Alaska. Figure 5 is the FNOC surface analysis for 18.00 UTC, with a superimposed isotherm analysis. The analyses substantiate a condition of warmer air flowing over colder water despite the cold air advection in progress.

3. Kamishak wind effect as an anomalous grey shade

The DMSP visible high resolution sensor has a wave length extending from 0·4 to 1·1 μm. This wavelength optimizes detection of atmospheric haze, aerosols, sea spray etc., as an anomalous grey shade (Fett and Isaacs 1979). An example of a Kamishak Gap wind as an anomalous grey shade is shown in figure 6. The light-toned grey shade extending south-east of the entrance to Cook Inlet is caused by sea spray and aerosols created by hurricane-force winds over the open water. The aircraft carrier U.S.S. Constellation was located just south of the Barren Islands at

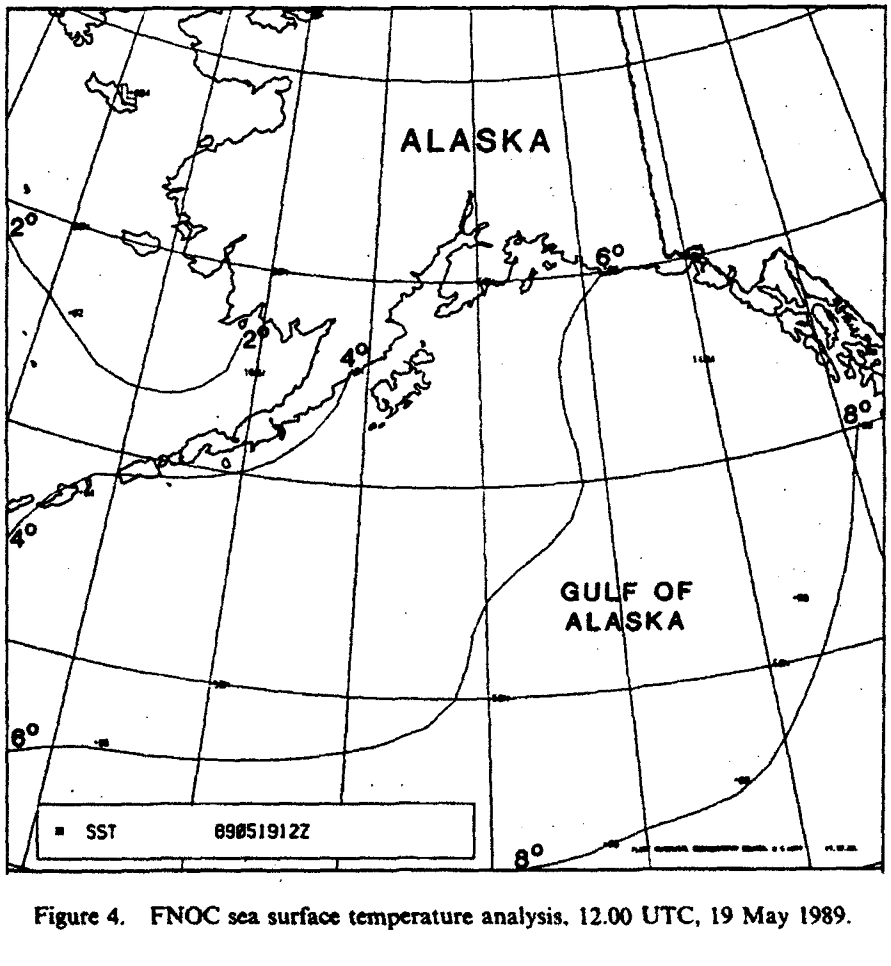


Figure 4. FNOC sea surface temperature analysis, 12.00 UTC, 19 May 1989.

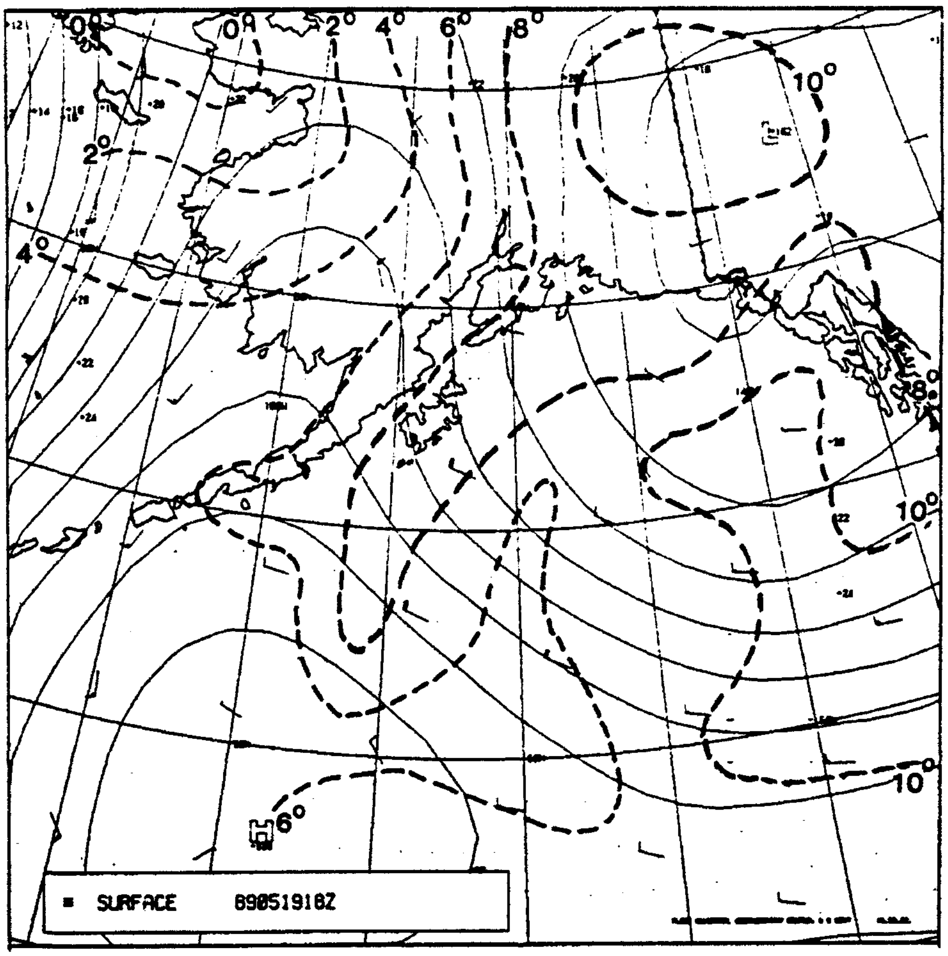


Figure 5. FNOC surface analysis with superimposed isotherm analysis, 18.00 UTC, 19 May 1989.

the time of these data, attempting passage through the Cook Inlet for a port visit to Anchorage, Alaska. Maximum winds of 75 knots were recorded 3 hours earlier with numerous gusts to 85 knots. The ship was forced to slow its approach to only 2–3 knots to reduce the relative wind across the flight deck, as blades from their only search and rescue helicopter snapped and blew overboard (Moren 1990, personal communication). Due to the limited fetch, Constellation was not experiencing high seas; however, sea spray was lifted in the strong wind and was blown horizontally past the ship, severely reducing low-level visibility. Aloft, according to the weather officer on board, skies were 'crystal-clear without a cloud in sight'.

Note that the Kenai Peninsula in this example is not forming an effective block, since a grey shade also indicates an aerosol spray effect in this region. The FNOC surface analysis for 18.00 UTC on this date (figure 7) shows the tightly-spaced isobars indicating a steep pressure gradient over the Cook inlet. Kodiak weather station, on the north-east end of the island, reported a 45 knot wind from the north-west, while a buoy south-east of Montague Island (see figure 6) indicated a 50 knot northwesterly wind, verifying the strong winds south-east of the Kenai Peninsula implied by the satellite data.

Careful examination of the anomalous grey shade region reveals a gravity wave pattern aligned at about a 30° angle from a perpendicular to the main flow axis. If the clear wake pattern of the Barren Islands is used as an indication of the surface wind, and the gravity wave pattern is assumed to be in response to a higher level wind from the north-west at the top of the spray-induced grey shade, this implies a backing of wind with height and on-going cold air advection.

This is in agreement with the isotherm analysis directed in figure 7. Sea surface temperatures, shown in the FNOC 24 September 00.00 UTC analysis (figure 8) range from 10–14°C. Comparing this analysis with the isotherm analysis figure in figure 7, indicated air temperatures are 2–4° colder than the Gulf waters. This spread

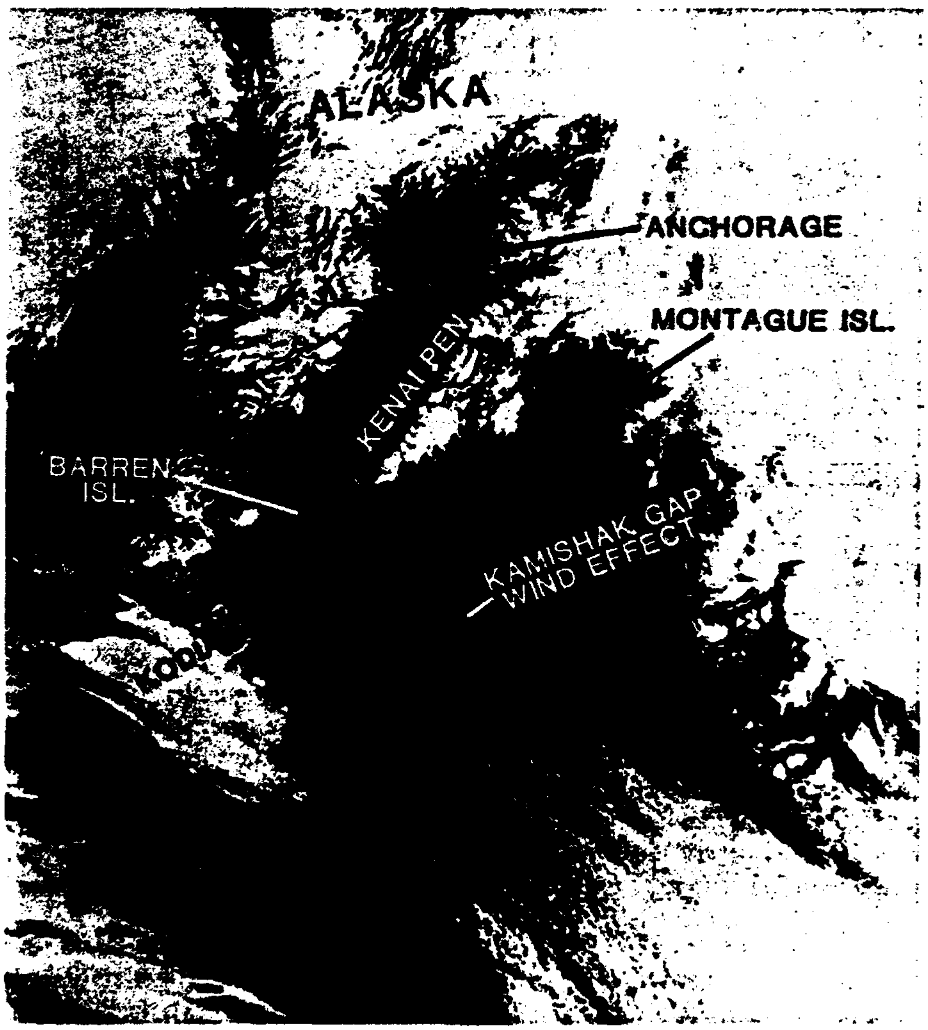


Figure 6. DMSP visible light fine (LF) data, 19.31 UTC, 23 September 1986.

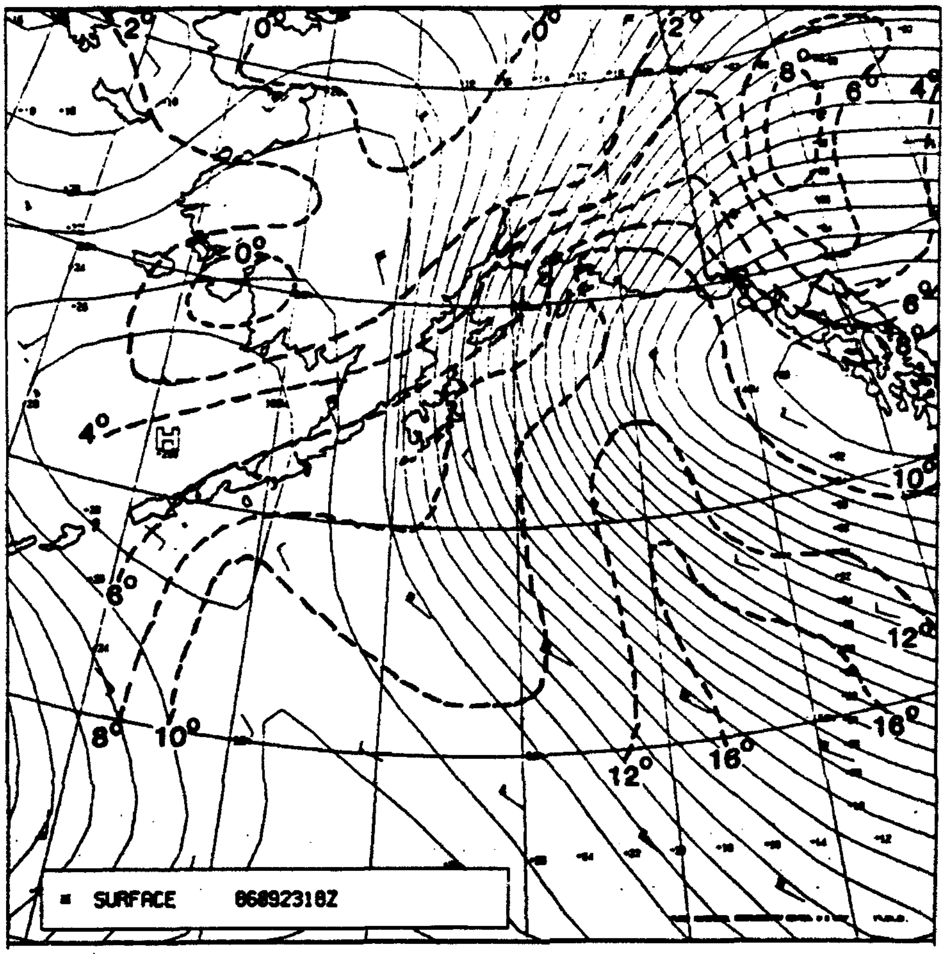


Figure 7. FNOC surface analysis with superimposed isotherm analysis, 18.00 UTC, 23 September 1986.

was decreasing during daytime hours and the air was very dry as shown by the 24 September 00.00 UTC radiosonde observation for Kodiak (figure 9). The sounding verifies the dry air, strong winds, and low-level temperature inversion, under which the gravity waves were forming. Note also that Kodiak's surface temperature at this time had warmed to almost 12°C. Under such conditions some time was required for the air to be moistened sufficiently for low cloud production. This occurred in a gradual fashion several hundred kilometres downstream, as shown in the DMSP image (figure 6).

4. The Kamishak wind effect as a cold surge outbreak

When the air temperature is appreciably colder than the sea surface temperature and wind speeds are high, the strong moisture flux from the water to the air rapidly produces cloud lines due to condensation. Topographically blocked areas, by contrast, are regions of relatively slow moving, conditioned air with a longer residence time over the area. Entrainment of some of this air into the adjacent, faster moving non-blocked air may force subsidence into the blocked region which, in cold air outbreaks, appear generally clear of clouds.

Figure 10 is a DMSP infrared example on 27 January 1989 at 18.40 UTC. The image reveals a cold surge in progress, passing over the Alaskan Peninsula and through the Kamishak Gap. Cloud lines act as tracers, revealing the position of each gap location. Mesoscale effects appearing in Cook Inlet are of special interest. Winds are funnelled from the NNE between the Chigmit Mountains, west and south-west of Anchorage, and the Kenai Mountains, south of Anchorage. Winds shift suddenly to N-W in the lee of the Chinitna Peninsula, where an enhanced cloud line can be seen extending southeastward past the southern tip of the Kenai Peninsula. A short distance away from the Chinitna Peninsula, Augustine Island shows lee effects which indicate due-westerly flow. The separate flows converge into the enhanced cloud line extending leeward of the Chinitna Peninsula.

The enhanced cloud line starting close to the shore near the northeastern end of the Alaskan Peninsula appears to emanate from Kiukpalik Island, which appears as

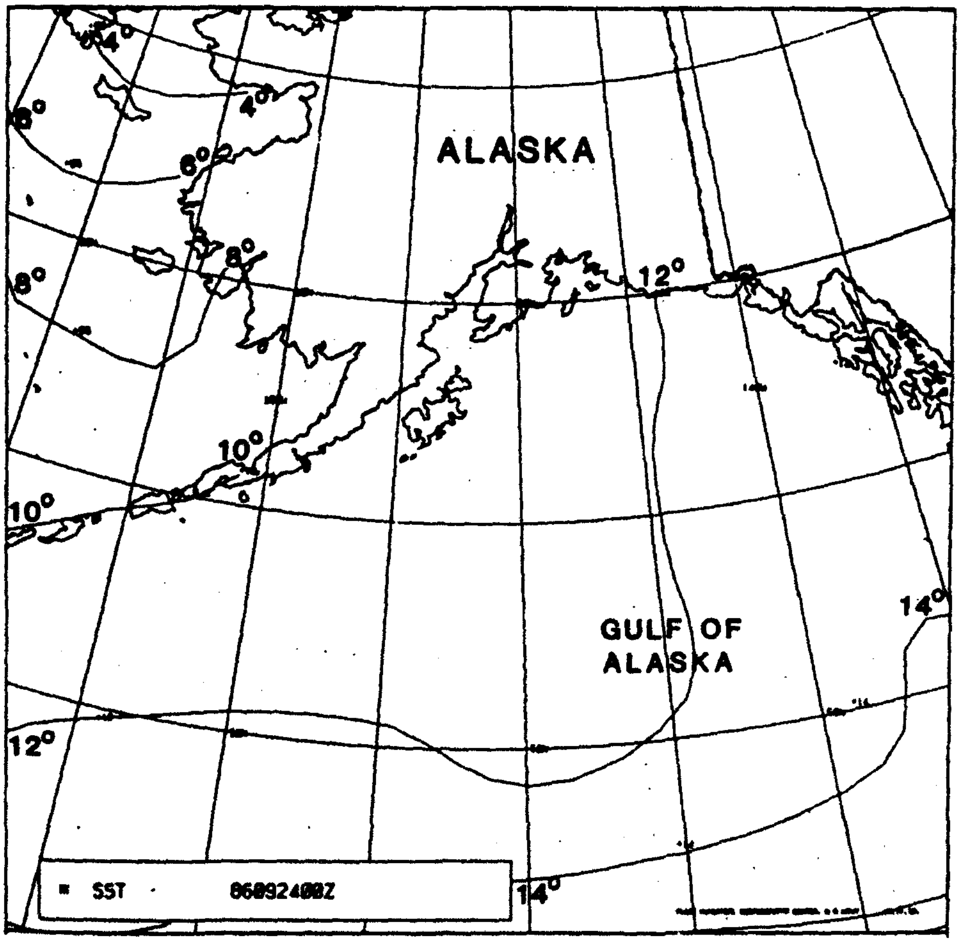


Figure 8. FNOC sea surface temperature analysis, 00.00 UTC, 24 September 1986.

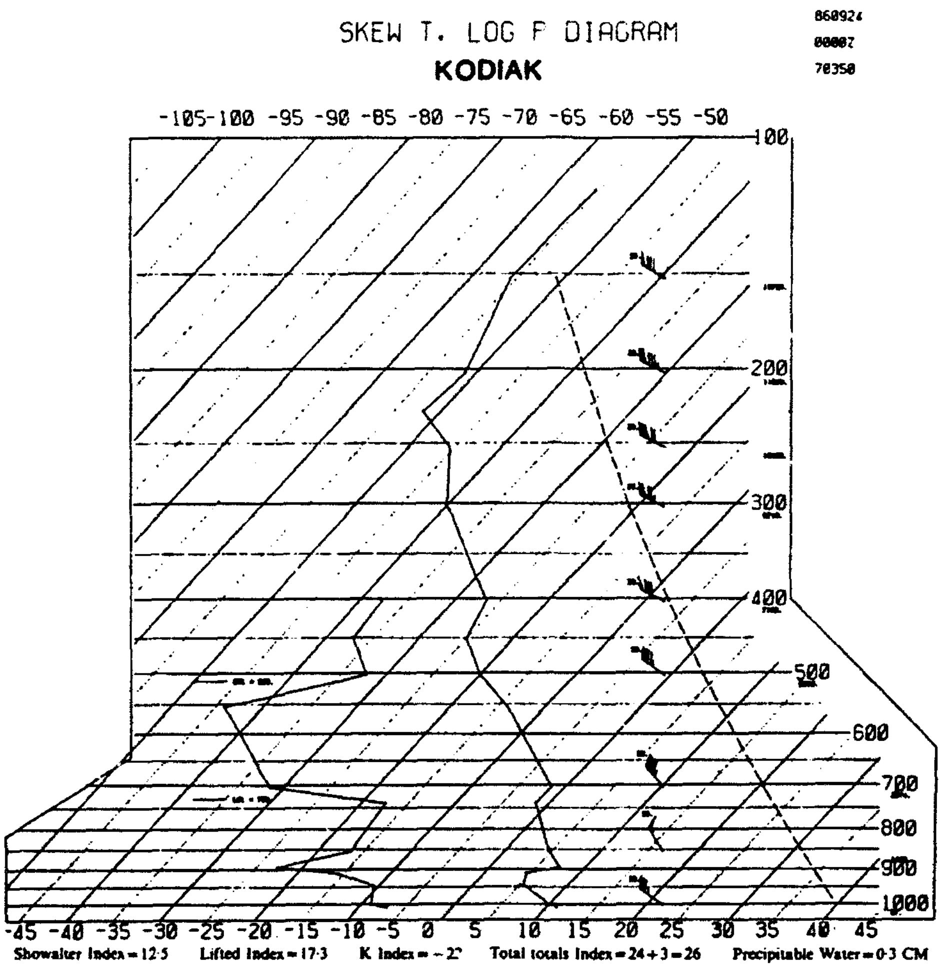


Figure 9. Radiosonde profile showing temperature and dew point in °C for Kodiak, Alaska, 00.00 UTC, 24 September 1986. Wind barbs show speed in knots: 1 barb = 10 kts ($5\,m\,s^{-1}$); $\frac{1}{2}$ barb = 5 kts ($2\frac{1}{2}\,m\,s^{-1}$); a pennant-50 kts ($25\,m\,s^{-1}$).

a small white 'dash' at the source of the plume. A river valley leads from Kamishak Bay around Mount Douglas into the Shelikof Strait. The plume, therefore, appears to be an effect of the diversion of a branch of the Kamishak Gap wind through this valley and over the island. The cloud lines, in general, extend about 375 km downstream from the coast and exhibit a marked anticyclonic turning, reflecting the coriolis deflection noted by Macklin *et al.* (1990).

Augustine Island, with an elevation of 1197 m, shows a clear wake effect, while the Barren Islands, between Kodiak and the Kenai Peninsula, show enhanced cloud trails. The Barren Islands have a maximum elevation of 605 m, considerably lower than St Augustine. Kodiak's sounding for 28 January at 00.00 GMT (figure 11), reveals an inversion base near 870 mb, or about the 1280 m level. The base was probably even lower near Augustine Island, since heat flux would tend to raise the base after the air passed over the water to Kodiak. Because of the stabilizing effect of the low-level inversion, air flow passing Augustine Island would be largely forced around the island rather than over it, thereby creating a clear wake in the process. Air moving past the Barren Islands, on the other hand, where the inversion was higher, could easily pass over the islands, inducing some upward vertical motion in the process, thereby giving rise to an enhanced cloud trail.

The FNOC surface analysis for 18.00 UTC on 27 January (figure 12) shows the pronounced gradient over Cook Inlet that existed on this date. Temperatures (not shown) were extremely cold. Fairbanks indicated a temperature of −50°C, King Salmon, −39°C, and Kodiak, −17°C. Temperatures of below freezing existed well out into the Gulf of Alaska.

The FNOC sea surface temperature analysis (figure 13) indicates temperatures ranging from close to 0°C, at the coast, to 6°C in the central Gulf of Alaska. This implies extremely large, air-sea temperature differences over the region, with the air much colder than the water.

5. The Kamishak Gap wind as revealed in SSM/I data

At 12.00 UTC, 8 January 1990, the FNOC surface analysis (figure 14) revealed a pressure configuration favourable for northwesterly gap winds through the entrance to the Cook inlet and beyond. Temperatures of below freezing extended more than 200 km south-east of the Cook Inlet and south of the Aleutian Peninsula.

Figure 10. DMSP infrared temperature smooth (TS) data, 18.40 UTC, 27 January 1989.

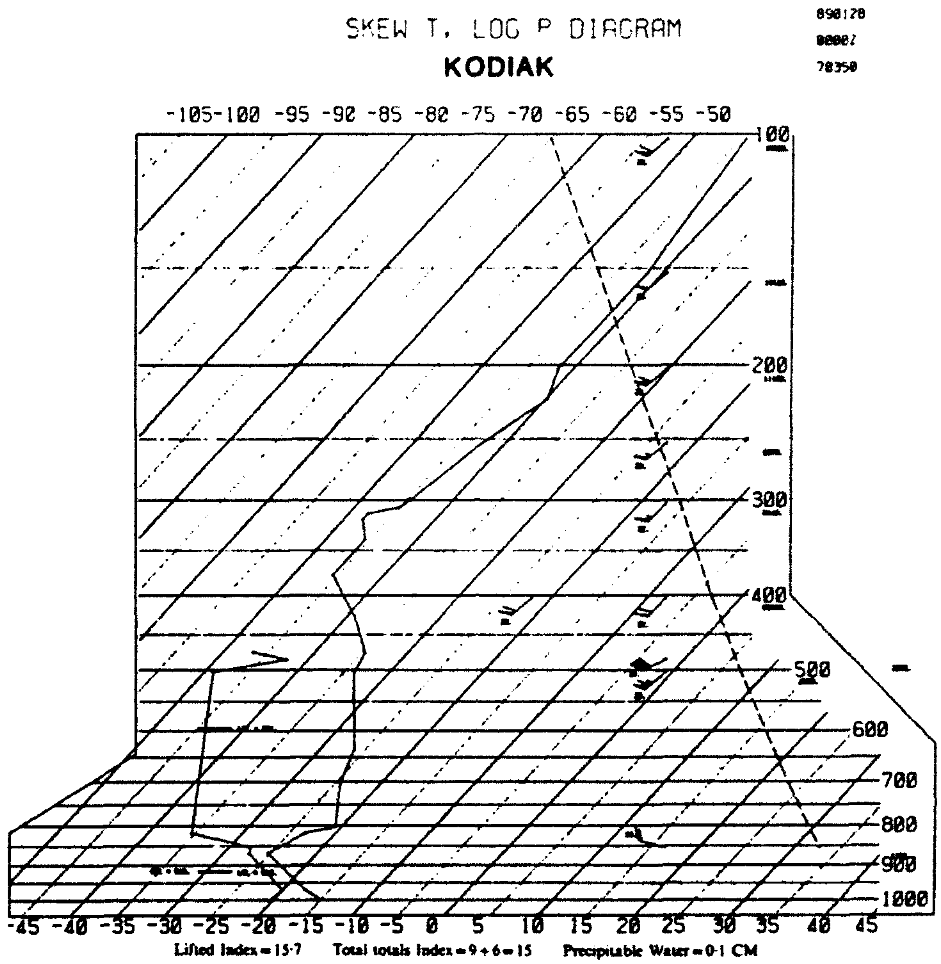


Figure 11. Radiosonde profile showing temperature and dew point in °C for Kodiak, Alaska, 00.00 UTC, 28 January 1989. Wind barbs show speed in knots: 1 barb = 10 kts ($5\,m\,s^{-1}$); $\frac{1}{2}$ barb = 5 kts ($2\frac{1}{2}\,m\,s^{-1}$).

A DMSP infrared image at 14.57 UTC, 8 January 1990 (figure 15), shows conditions similar to that of figure 8, but probably less intense. Cloud lines indicating a Kamishak Gap wind effect are fewer in number and less tightly spaced than observed in stronger gradients. Blocking effects are apparent as delineated by the clear areas on the southeast side of Kodiak Island and the Kenai Peninsula. The flow past the southwestern end of Kodiak deflects anticyclonically, reflecting the coriolis effect in that region. Comma-shaped cloud masses south-east of the Kenai Peninsula indicate vorticity maxima associated with the low pressure centre in the northern Gulf of Alaska.

Kodiak's radiosonde data for 00.00 UTC on 8 January (figure 16) reveal a backing of winds from the surface to 850 mb, indicating cold air advection at lower levels, while the 12.00 UTC sounding (figure 17) shows considerable strengthening of winds from lower levels up to the 250 mb level. An inversion base near 860 mb appears in both soundings, capping cloud development as in the previous example.

Microwave imager data (SSM/I), from the DMSP satellite on the same date, were obtained near the same time as the infrared data for this example. Wind speed can be inferred from the SSM/I data due to the fact that, at microwave wavelengths, a roughening of the sea surface and creation of sea foam directly affects the measured emissivity. At 19 GHz calm water has an emissivity of about 0·4. In strong wind conditions emissivity can approach 1·0. The algorithm for measuring wind speed is assumed to be accurate up to about 20 m sec^{-1} and wind speed determinations are not attempted above that value.

Figure 18 is a color-coded version of the SSM/I data at 15.00 UTC, on 8 January 1990. In this example high wind speeds in excess of 19·5 m sec^{-1} are coded essentially black; winds of 17·5–19.5 m sec^{-1} are shown as dark red; moderate winds of 12–17·4 m sec^{-1} are coded yellow and orange; and lighter winds less than 10 m sec^{-1} by light, and finally, dark blue. The data indicate that high wind speeds extend approximately 220 km downstream from the coastline of Kamishak Bay. Kodiak Island and the Kenai Peninsula form topographic barriers so that winds are

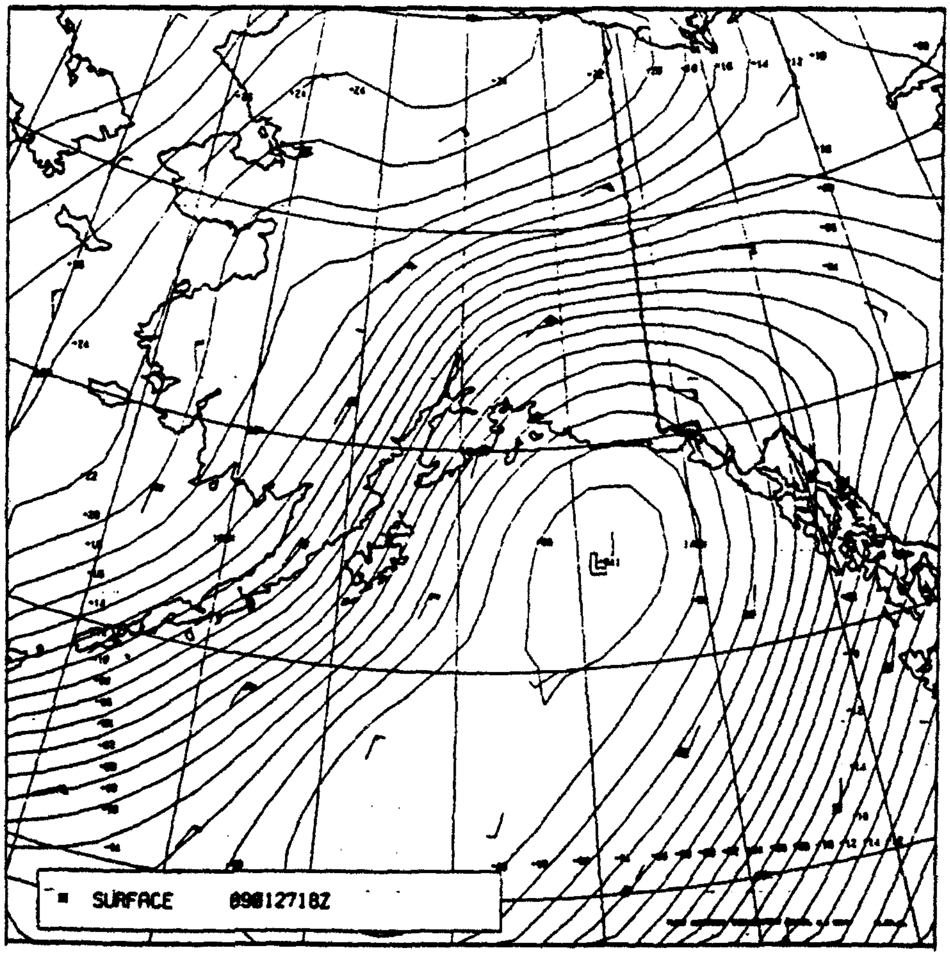


Figure 12. FNOC surface analysis, 18.00 UTC, 27 January 1989.

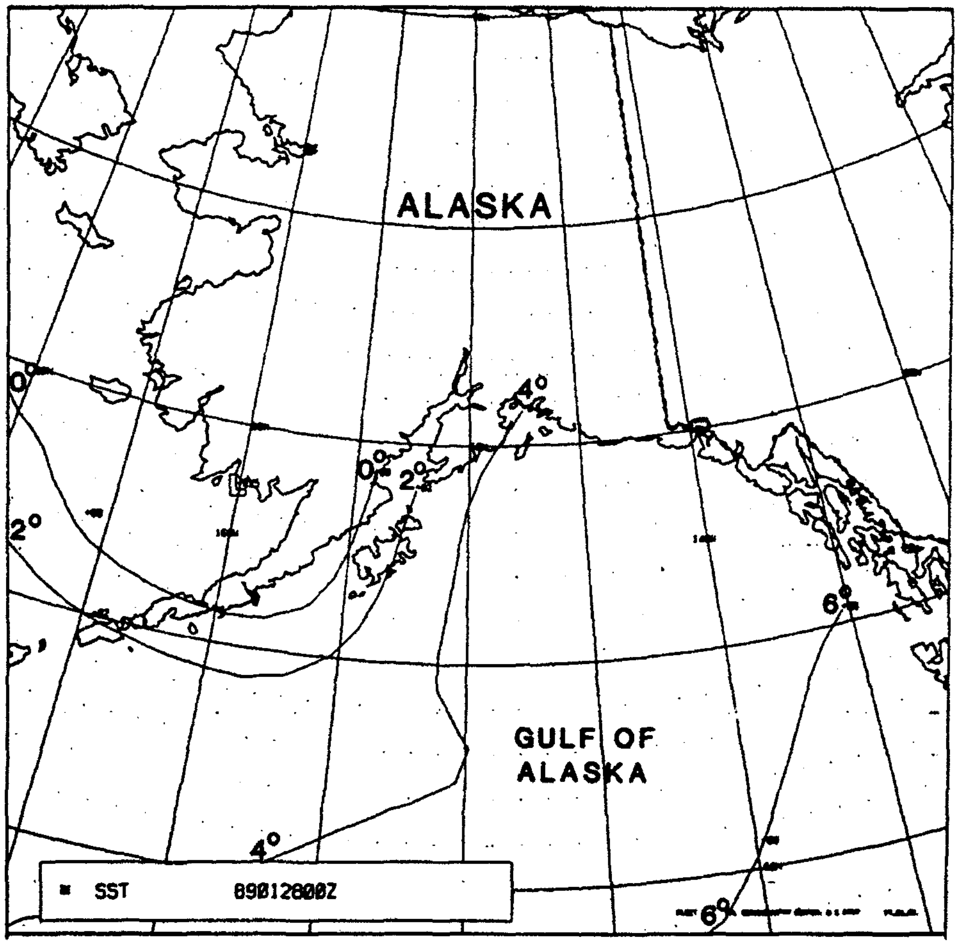


Figure 13. FNOC sea surface temperature analysis, 00.00 UTC, 27 January 1989.

reduced somewhat in those areas. An area of higher wind speeds can also be seen extending from the coastline of the southwestern portion of Kodiak Island where corner effects and another gap region through the Alaskan Peninsula combine to produce the higher winds.

The SSM/I data can be processed to yield information on integrated water vapour content (WV). The algorithm for calculating WV consists of a linear combination of the 19 V, 22 V and 37 V channels and of the square of the 37 V channel (where V refers to the vertically polarized data). Figure 19 is a graph showing calculated values of wind speed and WV along the 'across track' line from the Alaskan coastline southwestward past Kodiak Island, shown on figure 18. Of special interest is the reduction of water vapour coincident with the maximum wind speed downstream from the Kamishak Gap and in the lee of Kodiak Island.

The moisture minimum shown to be associated with the low-level jet is indicative of the cold, dry, nature of the air flowing through the Gap. The secondary minimum south of Kodiak may be attributed to an upstream condensation effect as clouds formed over the mountainous terrain of Kodiak. This possibility is supported by

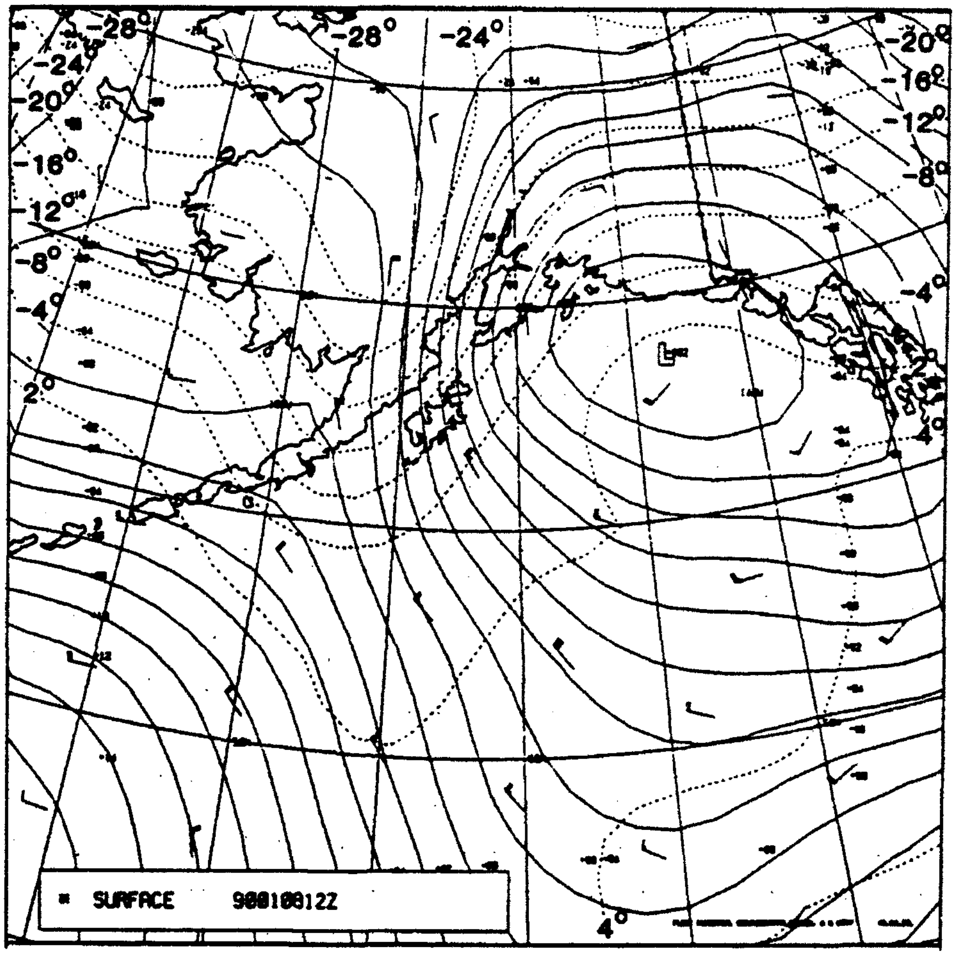


Figure 14. FNOC surface analysis, 12.00 UTC, 8 January 1990.

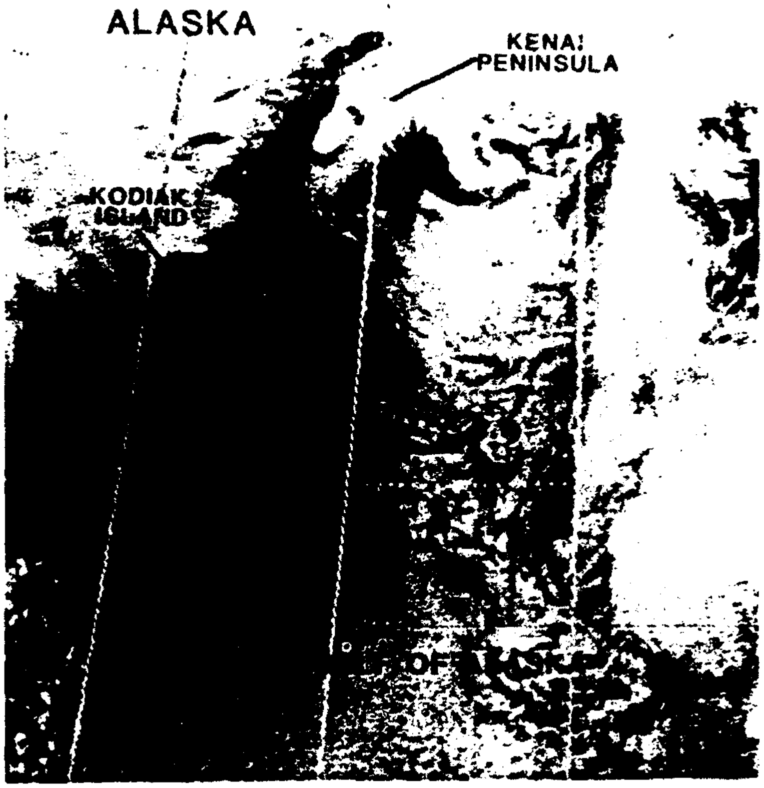


Figure 15. DMSP infrared temperature smooth (TS) data, 14.57 UTC, 8 January 1990.

Kodiak's 12.00 UTC, 8 January surface observation which indicate an overcast condition of stratocumulus cloudiness at that time.

The along jet comparison of wind speed and WV (figure 20) show that strong winds persist over 350 km downstream. Consistent with the findings of Macklin *et al.* 1990, WV shows a tendency to increase with fetch, reflecting the continued flux of moisture into the air as it moves over the warmer water. The early peak at 200 km may have been associated with an enhanced cloud line or cloud patch downstream.

6. Conclusion

Various effects of the Kamishak Gap wind, as revealed in satellite visible and infrared imagery have been demonstrated. The existence of the wind may be inferred from any of the following: (1) a darkened swath in an illuminated region of sunglint; (2) as an anomalous grey shade resulting from the aerosol or sea spray effect in an area not in sunglint; and (3) as a tightly spaced cloud line region, indicating strong northwesterly flow. Quantitive validation of strong winds can be obtained from the microwave imager data, or SSM/I of the DMSP satellite. These data also show integrated water vapour effects revealing the dry conditions associated with the wind

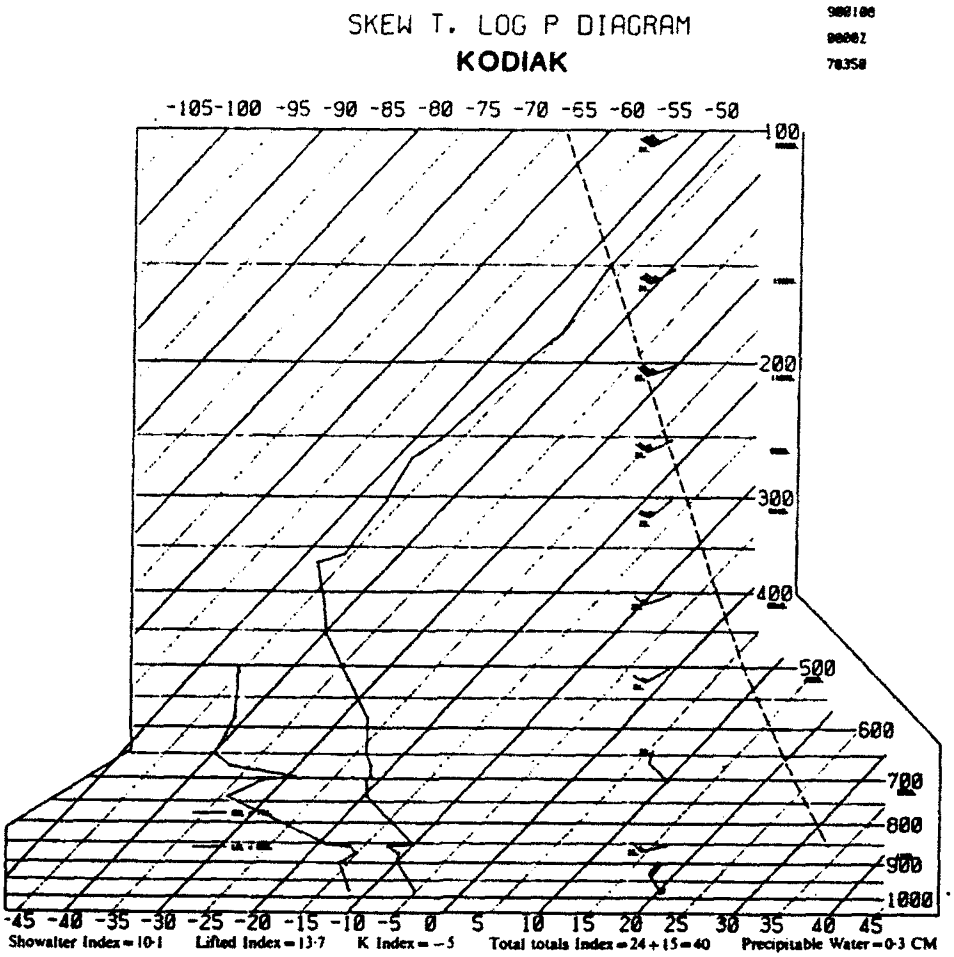


Figure 16. Radiosonde profile showing temperature and dew point in °C for Kodiak, Alaska, 00.00 UTC, 8 January 1990. Wind bards show speed in knots: 1 barb = 10 kts ($5\,m\,s^{-1}$); $\frac{1}{2}$ barb = 5 kts ($2\frac{1}{2}\,m\,s^{-1}$).

and lee mountain barriers, and of the gradual increase in WV downstream of the mountain gap.

Acknowledgments

This research was sponsored by the U.S. Navy, Space and Naval Warfare Command (PMW-141). The assistance of Dr James Boyle, NOARL, in processing the SSM/I data was essential for the development of this paper. Photographic services were provided by PH2 Kathy Smith. Additional help by Tom Lee, and Steve Bishop, NOARL, and Maureen Thompson, Computer Sciences Corp., is gratefully acknowledged. 441:044:91 Approved for public release; distribution is unlimited.

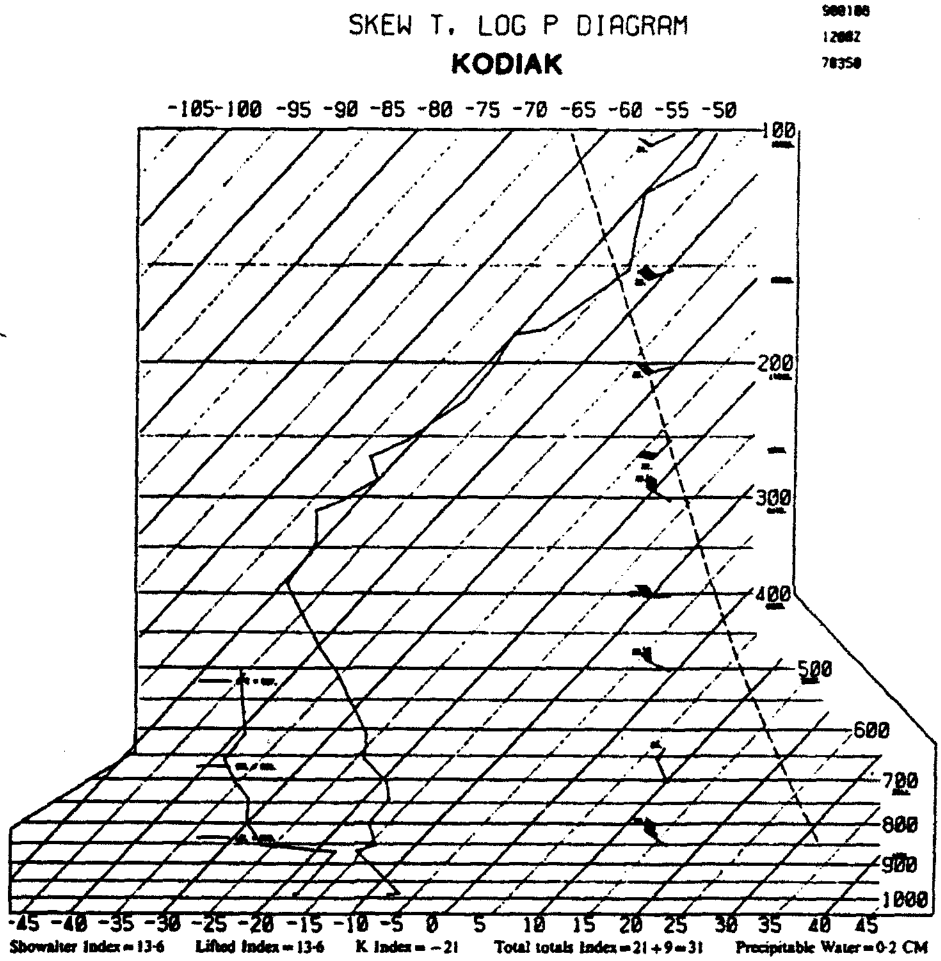


Figure 17. Radiosonde profile showing temperature and dew point in °C for Kodiak, Alaska. 12.00 UTC, 8 January 1990. Wind barbs show speed in knots. 1 barb = 10 kts ($5\,m\,s^{-1}$); $\frac{1}{2}$ barb = 5 kts ($2\frac{1}{2}\,m\,s^{-1}$). A pennant = 50 kts ($25\,m\,s^{-1}$).

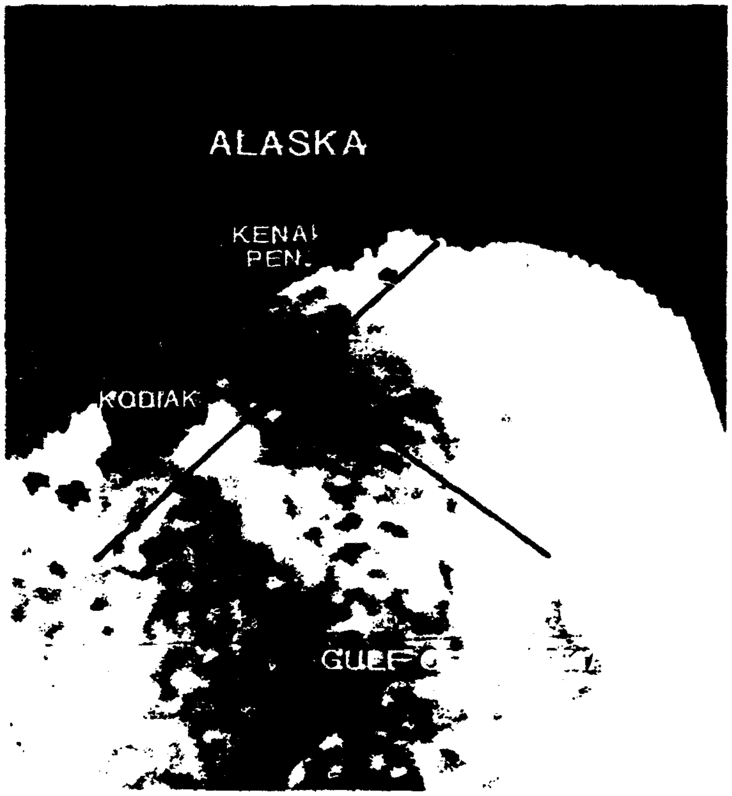
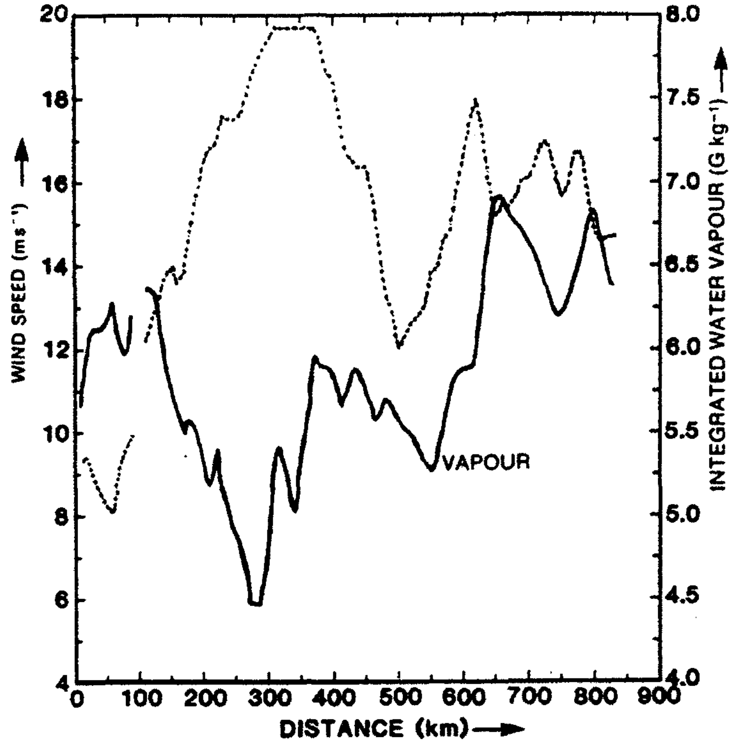
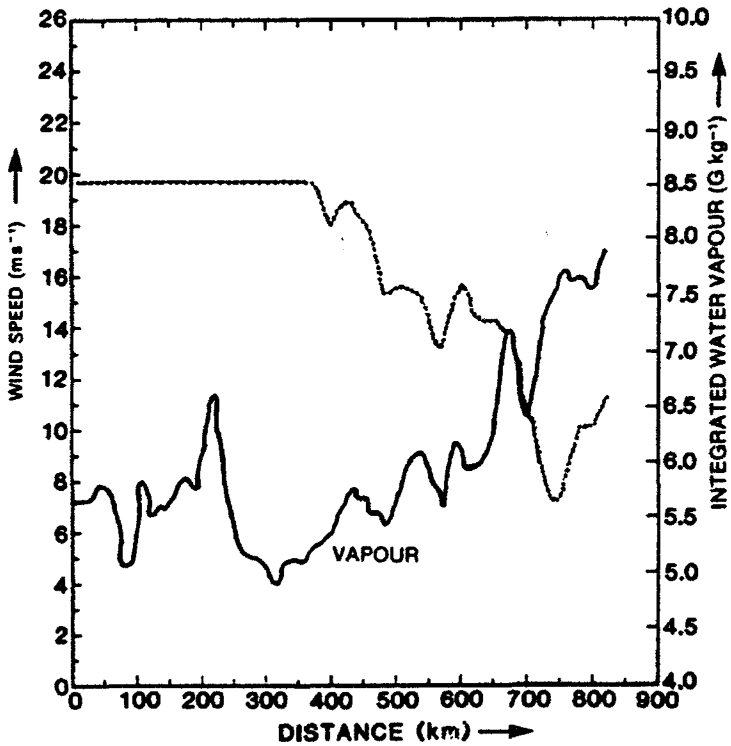


Figure 18. A colour coded image of DMSP microwave imager (SSM/I) data, 15.00 UTC, 8 January 1990. Winds in excess of $19{\cdot}5\,m\,s^{-1}$ are indicated as black; $17{\cdot}5$–$19{\cdot}5\,m\,s^{-1}$ are shown as dark red; 12–$17{\cdot}4\,m\,s^{-1}$ are shown as yellow and orange; blue indicates winds of less than $12\,m\,s^{-1}$. Black regions close to the coastline are contaminated by a land effect and should be ignored.



(60°N, 145°W to 55°N, 155°W)

Figure 19.



(58.44°N, 153.16°W to 55°N, 142.5°W)

Figure 20.

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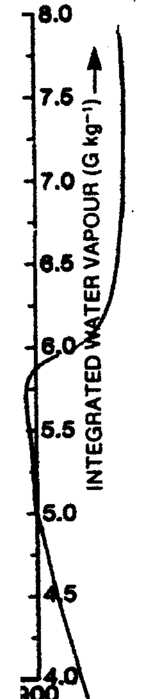

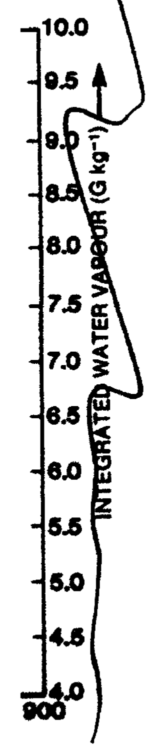

Figure 19. A graph of wind speed (m s^{-1}) and integrated water vapour content (kg m^{-2}) perpendicular to the axis of the Kamishak Gap wind from the Alaskan coastline southwestward over the Gulf of Alaska past Kodiak Island.

Figure 20. A graph of wind speed (m s^{-1}) and integrated water vapour content (kg m^{-2}) along the axis of the Kamishak Gap wind from the north-west coastline of Cook Inlet, extending southeastward past the Barren Islands into the Gulf of Alaska.