NOTES AND CORRESPONDENCE

Guadalupe Island Cloud Trail

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ABSTRACT

Clouds were observed forming in the lee of Guadalupe Island under a special sequence of events. One cloud was a narrow, linear cloud, 200 km long, that could not have been advected. Instead, a transparent linear wake was advected downwind. Later, synoptic-scale convergence caused the wake to condense, forming the linear cloud trail. That weak synoptic-scale variation may cause a linear cloud trail and has important implications for understanding ship cloud trails.

1. Introduction

There is interest in the physics of the marine boundary layer on the eastern side of midlatitude oceans that are capped by an air temperature inversion. Some recent focus has been on the effects of ships on the marine boundary layer that includes the generation of long, linear cloud trails apparent in satellite photographs (Conover 1966; Coakley et al. 1987; Porch and Kao 1990). It has been suggested that the condensation nuclei and or heat from the ship's exhaust are responsible for the ship trails. When there is overcast stratus at the top of the marine layer, long linear signatures (ship tracks) are seen in the stratus that are spatially comparable to the ship cloud trails and are believed to be caused by a similar process.

Cloud lines trailing behind isolated islands are also observed in cases where a marine layer is capped by an inversion. If the inversion is much lower than the island top, the island is sufficiently wide, and the low-level winds sufficiently strong, von Kármán vortices will be shed from the island and carried great distances downstream (Lyons and Fujita 1968; Zimmerman 1969; Thomson and Grower 1977, and others, reviewed in Atkinson 1981). If the stability is concentrated in the inversion base and the inversion base is near the top of the island, Kelvin ship waves will be generated (Edinger and Wurtele 1972; Scorer and Wilkinson 1956; Sharman and Wurtele 1983). Ship waves are also responsible for a "V" clearing in stratus in the lee if the inversion is near the top of the island or if the atmosphere below the inversion is stably stratified (Edinger and Wurtele 1972).

The purpose of this paper is to present a case where Guadalupe Island generated a cloud trail that could not have been simply advected downwind. Evidence will be given that synoptic-scale lifting plays a crucial role in the formation of the cloud. We shall suggest that this has application to the generation and maintenance of ship cloud trails.

2. The problem

Our attention is directed to Guadalupe Island, which is in the Pacific, 300 km west of Baja California. The base of the island extends 37 km north–south and 13 km east–west. A 1300-m peak is on the northern third of the island and a 1200-m peak on the southern third.

Attracting our interest were GOES-West satellite photos taken in April 1982. A cold front approached the island from the northwest and by 1915 UTC 1 April a short trail of four gravity-wave crest clouds extended eastward from Guadalupe Island (Fig. 1). By 2315 UTC, the crests extended 150 km eastward with both diverging crests and transverse waves (Fig. 2). Two hours later, the crests extended to Baja California. These were Kelvin ship waves in the base of the air temperature inversion.

No further lee clouds were noticed for three days. At 1915 UTC 4 April, there were some low clouds along the island that extended less than 20 km downwind (Fig. 3). Surface winds at this time were from the north. One hour later at 2045 UTC, there was a cloud extending 50 km southward in the lee of the island (not shown). At 2245 UTC, the lee cloud was at least 150 km to the lee on the infrared photo (not shown). At 2315 UTC, a sharp, robust linear cloud

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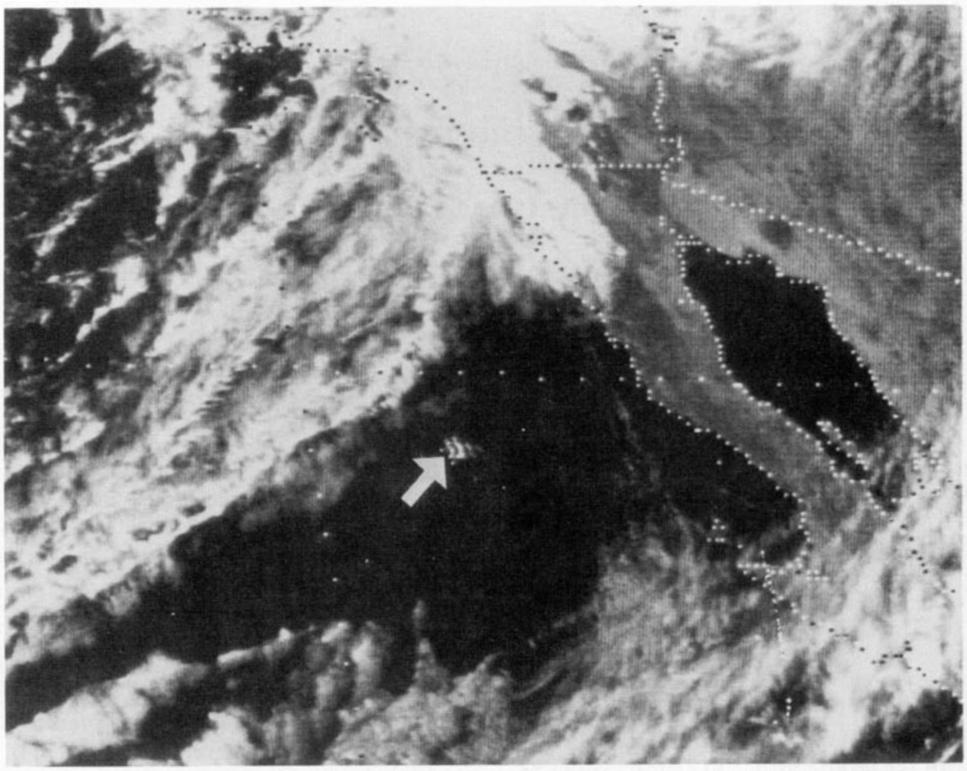

FIG. 1. GOES-West visual photograph for 1915 UTC 1 April 1982. Ship waves with four crests extend eastward of Guadalupe Island. A cold front is approaching from the northwest. Arrow points toward the island.

FIG. 2. GOES-West visual photograph for 2315 UTC 1 April 1982. Ship waves extend more than 150 km east of Guadalupe Island. The cold front has just passed the island.

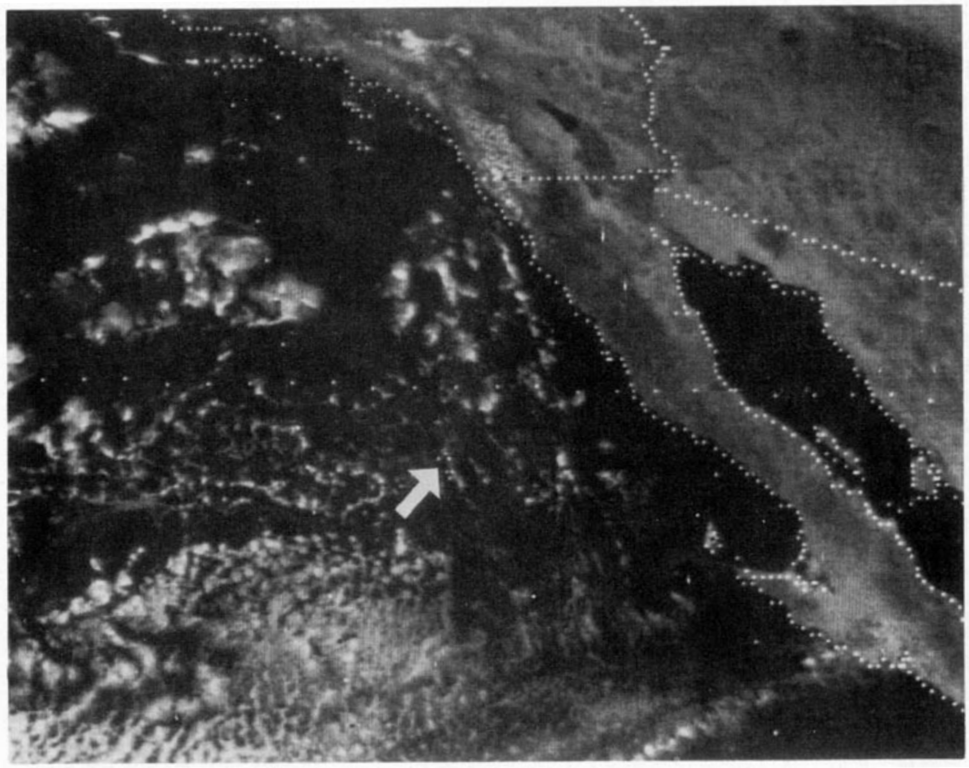

FIG. 3. GOES-West visual photograph for 1915 UTC 4 April 1982. Isolated clouds are in the general area.

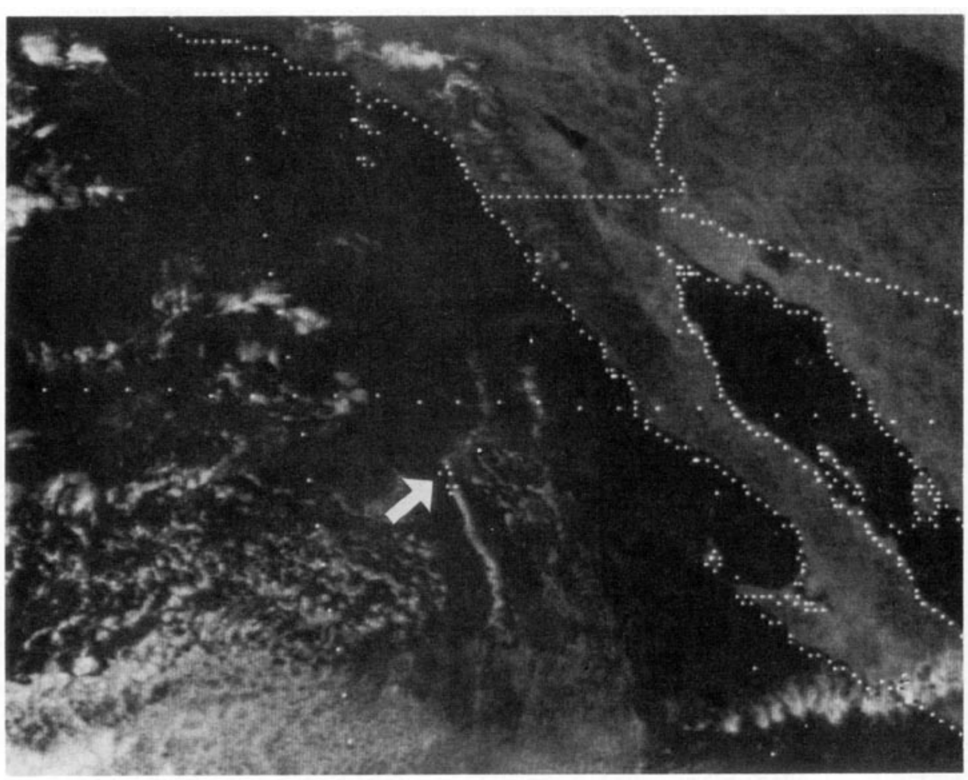

FIG. 4. GOES-West visual photograph for 2315 UTC 4 April 1982. A cloud trail extends 200 km south of Guadalupe Island. Thin, patchy clouds are just to the east.

extended 200 km south of the island in a visual photo (Fig. 4). Also at this time, faint, stratiform clouds were in the general area of the island, suggesting weak lifting of the inversion. An hour later, the southern end of the cloud trail extended into broken stratus prohibiting further tracking of the cloud extension.

Synoptically, a cold front pushed over Guadalupe late on 1 April and was past by 2 April at 0000 UTC. At 700 hPa, there was a short trough and strong winds from the west over the island. Following behind the front, ridging was established at the surface and weaker zTnmeridional flow at 700 hPa. Late on 4 April the ridging around Guadalupe began to be relieved as the surface center of the anticyclone shifted to the north (Fig. 5) and a very weak trough at 700 hPa was over the area.

3. The vertical structure of the lower atmosphere

The lower atmosphere was sampled twice a day from the southern tip of Guadalupe Island by a Mexican Weather Service upper-air station. Details of the boundary layer for 1–8 April 1982 are in Table 1. Throughout the time period, there was an air temperature inversion that capped a cool, moist marine layer below (Fig. 6). Just after the cold front passed at 0000 UTC 2 April, the stratification was weakest in the upper portion of the marine layer, with a nearly isothermal layer between 1500 and 1900 m. For the rest of the period, the marine layer was weakly stable, capped by a quick transition to a rather uniformly warm and dry layer above. The inversion base was a minimum elevation under mesoscale ridging at 0000 UTC 1 April, before the frontal passage (lower frame, Fig. 7). The inversion was lifted to 1875 m at 0000 UTC 2 April, 575 m above the top of Guadalupe, as the front passed and the "ship wave" clouds appeared. Within a few hours, the inversion was brought down below the peak height, the wind slackened, and the ship wave clouds disappeared. Following that was a general declining trend in inversion height until it was down to 700 m at 0000 UTC 4 April. From the next 24 h, the inversion lifted slowly to a maximum of 1000 m at 0000 UTC 5 April, shortly after the long, linear cloud trail event was observed. Then the inversion dropped quickly over the next 12 h, which corresponded with the disappearance of the cloud trail.

Selected Guadalupe winds are also shown in Fig. 7 (upper frame). The peak wind at 850 hPa was 25 m s^{-1} from the west when the cold front passed and the ship wave clouds appeared. After this, the 850-hPa winds

TABLE 1. Guadalupe Island sounding characteristics. INV HT denotes air temperature inversion-base height. INV DT denotes inversion top temperature–base temperature. Lyr speed denotes average speed of three points about inversion base.

Month	Day	Hour (UTC)	INV HT (m)	INV DT (°C)	Lyr speed (m s^{-1})
March	31	0000	1651	3.3	11
		1200	716	3.2	11
April	1	0000	970	6.7	4
		1200	1120	5.6	19
	2	0000	1875	3.0	19
		1200	989	5.8	9
	3	0000	1120	6.0	3
		1200	830	4.2	4
	4	0000	770	4.2	4
		1200	859	4.2	8
	5	0000	982	3.8	3
		1200	544	5.8	—
	6	0000	762	7.4	8
		1200	703	5.6	5
	7	0000	836	4.7	3

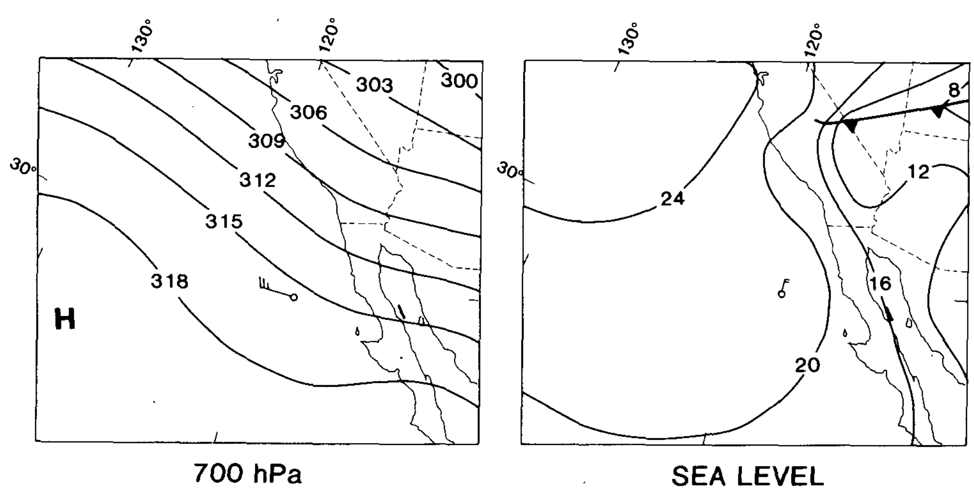

FIG. 5. Sea level and 700-hPa analysis for 0000 UTC 5 April 1982—coincident with cloud trail.

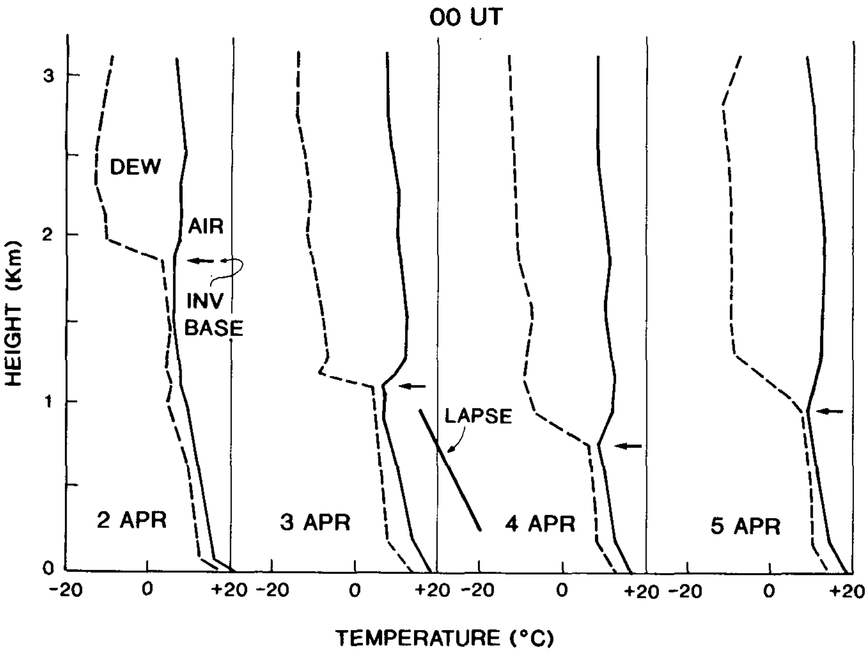

FIG. 6. Guadalupe soundings at 0000 UTC throughout event. Arrow marks the inversion base. The adiabatic lapse rate is shown.

shifted to more northwesterly, while the surface winds were mostly from the north after the frontal passage.

The winds measured at Guadalupe Island below 850 hPa for 0000 and 1200 UTC 4 April and 0000 UTC 5 April are presented in Table 2. The cloud trail must have occurred near the inversion base as there is too much turbulent mixing below and too little moisture above. Therefore, an average wind speed was taken of

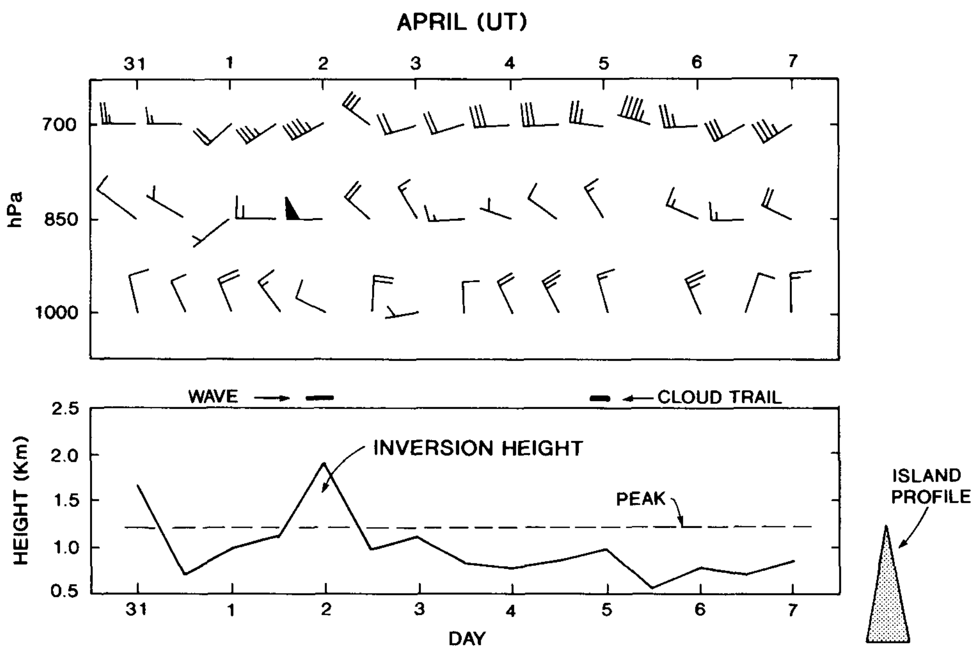

FIG. 7. Inversion-base height (lower frame): selected winds are shown. One barb is about 5 m s^{-1}, a half-barb is about 2.5 m s^{-1}, and a flag is about 25 m s^{-1} (upper frame). Most of the 700-hPa winds are from the west. Days are plotted on the top.

TABLE 2. Guadalupe Island sounding winds below 850 hPa. Asterisk denotes air temperature inversion base.

Height (m)	Pressure (hPa)	T_{air} (°C)	Wind direction (°)	Wind speed (m s^{-1})
0000 UTC 4 April				
1538	850	10.2	290	3
1164	889	12.4	304	3
1061	900	11.8	303	4
969	910	11.4	305	4
770	932	9.2	314	4*
611	950	10.1	322	10
182	1000	12.5	336	21
23	1019	16.0	360	17
1200 UTC 4 April				
1536	850	10.6	305	6
1060	900	11.1	320	6
986	980	11.1	322	7
859	922	6.9	327	7*
611	950	9.5	326	9
524	960	10.4	325	9
182	1000	13.0	335	12
23	1019	14.4	360	10
0000 UTC 5 April				
1541	850	12.2	328	7
1318	873	11.6	340	6
1064	900	9.3	360	3
982	909	8.6	004	3*
614	950	11.3	349	4
183	1000	14.3	346	8
23	1019	17.4	360	10

the three reported winds about the inversion base and will be used in the following to characterize the mean advection speed. Of this period, the fastest was 8 m s^{-1} at 1200 UTC 4 April, but the average of the last two soundings was 6 m s^{-1}.

We wish to see if simple advection by the mean wind near the base of the inversion could account for the cloud trail on 4 April. The lengths of cloud trailing Guadalupe at 1915, 2045, 2245, and 2315 UTC are listed in Table 3. The average speed of advection (assuming it started at the island at 1915 UTC) and the change of the cloud and position since the last photo were computed. Simple advection from the island would require mean speeds of 12 m s^{-1} at 2245 UTC and 14 m s^{-1} at 2315 UTC which is 50%–88% greater than the fastest speed of 8 m s^{-1} in the layer about the inversion, and a factor of 2 greater than the more likely

TABLE 3. Cloud trail characteristics for the 4 April event.

Time (UTC)	Type	Cloud length (km)	Advection from island (m s^{-1})	Advection from last (m s^{-1})
1915	Visible	<20	—	—
2045	Infrared	50	9	>6
2245	Infrared	150	12	14
2315	Visible	200	14	28

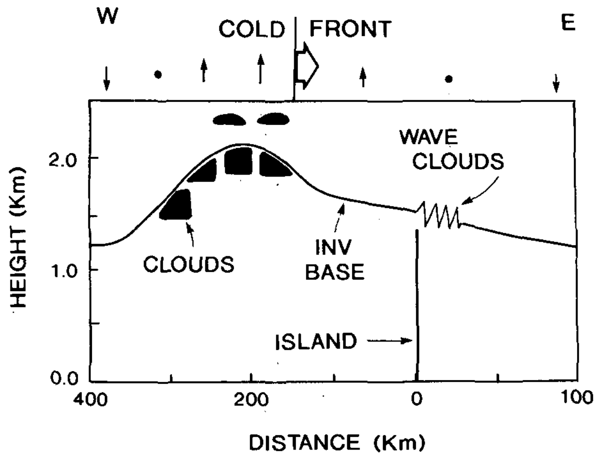

FIG. 8. Schematic of west–east section of inversion through Guadalupe at 1915 UTC 1 April. Front approaching from northwest is lifting and weakening the inversion. Ship wave clouds extend to the east of the top of the island, which is a little below the inversion base.

mean speed of 6 m s^{-1}. Even a bigger mismatch results between the observed winds and the change in trailing edge position between 2245 and 2315 UTC, which is 28 m s^{-1}. Simple advection does not explain the development of the cloud trail downwind of Guadalupe Island on 4 April.

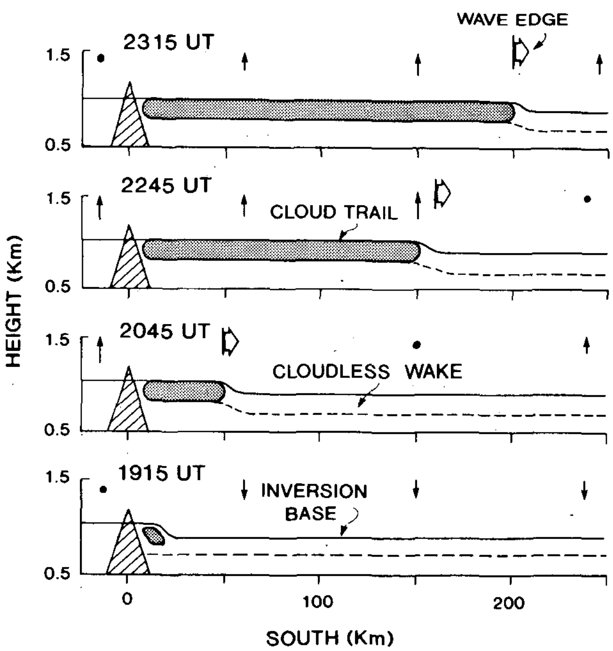

FIG. 9. Meridional schematic of inversion, wake, and cloud trail about Guadalupe Island. The cloudless wake is dashed. The cloud trail is solid. Vertical arrows represent relative changes in synoptic-scale subsidence. The leading edge of a weak convergence zone moving south is marked by the double arrow.

4. A model

The ship waves and cold front emphasize the relation between the upper-level conditions and the inversion base height. Shown in Fig. 8 is a schematic of an east–west section about Guadalupe Island at 1915 UTC 1 April. The cold front axis approached from the west, lifting the inversion to its maximum height near 1900 m. To the east of the front, the inversion was being lifted by the prefrontal zone of lesser convergence. At this moment, the inversion was estimated to be 200 m higher than the highest island peak and the first four crests of the ship waves were present. When the cold front moved farther to the southeast past Guadalupe, the ship wave extended farther eastward.

Turning to the cloud trail of 4 April, we have shown that simple advection cannot account for the cloud trail, so we propose a different mechanism. As noted earlier, when the marine layer is about two-thirds of the island height, then neither pure von Kármán vortices nor pure Kelvin ship waves are expected. The nature of the marine layer may be characterized by the Froude number, $\mathrm{Fr} = v(gh[D\theta/\theta])^{1/2}$, where v is the mean velocity of the marine layer, g is the gravitational acceleration, h is the depth of the marine layer, θ is the potential temperature of the lower layer, and $D\theta$ is the potential temperature change between the base and the top of the inversion (Winant et al. 1988). At Guadalupe Island, Fr was 0.6 at 1200 UTC 3 April and 1.0 for 0000 UTC 4 April through 0000 UTC 5 April. However, these were measured in the disturbed lee of the island. When the sounding balloon penetrated the top of the marine layer, it was no more than 2–3 km downwind of the launch site on the southern tip of the island.

The limited evidence encourages one to believe that the upwind Froude number was in the range between 0.4 and less than 1.0. If the windward Froude number were greater than 1.0, there would have been an expansion fan in the lee with a Froude number greater than 1.0 (Winant et al. 1988). If the windward Froude number were less than 0.4, then the winds would be much too slow to be consistent with the winds in the synoptic conditions observed at that time of year and there would be a substantial reversal of flow in the lee, which does not seem to have occurred. On the other hand, if the upwind Froude number is in the range of 0.4 but less than 1.0, then there will be a hydraulic jump in the lee of an isolated hill (Hunt and Snyder 1980; Smolarkiewicz and Rotunno 1989). Within the hydraulic jump, the Froude number will be 1.0, the average flow will be in the same direction as the upwind, and there will be turbulent mixing.

If the inbound flow were between 0.4 and less than 1.0, then there would be turbulent mixing of the lower-level air upward in the jump, forming air with higher humidity at the top than that in the surrounding air. An air parcel in the marine layer in the lee of Guadalupe Island on 4 April lifted only 300 m would become saturated. Any jump that either lifted marine air a lesser distance or mixed marine air with some dryer air above would increase the humidity in the upper portion of the jump without forming a cloud. Thus, a jump in the lee could have formed a cloudless wake that had higher humidity at the top than the surrounding air.

A wake is defined as a trail extending behind the island with different structure than the surrounding marine layer. What prevents a wake from merging quickly into the surrounding medium is not clear. However, they have been measured. An island cloudless wake in near-surface temperature and winds was measured 10 km to the lee of a small island 130 m high and 4 km across in the Gulf of California (Badan-Dangon et al. 1991). In that case, there was a marine layer capped by a weak temperature inversion based at 300-m elevation. Another factor to consider is that over the eastern Pacific marine layer the wind speeds are often weakest in the base of the inversion (Neiburger et al. 1961; Brost et al. 1982; Beardsley et al. 1987), as it appears to be near Guadalupe, although the vertical details are poorly resolved. The turbulence and diffusion rates should be minimal at this level, and therefore, the zone where the top of a wake should be subjected to the least turbulent energy to break down the wake and allow the longest duration.

It is proposed that turbulent mixing and lifting occurred in the lee, forming a cloudless, linear wake wedged into the base of the inversion. The wake humidity was greater than the surrounding air at the same level and much greater than the air at lower levels. If later there were modest lifting of the inversion by synoptic-scale changes, the linear wake would condense first, forming a cloud before the surrounding marine layer. Further, a continuously generated cloudless wake advected at 6 m s^{-1} for 24 h beginning at 0000 UTC 4 April would be a factor of 2 longer than the cloud trail of 4 April.

We hypothesize that a cloudless linear wake developed behind Guadalupe Island and extended southward beginning on 3 April when the inversion base was below the peak. Any tendency for a cloud to form in the wake was suppressed by the synoptic-scale subsidence and the general shallowing of the marine layer to 770 m at 0000 UTC 4 April. After this, the subsidence was relaxed so that the marine layer lifted weakly for the next 19 h, arriving at the structure shown in the lower frame of Fig. 9. We next postulate that a very weak divergence aloft spread southward extending about 50 km south of Guadalupe at 2045 UTC 4 April. This divergence caused additional weak lifting of the marine layer, which was sufficient to cause condensation and cloud formation in the linear wake but not enough to cause cloud formation in the surrounding marine layer. If this divergence area spread south of 68 km h^{-1}, it would covert the wake to a cloud at the same rate, reaching 170 km south at 2245 UTC (when the cloud was 150 km long) and 200 km south at 2315 UTC (when the cloud was 200 km long).

Following a couple hundred kilometers behind the weak convergence was a return to more convergence aloft and a sinking inversion. This in turn passed south of Guadalupe in the evening, so that at 1200 UTC 5 April the inversion had been depressed to 544 m and the visible cloud trail had dissipated.

5. Conclusions and discussion

A long, linear cloud trail behind Guadalupe Island formed too rapidly to have advected downwind. It is hypothesized that mechanical disturbance of the wind field by the island created a linear, cloudless wake that was advected downwind. The top of the wake was near the base of the temperature inversion and had a higher humidity than the surrounding marine air. When weak synoptic-scale divergence caused weak lifting of the marine layer, a linear cloud trail formed. When the weak divergence aloft was replaced by synoptic-scale convergence, the cloud trail dissipated.

Once the cloudless wake was established, it was weak synoptic changes that caused the cloud to form. It is suggested that this applies to ship cloud trails that occur under very similar synoptic circumstances. Of course, ships probably form the wake by different processes than an island. However formed, very slight lifting by a transitory weak synoptic system could convert a wake to a cloud. Slight depression of the marine layer could cause a cloud trail to disappear.

A similar effect may occur during the summer over the northeastern side of the Pacific where the inversion base increases in elevation to the south on account of the large-scale, quasi-stationary, synoptic structure. Southward-bound winds would advect a ship's cloudless linear wake along a higher inversion base that could cause the initial cloud formation and help maintain the cloud by supplying continued condensation. Unfortunately, the detailed synoptic-scale measurements of the inversion base in areas where ship cloud trails are occurring are not available to test this.

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