Coastal Southerlies and Alongshore Surges of the West Coast of North America: Evidence of Mesoscale Topographically Trapped Response to Synoptic Forcing

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ABSTRACT

One of the most important warm season weather phenomena of the west coast of North America is the temporal transition from northerly to southerly flow within a few hundred kilometers offshore from the coastal mountains. Such wind shifts are often accompanied by cooler temperatures, higher pressure, and a change from nearly cloud-free to low overcast conditions. The more vigorous coastal transitions, termed alongshore surges, are characterized by an abrupt change in wind direction, a sudden increase in wind speed to 15 m s^{-1} or more, a precipitous temperature drop exceeding 10°C, and a sharp rise in sea-level pressure.

This paper presents two detailed case studies of topographically-trapped coastal southerlies: the strong surge event of 15–17 May 1985 and the far weaker case of 3–7 May 1982. It is shown that coastal southerlies and alongshore surges are controlled by the alongshore pressure gradients created by the synoptic scale flow. At low levels and within approximately one Rossby radius of the coastal topography, geostrophic balance with the alongshore pressure gradient is not possible so that air flows downgradient ageostrophically. Under the proper conditions, southerly flow in the coastal zone can propagate northward as a topographically trapped density current.

It is shown that similar phenomena occur near topographic barriers throughout the world.

1. Introduction

Within a few hundred kilometers of the west coast of North America there are often rapid temporal transitions in the lower troposphere characterized by a switch from northerly to southerly flow, a rise in pressure, a drop in temperature, and usually a change from nearly cloud-free to low overcast conditions. Most frequent from late spring through early fall, these mesoscale coastal southerlies are often evident in visible satellite imagery as coastal tongues of stratus, a few hundred kilometers wide. In the stronger cases, which we shall call alongshore or coastal surges, a period of less than an hour can bring a wind shift from moderate northerlies (0–10 m s^{-1}) to southerlies of 15 m s^{-1} or more, temperature falls exceeding 10°C, abrupt pressure rises, and a shift from sunny skies to stratus and fog.

A vigorous example of an alongshore surge occurred along the California and Pacific Northwest coasts (Fig. 1) on 16–17 May 1985. At Astoria, Oregon the arrival of the surge (or surge front) brought a rapid shift in wind direction from northeast to southwest, wind gusts exceeding 17 m s^{-1}, a sudden rise in station pressure, and a temperature fall of over 15°C in less than an hour (Fig. 2). Similar transitions occurred at coastal locations to the north and south. East of the coastal mountains or a few hundred kilometers offshore, there was little evidence of a significant event. The localized, coastal nature of this phenomenon is further high-

lighted by the case of 3 June 1986, in which the fishing vessel Rosan reported southeast winds of 15 m s^{-1}, gusting to 20 m s^{-1}, and heavy seas immediately off the southeast coast of Vancouver Island, while ~150 km to the southeast another ship observed light northeast winds and relatively calm seas.

Coastal southerlies, alongshore surges and coastal stratus tongues are observed frequently along the Pacific Coast from Baja California to British Columbia. The southerly flow associated with these phenomena represents a deviation from the northerlies or northwesterlies that usually dominate this coast during the warm months of the year. Figure 3 presents the mean distribution of sea level pressure for May through September, based on a twenty year composite of National Meteorological Center surface analyses. High pressure dominates the eastern Pacific and extends slightly inland over the Pacific Northwest. A "thermal" trough is found over the interior of Mexico and extends into the Central Valley of California. Between these two features there is a fairly large pressure gradient, which produces northerly flow along most of the coast from British Columbia to southern California. The largest pressure gradients and associated winds are usually observed in the coastal waters of northern California and southern Oregon.

Although important for marine and aviation interests, relatively little research has been done on the coastal southerlies and alongshore surges of the west
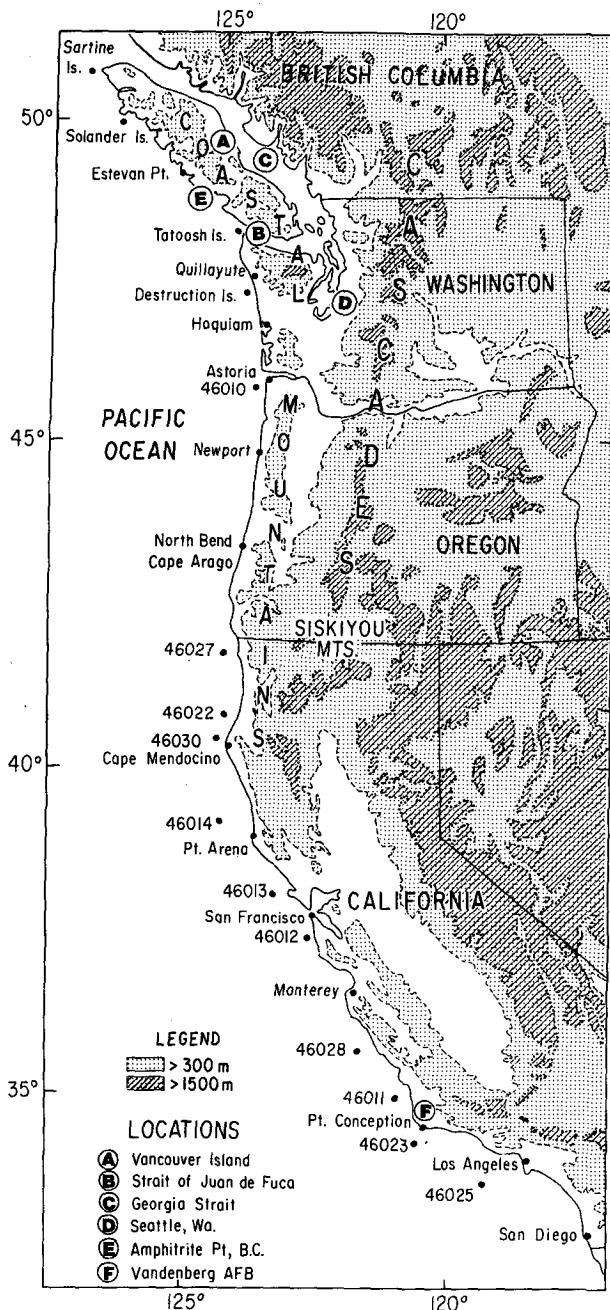
FIG. 1. Topography and important geographical locations along the west coast of North America from California to British Columbia.

coast of North America. Jackson (1983) noted that stratus tongues appear to follow the northward extension of the "heat troughs" of the western United States. Dorman (1985) examined the movement of coastal stratus and southerly winds off California during May 1982 and proposed the existence of topographically trapped Kelvin waves. Mass et al. (1986) observed that coastal southerlies are important components of the onshore movement of marine air into the Pacific Northwest.

The west coast of North America is a particularly advantageous region for studying topographically trapped phenomena in a coastal zone. Adjacent to the coast there is a two-tiered topographic barrier with the somewhat "leaky" coastal mountains to the west and the Cascade or Sierra Nevada Mountains further inland (Fig. 1). Over land there are a large number of surface and upper air stations while over water there are several (~15) buoys and a relatively large number of ship reports. Finally, during the warm season stratus and fog provide useful indicators of low-level winds and air trajectories.

This paper presents a detailed case study of the alongshore coastal surge of 15–17 May 1985 and critically examines the May 1982 event discussed by Dorman (1985). It is shown that coastal southerlies and alongshore surges appear to be manifestations of ageostrophic, downgradient flow forced by alongshore synoptic scale gradients; under the proper conditions the southerly flow can take on the properties of a topographically trapped gravity current. Similar phenomena in other parts of the world are also discussed.

2. The event of 15–17 May 1985

As illustrated in the Introduction, this case represents an example of a strong event with abrupt transitions in many basic meteorological parameters.

a. Synoptic description

Visible satellite imagery for the May 1985 event is displayed in Fig. 4. At 21 UTC 15 May, low clouds were observed in the southern part of the domain with a tongue of coastal stratus reaching just north of San Francisco. Nearly 24 hours later (19 UTC 16 May) the stratus tongue had widened and moved northward to southern Oregon. A spiral cloud mass associated with an upper level low was located over central Oregon. Later in the day (23 UTC 16 May) the upper low had drifted westward while a narrow tongue of stratus continued to move northward. The satellite pictures for the next day (15–23 UTC 17 May) indicate that the synoptic scale upper low maintained its westward movement, enhancing low clouds to the west but leaving a clear zone in its wake. During this period a narrow coastal tongue of stratus moved northward to Vancouver Island. Although some of this stratus spread around the northern tip of Vancouver Island, most continued out into the Pacific, and was swept southward to form an eddy-like structure. Figure 5 presents closeup views of the stratus tongue on 16 and 17 May.

The National Meteorological Center (NMC) synoptic charts for the event are shown in Figs. 6–8. At 500 mb (Fig. 6) the sequence begins (12 UTC 15 May) with a high amplitude ridge over the eastern Pacific and a closed low centered over northern Nevada. During the next two days the closed low slowly drifted
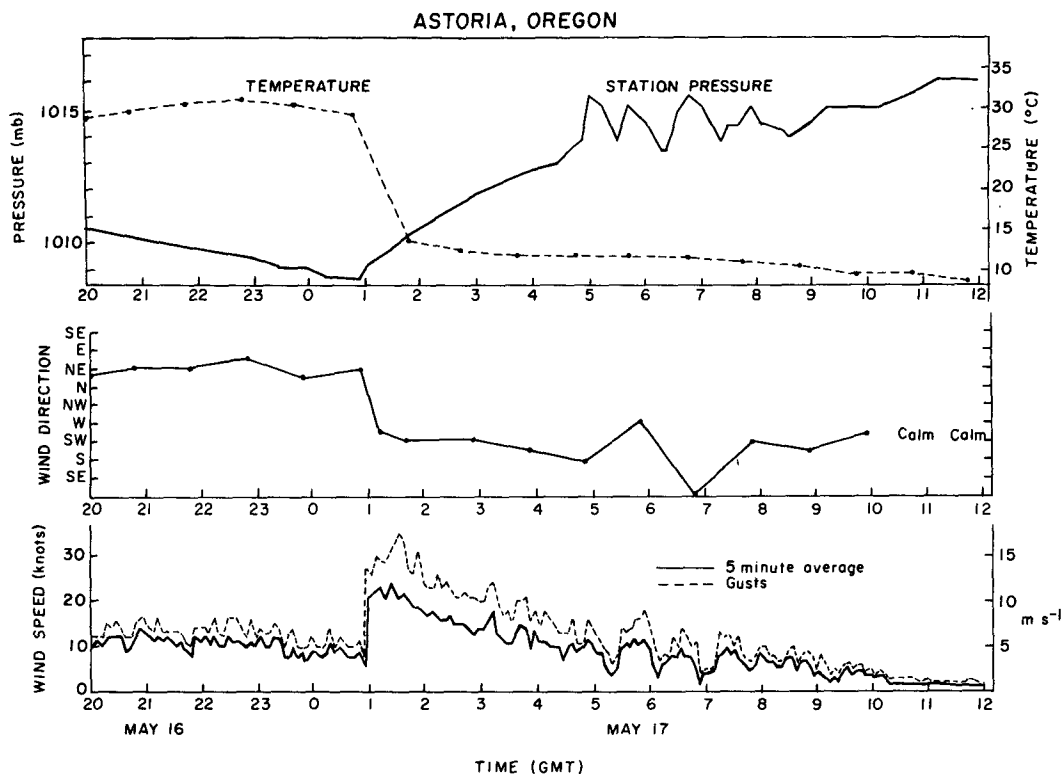
FIG. 2. Temperature, station pressure and winds at Astoria, Oregon from 20 UTC 16 May through 12 UTC 17 May 1985. Temperature and wind direction are based on hourly observations; station pressure and wind speed are from continuous recorders.

westward, eventually becoming an open trough that split the ridge. The initial 850 mb chart (12 UTC 15 May) indicates a closed high centered over British Columbia with a low center over southern California (Fig. 7). During the next 48 hours the high slid to the southeast while the low drifted to the west-northwest. Turning to the surface charts (Fig. 8) one notes that at 12 UTC 15 May high sea level pressure was centered over
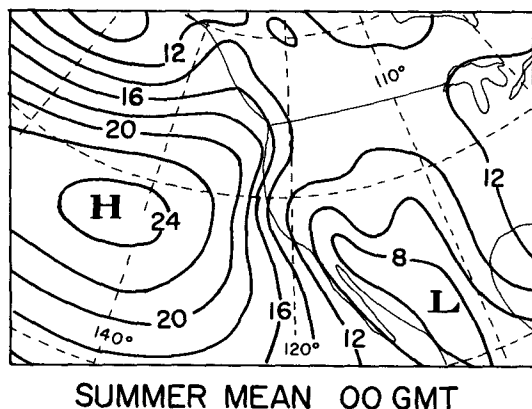

SUMMER MEAN 00 GMT

FIG. 3. Mean sea level pressure at 00 UTC for May through September over the eastern Pacific and western North America calculated from National Meteorological Center surface analyses. Isopleths are 10xx mb.

British Columbia and a trough extended northwestward from southeastern California to the coast. This trough is the superposition of the familiar California thermal trough and the westward-moving synoptic low. During the next two days the high drifted southeastward while a closed low moved westward from California into the Pacific. Also note the development of a narrow, coastal pressure ridge and the substantial increase in sea-level pressure off southern California.

b. Mesoscale description

Figure 9 presents mesoscale sea-level pressure analyses for the May 1985 event. These analyses make use of all available ship, buoy and land stations; the ship sea level pressures have been calibrated by comparison with intersecting ships, buoys and coastal stations. Also shown are the northern boundaries (heavy dashed lines) of the coastal stratus determined from GOES satellite imagery. At the initial time (12 UTC 15 May) high pressure dominated the northwest corner of the domain, a trough was positioned over central and coastal California, and a narrow, mesoscale coastal pressure ridge was evident just south of San Francisco. During the next 36 h (through 00 UTC 17 May) the synoptic component of the trough over California moved northwestward, while the mesoscale coastal pressure

23 GMT 16 MAY

23 GMT 17 MAY

19 GMT 16 MAY
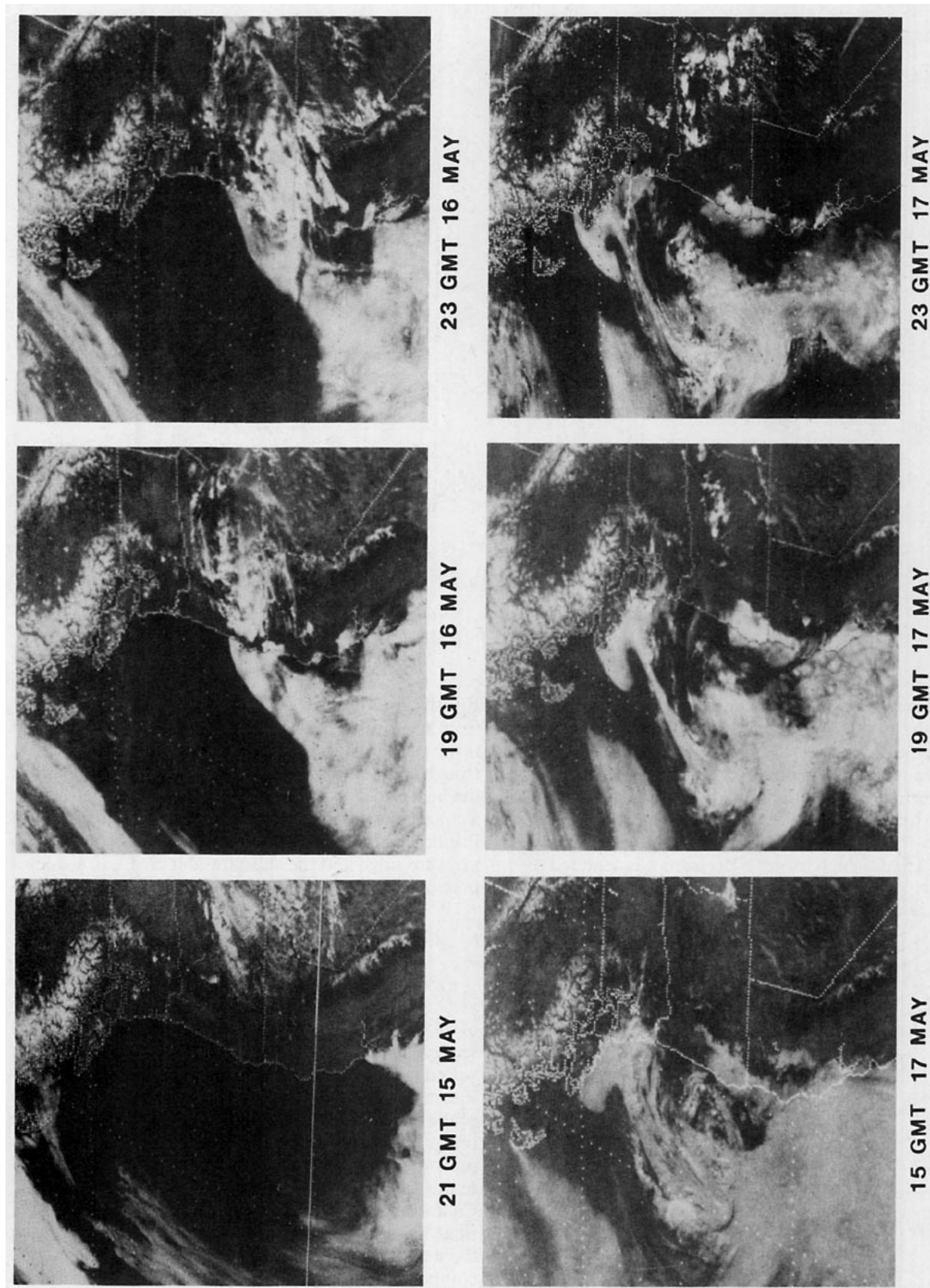
19 GMT 17 MAY

21 GMT 15 MAY

15 GMT 17 MAY

FIG. 4. GOES visible satellite imagery of the western United States and Canada for 21 UTC 15 May through 23 UTC 17 May 1985.
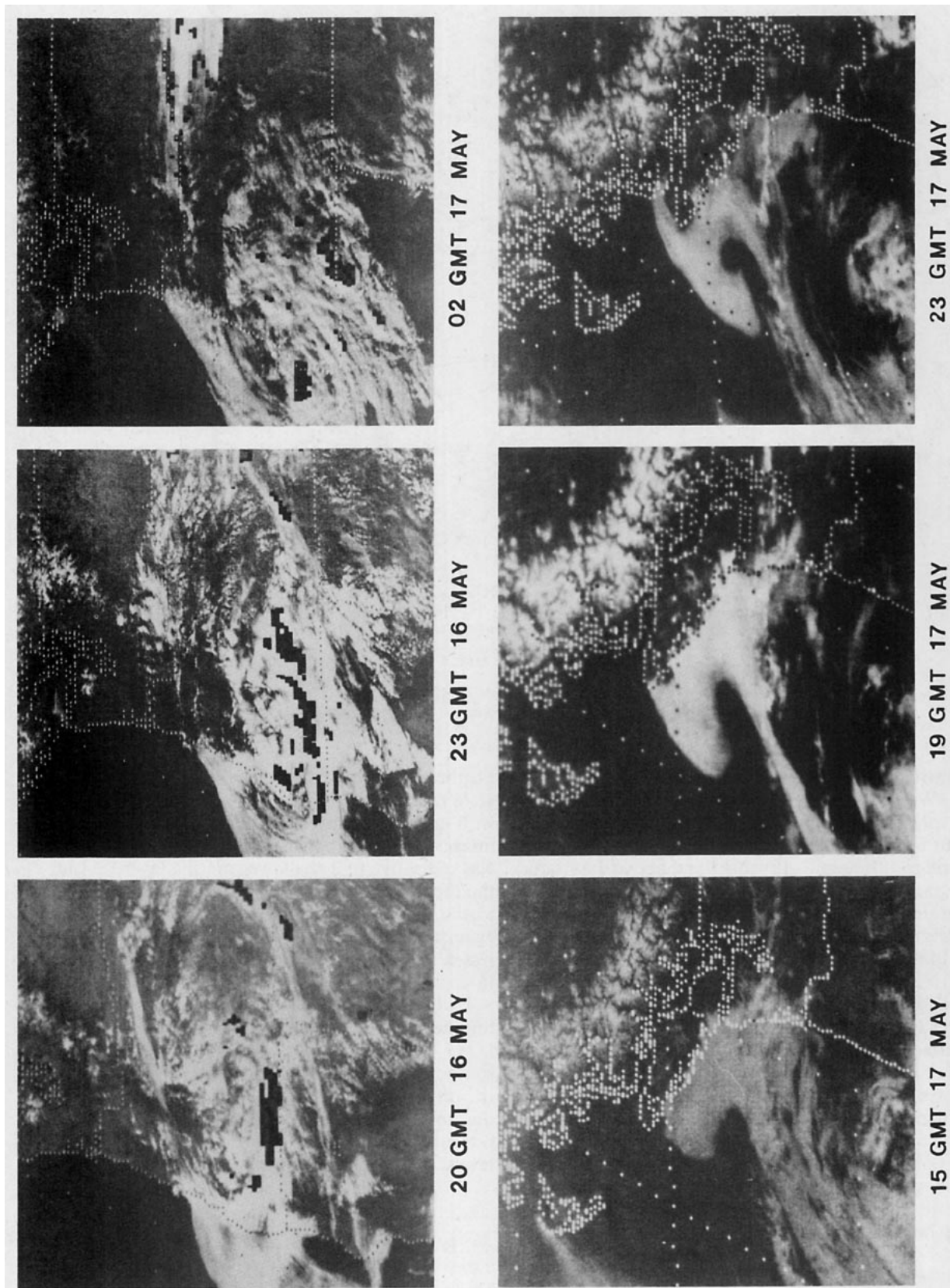
FIG. 5. Enlarged GOES visible satellite imagery of the area surrounding the May 1985 coastal surge. Infrared images of the cooler clouds are superposed on the first three pictures.
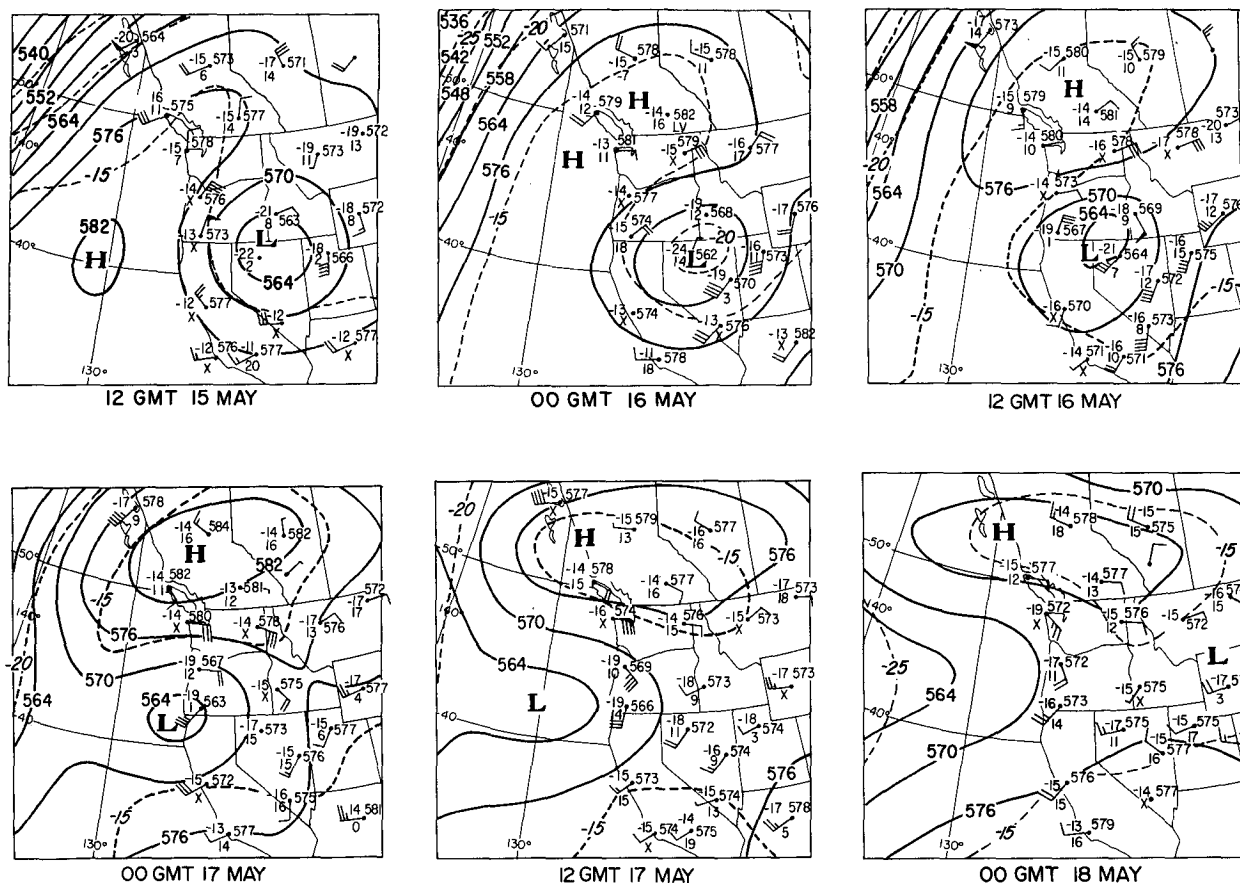
FIG. 6. National Meteorological Center (NMC) 500 mb charts for 12 UTC 15 May through 00 UTC 18 May 1985.
Geopotential heights (solid) are in decameters and isotherms (dashed) are in °C.

ridge strengthened and extended northward to the Oregon–Washington border. A coastal minimum in sea level pressure and the northern limit of the coastal stratus were located at the head of the mesoscale pressure ridge. It is noteworthy that the shape of the stratus boundary at 00 UTC 17 May suggests two scales of variation: a synoptic scale distortion (associated with the offshore synoptic low) and a narrow tongue adjacent to the coast. During the next day the coastal pressure ridge and its associated stratus tongue continued to move northward, reaching the northern tip of Vancouver Island by approximately 18 UTC 17 May.

Surface winds and sea level pressure fields near the head of the coastal pressure ridge are presented in Fig. 10 for several times during the May 1985 event. All five maps show southerlies south of the coastal pressure trough and northerlies or easterlies to the north. The winds also indicate large horizontal shear normal to the coast with southerlies near land and northerlies offshore. The 18 UTC 16 May surface chart was analyzed in greater detail to illustrate some interesting smaller scale structures. A mesoscale trough developed to the lee (north) of Cape Mendocino and was accompanied by a veering of the coastal winds to northwest.

Further north where the coast turns westward, a small-scale pressure ridge was observed, and was associated with enhanced stratus and fog on the visible satellite imagery (Figs. 4, 5). It appears likely that the troughing was indicative of a shallower marine layer leeward of the topography of Cape Mendocino while the ridging to the north occurred as the marine layer deepened against the blocking terrain. This effect appeared to lessen in time as the incoming marine layer increased in depth.

Isallobaric analyses of 6-hour pressure changes[1] during the May 1985 event are shown in Fig. 11. At 18 UTC 15 May there were moderate pressure rises in southern California and similarly sized pressure falls in western Oregon; these falls were at least partially due to troughing in the lee of the Cascades as high pressure building to the east forced offshore flow at low levels. After strong diurnal heating [00 UTC 16 May

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[1] The mean diurnal pressure variations have not been removed from these figures. For the West Coast the primary diurnal maximum and minimum in surface pressure occur at approximately 18 and 00 UTC, respectively.
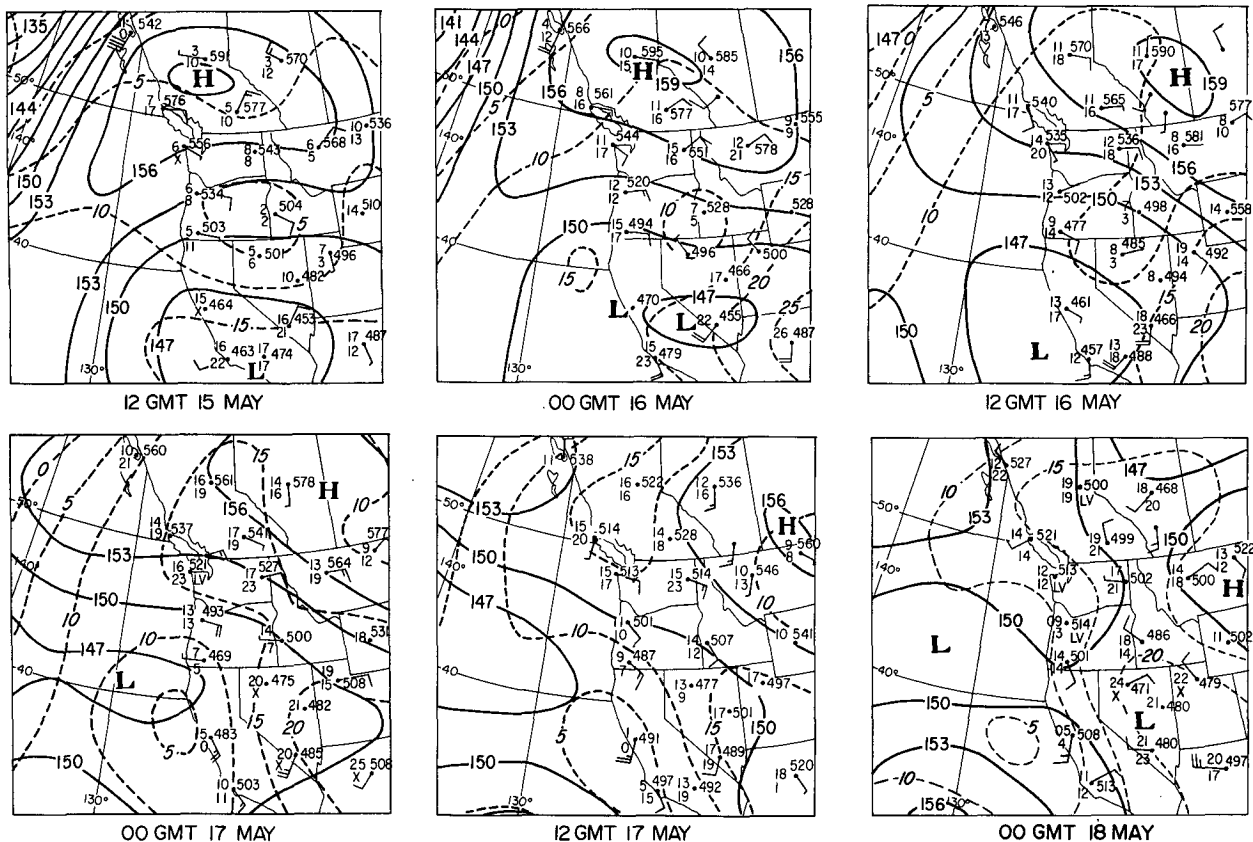
FIG. 7. The NMC 850 mb charts for 12 UTC 15 May through 00 UTC 18 May 1985. Geopotential heights (solid) are in decameters and isotherms (dashed) are in °C.
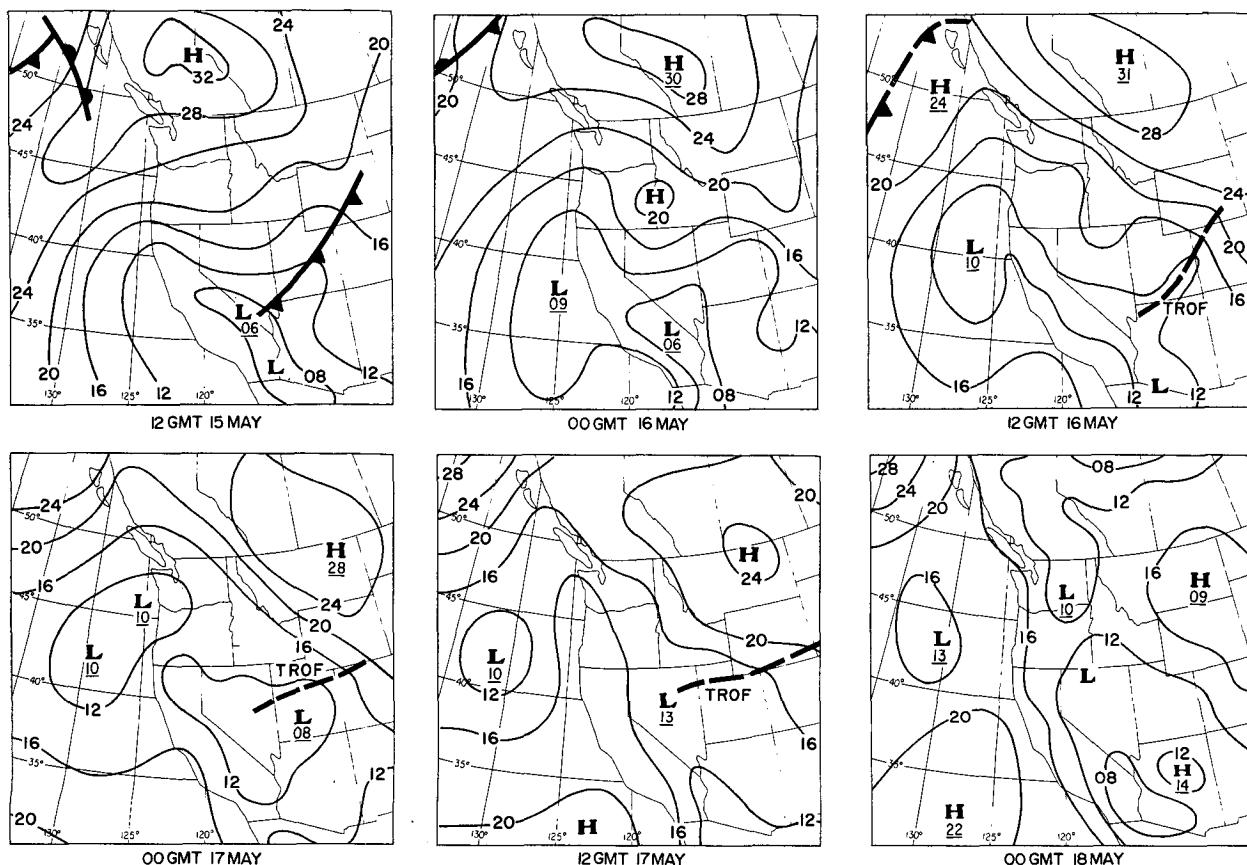

FIG. 8. The NMC surface charts for 12 UTC 15 May through 00 UTC 18 May 1985. Solid lines are sea level isobars (10xx mb).
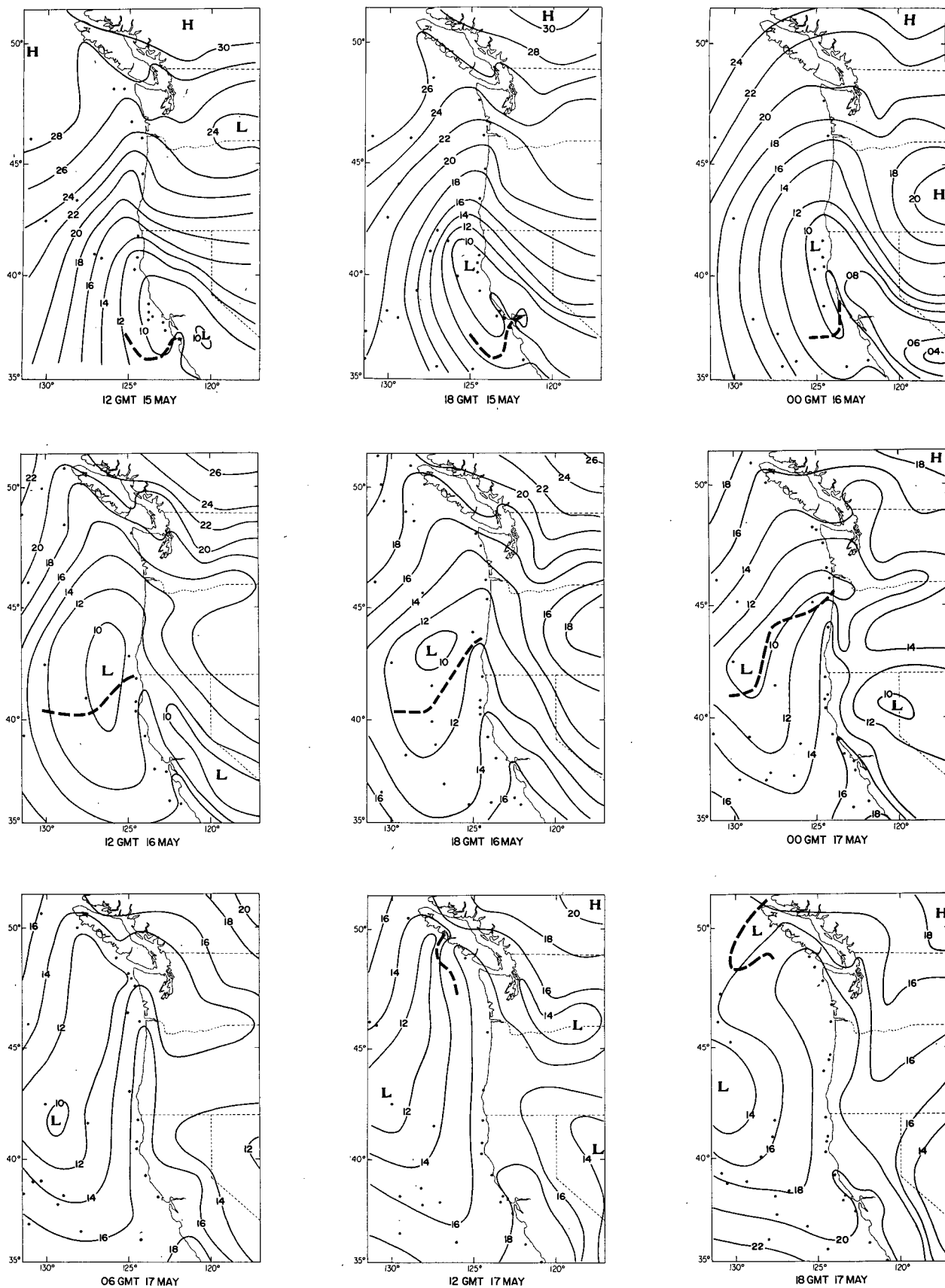
FIG. 9. Mesoscale sea level pressure analyses for 12 UTC 15 May through 18 UTC 17 May 1985. Heavy dashed lines are the northern boundaries of the coastal stratus, based on GOES satellite imagery. Isobars are 10xx mb. Observations over the Pacific Ocean are indicated by solid dots.
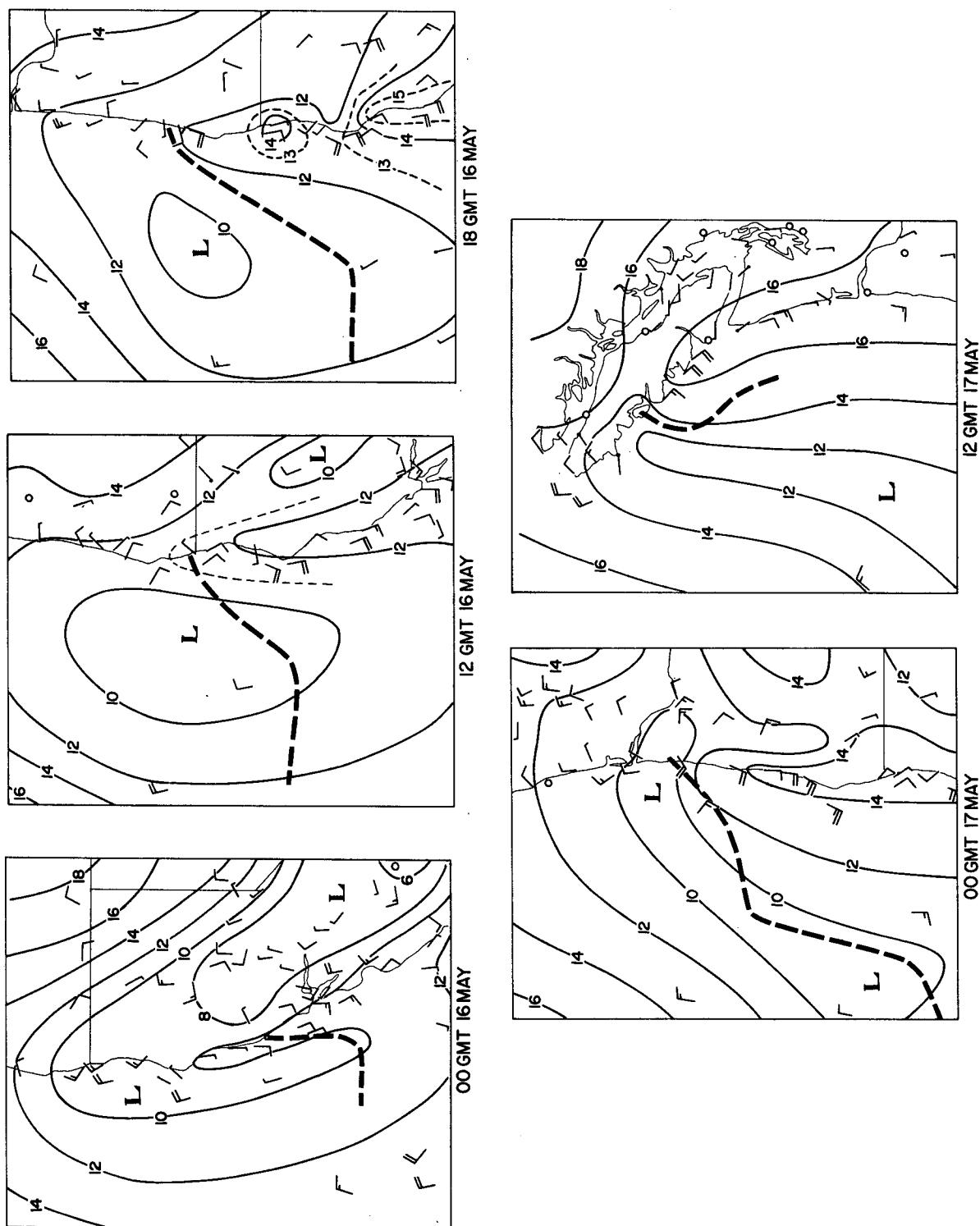
FIG. 10. Mesoscale sea level pressure analyses and surface winds in the immediate area surrounding the coastal surge for 12 UTC 15 May through 18 UTC 17 May 1985.
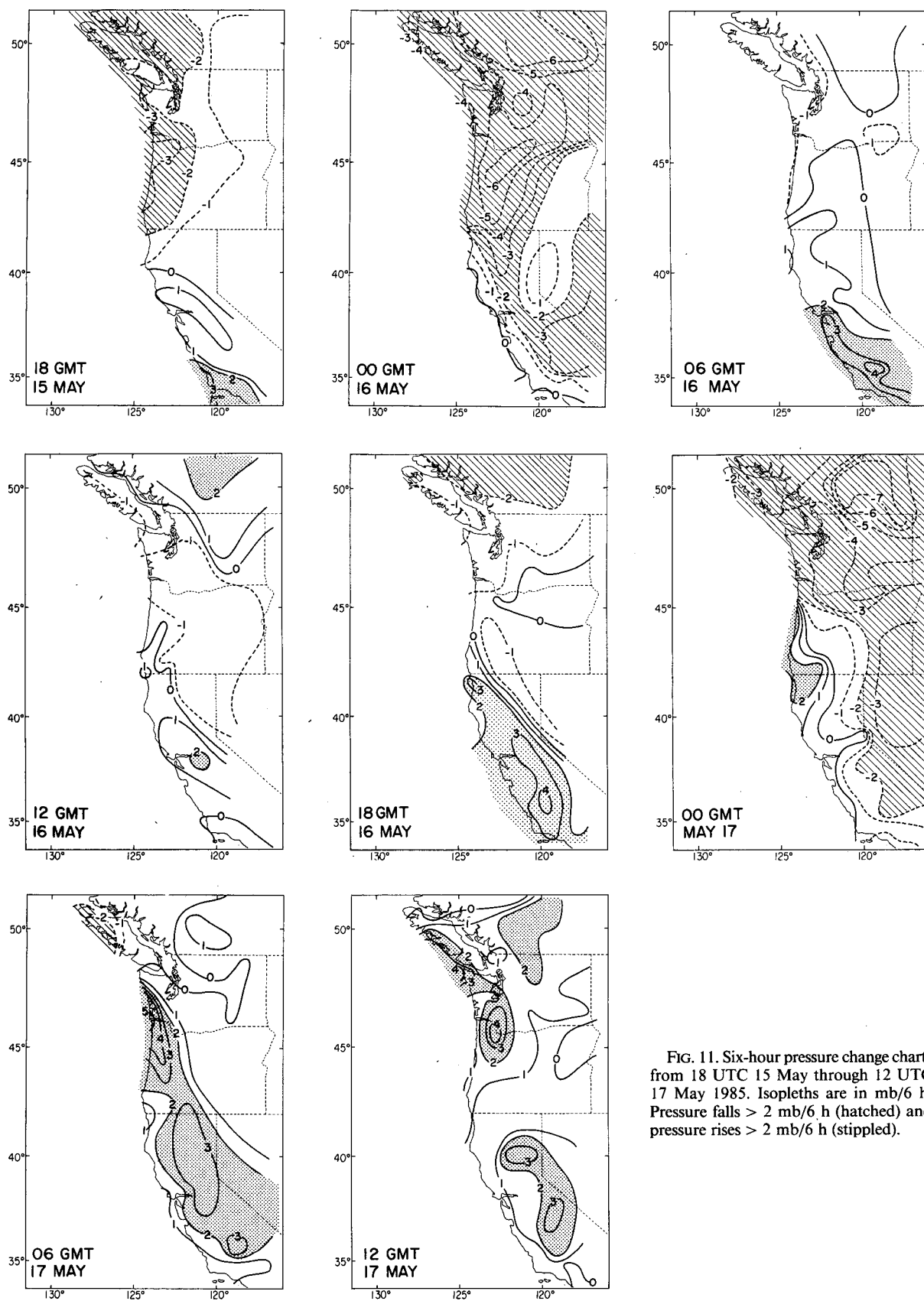
FIG. 11. Six-hour pressure change charts from 18 UTC 15 May through 12 UTC 17 May 1985. Isopleths are in mb/6 h. Pressure falls > 2 mb/6 h (hatched) and pressure rises > 2 mb/6 h (stippled).

(1600 LST)] large pressure falls were observed in western Oregon and Washington, as well as southern British Columbia. The pattern six hours later (06 UTC 16 May) is rather featureless except for large pressure rises in coastal California that occurred as the marine layer deepened and cool ocean air moved inland. At 12 UTC 16 May the pressure changes were relatively small with rising pressure in the Central Valley of California due to the continued influx of cool, marine air. Six hours later (18 UTC 16 May) large pressure rises were observed within the interior of California as well as along the northern California coast. To the north over Oregon, Washington and British Columbia pressure generally continued to fall. At 00 UTC 17 May the isallobaric signature of the coastal surge is clearly evident, with large pressure rises occurring along a narrow coastal strip; at the same time pressure was falling rapidly in the interior to the north and east. The surge-related pressure rises continued to propagate northward along the coast during the next six hours (06 UTC 17 May) and pressure increased in California's interior as marine air continued to pour inland through the gap in the coastal mountains surrounding San Francisco Bay. At 12 UTC 17 May the large pressure rises reached the coast of Vancouver Island; a substantial increase in pressure was also observed in the Willamette Valley of Oregon and the adjacent interior of western Washington as cool marine air broke through the coastal range and was deflected northward by the Cascade Mountains.

Figure 12 presents the hourly time evolution of sea level pressure at a series of coastal stations and buoys from central California to the nothern tip of Vancouver Island. For the central California locations (Buoys 46012 and 46013, Pt. Arena), sea level pressure fell until approximately 12 UTC 15 May and then slowly rose during the next two days. At Buoy 46027 near the Oregon–California border the pressure minimum occurred at 01 UTC 16 May and was followed by two relatively sharp pressure rises—one immediately after the pressure minimum and another starting at about 12 UTC 16 May. At Newport, Oregon there was a well defined pressure trough followed by a sharp jump in pressure. This feature, which was associated with the energetic alongshore coastal surge, moved northward past the remaining stations. North of Destruction Island, on the Washington coast, the amplitude of the trough and subsequent pressure rise appeared to diminish.

At several of the stations in Fig. 12 wavelike pressure undulations were observed several hours after the large pressure rise associated with the coastal surge. These features are more clearly evident in the microbarograph traces shown in Fig. 13. For example, at North Bend, Oregon (near Cape Arago) there is a moderate pressure rise around 20 UTC 16 May, followed four to five hours later by several wave-like pressure features. A similar pattern is noted at Newport, one hundred km to the
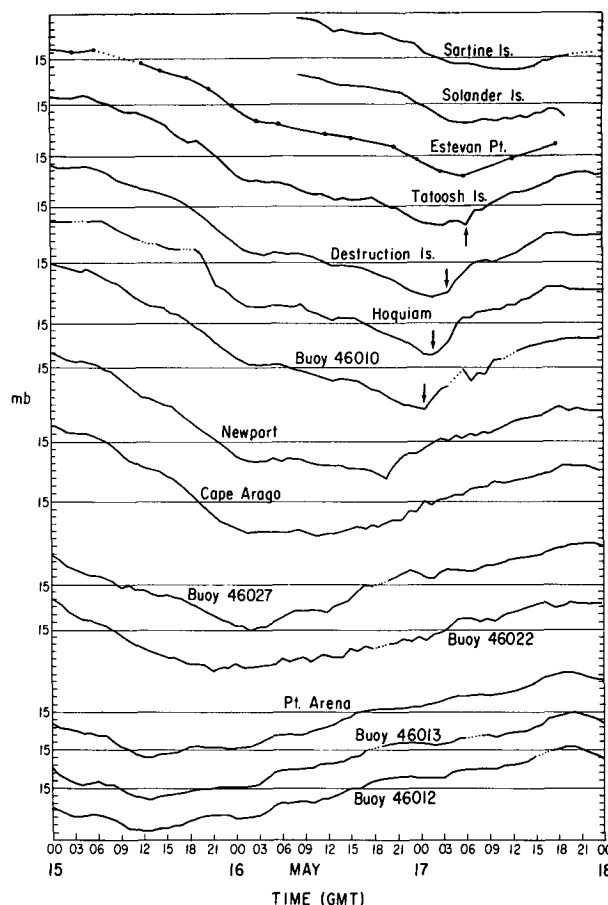

FIG. 12. Evolution of sea level pressure for a collection of coastal stations from central California to British Columbia for 00 UTC 15 May through 00 UTC 18 May based on hourly observations. Large solid dots indicate three hourly observations while dotted lines indicate periods in which an observation is missing. The vertical arrows indicate times of surge passage. Each pressure plot is relative to one of the horizontal 1015 mb lines. The tick marks indicate 1 mb intervals. The spacing of the traces is proportional to the distance along the coast between the observing sites.

north. The pressure rise at Astoria, Oregon (01 UTC 17 May) was particularly abrupt and the subsequent wavelike pressure perturbations were large. Wavelike variations were also apparent in the Astoria winds, as shown in Fig. 2. At Hoquiam and Quillayute on the Washington coast, wavelike pressure perturbations were noticeable but greatly attenuated. In the discussion section that follows it is suggested that these wavelike features are evidence of gravity waves propagating on the interface between cool marine air at low levels and warm subsiding air above.

Figure 14 shows the alongshore variation of sea level pressure from southern California to northern Vancouver Island during the May 1985 event. At 12 UTC 15 May the coastal pressure was relatively constant in southern California but increased substantially to the north. During the next 24 h (through 12 UTC 16 May)
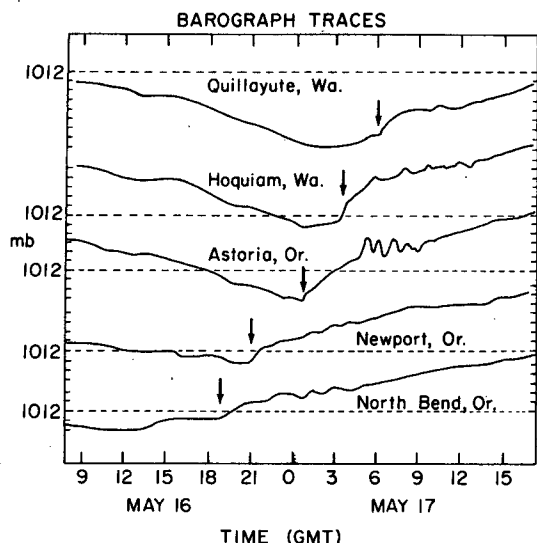
BAROGRAPH TRACES

FIG. 13. Microbarograph traces at North Bend, Newport, and Astoria, OR, and Hoquiam and Quillayute, WA from 08 UTC 16 May through 18 UTC 17 May 1985. The vertical arrows indicate times of surge passage. The dashed horizontal axes represent 1012 mb and the tick marks indicate 1 mb intervals.

this large alongshore pressure difference diminished because of weakening high pressure over the Pacific Northwest and rising pressure over the central California coast. The coastal pressure minimum also shifted northward from near Buoy 46013, along the central California coast, to Buoy 46027, near the California–Oregon border. The next 12 h (through 00 UTC 17 May) brought substantial sea level pressure gains along the northern California and southern Oregon coasts, with a particularly dramatic increase at Buoy 46027. These rises, coupled with pressure falls to the north, created a large alongshore pressure gradient along the Oregon coast, with higher pressure to the south. During the next half day (through 12 UTC 17 May) the region of strong coastal pressure gradient moved northward to Vancouver Island, leaving in its wake nearly uniform sea level pressure from central California to British Columbia. This pattern remained essentially unchanged through 00 UTC 18 May with the gradient along Vancouver Island increasing in time as pressure rose uniformly to the south.

The time evolution of both alongshore and cross-shore surface wind components for a series of coastal locations is shown in Fig. 15. In constructing this figure the alongshore direction was defined by a subjectively determined tangent to the coastline over a distance of ~50 km. Consider first the alongshore wind component. At the central California locations (Buoy 46012 and Pt. Arena) there was a switch from northerlies to southerlies around 12 UTC 15 May, which was close to the time of trough passage. This shift to southerlies was maintained for the remainder of the period. At Buoy 46027, near the California–Oregon border, the

evolution was significantly different. Here the period began with a strong northerly alongshore component (~ 17 m s^{-1}), which weakened to ~ 8 m s^{-1} at around 12 UTC 15 May and then shifted to southerly at approximately 03 UTC 16 May. A significant but brief increase in the southerly component was observed between 12 and 15 UTC that day (16 May). At the next station northward—Cape Arago, on the southern Oregon coast—the signature of the coastal surge is unmistakable. After more than 12 hours of minimal alongshore component, at ~ 15 UTC 16 May a southerly alongshore component increased suddenly to almost 15 m s^{-1} and maintained this speed for nearly 9 hours. This energetic signal then propagated northward past Newport, Buoy 46010 and Destruction Island. Figure 15 provides strong evidence that the alongshore surge continued up the coast of Vancouver Island (Amphitrite Point through Sartine Island).

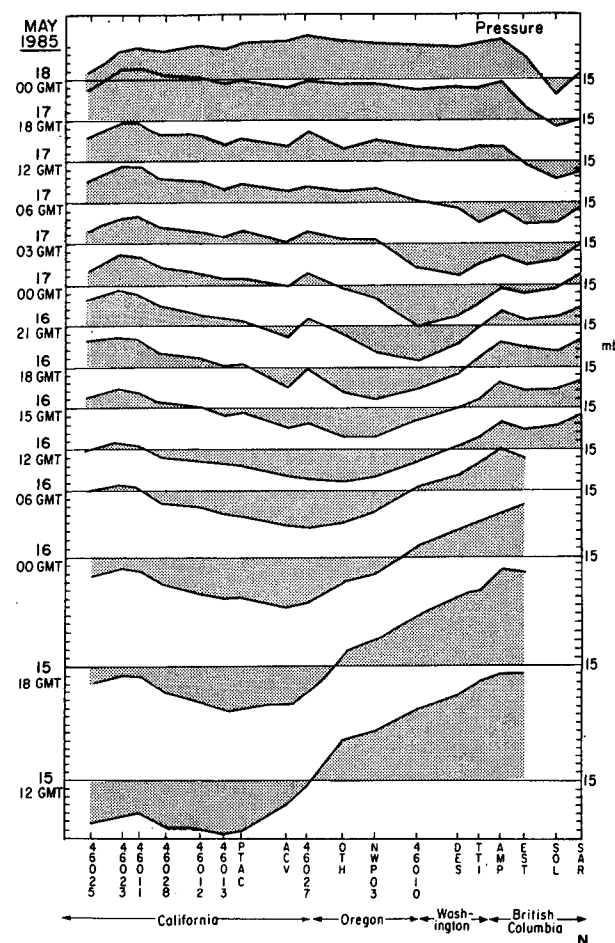In contrast to the alongshore component, the vari-

FIG. 14. Alongshore variation of sea level pressure from central California to northern Vancouver Island for several times between 12 UTC 15 May and 00 UTC 18 May. Shaded areas denote deviations from 1015 mb; this pressure is indicated by the horizontal lines. The tick marks denote 1 mb intervals.
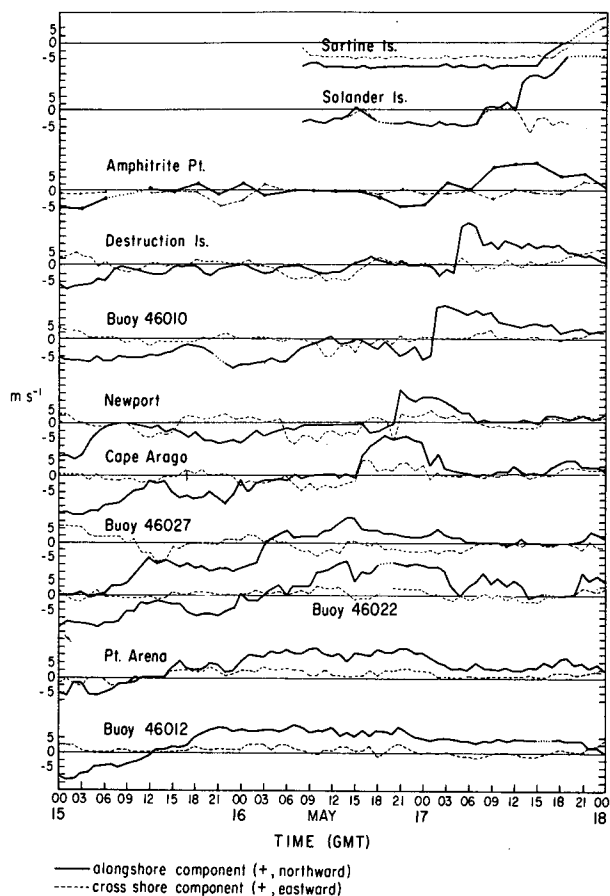
FIG. 15. Time evolution based on hourly observations of the alongshore and cross shore surface wind components for a series of coastal stations. Solid dots indicate three hourly observations and dotted lines indicate missing data. Tick marks represent 5 kt (2.5 m s⁻¹) intervals. The station spacing is approximately proportional to the distance along the coast.

ations of the cross-shore (normal to the local coastline) wind component were relatively small with amplitudes generally remaining below 5 m s⁻¹. Much of that variation can be explained by diurnal circulations.

c. Propagation characteristics

It is important to note that at some locations along the coast there were actually two transitions as northerlies gave way to strong southerlies. These locations first experienced a relatively gradual shift from northerlies to weak southerlies, and then hours later there was a separate surge of appreciably stronger southerlies, usually accompanied by stratus. Figure 16 presents the position of the transition from northerlies to southerlies as a function of time. In southern and central California from Pt. Conception (Buoy 46023) to Pt. Arena, the southerly transition occurred nearly *simultaneously* around 15 UTC 15 May, and then slowly inched up the coast during the next 12 hours. With nightfall (03–06 UTC) the transition seemed to jump northward. Finally, for the remainder of the event the southerly transition moved northward at a slowly accelerating pace.

d. Case discussion

On 15 May 1985 a synoptic low moved southwestward across the western United States and, as shown in a series of north–south 850 mb cross sections (Fig. 17), produced substantial 850 mb height falls over California by 12 UTC 15 May. As the low shifted northwestward during the next 12 hours (through 00 UTC 16 May), accompanying height rises over southern California created an 850 mb height gradient from San Diego to the San Francisco Bay area (Oakland), with higher heights to the south.
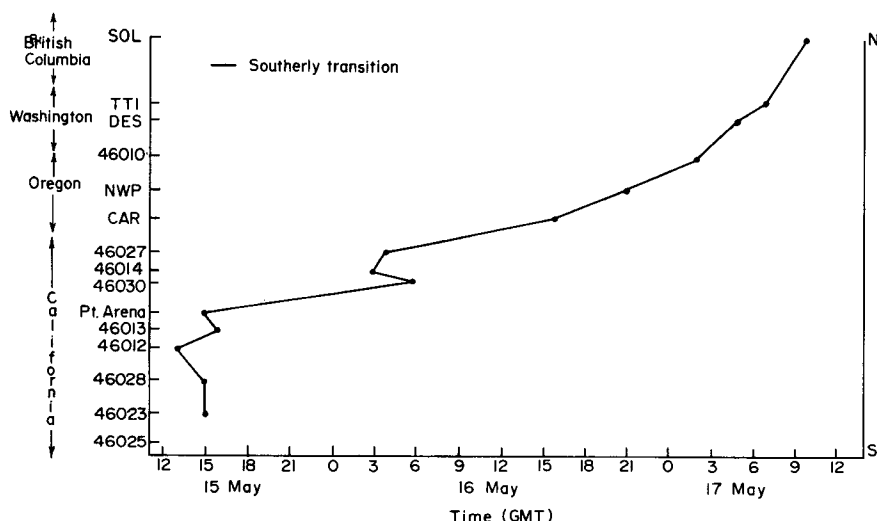

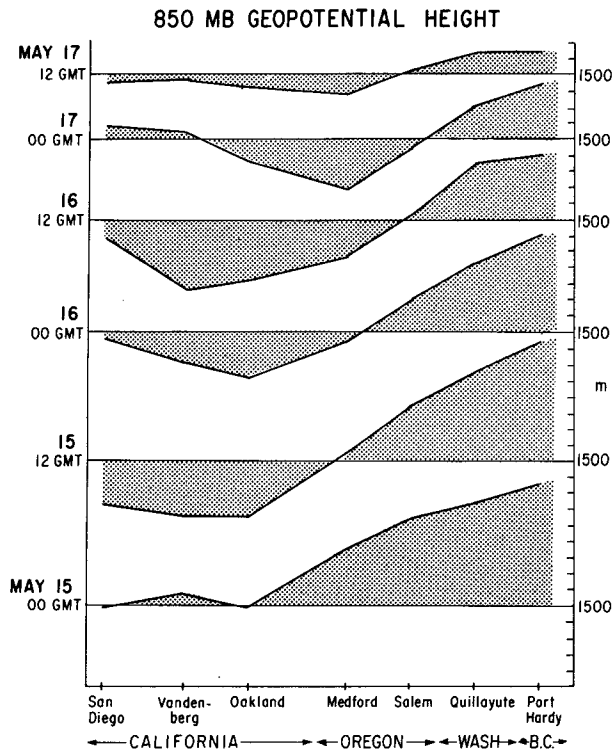FIG. 16. Positions of the southerly transitions as a function of time.

850 MB GEOPOTENTIAL HEIGHT

FIG. 17. Alongshore (north–south) 850 mb geopotential height variation from 12 UTC 15 May through 12 UTC 17 May 1985. Tick marks indicate 10 m intervals.

Over southern California the movement of the synoptic low on 15 May caused a switch to southerlies in the lower troposphere and an increase in the depth of the marine layer. For example, vertical soundings at San Diego (Fig. 18) suggest significant cooling below 950 mb between 00 UTC 15 May and 00 UTC 16 May, with the base of the low level inversion, separating marine air from the subsiding air aloft, rising from ~350 m to ~700 m. This low-level cooling continued through 12 UTC 16 May.

The origin of the low-level cooling and the deepened marine layer in the coastal zone can be explained by changes on the synoptic scale. Prior to the event the lower tropospheric flow over California was generally northerly or northeasterly and was subsiding around the eastern side of the Pacific High. In the coastal zone much of the subsiding air was of continental origin and had descended the sloping terrain to the east. As a result, the lower troposphere in the coastal zone was characterized by a shallow, well-mixed marine layer capped by warm subsiding air above. This situation was greatly altered by 00 UTC 16 May as the westward moving low caused winds to shift ~180° to the south or southwest offshore of southern California, bringing a change from warm, subsided air to sharply cooler, unsubsided air with an overwater trajectory. Finally, damming of cool, marine air on the windward slopes

of the coastal mountains could have occurred, either as a result of an onshore component of the synoptic flow or the eastward torque of the Coriolis force.

With heights rising at 850 mb and the marine layer cooling and deepening, sea level pressure rose sharply over southern California and the adjacent Pacific by 18 UTC 15 May (see Figs. 8, 10). Furthermore, pressure was falling over the Pacific Northwest as a synoptic high passed to the north and east. This high established lower tropospheric easterly flow, that brought additional, subsidence-induced pressure falls on the western (lee) side of topographic barriers such as the Cascade Mountains. With pressure rising to the south and falling to the north, a pressure gradient with higher pressure to the south was established between 12 UTC 15 May and 00 UTC 16 May from southern California to north of San Francisco (Fig. 14). This gradient had an immediate effect on the coastal wind field.

From 00 UTC 15 May through 00 UTC 16 May the winds of southern California and a large region of the adjacent Pacific turned from northerly to southerly or southwesterly throughout much of the lower troposphere as a result of the westward movement of the synoptic scale low. At the same time the surface winds shifted to southerly along the central and northern California coasts, but this change was limited to a zone within ~150 km of the coastal mountains (Figs. 10, 15). As shown in Fig. 16 the switch to southerlies at the surface was nearly simultaneous over much of the California coast at ~15 UTC 15 May, and does not indicate a propagating phenomenon. We suggest that this narrow tongue of southerly flow occurred within approximately a Rossby radius of the coastal mountains because geostrophic balance with the alongshore pressure gradient was impeded by the topography (see Overland, 1984), resulting in low-level downgradient flow towards lower pressure.

The Rossby radius can be calculated in several ways. If one assumes a two layer system (in this case a cool marine layer separated from warm subsiding air above by a strong inversion) the Rossby radius (R) can be defined as

$$R = \frac{\sqrt{g'H}}{f}, \quad g' = g\frac{\Delta\theta}{\overline{\theta}} \qquad (1)$$

where H is the depth of the marine layer, g is the gravitational acceleration, f is the Coriolis parameter, $\Delta\theta$ is the potential temperature jump across the inversion and $\overline{\theta}$ is the potential temperature of the lower layer. If a two fluid geometry is not appropriate, a Rossby radius based on continuous stratification (R_c) can be defined (Overland, 1986):

$$R_c = ND/f \qquad (2)$$

where N is the Brunt–Väisälä frequency and D is the height of the topographic barrier. For the May 1985 case Eq. 1 is probably more appropriate; applying this equation to the Vandenberg soundings at 00 UTC 15
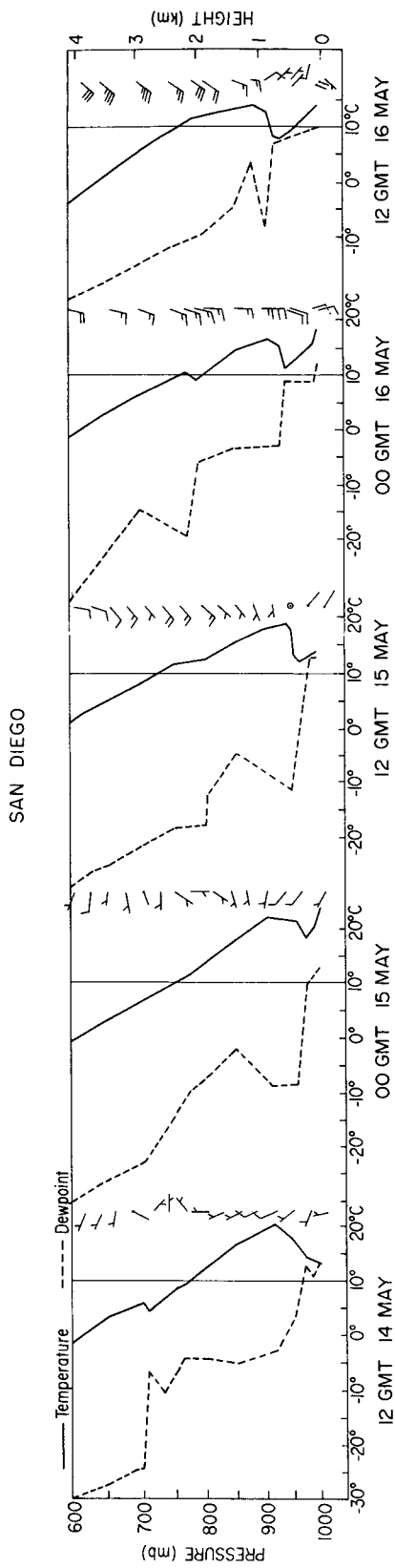
FIG. 18. Vertical soundings at San Diego, California from 12 UTC 14 May through 12 UTC 16 May 1985. Winds (knots) are plotted to the right of the corresponding temperature sounding.
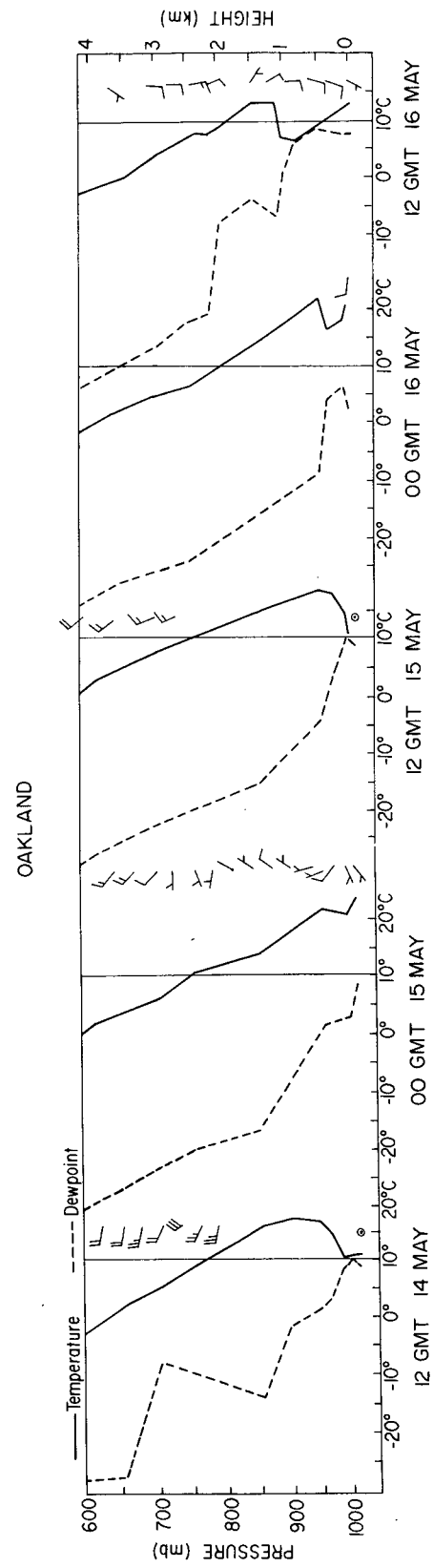
FIG. 19. Vertical soundings at Oakland, CA from 12 UTC 14 May through 12 UTC 16 May 1985.

TABLE 1. Gravity current calculations.

Time of passage	Location	Δp (mb)
13 UTC 16 May	Buoy 46027	1.2
16 UTC 16 May	Cape Arago, OR	0.3
20 UTC 16 May	Newport, OR	1.7
01 UTC 17 May	Astoria, OR	2.3
06 UTC 17 May	Quillayute, WA	3.3

May and 00 UTC 16 May (since the marine layer depth and inversion strength varied during this period) gave 178 and 168 km, respectively. The continuous stratification formula [Eq. (2)] produced slightly larger numbers.

Although air tends to flow ageostrophically down the alongshore (or along the barrier) pressure gradient, there *can* be geostrophic balance with the gradient normal to the barrier (Overland, 1984). In the case of California, the latter gradient undergoes a large diurnal cycle as daytime heating over land causes pressure to fall over the interior. The result is a strengthening of the northerlies during the day and their attenuation at night. The flow in the coastal zone is thus a superposition of both ageostrophic and geostrophic components, with the latter tending to be strongest during the day. This is probably why southerlies along the Pacific coast tend to be strongest and move northward most rapidly during the night and to weaken and stagnate during the daytime hours (e.g., Fig. 16). As noted previously, there is also the possibility of damming of cool, marine air on the western slopes of the coastal mountains. Such damming would produce a pressure force normal to the topography that could be geostrophically balanced, at least in part, by the eastward-directed Coriolis force associated with southerly flow.

The air within the mesoscale tongue of coastal southerlies was associated with a deepened marine layer and an overwater trajectory, and replaced a preexisting shallow marine layer with warm, subsided air above. Furthermore, there is the possibility of "damming" within approximately a Rossby radius of the coastal mountains.[2] The hydrostatic effect of these changes was the creation of a mesoscale coastal pressure ridge that followed the southerlies up the coast (Fig. 9). The deepening of the well-mixed marine layer enabled air to mix to its lifting condensation level, thus contributing to the development of coastal stratus and fog (Noonkester, 1979; Pilie et al., 1979; Petterssen, 1938). Furthermore, the low-level southerly flow had plenty of opportunity to pick up moisture during its trajectory over the relatively warm water to the south; the subsequent passage over the cooler, upwelled waters of

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[2] Unfortunately, the lack of upper air data in the coastal zone has not allowed the direct verification of a sloping, dammed layer.

coastal California would also contribute to saturation and the formation of low clouds.

Between 00 and 12 UTC 16 May the 850 mb low and associated surface trough moved westward into the Pacific. As a result, southerlies extended offshore from the California coast far beyond the Rossby radius as evidenced by several ship reports as well as the widening of the coastal stratus tongue (Fig. 4). The superposition of generally ageostrophic coastal southerlies (flowing down the alongshore gradient) with relatively geostrophic southerly flow circulating around the offshore low, resulted in a strengthening of the northward flow along much of the California coast by 12 UTC 16 May. At this time stratus had reached the Oregon–California border.

During the next 12 hours (12 UTC 16 May through 00 UTC 17 May) the 850 mb low off California moved west-northwestward, producing large 850 mb height rises over California and a substantial 850 mb height gradient between Vandenberg, California and Medford, Oregon, with higher heights to the south (Fig. 17). By 18 UTC 16 May surface pressure had risen 2–4 mb in 6 hr over much of California as the marine layer deepened and spread into the interior of California (see Fig. 19, a series of soundings at Oakland, California). At the same time pressure continued to fall over the Pacific Northwest under the influence of the receding synoptic high, troughing in the lee of the mountain barriers of the region, and the strong diurnal heating that accompanied this period. Temperatures that afternoon reached over 30°C at locations along the northern Oregon and Washington coasts, but remained near 13°C in the stratus-laden southerlies of southern Oregon and
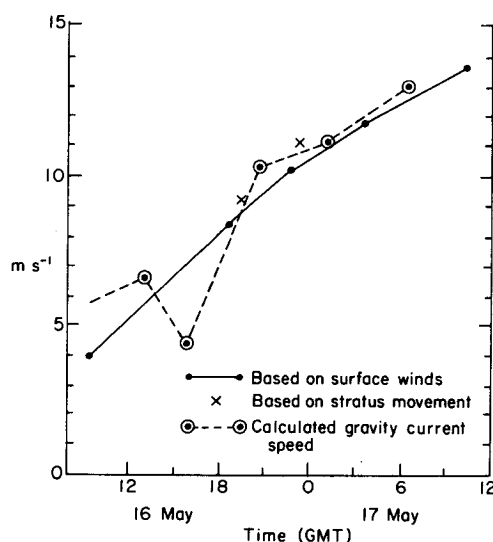

FIG. 20. Speed of the surge front in time based on coastal wind changes (solid lines) and the northern boundary of the coastal stratus (noted by Xs). Also shown are the theoretical gravity current speeds (dashed lines) calculated by the method of Seitter and Muench (1985).
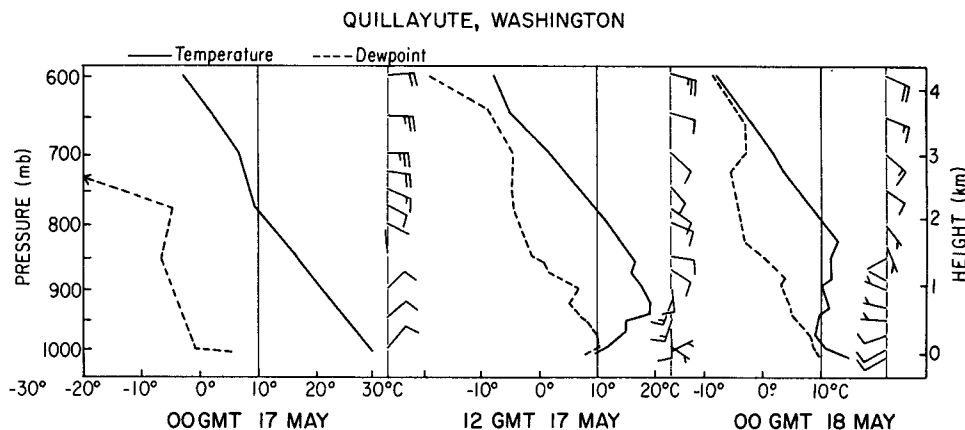
QUILLAYUTE, WASHINGTON

FIG. 21. Vertical soundings at Quillayute, WA before (00 UTC 17 May) and after (12 UTC 17 May, 00 UTC 18 May) the passage of the alongshore surge at that location. Winds are plotted to the right of the appropriate temperature sounding.

northern California. With large pressure falls to the north and moderate rises to the south the pressure gradient along the Oregon and Washington coasts was greatly enhanced. The superposition of ageostrophic acceleration down the alongshore gradient with the momentum supplied by the relatively geostrophic southwesterlies flowing around the offshore low produced strong winds that began to move up the Oregon coast. Around 15 UTC 16 May a southerly surge exceeding 12 m s^{-1} struck Cape Arago. Pressure rose only slightly as these winds increased in strength.

As the southerlies proceeded northward along the Oregon and Washington coasts they increasingly took on the characteristics of a topographically trapped gravity or density current, held against the barrier by the Coriolis force. This hypothesis is supported by several facts:

1) Moving up the Oregon coast, the surge brought not only a change in wind direction but progressively larger and more abrupt transitions in wind speed, pressure and temperature. Maximum winds increased from 10 m s^{-1} in southern Oregon to 17 m s^{-1} on the northern border, temperature drops varied from 6°C h^{-1} in southern Oregon to 16°C h^{-1} to the north, and pressure rises varied from 0.2 mb h^{-1} to the south to 2 mb h^{-1} in the north. It is well known (e.g., Charba, 1974; Griffiths, 1986) that the forward edge of a gravity current can steepen in time. By 00 UTC 17 May (when the surge was just south of Astoria, Oregon) the southerly transition involved a radical and abrupt change of air mass from warm, subsiding continental air to cool, stratus-filled marine flow.

2) The speed of movement of the surge front from southern Oregon northward closely matches that of a gravity current. To show this we have calculated the expected gravity current speed based on the scheme of Seitter and Muench (1985):

$$V = K\left(\frac{\Delta p}{\rho}\right)^{1/2} \qquad (3)$$

where V is the speed (m s^{-1}) of the density current, ρ is the density (kg m^{-3}) of the warm air, Δp is the pressure jump (pa) associated with the density current head and K is an empirical constant of 0.79. The pressure jump Δp was calculated by taking the average sea level pressure of the two hours after the surge minus that of the preceding hour. Since mean diurnal variations are fairly small on the coast (e.g., the mean diurnal pressure range at Astoria, Oregon, for May 1985 was 0.5 mb) they were not removed for these calculations. Table 1 shows locations, times and pressure jumps used in the calculations that produced Fig. 20.

Figure 20 presents the results of the gravity current speed calculations as well as the observed northward speed of the transition to southerly flow. Also shown is the speed of movement of the northern edge of the coastal stratus tongue. This figure indicates that starting at ~18 UTC 16 May and continuing into 17 May the calculated gravity current speed and observed speed of the southerly transition were nearly identical; prior to the period of this figure the correspondence breaks down since the southerly transition appeared to jump northward at ~05 UTC 16 May (Fig. 16).

3) Coastal southerlies and stratus were observed within approximately one Rossby radius of the coastal barrier. This radius was found to be 180 km by applying Eq. (1) to the Quillayute, Washington, sounding at 12 UTC 17 May. This spatial scale is what would be expected for a topographically trapped gravity (or density) current as shown by previous theoretical work (e.g., Baines, 1980; Griffiths, 1986; Griffiths and Hopfinger, 1983). Early on 16 May the coastal stratus wedge, as seen by visible satellite imagery, was relatively wide but by 00 UTC 17 May a narrow, northward moving tongue had become obvious (Figs. 4, 5). This northward propagating stratus feature remained quite narrow

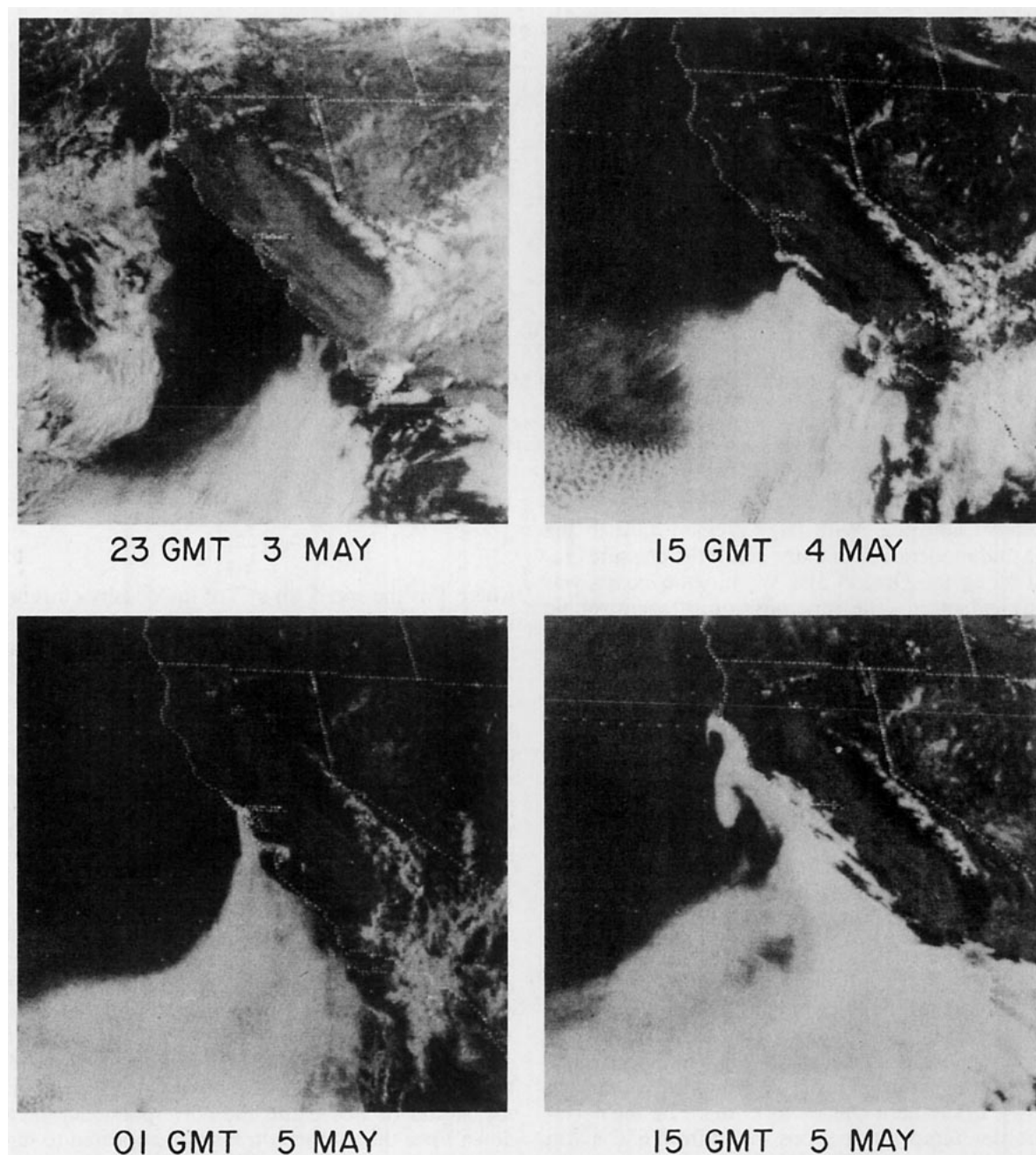23 GMT 3 MAY

15 GMT 4 MAY

01 GMT 5 MAY

15 GMT 5 MAY

FIG. 22. GOES visible satellite imagery of the southwest United States and the adjacent Pacific Ocean for 23 UTC 03 May through 15 UTC 07 May 1982.

during the next day. Ship reports in this and similar cases support the narrow nature of the southerly flow accompanying the coastal stratus. The gravity current was initially blocked by the coastal mountains; for example, the isallobars of Fig. 11 indicate that pressure rises were at first limited to the coastal zone and did not extend east of the coastal terrain. However, the coastal mountains do have significant breaks and eventually the deepening marine air surged into the western interiors of Oregon and Washington.

4) As in other gravity current examples (e.g., Charba, 1974; Shapiro et al., 1985) the vertical scale of this phenomenon is very shallow and appears to be mainly limited to the lower troposphere below 850 mb. It has already been shown (Fig. 7) that coastal ridging and large temperature changes were not observed at 850 mb. To study the surge's vertical structure, we examined the radiosonde observations at Quillayute, on the Washington coast (Fig. 21). At this location the surge front passed at approximately 06 UTC 17 May
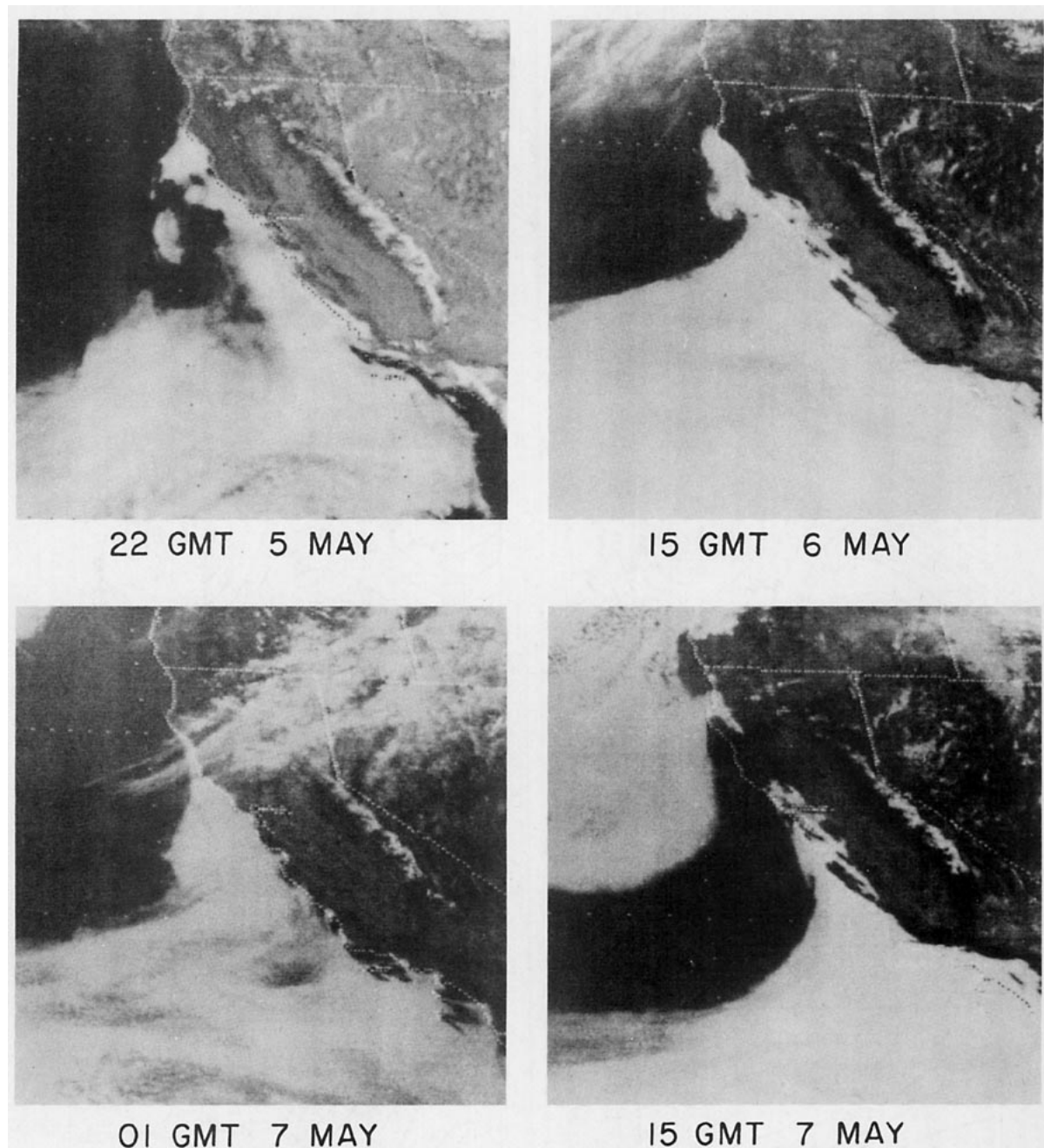
FIG. 22. (Continued)

1985. Prior to the event (00 UTC 17 May) the sounding was quite warm and dry with easterly winds prevailing through much of the sounding. After passage of the surge (12 UTC 17 May) there was dramatic cooling and moistening below 850 mb and a shift to southerly or southwesterly flow below 870 mb. (The easterly winds in the lower few hundred meters were associated with nighttime katabatic flow off the nearby Olympic Mountains). At 00 UTC 18 May cooling had continued below 830 mb, with only minor cooling aloft.

In summary, there is strong evidence to suggest that on the Oregon coast between 12 UTC 16 May and 00 UTC 17 May synoptically forced coastal southerlies were transformed into a northward propagating, topographically trapped gravity current. During the next 24 hours this gravity current (or alongshore surge) continued northward along the Washington and British Columbia coasts. In a real sense, synoptic scale changes "launched" the alongshore surge, after which it continued to propagate on its own.
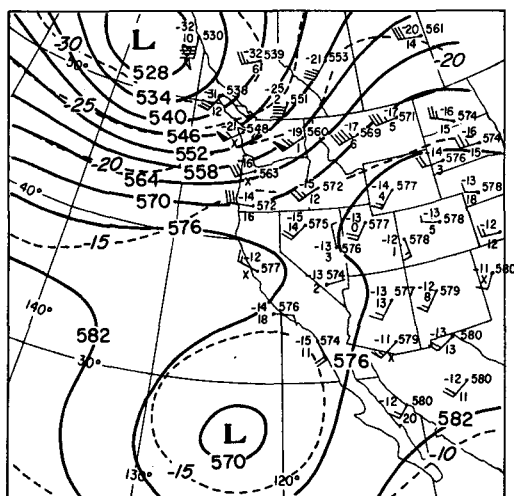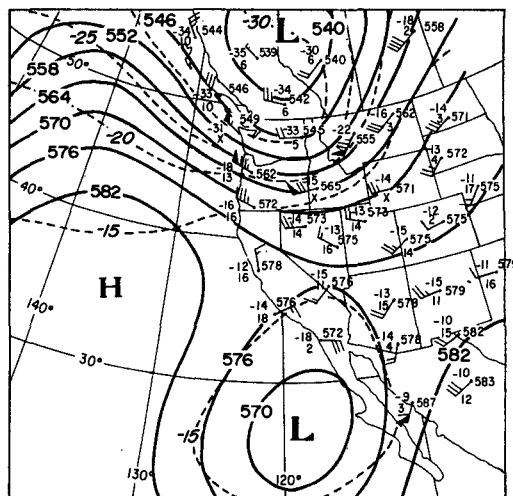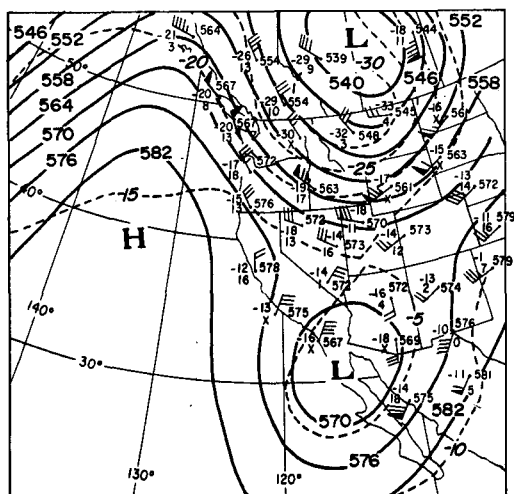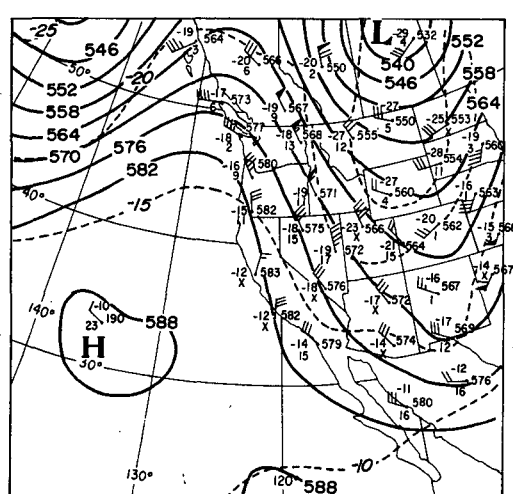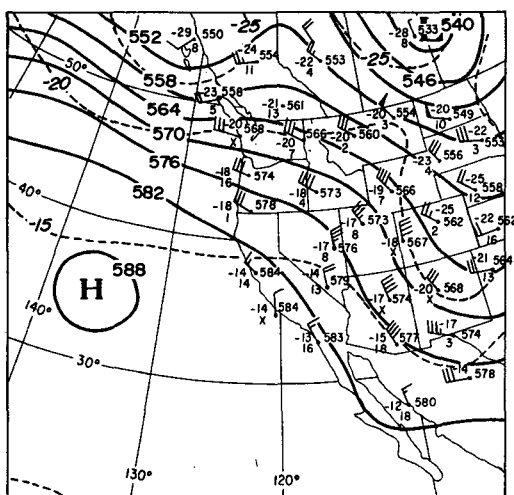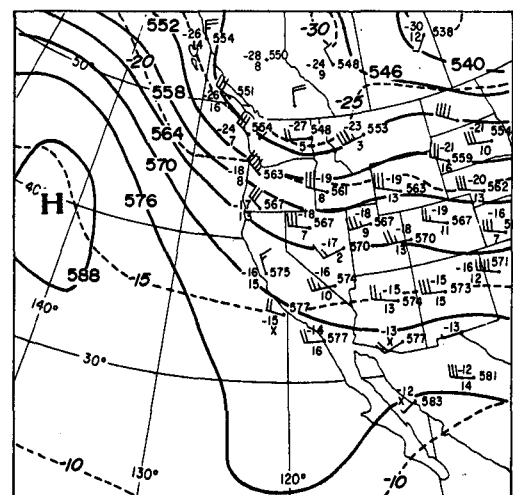
FIG. 23. NMC 500 mb charts for 00 UTC 03 May through 00 UTC 08 May 1985. Geopotential heights (solid) are in decameters and isotherms (dashed) are in °C.

As shown in Fig. 12, the pressure perturbation associated with the surge weakened to the north. One source of this attenuation is probably diurnal cooling since the temperature contrast between pre- and post-surge air was a maximum during the afternoon of 16 May and decreased during the night. The gravity current could also have been weakened by the breaks or gaps in the coastal mountains of Oregon, Washington and British Columbia. As the surge and the associated coastal pressure ridge propagated northward, creating a large onshore pressure gradient, some of the cool marine air "leaked" through the gaps into the lowlands between the coastal mountains and the Cascades.

Several investigators have suggested that mesoscale coastally trapped phenomena along the coasts of California (Dorman, 1985) and South Africa (e.g., Gill, 1977; Bannon, 1981) are topographically trapped Kelvin waves. Although topographically trapped Kelvin waves and topographically trapped gravity currents are closely related and share many characteristics, there are important differences. In topographically trapped Kelvin waves there are wavelike transverse displacements of a stable fluid; this fluid is capped by a layer of sufficient stability to maintain the blocking effect of a topographic barrier. The Kelvin wave studies cited above have assumed the existence of a cool, marine layer capped by a strong inversion at levels below the top of the blocking topography. In contrast, from Oregon northwards during the May 1985 event, the cool air of the alongshore surge was moving into relatively uniform, subsiding warm air (see Fig. 21). A two fluid system did not exist north of the surge, rather such a vertical structure was created by the surge. Furthermore, the surge was basically a solitary feature with no evidence of any subsequent mesoscale trough. This evidence, coupled with the information presented above, suggests that the alongshore surge of May 1985 is best described as a topographically trapped gravity current as it moved northward from Oregon into British Columbia.

Although the case for mesoscale wavelike response in the coastal zone during the May 1985 event is weak, the surface pressure variations at several coastal stations (Figs. 12, 13) did show high frequency, wavelike perturbations along the Oregon and Washington coasts. These features began four to six hours after the passage of the alongshore surge and had amplitudes of ~1 mb. Such oscillations might be explained by gravity waves propagating on the interface between the cool, marine layer and the warm, subsiding air above. At Astoria, where the signal was strongest, the period was ~1 h and 5–6 waves were evident. As shown in Fig. 2, there was also a wavelike variation in wind speed at Astoria that is consistent with the existence of gravity waves. Wind direction was also undergoing rapid changes at that location, but the sampling rate (hourly) could not resolve the variation. At this point we can only speculate on the triggering mechanism of this wave activity.

3. The event of 3–7 May 1982

The May 1985 case is an example of a strong alongshore surge event. In order to assess the generality of the ideas expressed in the previous section, we examined a less energetic southerly transition that occurred during 3–7 May 1982. This case was also considered in Dorman (1985), where it was concluded that the northward movement of stratus tongues and southerly winds are manifestations of Kelvin waves trapped by the coastal topography.

a. Synoptic description

Visible satellite imagery of the May 1982 event is presented in Fig. 22. The sequence begins (23 UTC 3 May) with clear skies along most of the California coast and a large area of stratus offshore to the southwest. By 15 UTC the next day (4 May) low clouds had spread northward along the southern California coast as far north as Monterey. Ten hours later (01 UTC 5 May) a narrow tongue of stratus had extended northward along the coast to San Francisco. Also evident is afternoon clearing within ~50 km of much of the southern California coast (see Lee et al., 1980) and a southward retreat of the stratus farther out in the Pacific. By 15 UTC 5 May the narrow stratus tongue had extended northward along the coast, forming eddies at both Point Arena and Cape Mendocino. Stratus had inundated coastal California and had spread northward in the eastern Pacific. Later that day (22 UTC 5 May) the coastal eddies appear to have fallen apart, and diurnal retreat and thinning of the stratus was again observed both in the coastal zone and further out in the Pacific. The next morning (15 UTC 6 May) the stratus had again thickened and flooded the coastline, and there was a strong suggestion of an eddy at Pt. Arena. By 01 UTC 7 May a retreat of the low clouds is obvious both in the coastal zone and over the adjacent Pacific. During the next day (15 UTC 7 May), the retreat of the stratus accelerated as a weak front (with more stratus behind) moved southeastward into the region.

Figure 23 presents NMC 500 mb charts for the May 1982 case. At 00 UTC 3 May there was a closed low west of Baja California and a trough in the westerlies approaching the Pacific Northwest. During the next 48 h (through 00 UTC 5 May) the closed low moved northeastward to northern Baja California, the trough in the westerlies moved inland to the Rockies, and a high amplitude ridge developed in the eastern Pacific. During the next 72 h (through 00 UTC 8 May) the closed low opened into a trough that quickly moved eastward, the ridge over the eastern Pacific shifted eastward and then back to the west, and a new short wave approached the Pacific Northwest.

At 850 mb (Fig. 24) the sequence begins (00 UTC 3 May) with a trough off northern Baja California that drifted northeastward during the next two days. At the same time a ridge over the eastern Pacific extended

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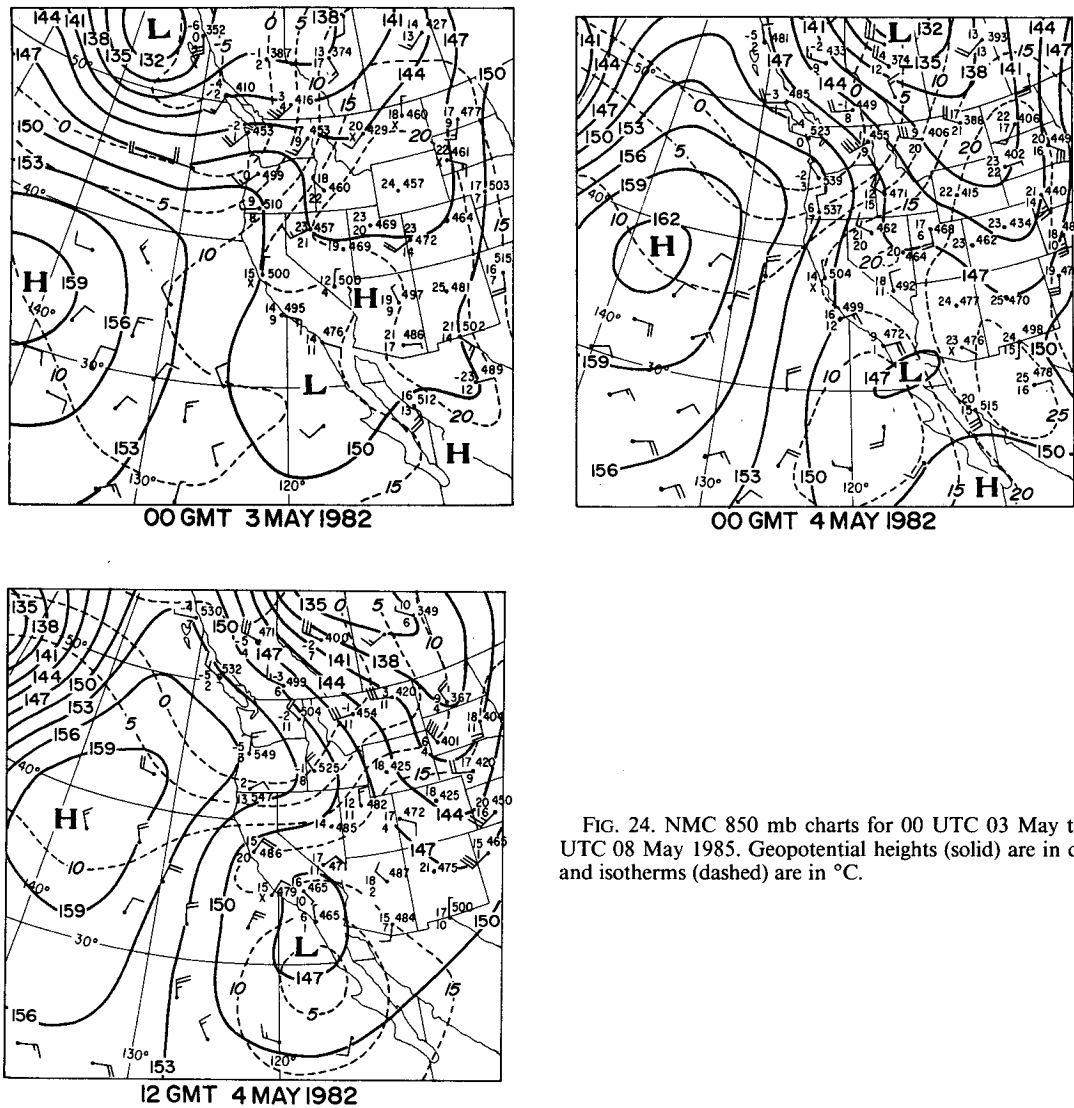

OO GMT 4 MAY 1982

12 GMT 4 MAY 1982

FIG. 24. NMC 850 mb charts for 00 UTC 03 May through 00 UTC 08 May 1985. Geopotential heights (solid) are in decameters and isotherms (dashed) are in °C.

northeastward into the Pacific Northwest behind a cold front; as a result a trough was created over central and northern California. During the remainder of the period the ridge appeared to retreat westward, and a short wave and associated pulse of colder air entered the Pacific Northwest.

NMC surface analyses (Fig. 25) during the first two days of the case (through 00 UTC 5 May) show a front moving southeastward through the western United States, and an extension of the Pacific High spreading into the Pacific Northwest. At the same time the trough over northern Baja California extended northward up the interior valley of California and combined with the trough associated with the southward propagating front; in addition, pressure built off southern California. These changes established a large sea level pressure gradient over northern California and southern Oregon that brought strong northerlies to the coastal zone.

During the remainder of the period high pressure retreated from the Pacific Northwest and the California trough weakened.

b. Mesoscale description

Mesoscale surface charts for the May 1982 case are shown in Fig. 26. At the initial time (00 UTC 4 May) there was an intense pressure gradient and strong northerlies in northern California, southern Oregon and the adjacent Pacific. Several ships offshore of northern California reported gale force northerly winds of 15 to 30 m s^{-1}. Twelve hours later (12 UTC 4 May) the pressure gradient weakened off central California and stratus began to move up the coast. A mesoscale coastal pressure ridge and weak southerlies are evident west of San Diego. Six hours later (18 UTC 4 May) the coastal pressure ridge, southerly flow and stratus
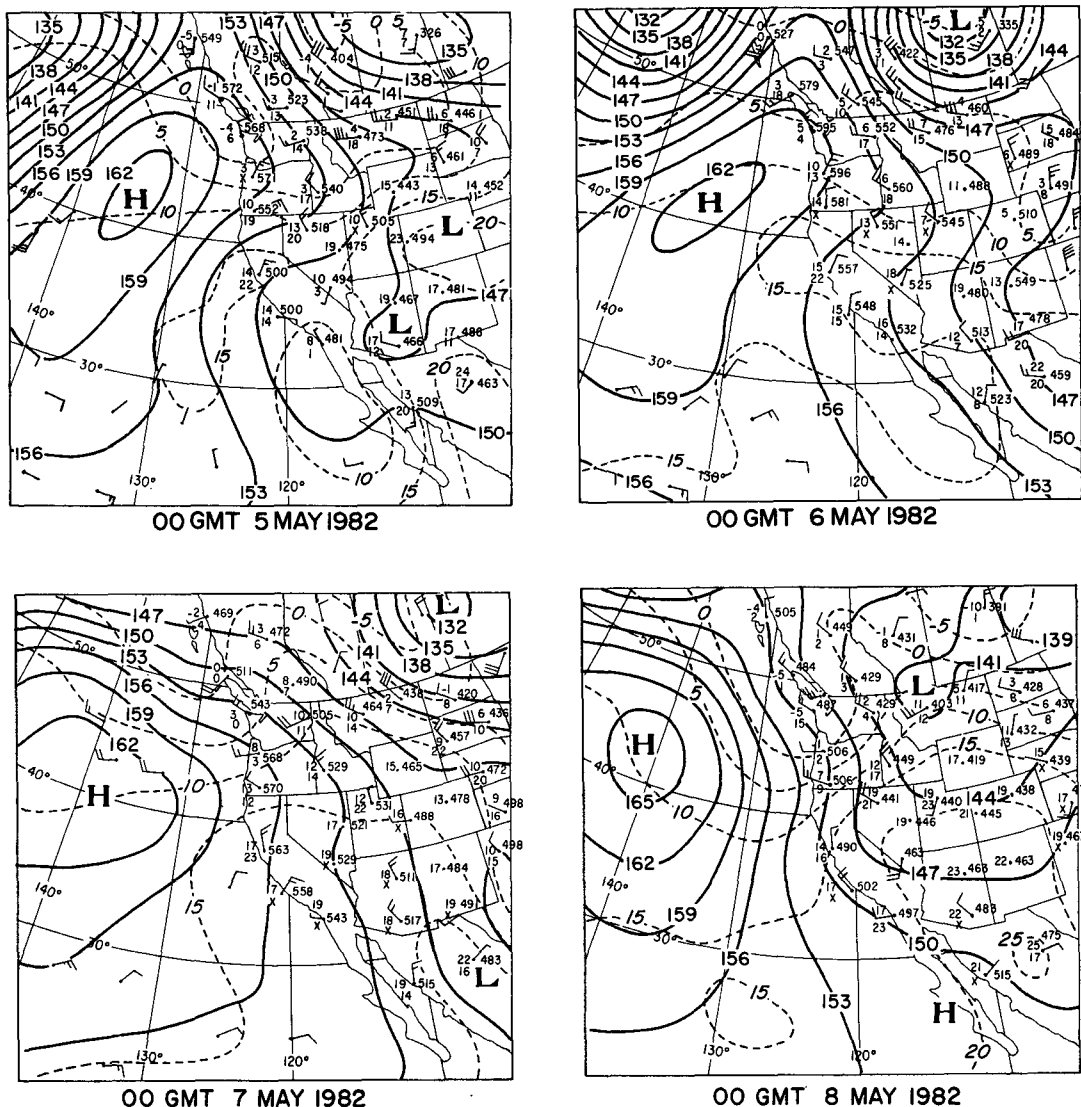
00 GMT 5 MAY 1982

00 GMT 6 MAY 1982

00 GMT 7 MAY 1982

00 GMT 8 MAY 1982

FIG. 24. (*Continued*)

had abruptly pushed northward to San Francisco. The next morning (12 UTC 5 May) the pressure gradient was relatively flat along most of the California coast with southerlies and stratus extending to the pressure minimum near Cape Mendocino on the northern coast. Over the next 24 hours (through 12 UTC 6 May) the situation did not significantly change except for the diurnal variations of the California thermal trough and the weakening of the alongshore gradient and associated southerlies. On 7 May surface ridging in the eastern Pacific reestablished a strong pressure gradient and northerly flow over the California coast. As a result, the coastal stratus was swept southward.

Figure 27 presents the time evolution of alongshore sea level pressure during the May 1982 case. Early in this event (00 UTC 3 May–00 UTC 4 May) pressure

was relatively uniform along the southern California coast and increased northward from Buoy 46011. A significant change occurred at 12 UTC 4 May as falling pressure along the central California coast and rising pressure to the south produced a pressure gradient with higher pressure to the south equatorward of Buoy 46011. During the next 6 hours this pressure gradient rapidly extended northward to Buoy 46014. As shown in Fig. 26, this change was accompanied by an abrupt switch to southerlies along much of the central and southern California coast. During the next 24 hours (through 18 UTC 5 May) pressure rose along the entire California coast, with especially large increases north of San Francisco at Buoys 46013 and 46014. At 12 UTC 6 May the highest pressure on the coast was at Buoy 46013. Finally, during the next day (through 12
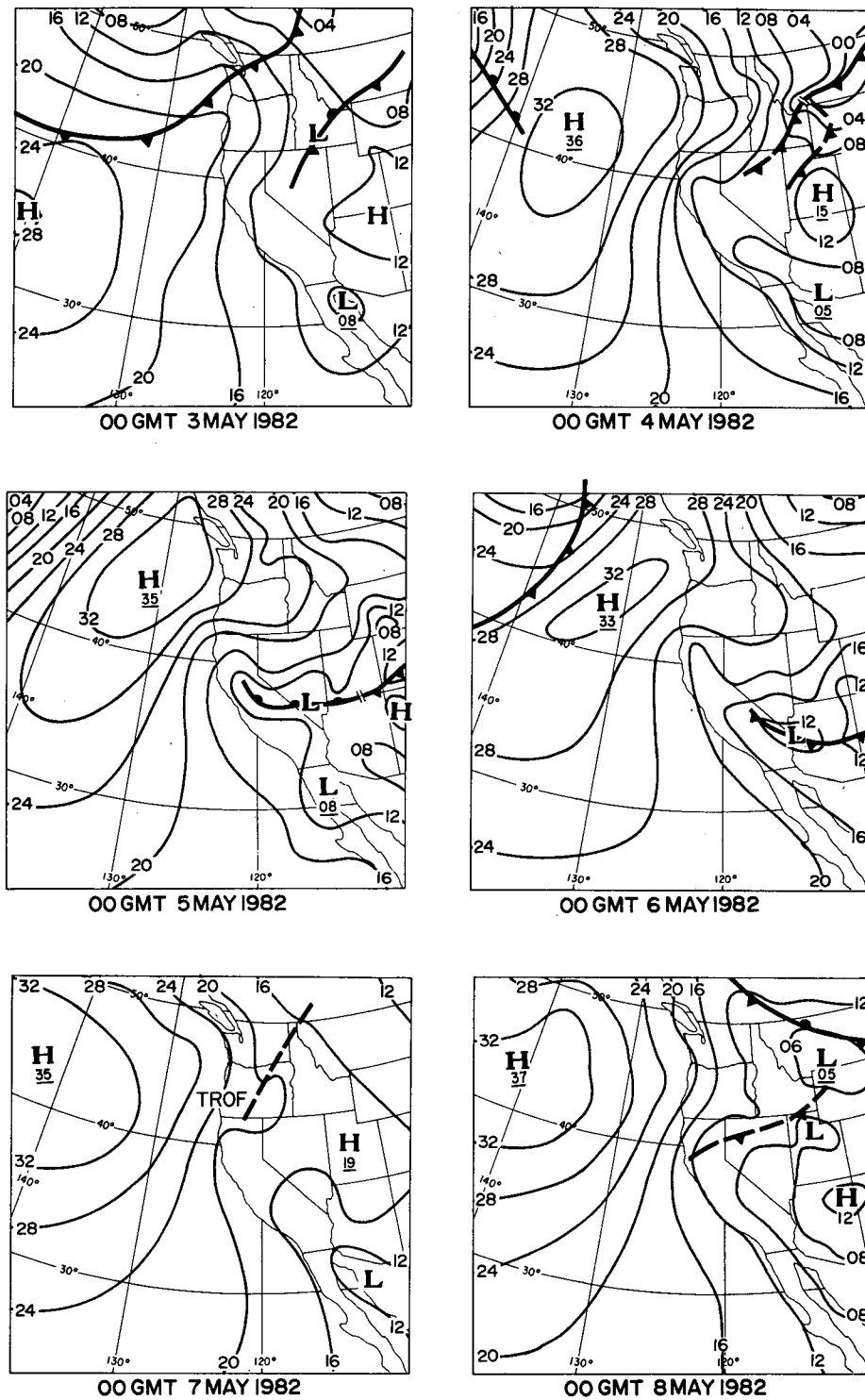
FIG. 25. NMC surface charts for 00 UTC 03 May through 00 UTC 08 May 1985.
Solid lines are sea level isobars (10xx mb).

UTC 7 May) increasing pressure along the northern California coast and falling pressure to the south produced a northward pressure gradient (higher pressure to the north) along the entire California coast; as a result northerlies and northwesterlies were reestablished.

The alongshore pressure variations shown in Fig. 27 generally extended well inland from the coast. Proof of this is given in Fig. 28, which displays 6 hour isallobars during the initial half of the May 1982 event. At 00 and 12 UTC 4 May pressure was falling over much of California, with the exception of the state's northeast corner. Along the coast maximum pressure falls occurred in central California. At 18 UTC 4 May, there were moderate pressure rises in all of southern California that clearly extended inland from the coast. Pressure falls were observed in northwestern California as easterly flow descending the Siskiyou Mountains produced leeside troughing. These changes established an alongshore pressure gradient, with higher pressure to the south. During the next 6 hours (through 00 UTC 5 May) pressure remained constant along most of the coast, with the exception of falls to the far north. During the following 12 hours (through 12 UTC 5 May) pressure rose in central California and produced a pressure ridge near Buoy 46013.

Further indication that the pressure at coastal and inland locations varied in a similar way is given in Fig. 29, which shows the pressure evolution at a coastal buoy (46014) and at Sacramento, in California's interior valley. Figure 29 also presents the winds at Buoy 46014. From 12 UTC 4 May through 06 UTC 5 May the winds were generally northwesterly, but as the pressure began to rise around 03 UTC 5 May the northerlies decelerated and then reversed direction.

c. Case discussion

The May 1982 event was far less energetic than the May 1985 case and evolved within a considerably different synoptic environment. Early in this case (00 UTC 3 May–00 UTC 4 May) strong northerlies dominated the coast of northern California with weaker northwesterlies and westerlies in the southern part of the state. With air subsiding around the eastern periphery of the Pacific High coupled with offshore flow down the mountain barriers of the Pacific Northwest and northern California, stratus and fog were limited to the waters offshore of southern California.

Between 00 UTC and 12 UTC 4 May a synoptic low moved across southern California producing modest pressure falls over the lower two thirds of the state, while to the north sea level pressure rose as high pressure extended into the Pacific Northwest behind a cold front (Fig. 28). During the next 6 hours (through 18 UTC 4 May) the low continued to move eastward, leaving lower tropospheric cooling in its wake; the result was relatively uniform pressure rises in the southern half of California. At the same time, pressure actually fell in the northwest corner of the state as subsiding offshore flow led to troughing in the lee of the mountains of northern California and southern Oregon.

These changes produced a reversal in the alongshore coastal pressure gradient (Fig. 27) with sea level pressure increasing to the south over the lower two-thirds of California (i.e., south of Buoy 46014). This change in gradient caused the winds to abruptly turn southerly along much of the central California coast, with the air flowing ageostrophically down the alongshore pressure gradient within approximately one Rossby radius ($\sim$150 km) of the coastal mountains. As illustrated in a series of soundings at Vandenberg AFB, California (Fig. 30) the southerly flow was relatively shallow, being limited to approximately one km above sea level. This height is close to the crest level of the coastal mountains. By 00 UTC 5 May the shift from northerly to southerly flow at low levels brought substantial low-level cooling as subsiding, generally continental air was replaced by cool maritime flow. As noted in the previous case, the shift to southerlies might also have resulted in damming of cool, marine air on the western slopes of the coastal mountains. The deepened marine layer created a mesoscale, coastal pressure ridge (Fig. 26) and was associated with the northward movement of coastal stratus.

During the next 12 hours (through 12 UTC 5 May), sea level pressure rose over most of the region with the largest increases in central California and Nevada (Fig. 28). This pattern occurred because cooler air and associated higher surface pressure were moving southward into central California behind a weak front (Fig. 25). In northern California this pressure rise was offset by troughing in the lee of the coastal mountains and resulted in the extention of the California inland pressure trough to the northern California coast. As the trough built northward the southerlies and stratus followed. By 12 UTC 5 May southerlies and associated low clouds had pushed to Cape Mendocino and produced stratus eddies at both Cape Mendocino and Pt. Arena. It appears that southerly flow cannot easily follow sharp bends in the coastline around prominent headlands and capes and thus surges off the coast as a "jet" that is bent southward by the strong northerlies just offshore.

Between 12 UTC 5 May and 00 UTC 6 May the California heat trough deepened under daytime solar heating and created a larger onshore pressure gradient (normal to the coast and coastal mountains); as a result the southerly flow off northern California was attenuated and the coastal eddies dissipated. As noted for the previous case, although geostrophic balance for an alongbarrier pressure gradient is not possible close to the barrier such a balance is still possible for the pressure gradient normal to the blocking terrain (Overland, 1984). Thus, lower pressure over land produces a northerly geostrophic component, which weakens the southerlies flowing down the alongshore pressure gradient.

During the next night (00 UTC 6 May–12 UTC 6 May) weak southerlies again appeared as the heat trough weakened, leaving the weak northward pressure gradient force in the coastal zone to dominate. Again the stratus thickened and moved northward to Cape

00 GMT 4 MAY

12 GMT 4 MAY

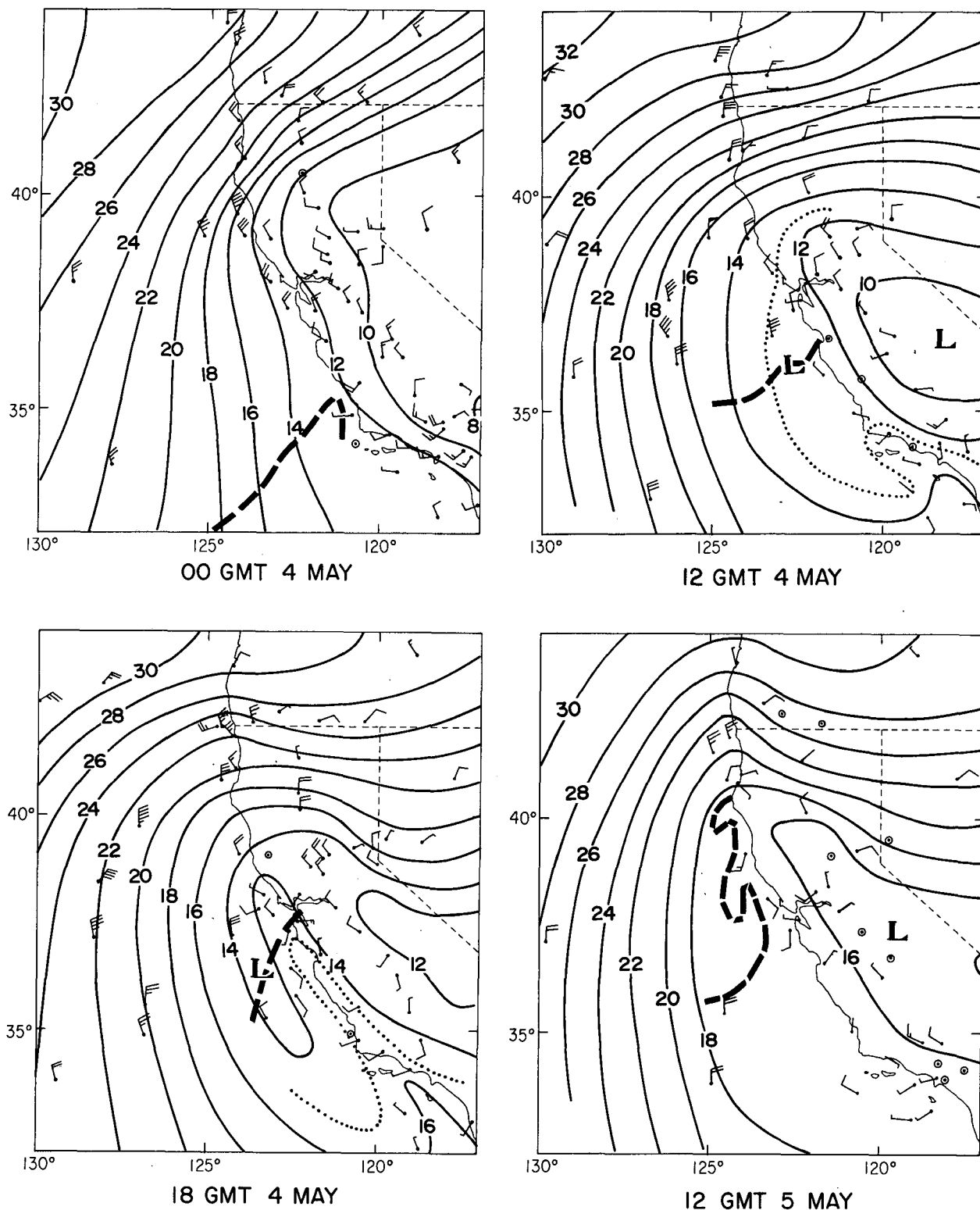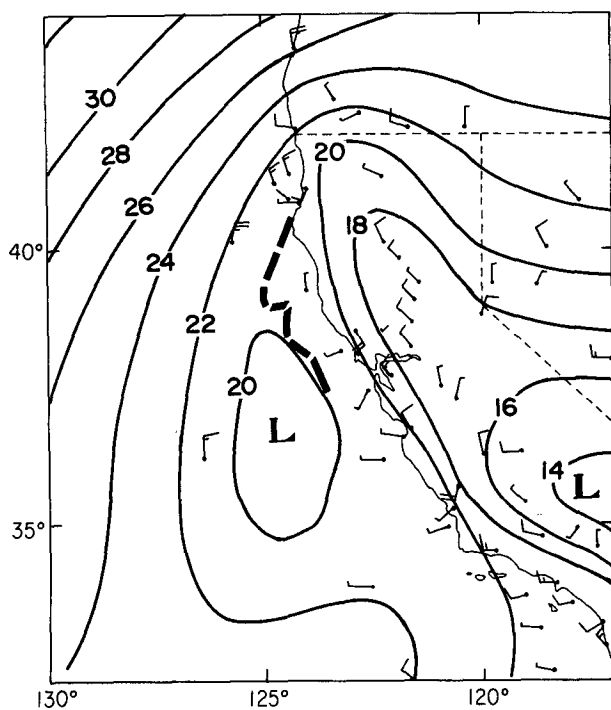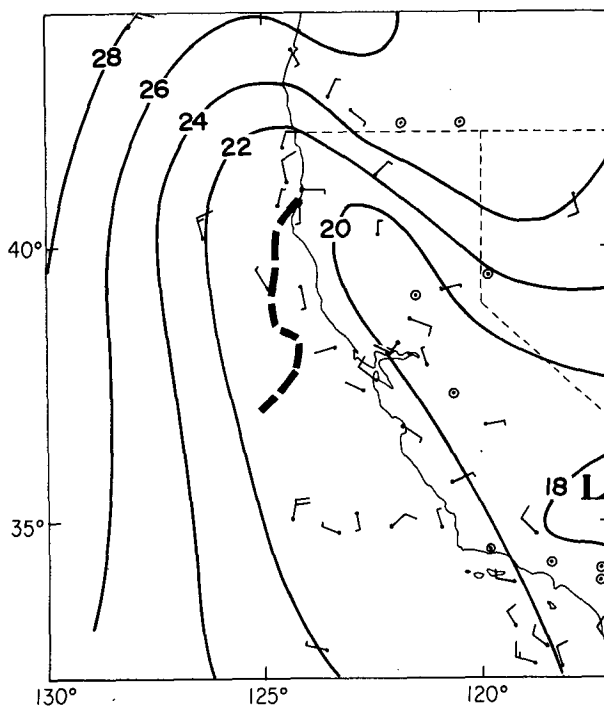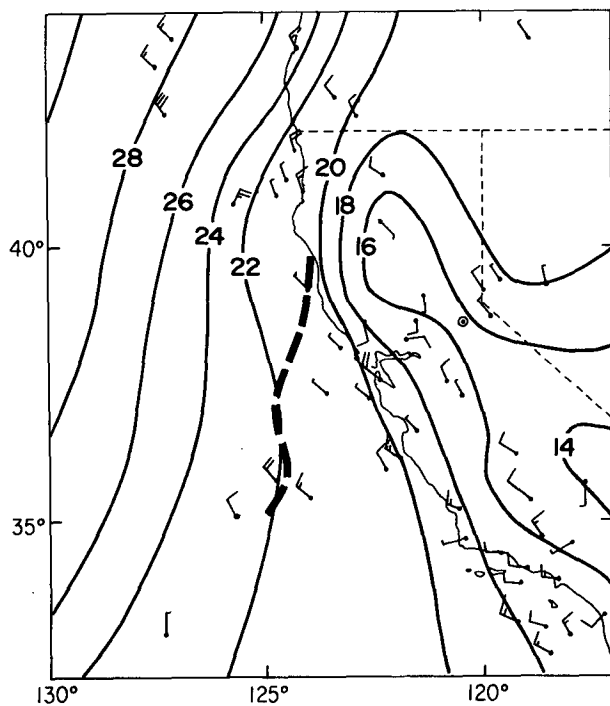**18 GMT 4 MAY**

12 GMT 5 MAY

FIG. 26. Mesoscale sea level pressure analyses and surface winds for 00 UTC 4 May through 18 UTC 7 May 1982. Solid lines are sea level isobars (10xx mb) and winds are in knots. Heavy dashed lines are the northern boundaries of coastal stratus as defined by GOES visible imagery.
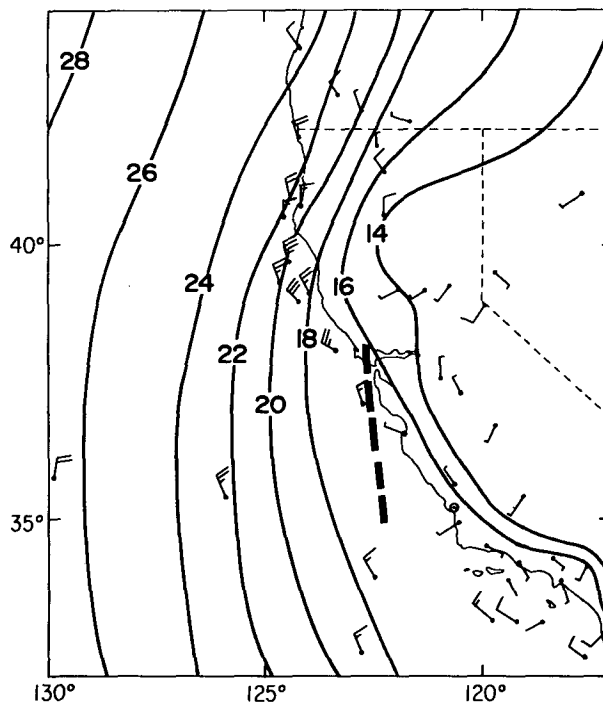
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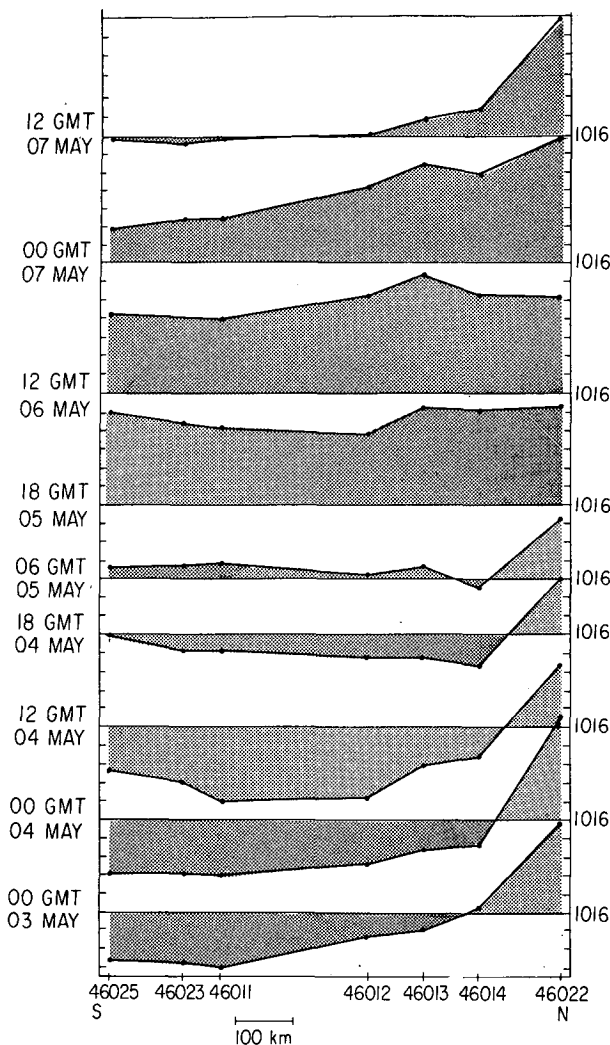
18 GMT 7 MAY

FIG. 26. (Continued)

FIG. 27. Variation of sea level pressure along the California coast for several times between 00 UTC 03 May through 12 UTC 07 May 1982. Shaded areas indicate deviations from 1016 mb; this pressure is indicated by horizontal lines. The tick marks indicate 1 mb intervals.

Mendocino, with a hint of the eddies observed the previous morning.

Finally, between 12 UTC 6 May and 18 UTC 7 May, high pressure retreated from the Pacific Northwest and pressure fell over the southwest U.S. The result was a weakening of the lee trough in northern California, the reestablishment of a large pressure gradient and northerly flow over the northern half of California, and the retreat of stratus to the south.

In summary, during this event changes on the synoptic scale, interacting with complex terrain and land–water contrasts, produced large variations in the low-level pressure distribution along the California coast. These pressure changes in turn controlled the coastal winds. Within a few hundred kilometers of the coastal topography, winds were the superposition of 1) a com-

ponent that flowed ageostrophically down the along-shore pressure gradient or decelerated while flowing upgradient and 2) a component that was nearly in geostrophic balance with the pressure gradient normal to the barrier. During the day strong diurnal heating over land created a large gradient normal to the coast and a significant northerly geostrophic component, while during the night the relaxation of the diurnal gradient allowed the weaker alongshore pressure gradient to dominate, strengthening the southerlies in the coastal zone.

The generation of coastal southerlies as described above serves as an alternative to the hypothesis of Dorman (1985), which suggested that the May 1982 event could be explained as a topographically trapped Kelvin wave. There are several points which argue against the selection of the Kelvin wave mechanism for the May 1982 event:

1) The coastal southerlies can be adequately explained by ageostrophic flow controlled by the synoptic scale alongshore pressure distribution, superposed on a geostrophic component associated with the pressure gradient normal to the coast.

2) There is little evidence of a wave-like propagating disturbance in the coastal pressure and wind fields. Furthermore, the significant pressure changes (Figs. 28, 29) generally were not limited to the coastal zone.

In short, it appears that the coastal pressure and wind fields were responding to changes on the synoptic scale rather than a northward propagating coastal disturbance.

4. Coastal wind transitions and surges as a global phenomenon

The coastal southerlies and alongshore surges of the Pacific Coast of North America possess many similarities with phenomena observed near topographic barriers around the world. One example is from South Africa, where the topography consists of a relatively narrow coastal plain that climbs abruptly to a high (>1000 m) interior plateau. Taljaard et al. (1961), van Loon et al. (1972), Preston-Whyte (1975), Tyson (1964), Gill (1977) and others have shown that the interaction of eastward moving synoptic-scale systems with the South African topography produces coastal lows that propagate along the coast. These lows are associated with warm, dry conditions and appear to be produced by subsidence warming as the synoptically forced flow descends the coastal escarpment. As a low passes a location there is a rapid switch in wind direction (from northerly to southwesterly on the eastern coast), a large increase in wind speed (to 15 m s^{-1} or more), and temperature drops of as much as 15°C within a few minutes. Essentially, subsiding continental air is replaced by far cooler, moist maritime flow. This
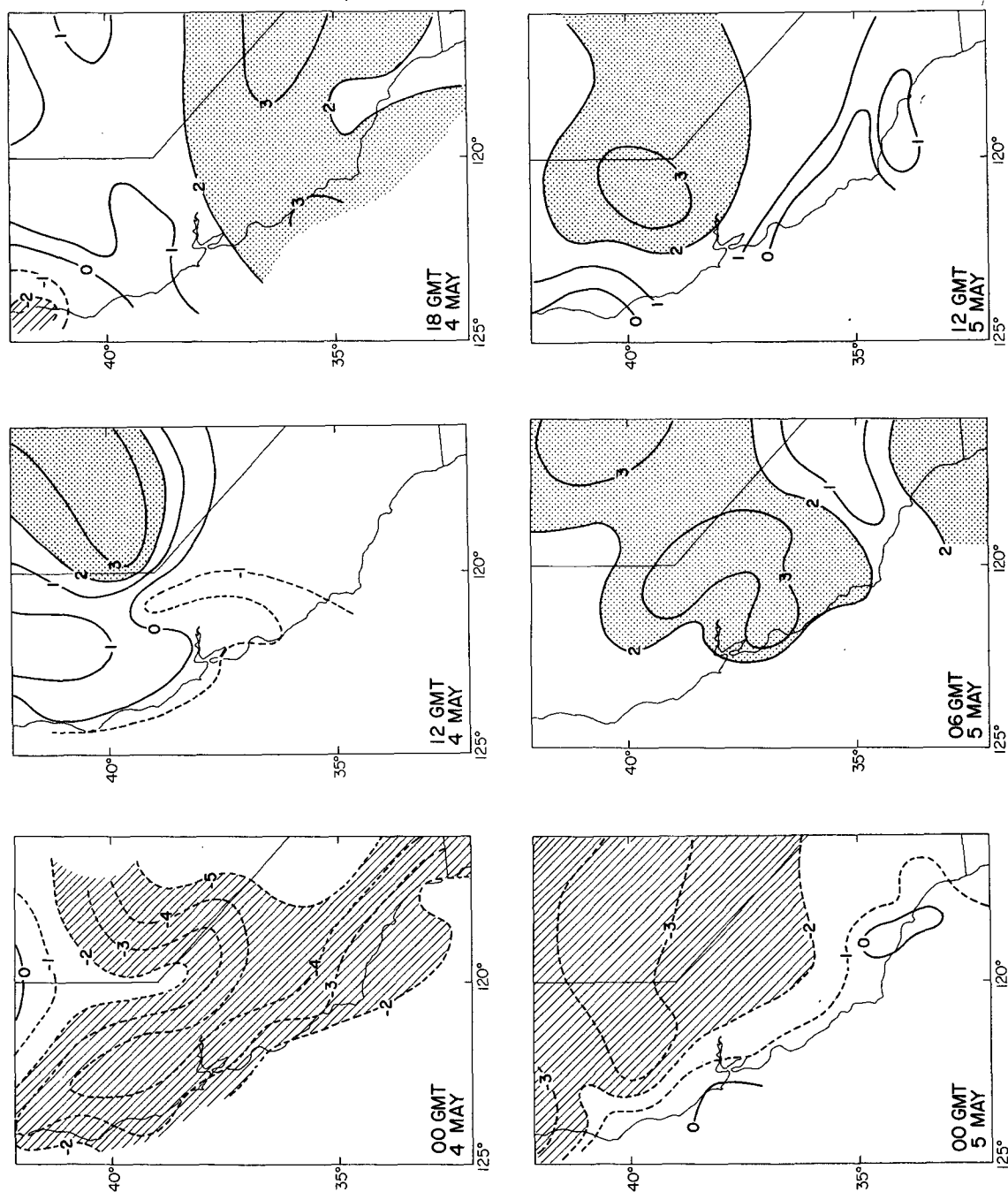
FIG. 28. Six-hour pressure change charts from 00 UTC 4 May through 12 UTC 05 May. Units are in mb/6 h. Hatched areas = pressure fall > 2 mb/6 h; stippled areas = pressure rise > 2 mb/6 h.
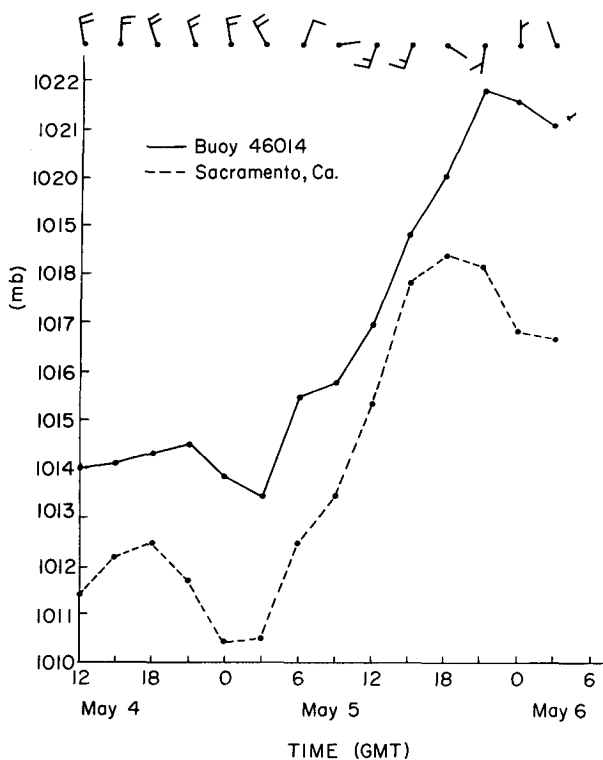
FIG. 29. Sea level pressure (mb) and wind (knots) at Buoy 46014 from 12 UTC 4 May through 06 UTC 6 May 1982. Also shown is the sea level pressure at Sacramento, CA.

transition to maritime air, which is usually quite shallow (below ~850 mb) and often associated with stratus and fog, is sometimes called a "leader front" because it precedes the passage of the true (deep baroclinicity) synoptic front by hundreds of kilometers. It appears that the South African leader front/coastal low phenomenon has much in common with the West Coast alongshore surge.

Gill (1977), Bannon (1981) and others have suggested that the South African coastal lows are propagating Kelvin waves, trapped by the coastal barrier. However, this interpretation is weakened by the lack of correspondence between the theoretical and observed phase speeds, and the lack of two layer stratification in the warm subsiding air of the coastal low. Furthermore, the identical periods of the coastal lows and synoptic scale disturbances (~6 days as shown by Preston-Whyte and Tyson, 1973) strongly support the idea that the lows originate in the interaction between the synoptic flow and the formidable topography of the region.

Another example of a topographically trapped coastal phenomenon is the southerly buster (or burster) of southeastern Australia. In this region a near sea level coastal zone gives way to a topographic barrier that roughly parallels the coastline. Colquhoun et al. (1985) described the buster as "marked by a sudden onset of

strong southerly wind squalls of maritime origin which often replace hot northwesterlies originating over the continent." As the buster arrives, winds can increase to over 15 m s^{-1}, with at least one event having reached 37 m s^{-1}. Temperature changes can be very large, with drops of 10°–15°C within a few minutes being a common occurrence. Busters usually precede the arrival of a Southern Ocean front, are generally not associated with precipitation, and usually are accompanied by mesoscale pressure ridges in the coastal zone. In nearly all cases, a mesoscale low precedes the southerly surge up the coast. The changes associated with southerly busters are shallow, generally being limited to 850 mb and below. Both analytical (Baines, 1980) and numerical (Gauntlett et al., 1984) models indicate that the buster depends on the existence of the topographic barrier of southeast Australia. Baines suggested that this phenomenon is a topographically trapped gravity current initiated by synoptic scale disturbances. Holland and Leslie (1986) proposed that although some coastal ridging events can be explained by the gravity current model, others possess characteristics of topographically trapped Kelvin waves. The above studies and others (e.g., Coulman et al., 1985; Berson, 1953; Gentilli, 1969; Wilson and Stern, 1985) indicate that the southerly buster and coastal pressure ridging of southeastern Australia have much in common with the alongshore surge and associated phenomena of the Pacific coast of North America.

Topographically trapped surges and related phenomena are observed at many other locations around the world. Mesoscale cold surges frequently propagate southward along the eastern slopes of the Rockies (Lilly, 1981), backdoor cold fronts and associated cold air damming are observed east of the Appalachians of the eastern United States (Carr, 1951; Bosart et al., 1973), and propagating coastal lows and associated invasions of marine air occur west of the Chilean Andes (Rutllant, 1981). It is probably no exaggeration to state that topographically trapped surges occur near most mountain barriers.

5. Conclusions and summary

This paper has examined two cases of topographically trapped southerly currents in the coastal zone. In the first case (May 1985) a relatively benign southerly transition moved northward along the California coast and then in southern Oregon was transformed into a strong, alongshore surge associated with an abrupt shift in wind direction, a rapid increase in wind speed and pressure, and the sudden onset of stratus and fog. Early in this case the southerlies were simply responding to the alongshore pressure gradient created by the synoptic scale flow. Within approximately one Rossby radius of the coastal topography (~150–200 km) the winds were a superposition of ageostrophic flow down the alongshore pressure gradient, and relatively geostrophic
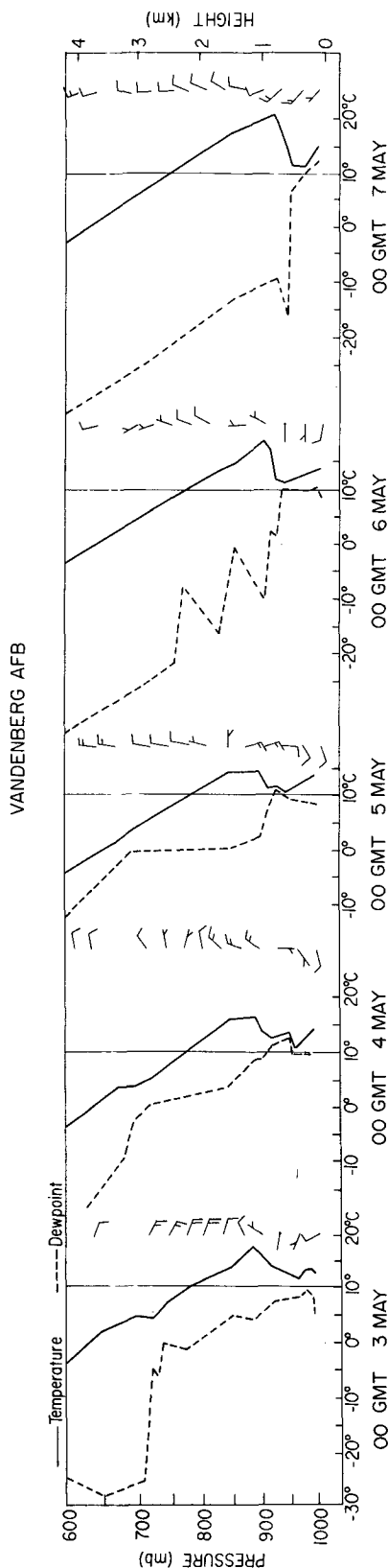
FIG. 30. Vertical soundings at Vandenberg AFB during the May 1982 event.

flow associated with the pressure gradient normal to the coast. In northern California the coastal southerlies were strengthened by nearly geostrophic flow circulating around a nearby offshore low. As synoptically forced leeside troughing occurred to the north over western Washington and southwestern British Columbia, the southerly current surged northward as a topographically trapped gravity current.

The second case (May 1982) represents a less intense event. Again, changes on the synoptic scale, interacting with coastal mountains, created an alongshore pressure gradient to which the coastal winds responded rapidly.

This paper describes some topographically trapped phenomena in the coastal zone of other regions, including the southerly buster of southeast Australia, and the coastal low and "leader front" of South Africa. It appears that these phenomena have much in common with the coastal southerlies and surges of western North America both in their synoptic environment and mesoscale structure.

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