The Onshore Surge of Marine Air into the Pacific Northwest: A Coastal Region of Complex Terrain

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ABSTRACT

Many coastal locations around the world experience rapid transitions from warm, dry continental air to cool, moist marine air. These onshore "pushes" or surges of marine air can be accompanied by strong winds, large temperature drops and a substantial increase in low clouds. A detailed case study of a typical Pacific Northwest event as well as a composite of several events are presented. It is shown that all major surges are initiated by synoptic-scale changes and that the mesoscale topography of the region "amplifies" the synoptic signal. Annual, monthly and diurnal climatologies are discussed. This paper also discusses the origin of associated West Coast phenomena such as heat troughs and narrow coastal pressure ridges.

1. Introduction

The most important warm season (April–September) forecasting problem for the western sections of Oregon, Washington and British Columbia is predicting the transition from warm, dry continental air to cool, moist marine air. Frequently, these transitions occur as onshore surges or "pushes" of marine air that are accompanied by rapid temperature drops, dewpoint rises, strong gusty winds and dramatic increases in low-level cloud cover. Occasionally, precipitation and thunderstorms are associated with these events.

The topography of the region (Fig. 1) is dominated by the north–south oriented Cascade Range, which effectively isolates the temperate coastal zone from hot, arid areas to the east. Paralleling the Cascades to the west lie the coastal mountains; however, their generally lower elevation and many gaps allow marine air to spread to the western foothills of the Cascades. As a result of the marine air influence, summer maximum temperatures west of the Cascades average in the mid-20s °C. Upwelling in the coastal waters produces cold sea surface temperatures. The substantial difference in air temperature across the coastal zone, between the cool ocean and the heated interior land, results in strong sea breeze circulations on many summer days.

Interrupting the region's temperate weather are "heat waves" of high temperature and low humidity. These warm spells are usually associated with a northward extension of the central California "thermal" or "heat" trough into western Oregon and Washington and subsiding easterly flow across the Cascades. Maximum temperatures west of the Cascades can exceed 35°C during these events. Heat waves usually intensify over a period of a few days until broken by an onshore surge of marine air.

The most intense surges are often similar to mesoscale cold fronts since they can possess strong winds of 20 m s^{-1} or more, temperature drops of 5°–10°C within a few hours, and a considerable increase in low cloudiness. In other cases the marine air gradually infiltrates the area over a period of one or two days as synoptic conditions slowly evolve. The first day after a surge is normally the coolest and most cloudy with progressive clearing and warming during subsequent days. This cycle is repeated several times each summer.

In addition to the general public, many specific activities are strongly impacted by the occurrence of an onshore surge. For example, the presence of moist, marine air is a crucial factor in forest fire initiation and control. Aviation and boating can be greatly influenced by the often dense envelope of low-level stratus and fog present after marine air has invaded the region. Both small pleasure boats and aircraft are endangered by the strong winds often associated with the mesoscale fronts of vigorous surges.

Although there is a rich and varied literature on the coastal phenomena of Oregon (e.g., Cramer, 1973; Cramer and Lynott, 1970; Johnson and O'Brien, 1973), California (e.g., Schroeder et al., 1967, Fosberg and Schroeder, 1966; Bosart, 1983; Dorman, 1985) and Washington (e.g., Kinzebach, 1955; Staley, 1957; Mass, 1982; Jackson, 1983), no paper has thoroughly described the onshore surge. However, several of the above authors recognized the existence of this phenomenon, its apparent initiation by the approach of an upper-level trough, and the northward progression

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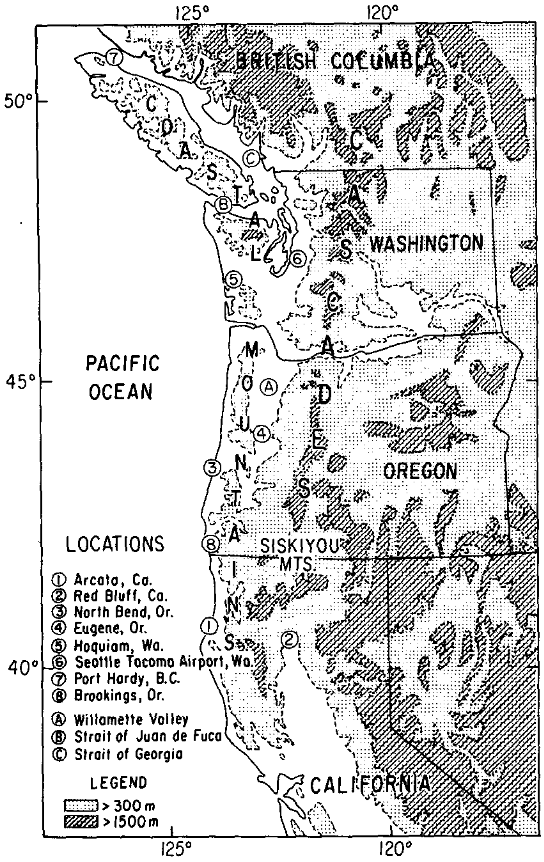

FIG. 1. Topography and important locations of the Pacific Northwest.

of both the California heat trough and coastal stratus that precedes most events. Furthermore, Kinzebach (1955) established useful rules for forecasting the inundation of stratus that often accompanies a significant onshore surge event.

The onshore surge represents a class of phenomena in which synoptic-scale changes are enhanced or amplified by mesoscale terrain. Such phenomena occur in coastal regions throughout the world. For example, Wilson and Stern (1985), Ryan and Wilson (1985) and others have described the Australian summertime "cool change," which is also characterized by a transition from warm, offshore flow to cool, marine air in a region with coastal topography. Similar phenomena have been reported off Chile and southern Africa (Gill, 1977; Preston-Whyte, 1975).

This paper describes the evolution and three-dimensional structure of the onshore surge as well as its basic physical mechanisms. Monthly and diurnal climatologies are examined and the potential for skillful forecasting is evaluated. Finally, closely related aspects of the meteorology of the Pacific Coast, such as stratus movement, thermal troughs and coastal pressure ridges, are also discussed.

2. A case study

Although onshore surges can vary somewhat in their evolution, many basic features are shared by the majority of such events. In this section we will present the case of 26–31 May 1983, which we believe is typical of a large number of cases.

To gain an overview of the event, consider the GOES visible satellite imagery shown in Fig. 2. On 26 and 27 May 1983 at 1800 GMT (Figs. 2a, b) much of the eastern Pacific was covered with clouds, mainly stratus and stratocumulus, which did not penetrate beyond the relatively low coastal mountains of California. The coastal ocean off the Pacific Northwest was nearly cloud free, due to an offshore flow of continental air. A tongue of stratus that hugged the northern California and southern Oregon coasts slowly widened and moved northward during this period. By 1800 GMT 28 May (Fig. 2c) both the tongue of stratus and the area of coastal clearing had moved northward. Some higher clouds, associated with a short wave aloft, are evident over California and the offshore waters. By 1800 GMT the next day (29 May, Fig. 2d) an offshore frontal system was located about 600 km off the northern California coast, and coastal stratus had penetrated further inland at several locations. Both the tongue of stratus and the region of coastal clearing continued to move northward. Roughly six hours later (0000 GMT 30 May, Fig. 2e) the front had progressed eastward and appeared to be weakening rapidly. Note how the low-level cloudiness seemed to disappear east of the front; this clearing is particularly dramatic off northern California where a nearly solid cloud cover had evaporated in six hours. Stratus appears to have begun moving inland in parts of the Oregon and Washington coasts. The marine air invaded the Pacific Northwest during the next 12 h so that by 1800 GMT 30 May (Fig. 2f) the visible imagery shows low clouds west of the Cascades of Oregon, Washington and British Columbia. Little remained of the once vigorous-looking Pacific front.

The temperature, sea level pressure and surface wind evolution at several Northwest locations (see Fig. 1) during the May 1983 event is shown in Fig. 3. On the coasts of northern California (Arcata) and southern Oregon (North Bend) the continual presence of marine air resulted in relatively small diurnal temperature variations with maximum temperatures remaining less than 21°C throughout the entire period. On the other hand, at Hoquiam, on the Washington coast, a period of offshore (easterly) flow (from 1800 GMT 27 May to 1800 GMT 28 May) was associated with warmer temperatures reaching 27°C. Sea level pressure at these coastal stations fell early in the period and then rose rapidly on 29 May, with rising pressure generally associated with westerly or southwesterly winds (i.e., the influx of marine air).

At the inland stations east of the coastal mountains, the situation was very different. At Red Bluff, in Cal-

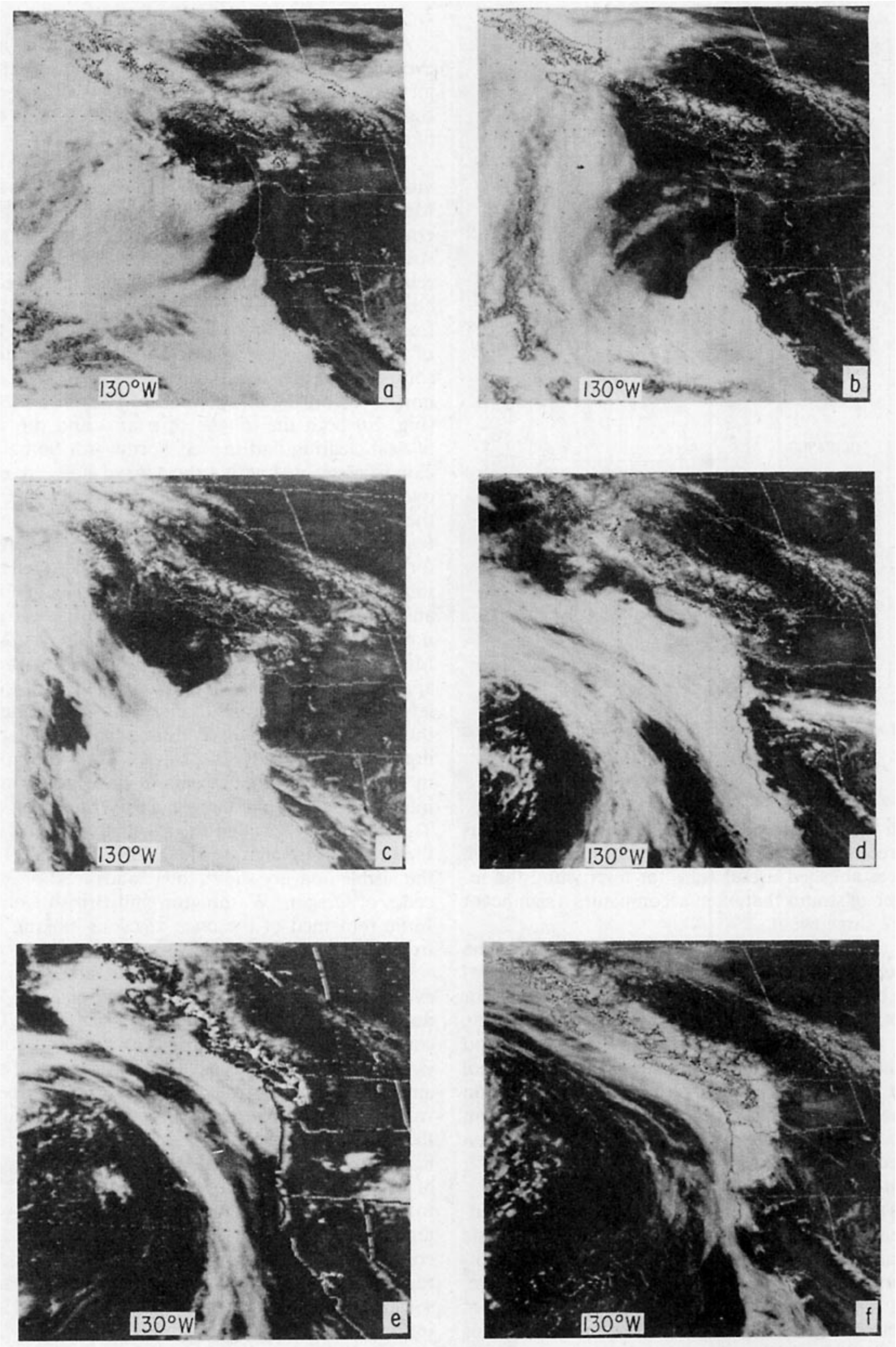

FIG. 2. GOES visible satellite imagery of the Pacific Northwest for (a) 1800 GMT 26 May, (b) 1800 GMT 27 May, (c) 1800 GMT 28 May, (d) 1800 GMT 29 May, (e) 0000 GMT 30 May and (f) 1800 GMT 30 May 1983.

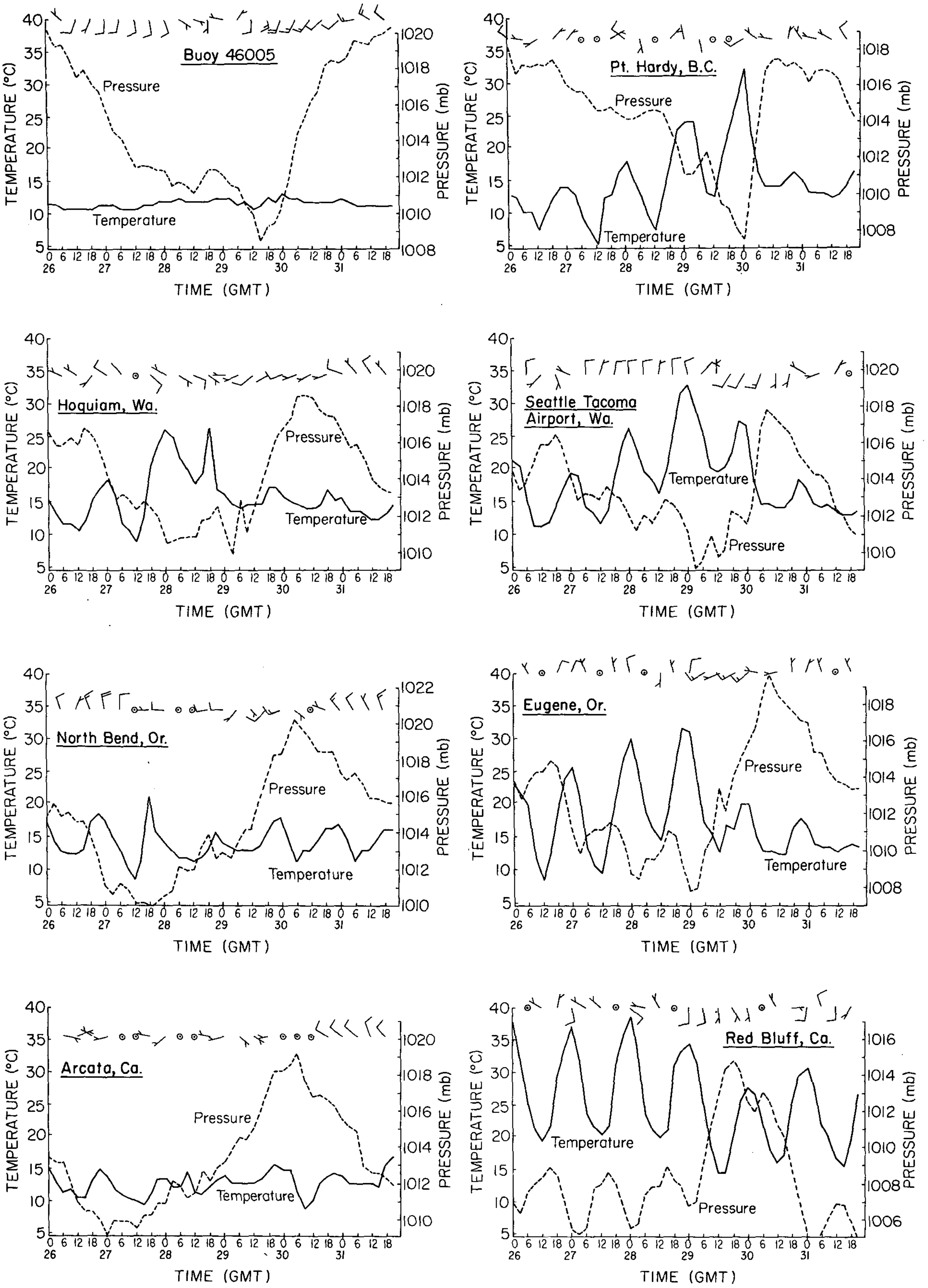

FIG. 3. Temperatures, sea level pressures and winds at Buoy 46005 (46°N, 131°W), Port Hardy, B.C.; Hoquiam, WA; Seattle–Tacoma Airport, WA; North Bend, OR; Eugene, OR; Arcata, CA; and Red Bluff, CA, from 0000 GMT 26 May through 2100 GMT 31 May. See Fig. 1 for locations.

ifornia's interior valley, temperatures exhibited a large diurnal cycle with maxima exceeding 38°C. However, around 0000 GMT 29 May, marine air began to move into the area as suggested by a shift to southerly winds, a substantial temperature drop and a subsequent rapid rise in sea level pressure. Further north at Eugene, in Oregon's Willamette Valley, warming and a large diurnal temperature cycle were observed through 0000 GMT 29 May. Subsequently, the winds shifted from weak northerlies to moderate southwesterlies as marine air began to invade the area. In concert with the wind shift, pressure rose rapidly and the temperature maxima of the next two days dropped precipitously. At Seattle–Tacoma Airport, located in western Washington, temperatures rose rapidly from 26 May through 29 May, culminating with a maximum temperature of 34°C on 28 May. During the same period this station experienced generally northerly winds and falling sea level pressure. By 1800 GMT 29 May the winds at Seattle–Tacoma switched to southwesterly as marine air began to move in. As a result, the maximum temperature on this day was ~5°C less than that of the previous day and sea level pressure began to rise. The next day the marine layer continued to deepen and the daily maximum temperature was held to only 18°C.

Port Hardy, located near the northern tip of Vancouver Island, experienced steady warming and falling pressure through 0000 GMT 30 May. Subsequently, the winds shifted to westerly, pressure jumped sharply, and the next day's temperature plummetted as cloudy, marine air flooded the area. Figure 3 also presents the observations at Buoy 46005, located about 800 km west of the northern Oregon coast. Unlike the land stations, there is little diurnal variation of temperature or pressure. Sea level pressure generally fell until 1500 GMT 29 May and then rose rapidly after frontal passage at approximately 0000 GMT 30 May. It is significant to note that both the pressure minimum and subsequent pressure rise at the buoy were later than similar events at every land station except Port Hardy, in the northern part of the domain.

The National Meteorological Center (NMC) 500 mb analyses (Fig. 4) indicate that prior to the surge (0000 GMT 26 May through 0000 GMT 30 May) there was dramatic ridging along the West Coast as well as southeastward digging of a closed low west of the Oregon coast. At the same time a short-wave trough initially located near 30°N, 140°W rotated northeastward around the larger-scale low and up the West Coast. During and shortly after the main surge (approximately 0000 GMT 30 May) the ridge moved northward into Canada and the closed low retreated to the northwest, leaving a col over the Pacific Northwest.

At 850 mb (Fig. 5) a weak offshore ridge amplified and progressed eastward during the days before the surge. As at 500 mb, a closed low drifted southeastward with a smaller-scale short wave rotating northeastward around its periphery. A pronounced thermal ridge developed in the western United States and Canada. It is significant to note that the warmest 850 mb temperatures on the coast occurred as the 850 mb short-wave trough approached from the south. This warming moved northward with the trough and was associated with easterly flow north of the trough. After the surge (31 May) the 850 mb isotherms were packed west of the Cascades as cooler air inundated the area west of the mountains.

The NMC surface analyses (Fig. 6) indicate that this case began (0000 GMT 26 May) with the mean summertime configuration of high pressure in the eastern Pacific and a thermal trough over central California. During the next three days (through 0000 GMT 29 May) the high pressure center moved northeastward into western Canada and then extended southward to the east of the Rocky Mountains. At the same time the California heat trough moved northward into the Willamette Valley of Oregon and then northwestward along the coasts of Washington and British Columbia. Farther west a low pressure center with associated fronts moved toward the east. During the next day (1200 GMT 29 May–0000 GMT 30 May), as the front approached land, a narrow coastal pressure ridge developed northward. Finally, following the surge (31 May) high pressure was restored to the eastern Pacific and the thermal trough shifted eastward, stretching from the interior of British Columbia into Nevada.

To better delineate the mesoscale evolution of this onshore surge, a series of detailed regional surface analyses were made (Fig. 7). To create these maps all available ship,[1] buoy and land stations were used in conjunction with high resolution visible satellite imagery.

The surface analysis for 1800 GMT 26 May (Fig. 7a) is typical of many summer days. High pressure in the eastern Pacific bulged northeastward into the Pacific Northwest. To the south the California thermal trough, apparently blocked by the Siskiyou Mountains of southern Oregon and northern California, extended into northern California and then angled westward to the coast.[2] Between the high pressure to the northwest and the thermal trough, there was a large sea-level pressure gradient near the Oregon–California border and in the adjacent coastal region. This gradient was associated with strong northerly and northeasterly winds in the coastal zone (Friehe and Winart, 1982). One notes (also see Fig. 2a) that the northern boundary of the coastal stratus was located within the coastal low. To the north of the stratus, northeasterly flow transported warm, dry continental air, while within the

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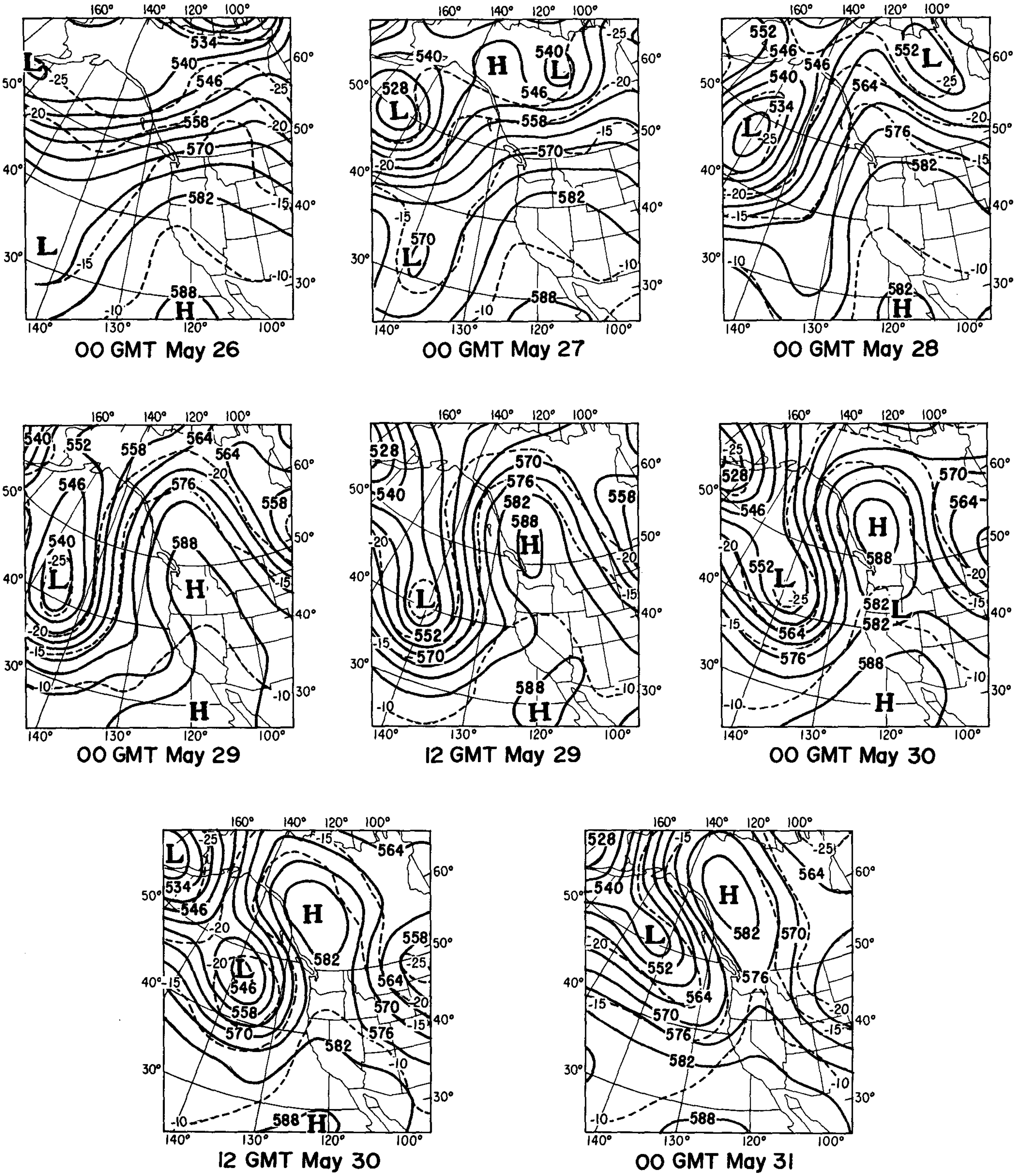
[1] The sea level pressure reports from each ship were compared to other ships, buoys and coastal stations to remove consistent biases.

[2] This coastal trough or "Brooking's Low," named after nearby Brookings, Oregon, is often associated with anomalously warm temperatures along a very limited stretch of the Pacific Coast near the Oregon–California border.



00 GMT May 26 00 GMT May 27 00 GMT May 28

00 GMT May 29 12 GMT May 29 00 GMT May 30

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FIG. 4. National Meteorological Center (NMC) 500 mb charts for 0000 GMT 26 May 1983 through 0000 GMT 31 May 1983. Solid lines are geopotential heights (decameters) and dashed lines are isotherms (°C).

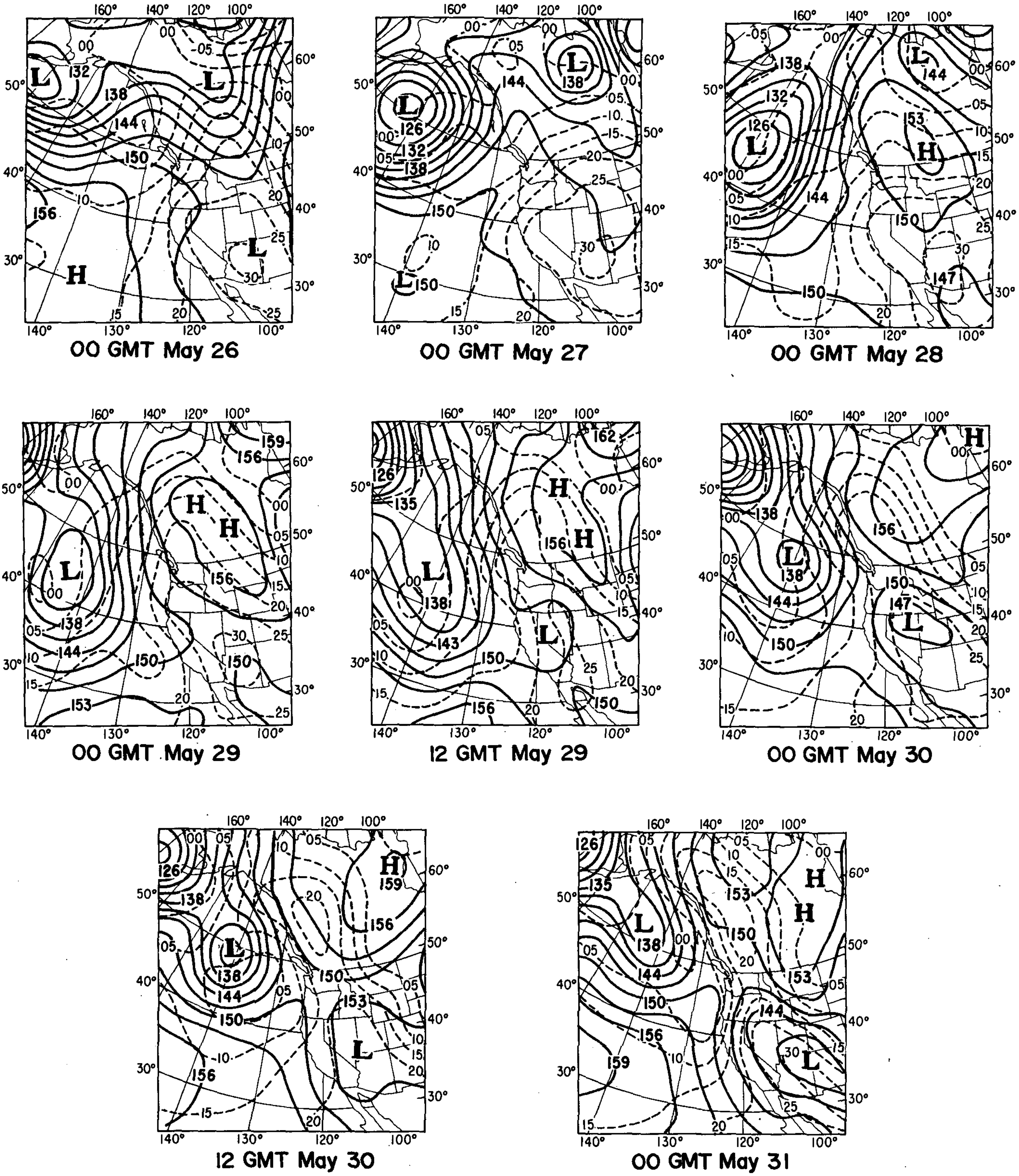

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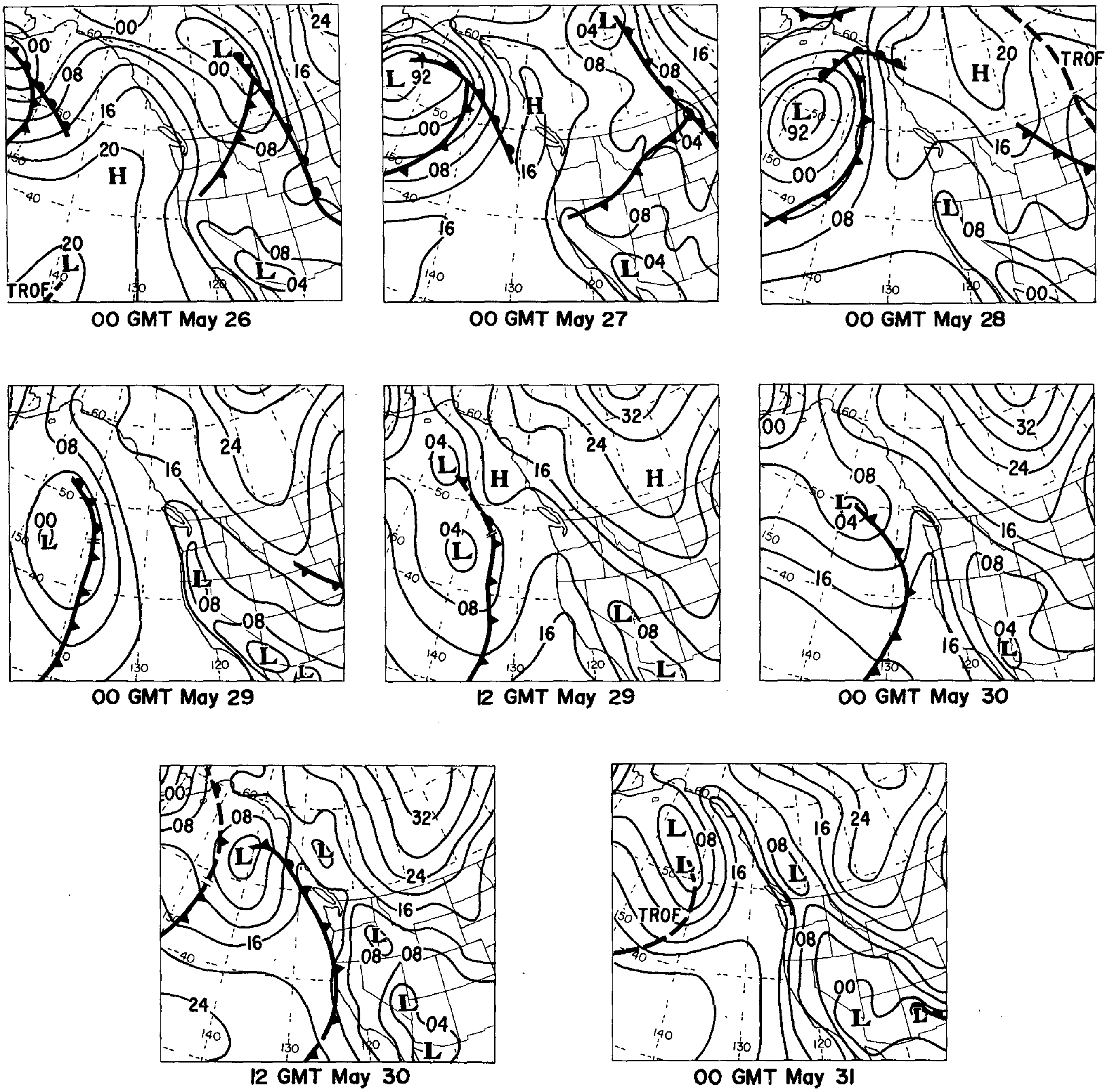
FIG. 5. NMC 850 mb charts for 0000 GMT 26 May through 0000 GMT 31 May 1983.



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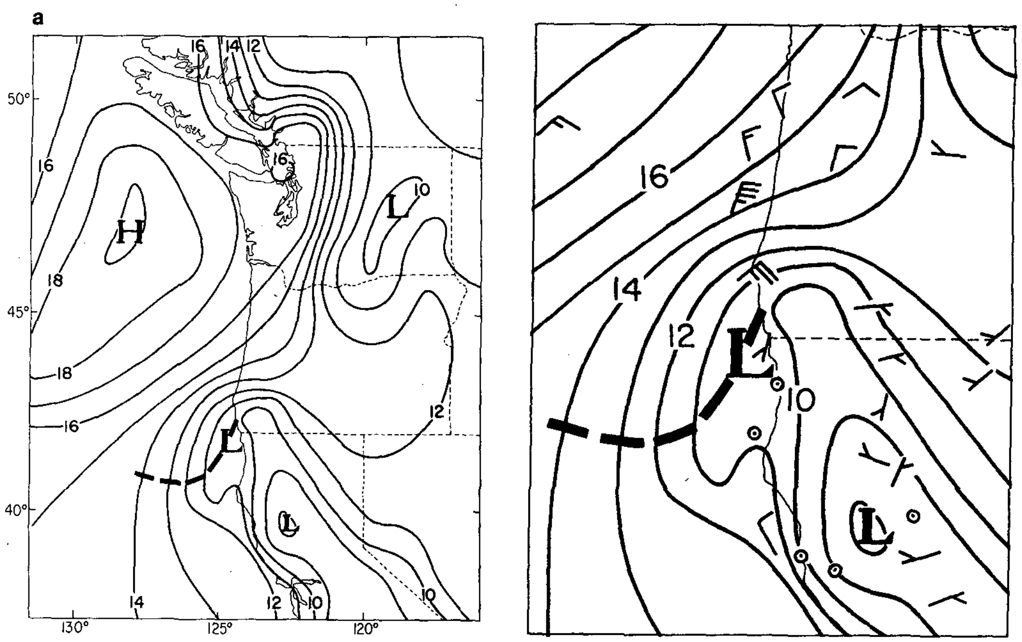
12 GMT May 30 | 00 GMT May 31

FIG. 6. NMC sea-level pressure analyses for 0000 GMT 26 May through 0000 GMT 31 May.

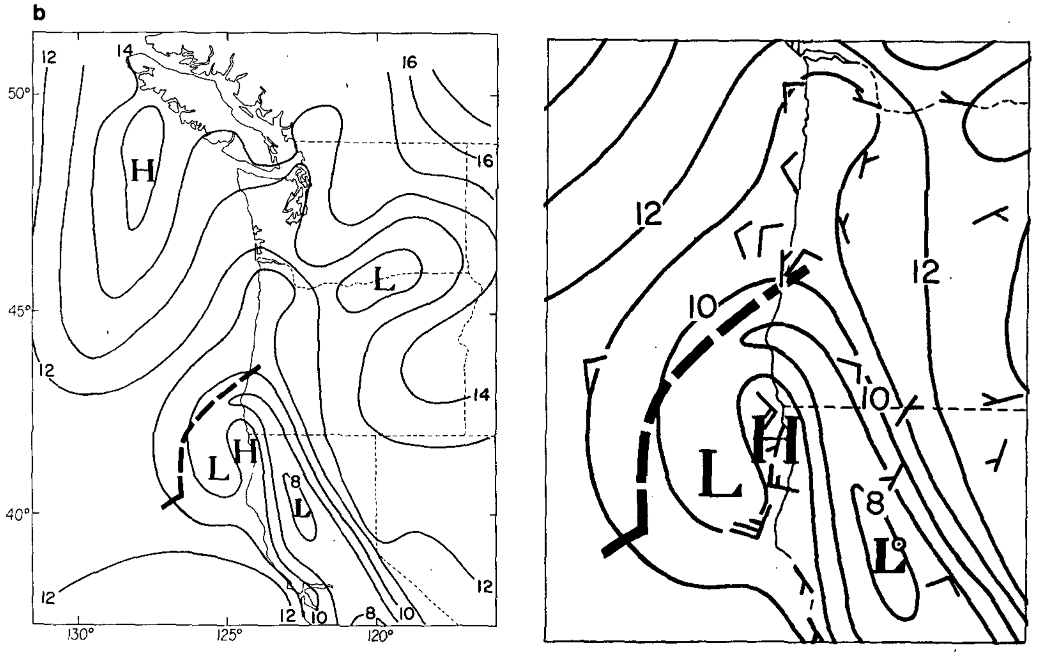
stratus and close to the coast the winds were generally light southerly; i.e., they possessed an overwater trajectory.

A day later (Fig. 7b) the eastern Pacific high had weakened while sea level pressure built rapidly east of the Cascades from British Columbia to Oregon. At the same time the stratus tongue widened and, in step with the coastal trough, began moving northward up the Oregon coast.

By 1800 GMT on 28 May (Fig. 7c) high pressure was well established east of the Cascades with the exception of a persistent thermal trough in an area of low elevation on the Oregon–Washington border. West of the Cascades, the thermal trough moved northward up the Willamette Valley into southwest Washington. Following the thermal trough, coastal stratus moved northward to the central Washington coast. South of the stratus boundary, coastal ridging and southerly or



1800 GMT May 26

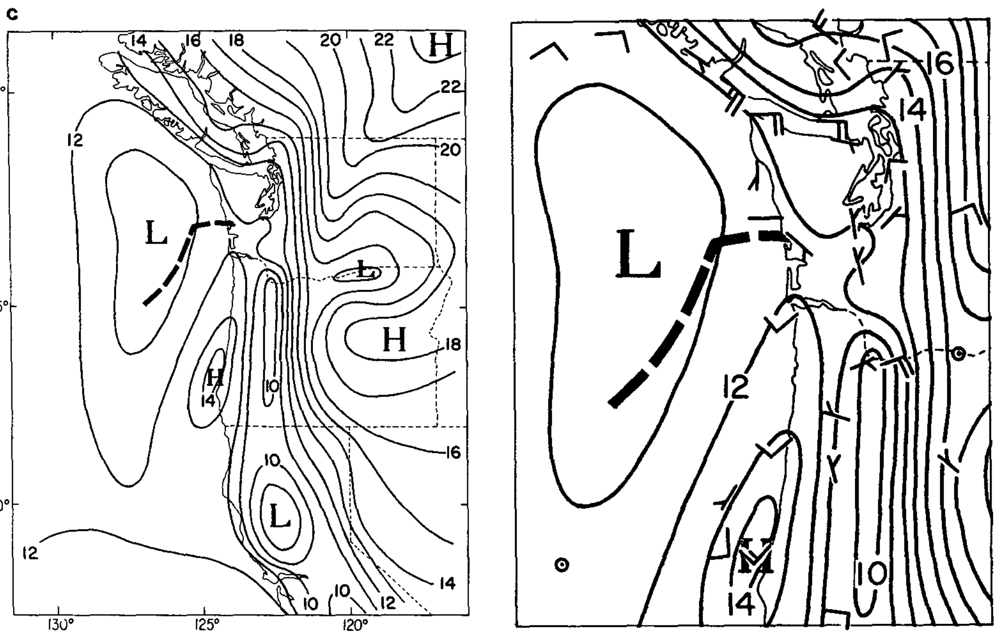


1800 GMT May 27

FIG. 7. Mesoscale sea-level pressure analyses for (a) 1800 GMT 26 May, (b) 1800 GMT 27 May, (c) 1800 GMT 28 May, (d) 1800 GMT 29 May, (e) 0000 GMT 30 May, (f) 0600 GMT 30 May and (g) 1800 GMT 30 May. Right-hand panels are enlarged sections of the regional (left-hand) analyses. Dashed lines indicate the northern boundary of the coastal stratus.

southwesterly winds were observed, while to the north the winds possessed an easterly component.

By 1800 GMT on 29 May (Fig. 7d) a weakening cold front had entered the domain from the west and the coastal pressure ridge had intensified and moved northward to Vancouver Island. The coastal trough,



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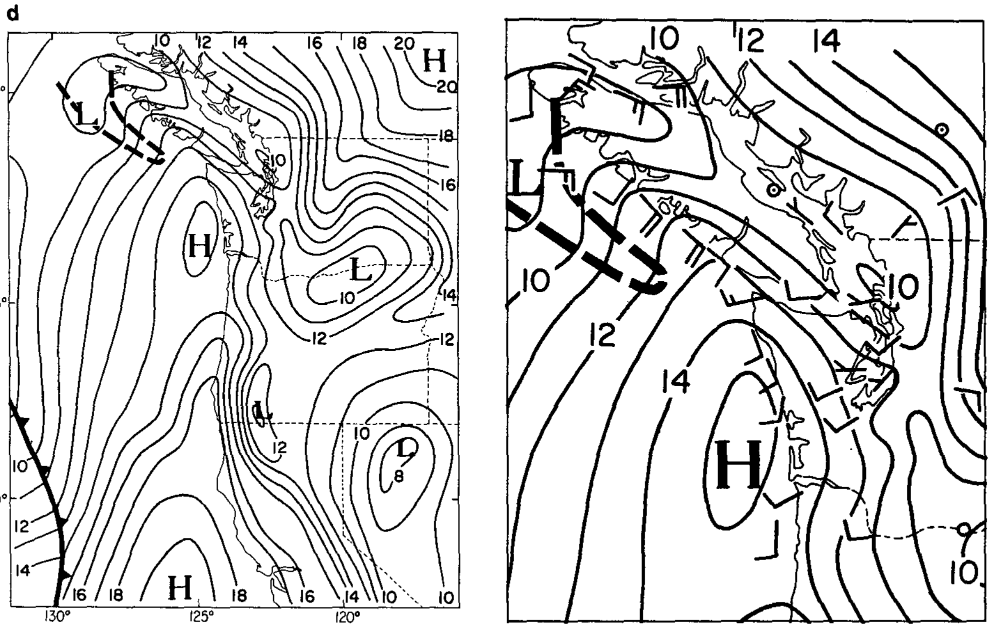
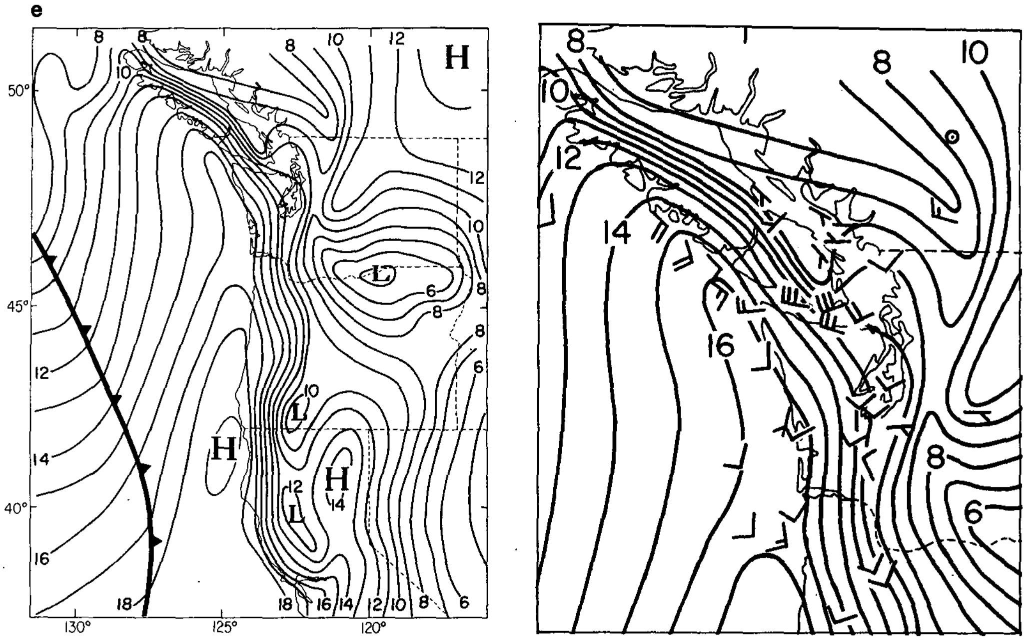


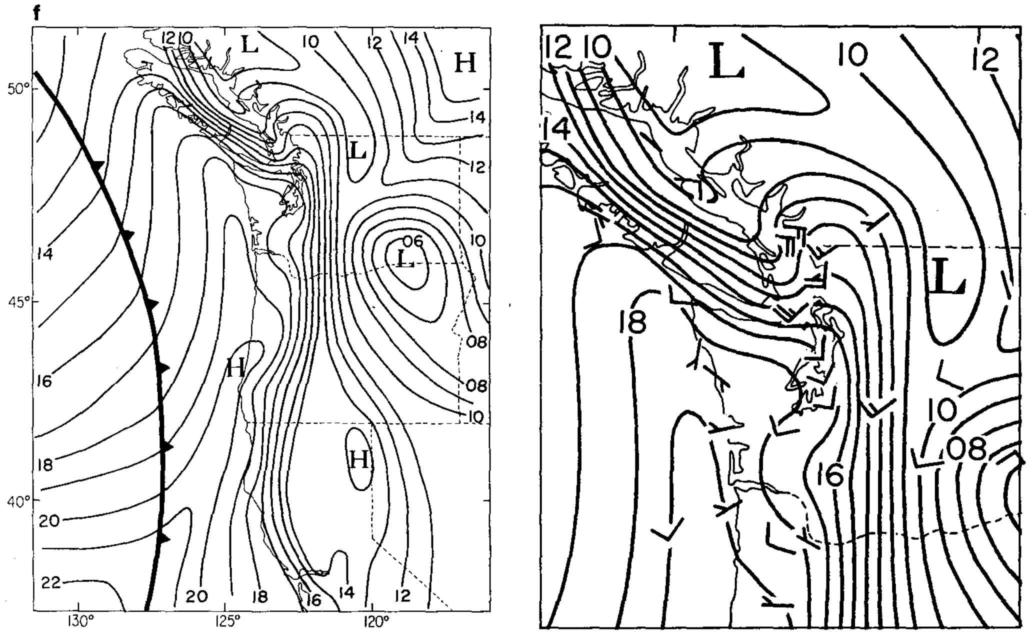
1800 GMT May 29

FIG. 7. (*Continued*)

located off northern Vancouver Island, again marks the northern boundary of the sharply defined stratus tongue. Paralleling the stratus, the inland heat trough moved northward through Puget Sound and east of Vancouver Island. By this time the heat trough in California and much of the Willamette Valley had nearly disappeared as cool marine air moved inland through gaps in the coastal mountains and as pressure fell rapidly in the eastern portions of Oregon, Washington and California.



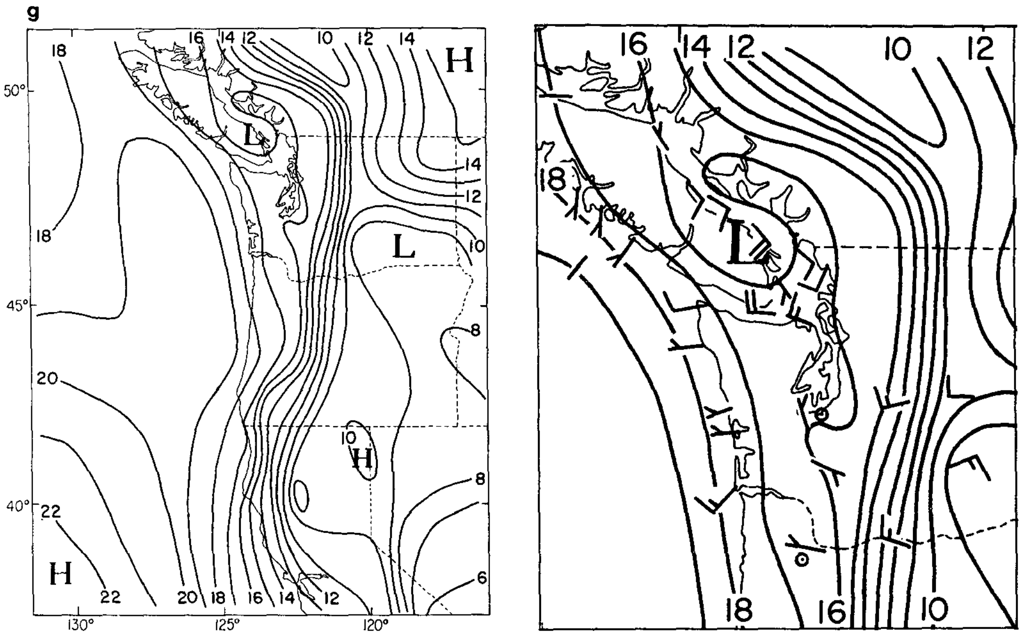
0000 GMT May 30



0600 GMT May 30

FIG. 7. (*Continued*)

Six hours later at 0000 GMT 30 May (Fig. 7e) as the offshore front continued its eastward movement, the coastal pressure ridge further intensified and the coastal low moved northwest of Vancouver Island. With an intense pressure gradient between the coastal pressure ridge and the inland pressure trough, marine air began to surge into the interior portions of western Washington and southwestern British Columbia. Strong winds of 15–20 m s^{-1} were observed in the Strait of Juan de Fuca and along the northwest coast of Van-



1800 GMT May 30

FIG. 7. (*Continued*)

couver Island. Troughing continued in eastern Washington and Oregon, and high pressure to the northeast rapidly weakened.

By 0600 GMT 30 May (Fig. 7f) isobars were packed over the Cascades as cool, marine air inundated western Oregon and Washington and as troughing continued east of the mountains. East of Vancouver Island along the Strait of Georgia, marine air surged northwestward towards lower pressure.

Finally, on 1800 GMT 30 May 1983 (Fig. 7g) the onshore surge was complete with marine air and stratus covering the entire region west of the Cascades. Little remained of the Pacific front, and high pressure was rebuilding over the eastern Pacific.

Figures 8a and 8b present time–height analyses of potential temperature and wind at two Pacific Northwest radiosonde locations: Salem, located in Oregon's Willamette Valley, and Quillayute, positioned on Washington's northwest coast. At Salem (Fig. 8a) lowering isentropes indicate warming from 26 May through 0000 GMT 29 May, with the largest potential temperature variation occurring in the lower troposphere below ~750 mb. Through 0000 GMT 29 May winds were generally northerly or northeasterly below 900 mb (approximately pass level in the nearby Cascade Mountains) with the largest low-level warming associated with an increasing easterly component. Warming in the air above was associated with synoptic-scale subsidence and warm advection. Between 0000 and 1200 GMT on 29 May marine air pushed into the Willamette Valley; below 900 mb winds switched from weak northerlies to moderate or strong southwesterlies and potential temperature dropped rapidly. Also evident on the cross section is a strong diurnal modulation of potential temperature below 950 mb with minima occurring at 1200 GMT (0400 LST). This modulation is greatly attenuated after the surge.

Lower tropospheric warming from 26 through 29 May was also observed at Quillayute, on the Washington coast (Fig. 8b). Early in this period (through 0000 GMT 27 May) the winds below 900 mb were generally northwesterly, while later an easterly component accompanied pronounced warming. By 0000 GMT 29 May some cooling, associated with a shift to southwesterlies, was observed in the lowest few hundred meters. The major transition occurred between 1200 GMT 29 May and 0000 GMT 30 May as potential temperatures dropped and winds switched to moderate southerlies in the lower troposphere.

Additional insight into the lower tropospheric changes along the Washington coast are provided by the Quillayute sounding for several times during this event (Fig. 9). From 0000 GMT 27 May through 0000 GMT 28 May there was substantial warming, especially below 800 mb, as well as a significant drop in dewpoint in much of the lower troposphere. At 0000 GMT 29 May temperatures had continued to increase between 950 and 850 mb, apparently associated with easterly flow in this layer. Below 960 mb a veneer of marine air, pushing in from the southwest, was associated with

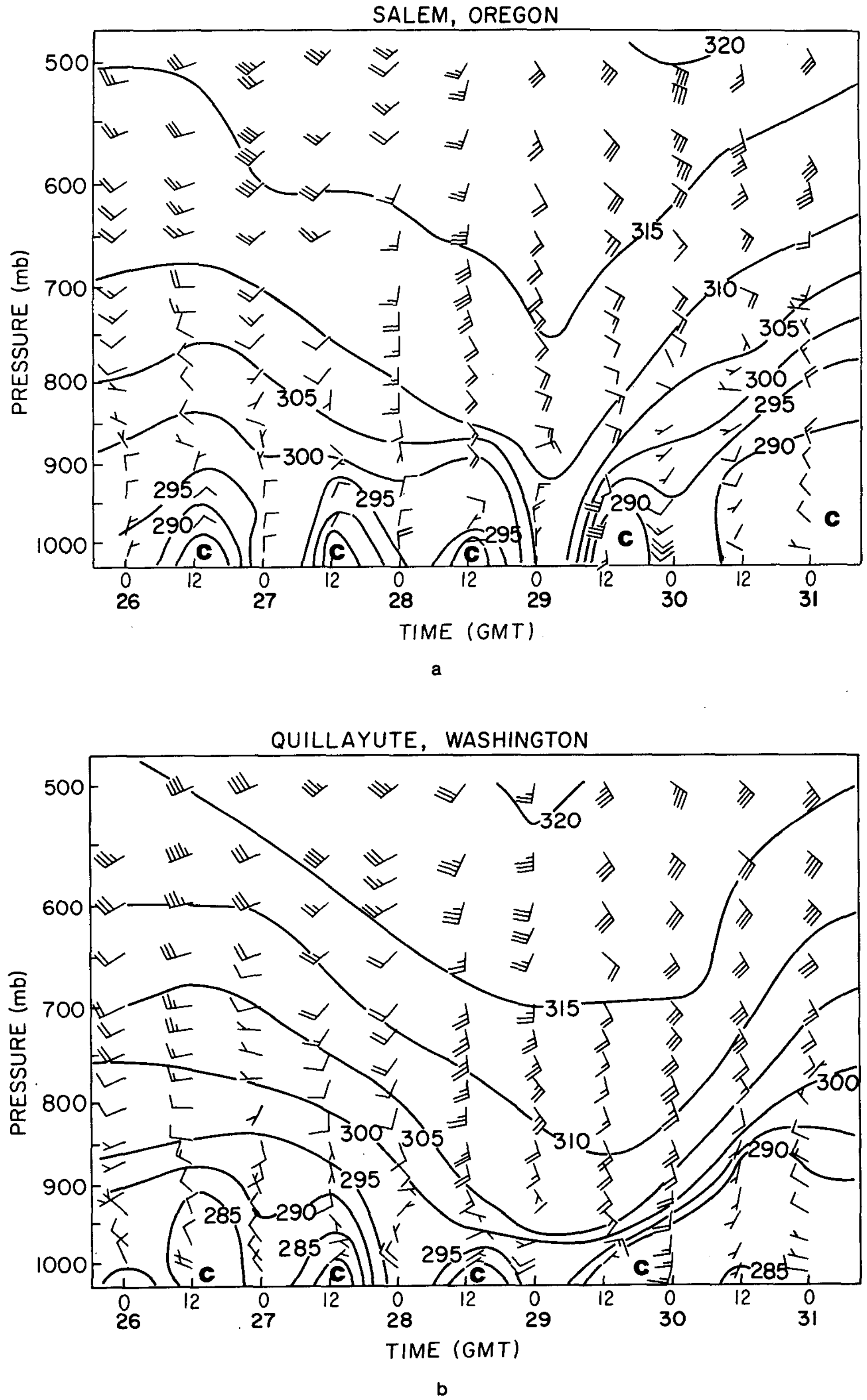


FIG. 8. Time–height analyses of potential temperature and winds at (a) Salem, OR, and (b) Quillayute, WA.

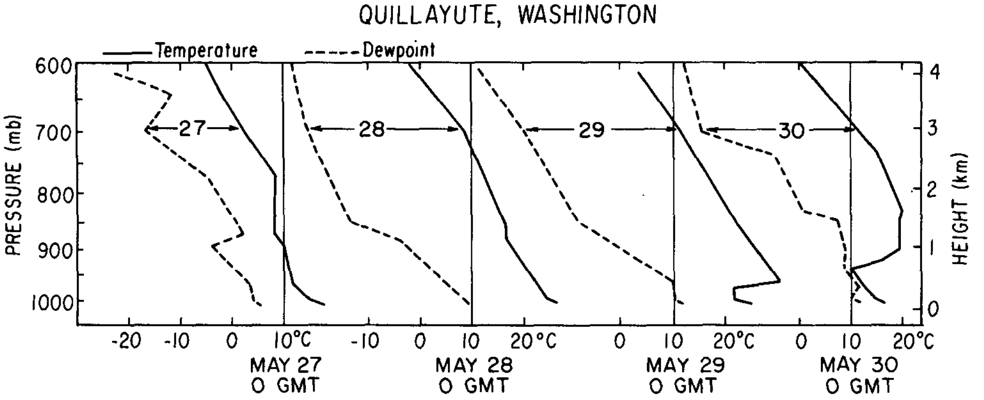


FIG. 9. Quillayute temperature and dew-point soundings from 0000 GMT 27 May through 0000 GMT 30 May.

shallow cooling below the still warming air above. At 0000 GMT 30 May as marine air began to surge inland, cooling occurred mainly below 850 mb. A nearly saturated, well-mixed marine layer was then observed up to ~940 mb. In summary, the Quillayute soundings indicate that the intrusion of marine air was a two-step process: first, a shallow layer of marine air moved in during the initial stratus surge up the coast, and later a deeper layer of cooling was associated with the main surge of marine air inland.

3. Synoptic scale control

A major question faced at the beginning of this study was whether the occurrence of an onshore surge requires a substantial synoptic-scale change or whether heating over land alone is sufficient to draw in marine air. After completing nearly ten case studies and observing dozens of additional events, it became apparent that virtually every significant onshore surge is preceded by synoptic-scale ridging aloft and that the influx of marine air is initiated by the approach of an upper-level trough. At the surface, surges are normally preceded by high pressure building east of the Cascades with the surge occurring as a surface frontal trough approached the coast from the west.

To more clearly illustrate the relationship of the surge to synoptic-scale changes, we composited 33 cases of strong surges observed between April and October 1970–82. These strong surges were identified by searching for 10°C drops in maximum temperature between contiguous days at Seattle–Tacoma Airport. This criteria effectively selects strong pushes while rejecting weak summertime fronts. Using the National Meteorological Center (NMC) grid-point dataset (horizontal resolution of 380 km), we composited sea level pressure and 500 mb heights every 12 h from 72 h before to 48 h after the event. For the sake of this analysis we defined the event time as 0000 GMT (1600 PST, Pacific Standard Time) of the last warm day.

Figure 10 presents the time evolution of composited 500 mb heights as well as the summer mean 500 mb analysis at 0000 GMT. Figure 11 presents the difference between these 500 mb composites and the summer mean field. These figures indicate that between 72 and 24 h before a surge a significant upper-level ridge develops along the west coast of North America. At −24 h (minus indicating before the event time) the ridge is associated with a 137 m positive height anomaly centered over the British Columbia coast. As the high builds and slowly moves inland, an eastward-moving trough over the eastern Pacific is also apparent. During the 24 h before the surge (−24 to 0 h) both ridge and trough drift eastward and the height anomalies gradually lessen. By 0 h a single, negatively tilting trough stretches from just off the California coast northwestward toward the Gulf of Alaska. During the next 48 h both the trough and ridge continue to weaken and move northeast while another trough south of Alaska deepens and drifts to the east.

The sea-level pressure composites (Fig. 12) show that at −72 h high pressure dominates much of the eastern Pacific with low pressure centered both over the Aleutians and in the familiar thermal trough of California and Mexico. The pressure deviation (from the 0000 GMT summertime mean) composites at this time (Fig. 13) indicate that the greatest variations from the mean pattern are associated with the extension of the Pacific high toward British Columbia as well as troughing south of Alaska. Through −24 h high pressure builds into British Columbia and then spreads southward to the east of the Rocky Mountains. This feature is probably an example of a topographically trapped Rossby wave (Hsu and Wallace, 1985.) At the same time, the Pacific trough moves eastward and the inland California trough extends northward. In the subsequent 24-h

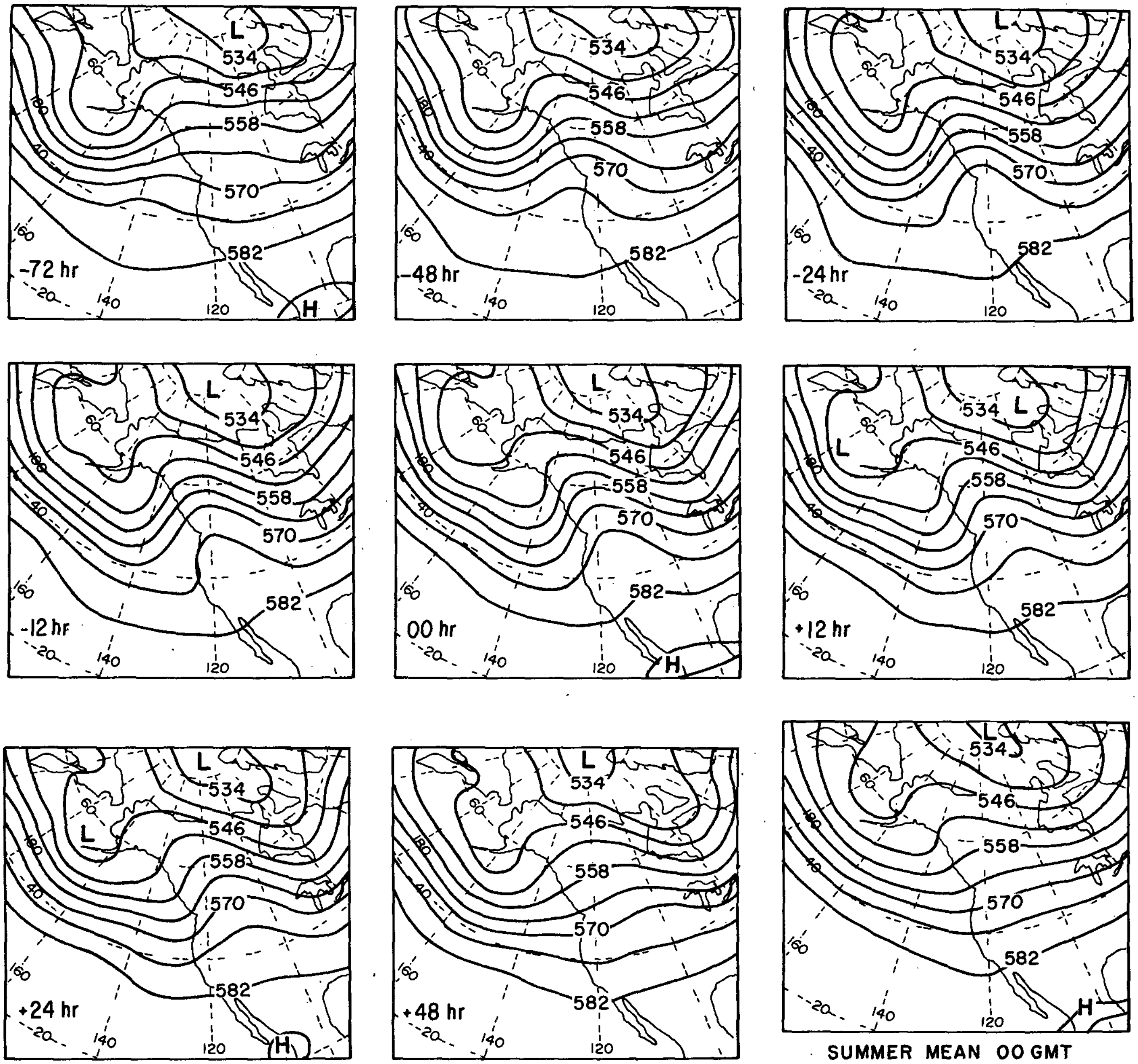


FIG. 10. 500 mb geopotential height composites based on 33 strong (≥10°C maximum temperature drop) surge cases. Hours shown are relative to the nominal time of the onshore surge. Contours are in decameters and the interval is 60 m.

period (−24 to 0 h), the West Coast thermal trough continues to intensify and move northward while the inland lobe of high pressure slowly attenuates and continues its southeast movement over the American Midwest. The Pacific trough fills rapidly while heading northeast. Finally, during the 48 h after the event, the thermal trough shifts eastward and weakens as the Pacific High again extends into the Pacific Northwest.

A natural question is whether the synoptic evolution presented in the above composites is representative of weaker events. To help answer this question similar composites were made for a set of substantially weaker events, i.e., all the 7.2°–7.8°C one-day maximum temperature drops between April and October at Seattle–Tacoma Airport for 1970 through 1982. Like the ≥10°C cases, these surges were preceded by 500 mb ridging over the Pacific coast with the surge initiated by the approach of a Pacific trough. However, the ridge

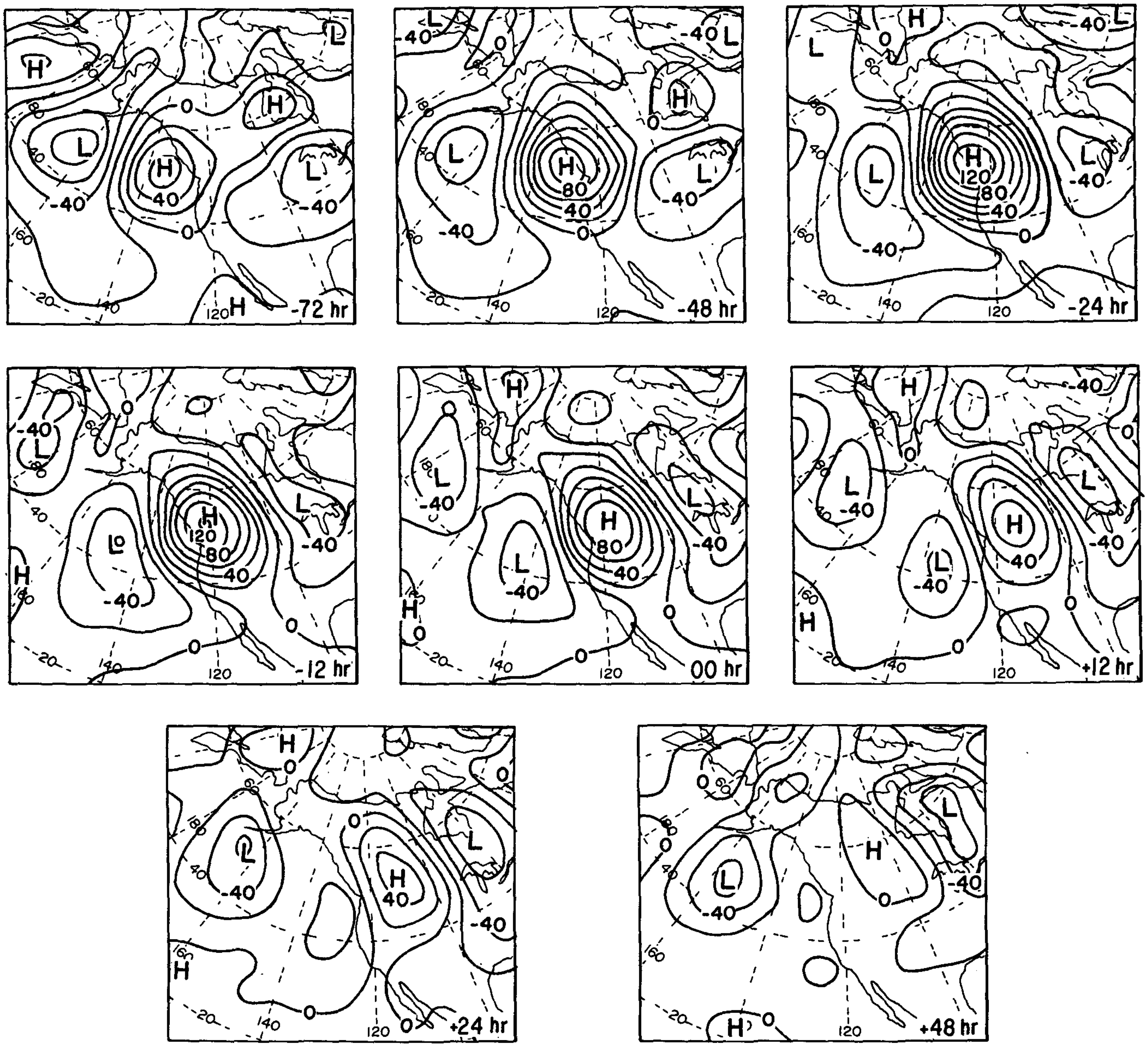


FIG. 11. Differences between the 500 mb geopotential height composites and the 0000 GMT summertime mean for strong surge cases. Contours are in meters and the contour interval is 20 m.

amplitude was substantially less for the weak surge cases and the trough was ~10° longitude farther offshore at the time of the push. At the surface, high pressure did not build up as much to the north and east of the Pacific Northwest, and the California heat trough extended only tenuously into Washington and Oregon.

4. Onshore surge climatology

The onshore surge events of Oregon, Washington and British Columbia are most frequent and of greatest amplitude during the warm season of April through September. To define this seasonal variation we examined the drops in maximum temperature between contiguous days at Seattle–Tacoma Airport for the period 1955–84. As noted above, a large drop in maximum temperature is a good indicator of onshore surge occurrence. It is also important to note that the Pacific fronts that pass through the Pacific Northwest rarely are associated with large temperature drops, even during the winter.

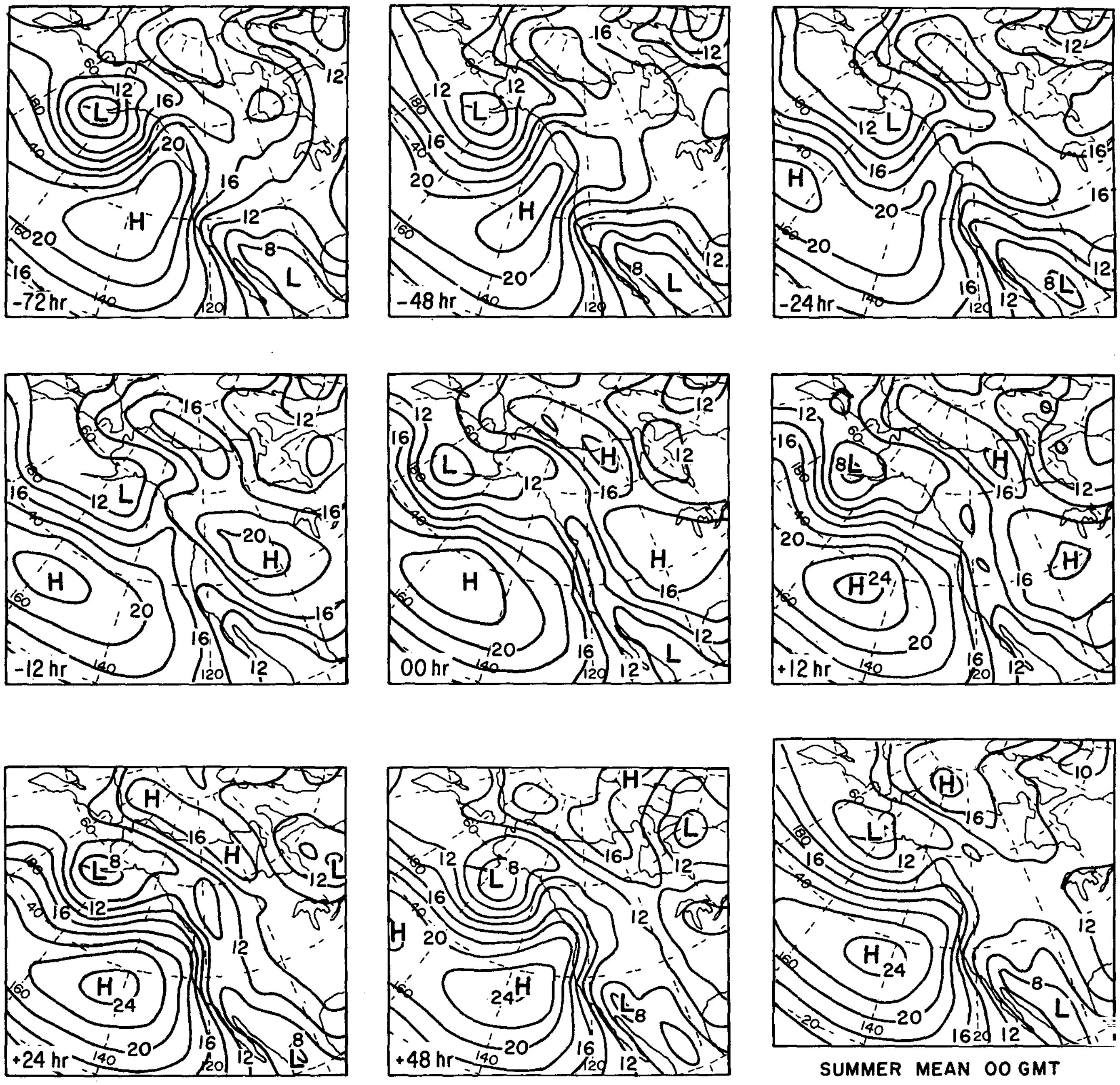


FIG. 12. Sea-level pressure composites for strong surge cases. Contours are for 10xx mb and the contour interval is 2 mb.

The results are summarized in Fig. 14, which breaks the temperature drops into several ranges. The most striking aspect of this figure is that moderate or greater (≥4.4°C) one-day falls in maximum temperature are most frequent from April through September, averaging three to four events per month. Breaking down the drops into subcategories, we find that for 4.5°–6.7°C temperature drops the greatest number of events is in August, while for drops ≥10°C, May is the month of greatest frequency. The larger drops are virtually nonexistent during the colder months of the year.

Considering that frontal passages are more frequent and vigorous during the winter months, how can one explain the summertime maximum in the frequency of moderate and large temperature drops? The essential point is that large temperature drops and onshore surges are generally preceded by warming to temperatures that are above the mean for that time of the

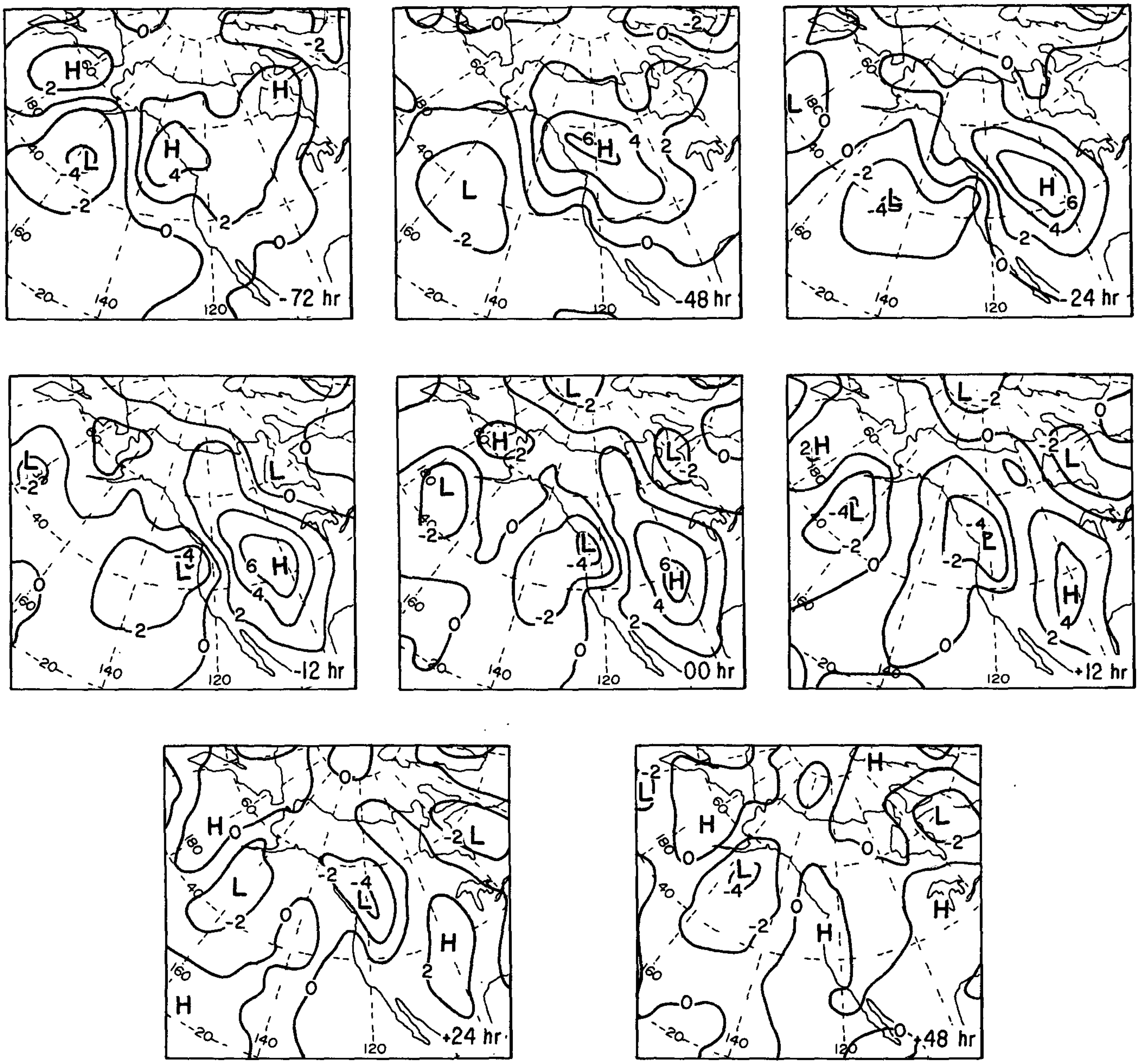


FIG. 13. Differences between the sea-level pressure composites and 0000 GMT summertime mean. The contours are in mb and the interval is 2 mb.

year. In a real sense, the warming preceding a surge or push is more anomalous than the subsequent cooling. During the winter, low-level flow is generally off the relatively warm Pacific Ocean and thus is highly moderated and uniform. Offshore continental flow during this time of the year usually brings temperature falls and not rises, since cold air tends to be trapped east of the Cascades. In contrast, during the summer with its strong insolation, the land can become considerably warmer than the ocean, so that a synoptic situation bringing offshore flow (e.g., high pressure inland) results in substantial warming west of the Cascades. This effect is magnified by downslope warming of the offshore flow, as well as the inhibition of marine air inflow by the coastal mountains. Because of the above factors, summer brings the greatest potential for large temperature increases.

Although the fronts and troughs that pass through the Pacific Northwest are considerably weaker during the summer months, only in July are their numbers

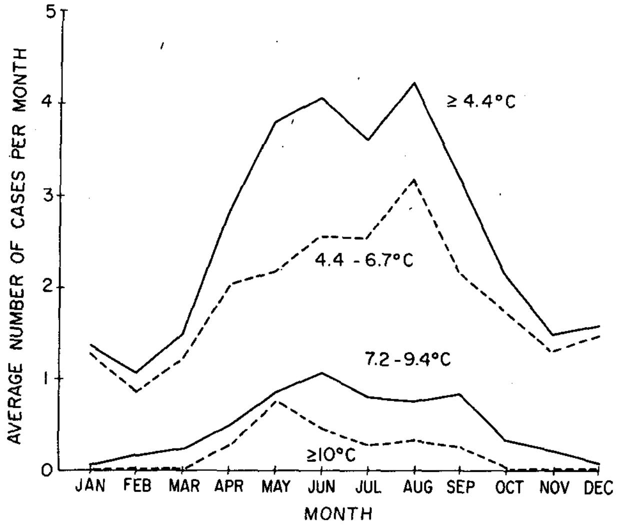


FIG. 14. Maximum temperature drop climatology by month for Seattle–Tacoma Airport.

substantially less than the rest of the year; furthermore, the maximum frequency of trough passage occurs in May.[3]

It appears reasonable that the slight suppression in the frequency of large temperature drops during July is due to the weakening and lower frequency of trough/ridge passages. The strongest events (≥7.1°C) have a maximum in May because of the large number of relatively vigorous trough passages and the near maximum strength of solar insolation and thus potential warming.

5. Diurnal variability

Onshore surges, especially the stronger ones, occur preferentially at certain times of the day. To explicitly determine the phase and amplitude of this diurnal variation, we first examined the timing of strong surge events (≥10°C fall in maximum temperature between two contiguous days) from 1951 to 1982 at Seattle–Tacoma Airport, a reasonably representative western Washington location. First, we subjectively determined the hour at which the surge began by looking for large pressure or dewpoint rises, wind shifts into the southwest, substantial temperature falls and rapid increases in wind speed. For about three-quarters of the 40 cases we examined, one specific hour was clearly the correct choice; for the other events the changes were too gradual to clearly pinpoint a specific hour. The results, shown in Fig. 15a, indicate a clear peak in the evening hours between 1800 and 2200 PST, with very few events beginning during the morning and early afternoon. Using a completely objective criterion (i.e., looking for the hour with SW, SSW or WSW winds at >5 kt and an hourly pressure jump of 0.5 mb after the time of maximum temperature on the last warm day) produced similar results (Fig. 15b).

Next, we examined the diurnal behavior of lesser events: 33 one-day maximum temperature drops of 7.2° to 7.8°C for April through September, between 1964 and 1982. Both subjective and objective (Fig. 15c) examinations of these weaker cases revealed that two, nearly equal frequency maxima appeared to exist: one during the evening hours from 1800 to 2200 LST and an early morning maximum from 0300 to 0700 LST. In general, weaker cases with lesser temperature falls tended to be more gradual and less diurnally controlled.

Why is the arrival of onshore surges at Seattle–Tacoma Airport and at similar locations in the western sections of Washington, Oregon and British Columbia most frequent during the late afternoon through early morning hours? To gain insight into this question we computed hourly averages of wind, temperature, dewpoint and sea level pressure at Seattle–Tacoma Airport, an inland location, and at Hoquiam, on the Washington Coast, using data from June through September 1977–82. Diurnal variations in the sea level pressure and temperature differences between these two stations are presented in Fig. 16. One notes that there is a well-defined diurnal modulation of the Hoquiam–Seattle pressure difference with the largest difference from 1500 to 2000 PST and a minimum from 0600 to 1000 PST. Clearly, the diurnal variation of this pressure difference and that of strong surges (also shown in Fig. 16) are very similar with the pressure gradient peaking just before the hours of maximum surge frequency. Similarly, the pressure difference minimum is nearly coincident with the minimum in onshore surge events.

The variation in the coastal–inland, sea-level pressure difference can be explained by the differing temperature regimes at the two locations. As shown in Fig. 16, the temperature difference between Seattle and Hoquiam possesses a diurnal modulation very much like that of the pressure difference, with warmer temperatures at Seattle in the late afternoon and early evening being associated with lower pressures than at Hoquiam. This temperature modulation occurs because the diurnal rise at the coast is cut short or greatly attenuated by the arrival of the sea breeze during late morning, while inland temperatures continue to rise. Associated hydrostatic changes produce the diurnal variation in the coastal–inland pressure difference.

The stratus and fog that accompany onshore surges also possess strong diurnal modulation. In the interiors of western Washington and Oregon such low-level cloudiness rarely comes in with the initial surge of marine air, but usually forms during the early morning hours under the influence of radiational cooling.

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[3] Trough passage statistics were based on a subjective examination of 500 mb charts for 1977–84.

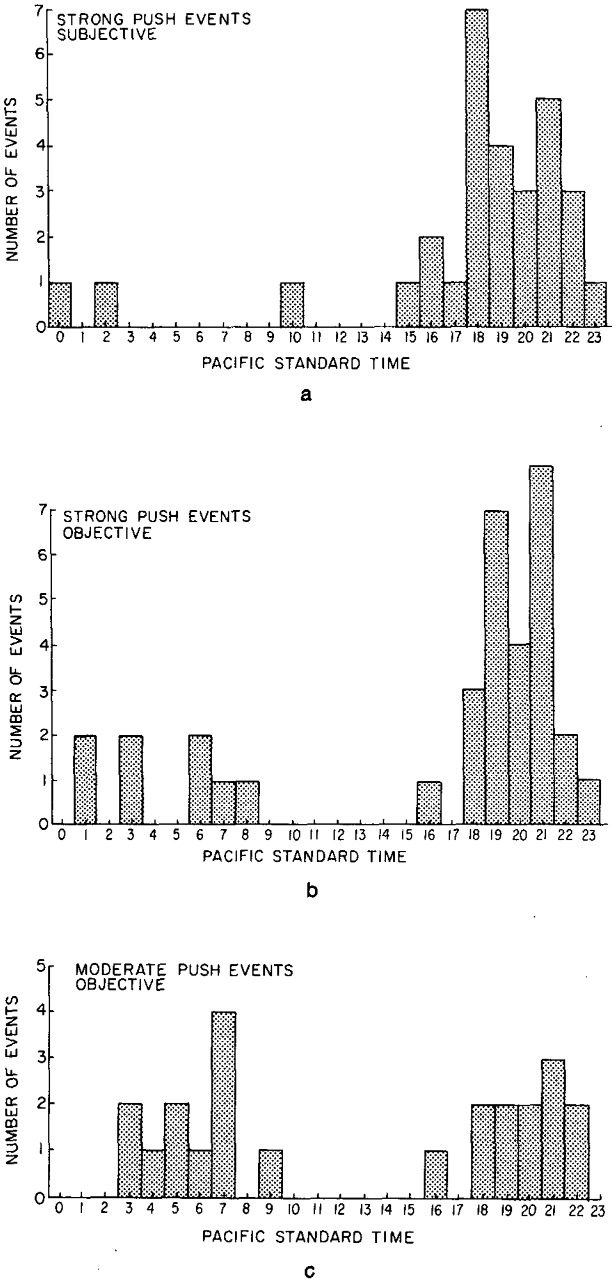


FIG. 15. Diurnal variation of strong surge events: (a) subjective and (b) objective methods. Diurnal variation of moderate (7.2°–7.8°C) events (c).

6. Forecasting the onshore surge

Although an important summertime weather feature, the onshore surge often proves difficult to forecast. Operational models lack the necessary horizontal and vertical resolution and detailed topography required to accurately model the evolution of this inherently mesoscale phenomenon; however, these models often successfully simulate the synoptic changes that set up and trigger these events.

Accurate forecasting of onshore surge occurrence depends on the forecaster's determination of whether the synoptic-scale flow has become incapable of maintaining warm temperatures west of the Cascades. Specifically, the eastward movement of a Pacific coast upper-level ridge and its associated surface high, coupled with the approach of troughs, both aloft and at the surface, are key elements for which a forecaster must keep a watchful eye.

Currently, the most extensively used tool for forecasting onshore surge occurrence in western Washington is the pressure gradient between North Bend, Oregon (OTH), and Seattle–Tacoma Airport, Washington (SEA). Kinzebach (1955) found that the low clouds associated with onshore surges are virtually nonexistent the following morning when there are offshore gradients (OTH − SEA negative) at 1630 PST; however, such cloudiness rapidly becomes more probable as the onshore pressure difference exceeds 2 mb. The relative success of this technique can undoubtedly be traced to the following factors.

1) Most onshore surges are preceded by the development of a coastal pressure ridge. As shown earlier, such ridging usually advances northward up the Pacific Coast from California; thus an Oregon coastal report such as North Bend would tend to be a better predictor than a location further north on the Washington coast.

2) The inland heat trough over western Washington intensifies as temperature increases.

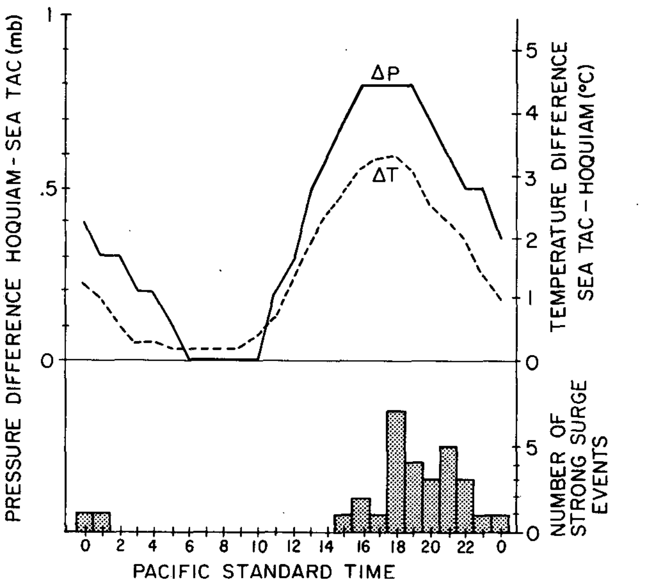


FIG. 16. Diurnal variation of surface temperature and sea-level pressure differences between Hoquiam and Seattle–Tacoma Airport, WA. Also shown is the diurnal variation of strong surge events.

As a result of these factors, a large OTH–SEA gradient often builds up during the afternoon preceding a surge.

Although useful, the OTH–SEA pressure gradient is not an infallible indicator of onshore surge occurrence. To illustrate this fact we examined the OTH–SEA pressure gradient at 1600 PST and the change in the following day's maximum temperature at Seattle–Tacoma Airport for May through September of 1977–82. The results are summarized in Table 1 for all days with maximum temperature greater than 21°C. With offshore pressure differences at 1600 PST, warming is generally experienced the following day, while for increasing onshore gradients, increasing cooling is evident. Unfortunately, the standard deviations of the temperature changes are quite large, as is the range of variation. However, for larger onshore pressure differences (4 mb and above) nearly all subsequent days experienced cooling, with over 60% of the days possessing cooling equal to or greater than the mean for the appropriate pressure difference categories.

After deciding that a major surge is imminent, a forecaster is faced with the prediction of specific temperatures. Although Table 1 gives some guidance, additional insight into the temperature changes that accompany a surge event is given in Fig. 17. Based on 30 years (1955–84) of data from Seattle–Tacoma Airport, a representative western Washington location, this figure presents the mean changes in maximum temperature for two ranges of surge amplitude and is stratified by month. The key aspect of the temperature evolution is the steady warming in the days preceding the surge, with the largest cooling being associated with the warmest presurge temperatures. As mentioned above, the warmth before an event is often stronger and more anomalous than the later cooling. Also interesting is the relative uniformity of the maximum temperatures for the day after the push ($D + 1$), irrespective of the temperature of the day before. Finally, temperatures slowly rise in the days following a surge.

7. Discussion

In the most general sense, an onshore surge is a relatively rapid transition from warm, dry, continental air to cool, moist, marine air. The preconditioning and initiation of a significant surge is the product of the interaction of the synoptic-scale flow with the mesoscale topography and land–water contrasts of the region. This complex terrain acts in many ways as a "mesoscale amplifier" which can significantly change the amplitude and phase of the synoptic-scale "signal." Thus, even relatively weak synoptic-scale changes can result in large and often rapid variations in temperature, pressure and cloudiness in the lower troposphere.

To illustrate the essential features of the onshore surge and the nature of "mesoscale amplification," consider the schematic surge presented in Fig. 18. This idealized case shares many common features with the May 1983 event and the composite cases, and is representative of many of the onshore surges we have examined.

The first schematic (Fig. 18a) represents the prewarming stage, possibly a day or two after a previous surge. High sea level pressure dominates the eastern Pacific and bulges eastward into the Pacific Northwest. Marine air flows into the western portions of Oregon, Washington and British Columbia, resulting in surface temperatures that are at or below normal. A heat trough in the central valley of California, limited by the Siskiyou Mountains of Northern California (A), extends westward to the coast. As a result, a strong pressure gradient develops immediately offshore (area B) and is associated with strong northerlies or northeasterlies at low levels. South of the coastal trough in an area of

TABLE 1. Temperature change statistics for varying pressure differences between North Bend, OR, and Seattle-Tacoma Airport, WA.

Δp OTH–SEA 1600 PST (mb)	Number of cases	Mean ΔT for subsequent day (°C)	Standard deviation of subsequent day ΔT (°C)	ΔT range (max/min) (°C)	Percentage of cases with maximum temperature falls (rises) $\geq$ Mean $\lvert\Delta T\rvert$ (%)
−5	6	1.7	4.4	6.1/−7.2	(83)
−4	17	2.8	2.5	7.2/−0.6	(53)
−3	16	1.1	2.8	5.6/−6.7	(75)
−2	26	1.7	1.9	5.6/−0.6	(57)
−1	53	2.8	2.6	7.2/−5	(73)
0	61	0.6	2.9	5.6/−7.2	(66)
1	50	0	2.9	5/−8.3	58
2	47	−2.2	3.4	2.8/−9.4	40
3	69	−2.8	3.2	3.3/−11.1	51
4	43	−3.3	3.2	1.7/−13.9	67
5	18	−5.6	4.2	0.6/−12.1	61
6	8	−6.7	5.3	2.2/−12.2	63

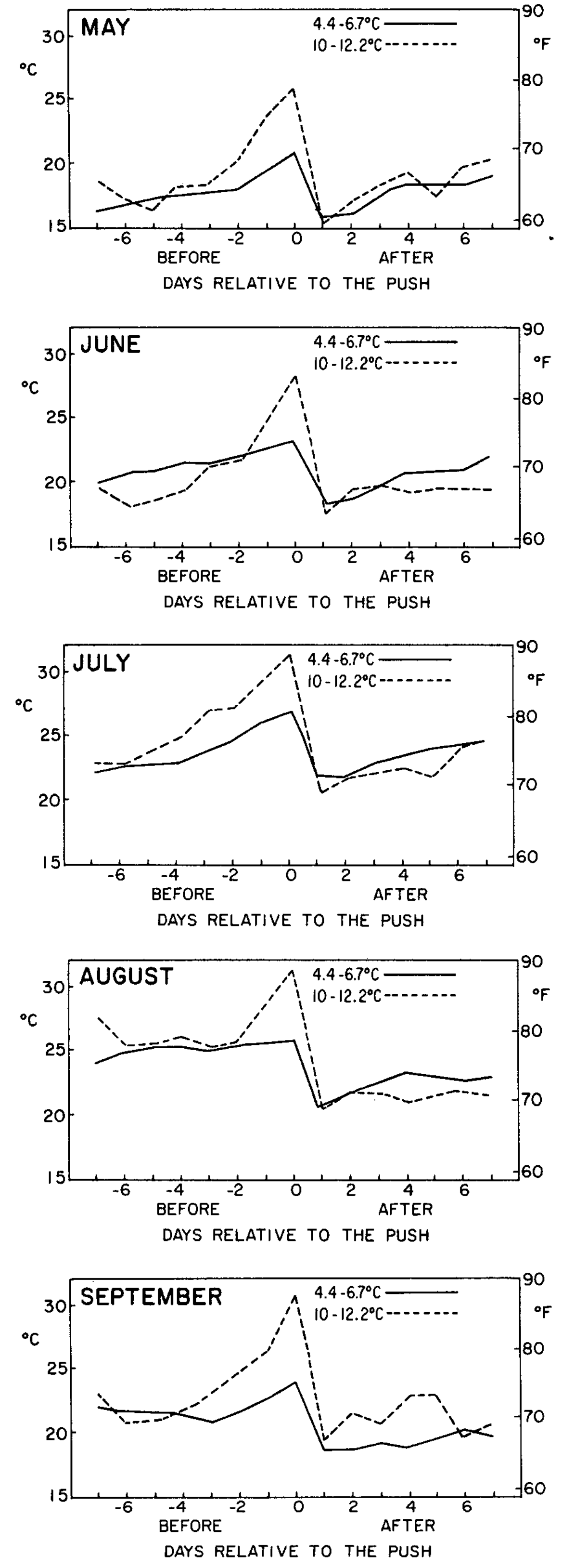


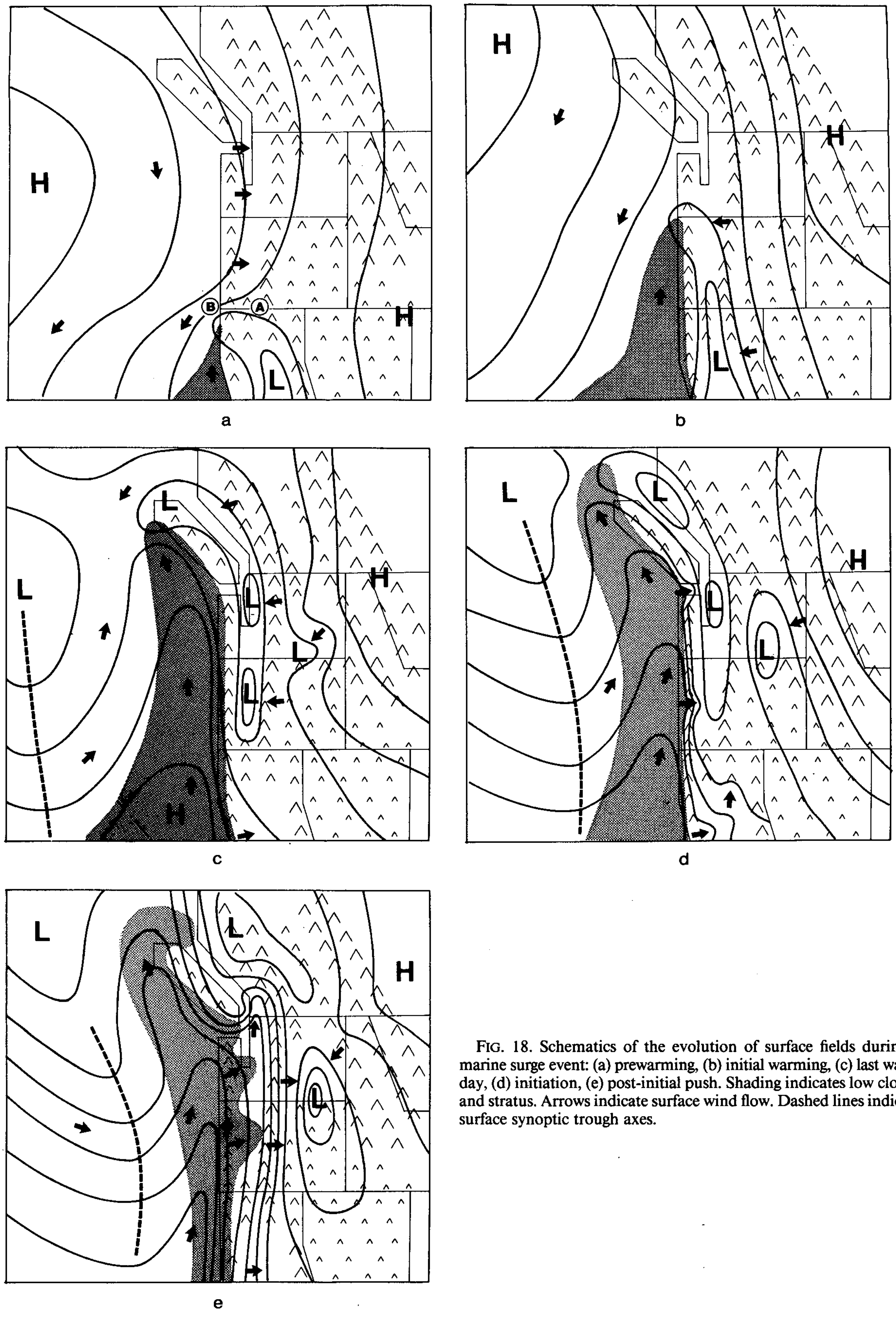
FIG. 17. Maximum temperature evolution at Seattle–Tacoma Airport before and after onshore surge events for May through September.

weaker gradient, the flow is southerly and laden with stratus and fog. At this stage the flow aloft (e.g., 500 mb) tends to be relatively zonal with some weak ridging offshore.

The second stage, the initial warming, occurs as an upper-level ridge builds over the West Coast, with subsidence and advective warming occurring in the lower troposphere of the entire region. An eastward-moving upper-level trough exists well offshore. At the surface, (Fig. 18b) pressure increases inland and the Pacific high shows signs of weakening. The result is a substantial westward-directed pressure gradient force over land. Air flows (ageostrophically) westward across the Cascades toward lower pressure and subsides and warms while it descends the lee slopes. It appears that this subsidence heating causes the California heat trough to intensify and move northward into the Willamette Valley of Oregon. Coastal southerlies and low-level clouds follow the heat trough northward.

The third stage occurs during the last warm day prior to the surge. The upper-level ridge has amplified and moved slightly inland while the short-wave trough over the Pacific approaches the coast. At the surface (Fig. 18c) synoptic-scale high pressure over the eastern Pacific has been replaced by an eastward-moving trough; as a result southwesterlies now dominate off the Pacific Coast. Closer to the coast a subsynoptic pressure ridge has built up within a few hundred kilometers of the coastline; at its crest one finds the northern extension of the heat trough. Again, coastal stratus is associated with southerly flow and extends north to the coastal trough. High pressure in the eastern part of the domain has begun to retreat eastward but still produces enough ageostrophic flow to support subsidence warming over the lee (western) slopes of the Cascades. Another heat trough in the basin of eastern Washington becomes more prominent at this time. Between the coastal pressure ridge and the inland heat trough a substantial onshore pressure gradient has grown. Stratus now hugs the coastal mountains and some marine air has begun to leak into the interiors of western Washington and western Oregon. Over California, marine air has already begun to surge inland, eliminating the usual heat trough.

The next stage marks the initiation of the surge into the western interiors of Washington, Oregon and British Columbia. Aloft, the upper-level trough is approaching the coast and the ridge has moved inland. At the surface (Fig. 18d) high pressure east of the Cascades continues to retreat eastward. In its wake the basin low of eastern Washington intensifies, possibly due to subsidence down the adjacent, western slopes of the Rocky Mountains. Over the ocean the surface synoptic trough is now a few hundred kilometers off the coast and the coastal ridge has intensified and extended further northward. An intense pressure gradient has developed over the coastal mountains, and marine air begins to surge inland through low-level gaps. In



a

b

c

d

e

FIG. 18. Schematics of the evolution of surface fields during a marine surge event: (a) prewarming, (b) initial warming, (c) last warm day, (d) initiation, (e) post-initial push. Shading indicates low clouds and stratus. Arrows indicate surface wind flow. Dashed lines indicate surface synoptic trough axes.

the Willamette Valley the heat trough has already weakened with the influx of cool, marine air at low levels.

Six to 12 h later (Fig. 18e) the most dramatic aspects of the surge have occurred. At the surface, marine air has pushed to the Cascades of Oregon and Washington and continues to surge northward east of Vancouver Island. The heat trough west of the Cascades is now only a memory, while in eastern Oregon and eastern Washington the basin low has further intensified. Over the Pacific the synoptic trough has edged closer to the coast, and the coastal pressure ridge has extended north of Vancouver Island.

The schematic case described above illustrates several aspects of mesoscale amplification. Consider the change in phase of the synoptic signal. Normally, one would expect cooling *after* passage of the surface synoptic trough or front; in most surge cases the cooling precedes the passage of the surface trough by several hours to a day. In fact, in many cases the surface trough never makes landfall at all, but slowly dissipates over the ocean. With respect to amplitude, it is clear that the mesoscale topography and land–water contrasts of the region dramatically increase the temperature and wind changes associated with synoptic-scale systems. Summertime Pacific troughs or fronts are usually quite weak with temperature drops of only a few degrees celsius and relatively minor wind shifts. As illustrated in the schematic case, ageostrophic downgradient flow across and down topographic barriers is associated with subsidence warming and leeside troughing. Furthermore, the existence of coastal mountains tends to slow the intrusion of marine air and helps create coastal mesoscale ridging. Thus, the mesoscale topography produces much warmer temperatures over the interior than would otherwise exist and allows the buildup of large pressure gradients, which then can be released quickly and energetically. A compressed spring is a fairly good analogy, with the initial "compression" coming from synoptic-scale forcing.

An important aspect of West Coast meteorology and onshore surge evolution is the development of heat lows or troughs. Observed almost daily during summertime in central California, such troughing is evident in a wide variety of locations including the Willamette Valley of Oregon and the basins of Puget Sound and eastern Washington. An examination of many heat trough events indicates the following common traits.

1) Heat troughs are generally located in areas of relatively low elevation compared to their surroundings. The most persistent and intense troughs appear to form in low areas adjacent to extensive, higher plateau regions. For example, the California thermal trough is found just west of the high Sierra Nevada and the extensive high plateau of Nevada; in addition, to the north lie the substantial Siskiyou Mountains, while to the west the Coastal Range acts as a partial barrier to marine air.

2) Heat troughs intensify when ridges build aloft (e.g., 500 mb) and their associated surface highs build over adjacent higher terrain.

3) The troughing does not appear to *require* a specific surface type or albedo since heat troughs occur over a wide variety of environments, from the relatively moist Puget Sound basin to the deserts of southern California. However, an easily heated surface (e.g., desert) does appear to facilitate development.

These observations suggest a simple origin and evolution for the heat troughs of the western United States, specifically, synoptic-scale subsidence associated with an upper-level ridge results in a general warming of the air over the region. High surface pressure, associated with the upper ridge, builds over higher terrain and downgradient flow toward lower pressure (and elevations) develops. This subsiding flow adiabatically warms the air over the basin and results in a drop of surface pressure. In areas close to a coastline, the existence of coastal mountains helps slow the intrusion of cool, marine air into the low.

A significant feature of most onshore surge events is a narrow (~150–200 km) tongue of stratus and fog that progresses northward up the coast. As discussed above, the northern boundary or "head" of this low cloudiness is nearly coincident with a windshift line separating northerly or northeasterly from southerly or southwesterly flows. North of the stratus tongue the marine layer is shallow or nonexistent, while to the south the marine layer deepens substantially. A coastal pressure trough is located north of the poleward stratus edge, while to the south pressure rises rapidly in a narrow pressure ridge. In most onshore surge cases the coastal trough is the coastal extension of the inland heat trough and is supported by easterly, subsiding flow found between the surface ridge to the north and the main body of the heat trough to the south.

An important factor associated with the occurrence of coastal pressure ridges and stratus tongues is the weakening of the usual east–west synoptic-scale pressure gradient in the eastern Pacific. As shown in both the composite surge and in the case studies, such weakening of the pressure gradient is the natural result of the attenuation of the sea level Pacific high and the building of high pressure inland. These changes, coupled with the development of a coastal trough result in the establishment of an alongshore pressure gradient force that is directed toward the north. In the presence of the substantial West Coast coastal topography, geostrophic or quasi-geostrophic balances are not possible within approximately a Rossby radius of deformation of the topographic barrier (Overland, 1984; Gill, 1977; Baines, 1980). Thus, within this distance from the coast the flow tends to flow ageostrophically toward lower pressure, i.e., toward the north. If one assumes a two-layer system (in this case a cool marine layer separated by a strong inversion from warm, subsiding air above), the Rossby radius (R) can be defined as

$$R = \frac{\sqrt{g'H}}{f}, \quad g' = g\Delta\theta/\bar{\theta},$$

where H is the height 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 $\bar{\theta}$ is the potential temperature of the lower layer. Assuming reasonable values of H = 700 m, $\Delta\theta$ = 10 K, θ = 290 K and $f = 10^{-4}$ s^{-1}, R is slightly over 150 km. This scale approximates the offshore dimension of the stratus tongues as well as the associated wind and pressure perturbations. Beyond a distance R from the coast the flow rapidly approaches quasi-geostrophic balance and takes on a northerly component. South of the coastal trough southerly flow produces a generally overwater trajectory, thus allowing stratus and fog formation, while to the north the warm, subsiding easterly flow from off the continent is free of low clouds. The coastal zone within a Rossby radius is analogous to a waveguide or pipe, in which air at higher pressure in the southern part of the domain is able to surge northward.

As mentioned above, onshore surges possess similar features to phenomena observed in other mountainous, coastal regions around the world. For example, the "southerly buster" of southeastern Australia (Colquhoun et al., 1985; Baines, 1980; Coulman et al., 1985) is an intense "cold" front with many properties in common with the onshore surge. As with the onshore surge, the buster is a warm season phenomenon that usually develops ahead of synoptic-scale fronts. Both are associated with rapid temperature falls and pressure rises, but rarely with precipitation. They also share mesoscale pressure ridges that extend only a few hundred kilometers from their mountainous coastal zones.

Another example is off the southern African coast where Gill (1977) and others have suggested that topographically trapped "coastal lows" propagate eastward around the Horn. As with the coastal lows of the onshore surge, these southern African lows are associated with subsiding continental air, which is rapidly replaced by marine air after their passage. Van Loon et al. (1972) describe a South African "leader front" that precedes a synoptic-scale cold front by 300 to 400 km. As the synoptic front approaches, a "coastal low" moves along the coast followed by an incursion of fog or low stratiform cloud. This description is strikingly like that of the Pacific Northwest onshore surge. Examples in other areas (e.g., South American coast) might also be given.

The clear implication is that the onshore surge phenomenon is quite common in coastal regions that are adjacent to topographic barriers. Subtropical regions of synoptic-scale subsidence appear to be especially favorable.

8. Conclusions and summary

The most significant meteorological phenomenon in the Pacific Northwest from May through September is the transition from warm, dry continental air to cool, moist marine air. Termed the onshore surge or "push," this transition is often associated with rapid temperature drops, dewpoint and pressure rises, abrupt wind shifts and speed increases, and finally, dramatic increases in low cloudiness. Detailed case studies as well as the creation of a composite surge using NMC grid-point data reveal the following.

1) All major onshore surges are initiated by changes on the synoptic scale. Specifically, the development of an upper-level ridge over the West Coast and building of high pressure over the interior produces warming and offshore flow at low levels. As a result, a heat trough builds northward up the coast, creating a large onshore pressure gradient in the coastal zone. When the synoptic pattern changes so that subsidence heating and coastal troughing is no longer supported, marine air moves inland as an onshore surge. In a real sense the mesoscale topography and land–water contrasts together act as an amplifier for synoptic-scale variations.

2) As the West Coast heat trough and its coastal extension move northward, a mesoscale pressure ridge and an associated tongue of coastal stratus usually follow from the south. Frequently, the northern boundary of this low cloudiness is associated with sharp windshifts, rapid temperature falls and pressure rises. The offshore scale of the pressure ridge is roughly a Rossby radius of deformation.

Onshore surges are most frequent from May through September with approximately four moderate or stronger (≥4.5°C one-day fall in maximum temperature) cases expected each month. Diurnally, the greatest frequency is during the late afternoon and evening hours, a period in which the coastal–inland pressure gradient is largest.

The onshore surge appears similar to phenomena observed in other coastal regions of complex terrain. The "southerly buster" of southeast Australia and the "coastal lows" and "leader fronts" of South Africa are prime examples.

By carefully evaluating the synoptic-scale evolution as well as several crucial sea-level pressure gradients, it is possible to forecast the occurrence of an onshore surge. Furthermore, climatological statistics can give helpful guidance for determining the temperatures on the day following a surge.

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