THE TEMPO
AND CL

in p

THE TEMPORAL CLIMATOLOGY, TELECONNECTIVE ASSOCIATIONS, AND CLIMATIC IMPACTS OF REGIONAL-SCALE TROUGHING IN THE SOUTHWESTERN UNITED STATES

by

Adam W. Burnett

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Geography

1990

THE

Al

southw

moistu

intens

models

southw

climat

effort

The

the cl

and we

were: (

feature

associa

systems

the cen

Data

ABSTRACT

THE TEMPORAL CLIMATOLOGY, TELECONNECTIVE ASSOCIATIONS, AND CLIMATIC IMPACTS OF REGIONAL-SCALE TROUGHING IN THE SOUTHWESTERN UNITED STATES

By

Adam W. Burnett

Although not common, long wave troughs over the southwestern United States produce strong temperature and moisture gradients and often favor the development of intense surface storms. Unfortunately, current numerical models poorly handle the strength and timing of southwestern troughing and very little related climatological research, which can direct future modelling efforts, has thus far been completed.

The analyses outlined in this dissertation focused on the climatological characteristics of southwestern troughs and were driven by three key objectives. These objectives were: (1) to determine the temporal frequency of these features; (2) to detail their middle tropospheric wave associations; and (3) to examine the contribution of these systems on precipitation and energy transfer processes in the central and western united States.

Data for these analyses included daily northern

hemisp
temper
latitu
totals
throug
southwe
objecti
500 mb
four ho
before
informa
changes
of spec
precipit
sensible
periods
trough t

Resul
Southwest
and fall
few event
same deve
formation
over the
the Gulf
these even

hemispheric 500 mb geopotential height (1946-1987) and temperature (1964-1987) values interpolated to a 5° latitude by 5° longitude grid and daily precipitation totals (1948-1963 and 1969-1976) for fifty-four stations throughout the central and western United States. All southwestern events during the data record were objectively identified and a series of seasonal composite 500 mb geopotential height, geostrophic wind, and twenty-four hour height change maps constructed for the period before and after the troughing period, thus providing information regarding climatology and associated wave changes. Precipitation influences were evaluated in terms of specific precipitation density and percent of total precipitation. In addition, daily mean transient eddy sensible heat transfers were calculated for troughing periods and compared to similar values calculated for non-trough transient eddies and quasi-stationary eddies.

Results of these procedures indicated that: (1) southwestern troughs occurred most frequently during spring and fall, with somewhat fewer events during winter and very few events in summer; (2) trough development followed the same developmental sequence each season and involved the formation and eastward movement of a triggering short wave over the western Pacific, amplified ridge development over the Gulf of Alaska, and downstream teleconnection; (3) these events provided the west-central United States with a large propo

the data re

transient e

to non-trou

large proportion of the monthly precipitation total during the data record; and (4) the southwestern trough daily mean transient eddy sensible heat flux was quite large compared to non-trough transient and quasi-stationary eddy flux.

During

individual

knowledge

reflected

to profes

to share

straight

addition,

the other

Julie Wi

graduate

previous

cartogra

Richard

convince

career

written

geomorp

is also

have tr

sweat s

in my

ACKNOWLEDGMENTS

During of my graduate career at Michigan State, many individuals helped to shape and focus my interest and knowledge of physical geography. Much of this interest is reflected in this dissertation. I am especially indebted to professor Jay Harman, who cared enough to take the time to share his thoughts, offer his advice, and keep me on the straight and narrow path toward degree completion. In addition, I owe a great deal of thanks and appreciation to the other members of my graduate committee. Professor Julie Winkler, who came to Michigan State early in my graduate career, brought knowledge and skills that were not previously available. My understanding of computer cartography can be attributed to the efforts of professor Richard Groop who, besides regularly defeating me in golf, convinced me not to drop out of graduate school for a career in construction when I didn't want to take my written comprehensive exam. Finally, my knowledge of geomorphology was provided by professor Harold Winters, who is also solely responsible for a reoccurring nightmare I have that culminates in me shooting out of bed covered in sweat screaming, "geomorphology is the most important thing in my life." My wife hates this.

TABLE OF CONTENTS

Chapter

Chapter

Chapter

Chapter

Table

3.1 Per
tro

LIST OF TABLES

Table

LIST OF FIGURES

Figure

3.47

3.48

3.49

3.50

3.51

3.52

3.53

3.54

3.55

3.56

3.57

3.58

3.59

3.60

3.61

3.62

3.63

3.1

3.1

3.1

3.1

3.1

3.1

3.1

3.1

3.1

3.1

3.1

3.1

T

trop

fact

tele

each

of c

nonl

diffe

north

the c

weste

Rocky

descr

Ameri

within

become

both t

States

Chapter 1

SOUTHWESTERN TROUGHING: OVERVIEW, REVIEW OF LITERATURE, AND RESEARCH QUESTIONS

Overview

The position, length, and amplitude of middle tropospheric long waves are influenced by a number of factors, including thermal contrasts, orography, and teleconnection. Although the individual significance of each mechanism has been historically debated, varying modes of circulation probably result from complex, often nonlinear combinations of forcing mechanisms operating on differing temporal and spatial scales. Traditionally, northern hemispheric circulation climatologies have noted the dominance of ridging over western Canada and the western United States and have associated its origin with Rocky mountain orographic influences similar to those described by Bolin (1950). Ridging over western North America is one of the most dominant circulation modes within the westerlies. When this circulation pattern becomes amplified and involves concordant troughing over both the Gulf of Alaska and the southeastern United States, it is often referred to as the Pacific/North

American (PNA) pattern (Yarnal and Diaz, 1986; Barnston and Livezey, 1987; Yarnal and Leathers, 1988).

Occasionally, ridging over the western and southwestern United States is replaced by a stationary or slowly moving trough with a length much longer than that of a typical travelling short wave (Eagleman, 1980). In an apparent reference to these disturbances, Eagleman called such features "long wave cyclones." As ridging over the western United States is replaced by troughing, upstream and downstream features reflect the changing circulation mode as pressure heights rise over the eastern Pacific and southeastern United States. Yarnal and Diaz (1986) refer to this circulation mode as a reverse Pacific/North American (RPNA) pattern. Hawes and Colucci (1986) found that regional-scale troughing of this type in the southwestern United States is poorly handled by the National Meterological Center models and consequently is associated with forecast error.

Southwestern troughs provide a mechanism by which large amounts of heat and moisture can be advected from the Gulf of Mexico into the interior states. As a consequence, these systems may serve an important role in the precipitation climatology of the western and central states. Additionally, the strongly meridional flow that accompanies southwestern troughing may serve as a significant transport mechanism for sensible heat.

The potential importance and distinctive qualities of southwestern troughs warrant a more detailed analysis of their climatology than has thus far been performed. Because southwestern troughs represent departures from the western North American modal circulation pattern, their occurrence implies changes throughout the total long wave system. Theoretically, such changes might be more likely during the transition seasons when energy redistribution and wave reorientation are especially common (Cressman, 1948; Douglas, 1974; Eagleman, 1980).

In this dissertation, I propose to examine the climatic characteristics of southwestern trough events with three main objectives: (1) to analyze the temporal frequency of these circulation types; (2) to examine systematic changes in the hemispheric wave configuration that occur in association with southwestern troughing; and (3) to assess the importance of these systems to the precipitation and meridional energy transfer processes in the western and central United States.

Review of Literature

A detailed discussion of the circulation features associated with middle tropospheric disturbances specifically in the southwestern United States has not emerged from the literature; however, a great deal of closely related information is available. Much of this mo

(f

sy

wa

S

ge

tr

fo

fl

in

ph

te

Z-

an

wh

or

mo

de

in

da

fr

te

Mc

more general literature falls into three broad categories: (1) surface cyclone and upper air climatology; (2) regional synoptic classification; and (3) theoretical aspects of wave dynamics and energy transfer.

Surface Cyclone Climatologies

The earliest analyses of cyclone behavior focused on the geography of surface cyclogenesis and subsequent storm tracks. Because of the close relationship between the formation and behavior of surface storms and upper level flow, many of these analyses represent indirect sources of information regarding middle tropospheric circulation phenomena.

Most of these surface studies were regionally and temporally focused (Petterssen, 1941; Colucci, 1976; Zishka and Smith, 1980). Others, such as those by Hosler and Gamage (1956), Klein (1957), Reitan (1974), and Whittaker and Horn (1981), examined annual North American or northern hemispheric cyclone behavior. In perhaps the most comprehensive surface cyclone study, Klein (1957) detailed a variety of monthly hemispheric statistics, including cyclogenetic frequency and storm tracks based on data spanning the years 1899-1939. Cyclogenetic frequencies in the western United States revealed a strong tendency for storms to form in association with the Rocky Mountains. This tendency was dominant during much of the

year. However, Klein noted that during spring, cyclogenetic activity in the Great Basin region became more common. The Great Basin track was considered secondary during the autumn and winter and was virtually absent in the summer.

In addition to his discussion of Great Basin cyclones, Klein stressed the increased springtime variability of cyclone features throughout the entire hemisphere, particularly in March, when both winter and late spring circulation characteristics were common. Klein theorized that the highly variable spring patterns are often associated with more frequent episodes of middle tropospheric blocking. He speculated that during the spring, when periods of blocking become more common over the northeastern Pacific, long wave variability increases. Variability of this type is thought to stem from flow adjustments that occur when one blocking regime breaks down and another forms (White, 1980; Reinhold and Pierrehumbert, 1982). As a consequence, cyclogenetic and anticyclogenetic patterns become more inconsistent during these periods, as well.

Reitan's 1974 cyclone climatology, based on data from the years 1951-1970, examined North American cyclone frequency and primary cyclone tracks for January, April, July, and October. Reitan noted a southwest shift in the zone of highest cyclone frequency during April. He speculated that this shift is the result of middle tropospheric split flow, with anticyclonic flow in the Northern Rockies and cyclonic flow in the southwestern states. Although Reitan never tested this hypothesis, it is consistent with Klein's springtime blocking theory. Spring blocking often produces split flow over western North America and adjacent ocean sectors (Rex, 1950a, 1950b; Treidle et al., 1981; Knox and Hay, 1984; Dole, 1986).

Whittaker and Horn (1981) further examined cyclogenetically preferred locations through a seasonal analysis of six North American cyclogenetic regions. Noteworthy in this evaluation was the seasonal behavior of the Great Basin zone in which a prominent spring frequency maximum and secondary autumn maximum were apparent. The secondary autumn cyclone frequency maximum implies that southwestern troughs may not be limited to the spring season only.

The significance of these surface cyclone analyses is twofold. First, the spring emergence of a primary cyclogenetic area in the southwestern United States and a southwesterly storm track implies the more frequent establishment of troughing and southwesterly flow over the western United States. A similar middle tropospheric arrangement may be common during the autumn months, also. Second, Klein's blocking hypothesis, coupled with Reitan's split flow theory, suggests that trough development in the western and southwestern United States is not necessarily local in character but may involve changes throughout the entire northern hemispheric wave train.

Upper Air Climatologies

The increasing availability of upper atmospheric data following the second World War provided a means by which middle tropospheric activity could be studied more directly. Most of the detailed long wave trough and ridge climatologies were compiled in the late 1950's and early 1960's using five day mean maps or monthly mean maps (Klein and Winston, 1958; Lahey et al, 1958; O'conner, 1961; Stark, 1965). Unfortunately, the relatively short data record and the averaging techniques used to remove shorter wave perturbations produced maps that were heavily biased toward the stationary long wave features. As a result, maps published by Klein and Winston, 1958, Lahey et al, 1958, and O'conner, 1961, showed little evidence of increased trough activity in the southwestern United States during any season. However, Stark's 1965 study, which used monthly mean maps to locate major trough and ridge axes, produced patterns that indicate a slight tendency for troughs to elongate in a SW-NE direction during the spring.

Rather than examining trough axes, Duquet and Spar (1957) performed a geographic frequency analysis of North

Ar [illegible]

th [illegible]

s [illegible]

v [illegible]

i [illegible]

f [illegible]

s [illegible]

f [illegible]

c [illegible]

s [illegible]

([illegible]

c [illegible]

l [illegible]

m [illegible]

t [illegible]

a [illegible]

f [illegible]

t [illegible]

w [illegible]

l [illegible]

c [illegible]

a [illegible]

a [illegible]

t [illegible]

n [illegible]

American 500 mb closed cyclones using daily maps spanning the period 1946-1952. Duquet and Spar noted that the spring and autumn upper-level cyclone patterns showed more variability than the winter and summer patterns. Most interesting is a distinct high frequency belt stretching from the southwestern United States toward the northeastern states on the spring map only, suggesting southwesterly flow aloft during this period.

A 1974 study performed by Douglas evaluated the effects of 500 mb cutoff troughs on the climatology of the southwestern United States. Using historical weather maps (1945-1960) and daily weather maps (1961-1972), Douglas observed that during the spring and autumn, when seasonally induced circumpolar vortex adjustments are occurring, middle tropospheric cutoff troughs become more common along the western coast of North America. Cutoffs usually begin as large migratory open waves over western North America followed by the progressive southward shearing of the trough away from the main westerly stream. Because Douglas was interested in cutoff troughs only, he did not include large open waves in his climatology. His selection criteria assumed that deep open troughs are associated with a split polar jet with one branch north of the main trough and a second branch within the trough. Douglas theorized that cutoff lows would occur south of the main jet core and not be associated with a second jet branch within the

tr
hi
Ju
fr
fo
pr
the
sp
tha
clo
nor
tho
cut

sim
mb
Ame
eac
a c
sou
sim
A c
sou
fre
acti
area

trough. As a result of this criterion, Douglas found the highest frequency of cutoff lows occurring throughout May, June, September, October, and November with slightly higher frequencies during the autumn months. Furthermore, he found that these storm systems accounted for a significant proportion of total cloudiness and precipitation throughout the southwestern United States. Using O'connor's (1969) spring and fall teleconnection summaries, Douglas concluded that cutoff troughs in the southwestern United States are closely associated with amplified ridging to the west or north of the trough center. This "parent anticyclone" was thought to initiate the amplification and subsequent cutting off of the wave.

Recently, Parker et al. (1989) performed an analysis similar to that of Duquet and Spar (1957). Using daily 500 mb data for the years 1950-1985, they examined North American upper air cyclone and anticyclone positions for each month. The April cyclone frequency map, which depicts a corridor of higher cyclone frequency stretching from the southwestern United States northeastward, looks very similar to the spring results published by Duquet and Spar. A concentrated center of cyclone activity over the southwestern states is also observed on the October frequency map. During the summer, very little cyclone activity is seen the southwestern United States, when this area is dominated by anticyclonic flow. The authors at

sh

re

als

au

an

sea

sou

dif

Nor

(19

con

cyc

Usi

lat

eac

por

wes

spe

mig

Bel

thr

fin

Uni

attributed summer anticyclonic dominance to a seasonal shift in the position of the subtropical high toward the relatively warm North American continent. Parker et al. also noted that the mechanisms underlying the spring and autumn southwestern cyclone maxima are poorly understood and often contribute to forecast error during these seasons.

Hypothesizing that the development of troughing in the southwest during the spring and autumn was the result of diffluent flow over the eastern Pacific Ocean and western North America, similar to the idea proposed by Reitan (1974), Parker et al. (1989) examined a five year data set containing twenty-two cases of southwestern 500 mb cyclogenesis for evidence of split flow characteristics. Using a compositing technique, they averaged the latitudinal position of the 5340 and 5640 gpm contours for each of the twenty-two cases. Their composite map clearly portrays flow separation over the eastern Pacific Ocean and western North America. However, the authors did not speculate on the overall circumpolar vortex changes that might be associated with the flow separation.

In another evaluation of daily closed 500 mb cyclones, Bell and Bosart (1989) examined cyclone genesis and lysis throughout the entire Northern Hemisphere. Based on their findings, closed cyclone days increased in the southwestern United States during the spring, with a maximum in May.

Cyclone occurrence decreased sharply during the summer and increased again in October. During all seasons except summer, closed cyclones commonly form and dissipate over the southwestern United States. The high incidence of cyclone lysis in this region was attributed to most closed cyclones eventually opening and moving eastward, becoming reabsorbed by the main core of the westerlies.

Additionally, Bell and Bosart examined each closed trough to determine the position of the cyclone center in reference to the core of highest wind velocities. These results demonstrated that spring closed cyclone centers in the southwestern United States are predominantly north of or within the jet core. Such a arrangement occurs when the closed center is part of a meridionally large wave with a single jet maximum. In contrast, the autumn closed cyclone maximum is dominated by events south of the main wind maximum. Such events are similar to those described by Douglas (1974) in which a large open trough deepens and eventually cuts off, settling southward and leaving the main wind maximum to the north of the cyclone.

Synoptic Classifications

Synoptic classifications, by virtue of their ability of reduce large numbers of daily synoptic charts into a few key synoptic types, offer another perspective on the circulation climatology of the southwestern United States.

Using daily weather maps spanning the period 1958-1963, Sands (1966) developed a large catalog of synoptic circulation types for the western and southwestern United States. Basing most of his classification on subjective criteria, Sands distinguished 105 different circulation types. Of these, nine 500 mb patterns and one surface pattern involve a well-developed trough in the American southwest. Most patterns display spring occurrence maxima; however, two types do exhibit autumn maxima.

Barry, Kiladis, and Bradley (1981) chose an objective circulation classification scheme to characterize surface features in the western United States. Using Kirchhofer's sum of squares technique and a gridded data set consisting of daily surface pressure values for thirty-five points covering western Canada, the United States, and Mexico, Barry et al. identified six key synoptic types. A large closed surface low over the Great Basin area, which the authors called type 8, has a distinctive spring occurrence maximum. Unique to Barry's type 8 is the presence of a strong anticyclone over southern Canada. The presence of this anticyclone may be the indirect result of a split flow pattern similar to that described by Reitan (1974) and Parker et al. (1989).

Barry et al. (1981) also studied the importance of each synoptic type in the precipitation climatology of the western states. Using a parameter called the specific precipitation density, which is defined as the ratio of the mean daily precipitation during a particular synoptic type compared to the mean daily precipitation associated with all types, they calculated the precipitation contribution of each synoptic type. Their density map for type 8 depicts a large corridor of values greater than 100 extending from southern California northeast into Montana. Values larger than 100 imply that these locations receive greater than average daily precipitation amounts during type 8 events.

Hoard and Lee (1986) used the Kirchhofer sum of squares approach, also, to classify synoptic patterns in the western United States. However, instead of using surface data they used a gridded network of 500 mb pressure heights consisting of sixty-four points covering a large portion of the western United States. Twelve key patterns were identified, of which their key day 4 exhibited broad scale troughing throughout the western United States. Seasonally, key day 4 was most common during the spring season. However, no indication of split flow can be seen with this pattern.

Wave Dynamics

The seasonal preference, spatial magnitude, and migratory character of southwestern events imply that these storms are associated with rapid changes in planetary scale wave dynamics. Eagleman's 1980 subjective assessment, if correct, associated these storms with migratory long waves. Although long waves can be stationary, variations in forcing dynamics can result in wave rearrangement. If surface thermal contrasts provide a large portion of the total long wave anchoring force, as described by Palmen and Newton (1969), spring and autumn should theoretically be active periods of wave movement. Eagleman did note that long-wave cyclones were most prevalent during the spring, with March being the month of maximum occurrence. Although Eagleman acknowledged that long-wave cyclones do occasionally occur during the autumn and winter, these were not considered key periods for such storms.

The theoretical aspects of planetary wave motion provide some understanding of the mechanisms controlling wave movement. In an early examination of planetary wave motion, Cressman (1948) used Rossby's long wave equation to examine aspects of wave motion as a tool in long range forecasting. Rossby's (1939) formula can be written:

$$(1) \qquad c = U - \beta L^2/4\pi^2$$

where c is the speed of long wave movement, U is the zonal wind velocity, L is the wavelength, and β is the northward change in the coriolis parameter. For a stationary wave train, c=0 and equation (1) becomes:

$$(2) \qquad U = \beta Ls^2/4\pi^2$$

where Ls is the stationary wavelength. Cressman noted that the stat

zonal w

eliminat

The the

(Ls^2-L^2

theoret

calcul

observ

is zer

when t

wavele

wave r

progre

sign c

Acc

the o

longe

Given

wavel

more

decre

Cress

resul

Overa

retrog

the stationary wavelength is largely a function of the zonal wind velocity (U). Using equations (1) and (2) to eliminate U, Cressman derived the following equation.

$$(3) \quad c = \beta/4\pi^2 \ (Ls^2 - L^2)$$

The theoretical significance of equation (3) rests in the (Ls^2-L^2) term. Cressman explained that if the theoretically derived stationary wavelength (Ls), which is calculated using the observed zonal wind speed, and the observed wavelength (L) are the same, the wave velocity (c) is zero and the wave train will be stationary. However, when the actual wavelength differs from the stationary wavelength, the system theoretically becomes unstable and wave rearrangement should occur. Whether the wave progresses eastward or retrogresses westward depends on the sign of the wave velocity (c).

According to Cressman, retrogressive periods occur when the observed planetary wavelength (L) is significantly longer than the calculated stationary wavelength (Ls). Given the higher zonal wind velocity and longer stationary wavelengths of winter, retrogressive situations might be more prevalent during the spring when zonal wind speed is decreasing yet observed wavelength is still quite long. Cressman also observed that retrogressive situations often result in an increase in wave number, thus producing overall shorter wavelengths. Cressman described the retrogressive process as a weakening in a major trough axis fc

fc

tr

wa

st

cc

th

Ac

th

de

de

sp

ov

ce

Pa

a

pa

mc

wi

sp

la

rc

to

th

followed by rapid movement eastward. A new trough then forms slightly west of the position vacated by the initial trough.

Progressive periods should occur when the observed wavelength is significantly smaller than the calculated stationary wavelength. Whereas the retrogressive situation could be expected most often in spring, autumn should be the most active season for progressive waves. Additionally, a decrease in wave number should theoretically occur. Wave rearrangement, such as that described by Cressman, may play an important role in the development and maintenance of southwestern troughs.

Pyke (1972) hypothesized that the development of springtime southwestern storms is related to flow changes over the Asian coast. Pyke observed that during spring the center of maximum surface cyclone frequency in the western Pacific shifts from a winter position near 42°N latitude to a more southerly position near 35°N. The spring cyclone pattern in the western Pacific tends to be oriented in a more SW-NE direction, also, and is in contrast with the winter WSW-ENE orientation. The resultant tendency is for spring disturbances to exit the Asian coast at lower latitudes over warmer water and move in a more northeastward direction. As a result, spring storms tend to intensify in the Aleutian area and drop southeastward through the Gulf of Alaska toward the southwestern United

S

b
r
S
p
p
t
w
R
w
e
i
c
c
c

m
s
w
e
p
pe
Tr
by
de

States.

Yarnal and Diaz (1986) postulated a similar linkage between features near the Asian coast and the winter reverse Pacific/North American circulation pattern. Seeking to develop a statistical link between the opposite phases of the southern oscillation and winter circulation patterns along the eastern Pacific coast, the authors found that, in general, the PNA circulation mode is associated with the warm phase of the southern oscillation whereas the RPNA pattern occurs more often during cold phases. Unlike warm episodes, which have been shown to exert extratropical influence on the atmosphere, cold phase influences had not been demonstrated. Yarnal and Diaz concluded that the dominance of RPNA circulation during cold episodes is related to cold surges and enhanced convection near the Asian coast.

The cold surge is initiated by a travelling disturbance moving over the Asian coast. As this cold air moves southeast off of the Asian coast over warmer equatorial water, increased convection enhances upper level wind speed east of the Asian long wave trough. Downstream wave propagation occurs, with amplification of an especially persistent ridge in the Bering Sea/Gulf of Alaska region. This ridge is similar to the "parent anticyclone" described by Douglas (1974) and may play an important role in the development of troughing over western United States.

Energy Transfer

Given the high amplitude and slow movement of migratory long waves, these features may serve as strong meridional transports of transient eddy sensible heat. Unfortunately, little attention has been focused on the energy transfer contributions of individual storm events. Eddy sensible heat transport climatologies, such as those of Haines and Winston (1963), van Loon (1979), van Loon and Williams (1980), and Carleton (1988), addressed seasonal quasi-stationary and transient energy transfers on a hemispheric scale. Results showed that, on the average, the majority of meridional eddy sensible heat transport occurs during the winter months near 45°N. Energy transfer decreases during the spring and autumn with minimum transport during the summer. In addition, much of this energy is transferred between the 850 mb and 700 mb levels (van Loon, 1979). The transfer of eddy sensible heat via individual synoptic events, such as southwestern troughs, remains unexamined.

Research Questions

These references provide a rudimentary view of the climatology of regional-scale troughing over the southwestern United States. Unfortunately, many questions regarding trough climatology, development, and impact remain unanswered. The springtime emergence of a southwesterly storm track originating in the Great Basin region and the synoptic classification of distinct troughing patterns throughout the southwest imply that this pattern is seasonally specific. However, Douglas's (1974) autumn cutoff low maximum, Eagleman's (1980) mention of autumn and winter occurrences, and Bell and Bosart's (1989) closed low climatology leave a question as to the precise seasonal distribution of southwestern troughing events. The scale of southwestern trough events implies that their occurrence is related to planetary scale wave dynamics. Cressman's (1948) wave movement theory, Pyke's (1972) and Yarnal and Diaz's (1986) Asian coast link, and Parker et al. (1989) split flow hypothesis all addressed possible associations with southwestern events; however, these relationships remain unexamined. Additionally, the geography of these events raises questions as to their influence on the precipitation and energy transfer climatology of the southwestern and central United States.

Given the diversity of information regarding the seasonal climatology of regional-scale troughing in the southwestern United States, their hemispheric associations, and their possible effect on the precipitation and meridional eddy sensible heat transfer processes, several research questions have been developed.

1. W
even
even
seco
clim

2. A
in h
(1)
simi
(197
flow
(197
flow
Amer
Furt
all

3. T
to t
cent
et a
Amer
into
posi
stor
into

4. T
to t
thro
(196
desc
tran
indi
sout
nort
flow
shou

1. What is the seasonal climatology of southwestern trough events? Although most authors contend that southwestern events occur predominantly during the spring months with a secondary autumn maximum, the lack of a detailed climatology justifies this examination.

2. Are southwestern events associated with distinct changes in hemispheric long wave geometry? These might include: (1) systematic variations in wave position and wave number, similar to those theorized by Cressman (1948), Douglas (1974) and Yarnal and Diaz (1986); (2) systematic shifts in flow trajectory and speed along the Asian coast as Pyke (1972) and Yarnal and Diaz (1986) described; and (3) split flow over the eastern Pacific Ocean and western North America, as theorized by Parker et al. (1989). Furthermore, are these associations consistent throughout all seasons?

3. To what degree do southwestern trough events contribute to the precipitation climatology of the southwestern and central United States? Duquet and Spar (1957) and Parker et al. (1989) showed that closed troughs forming in the American southwest generally move in a northeast direction into the central states. As a result of their geographic position relative to the Gulf of Mexico, southwestern storms should be able to advect large amounts of moisture into the interior states.

4. To what degree do southwestern trough events contribute to the meridional transport of eddy sensible heat throughout the central United States? Haines and Winston's (1963) examination of meridional sensible energy transport described seasonal and latitudinal patterns of energy transport but did not comment on the relative importance of individual storm events. Given the geography of the southwestern trough event, with relatively cold air to the north, warm air to the south, and a generally meridional flow pattern, significant transfer of eddy sensible heat should be expected.

N
fiel
were
Rese
Exce
were
the
peri
used
as r
198
N
were
temp
heig
the
used
repl
I

Chapter 2

DATA AND PROCEDURES

Data

Northern hemispheric daily 500 mb geopotential height fields interpolated to a 5° latitude by 5° longitude grid were obtained from the National Center for Atmospheric Research (NCAR) for the period 1946-1987 (Jenne, 1975). Except for a ten year period before March, 1955, all grids were evaluated from 1200Z soundings. Before March, 1955, the grids were evaluated using 1500Z soundings. Because periods of missing data usually last only a few days, I used linearly interpolated values based on surrounding days as replacements (Shukla and Mo, 1983; Barnston and Livezey, 1987).

Northern hemispheric daily 500 mb temperature fields were obtained from NCAR, also. The grid density of the temperature data was the same as the 500 mb pressure height data; however, the temperature data were limited to the years 1964-1987. As with the pressure height data, I used linearly interpolated temperature values as replacements during periods of missing data.

In addition to the 500 mb data, NCAR daily precipitation data for fifty-four stations west of the Mississippi River were obtained (Figure 2.1). These data span the periods 1948-1963 and 1969-1976 and were used to evaluate the influence of southwestern trough events to the precipitation climatology of the southwestern and central United States.

Documented use of interpolated upper atmospheric data has led to the recognition of a number of possible problems regarding their reliability. In a detailed discussion of the NCAR 700 mb data set accuracy Barnston and Livezey (1987) noted areas of positively biased height values throughout the Caribbean, North Africa, and the Himalayas. These inaccuracies appeared to be most prevalent during the summer. Although these observations were based on 700 mb data and may be influenced by surface thermal features and terrain, a similar bias may occur at other data levels, as well. Because these areas lie predominantly outside the middle latitudes, which is the region of interest in this study, they should not significantly influence the outcome of this analysis. However, the potential for biased results should be noted and physical interpretations limited within the affected regions.

Another problem associated with upper level data involves historical changes in the interpolation and smoothing methods used by the National Meteorological Center. Prior to the widespread use of objective analysis

Figure 2.1 - NCAR 54 station precipitation network

using numerically generated first guess fields in areas with few observations (the early 1960's), subjective estimates of geopotential height based on persistence were used (Cressman, 1959). Few climatological studies mention this data characteristic; however, some authors, such as Haines and Winston (1963), Wahl (1972), Carleton (1988), and Knox et al. (1988), discussed their results in light of this problem. Haines and Winston (1963) and Wahl (1972) noted a difference in meridional circulation characteristics after the changeover to an objective scheme. The objective analyses were not capturing the same number of higher order waves as had the subjective analyses. However, Wahl noted that adjustments were made shortly after 1962 in order to recapture the original level of wave sensitivity.

This problem becomes particularly important in the interpretation of circulation statistics or eddy dependent parameters that span this changeover period. What appears to be a climate change may simply be a ramification of the interpolation and smoothing scheme (Wahl, 1972). The only calculations sensitive to interpolation changes in this study were those associated with eddy meridional heat transfer. Eddy meridional heat flux calculations require v-component geostrophic wind values and therefore are sensitive to variations in wave amplitude. Because gridded temperature data, which are necessary in the eddy heat transfer calculations, were available after 1964 only, my calculations were limited to this later data period. Therefore, the NMC operational changeover was not of concern in this analysis.

Finally, because the NCAR data are in a gridded format with values at each 5° latitude and longitude intersection, the meridional distance between grid values converges poleward. This data feature can be very disruptive, particularly if a statistical procedure sensitive to spatial correlation is used or area-dependent frequencies are calculated. North (1987) showed that zonally averaged parameters possess greater variances toward the poles simply by virtue of the spherical geometry of the geographic grid. Depending on the nature of the analysis, equal area standardization should be used to alleviate this problem. Because the procedures that were used in this study did not involve the extensive comparison of zonal averages or spatial statistical techniques, equal area standardization was not deemed necessary.

Procedures

Southwestern Trough Event Selection

The southwestern trough selection process was broken into two phases. In the first phase, each daily 500 mb geopotential height field was numerically examined to determine whether long wave troughing was occurring over the southwestern United States. For each day during the forty-two year data record, the lowest 500 mb geopotential height along the 35°N parallel between 75°W and 150°W longitude was found. The 35°N parallel was chosen because it traverses the southwestern United States. The location of the lowest pressure height over such a large longitudinal belt should closely approximate the longitudinal axis of a long wave trough. This position was further examined to determine whether it lay between 105°W and 120°W, which is a smaller transect that traverses the southwestern United States. If this condition was satisfied, that day was selected as a potential southwestern troughing day.

The second phase of the southwestern trough selection process was designed as a check of wave form and baroclinicity. The v-component of the geostrophic wind was calculated for one location northwest and one location northeast of the lowest pressure height grid point found in the first phase of the selection process. The first check point was 10° west and 5° north of the lowest height grid point and the second check point was 10° east and 5° north of the lowest height grid point. Those days during which the v-component changed from a negative to a positive value between the two check points, as should be expected when troughing is present, and also possessed a minimum resultant speed of 10 m/s at each point were included in the final trough data set. The v-component check assured that the selected trough possessed a minimum longitudinal size, whereas the minimum speed threshold prevented the inclusion of days during which the southwestern United States was dominated by a weak pressure gradient.

I then examined all days that satisfied the selection criteria to determine whether they represented single day troughing events or were part of a multiple day troughing period. Adjacent periods of troughing days separated by only one day were combined to form a single troughing event. Troughing periods separated by more than one day were considered as separate events. Each troughing event was categorized based on the month during which it occurred. Events that bridged two months were classed with the month in which most of the troughing days occurred, whereas events equally split between two months were classed with the month during which the troughing period began.

Temporal Climatology

The trough event data set was categorized into annual and seasonal trough frequencies for each year during the data record. Based on Eagleman's (1980) evaluation, long-wave trough events normally last several days. Therefore, in an effort to evaluate the effect of unwanted noise caused by fast moving, poorly-defined single day events, I further subdivided the seasonal and annual time series into two groups. The first group of frequencies contained all southwestern trough events regardless of their duration. The second set included only those southwestern trough events lasting longer than one day. I then subjected the annual and seasonal time series to a number of exploratory statistical procedures to determine the mean frequency, range, and standard deviation of events during the data record. Because southwestern trough events may be related ultimately to periodically occurring forcing mechanisms, such as the cold phase of the southern oscillation, a runs test and spectrum analysis were performed to assess the presence of non-random clustering and periodic behavior.

The Compositing Approach

The problem of reducing sets of meteorological information into meaningful, yet objective, information occurs when large numbers of events make individual case analysis inefficient. Historically, composite analysis has proven an efficient and objective alternative when the individual analysis of a large set of events is unsuitable (Winkler, 1988). Although little work of this form has been directed at the southwestern trough question, several studies of wave behavior during cold-air outbreaks over East Asia have been based on composite analysis (Joung and Hitchman, 1981; Lau and Lau, 1984). For the construction of these cold-air outbreak composites, the outbreak periods and the key dates of each event were first identified and then a series of middle tropospheric twenty-four hour height change maps for several days before and after the key date were constructed. Through this series of maps, the evolution of total hemispheric activity was characterized by the magnitude and location of key height change centers. A similar technique was adopted for this study.

The gridded hemispheric 500 mb NCAR height data served as the data set. A set of composite 500 mb geopotential height and twenty-four hour height change maps was constructed for each season. As in the cold-air outbreak studies, the composite charts represent a series of successive days (four in this case) before and after each troughing period. The four days prior to the beginning date were identified as day (-1) through day (-4) and those after the ending date as day (+1) through day (+4) (Figure 2.2). The composite period spanned by day -1 through day -4 was referred to as the trough genesis period and the period spanned by day +1 through +4 was called the trough lysis period. Only those troughing events that were at least four days from adjacent events and had durations greater than one day were used in the genesis and lysis composites in order to avoid situations in which the lysis period of one trough event overlaps the genesis period of

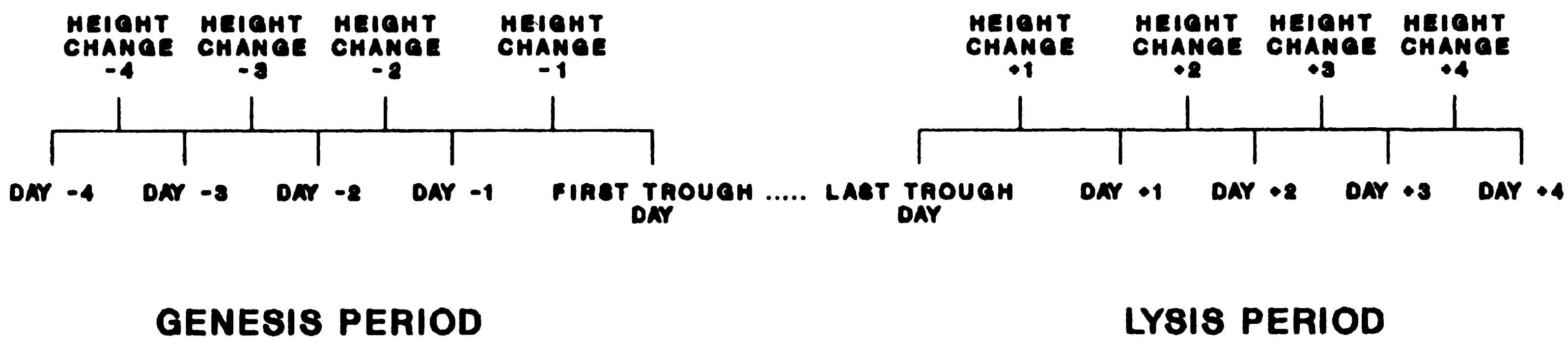


Figure 2.2 - Southwestern trough compositing scheme

the following trough.

In addition to the composite pressure height and height change summaries, composite geostrophic wind components were calculated for the genesis period. Because geostrophic wind calculations are technically appropriate in nonaccelerated flow only, observed wind magnitude will differ from that calculated using the geostrophic approximation. Therefore, my wind calculations, which do not include ageostrophic contributions, are not entirely realistic. However, because of the dominance of geostrophic contributions and the broad geographic scale of this analysis, these calculations should provide a fairly accurate assessment of wind character.

Wave Train Analyses

Ultimately, the composite results must indicate: (1) where southwestern troughs originate and whether their origin varies seasonally; (2) whether height change features located in other parts of the world are associated with the onset of southwestern troughing; and (3) what changes in wave movement and wave number occur during the development of southwestern troughing.

For each season, I examined the series of composites to determine whether systematic wave train changes could be qualitatively established during the onset and breakdown of southwestern troughing. By inspecting each series of v

t

c

po

s

as

on

trou

mean

troug

height change composites during the genesis period, I determined whether troughing in the southwestern United States resulted from large perturbations moving eastward across the Pacific or was the teleconnective result of some key upstream feature. In a similar fashion, the height change composites were examined to assess the linkages between wave changes in other parts of the Hemisphere and the establishment and maintenance of southwestern troughing. By examining the day-to-day progression and strength of the dominant height change centers (exceeding 20 m) for each set of seasonal composites, I identified regions of consistently active height change.

Changes in wave number during southwestern trough development were determined with the composite 500 mb geopotential height and v-component summaries. Because the v-component composites express the meridional component of the geostrophic flow, changes in positive and negative centers are closely associated with changes in wave position and wave number. In this manner, wave changes similar to those described by Cressman (1948) were assessed.

The influence of regionally specific forcing mechanisms on the establishment and maintenance of southwestern troughing was examined further through a comparison of the mean 500 mb geopotential height field during southwestern trough periods with that of non-southwestern troughing periods. For each season, I identified all days during which southwestern troughing occurred and averaged their 500 mb height fields. In this same manner, all non-southwestern trough days were identified seasonally and their 500 mb height fields averaged. A pressure height difference field was calculated and the resulting pattern used to judge the presence of strongly dissimilar regions in the hemispheric wave train.

Asian Coastal Analyses

If southwestern troughing is associated with a southward shift in flow trajectory off the Asian coast and increased momentum transfer and wind velocity aloft, as Pyke (1972) and Yarnal and Diaz (1986) have postulated, these signals should be visible in the geostrophic wind analyses, twenty-four hour height change composites, and the southwestern versus non-southwestern troughing period height difference charts.

Pyke described two changes in cyclone behavior over the Asian coast that he thought were associated with the emergence of storm activity in the southwestern United States during the spring. These changes were: (1) a southward shift in the position of the cyclone frequency maximum; and (2) the development of a more SW-NE flow trajectory near Japan. Using the monthly composite u and v geostrophic wind components along the 145°E meridian, I examined Pyke's assertion by constructing the average resultant wind speed profiles for the southwestern trough and non-trough periods each month. The 145°E meridian was chosen because it lies east of Japan and traverses the region discussed by Pyke. By examining monthly changes in the latitude, magnitude, and direction of the maximum resultant velocity, I was able to determine whether a southerly shift in the position of the wind maximum occurred between the trough and non-trough periods. Additionally, the wind direction information was used to ascertain whether the flow direction shifted from a winter WSW-ENE orientation to a more SW-NE orientation during spring and whether these changes were more dramatic during southwestern trough periods.

The southwestern versus non-southwestern trough 500 mb difference maps were examined, also, to determine whether pressure heights over the Asian coastal region were lower during southwest trough periods. Such a condition would imply that the zone of maximum wind speed is in a more southerly position, matching Pyke's model.

Yarnal and Diaz (1986) found that the winter RPNA circulation mode was statistically more frequent during cold phases of the southern oscillation. During these periods, land/sea thermal contrasts and atmospheric instability are enhanced over the eastern Pacific and become particularly strong when Arctic pulses move southeast toward the East and South China Seas. As cold, continental air comes into contact with the warm sea surface, increased momentum transfer and wind speed results in downstream wave propagation. This downstream transfer of energy culminates as a large, amplified ridge over the Gulf of Alaska, driving the RPNA arrangement.

Because southwestern troughs represent extreme examples of the RPNA pattern, the seasonal southwestern trough genesis composites were examined for signals similar to those described by Yarnal and Diaz. Each set of genesis composites was examined for evidence of an eastward moving wave near the Asian coastal region.

As a final analysis, RPNA and PNA pressure height and geostrophic wind speed composite maps were constructed using a listing of RPNA and PNA winter months published by Yarnal and Diaz (1986). A wind speed difference map was compiled to determine whether Asian coastal values during RPNA periods were greater than those during PNA setups.

Split Flow Analyses

If split flow aloft over western North America is associated with southwestern trough occurrence, an analysis of the geostrophic resultant wind should reveal this tendency. Rather than analyzing composite speed maps, which represent the average of several individual days, I examined the total set of individual daily wind fields during southwestern troughing periods. For each day, the wind speeds at each latitudinal intersection between 150°W and 90°W longitude, were examined to determine the latitude of highest value at each 5° meridian. After the position of the highest wind speed was found, the latitudinal position of the second highest value was located. Because I was interested in detecting those conditions during which the wind maximum was split between a primary and secondary branch, the latitude of the second highest wind maximum had to be at least 15° latitude removed from that of the highest wind speed. This procedure excluded high speeds directly adjacent to the primary wind maximum. Finally, I constructed quartile frequency distributions showing the number of times the primary maximum or secondary wind maximum occurred at each latitudinal intersection.

As an additional examination, the Parker et al. (1989) composite technique was used to determine whether split flow over western North America was indicated on the monthly southwestern trough composite maps. Parker et al. calculated the composite positions of 5340 and 5640 meter 500 mb contours for twenty-two cases of 500 mb cyclogenesis over the southwestern United states during 1980-1985 and used these contours as determinants of flow diffluence and confluence. I initially attempted to use these same contours in this analysis. Unfortunately, the broader temporal scope of this study forced the use of higher representative contour values during the late spring and early autumn. During these months, a composite contour that passed through the southwestern United States was subjectively chosen as the higher representative contour. The contour 300 meters less than the higher value was then chosen as the lower representative contour. By assuming that wind flow is approximately parallel to the geopotential height contours, I evaluated the relative positions of the representative contours for indication of wind diffluence.

Precipitation Analyses

Two different precipitation analyses were used to determine the geographic and temporal significance of southwestern trough events as precipitation producers. The specific precipitation density approach used by Barry et al. (1981) offers a method of evaluating precipitation contributions associated with individual synoptic types. The resultant values are easily mapped and provide one method of assessing the influence of certain synoptic types in the precipitation climatology of a region. A similar approach was used to examine the precipitation influence of southwestern trough events.

Specific precipitation density calculations are not data intensive and require only a record of daily precipitation for each location in question. The precipitation density formula for the southwestern event is detailed in the following equation.

$$SPD = \frac{\text{mean daily precip. during sw trough days}}{\text{mean daily precip. during all precip. days}} * 100$$

Locations in which southwestern events contribute average amounts of precipitation have density values of 100. If southwestern events provide daily average precipitation greater than the overall daily average during precipitation days, this location will have a density value greater than 100.

Using the daily precipitation data, I constructed monthly precipitation density isoline maps and used them to compare the average precipitation associated with southwest troughing events with that associated with all circulation types. By examining the spatial distribution and magnitude of precipitation density values, I identified those regions most influenced by southwestern trough events. Unfortunately, during months in which southwestern event precipitation makes up a large proportion of the monthly total, specific precipitation density values may not be very illustrative. Therefore, a second analysis was performed in which I calculated the percentage of the total precipitation that was associated with southwestern troughing. The resultant percentages augmented the monthly density maps in detailing the geographic and temporal importance of southwestern trough events as precipitation producers.

Meridional Transport of Eddy Sensible Heat

The importance of southwestern trough events in the meridional transport of eddy sensible heat was examined with the equations described by van Loon (1979) and Carleton (1988). Van Loon found that most eddy sensible heat transfer takes place between the 850 mb and 700 mb levels. Although heat transfers are smaller at 500 mb, the overall flux patterns occurring in the lower atmosphere should be preserved in the higher levels, as well.

Using a subset of the NCAR 500 mb geopotential height and temperature data, bounded by 90°W and 120°W longitude and 30°N and 50°N latitude for the period 1964-1987, I calculated the mean daily total eddy heat flux for southwestern trough and non-southwestern trough periods. The total eddy heat flux for each day was calculated by multiplying the v-component geostrophic wind by the latitudinal temperature departure at each grid intersection. The latitudinal temperature departure represented the difference between the 500 mb temperature at that grid point and the mean latitudinal 500 mb temperature for that day. The resultant flux value reflected the combined contributions of quasi-stationary and transient eddies. These values were calculated each day, totaled, and averaged. I then calculated the average daily quasi-stationary eddy heat flux using the seasonal mean 500 mb v-component and temperature fields and subtracted these values from the total heat flux quantities during southwestern trough and non-trough periods thereby determining the mean daily quantity of sensible energy transferred by each transient eddy.

According to Haines and Winston (1963), the use of geostrophic approximation, which does not include the more realistic ageostrophic contributions, to calculate heat flux presents little problem at latitudes higher than 20°. Positive contributions toward northward heat transport occur at grid intersections where the temperature is above the latitudinal mean and the v-component is positive (southerly flow) and where the temperature is below the latitudinal average with a negative v-component wind (northerly flow). Any other combination results in a negative northward flux value and contributes negatively to the net northward transport of energy (Haines and Winston, 1963). Problems associated with changes in the NMC data analyses prior to 1963 were avoided in this analysis by using data after 1964 only. A series of maps were constructed portraying the average daily transient meridional heat transport during southwestern troughing days and non-southwestern troughing days for each season. Seasonal maps were also constructed depicting the quasi-stationary eddy heat flux. Furthermore, zonally averaged heat flux

across th

distribut

fields an

the relat

of sensib

heat flux values for each eddy condition were calculated across the study area (90°W-150°W). By comparing the distribution, sign, and magnitude of the energy transfer fields and the zonal flux averages, I was able to assess the relative importance of southwest troughing as a source of sensible heat flux.

The mont

trough even

that they w

being the m

events were

most of the

less freque

common. Ve

August.

A simila

multiple da

Chapter 2,

distributio

multiple da

noise carri

However, th

of these da

events. Th

applied to

Chapter 3

RESULTS

Temporal Climatology

The monthly frequency analysis of total southwestern trough events during the forty-two year data record reveals that they were most common during the spring, with April being the month of maximum occurrence (Figure 3.1). Trough events were somewhat less common during the autumn, with most of these occurring in November. Although slightly less frequent, winter southwestern troughs were also common. Very few trough events occurred during July and August.

A similar bimodal frequency distribution occurred in the multiple day trough event data set. As discussed in Chapter 2, I chose initially to examine the frequency distributions of both total southwestern events and multiple day events separately because of potential data noise carried by the weakly defined, single day events. However, the nearly synchronous frequency profiles of each of these data sets suggest little need to separate these events. Therefore, all following statistical analyses were applied to the total trough data set only.

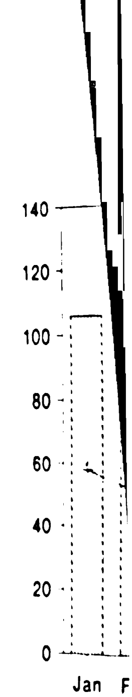


FIGURE 3.

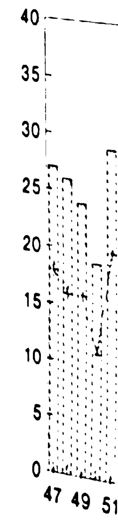


FIGURE 3.2

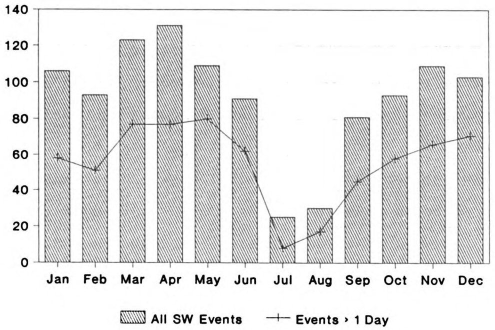


FIGURE 3.1 - Southwestern trough monthly frequency (1946-1987)

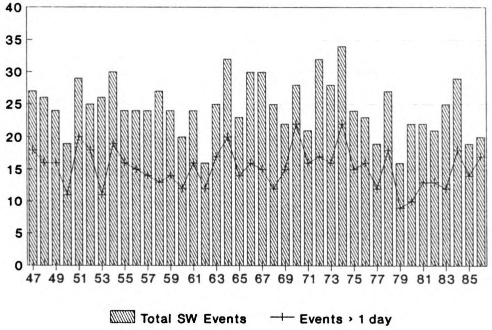


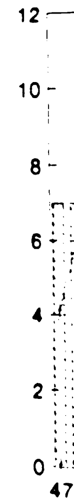
FIGURE 3.2 - Annual (Sep-Jun) southwestern trough time Series

After
events,
and Augu
using th
because
those of
months,
frequenc
December
calculat
November

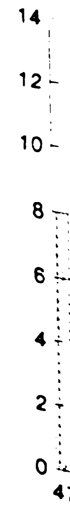
Visua
events a
events r
1979, to
3.2). S
troughs
1970, 19
occurred
The autu
which oc
maximum
autumns
of these
period.
even str

After examining the monthly distribution of southwestern events, which shows little troughing activity during July and August, I calculated the annual trough frequencies using the period September through June. Furthermore, because the June trough frequency more closely resembles those of March, April, and May than those of the summer months, June events were incorporated into the spring frequency summaries. Winter summaries were based on December through February totals, whereas autumn calculations used events occurring between September and November.

Visually, the annual frequency distribution of trough events appears quite variable. The total number of annual events ranged from a minimum of sixteen events, in 1962 and 1979, to a maximum of thirty-four events in 1974 (Figure 3.2). Seasonally, the frequency of winter southwestern troughs ranged from a minimum of three events, in 1963, 1970, 1980, and 1986, to a maximum of ten events, which occurred six times during the data record (Figure 3.3). The autumn frequency ranged from a minimum of four events, which occurred six times during the data record, to a maximum of ten events in 1972 (Figure 3.4). Of the six autumns during which only four trough events occurred, four of these were during the last twelve years of the data period. The spring southwestern trough summary reveals an even stronger tendency for lower trough frequencies during



FIGURE



FIGURE

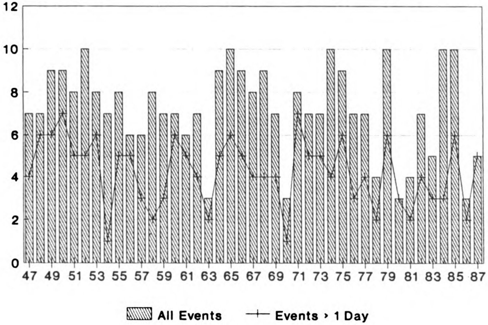


FIGURE 3.3 - Winter (Dec-Feb) southwestern trough time series

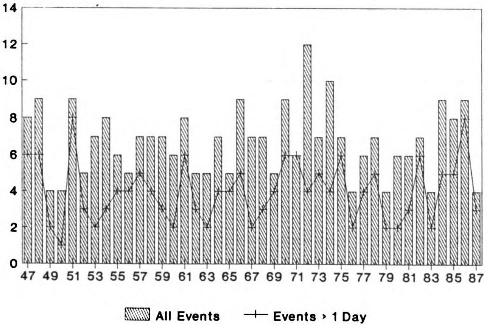


FIGURE 3.4 - Autumn (Sep-Nov) southwestern trough time series

the latte

spring fr

to a maxi

Based

(1988), w

of annual

data reco

change in

series, c

the pre-1

of the Wo

spring tr

at the .

departure

tendency

1952-196

occurren

1978-198

Spect

reveal n

at the .

set with

year pea

signific

the latter portion of the data record (Figure 3.5). The spring frequencies ranged from a minimum of six, in 1986, to a maximum of fifteen, in 1965.

Based on the sliding-scale t-statistic described by Knox (1988), which was used to determine whether the mean number of annual and seasonal trough events changed during the data record, I found that a statistically significant change in mean trough frequency occurred in the spring time series, only, and that this difference was greatest between the pre-1975 and post-1975 periods. Furthermore, results of the Wolf-Waldowitz runs test indicate that only the spring trough event data set contains non-random variation at the .10 significance level. A plot of the annual mean departures for the spring data (Figure 3.6) shows a tendency for above average clustering during the periods 1952-1960 and 1965-1977 and below average trough occurrences during the years 1948-1952, 1961-1964, and 1978-1987.

Spectrum analyses of the annual and seasonal data sets reveal no significant peaks in any spectral band. However, at the .05 level, two peaks in the spring total event data set with periods of two and ten years and a four-to-five year peak in the multiple day autumn record are nearly significant.

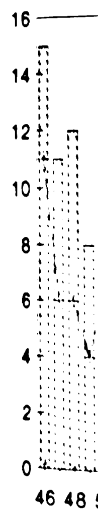


FIGURE 3.5

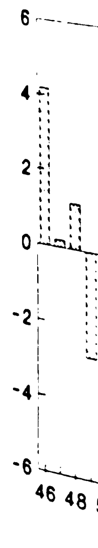


FIGURE 3.6

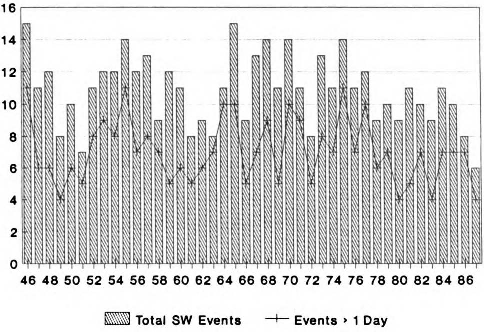


FIGURE 3.5 - Spring (Mar-Jun) southwestern trough time series

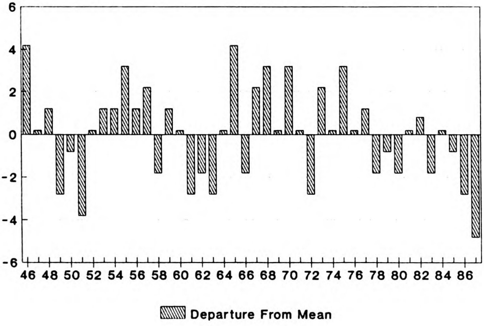


FIGURE 3.6 - Spring southwestern trough mean departure

The wa

maintena

Therefor

which in

hour hei

presente

examinat

troughin

the trou

signals

of south

winter w

are pres

results.

Winter 5

The w

period f

troughin

mean win

troughs

distinct

this com

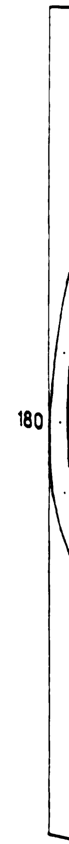
less def

Wave Train Composite Summaries

The wave train composite results follow the development, maintenance, and breakdown of southwestern troughing. Therefore, results of the seasonal genesis composites, which include the 500 mb geopotential height, twenty-four hour height change, and v-component summaries, are presented first. These results are followed by an examination of height characteristics during southwestern troughing periods and conclude with a brief presentation of the trough lysis composites. Because many of the important signals that emerge during the development and maintenance of southwestern troughing are best revealed during the winter when energetics are greatest, the winter composites are presented first, followed by the spring and autumn results.

Winter 500 mb and Height Change Genesis Composites

The winter 500 mb geopotential height composite for the period four days prior to the onset of southwestern troughing (day -4) possesses many characteristics of the mean winter circulation pattern (Harman, 1990). Large troughs over the Asian coast and eastern North America and distinctive ridging over western North America characterize this composite (Figure 3.7). Flow over Europe and Asia is less defined. The day (-4) pattern best approximates a



FI

three wave configuration, although a smaller fourth wave is observable over the Bering Sea and Gulf of Alaska.

During the next twenty-four hours, little change occurs in the 500 mb geopotential height configuration (Figure 3.8). The height change pattern (Figure 3.9) is generally weak, especially over Europe and Asia. Of those regions that exhibit greater than a twenty meter change, the largest is an area of height rise over the middle Pacific, south of the Aleutian Islands. This center appears to be coupled with a smaller height fall region over southwestern Canada. The most westward center of greater than twenty meter change is a small region of height rise over Japan.

By composite day (-2), a center of troughing near 170°E pulls away from the main axis of the Asian trough (Figure 3.10), and is best displayed on the twenty-four hour height change composite (Figure 3.11). The height rise center over Japan on the previous change composite moves eastward and is replaced by a center of height fall. Most dominant are three centers of change, exceeding forty meters, in the eastern Pacific. As the western Pacific disturbance pulls away from the Asian trough, the combination of wave movement and regional amplification produces sharply rising heights in the Gulf of Alaska, helping to drive height falls along the western coast of North America.

The day (-1) height composite clearly shows the effects of wave progression and amplification in the eastern

180

FIGURE 3.

16

FIGURE 3.9

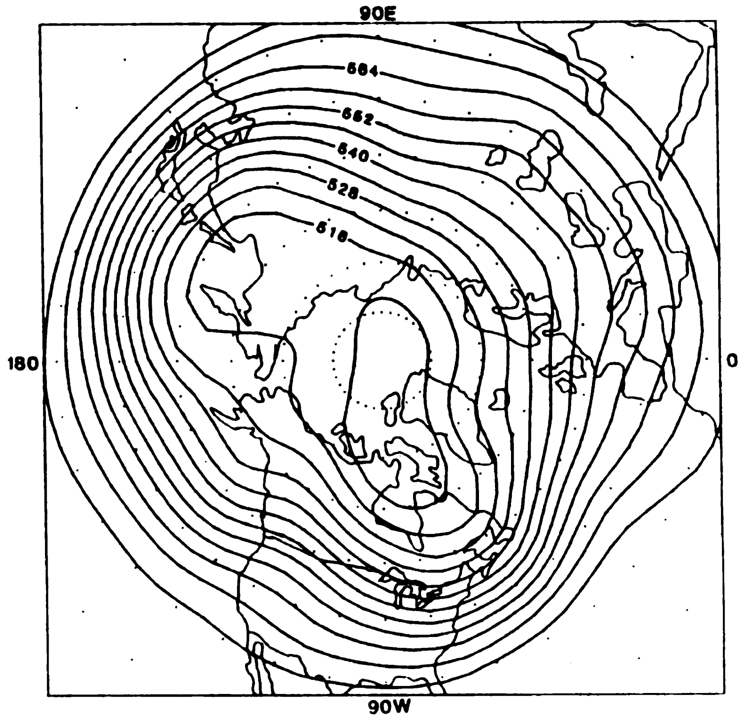


FIGURE 3.8 - Winter genesis day (-3) 500 mb height composite (in decimeters)

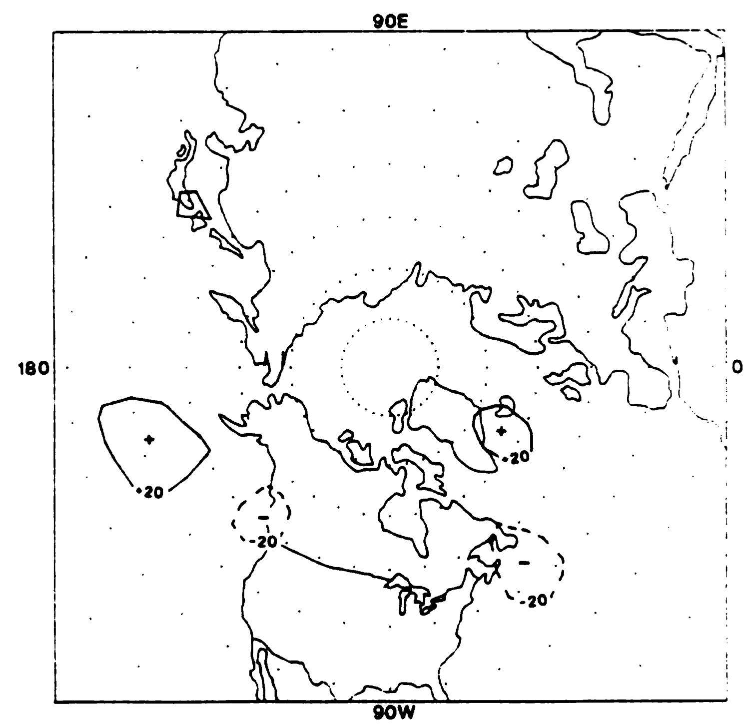


FIGURE 3.9 - Winter genesis day (-3) - day (-4) height change composite (in meters)

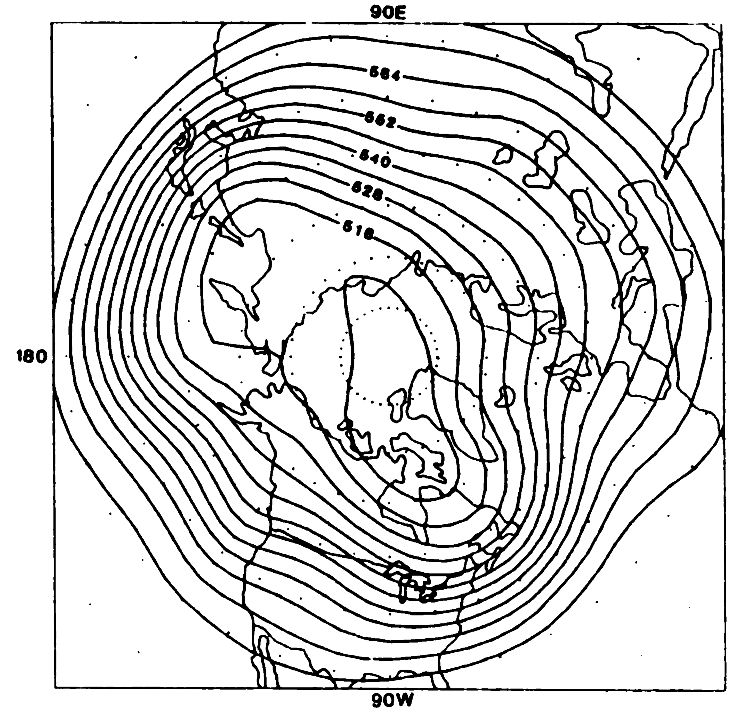


FIGURE 3.10 - Winter genesis day (-2) 500 mb height composite (in decimeters)

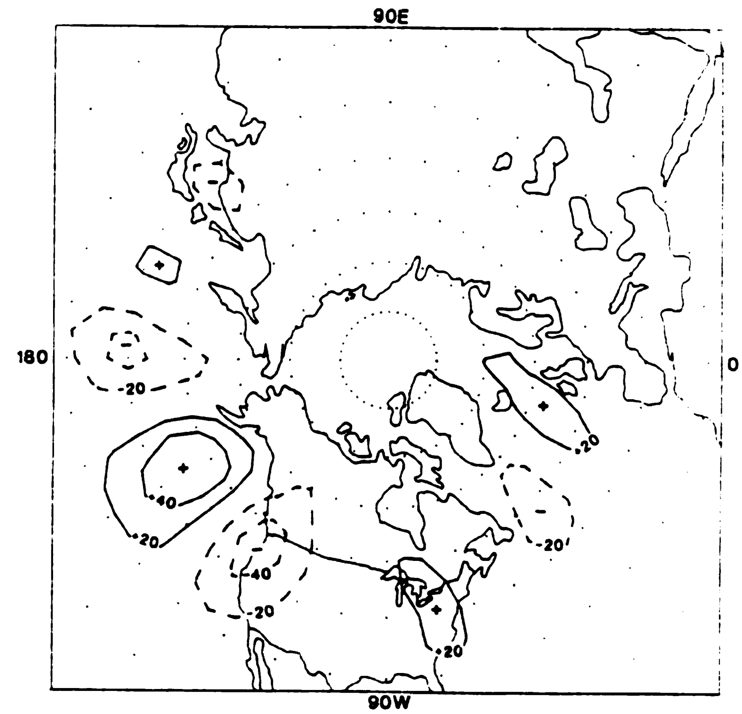


FIGURE 3.11 - Winter genesis day (-2) - day (-3) height change composite (in meters)

Pacific (Figure 3.12). By this time, much of the activity in the western and central Pacific has subsided (Figure 3.13). The Gulf of Alaska height rise center continues to amplify and is accompanied by concordant height falls in the western United States. The increase in size and magnitude of the height rise center over the eastern United States suggests teleconnective relationships.

The southwestern trough becomes firmly established during the final twenty-four hours of the winter genesis period (Figures 3.14 and 3.15). With troughing in the southwestern United States, flow trajectory over a large part of the country is southwesterly, with a broad, flat ridge over much of the eastern United States. As a result, the zone of greatest geopotential height gradient stretches from the axis of the southwestern trough, in the extreme southwestern United States, northeastward through the south-central and middle Atlantic states. Little change in the flow arrangement occurs over Europe and Asia during the winter genesis period. However, with the development of troughing in the southwestern United States the overall wave number appears to increase from three to four.

Spring 500 mb and Height Change Genesis Composites

The 500 mb spring composite for day (-4) possesses many of the same features seen on the winter day (-4) pressure height composite (Figure 3.16). For example, extensive

FI

FIGU

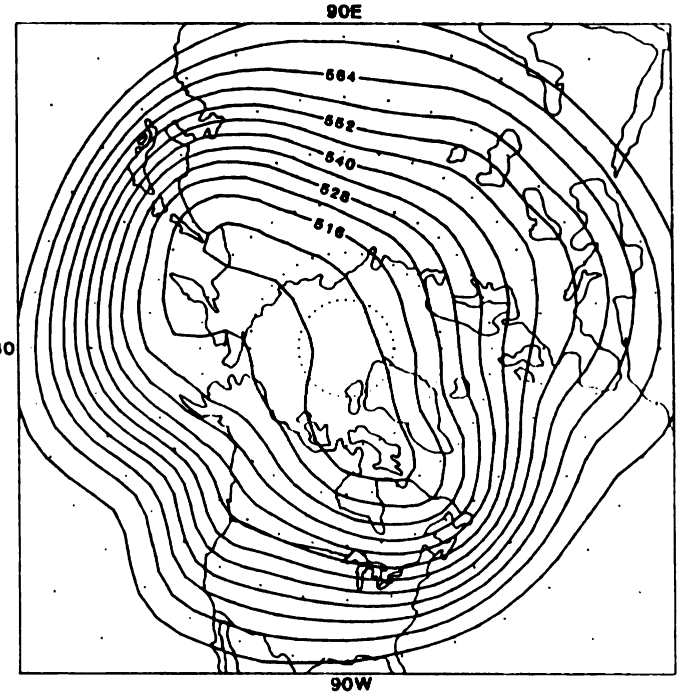


FIGURE 3.12 - Winter genesis day (-1) 500 mb height composite (in decimeters)

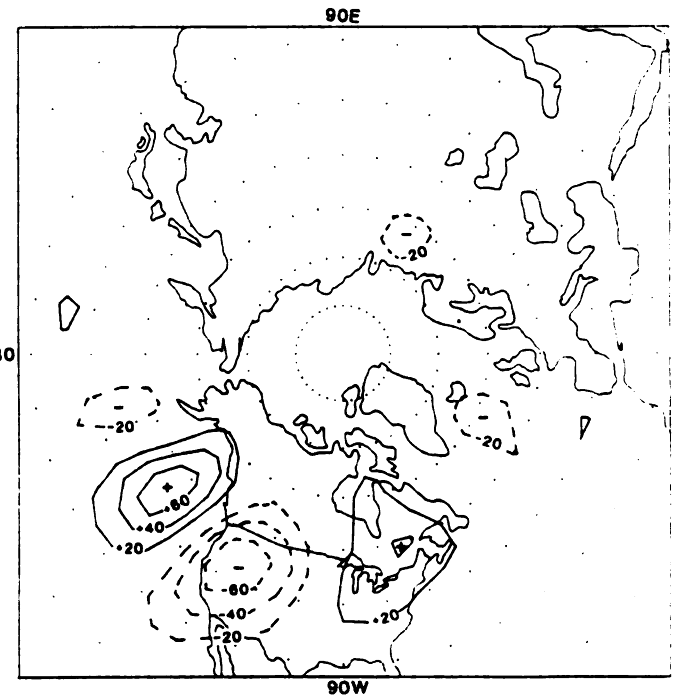


FIGURE 3.13 - Winter genesis day (-1) - day (-2) height change composite (in meters)

FIGURE 3

FIGURE 3.

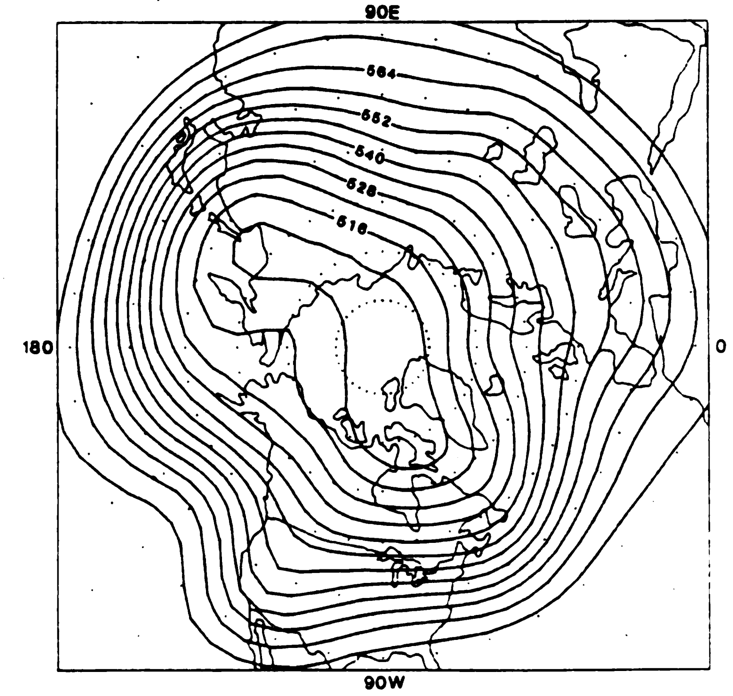


FIGURE 3.14 - Winter genesis day (0) 500 mb height composite (in decimeters)

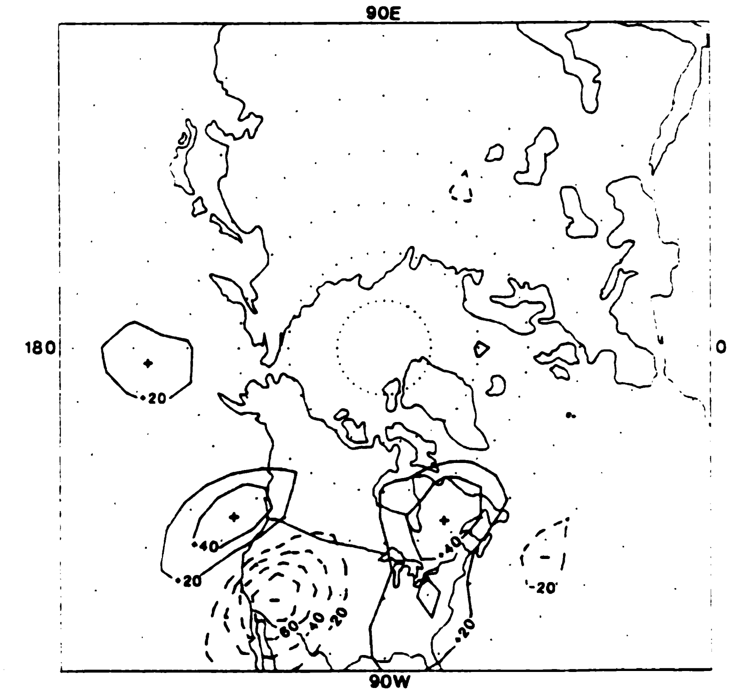


FIGURE 3.15 - Winter genesis day (0) - day (-1) height change composite (in meters)

troughing

America,

dominant

troughing

Hemispher

day (-4),

shows sig

trough.

wave conf

Betwee

overall w

over the

height ch

rises in

reflect t

regional

During

propagate

Asian coa

Associate

in the G

Even thou

than for

sixty me

By da

western M

troughing over the Asian coast, ridging over western North America, and troughing over eastern North America are the dominant features. Although some evidence of weak troughing exists over southern Europe, most of the Eastern Hemisphere is dominated by zonal flow. Unlike the winter day (-4), however, the height field near 160°E already shows signs of wave movement within the larger Asian trough. Although difficult to assess, the initial spring wave configuration contains three or four waves.

Between day (-4) and day (-3), little change in the overall wave pattern occurs (Figure 3.17). Wave movement over the western Pacific produces a positive and negative height change couplet east of Japan (Figure 3.18). Height rises in excess of twenty meters in the eastern Pacific reflect the beginning of eastward wave movement and regional amplification.

During the next twenty-four hours, the wave train propagates slowly eastward, as shown by the location of the Asian coastal wave couplet (Figures 3.19 and 3.20). Associated with this wave movement, pressure heights rise in the Gulf of Alaska and fall in western North America. Even though height changes in the Asian couplet are less than forty meters, those in the Gulf of Alaska approach sixty meters.

By day (-1) the wave train over the eastern Pacific and western North America becomes noticeably amplified (Figures

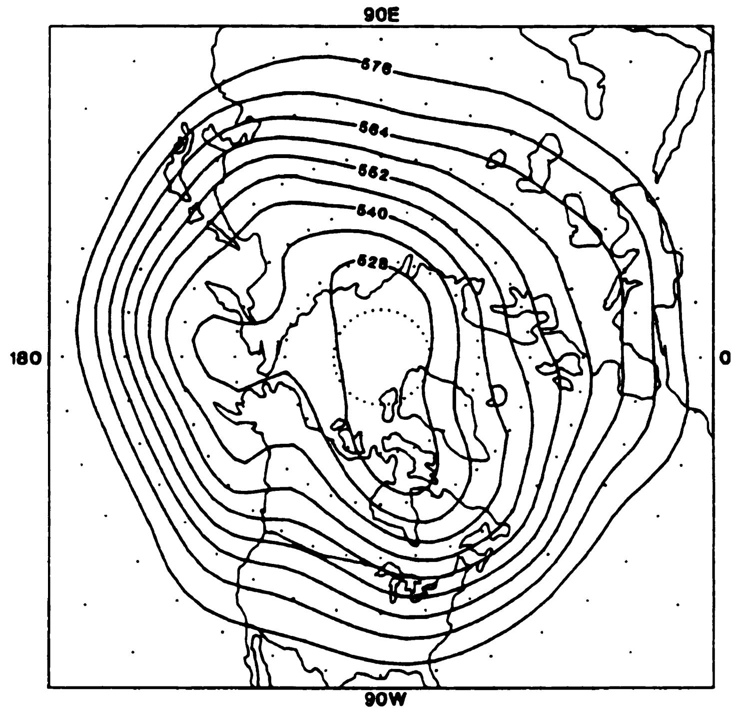


FIGURE 3.17 - Spring genesis day (-3) 500 mb height composite (in decimeters)

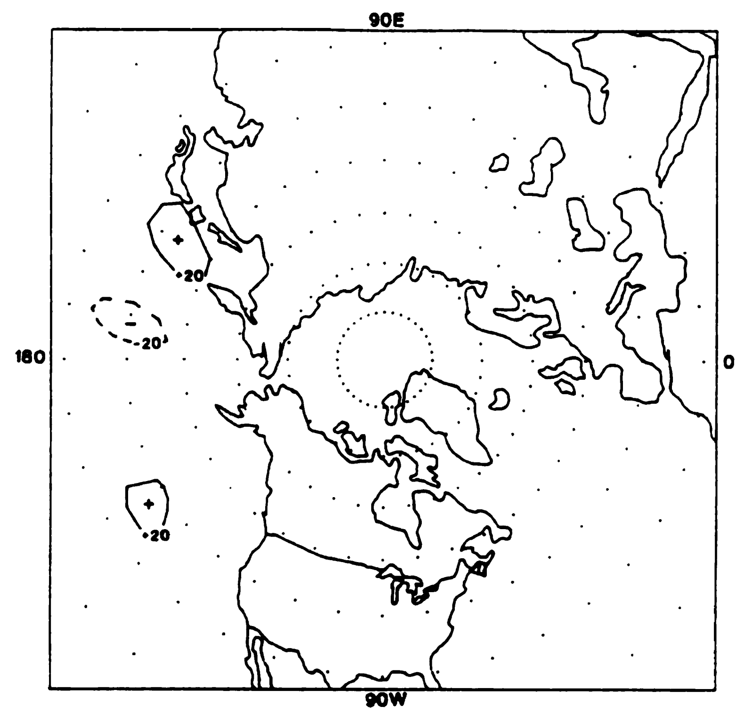


FIGURE 3.18 - Spring genesis day (-3) - day (-4) height change composite (in meters)

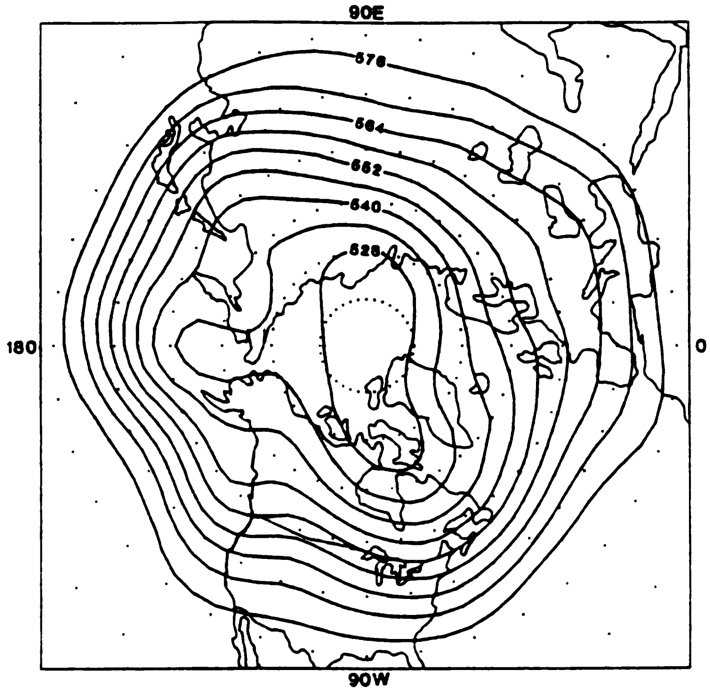


FIGURE 3.19 - Spring genesis day (-2) 500 mb height composite (in decimeters)

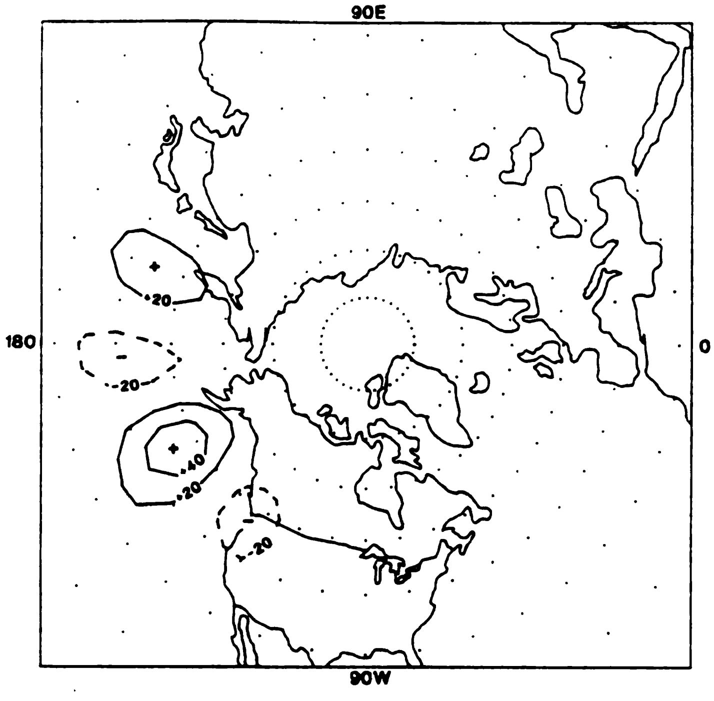


FIGURE 3.20 - Spring genesis day (-2) - day (-3) height change composite (in meters)

3.21 and 3.22). The most prominent height change feature is the Gulf of Alaska height rise center. Its slight eastward movement and amplification help drive height falls in the western United States and height rises in the eastern United States.

Geopotential heights in the southwestern United States continue to fall by the final spring composite day (Figures 3.23 and 3.24). The dominance of southwestern troughing appears a response to the eastward movement and amplification of wave features in the eastern Pacific. As a result of strong height falls in the southwestern United States, the areal extent of the height rise center in the eastern United States increases.

The wavelength of the spring southwestern trough appears slightly shorter than that of its winter counterpart. Although the trough axis is positioned over the extreme southwestern United States, as it is during winter, its downstream flow is more southwesterly. The apparently larger meridional component places the zone of greatest height gradient through the central and north central states. In addition, the emergence of southwestern troughing is associated with a shift from an initial three-to-four wave configuration on day (-4) to a four-to-five wave arrangement by day (0).

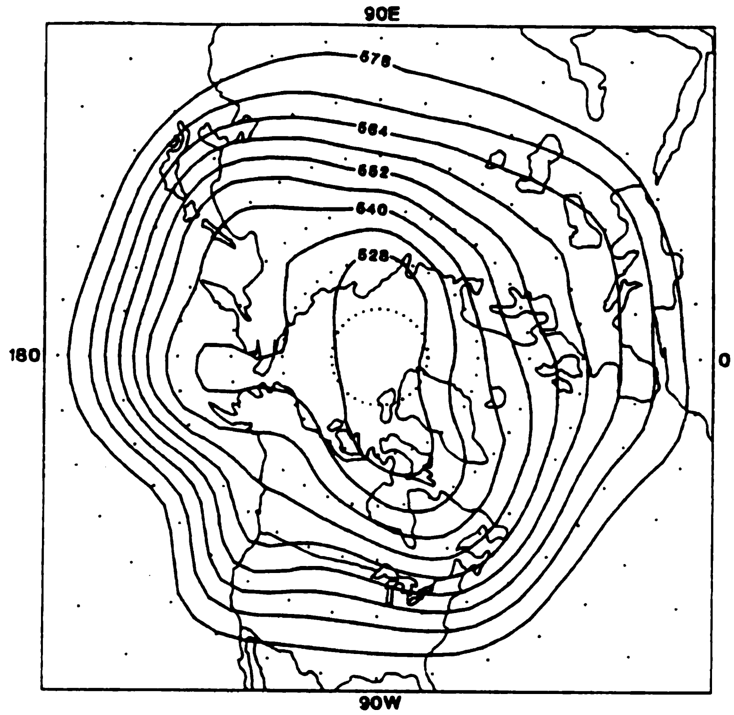


FIGURE 3.21 - Spring genesis day (-1) 500 mb height composite (in decimeters)

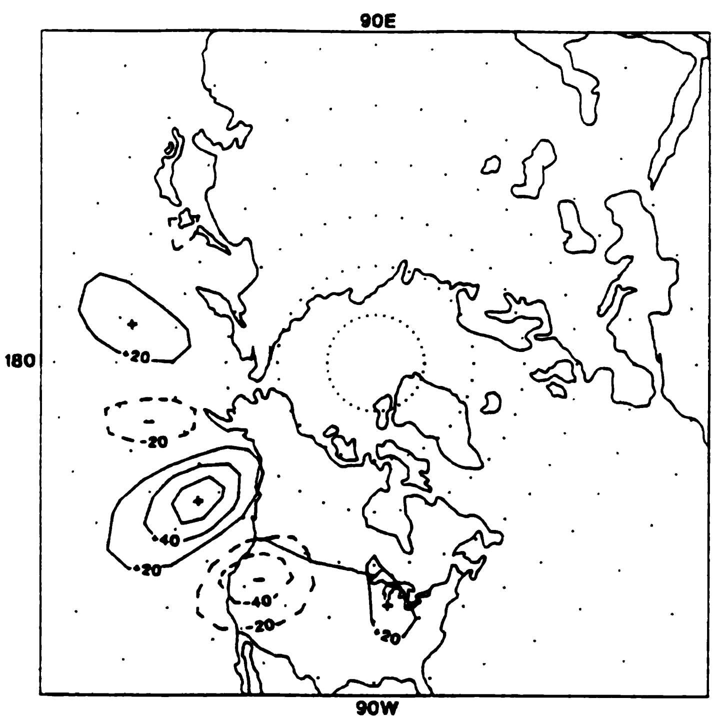


FIGURE 3.22 - Spring genesis day (-1) - day (-2) height change composite (in meters)

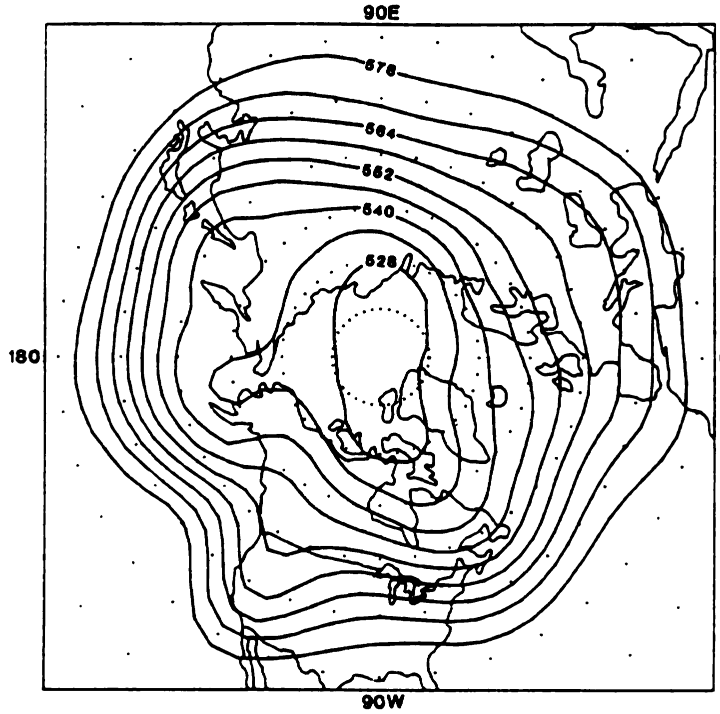


FIGURE 3.23 - Spring genesis day (0) 500 mb height composite (in decimeters)

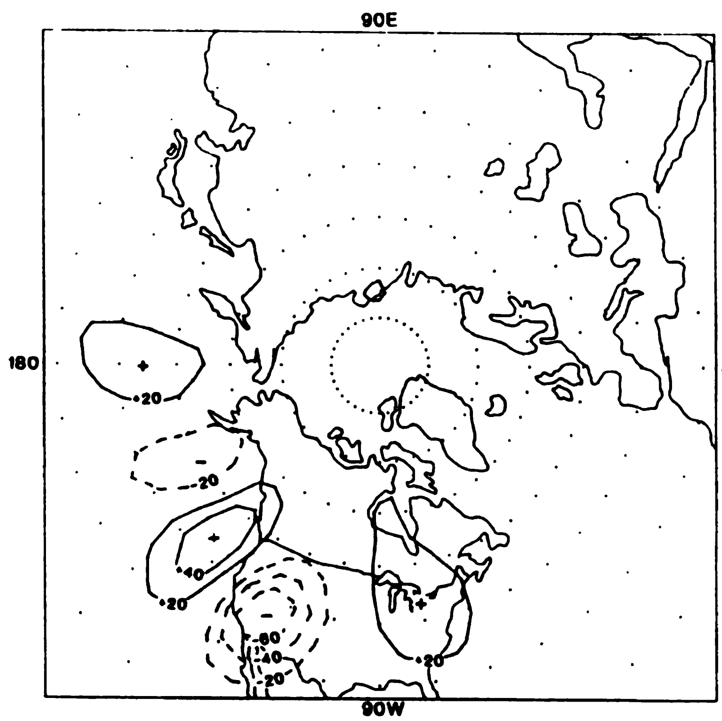


FIGURE 3.24 - Spring genesis day (0) - day (-1) height change composite (in meters)

Autumn 500 mb and Height Change Genesis Composites

The 500 mb circumpolar configuration on autumn day (-4) is characterized by a well-defined ridge over western North America and troughing over the western Pacific and eastern North America (Figure 3.25). As in the spring day (-4) composite, the western Pacific trough is very broad with indication of secondary wave development in the western Pacific. European and Asian features appear weak, also. Although difficult to assess, the day (-4) configuration contains three-to-four long waves.

Between day (-4) and day (-3), pressure heights fall in the western Pacific, south of the Kamchatka Peninsula, near 170°E longitude (Figures 3.26 and 3.27). This disturbance is accompanied by the emergence of a weak downstream ridge over the Aleutian Islands and a trough over western North America. Even though this pattern is less defined, it resembles the conditions seen in the winter and spring composites. By composite day (-2), the Kamchatka Peninsula trough amplifies and moves eastward over the Bering Sea (Figure 3.28). As a consequence, heights rise sharply in the Gulf of Alaska and fall in western North America (Figure 3.29).

During the next twenty-four hours, the wave train in the eastern Pacific continues to progress and amplify (Figures 3.30 and 3.31). Heights in the Gulf of Alaska ridge and the Bering Sea and western North American troughs each

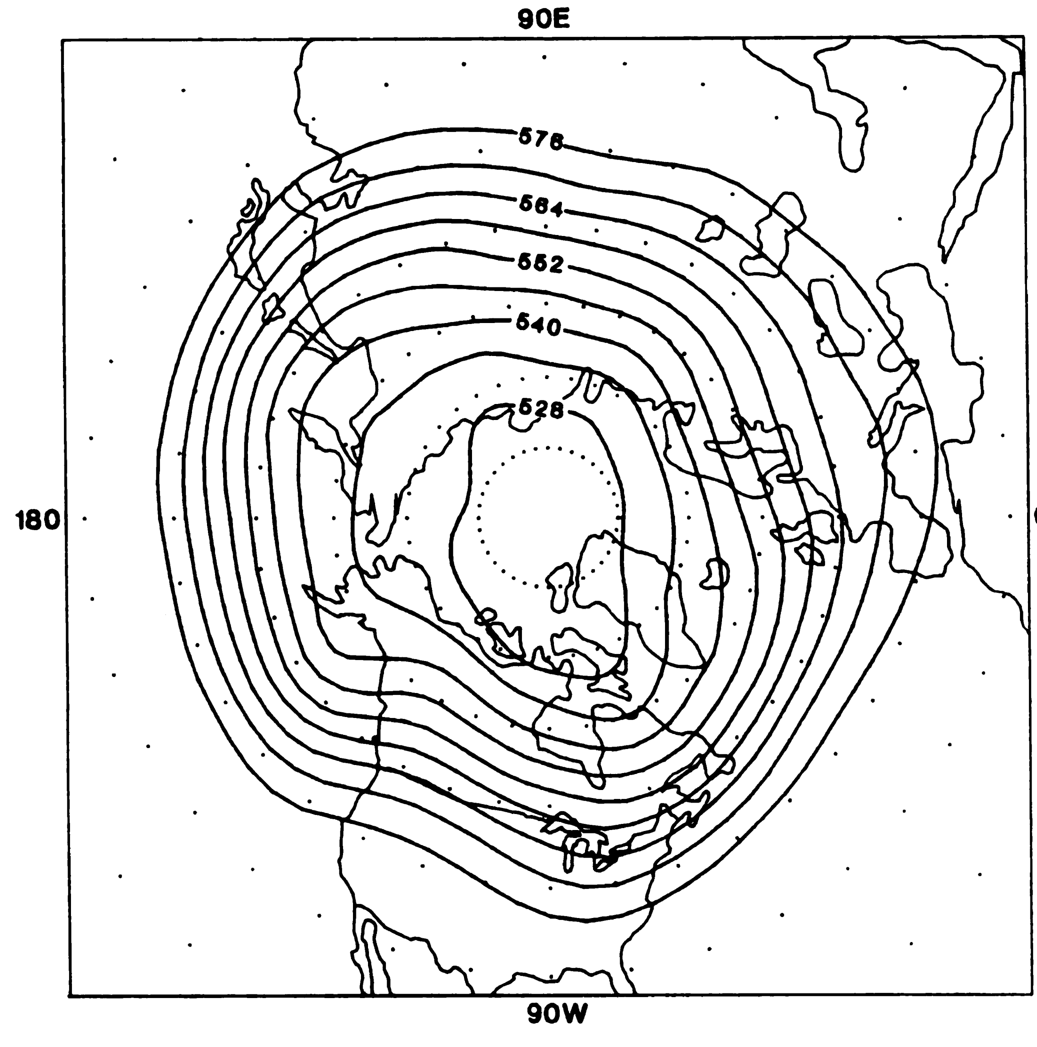


FIGURE 3.25 - Autumn genesis day (-4) 500 mb height composite (in decimeters)

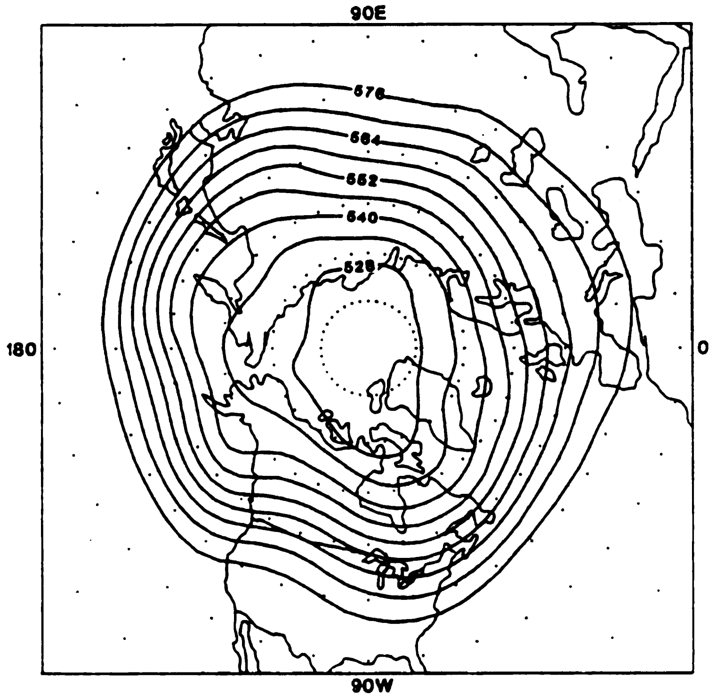


FIGURE 3.26 - Autumn genesis day (-3) 500 mb height composite (in decimeters)

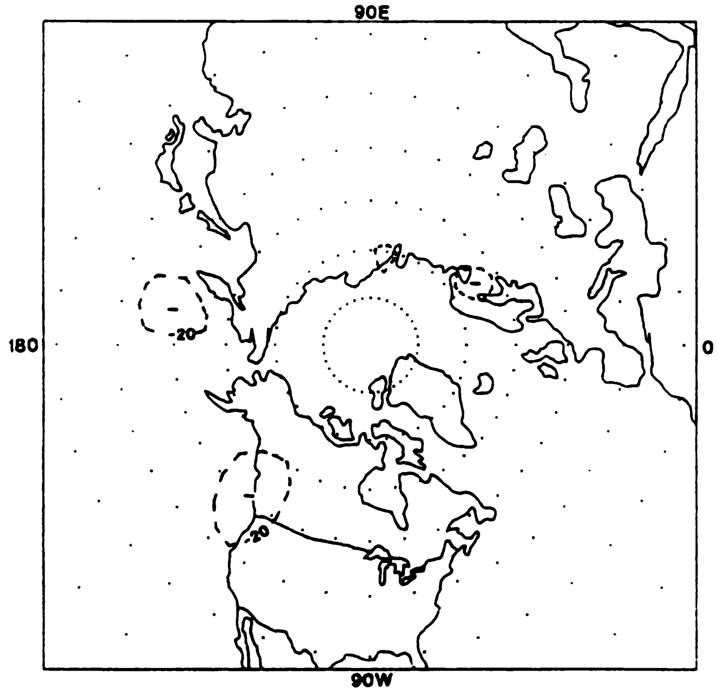


FIGURE 3.27 - Autumn genesis day (-3) - day (-4) height change composite (in meters)

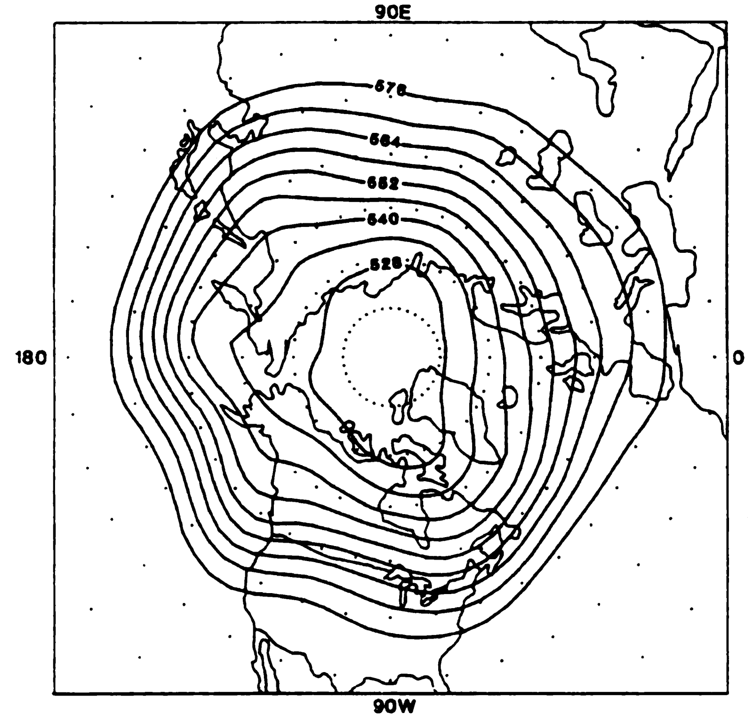


FIGURE 3.28 - Autumn genesis day (-2) 500 mb height composite (in decimeters)

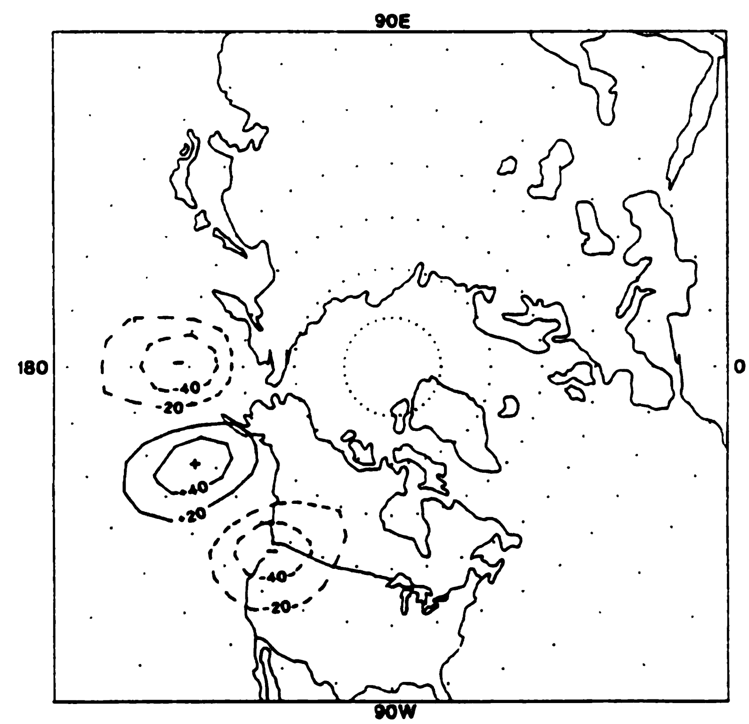


FIGURE 3.29 - Autumn genesis day (-2) - day (-3) height change composite (in meters)

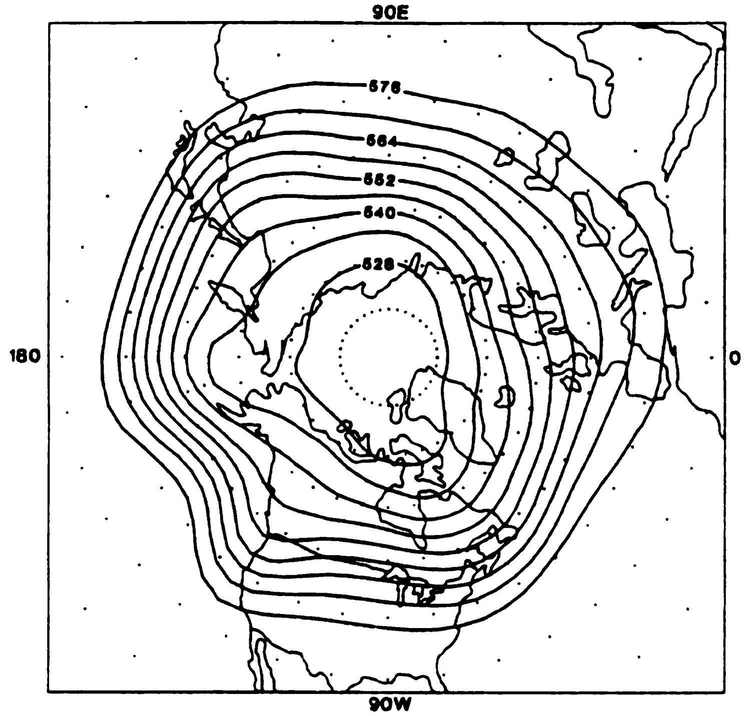


FIGURE 3.30 - Autumn genesis day (-1) 500 mb height composite (in decimeters)

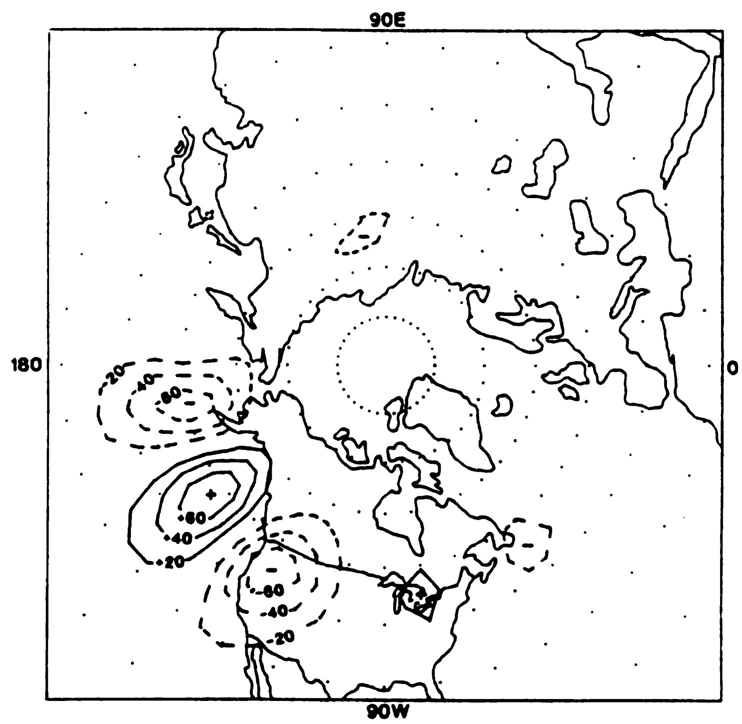


FIGURE 3.31 - Autumn genesis day (-1) - day (-2) height change composite (in meters)

change in excess of sixty meters.

In the final composite, the Bering Sea trough moves eastward over the Aleutian Islands (Figures 3.32 and 3.33). The Gulf of Alaska height rise center and the southwestern United States height fall center move eastward, also, and amplify sharply. The circumpolar vortex is more contracted than that of winter and spring and reflects the influence of the warmer autumn atmosphere. This characteristic is especially apparent in the southeastern United States where pressure height gradients are weak. As a consequence, the zone of greatest geopotential height gradient lies in a steep southwest-northeast belt, extending from the extreme southwestern states into the north central and Great Lake states.

Summary of 500 mb and Height Change Genesis Composites

A key feature in the development of southwestern troughing is the growth of a secondary disturbance within the Asian long wave trough, near Japan. This feature is best displayed during spring and more weakly defined during winter and autumn. As this secondary disturbance progresses eastward, heights fall over the Bering Sea and rise in the Gulf of Alaska. The magnitude of height change in the Gulf of Alaska is much greater than that associated with the Asian trough secondary disturbance, suggesting some form of regional wave enhancement independent of

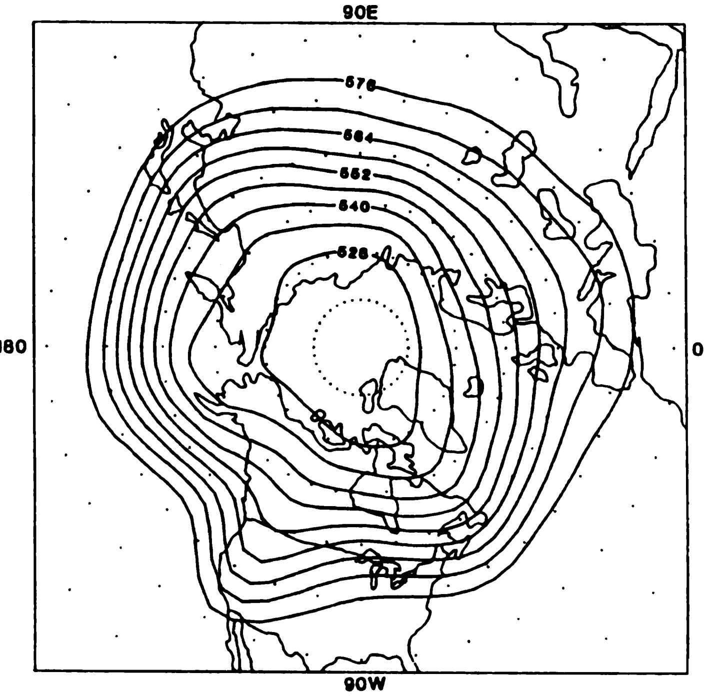


FIGURE 3.32 - Autumn genesis day (0) 500 mb height composite (in decimeters)

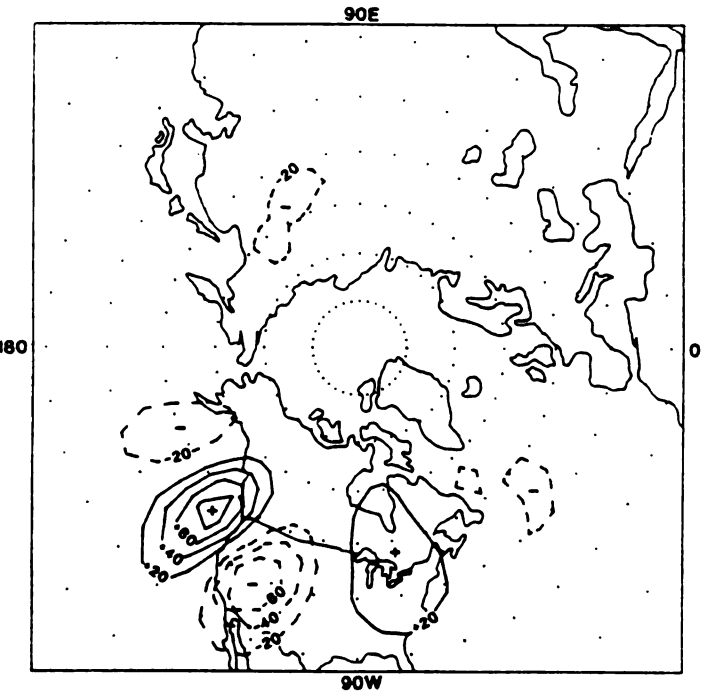


FIGURE 3.33 - Autumn genesis day (0) - day (-1) height change composite (in meters)

upstream features in the eastern Pacific. These changes are teleconnectively transferred downstream, driving height falls in western North America and height rises in eastern North America. The trough axis is at approximately the same longitude during each of the seasons; however, seasonal differences in stationary wavelength contribute to variations in downstream flow trajectory. Finally, as a consequence of deep troughing in the southwestern United States, overall wave number appears to increase during the genesis period.

Winter V-component Genesis Composites

Because v-component calculations portray only the meridional characteristic of the geostrophic wind, they provide information regarding wave number, location, and strength that is not easily obtained from 500 mb geopotential height data. For example, on winter day (-4), the v-component composite field contains two clearly defined negative centers, over eastern Asia and central North America, and a third weaker region over southern Europe (Figure 3.34). The east Asian negative center reflects northerly flow in the western limb of the Asian long wave trough, whereas the North American negative v-components reflect northerly flow east of the North American ridge. These areas, coupled with three positive centers over the middle Pacific, the western Atlantic and

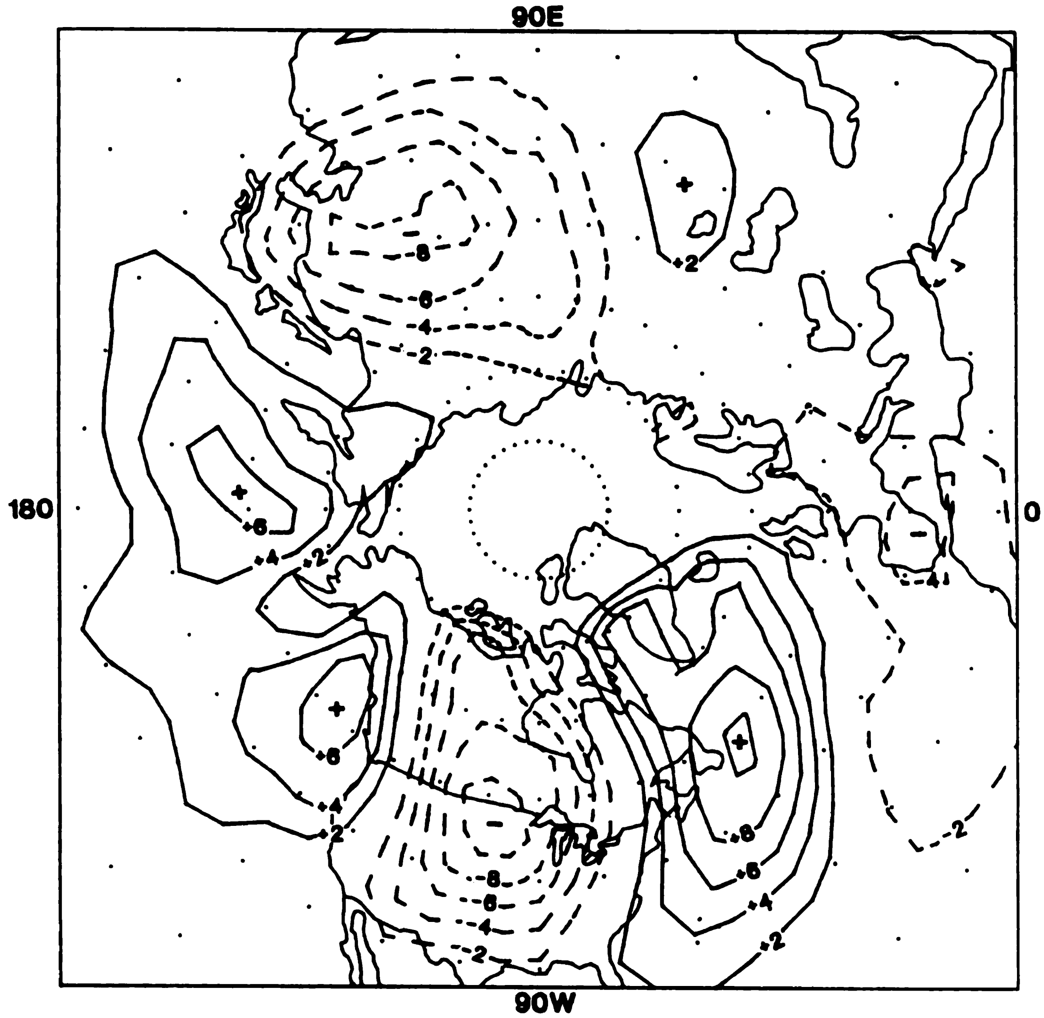


Figure 3.34 - Winter genesis day (-4) 500 mb v-component composite (in m/s)

central Asia, make up a strong three wave circulation pattern.

Little change occurs in the v-component pattern between day (-4) and day (-3) (Figure 3.35). Except for the area of positive components over the central and east Pacific, which is associated with the eastern limb of the Asian long wave trough, the other systems remain fixed in their day (-4) positions. A weakening in the v-component values near 150°W signals the development of an additional ridge and trough couplet.

By day (-2), the wave train progresses eastward and a new center of negative values expands into the Gulf of Alaska, indicating ridge growth over the Aleutian Islands and trough development over the American coast (Figure 3.36). By day (-1), the negative v-components over the Gulf of Alaska strengthen (Figure 3.37). Eastward movement in the positions of the adjacent v-component centers suggests wave train reorientation. However, the lack of wave movement over east Asia indicates that wave reorientation over the eastern Pacific, North America, and the Atlantic does not appear to be associated with energetics over the Asian mainland.

The final winter v-component composite depicts continued strengthening and eastward movement of the ridge supporting the Gulf of Alaska negative center (Figure 3.38). With its eastern influence expanding into the western United States,

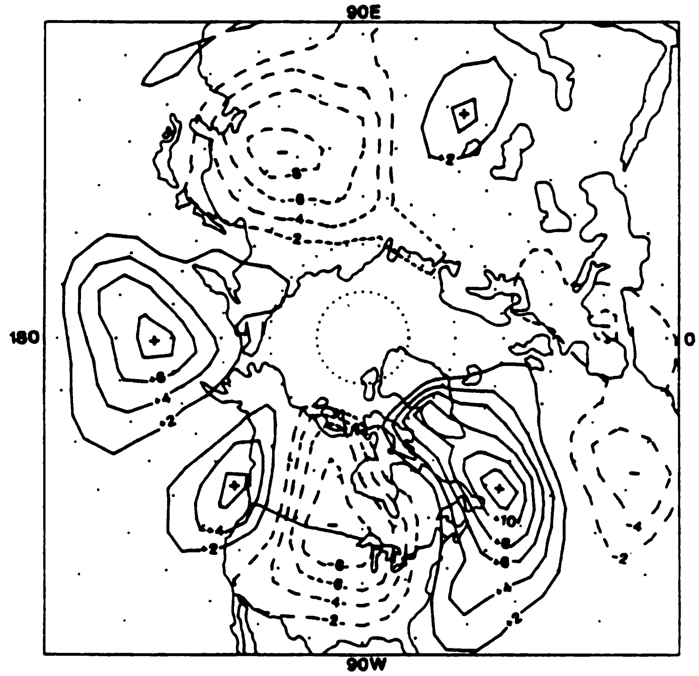


Figure 3.35 - Winter genesis day (-3) 500 mb v-component composite (in m/s)

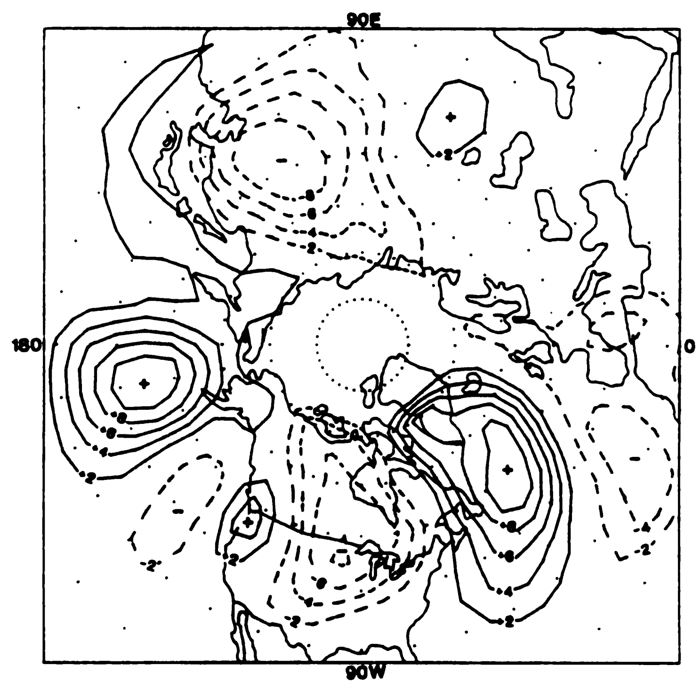


Figure 3.36 - Winter genesis day (-2) 500 mb v-component composite (in m/s)

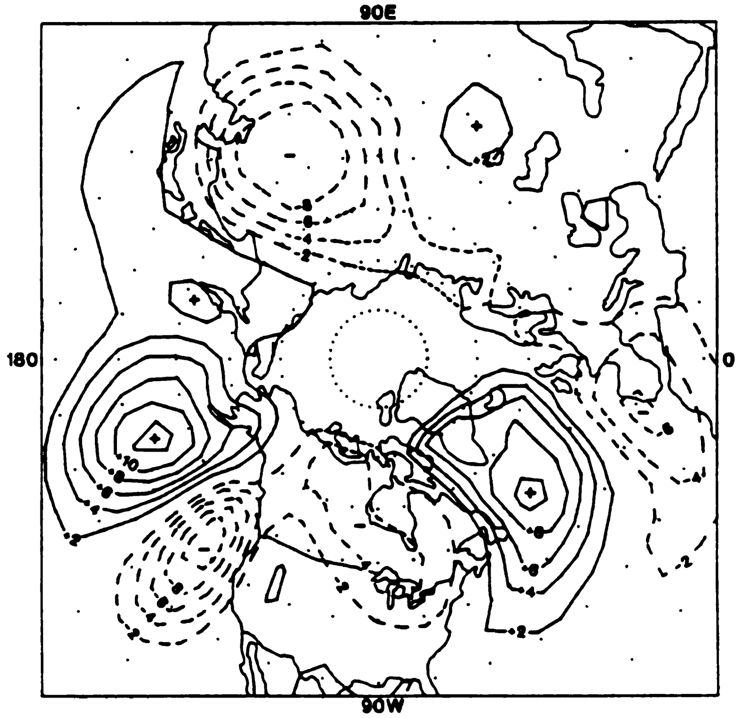


Figure 3.37 - Winter genesis day (-1) 500 mb v-component composite (in m/s)

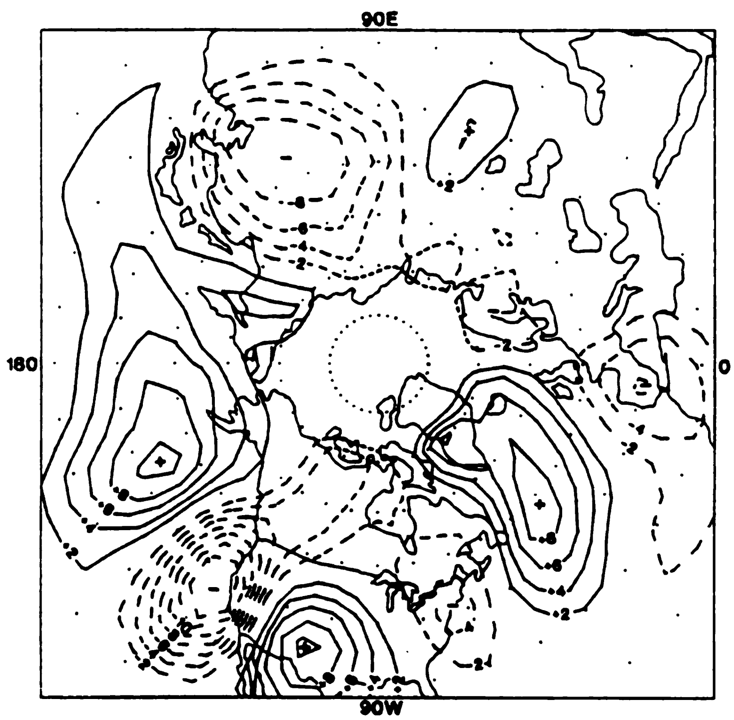


Figure 3.38 - Winter genesis day (0) 500 mb v-component composite (in m/s)

this wave is associated with southwestern troughing. The addition of the eastern Pacific ridge and southwestern trough signifies an increase in wave number from three to four during the winter genesis period. The addition of this new wave in the eastern Pacific implies that wave dynamics in this region may play an important role in the development of southwestern troughing.

Spring V-component Genesis Composites

The spring day (-4) v-component values are generally weaker and the pattern less defined than that of winter and appears to reflect seasonal contrasts in stationary wavelength and wave amplitude (Figure 3.39). However, as during the winter genesis period, two large areas of negative components lie over eastern Asia and central North America. These features represent the western limb of the Asian long wave trough and the eastern limb of the North American ridge. Two weaker negative regions are centered over the eastern Pacific, near 140°W, and over the eastern Atlantic, near 30°W. A broad region of positive values covers much of the middle Pacific. This region of weak southerly flow gradually increases toward the east and reaches its maximum over the western coast of North America, where it represents the western limb of the North American ridge. However, a smaller region of slightly larger positive v-components near 170°W and the small

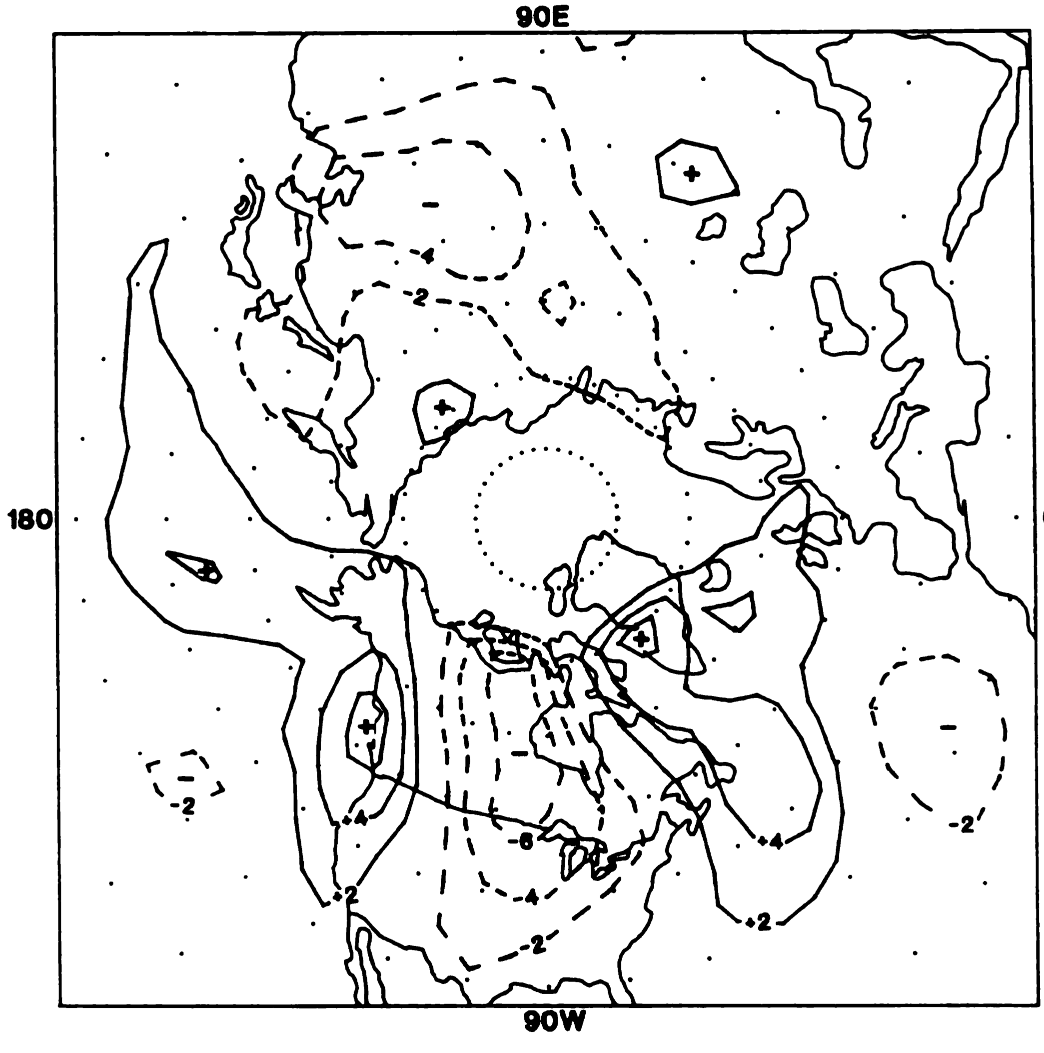


Figure 3.39 - Spring genesis day (-4) 500 mb v-component composite (in m/s)

negative center near 140°W suggest the presence of an additional lower latitude wave over the eastern Pacific.

The weaker pattern and presence of smaller, less defined component centers make spring wave number assessment difficult. This pattern contains three large negative and positive centers, over the Pacific, North America, and the Atlantic, and a series of smaller centers over Europe and Asia, reflecting the presence of at least four waves.

Between day (-4) and day (-3), an additional secondary wave begins to develop over the Asian coast as indicated by the appearance of a small additional negative component center north of Japan (Figure 3.40). At the same time, southerly winds over the eastern Pacific expand, as ridging becomes established near 150°W. The development of ridging over the eastern Pacific is similar to that of winter; however, the addition of the secondary Asian wave is not apparent on the winter v-component genesis composites. As the smaller west Pacific wave moves eastward, the region of strongest northerly flow remains anchored over eastern Asia near 120°E.

By day (-2), the secondary wave east of the Asian coast becomes more clearly defined as a region of southerly flow expands over Japan (Figure 3.41). During this same period, the region of negative v-components near 140°W strengthens and spreads northward into the Gulf of Alaska and is driven by amplified ridging over the Aleutian Islands.

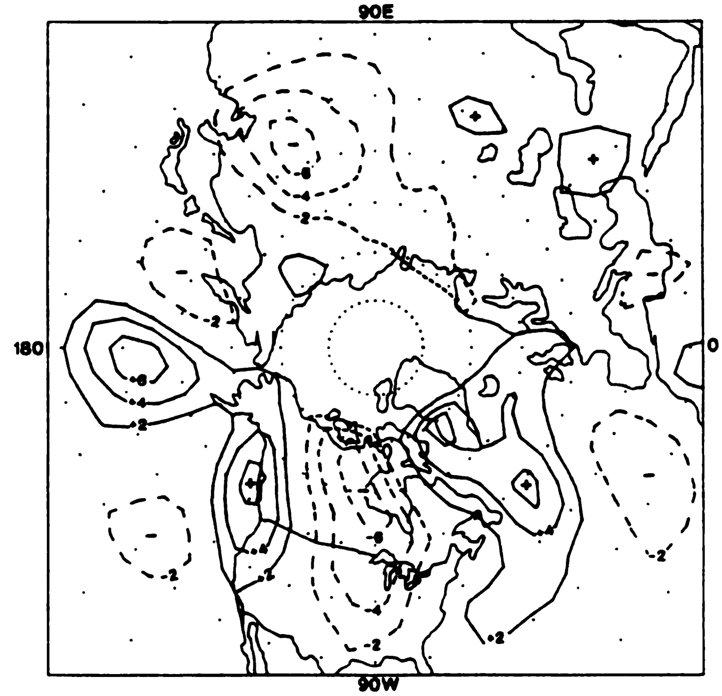


Figure 3.40 - Spring genesis day (-3) 500 mb v-component composite (in m/s)

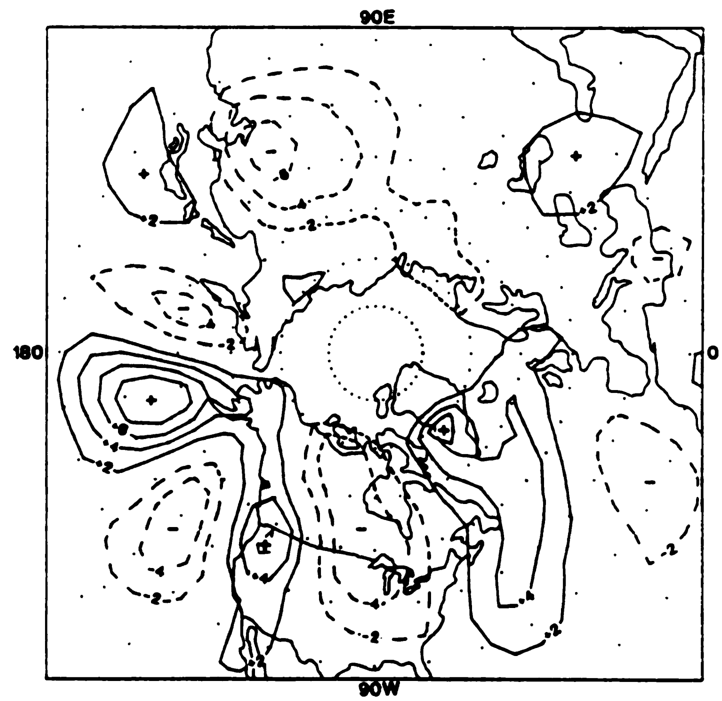


Figure 3.41 - Spring genesis day (-2) 500 mb v-component composite (in m/s)

On day (-1), eastward wave progression and continued amplification help establish a large trough axis over western North America (Figure 3.42). As during the winter genesis period, movement of the waves supporting the major Pacific and North American component centers occurs without movement of the east Asian long wave trough.

On day (0), ridging in the eastern Pacific strengthens and pushes eastward toward the western United States (Figure 3.43). The continued stability of the east Asian center implies that wave movements associated with southwestern trough development are limited to regions east of the Asian mainland. Furthermore, the addition of the eastern Pacific ridge and the southwestern trough results in an increase in wave number from four to five. However, unlike during the winter genesis period, clearly defined wave movement over the western Pacific during spring implies southwestern trough developmental associations in both the eastern and western Pacific.

Autumn V-component Genesis Composites

Although the general magnitudes of the initial autumn v-components are slightly less than those of spring, the pattern of individual centers is similar (Figure 3.44). Large negative centers are located over eastern Asia and central North America, whereas positive components dominate much of the central and western Atlantic as well as the

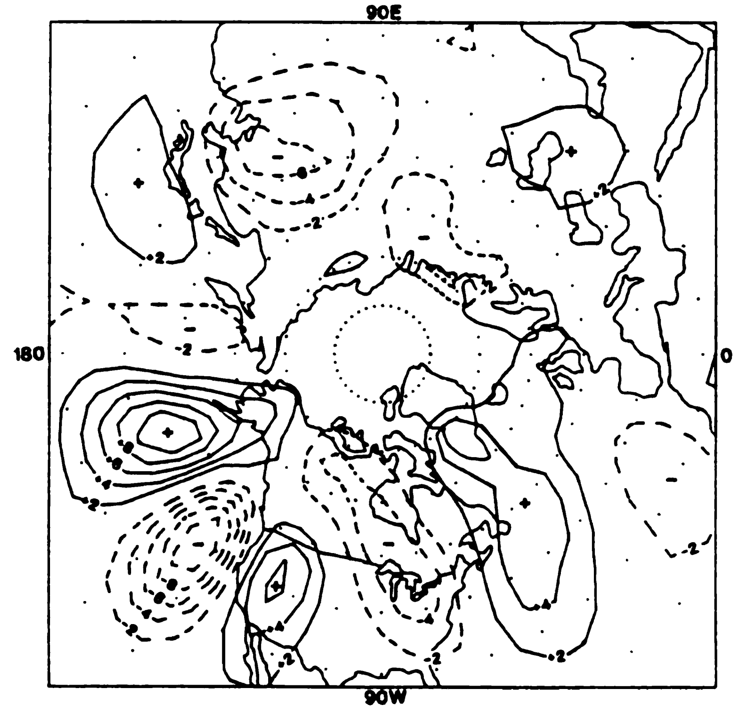


Figure 3.42 - Spring genesis day (-1) 500 mb v-component composite (in m/s)

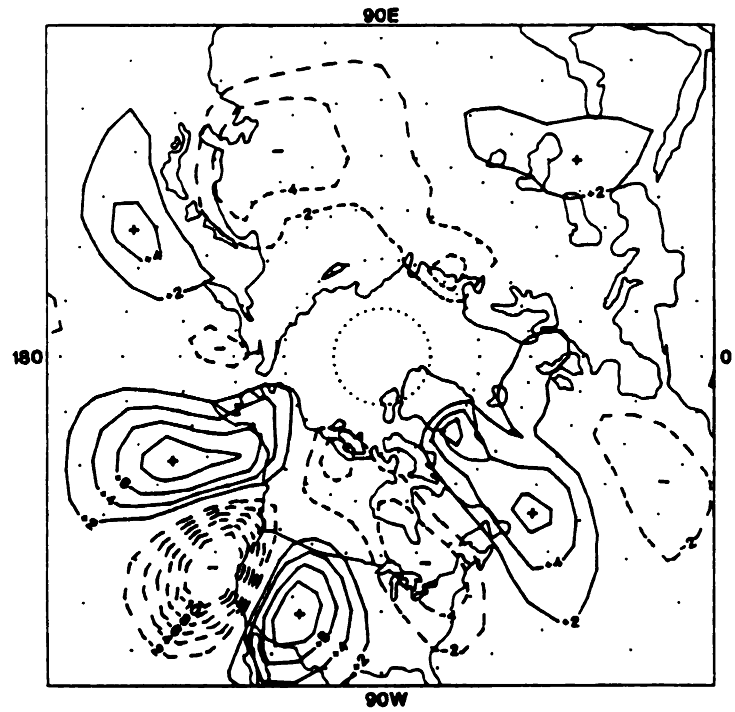


Figure 3.43 - Spring genesis day (0) 500 mb v-component composite (in m/s)

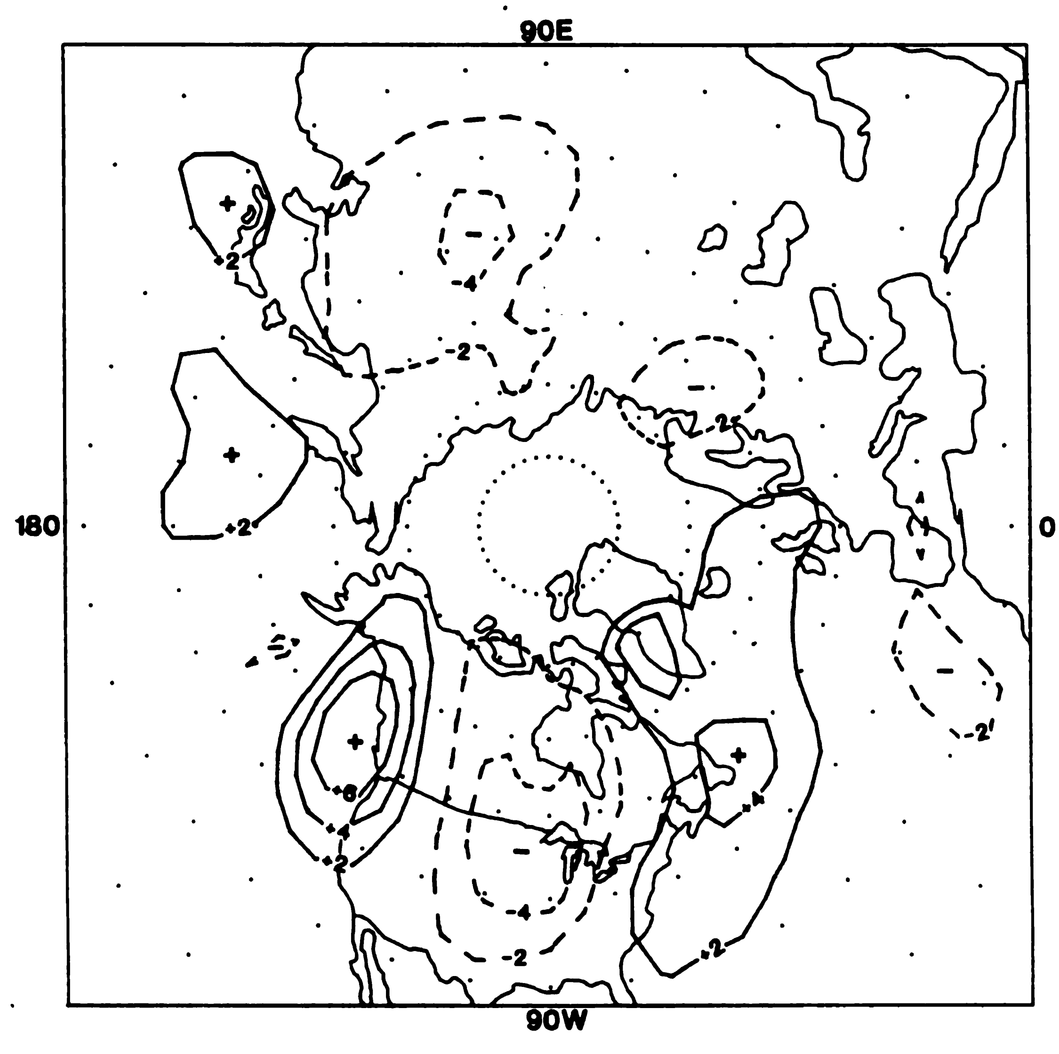


Figure 3.44 - Autumn genesis day (-4) 500 mb v-component composite (in m/s)

entire Pacific. Unlike in the spring and winter day (-4) composites, the positive Pacific center is much more fragmented during the autumn and indicates the presence of a smaller perturbation over the central Pacific. The autumn day (-4) configuration reflects a minimum of four long waves.

On day (-3), the wave train over the eastern Pacific becomes more organized, as v-component wind magnitudes increase near 150°W (Figure 3.45). This region of northerly winds signals the development of ridging over the Aleutian islands and troughing over the Gulf of Alaska.

Between day (-3) and day (-2), the v-component values over the eastern Pacific and North America increase in magnitude (Figure 3.46). A weak secondary wave develops over the Kamchatka Peninsula and is accompanied by the progression of downstream features. The addition of this secondary wave is similar to that observed over the western Pacific during the spring genesis period.

By day (-1), wave amplitude continues to increase over the eastern Pacific and is accompanied by a slight eastward wave movement (Figure 3.47). As in the winter and spring v-component genesis composites, the position of the western limb of the Asian long wave trough remains fixed.

The final autumn v-component genesis composite depicts a pattern that closely resembles the spring day (0) configuration (Figure 3.48). An eastward shift in the

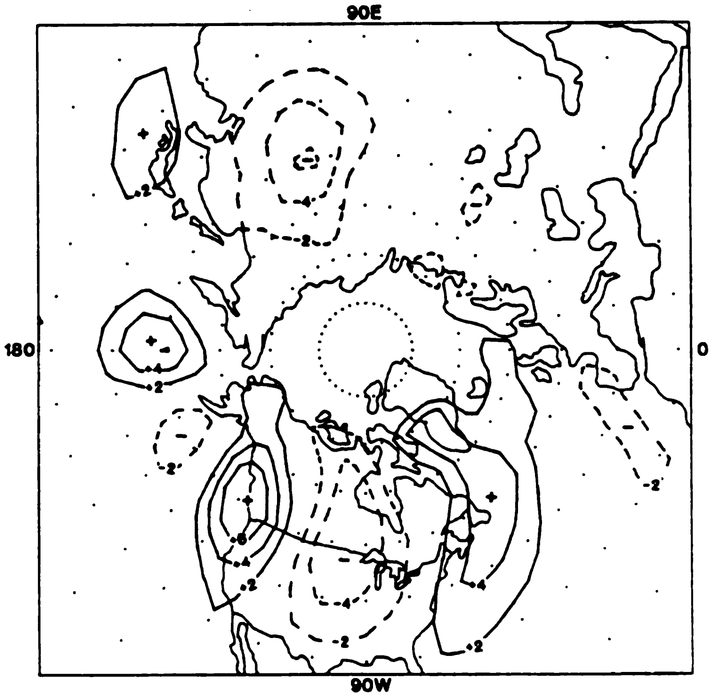


Figure 3.45 - Autumn genesis day (-3) 500 mb v-component composite (in m/s)

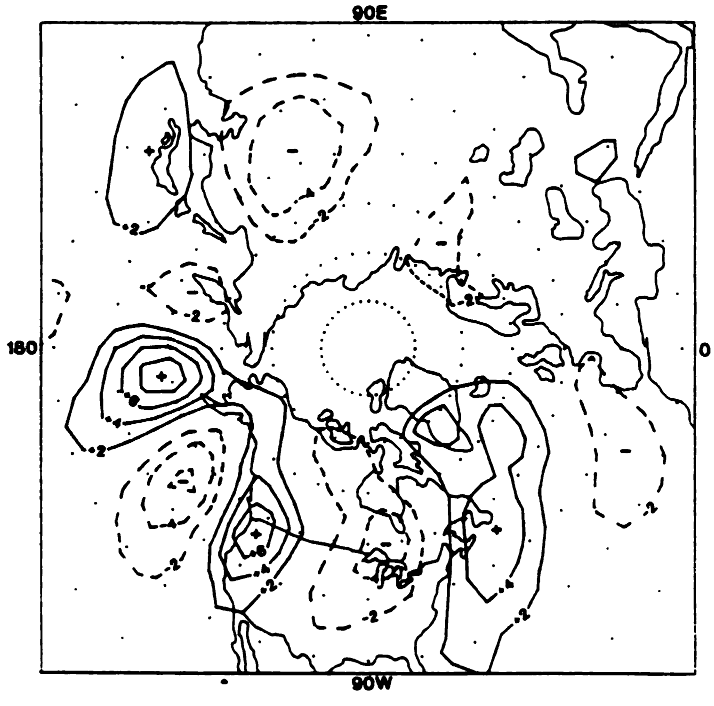


Figure 3.46 - Autumn genesis day (-2) 500 mb v-component composite (in m/s)

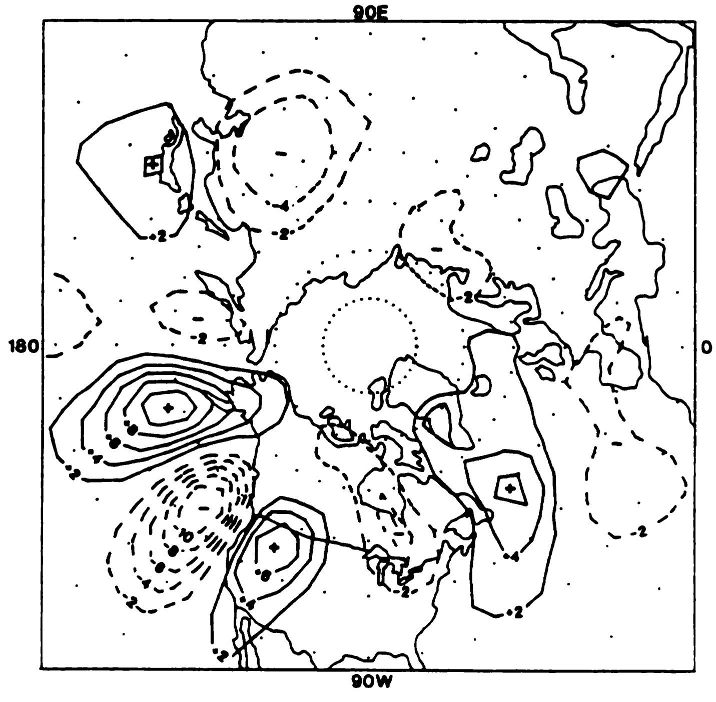


Figure 3.47 - Autumn genesis day (-1) 500 mb v-component composite (in m/s)

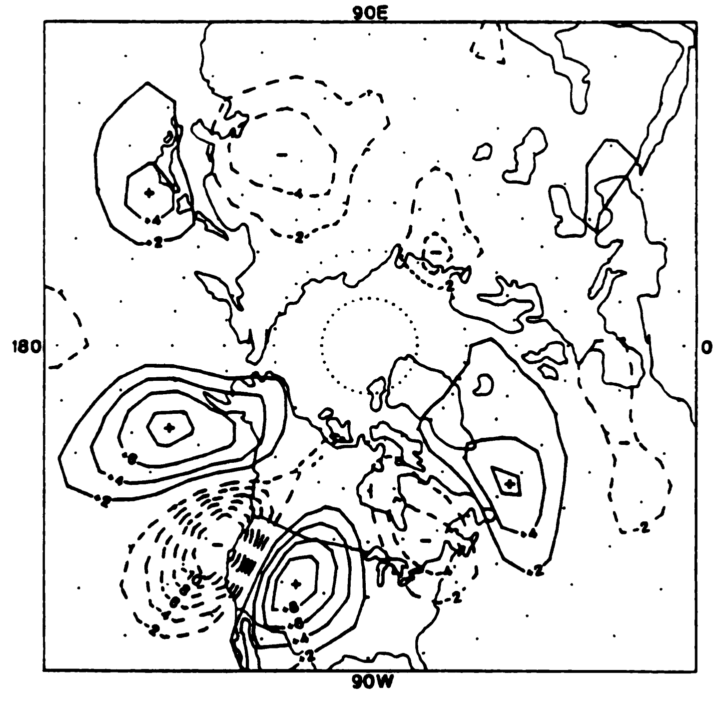


Figure 3.48 - Autumn genesis day (0) 500 mb v-component composite (in m/s)

eastern Pacific wave train pushes the Gulf of Alaska ridge closer to the North American coast and drives the development of southwestern troughing. As in the spring composites, the number of waves increases from four to five and the east Asian negative center remains a stable feature. Furthermore, key changes occur not only in the eastern Pacific, but in the western Pacific, as well.

Summary of V-component Composites

The v-component genesis composites reveal several key similarities and one important difference in the evolution of v-component centers during the winter, spring, and autumn. In all cases, the development of southwestern troughing is associated with the emergence and eastward movement of ridging over the Gulf of Alaska. This feature consistently strengthens throughout the genesis period, reflecting an increase in wave meridionality. Furthermore, the eastward progression of the Pacific and North American waves associated with component centers throughout this region occurs without movement in the position of the Asian long wave trough. Therefore, wave changes that occur during the development of southwestern troughing seem to be independent of activity over the Asian mainland. A final similarity among each season is an observed increase in wave number. During winter, wave number increases from three to four and during the spring and autumn it increases from four to five.

The difference in v-component composites occurs between the winter summaries and the transition season results. During the winter genesis period, major wave additions, movement, and amplification occur over the central and eastern Pacific. During spring and autumn southwestern trough development, a smaller secondary wave develops over the western Pacific, as well. However, this feature is much less organized during autumn.

Southwestern Trough versus Non-Trough Composites

The 500 mb geopotential height difference patterns produced by subtracting the mean 500 mb height field during all days in which southwestern troughing occurred from that of all non-trough days are alike for each season (Figures 3.49, 3.50, and 3.51). Negative values indicate areas where 500 mb geopotential heights are lower during southwestern trough periods, whereas positive values signify higher geopotential heights during trough events. For each season, a deep center of negative departures occurs over the southwestern United States and reflects the presence of regional-scale troughing. A weaker region of negative departures occurs east of Newfoundland, also. The Gulf of Alaska and eastern North America are characterized by higher pressure heights during southwestern troughing periods. Overall, the concordant behavior of these

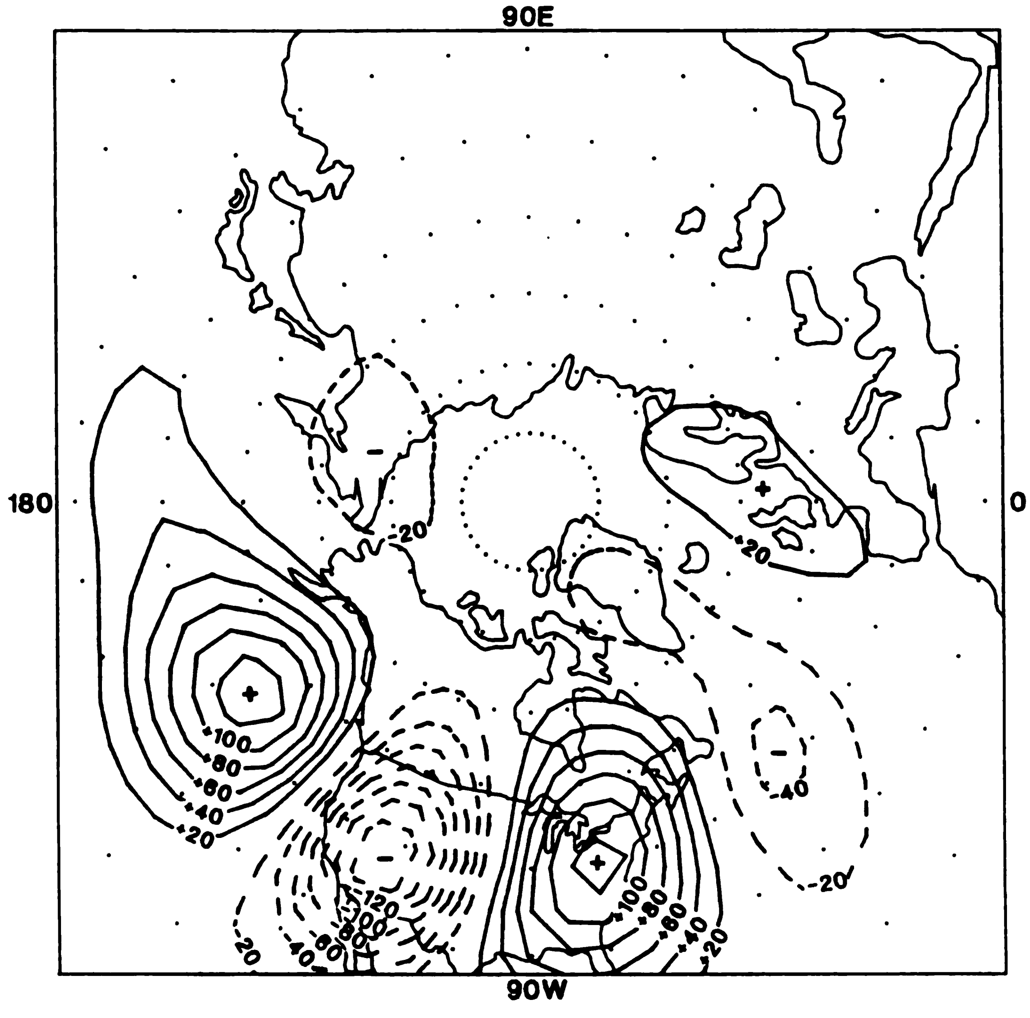


Figure 3.49 - Winter SW trough - non-trough 500 mb height difference summary (in meters)

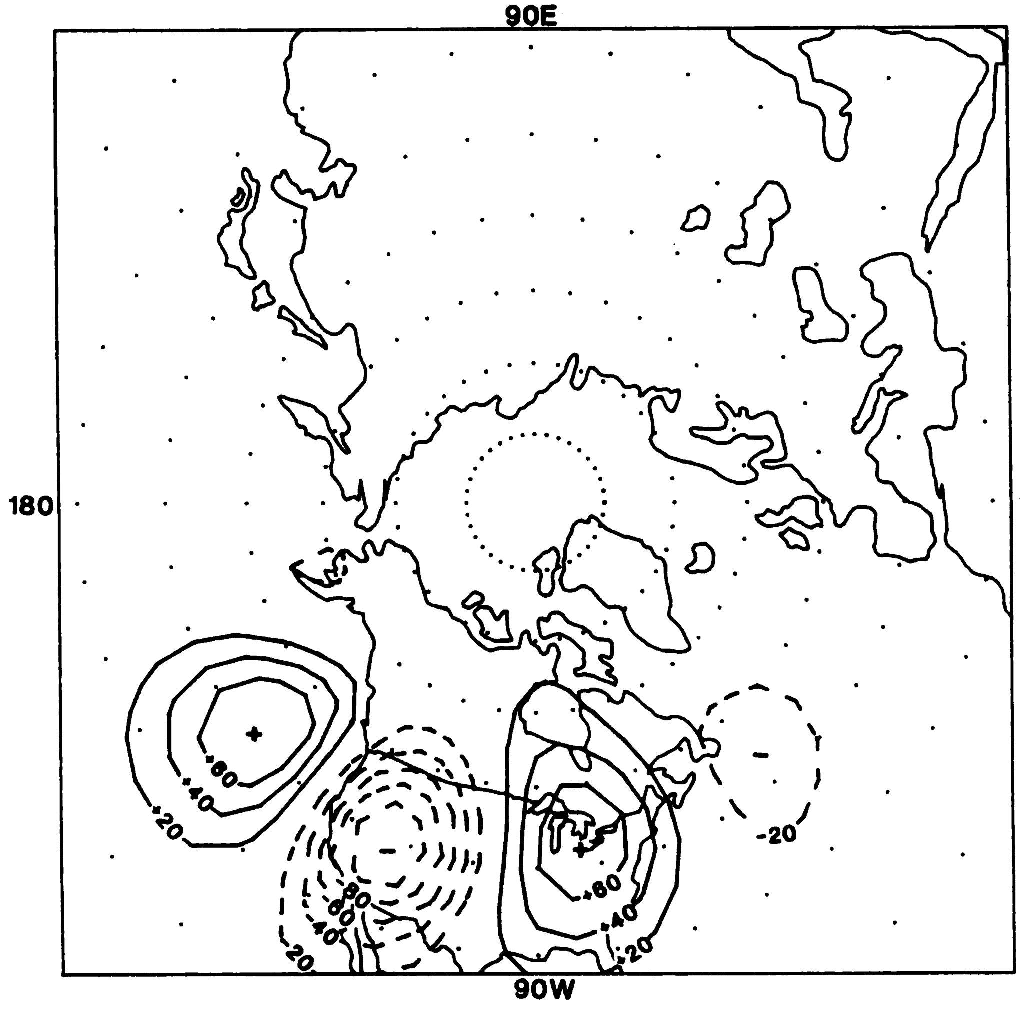


Figure 3.50 - Spring SW trough - non-trough 500 mb height difference summary (in meters)

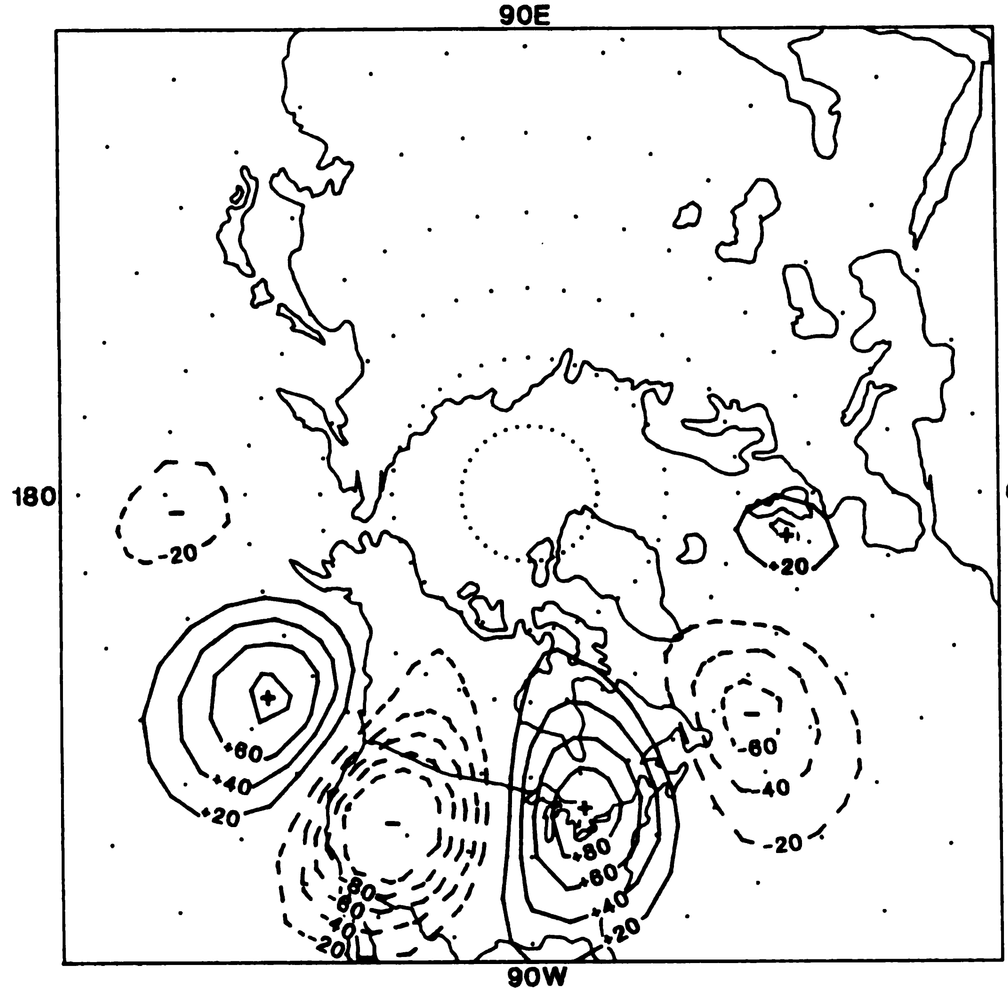


Figure 3.51 - Autumn SW trough - non-trough 500 mb height difference summary (in meters)

departure centers suggests a strong teleconnective relationship throughout the eastern Pacific and over much of North America.

Seasonal differences that do exist among these patterns appear to result primarily from variations in stationary wavelength and wave amplitude. Even though the southwestern trough axis is at nearly the same longitude each season, the locations of upstream and downstream features vary seasonally as a response to changing stationary wavelength. During winter, when stationary wavelength is at its annual maximum, the longitudinal distance between height difference centers is greater. The lack of height differences across most of Europe, Asia, and the western Pacific indicates that the pressure height configuration during southwestern trough periods differs very little from the non-trough periods throughout these regions. During the period in which troughing is established, major variations in the hemispheric wave train look to be limited to the Western Hemisphere. Any wave change in the western Pacific that is specific to the development of southwestern troughing has already occurred by the time of trough onset.

Seasonal Geopotential Height and Height Change Lysis Composites

Principal changes in the 500 mb flow configuration during the lysis period are limited geographically to the eastern Pacific and North America and involve the eastward progression and deamplification of the southwestern trough. During the winter, the southwestern trough moves rapidly eastward between day (0), which represents mean conditions on the final day of troughing, and day (+1), producing height falls throughout the central United States (Figures 3.52, 3.53, and 3.54). The Gulf of Alaska ridge, which is a principal feature during trough periods, slides eastward over the western coast of North America and amplifies. As the axis of the southwestern trough continues to move eastward, wave amplitude over the eastern Pacific decreases. The gradual development of ridging over western North America signals a return to the mean winter arrangement. By day (+2), height change throughout most of the westerlies is small, with differences in excess of twenty meters occurring over North America only (Figures 3.55 and 3.56). Between day (+2) and day (+3), the trough moves through the Great Lakes region, decreasing the longitudinal distance between it and a nearly stationary downstream trough over the middle Atlantic near 50°W longitude (Figures 3.57 and 3.58). As the lysis period concludes, the southwestern and Atlantic troughs appear to merge and stabilize near 55°W, thereby reducing the number of long waves from four to three (Figures 3.59 and 3.60).

The geopotential height field undergoes similar changes during the spring lysis period. Between day (0) and day

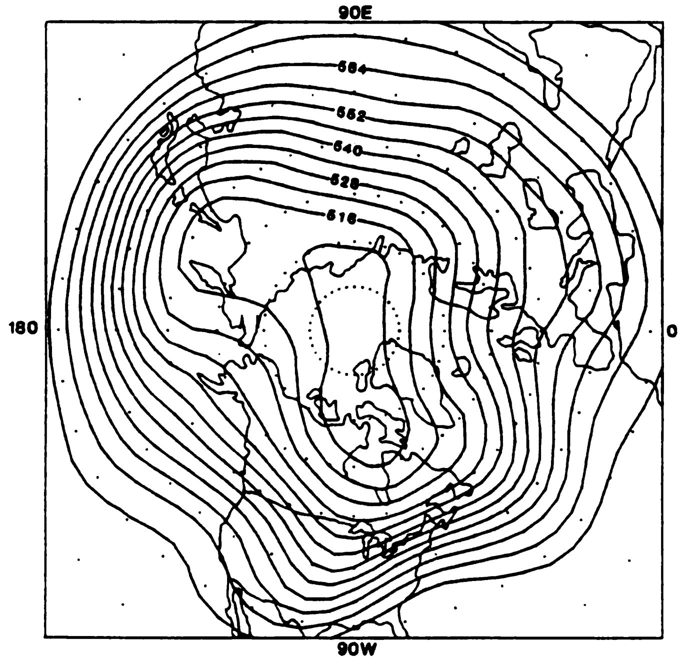


Figure 3.53 - Winter lysis day (+1) 500 mb height composite (in decimeters)

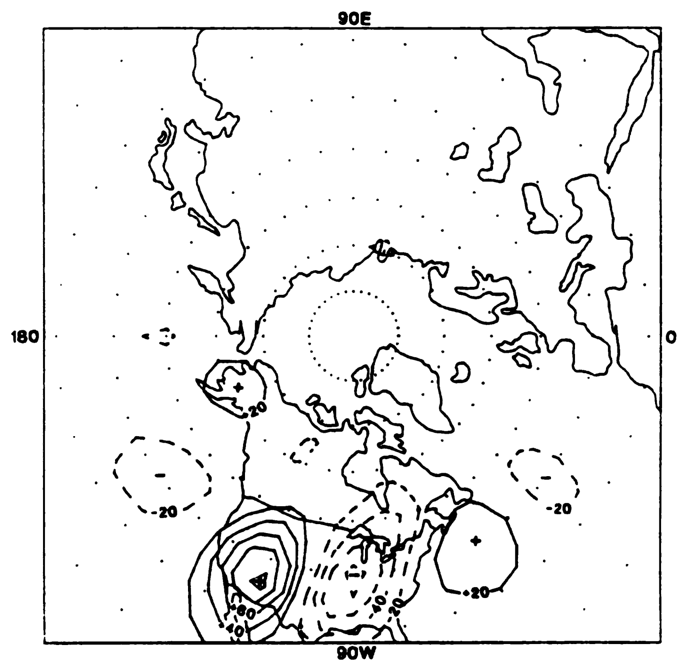


Figure 3.54 - Winter lysis day (+1) - day (0) height change composite (in meters)

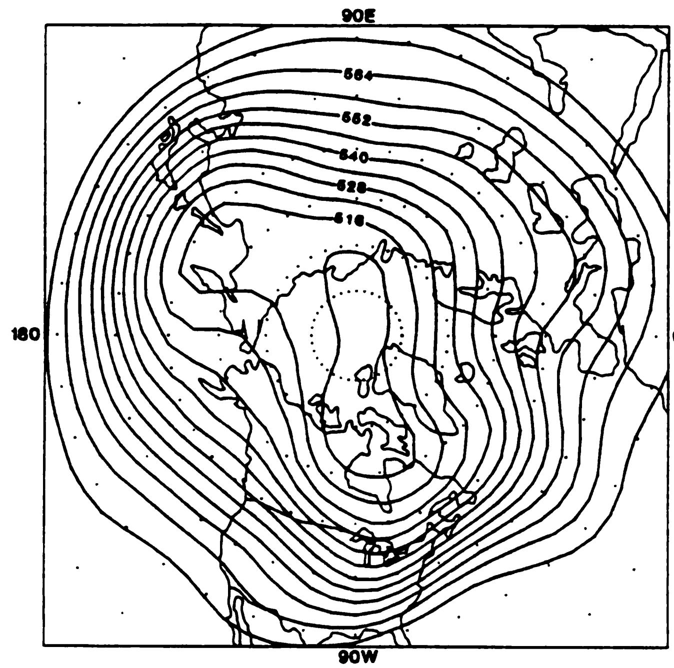


Figure 3.55 - Winter lysis day (+2) 500 mb height composite (in decimeters)

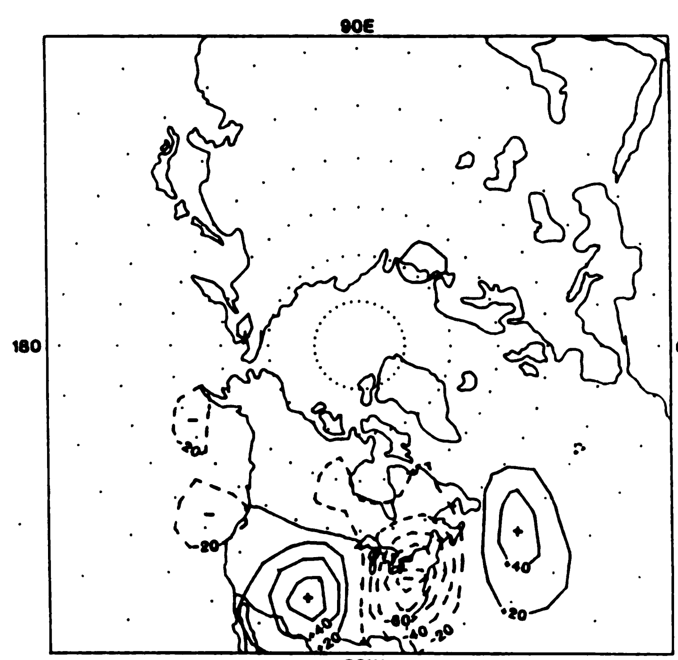


Figure 3.56 - Winter lysis day (+2) - day (+1) height change composite (in meters)

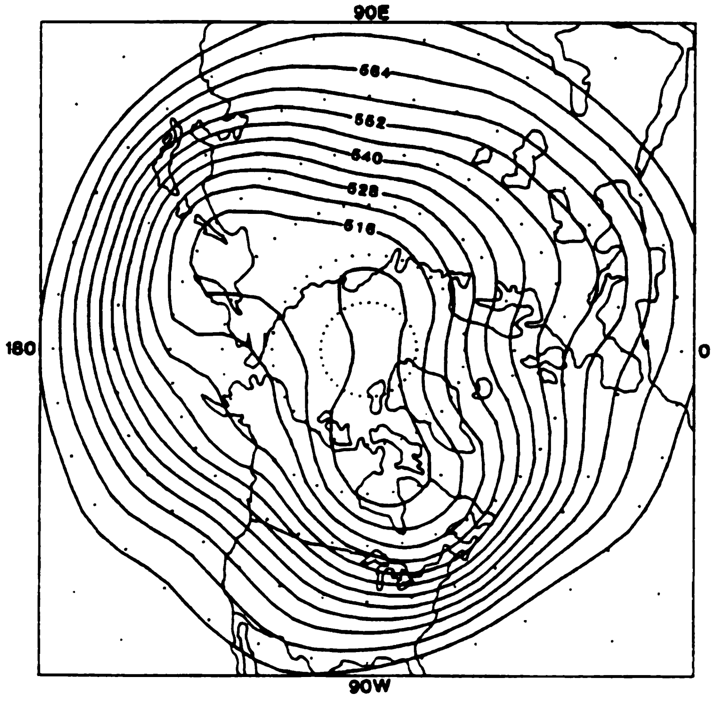


Figure 3.57 - Winter lysis day (+3) 500 mb height composite (in decimeters)

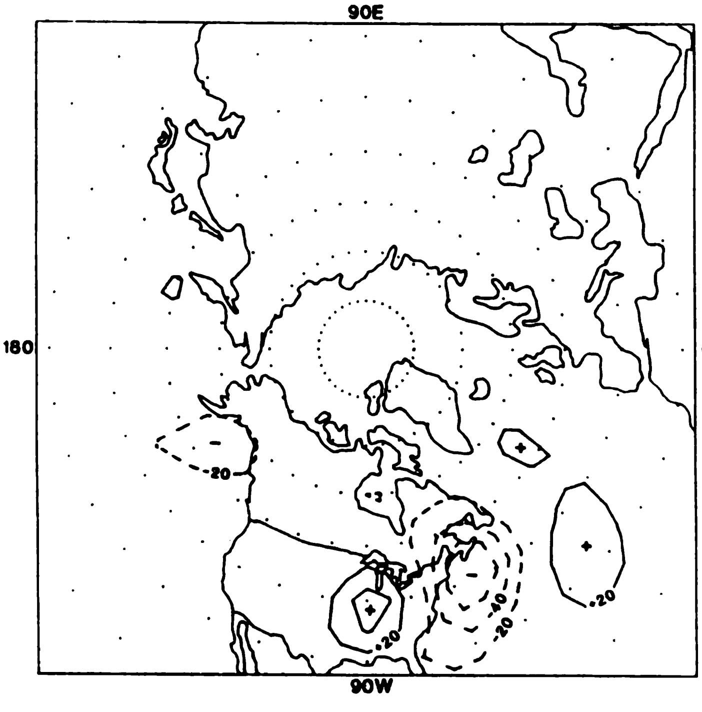


Figure 3.58 - Winter lysis day (+3) - day (+2) height change composite (in meters)

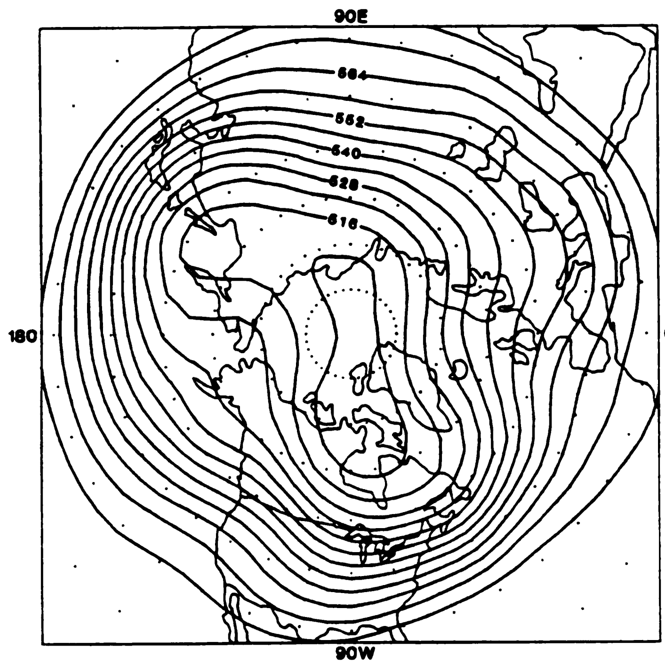


Figure 3.59 - Winter lysis day (+4) 500 mb height composite (in decimeters)

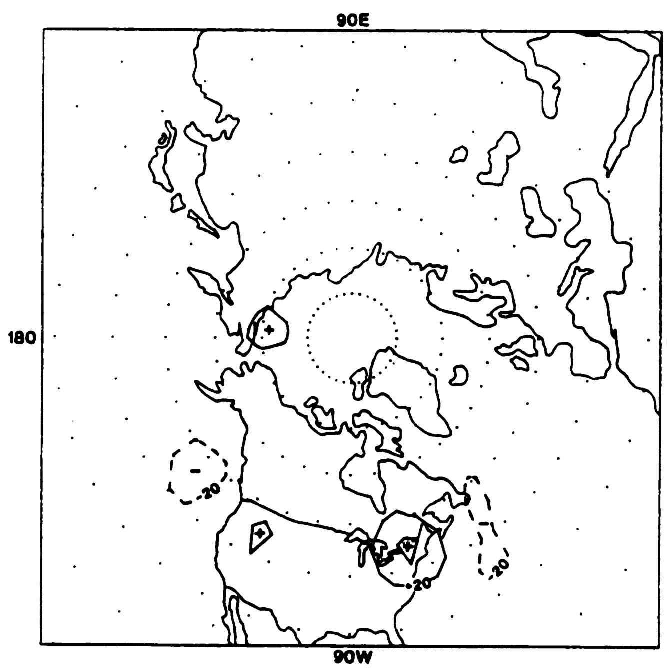


Figure 3.60 - Winter lysis day (+4) - day (+3) height change composite (in meters)

(+1), the eastern Pacific and North American wave train progresses eastward, pushing the southwestern trough into the central United States. As a result, heights rise throughout western North America and fall over the Gulf of Alaska and central North America (Figures 3.61, 3.62, 3.63). The lack of height change activity throughout other parts of the Hemisphere is similar to that displayed during the winter. By day (+2), ridging becomes the dominant feature over western North America, as the southwestern trough continues to progress (Figures 3.64 and 3.65). Furthermore, the wavelength between the southwestern trough and the downstream Atlantic trough near 50°W becomes increasingly smaller throughout the lysis period. During the final days of trough lysis, the North American wave configuration returns to its modal pattern, with ridging over western North America and troughing over eastern North America. The distinction between the eastward moving southwestern trough and the middle Atlantic trough weakens through day (+3) and day (+4), suggesting a decrease in wave number (Figures 3.66, 3.67, 3.68, and 3.69). The height change field between day (+3) and day (+4) depicts no changes exceeding twenty meters and implies persistence in the resultant pattern.

Many of the wave changes that occur during the winter and spring lysis period develop during the autumn, also. Between day (0) and day (+1), the southwestern trough moves

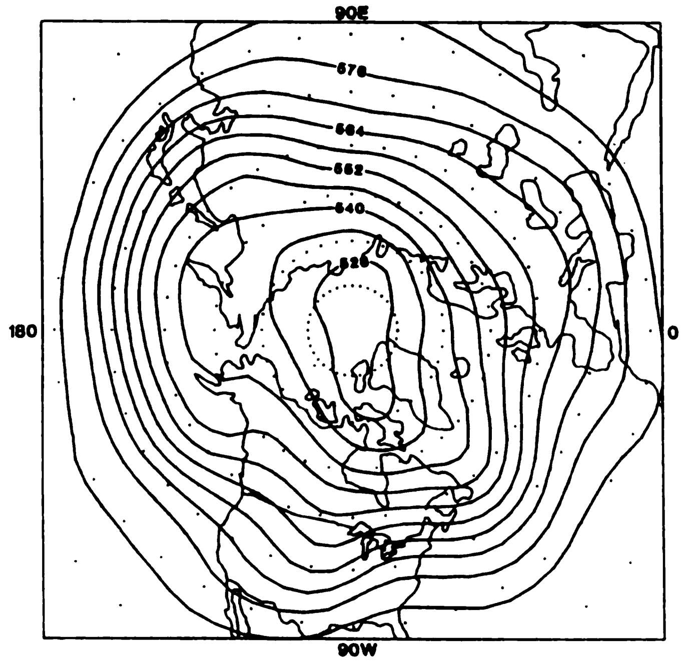


Figure 3.62 - Spring lysis day (+1) 500 mb height composite (in decimeters)

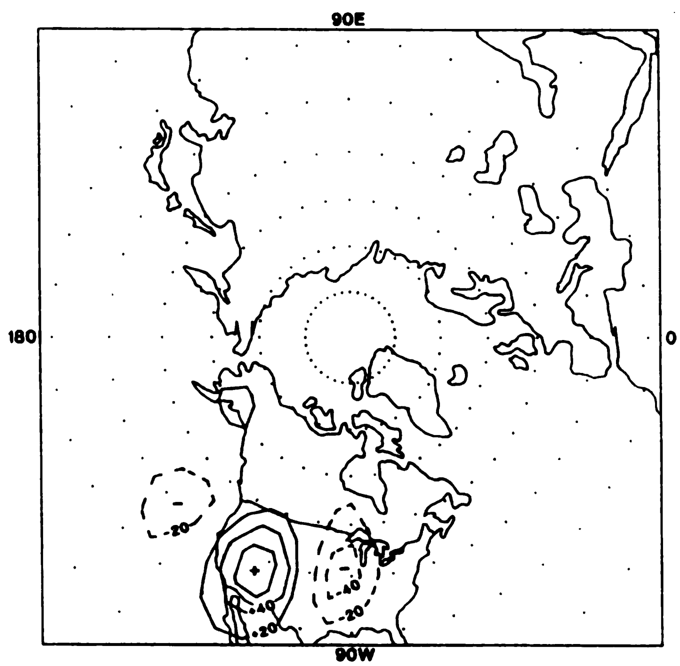


Figure 3.63 - Spring lysis day (+1) - day (0) height change composite (in meters)

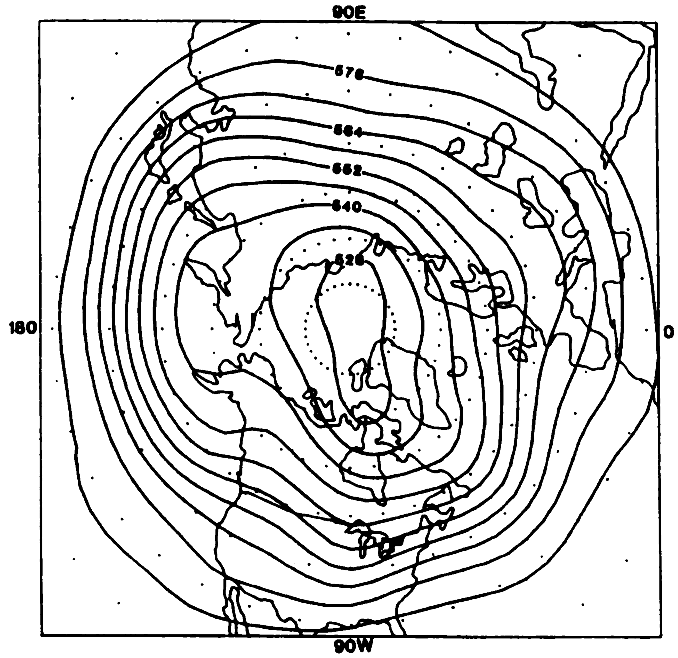


Figure 3.64 - Spring lysis day (+2) 500 mb height composite (in decimeters)

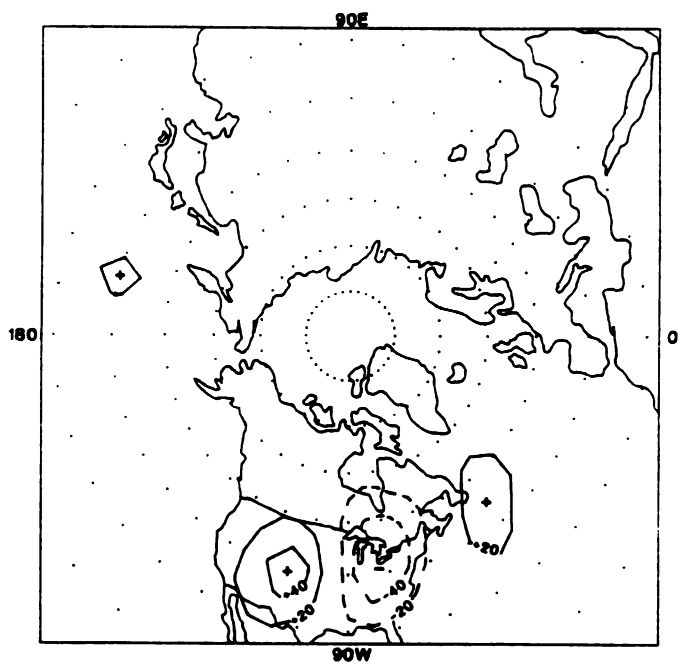


Figure 3.65 - Spring lysis day (+2) - day (+1) height change composite (in meters)

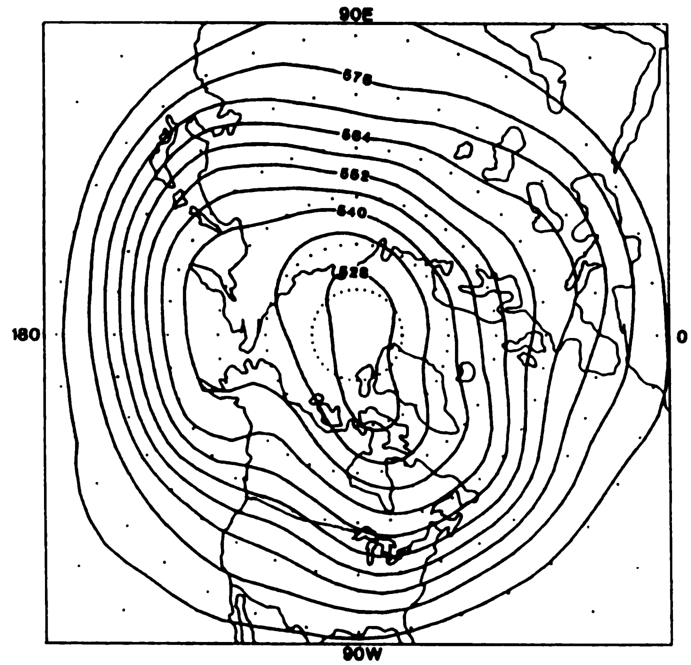


Figure 3.66 - Spring lysis day (+3) 500 mb height composite (in decimeters)

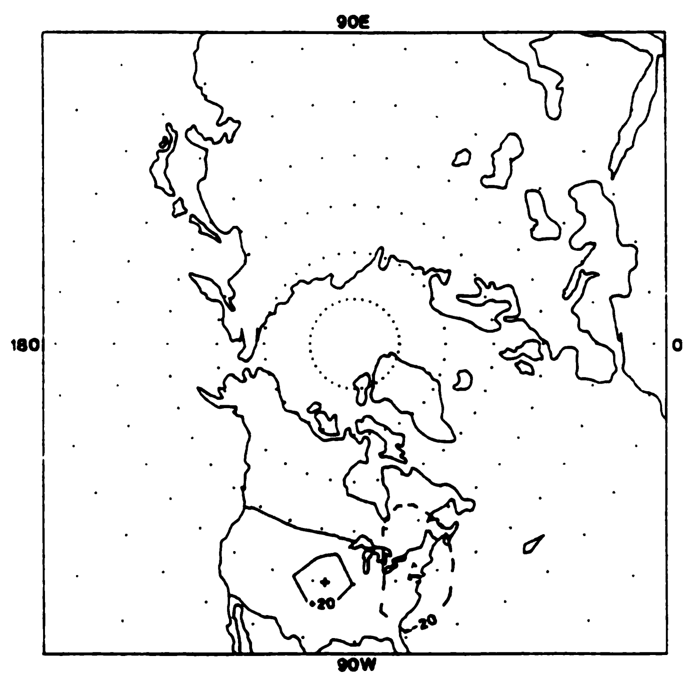


Figure 3.67 - Spring lysis day (+3) - day (+2) height change composite (in meters)

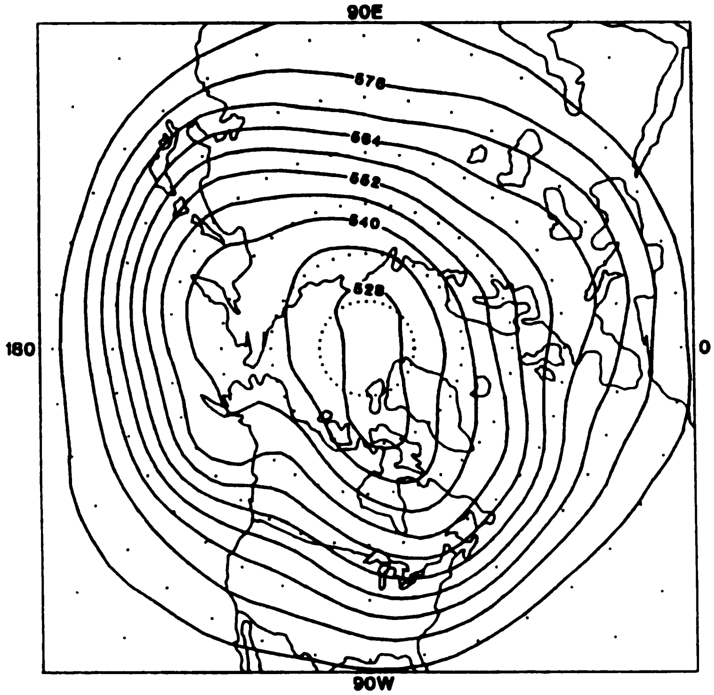


Figure 3.68 - Spring lysis day (+4) 500 mb height composite (in decimeters)

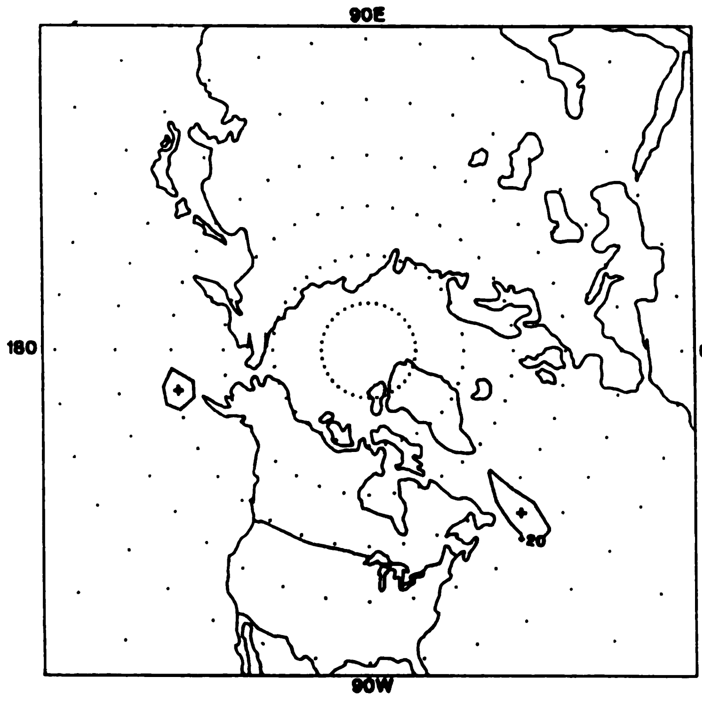


Figure 3.69 - Spring lysis day (+4) - day (+3) height change composite (in meters)

east, allowing heights to fall over the Gulf of Alaska and rise over the southwestern United States (Figures 3.70, 3.71, and 3.72). By day (+2), troughing moves into the Great Lakes region, carrying the zone of greatest height fall over Ontario, Canada (Figures 3.73 and 3.74). Unlike the conditions that occur during the winter and spring, wave features over the Atlantic appear to progress eastward, as well, during the autumn. The eastward moving southwestern trough remains a clearly defined feature throughout the remainder of the lysis period (Figures 3.75, 3.76). Because the next downstream trough, which is located over the central Atlantic near 50°W on day (0), moves east at a rate similar to that of the southwestern trough, wave merger and wave number decrease observed during the other seasons is not as apparent (Figures 3.77 and 3.78).

Summary of Lysis Features

The seasonal lysis composites reflect the effects of wave progression, deamplification, and, in winter and spring, wave number reduction. The principal height change features include height falls over the Gulf of Alaska and eastern North America, and height rises over the western United States. During the winter and spring, significant height changes are almost exclusively limited to the east Pacific and North America, whereas during the autumn, wave

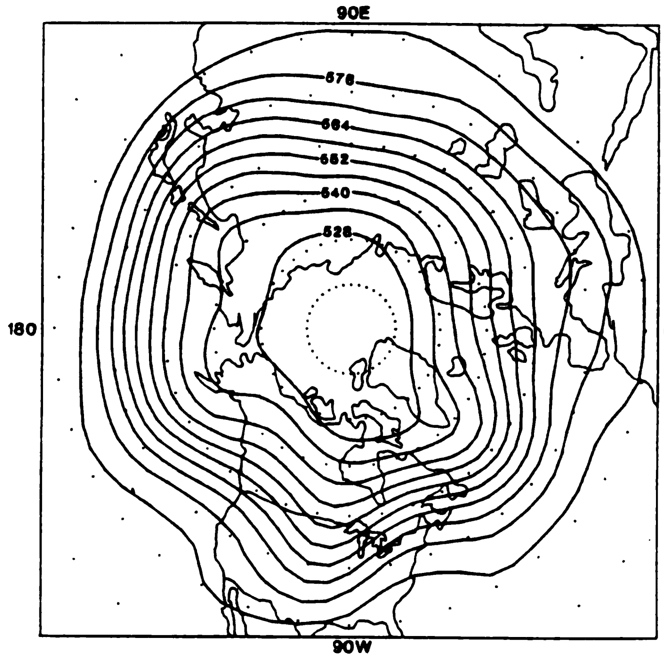


Figure 3.71 - Autumn lysis day (+1) 500 mb height composite (in decimeters)

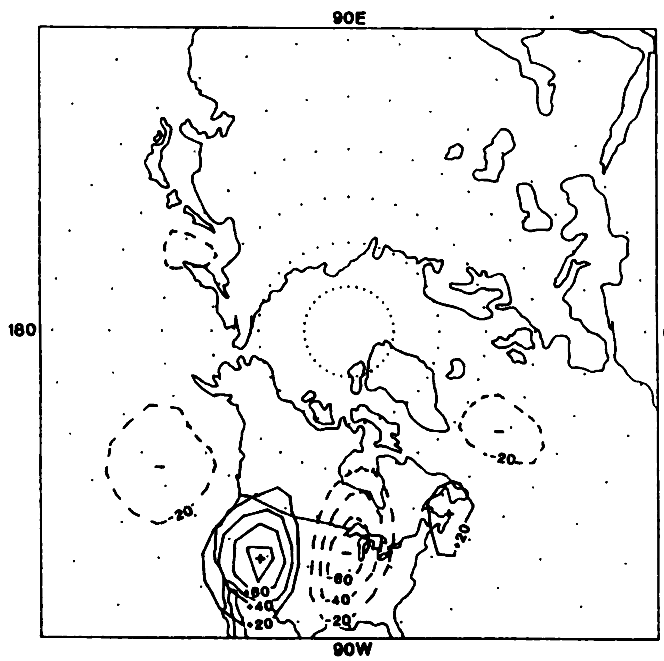


Figure 3.72 - Autumn lysis day (+1) - day (0) height change composite (in meters)

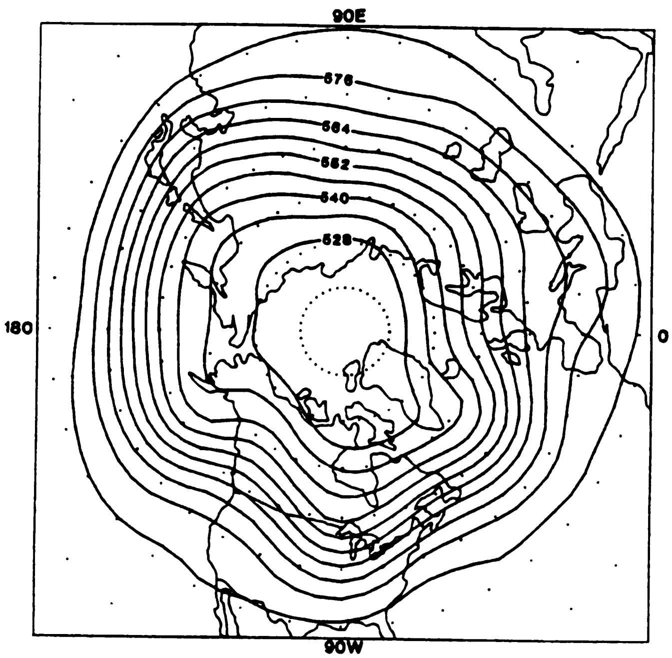


Figure 3.73 - Autumn lysis day (+2) 500 mb height composite (in decimeters)

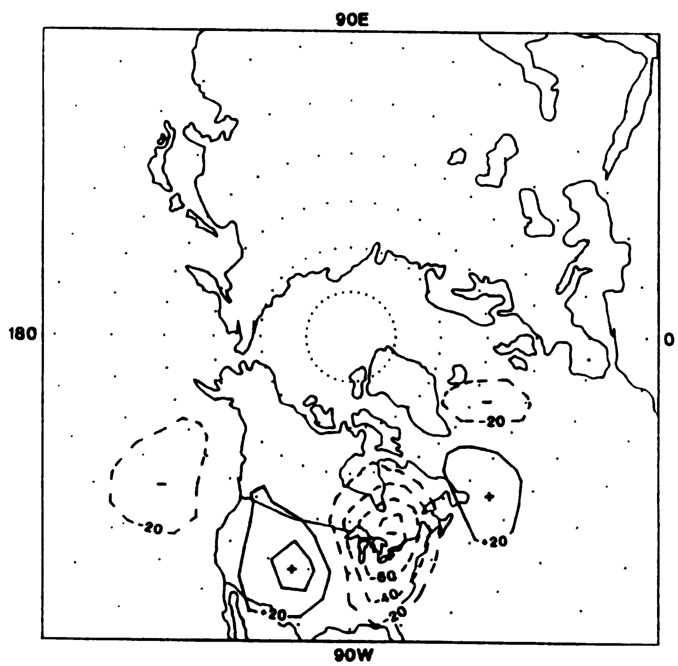


Figure 3.74 - Autumn lysis day (+2) - day (+1) height change composite (in meters)

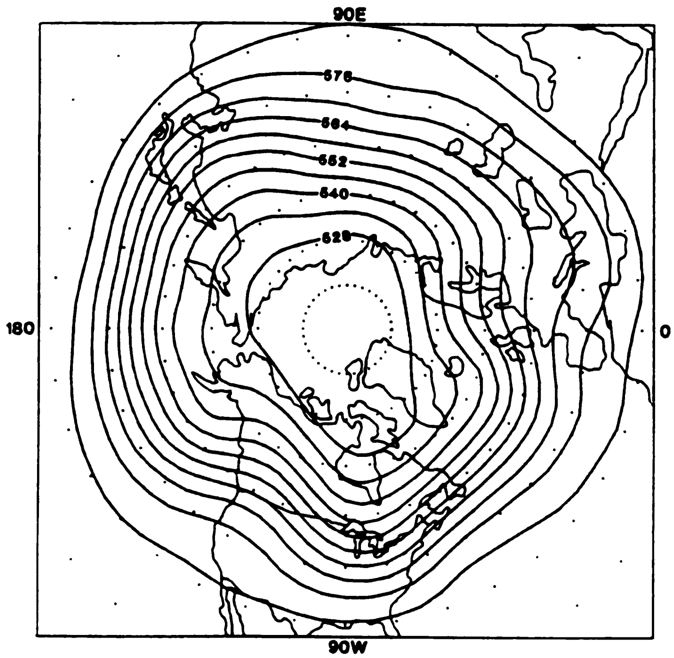


Figure 3.75 - Autumn lysis day (+3) 500 mb height composite (in decimeters)

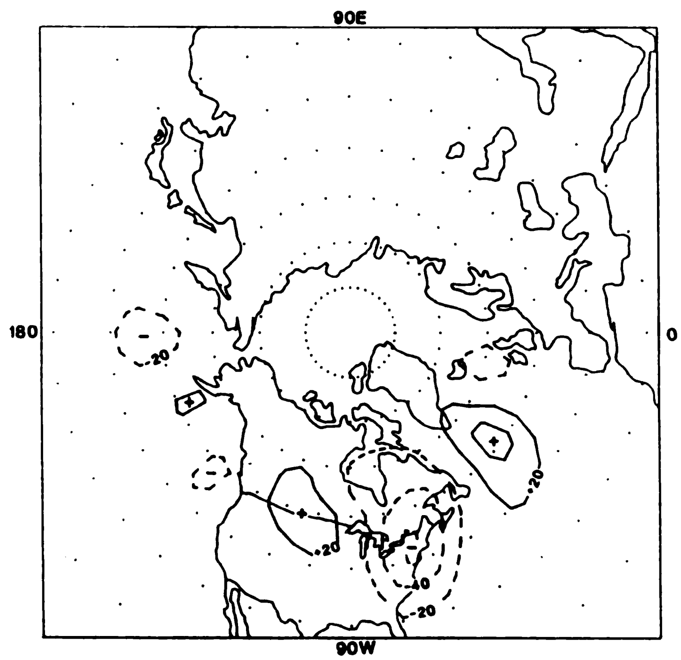


Figure 3.76 - Autumn lysis day (+3) - day (+2) height change composite (in meters)

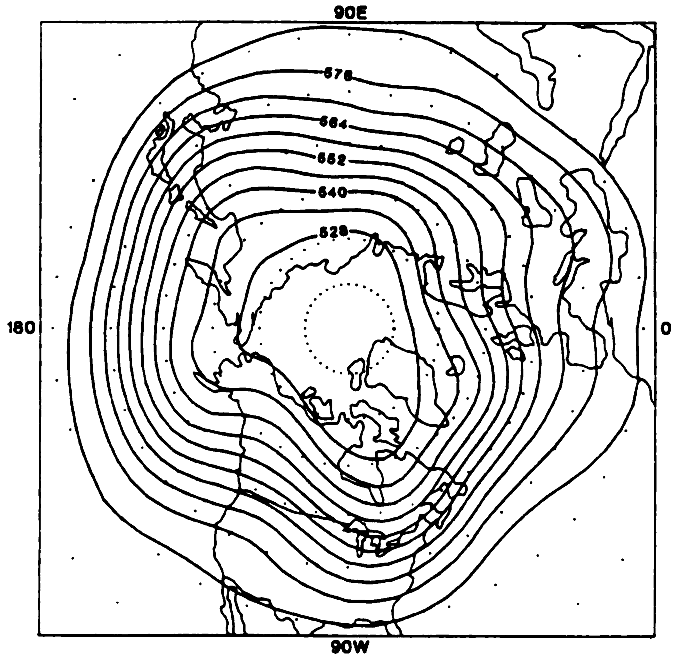


Figure 3.77 - Autumn lysis day (+4) 500 mb height composite (in decimeters)

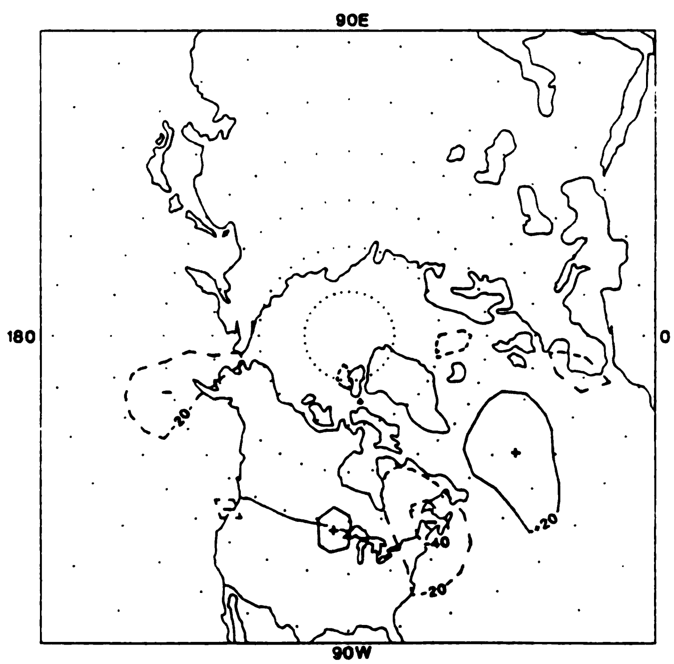


Figure 3.78 - Autumn lysis day (+4) - day (+3) height change composite (in meters)

changes occur over much of the Atlantic, as well. Wave number reduction occurs in winter and spring, and is accomplished by merging the eastward moving southwestern trough with a downstream Atlantic trough located near 50°W longitude. Wave merger and wave number reduction are not apparent during autumn.

Asian Coastal Dynamics

Asian Coastal Wind Profiles

In his analysis of western North American precipitation characteristics, Pyke (1972) noted an increase in cyclonic activity in the southwestern United States during the spring and attributed this pattern to seasonal changes in cyclone movement in the western Pacific. According to this view, during spring west Pacific cyclones move off the Asian coast more frequently at lower latitudes. As a result of air trajectory associated with absolute vorticity conservation, these storms track in a northeasterly direction, toward the Bering Sea, rather than in the more common easterly direction.

The monthly geostrophic wind speed and directional profiles along 145°E provide a general comparison between 500 mb wind characteristics during southwestern trough periods and non-southwestern trough periods. With few exceptions, the monthly speed profiles for the southwestern trough and non-trough periods are very similar (Figure

3.79). The latitude of maximum wind speed increases between February and June, in response to the seasonal contraction of the polar vortex, and decreases between September and January. Minor differences in the magnitude of the maximum flow between trough and non-trough periods do occur during January and February, when the non-trough wind speed is slightly greater, and during September when trough flow is stronger. Resultant winds become slightly more southwesterly in April, May, June, and, to a lesser extent, December during southwestern trough days.

Asian Coastal Triggering Disturbances

Yarnal and Diaz (1986), in their analysis of winter reverse Pacific North American (RPNA) circulation modes, theorized a link among the movements of cold disturbances off of the Asian Coast, cold phases of the Southern Oscillation, and negative height departures over the eastern Pacific coast. These authors demonstrated a statistical association between more frequent occurrences of winter RPNA flow and cold phases of ENSO. Although Yarnal and Diaz did not examine the energetics associated with this phenomenon, they did theorize that during cold phases of ENSO, cold disturbances moving off of the Asian coast cause enhanced instability over the western and southwestern Pacific. As a consequence, energy is propagated downstream where it culminates in wave

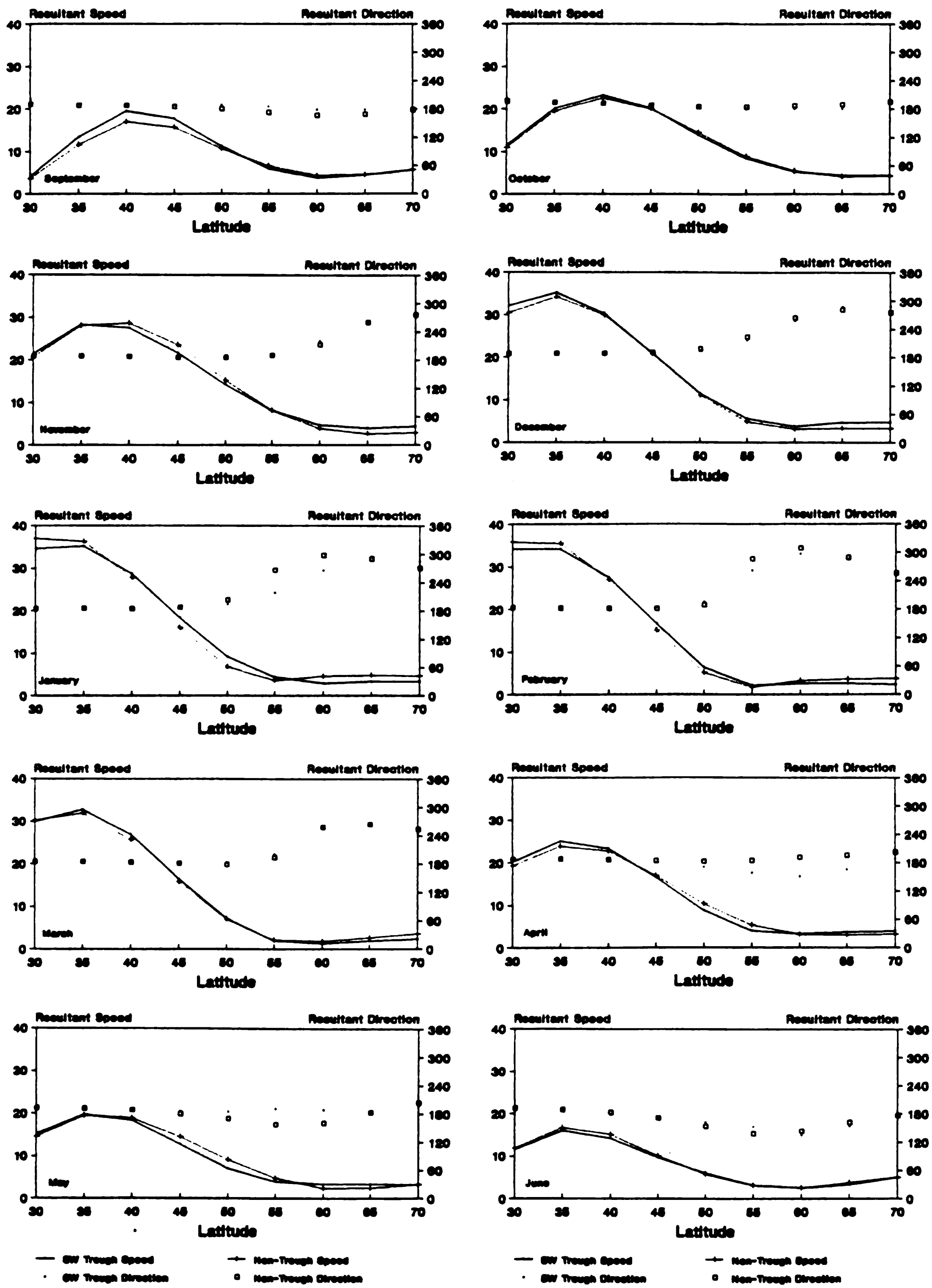


Figure 3.79 - Resultant geostrophic wind speed and direction profiles along 145°E for trough and non-trough periods

amplification over the eastern Pacific. Even though this mechanism was thought most active during cold phases of ENSO, the authors noted that RPNA configurations occur during warm phases, as well. Because southwestern troughing represents a form of RPNA circulation, processes similar to these described by Yarnal and Diaz may be critical in the development of trough events.

A plot of the mean winter 500 mb geopotential height field for all RPNA winter months (Yarnal and Diaz, 1986) reflects many characteristics of a winter southwestern trough setup and is quite different from a similarly constructed chart based on winter Pacific North American (PNA) months (Figures 3.80 and 3.81). Throughout the lower latitudes of the eastern and central Pacific, the pressure gradient appears slightly stronger during the PNA period. During the RPNA period, the pool of coldest air, which is delineated by pressure heights less than 5100 meters, covers a larger area, especially in northeast Asia, and provides a source of cold air for Yarnal and Diaz's (1986) RPNA mechanism.

A difference summary of the resultant geostrophic wind speeds between the RPNA period and the PNA period indicates that wind magnitude throughout much of the Pacific is less (negative differences) during RPNA periods (Figure 3.82). Weaker wind speeds over the Pacific during RPNA periods are in contrast to that expected from Yarnal and Diaz's (1986)

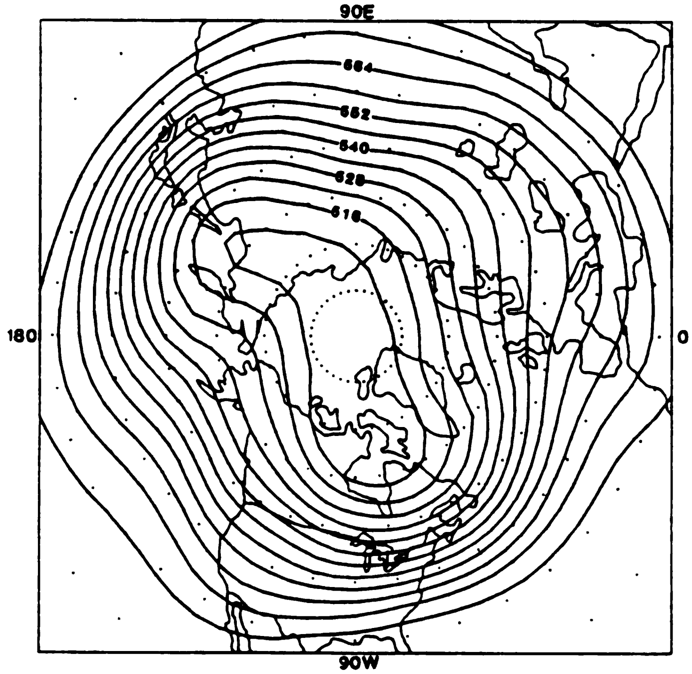


Figure 3.80 - Mean 500 mb height field during Yarnal and Diaz (1986) RPNA winter months (in decimeters)

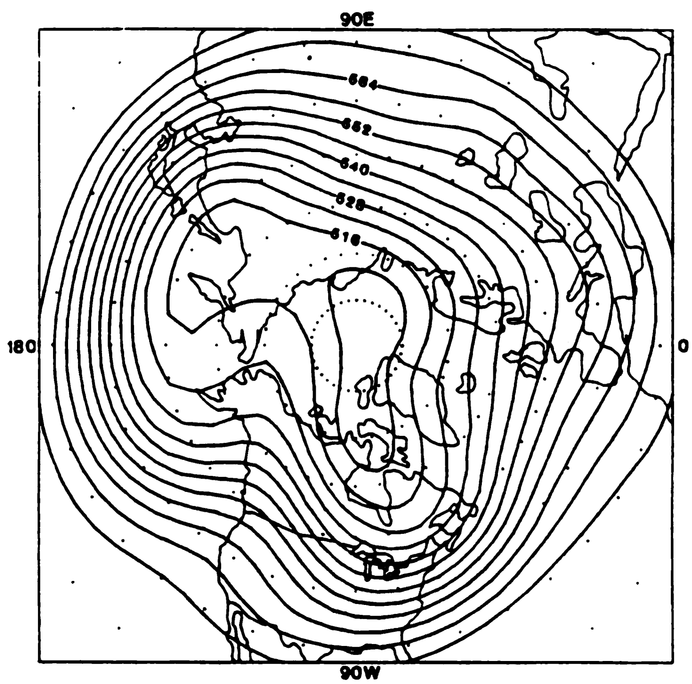


Figure 3.81 - Mean 500 mb height field during Yarnal and Diaz (1986) PNA winter months (in decimeters)

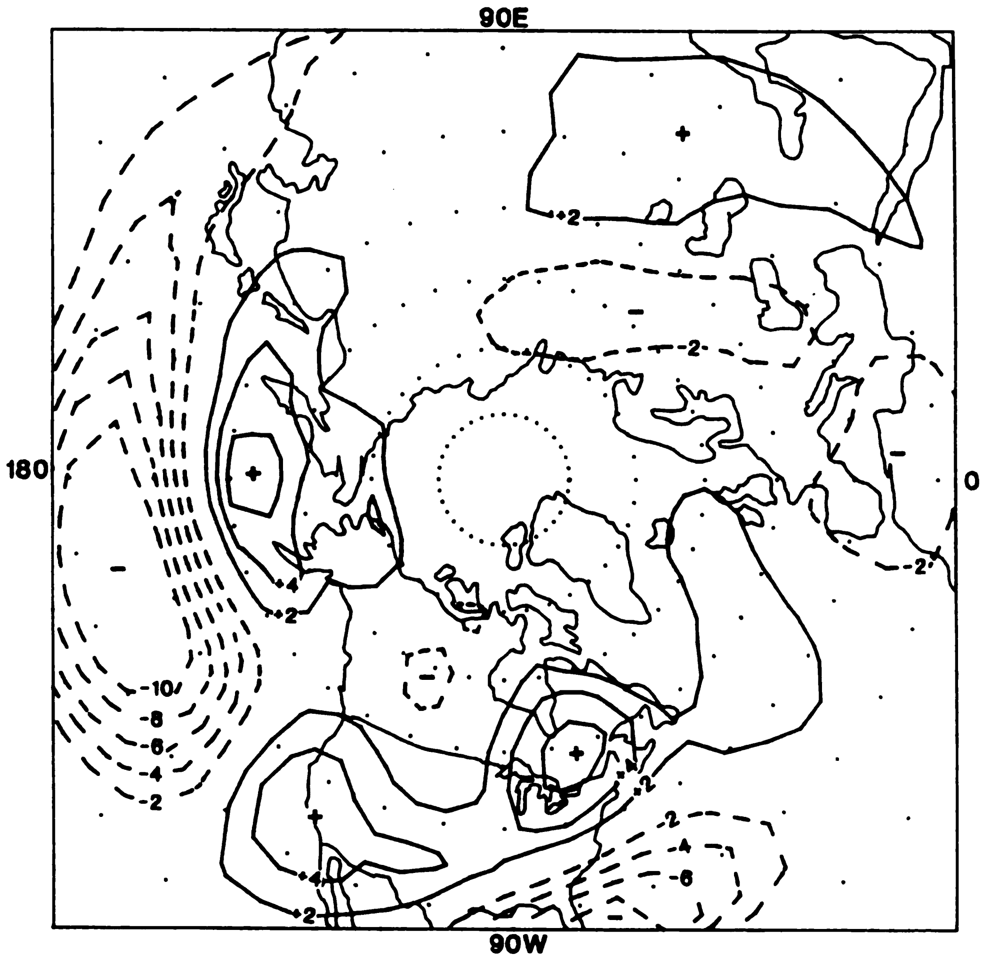


Figure 3.82 - RPNA-PNA geostrophic wind speed difference summary (in m/sec)

views, which attributed wave amplification over the eastern Pacific to increased wind speed and downstream energy transfer in the western Pacific. However, a strong center of positive differences over the Bering Sea indicates that wind speeds are greater in the north Pacific during RPNA periods, and may play an important role in RPNA development. The other areas of noteworthy velocity difference occur in a southwest-northeast belt across most of the United States, where speeds are greater during RPNA periods, and a region of negative differences over the southeastern United States.

The theory that the development of troughing over western North America can be linked to a downstream interplay of energy inputs over the western Pacific can be examined using the results of the wave train genesis composites. Results of the 500 mb geopotential height, twenty-four hour height change, and v-component analyses suggest that the appearance of an eastward moving wave over the western Pacific and the development of amplified ridging over the Gulf of Alaska occur in varying degrees each season (Figures 3.7-3.48). As the western Pacific wave first appears, height changes are relatively small. However, upon progression into the central and eastern Pacific, wave amplification occurs, resulting in height rises in the Gulf of Alaska, height falls over the southwestern United States, and an overall increase in wave number. Although impossible to assess using these composite results, this secondary wave may be similar to the initiating cold disturbance described by Yarnal and Diaz (1986).

Seasonal differences in the strength of the western Pacific triggering wave do exist. This wave is least defined during winter, when the Asian long wave trough is the dominant feature. Wave change in the western Pacific is most organized during the spring. Unlike during winter, the spring Asian long wave trough is not as persistently characterized by a single trough axis over the Asian coast. In fact, between spring day (-4) and day (-2), a new wave, with clearly defined negative and positive v-component centers, moves off the Asian coast. The autumn patterns in the western Pacific are less organized than those of spring. Nevertheless, similarities do exist. The emergence of a zone of northerly flow over the Kamchatka Peninsula and the initiation of eastward movement in all features east of 170°E longitude are characteristics common to both spring and autumn and are consistent with the notion of a travelling trigger wave proposed of Yarnal and Diaz. However, the location of this triggering feature near the Kamchatka Peninsula is more northerly than might be expected based on Yarnal and Diaz's mechanism.

Summary of Asian Coastal Dynamics

As compared to non-southwestern trough periods, the latitude of the maximum 500 mb geostrophic flow at 145°E longitude during trough periods is nearly identical for each month. Geostrophic wind direction, however, does differ slightly between the two periods during the spring when the troughing period trajectories are more southwesterly. When the mean resultant geostrophic wind speed fields in the western Pacific during Yarnal and Diaz RPNA winters are compared to those of their PNA winters, PNA speeds are greater throughout the lower Pacific latitudes (30°N-35°N), whereas RPNA speeds are greater in the Bering Sea.

Analysis of the wave train genesis composites indicates that, during each season, southwestern trough development is associated with wave movement over the western and central Pacific, east of Japan, and partially fits the RPNA mechanism described by Yarnal and Diaz (1986). During the spring and autumn, this wave develops as an additional feature within the long wave configuration. As this wave moves eastward, it is accompanied by the development and amplification of ridging over the Gulf of Alaska and troughing over the western United States.

Split Flow Analyses

Numerous studies have sought to associate increased cyclonic activity in the southwestern United States with the occurrence of middle tropospheric split flow over western North America (Klein, 1957; Reitan, 1974; Parker et al., 1989). Klein (1957) noted an increased frequency of Great Basin cyclones during the spring and related this pattern to the more frequent occurrence of middle tropospheric blocking during these months. Blocking, which is climatologically common during spring, is often characterized by flow separation and provides a possible causal link between spring southwestern troughs and split flow. Most of these early studies, however, rarely examined causal relationships. Such relationships also are not determined in this analysis, as this study seeks only to describe associations between southwestern troughing and split flow.

The longitudinal frequency distributions of the combined primary and secondary 500 mb wind maxima and the Parker et al. (1989) split flow analysis provide the means whereby flow character over western North America during southwestern trough periods is established. The longitudinal frequency distribution (grouped by quartiles) of the wind maxima for September, which is the first month in the southwestern trough year (September-June), is essentially unimodal, with the highest frequencies arranged in a narrow band outlining the Gulf of Alaska ridge and the southwestern trough (Figure 3.83). This pattern reflects the modal position of the zone of greatest baroclinicity and wind speed during troughing periods.

Within the context of this analysis, the more interesting patterns are those occurring in the higher latitudes, as these provide information regarding a secondary wind maximum, such as might occur during split flow. Unfortunately, the high latitude frequency results are quite variable and may be influenced by the secondary wind maximum selection criteria.

The high latitude frequency pattern for September lacks a well-defined secondary wind maximum. However, a weak cluster of higher frequencies does stretch eastward across the extreme northern latitudes of the study area between 150°W and 130°W. This cluster drops southeastward toward Hudson Bay and appears to converge with the lower latitude primary flow originating from the southwestern United States. Although the higher frequencies in the northern latitudes may be more a function of the wind maximum selection criteria, one of which specifies that the location of the secondary maximum be 15° latitude removed from the primary maximum, a similar signal emerges from the 5520 meter and 5820 meter contour composite (Figure 3.84). The higher latitude wave train is slightly out of phase with the lower latitude wave configuration. As a result,

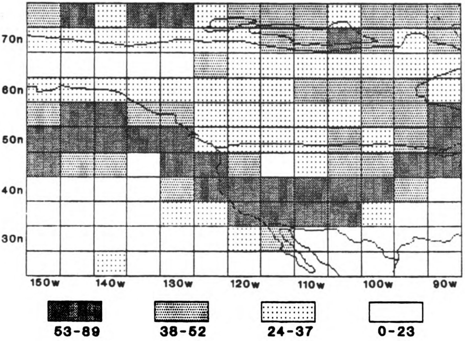


Figure 3.83 - Longitudinal frequency distribution of primary and secondary wind speed maxima during September southwestern trough periods

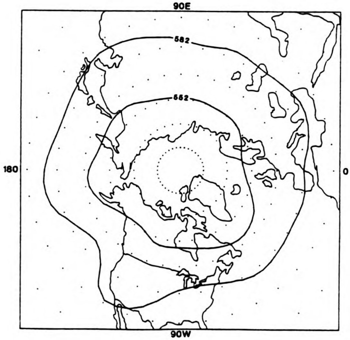


Figure 3.84 - Representative 500 mb pressure height contours during September southwestern trough periods (in decimeters)

mean flow is somewhat diffluent over the Gulf of Alaska and confluent over central North America during trough periods.

The October wind maxima frequency pattern is better defined than that of September and is highlighted by a series of high values outlining the primary wind maximum in the Gulf of Alaska ridge and southwestern trough (Figure 3.85). The distribution is predominantly unimodal west of 135°W, but becomes bimodal over western North America. A second series of lower frequencies branches northeastward from the primary wind maximum near 135°W, traverses central Canada between 55°N-60°N latitude, and shifts southward toward Hudson Bay where it recombines with the primary wind maximum. The composite positions of the 5400 meter and 5700 meter contours during southwestern troughing reveal a similar pattern (Figure 3.86). As during September, a slight eastward offset in the positions of the high latitude wave axes produces flow diffluence over the Gulf of Alaska and confluence over central North America.

Even though the primary concentration of high frequencies remains in the Gulf of Alaska ridge and southwestern trough during November, the high latitude frequency pattern becomes more varied during this time (Figure 3.87). The November high latitude pattern is weak with little indication of flow separation over the Gulf of Alaska. The representative contour composite substantiates this finding by portraying an increased agreement between

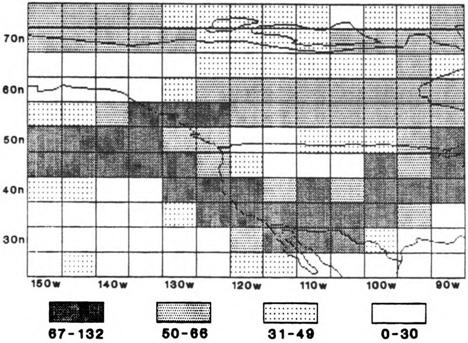


Figure 3.85 - Longitudinal frequency distribution of primary and secondary wind speed maxima during October southwestern trough periods

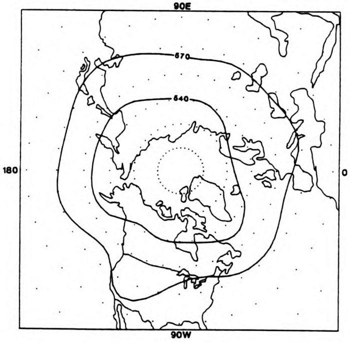


Figure 3.86 - Representative 500 mb pressure height contours during October southwestern trough periods (in decimeters)

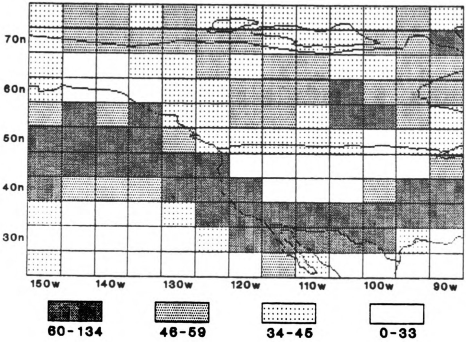


Figure 3.87 - Longitudinal frequency distribution of primary and secondary wind speed maxima during November southwestern trough periods

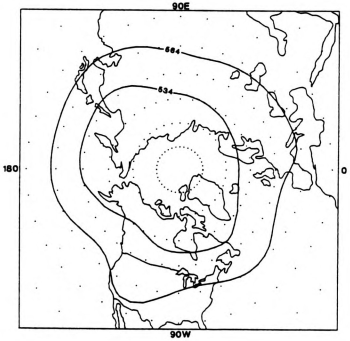


Figure 3.88 - Representative 500 mb pressure height contours during November southwestern trough periods (in decimeters)

the phasing of the high and low latitude wave train (Figure 3.88). The mean flow, as implied by the representative contours, is less diffluent over the Gulf of Alaska and suggests fewer occurrences of split flow during November trough events.

The December frequency pattern is similar to that of October (Figure 3.89). The frequency distributions over the eastern Pacific between 150°W and 130°W are unimodal, with maximum frequencies occurring near 50°N. Distributions become bimodal east of 130°W, where the primary mode shifts southeast, toward the southwestern United States, and the secondary mode pivots northeast through Canada. The representative contour composite is less revealing, however, as it indicates a continued evolution toward a full latitude wave train with reduced tendency for flow separation over North America (Figure 3.90). The lack of evidence supporting diffluence over the Gulf of Alaska and confluence over central North America may be a function of the smoothing that occurs during the compositing process.

The low latitude frequency distributions for January and February maintain the same general pattern observed during December (Figures 3.91 and 3.93). The distributions in the eastern Pacific, between 150°W and 130°W are unimodal. Although not as strongly developed as during October and December, the distributions for January and February are

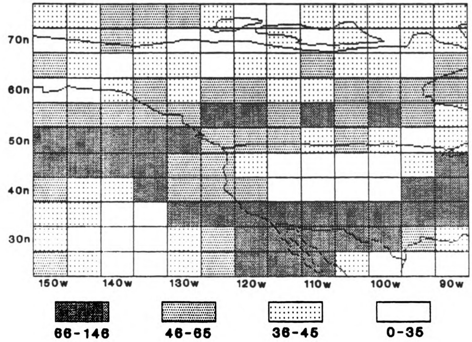


Figure 3.89 - Longitudinal frequency distribution of primary and secondary wind speed maxima during December southwestern trough periods

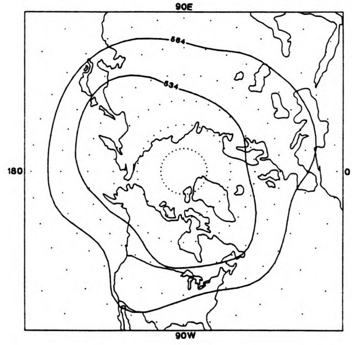


Figure 3.90 - Representative 500 mb pressure height contours during December southwestern trough periods (in decimeters)

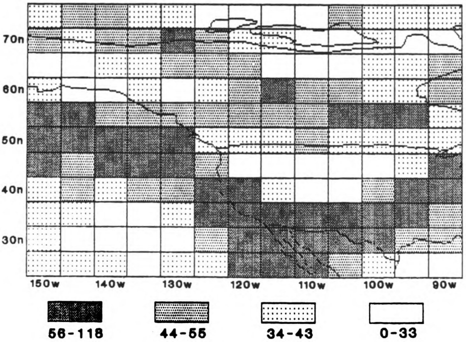


Figure 3.91 - Longitudinal frequency distribution of primary and secondary wind speed maxima during January southwestern trough periods

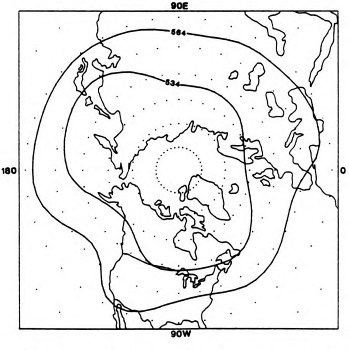


Figure 3.92 - Representative 500 mb pressure height contours during January southwestern trough periods (in decimeters)

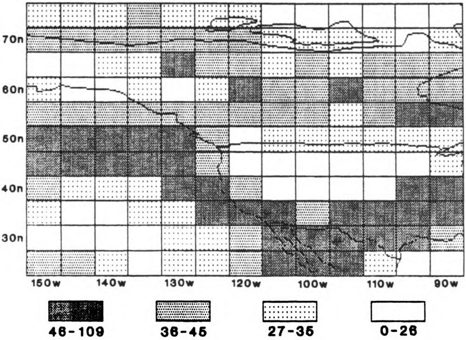


Figure 3.93 - Longitudinal frequency distribution of primary and secondary wind speed maxima during February southwestern trough periods

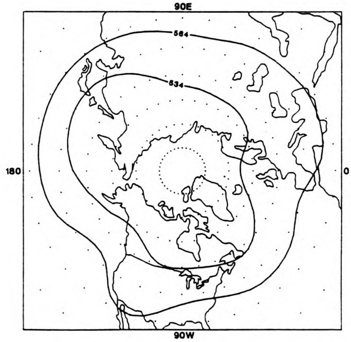


Figure 3.94 - Representative 500 mb pressure height contours during February southwestern trough periods (in decimeters)

bimodal over western North America. The less distinct secondary wind maxima of January and February suggest fewer occurrences of split flow events during late winter troughing. The contour composites give little indication of split flow and imply that late winter southwestern troughing more frequently involves a full latitude, in-phase wave train (Figures 3.92 and 3.94).

High frequencies in the Gulf of Alaska ridge and southwestern trough continue to dominate throughout the spring. The high latitude patterns that develop during March resemble those of February (Figure 3.95). A tendency for the pattern to become weakly bimodal east of 125°W suggests that split flow does occur during some March southwestern events. The bimodal distribution over North America continues during April and appears to be located more northward than during the autumn and winter months (Figure 3.97). By May and June, the distributions are strongly bimodal, with the high latitude mode sweeping southeast, out of the extreme northwest corner of the study area toward the Great Lakes region (Figures 3.99 and 3.101). The tendency for flow confluence south of Hudson Bay appears to increase, especially during May.

Flow becomes gradually more diffluent over the Gulf of Alaska and confluent over central North America throughout the spring months (Figures 3.96, 3.98. 3.100, and 3.102). High latitude flow trajectory over the Gulf of Alaska is

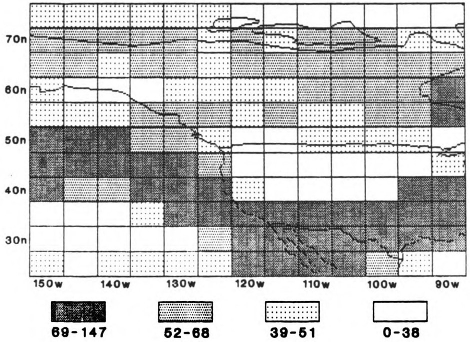


Figure 3.95 - Longitudinal frequency distribution of primary and secondary wind speed maxima during March southwestern trough periods

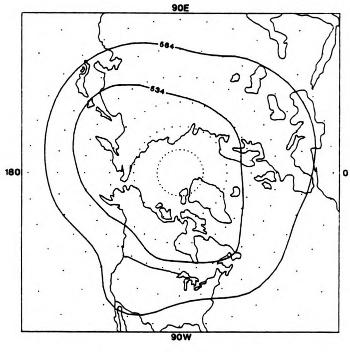


Figure 3.96 - Representative 500 mb pressure height contours during March southwestern trough periods (in decimeters)

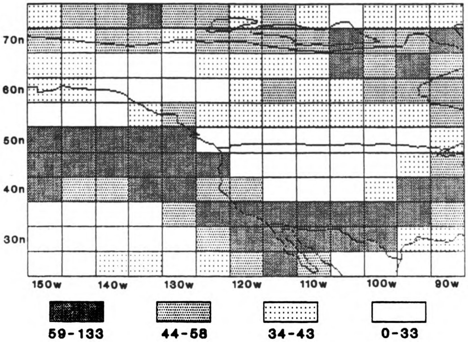


Figure 3.97 - Longitudinal frequency distribution of primary and secondary wind speed maxima during April southwestern trough periods

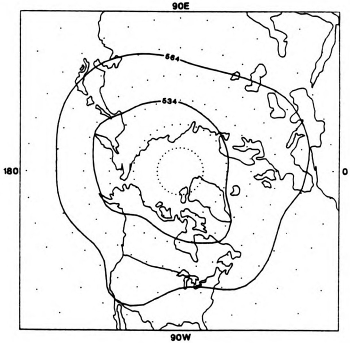


Figure 3.98 - Representative 500 mb pressure height contours during April southwestern trough periods (in decimeters)

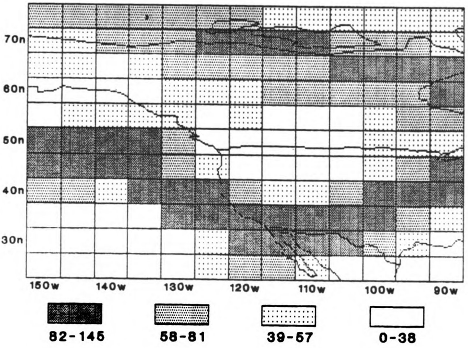


Figure 3.99 - Longitudinal frequency distribution of primary and secondary wind speed maxima during May southwestern trough periods

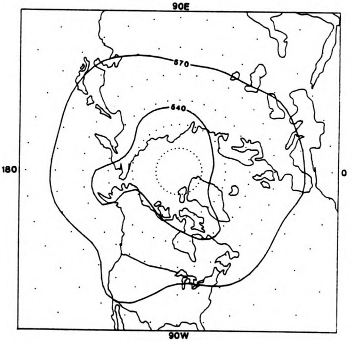


Figure 3.100 - Representative 500 mb pressure height contours during May southwestern trough periods (in decimeters)

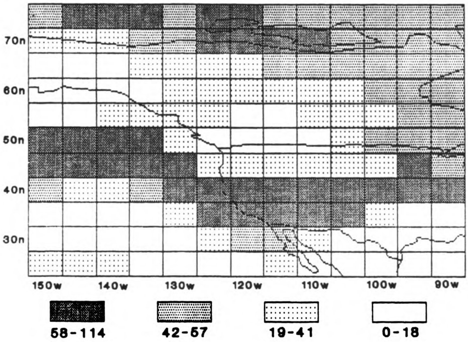


Figure 3.101 - Longitudinal frequency distribution of primary and secondary wind speed maxima during June southwestern trough periods

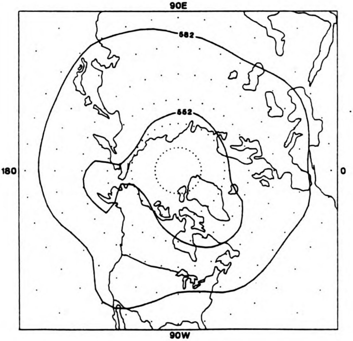


Figure 3.102 - Representative 500 mb pressure height contours during June southwestern trough periods (in decimeters)

strongly diffluent in May and June. During these months, the high and low latitude wave trains are distinctly out of phase and quite meridional over western North America. Deep troughing over the Bering Sea and ridging over northeast Asia and Alaska are the principal high latitude features. Meridionality of this type is characteristic of blocking, such as that described by Klein (1957). As a consequence, the high latitude flow over western North America is pushed northeastward through Alaska and then steered southeastward to rejoin the low latitude primary flow over eastern North America near Hudson Bay.

Summary of Split Flow Analyses

Results from the longitudinal wind maxima frequency distributions and representative contour composites indicate that southwestern troughing is often accompanied by split flow over western North America, but that the consistency of this association varies from month-to-month. Signals are strongest during the late spring, when high latitude frequency distributions and the contour composites imply flow separation near the Gulf of Alaska and confluence south of Hudson Bay. The high latitude wave train is very meridional during spring and may be related to more frequent episodes of blocking. Although somewhat less developed, the autumn results are similar to those of spring. During winter, the frequency distributions are more unimodal throughout the study area; however, a weak clustering of higher frequencies over central Canada indicates that split flow may occur in association with southwestern troughing during the winter, as well.

Precipitation Analyses

Monthly specific precipitation density and percent total precipitation results reflect the influences of southwestern troughing on dynamic uplift and moisture advection throughout the western and central United States. Resultant patterns vary spatially from month-to-month and appear to be a function of trough location, downstream flow trajectory, and moisture availability.

The pattern of September precipitation density values, which are calculated as the ratio of average daily precipitation during southwestern trough days to that occurring during all precipitation days, features a broad area of high values covering much of the central and northeastern portion of the study area (Figure 3.103). Densities in excess of 140 stretch northeastward from Arizona into Minnesota, indicating that during southwestern trough days daily precipitation exceeds 140 percent of that received during average precipitation days in this region. A smaller area in eastern Montana, North Dakota, and Northern Minnesota exhibits densities exceeding 160. Patterns in the southwestern states are variable, and may

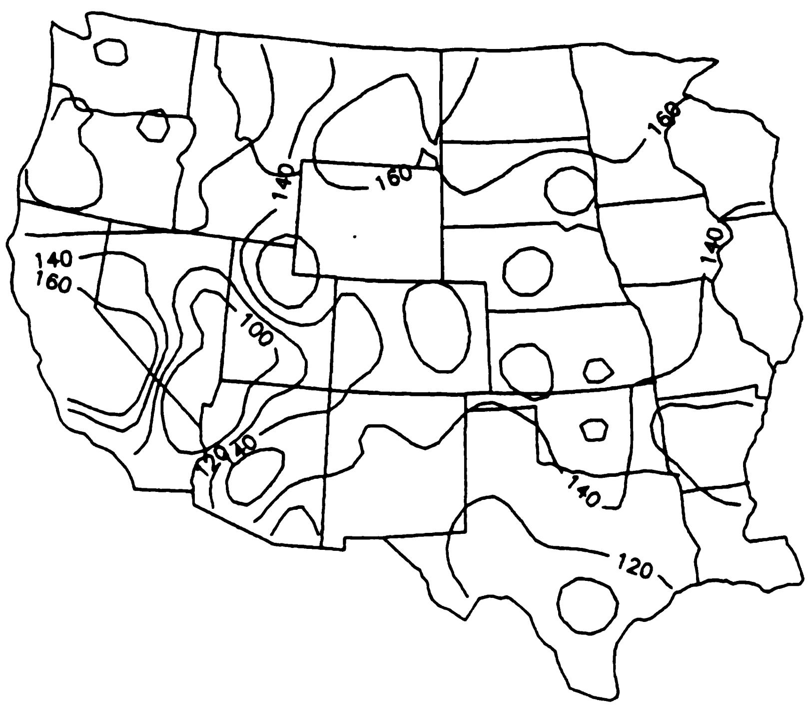


Figure 3.103 - September southwestern trough specific precipitation density

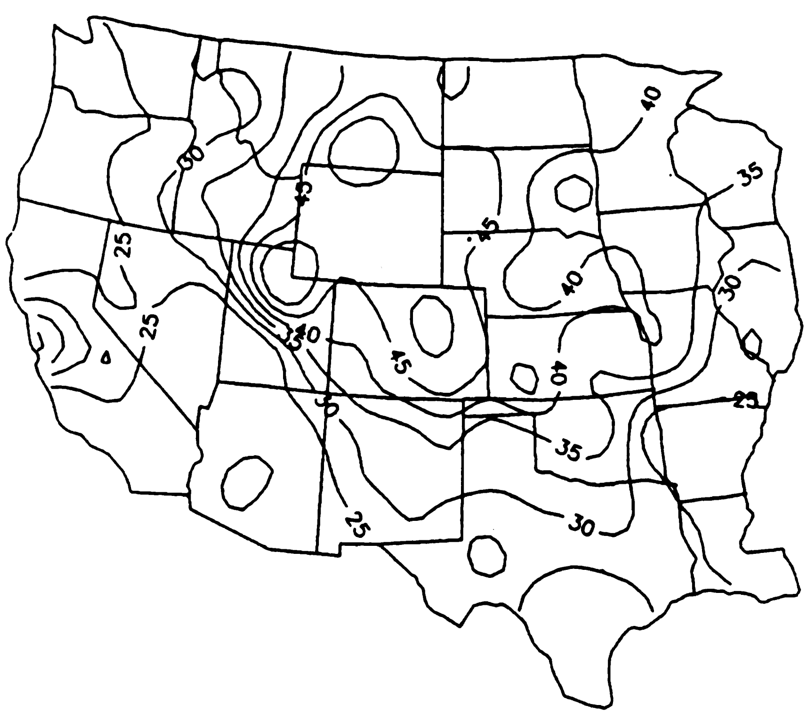


Figure 3.104 - Percentage of total September precipitation produced by southwestern troughs

be the result of infrequent convective events in an otherwise dry region. West of the southwestern trough axis, in Oregon and Washington, densities are low.

The importance of southwestern trough derived precipitation, as represented by specific precipitation density values, can be misleading. Areas that receive large proportions of their total precipitation from southwestern trough events will have density values close to 100. In such cases, the precipitation that occurs during troughing days expressed as a percentage of the total precipitation is a more revealing statistic and was calculated, also.

The number of trough days during the 719 September days in which precipitation data were available was 121 and represented 16.6 percent of the total. Therefore, total September trough precipitation was received during a combined period that represented only 16.6 percent of the full period. As revealed in Table 3.1, the percentage of troughing days that occurred during the other months was slightly higher, but never exceeded 28.9 percent.

The percent of total September precipitation that occurred during southwestern trough events, calculated for each station, indicates a distinct percentage gradient over Idaho, Utah, Arizona, and Texas, separating smaller values in the west from larger values in the east (Figure 3.104).

Table 3.1 - Percentage of total days in which southwestern troughs occurred

MONTH	NUMBER OF DAYS IN RECORD	NUMBER OF SW TROUGH DAYS	PERCENT OF TOTAL DAYS
September	719	121	16.6
October	687	187	27.2
November	665	143	21.5
December	687	154	22.4
January	713	170	23.8
February	650	147	22.6
March	719	193	26.8
April	696	166	23.8
May	719	208	28.9
June	696	144	20.6

A weaker gradient over Oklahoma and Missouri separates lower percentages in the west and south from higher values in the north. Southwestern troughs are especially important in the September precipitation climatology of northern Utah, Colorado, and Wyoming, where they provide over 45 percent of the total precipitation. Trough derived precipitation is less important in the western and southern states.

The October and November density patterns are better defined and feature lower densities in the western and southwestern portions of the study area, and higher values in the northeast (Figures 3.105 and 3.107). When southwestern troughs occur during these months, portions of Minnesota, Wisconsin, and Illinois receive daily precipitation totals in excess of 160 percent of that

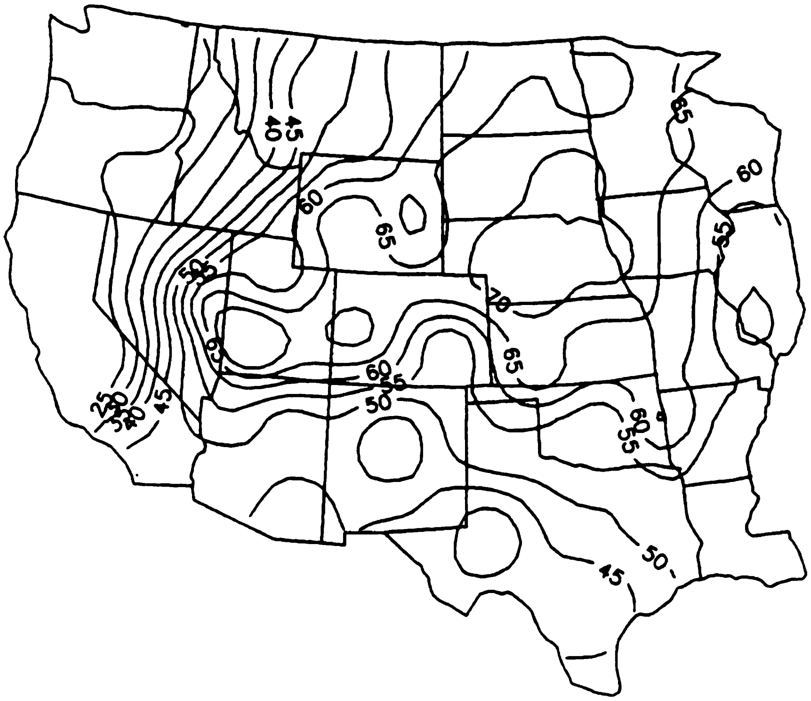


Figure 3.105 - October southwestern trough specific precipitation density

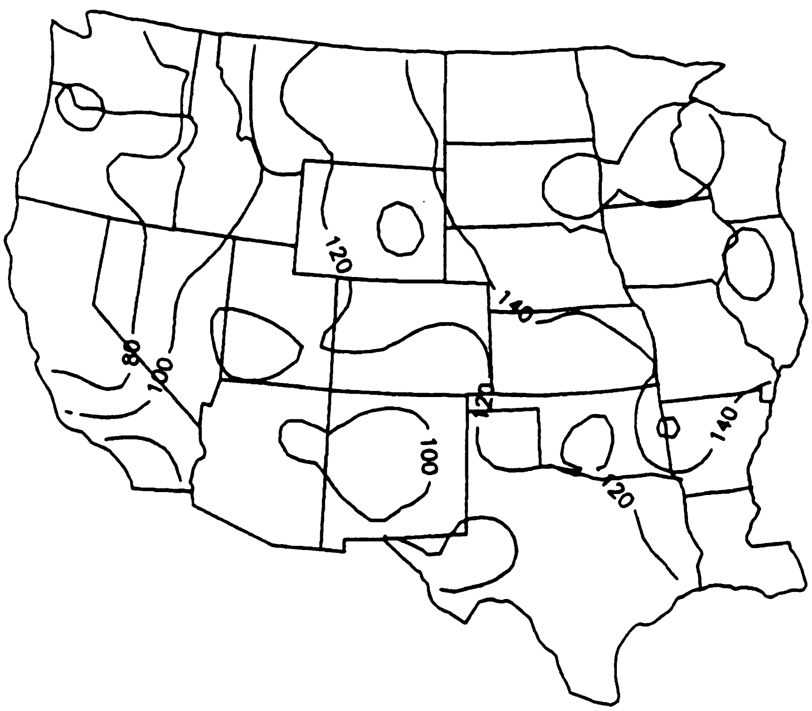


Figure 3.106 - Percentage of total October precipitation produced by southwestern troughs

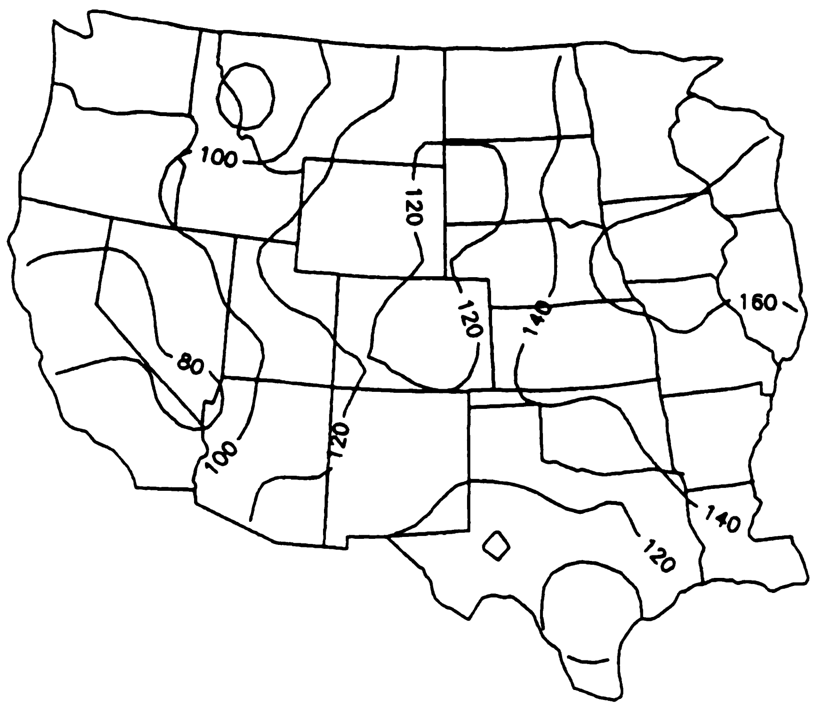


Figure 3.107 - November southwestern trough specific precipitation density

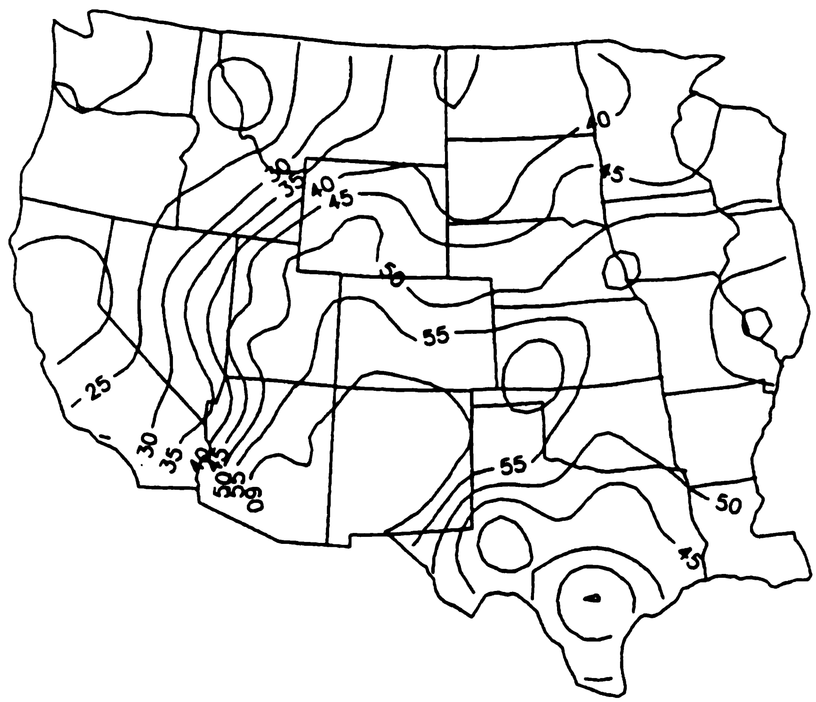


Figure 3.108 - Percentage of total November precipitation produced by southwestern troughs

received during average precipitation days. The October and November density patterns are less variable in the southwestern states than during September, and are characterized by values near 100.

The October percentage map differs slightly from that of September, as the highest percentages occur more eastward over South Dakota and Nebraska (Figure 3.106). A strong gradient trends southward through Idaho, Nevada, and southern California and then eastward through the four corners area into Oklahoma. Percentages are high east of this gradient, where values exceed 70 percent throughout much of Nebraska and South Dakota. As compared to September, October percentages throughout Arizona, New Mexico, and Texas are higher, also.

By November, the highest percentages occur in the southwest. Values in excess of 60 cover much of Arizona and New Mexico (Figure 3.108). The strong gradient that extends through the four corners area in October weakens and shifts into southern Texas. The orientation of the western gradient changes slightly during November, becoming aligned in a more southwest-northeast position through southern California, Nevada, Wyoming, and South Dakota. General characteristics of the winter precipitation density summaries are similar to those of October and November. Values are greatest in the northeastern portion of the study area and decrease westward and southwestward. The core of highest densities during December is located over South Dakota and Minnesota, and stretches southwest into Wyoming (Figure 3.109). Values throughout the western and southwestern states remain under 100. During January, the highest densities occur more southeastward than during December (Figure 3.111). Portions of Iowa and Illinois receive precipitation in excess of 180 percent of average during January trough days. Densities in the northeastern portion of the study region remain high throughout February (Figure 3.113). Values in the southwest, however, are much lower in February than during the early winter, as densities drop below 100 throughout most of Arizona, New Mexico, and Texas.

A strong northwest-southeast percentage gradient, similar to that occurring in November, trends from North Dakota, southwest through Idaho, Utah, and Nevada in December and January (Figures 3.110 and 3.112). West of this gradient, percentages decrease rapidly. Portions of northern California, Oregon, and Washington receive less than 20 percent of their total December and January precipitation during southwestern trough days. In states east of the gradient, trough-derived precipitation accounts for greater than 45 percent of the total December precipitation and more than 55 percent of the total January precipitation. Highest December percentages occur in Arizona and New Mexico, whereas in January the largest

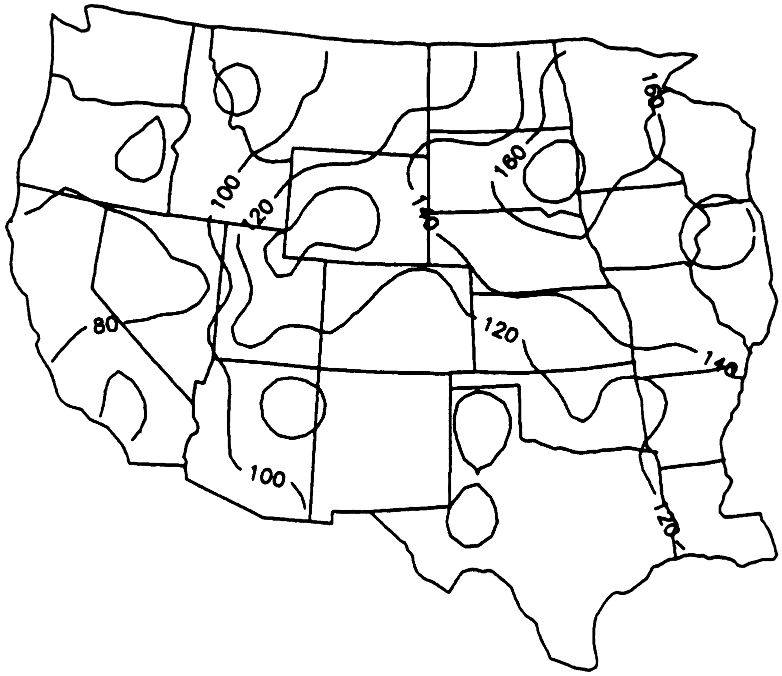


Figure 3.109 - December southwestern trough specific precipitation density

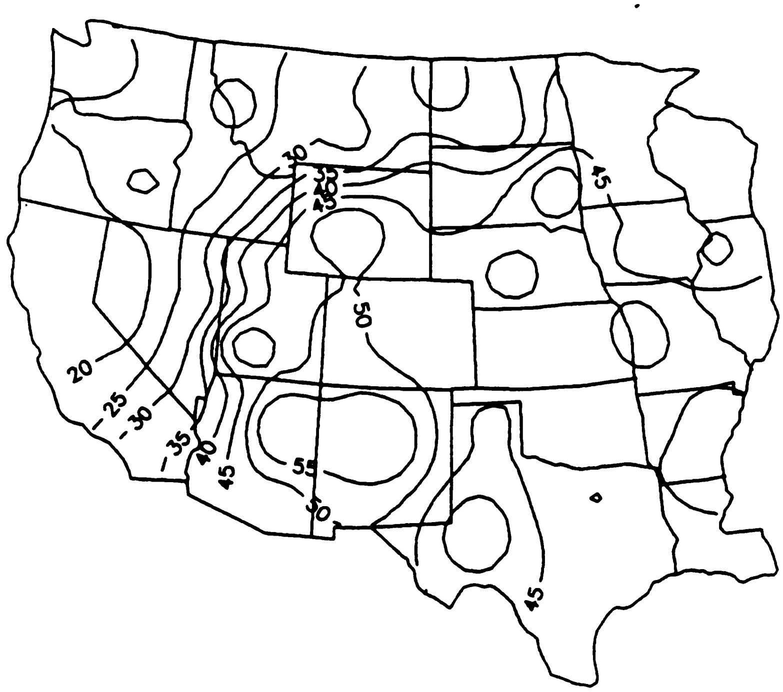


Figure 3.110 - Percentage of total December precipitation produced by southwestern troughs

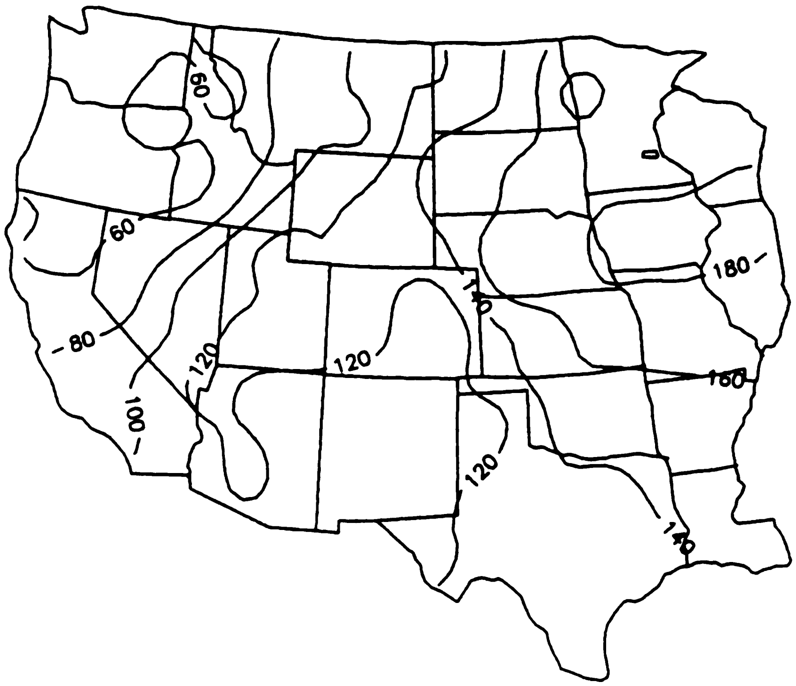


Figure 3.111 - January southwestern trough specific precipitation density

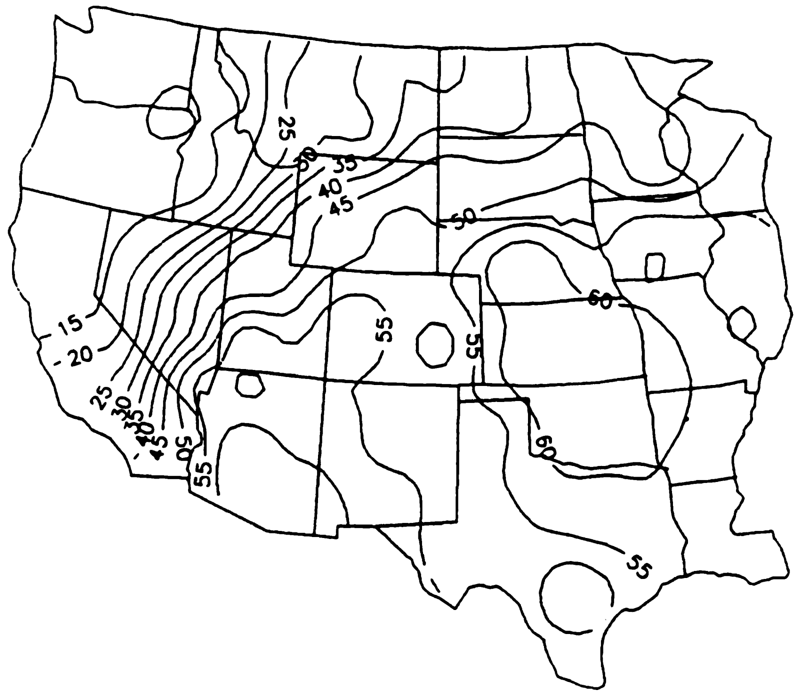


Figure 3.112 - Percentage of total January precipitation produced by southwestern troughs

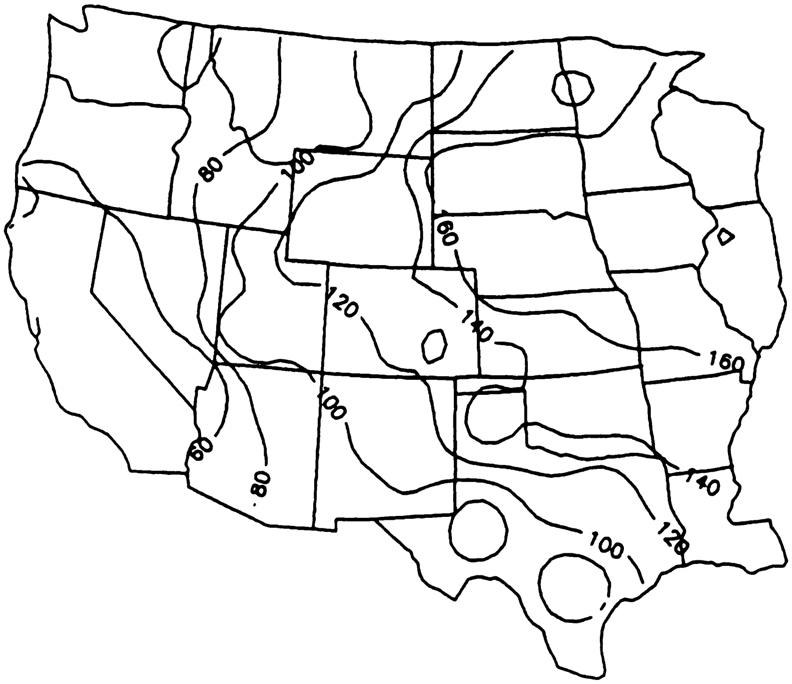


Figure 3.113 - February southwestern trough specific precipitation density

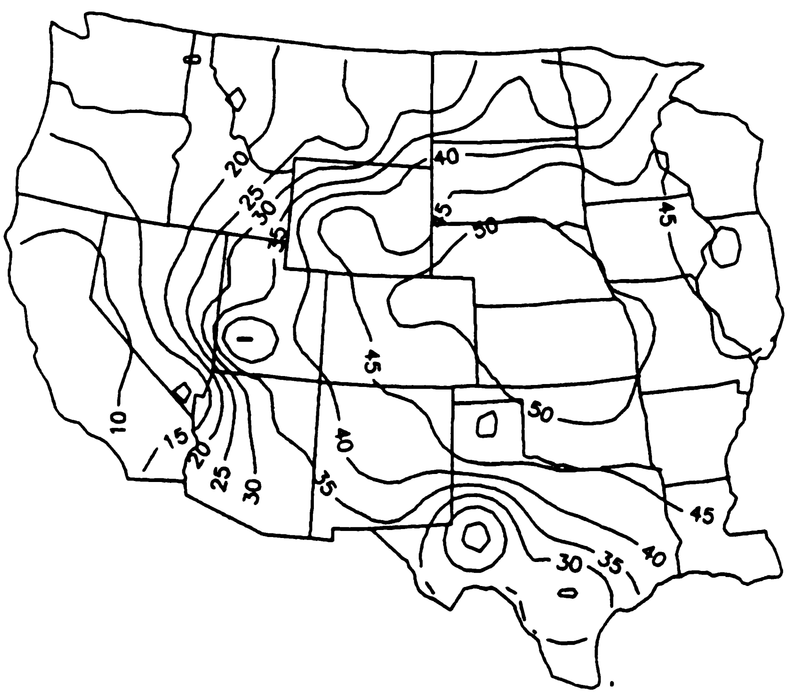


Figure 3.114 - Percentage of total February precipitation produced by southwestern troughs

values are found over Oklahoma and Kansas.

By February, the strong northwest-southeast percentage gradient that occurs in the western states during January changes slightly. During January, California is split between low percentages in the north and higher values in the south. By February, all of California experiences low percentages, as the boundary between high and low values realigns eastward through Arizona, New Mexico, and Texas (Figure 3.114). Furthermore, percentages throughout the southwestern states decrease during February, with the highest values occurring in Nebraska and Kansas.

The evolution of density patterns throughout spring is characterized by a gradual northwest shift in the region of highest values. The March density pattern is similar to that of February, in which the largest values are located in the northeastern corner of the study area and decrease toward the southwest (Figure 3.115). The highest values are found in Iowa, where daily trough precipitation exceeds 160 percent of average.

A sharp contrast in density pattern occurs between March and April (Figure 3.117). The region of greatest influence shifts northwestward over Montana and Wyoming and a strong density gradient develops through Idaho, Nevada, northern Arizona, and northern New Mexico. Densities rapidly decrease west and south of this gradient.

The density pattern is less defined during May and June,

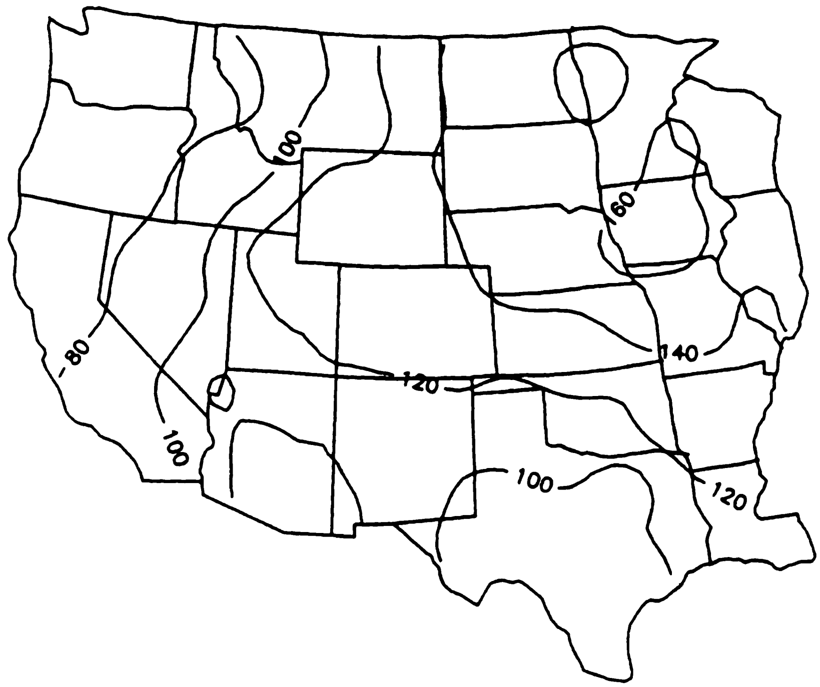


Figure 3.115 - March southwestern trough specific precipitation density

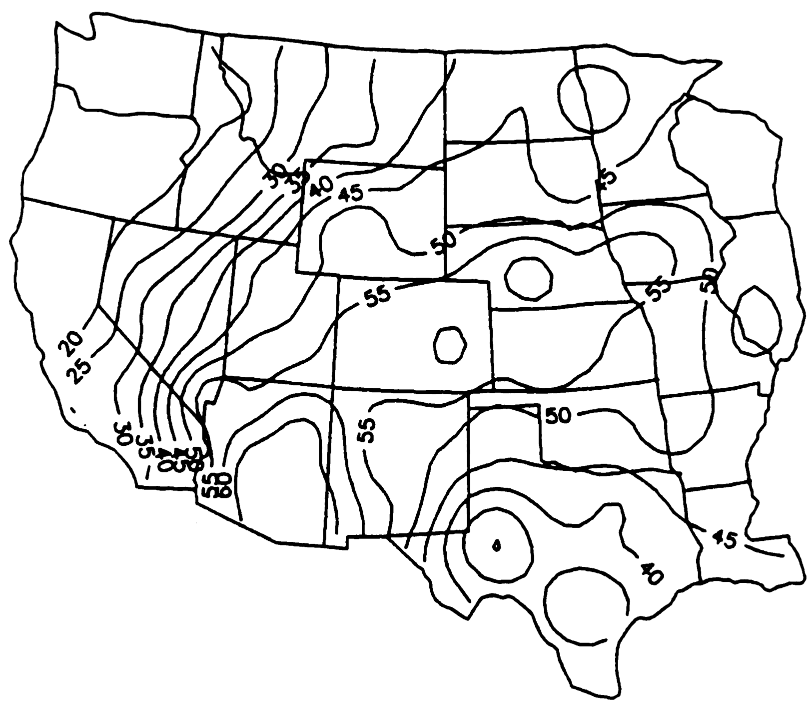


Figure 3.116 - Percentage of total March precipitation produced by southwestern troughs

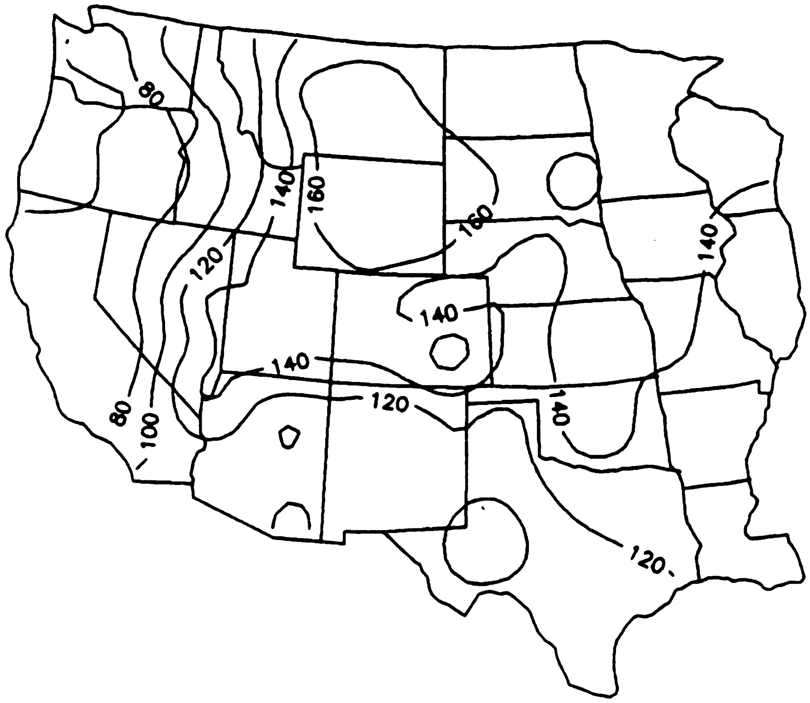


Figure 3.117 - April southwestern trough specific precipitation density

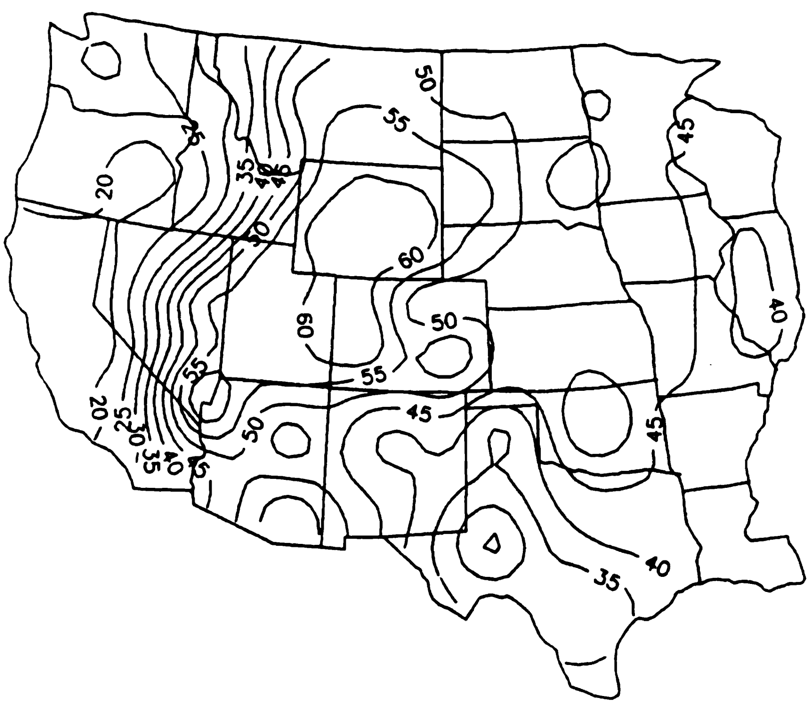


Figure 3.118 - Percentage of total April precipitation produced by southwestern troughs

as the western and southern gradients weaken (Figure 3.119 and 3.121). Densities over the north central states continue to be high, whereas those over Oregon and Washington remain low. Values throughout most of Arizona, New Mexico, and Texas decrease sharply by June.

The pattern of spring percentages reflects a similar northwestward shift in the region of highest values. The March pattern maintains many of the winter characteristics, with the largest values extending northeastward from Arizona into Iowa and Wisconsin (Figure 3.116). A strong gradient is present over Montana, Idaho, Nevada, and California, and separates lower percentages in the west from higher values in the eastern states. By April, highest percentages occur more northwestward over Wyoming (Figure 3.118). As values increase at the northern stations, a strong north-south percentage gradient develops over Arizona, New Mexico, and Texas. South of this gradient, percentages decrease rapidly. The May and June summaries continue to indicate a tendency for values in the west to large, reducing the importance of trough derived precipitation over the eastern and southwestern states (Figures 3.120 and 3.122).

Summary of Precipitation Analyses

Most of the central and eastern portions of the study area experience consistently large density and percentage

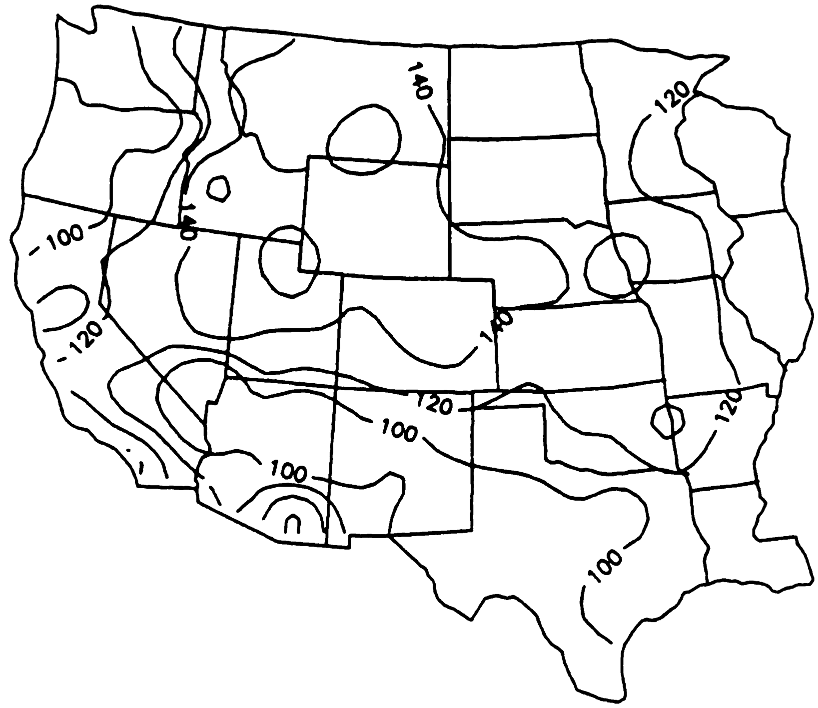


Figure 3.121 - June southwestern trough specific precipitation density

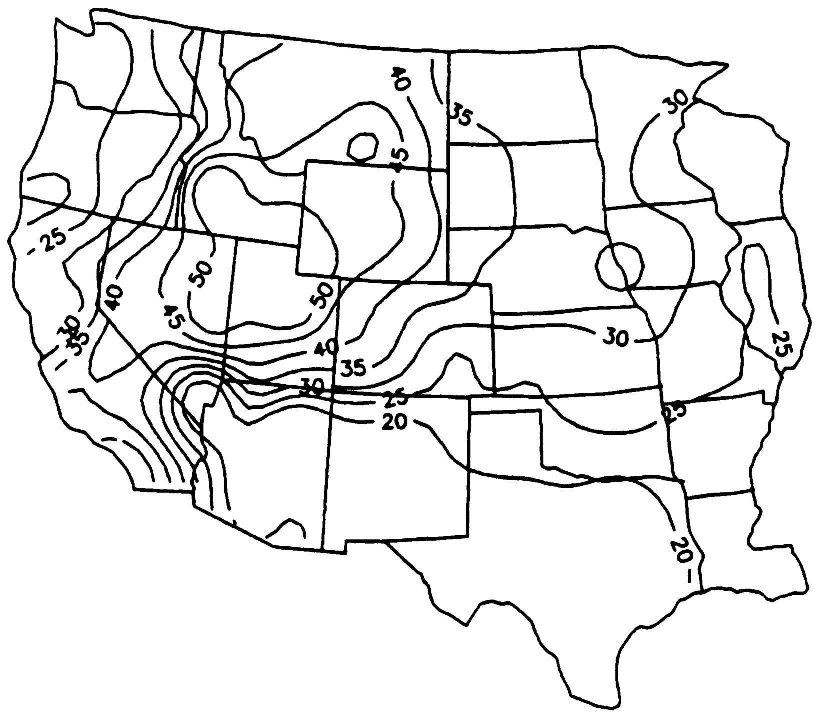


Figure 3.122 - Percentage of total June precipitation produced by southwestern troughs

values during southwestern trough periods. Values throughout this region are high regardless of month and attest to the significance of southwestern troughs in the precipitation climatology of the central United States. During the autumn and spring, the region of maximum trough influence shifts northwestward, over the north-central states, whereas during the winter, the core of greatest influence expands over much of the central and southeastern states. As a result of this seasonal shift, trough influence in the southwestern states decreases during the transition seasons and is especially small during June. Values in the extreme western states are consistently small throughout all months and reflect the lack of dynamics and available moisture in this region during southwestern troughing.

Eddy Heat Flux Analyses

Although the climatology of Northern Hemispheric quasi-stationary and transient eddy heat transfer has been examined by previous studies, most of these were based on zonally averaged flux values and very few attempted to describe the regional contributions of individual synoptic types (Haines and Winston, 1963; van Loon, 1979; van Loon and Williams, 1980; Carleton, 1988). The high amplitude flow and slow movement of southwestern troughs make these systems potentially large sources of transient eddy heat flux throughout the western and central United States. Because southwestern troughs represent departures from the average flow, the pattern and strength of northward transient eddy heat flux during trough events are much different from those associated with quasi-stationary and non-trough transient flux.

Quasi-Stationary Eddy Flux

Throughout much of the year, the mean long wave configuration over western North America features a large ridge, with southerly flow over the eastern Pacific and northerly flow over the western and central Unites States (Lahey et al., 1958). As a consequence, middle tropospheric temperatures within this ridge are generally warmer than latitudinal mean temperatures. Because eddy heat flux is calculated as the product of the v-component geostrophic wind and the latitudinal temperature departure, the dominance of negative v-component winds and positive latitudinal temperature departures throughout the western and central United States make this area one in which the daily average quasi-stationary northward eddy heat flux is largely negative.

Seasonally, the 500 mb quasi-stationary heat flux pattern in the western and central United States is poorly defined during autumn months, when the atmosphere is nearly barotropic and the v-component winds are weak (Figure

3.123). Throughout most of the southern section of the study area daily average quasi-stationary heat flux values are near 0 °C m/s. Farther north, values become more negative and approach -4 °C m/s over northern Montana and North Dakota.

During winter, the circumpolar vortex expands southward and the flow strengthens. As a result, the quasi-stationary eddy heat flux becomes increasingly negative over the north-central states (Figure 3.124). The core of largest negative northward flux occurs over Montana, where large negative latitudinal temperature departures and strong v-component winds drive flux values near -12 °C m/s.

By spring, v-component winds weaken and the latitudinal temperature departures decrease, as flow becomes more zonal (Figure 3.125). During the spring months, the center of largest negative northward heat transport shifts from its winter location over Montana to a new position over the Dakotas and Minnesota, where values are near -3 °C m/s. This eastward shift in the core of greatest negative heat flux is accompanied by an emergence of weak positive flux values over the extreme western portion of the study area and is associated with a slight eastward alignment in the position of the modal position of the spring ridge axis.

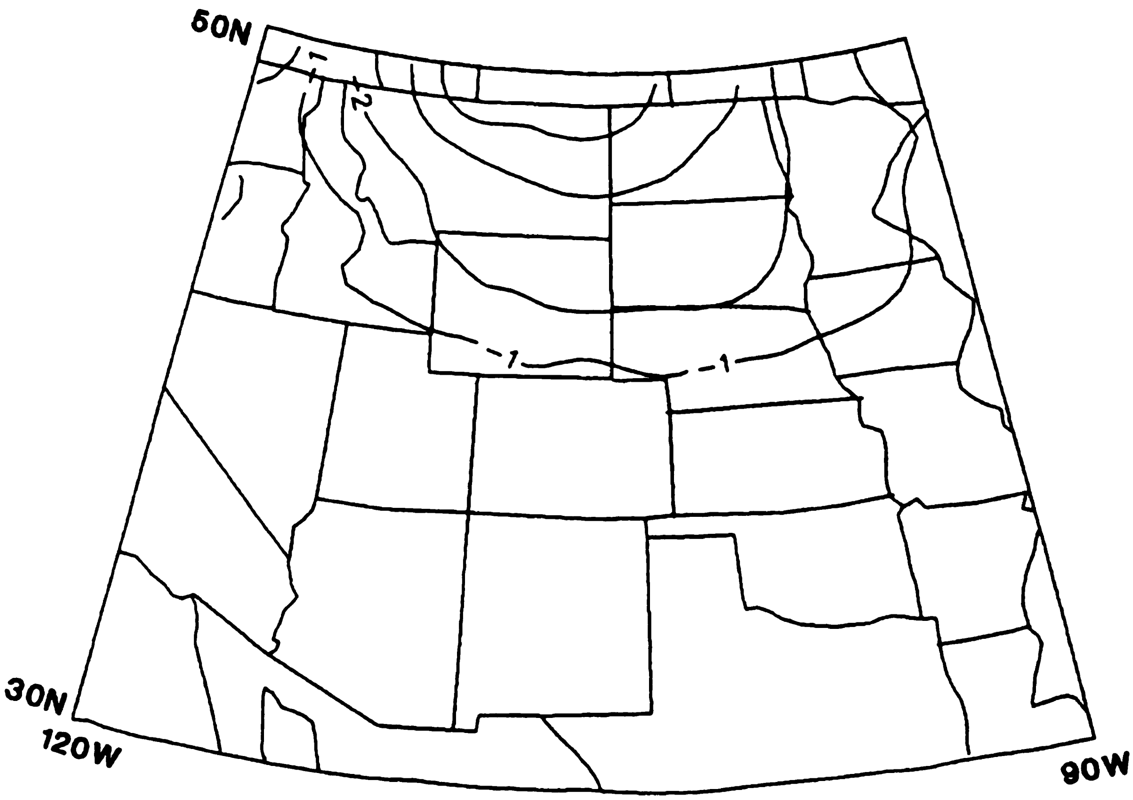


Figure 3.123 - Daily average autumn quasi-stationary eddy sensible heat transfer (in °C m/s)

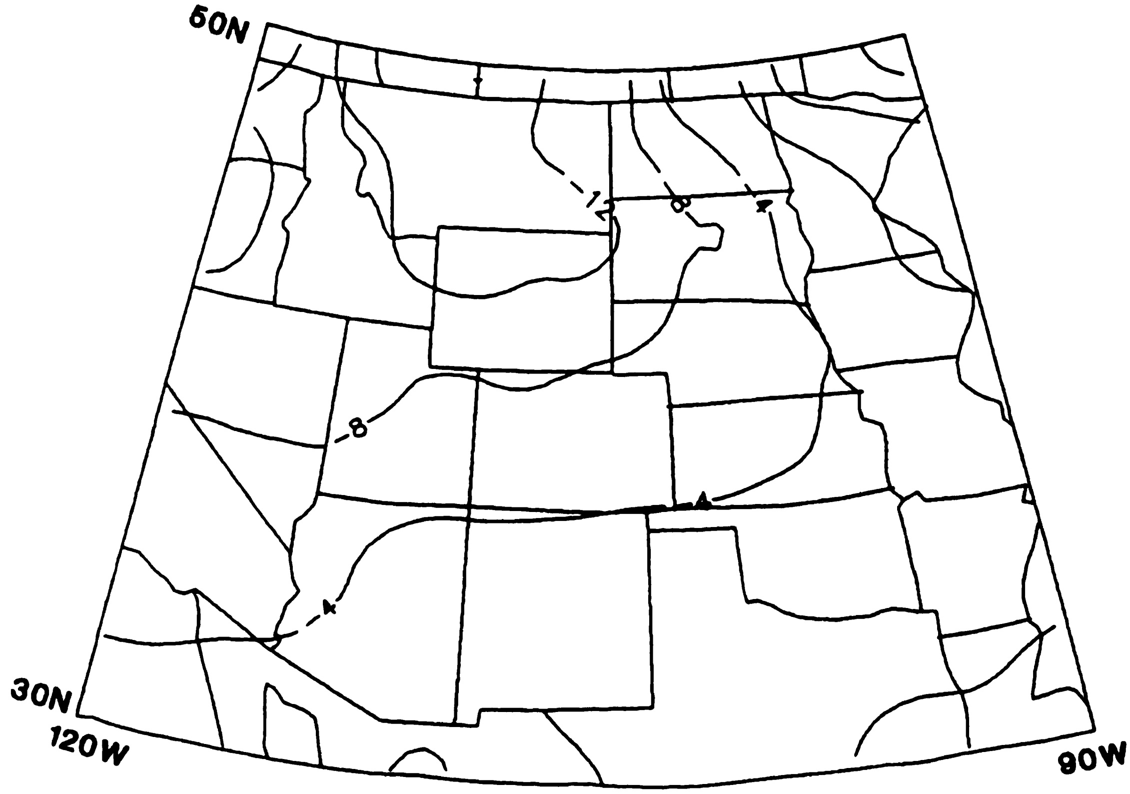


Figure 3.124 - Daily average winter quasi-stationary eddy sensible heat transfer (in °C m/s)

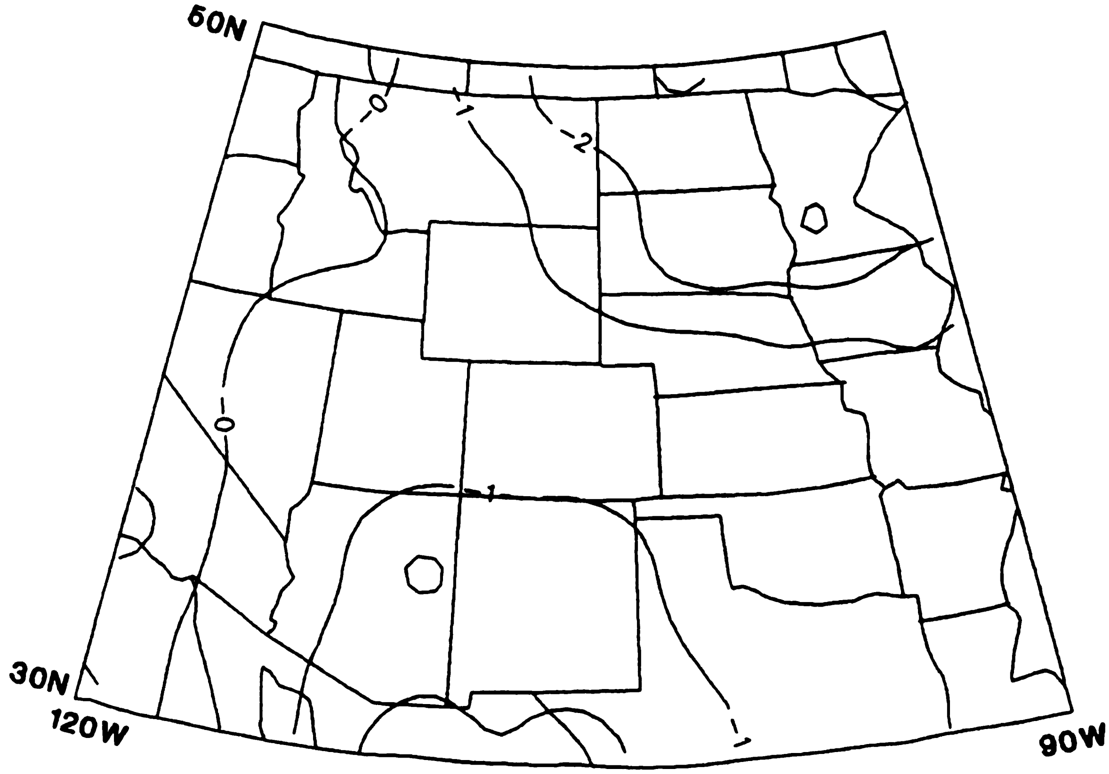


Figure 3.125 - Daily average spring quasi-stationary eddy sensible heat transfer (in °C m/s)

Transient Eddy Flux

In contrast to the daily quasi-stationary eddy heat flux, the northward transfer of energy by transient eddies is predominantly positive and is especially vigorous during southwestern trough events. The transient eddy heat flux during autumn non-trough periods is positive throughout the northeastern portion of the study area, with values approaching 12 °C m/s across Minnesota (Figure 3.126). Values decrease toward the southwest and become weakly negative over Nevada, California, and Arizona.

By comparison, the values of daily average transient eddy heat transfer during southwestern trough periods are much larger than during non-trough periods (Figure 3.127). As with non-trough transient disturbances, southwestern trough northward energy transfer increases toward the northeastern corner of the study area and decreases toward the southwest. Daily average values exceed 24 °C m/s throughout areas of Minnesota and Iowa and partially reflect the influence of strongly positive v-components east of the trough axis. Furthermore, higher geopotential heights over the eastern United States, which are teleconnectively forced by troughing in the Southwest, result in strongly positive latitudinal temperature departures and help to drive large positive heat flux values throughout the eastern portions of the study area.

The winter non-trough transient eddy heat flux pattern

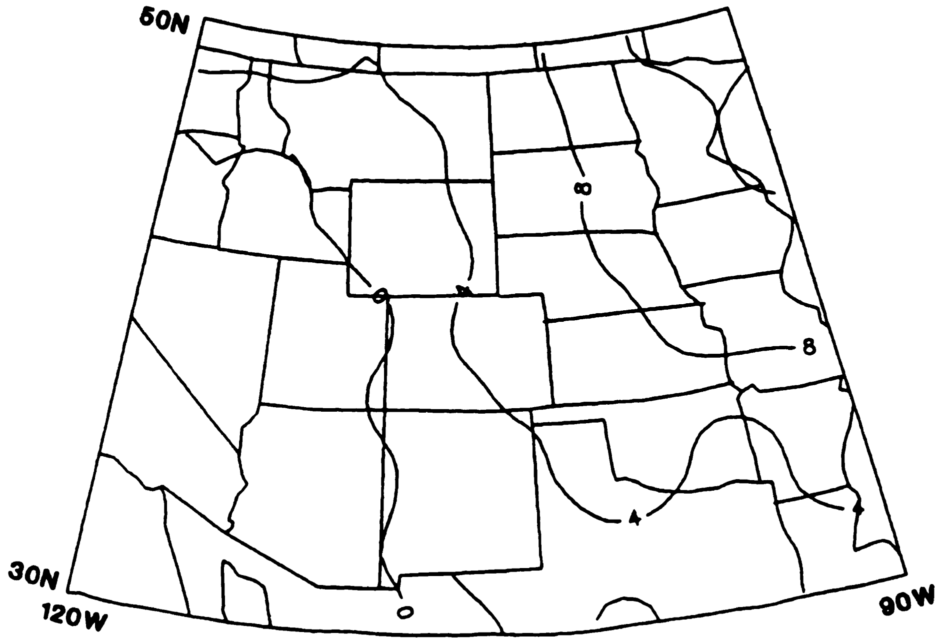


Figure 3.126 - Daily average autumn non-trough transient eddy sensible heat transfer (in °C m/s)

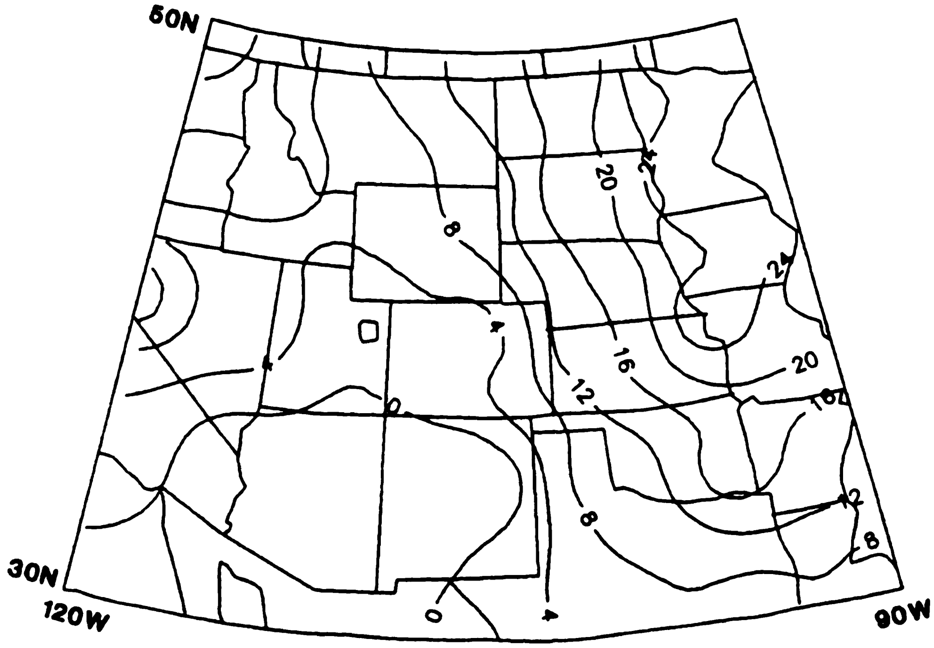


Figure 3.127 - Daily average autumn southwestern trough transient eddy sensible heat transfer (in °C m/s)

resembles that of autumn in that the heat flux decreases gradually from the northeast toward the southwest (Figure 3.128). Winter non-trough transient eddy heat flux over the northeastern states is slightly higher than during autumn and exceeds 12 °C m/s throughout much of Minnesota and Iowa. The only area of negative transient heat flux occurs over central Arizona.

During winter southwestern trough events, transient eddy heat flux values are much larger, exceeding 16 °C m/s over much of the study area (Figure 3.129). The general pattern of trough eddy heat flux differs from that of autumn. Rather than a single core of highest flux, which is located over Minnesota during the autumn, the winter pattern exhibits two separate centers of maximum flux. Energy transfer exceeds 24 °C m/s near Montana and Wyoming, and near Missouri and Arkansas. Flux values are smaller throughout the southwestern and northeastern sections of the study area. The only negative northward transport occurs in two small areas over New Mexico and Oregon.

The spring non-trough transient eddy heat flux pattern is similar to that of winter and autumn (Figure 3.130). The largest values remain over the northeastern part of the study region, where daily average non-trough transient heat flux is near 12 °C m/s. Unlike the winter non-trough flux pattern, in which few negative values occur, negative flux becomes more dominant over the western states during

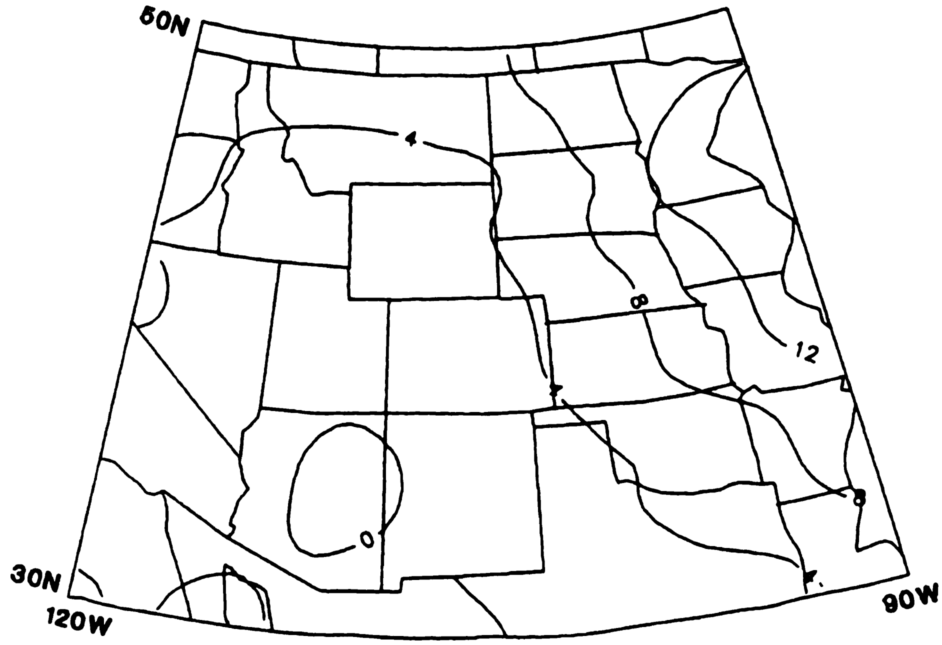


Figure 3.128 - Daily average winter non-trough transient eddy sensible heat transfer (in °C m/s)

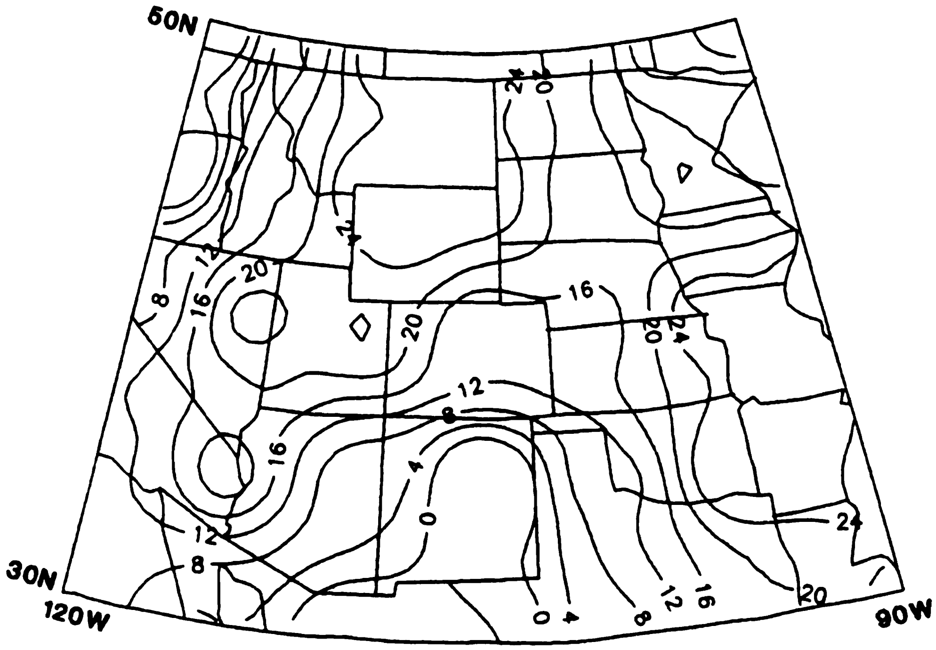


Figure 3.129 - Daily average winter southwestern trough transient eddy sensible heat transfer (in °C m/s)

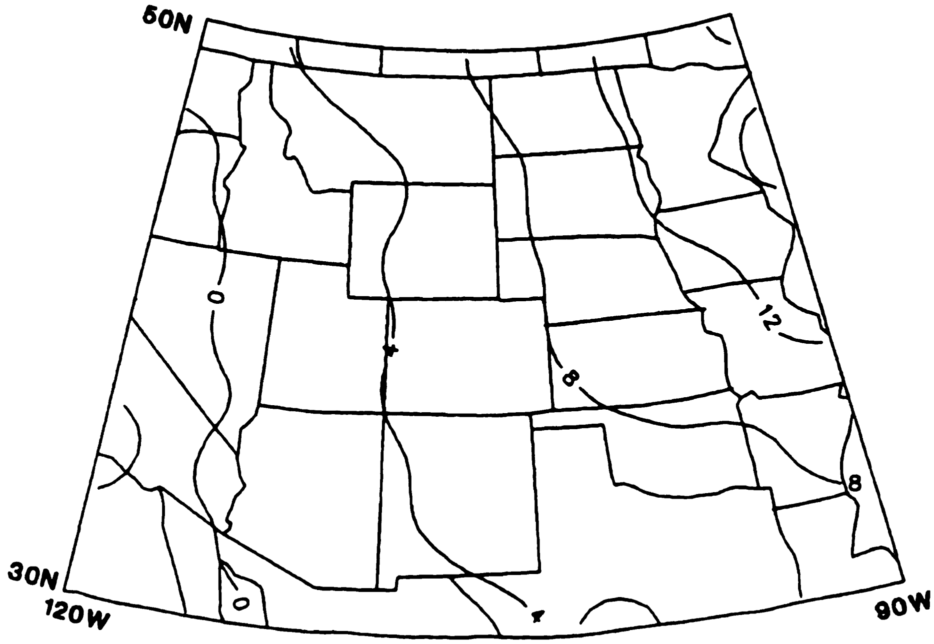


Figure 3.130 - Daily average spring non-trough transient eddy sensible heat transfer (in °C m/s)

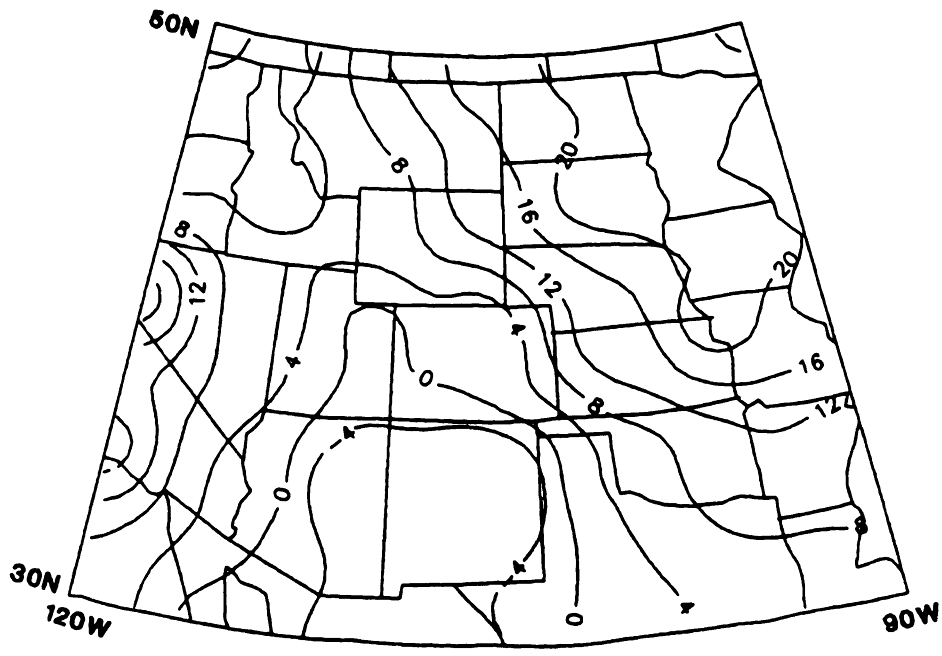


Figure 3.131 - Daily average spring southwestern trough transient eddy sensible heat transfer (in °C m/s)

spring.

As in autumn and winter, the spring southwestern trough transient eddy heat flux is stronger than the non-trough transient flux (Figure 3.131). The overall pattern is similar to that of autumn, with a single core of maximum flux over North and South Dakota, Iowa, and Minnesota where eddy heat flux is in excess of 20 °C m/s during spring southwestern trough days. Within the trough, over Arizona and New Mexico, flux values are negative.

Zonally Averaged Flux Comparisons

Zonally averaged quasi-stationary, transient non-trough, and transient southwestern trough eddy heat flux, calculated within the study area (90°W-120°W), provide a comparison of the relative transport efficiency of each process (Figures 3.132, 3.133, and 3.134). During all seasons, daily southwestern trough eddy heat flux is largest, followed by non-trough transient flux and quasi-stationary flux. When compared with other transient disturbances, the magnitude of northward heat transport by southwestern troughs is impressive. Maximum southwestern trough energy flux occurs near 45°N latitude and is greatest during winter when daily averages approach 20 °C m/s. Southwestern trough flux decreases at lower and higher latitudes. Only during spring at 30°N and 35°N does non-trough transient flux exceed southwestern trough eddy

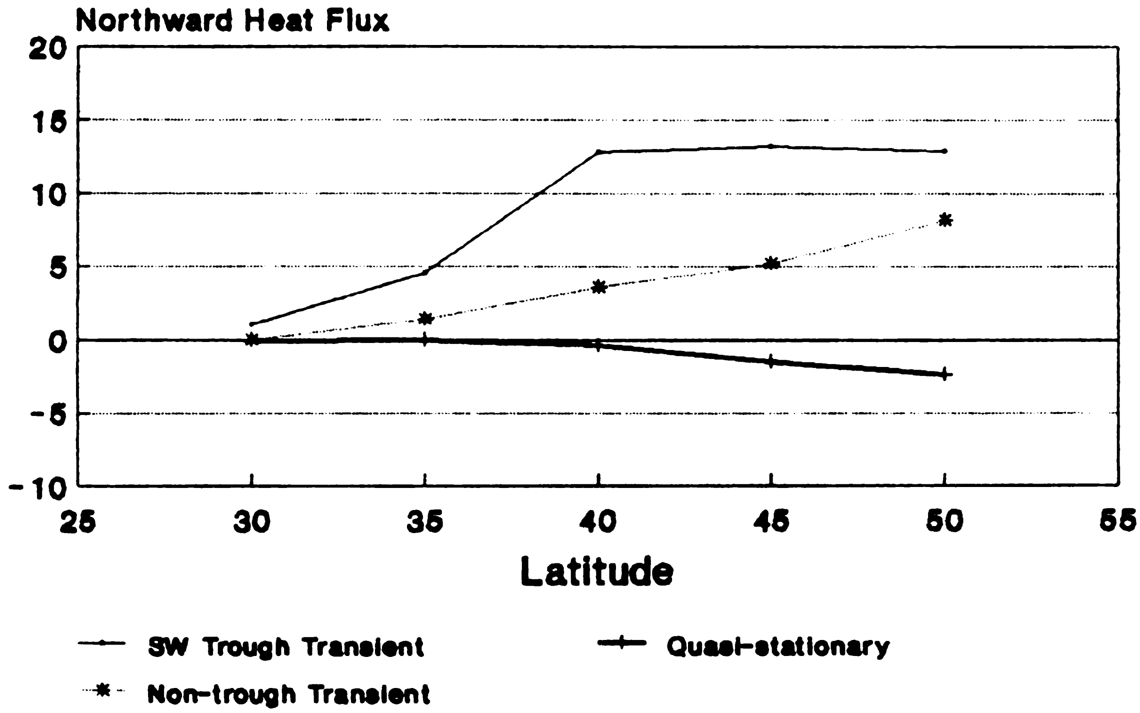


Figure 3.132 - Zonally averaged autumn quasi-stationary, non-trough transient, and southwestern trough transient eddy sensible heat transfer for 90°W-120°W (in °C m/s)

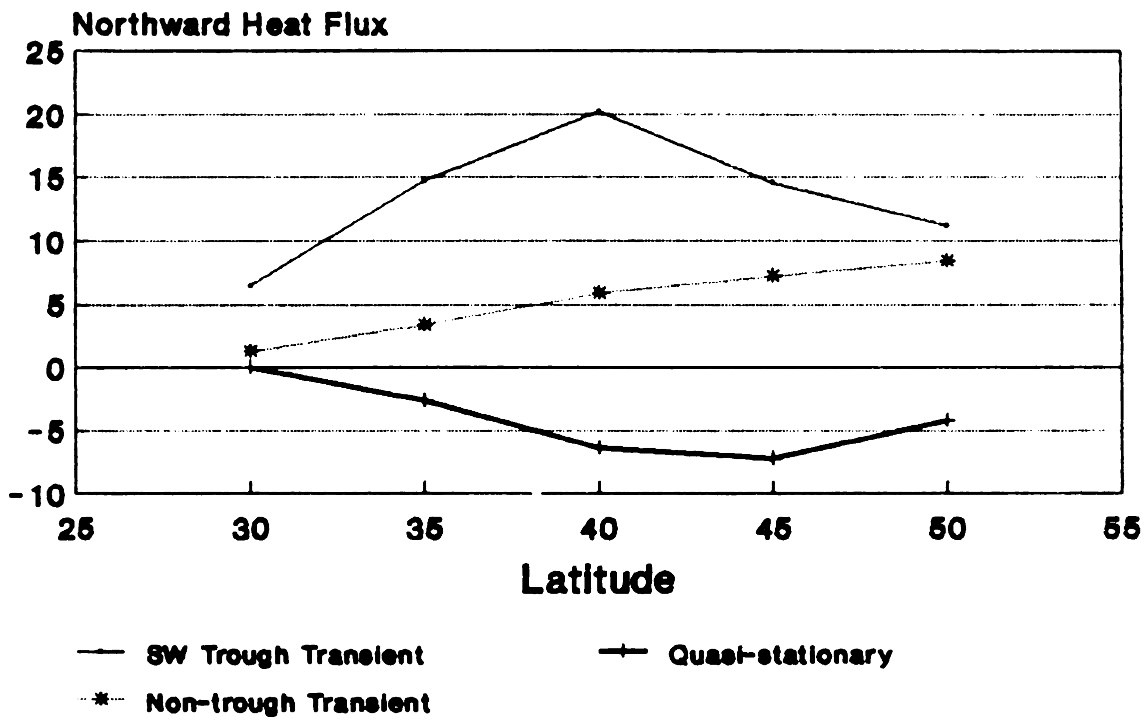


Figure 3.133 - Zonally averaged winter quasi-stationary, non-trough transient, and southwestern trough transient eddy sensible heat transfer for 90°W-120°W (in °C m/s)

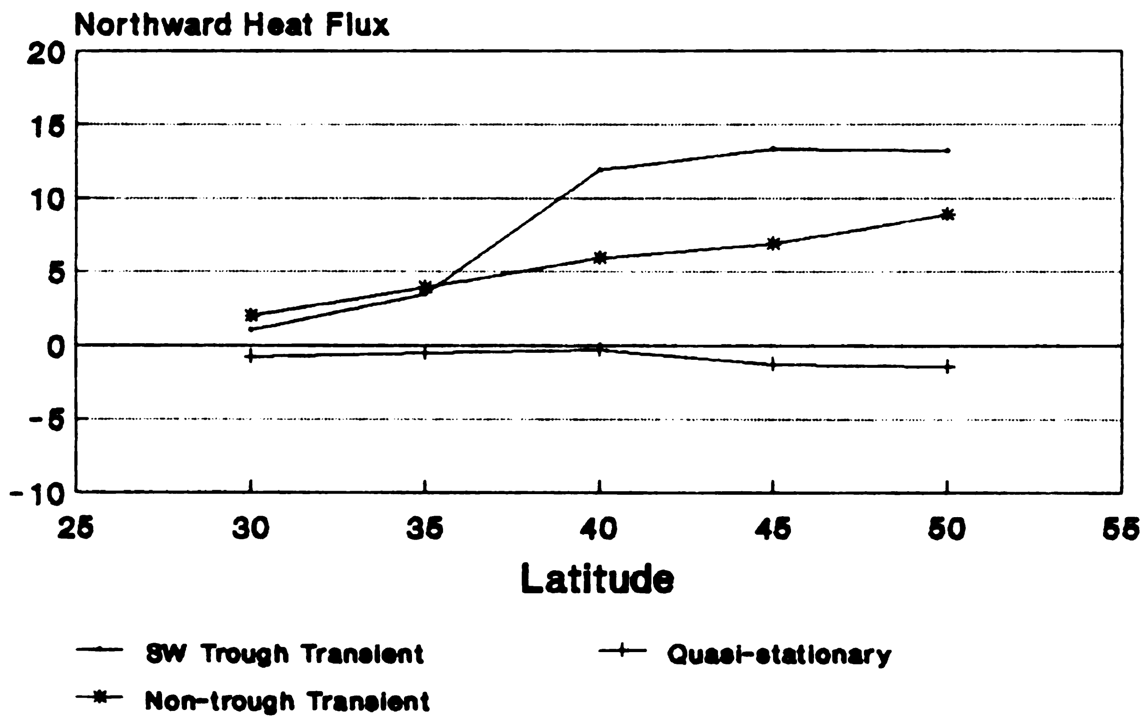


Figure 3.134 - Zonally averaged spring quasi-stationary, non-trough transient, and southwestern trough transient eddy sensible heat transfer for 90°W-120°W (in °C m/s)

heat flux; however, values here are very close to 0 °C m/s.

The zonally averaged quasi-stationary eddy heat flux is small and, at all latitudes, negative throughout the study area. During winter, the southwestern trough transient and quasi-stationary zonal trends are nearly asynchronous, underscoring the unique character and strength of southwestern trough energy transfer as compared to that transported by quasi-stationary eddies.

Summary of Eddy Heat Flux Results

The 500 mb eddy heat flux calculations for the western and central United States reveal that comparatively large amounts of sensible heat are transported northward during southwestern trough days. In autumn and spring, the largest values of southwestern trough transient heat flux occur in the northeastern corner of the study area over Minnesota and Iowa. Values decrease toward the west and southwest, where they become negative. In contrast to spring and autumn, the core of largest winter southwestern trough transient flux is split between two centers near Montana and Missouri. Zonally averaged flux values indicate that southwestern trough transient eddy heat transport is largely positive and is in contrast to the predominantly negative transport accomplished via quasi-stationary flow. Furthermore, southwestern trough daily average transient flux is much larger than that transported by non-trough transient disturbances.

Chapter 4

DISCUSSION AND SYNTHESIS

Seasonal Trough Frequency and Implications

As reported in Chapter 3, southwestern troughs exhibit a bimodal monthly distribution, with maxima during spring and autumn, a primary minimum during summer, and a secondary minimum in winter. This distribution is consistent with the middle tropospheric climatologies presented by Duquet and Spar (1957), Douglas (1974), Parker et al. (1989), and Bell and Bosart (1989). These authors found an increased tendency for closed low development over the southwestern and western United States during the spring and autumn, as well. The distribution of southwestern troughs also resembles the long-wave cyclone climatology presented by Eagleman (1980), in which he noted a higher frequency of progressive long waves over the western United States during early spring. He found that, whereas these events develop also during autumn and winter, very few long-wave cyclones occur during summer. Eagleman offered no explanation as to the cause of this climatology; however, his findings, coupled with the southwestern trough distribution revealed here, can be explained at least in part by normal seasonal changes in long wave anchoring mechanisms.

These anchoring mechanisms are numerous and often complex; however, much has been attributed to the influence of surface thermal characteristics (Namias, 1986). The geography and strength of thermal gradients influence long wave placement, zonal wind velocity, stationary wavelength, and wave number. During the spring and autumn, when land/sea thermal contrasts and other baroclinic zones are in transition, long wave features in general become more variable and circulation regimes less persistent, with more frequent episodes of wave reorientation and troughing over the southwestern United States.

I interpret the summer decrease in trough occurrence to be related to the combined influence of circumpolar vortex contraction and continental heating over the southwestern and central United States. These influences push the summer westerlies north of the southwestern states and are expressed climatologically by a mean pattern that features a broad, persistent ridge over central North America (Harman, 1990). During the summer months, the Southwest is nearly barotropic and free of travelling disturbances.

Unfortunately, seasonal changes in long wave energetics cannot be used to account for the large number of troughing events occurring during the winter, when anchoring mechanisms are normally quite strong and persistent.

Although the monthly distribution of trough events suggests that transition season dynamics are associated with southwestern trough development, other processes appear to be at work during winter and perhaps spring and autumn, as well. For example, trough development may also involve regional wave modifications over the western and eastern Pacific ocean that are enhanced by, but not totally dependent on, transition season dynamics. The wave train composites provide information as to how these modifications might operate.

Wave Train Analyses

The composite summaries indicate that those features associated with the development of southwestern troughs are seasonally consistent. These events are not the result of strongly progressive long waves, in which the southwestern trough travels eastward across the Pacific, but are associated with a series of Pacific interactions including: (1) a triggering short wave perturbation in the western Pacific; (2) slight eastward wave adjustments; (3) regional-scale wave modification in the Gulf of Alaska; and (4) downstream teleconnection.

The composite summaries indicate that autumn, winter, and spring southwestern troughs are large, open waves. This result differs slightly from expectations based on the climatologies of Douglas (1974) and Bell and Bosart (1989), who noted an increased tendency for troughs over the southwestern United States, during autumn, to be cut-off waves. My autumn composite southwestern trough arrangement reveals little evidence of cut-off characteristics. This conclusion is further supported by the longitudinal wind maxima frequency analyses over western North America, which display a distinct primary wind maximum within southwestern troughs during the autumn months. According to Douglas (1974) and Bell and Bosart (1989), cut-offs are characterized by the lack of such a well-defined wind maximum. The lack of agreement between these earlier cut-off climatologies and the results presented here may be a function of my trough selection criteria, in which restrictions were placed on wave size and strength. By imposing these requirements, I may have prevented the inclusion of the less-defined cut-off troughs. In this event, the weakest cut-offs are excluded from the trough data set and are therefore not evaluated as to their influence in the temporal, precipitation, and energy transfer climatologies. Fortunately, because this problem involves only the weakest, least-defined troughs, their exclusion should not seriously influence the overall climatological trends revealed by this study. Another explanation for the lack of cut-off distinction in the autumn composite summaries is the possibility that the weaker cut-off features are being masked in the compositing

scheme by the stronger open wave troughs. Although the lack of distinction between cut-off and open wave troughs in the wave train compositing scheme prevents an evaluation of how these features compare developmentally, it does not compromise the key objectives of the study.

The onset of troughing is first signaled by the appearance of a weakly expressed wave within the larger Asian trough, east of Japan. The development of this wave does not appear to disrupt the behavior of the larger Asian trough, nor does it appear to be teleconnectively linked with upstream changes over the Asian mainland. As this wave develops and moves eastward, 500 mb geopotential heights fall over the Bering Sea.

This perturbation is best expressed during the spring and, to a lesser extent, autumn. In winter, its characteristics are poorly defined, possibly because of the overwhelming stability of the larger Asian trough. Because the placement and amplitude of the Asian trough are ultimately linked to instability caused by land/sea temperature contrasts, it is stronger and more stable during winter.

A similar pattern emerges from the v-component genesis composites, which provide a more detailed representation of wave development and amplitude. During spring and fall, the v-component genesis patterns portray wave development in the western pacific, within the larger Asian trough.

The amplitude of this triggering wave during winter is small and, as a result, is weakly portrayed by the v-component composites.

The western Pacific triggering wave has a wavelength of approximately 30° longitude and looks to be no more than a travelling short wave. Its continued eastward movement into the Bering Sea produces a synchronous rise in pressure heights over the Gulf of Alaska. The development of ridging over the eastern Pacific is subsequently linked to height falls over the southwestern United States. The coincident increase in pressure heights over the Gulf of Alaska with wave development in the western Pacific suggests a teleconnective link. However, the amplitude and longitudinal extent of the eastern Pacific height change field far exceed those of the western Pacific wave, indicating some form of regional enhancement over the Gulf of Alaska.

Together, the Gulf of Alaska ridge and the southwestern trough possess the size and amplitude characteristics of a planetary long wave. This view is supported by the v-component composites, which depict the rapid development of additional strong northerly and southerly flow over the eastern Pacific. These additions serve to increase overall long wave number during the course of trough development.

Climatologically, wave number increases are most frequent during spring, when zonal wind speed and stationary wavelength are decreasing (Cressman, 1948). According to Cressman, such increases in wave number are accomplished through wave retrogression. During autumn, when zonal winds and stationary wavelength are increasing, wave number decreases. Although wave number increase is observed during spring trough genesis, wave number decrease does not occur during the autumn genesis period. In fact, both autumn and winter trough genesis involve wave number increases.

The trough lysis composites indicate that the increase in wave number during trough genesis is only temporary. During the winter and spring lysis periods, the composite southwestern trough slides rapidly eastward and appears to merge with a stationary trough over the middle Atlantic. This signal is far less apparent during the autumn lysis period and may once again be a function of the compositing technique, which serves to dampen the subtle features of individual trough events. Therefore, based on my lysis results, I conclude that southwestern troughs are transient features, only. This conclusion might explain the lack of agreement between expectations based on Cressman's theory and actual southwestern trough developments.

The evolution of southwestern troughing appears to be a function of several interactive factors, one of which may be transition season wave variability. The significance of the small, western Pacific triggering wave indicates that energetics throughout this region may be related to trough development, also. Although the causal dynamics supporting such a relationship are beyond the scope of the analysis, these energetics may be associated with Asian coastal activities similar to those described by Pyke (1972) and Yarnal and Diaz (1986).

Asian Coastal Energetics

Pyke (1972) noted an increase in storm activity in the southwestern United States during spring and attributed its occurrence to seasonally forced changes in cyclone tracks over the Asian coast. Pyke observed that springtime Asian cyclones more frequently move off the mainland at latitudes near 35°N, whereas in winter these disturbances moved off the coast closer to 42°N. Conservation of absolute vorticity trajectory directs these more southerly cyclones toward the northeast and produces downstream wave changes that result in storm movement through the southwestern United States. Although Pyke's discussion was limited to the development of spring storms, his views relating Asian coastal flow trajectory and storm development in the southwestern United States offer a potential link between energetics over the western Pacific and southwestern troughing.

Unfortunately, my comparison of non-trough and southwestern trough geostrophic wind characteristics along the 145°E meridian reveals little difference in the latitude and trajectory of maximum wind velocity between the two periods. Furthermore, the trough and non-trough 500 mb geopotential height fields over the western Pacific are similar and give no indication of significant differences between the two periods. A weak tendency for maximum flow to become slightly more southwesterly, similar to that described by Pyke, does occur during spring trough events; however, this tendency is very weak and does not appear to be significant.

The lack of agreement between the Asian coastal wind profile results and those expected based on Pyke's observations might be a reflection of my choice to compare composite trough and non-trough periods. The southwestern troughing profiles were originally constructed based on days during which troughing was occurring. However, the wave genesis composites indicate that western Pacific triggering activity may have already subsided by the time southwestern troughing actually becomes established. For this reason, I constructed a second set of geostrophic wind profiles using genesis day (-4) data and compared these to the non-trough profiles. Again, the results are nearly identical.

Pyke noted only a seven degree latitudinal difference between the more northerly winter Asian cyclone track and the southerly spring cyclone track. Unfortunately, the five degree grid resolution of my data might be too coarse to distinguish such subtle details. Furthermore, my choice to construct the wind profiles at 145°E may have also influenced the results. A larger longitudinal coverage might be needed to better detail actual trajectory variations.

Nevertheless, the wave train genesis composites reveal that southwestern troughing is associated with the emergence of a western Pacific triggering wave and the development of ridging in the Gulf of Alaska. These features partially match those described by Yarnal and Diaz (1986) in their analysis of winter RPNA development. Although Yarnal and Diaz used monthly mean data only, the similarities between their RPNA mechanism and those features that precede southwestern trough development suggest similar causal associations.

The key to Yarnal and Diaz's (1986) mechanism involved the movement of cold, continental air from the Asian mainland over the adjacent warmer sea surface and the transfer of energy, via an eastward moving wave, into the eastern Pacific. These processes were thought to be especially active during cold phases of the El Niño/Southern Oscillation, but not limited to these periods. Aside from the still unknown importance of ENSO phase, such a mechanism should be climatologically most active during the winter, which was the season upon which Yarnal and Diaz formulated their RPNA views, when surface thermal gradients near the Asian Coast are especially strong. In fact, the winter 500 mb geopotential height genesis composites do reveal, as expressed by lower pressure heights, a pooling of colder air into the Asian coastal region during trough development, thus providing a source of cold, continental air for a mechanism similar to that proposed by Yarnal and Diaz. In other seasons, the temperature contrast between the Asian mainland and the adjacent sea surface is not as large as during winter. Particularly during autumn, the Asian continent is still quite warm from summer heating and the land/sea temperature contrast may not be sufficient to drive the instability and momentum transfers necessary for the required downstream energy propagation envisioned by Yarnal and Diaz. However, my results indicate that southwestern troughs do occur during the autumn and exhibit many of the same developmental features as those of spring. This result suggests that cold air movement off the Asian mainland may play a less significant role in the development of southwestern troughs. The similarity between autumn southwestern trough development and that of winter and spring may be related to the seasonal averaging process used in this analysis, in which late autumn events that occur after Asian coastal thermal contrasts are reestablished mask the potentially different formative features associated with early autumn trough events. In order to address this possibility, I compared wave train genesis composites calculated with September events, only, to those calculated with October and November events. Although the September genesis composites exhibit a much weaker overall signal, western and central Pacific wave developments during this month are similar to those occurring in the later autumn months. Therefore, a strong land/sea thermal gradient in the western Pacific and the movement of Arctic air off the Asian coast are not always necessary for southwestern trough development. As noted by Yarnal and Diaz, subtle ENSO interactions over the maritime continent may be more influential in trough formation.

The objectives of this study prevent a more detailed examination of the momentum and energy transfer characteristics throughout the western Pacific during trough genesis. Because this analysis represents the first attempt to comprehensively examine southwestern troughing events, it is, as a result, broad in scope. Furthermore, such an analysis would require more detailed data in the Asian coastal and adjacent regions than was available for this study. Although the composite summaries indicate that southwestern troughing is associated with some form of wave development in the western Pacific, these developments are not consistent each season. Furthermore, the location of the triggering wave appears to be more northerly than expected based on Yarnal and Diaz's (1986) theory.

Clearly, the most consistent characteristic during southwestern trough onset is the rapid development and amplification of ridging in the Gulf of Alaska. This feature, which is similar to Douglas's (1974) "parent anticyclone" and is teleconnectively responsible for the formation of troughing over the southwestern United States, has an amplitude that far exceeds that of the upstream triggering wave. The rapid amplification of the Gulf of Alaska ridge, as compared to smaller changes in amplitude over the middle and western Pacific, may again be related to the stability of the Asian trough. Perturbations travelling through the Asian trough, which is a known long wave anchoring region at least during winter, may be subdued by the larger trough. Upon movement into the eastern Pacific, where long wave forcing mechanisms are less understood and more variable, wave features are able to undergo strong amplifications. However, the disparity in amplitude between wave activity over the western and central Pacific and that over the eastern Pacific suggests the presence of an additional source of regional-scale wave modification.

These modifications may be thermal in character and involve sea-atmosphere interactions. Studies regarding the relationship between sea surface temperature and atmospheric circulation have traditionally focused on two differing themes. The first theme involves the influence of tropical sea surface temperature on extratropical flow, such as that associated with ENSO, whereas the second is concerned with the influence of extratropical sea surface temperature on extratropical flow. Most studies have concentrated on the first of these themes.

Many authors have statistically associated episodes of PNA circulation with warm phases of ENSO, when tropical waters near the western South American coast are abnormally warm (Wright, 1978; Horel and Wallace, 1981; Trenberth and Paolino, 1981; van Loon and Madden, 1981). However, these studies note that ENSO induced wave modifications are quite variable and often accompany differing flow configurations. Hamilton (1988) theorized that tropical influences on extratropical flow are very sensitive to the magnitude and location of the tropical temperature anomaly and are therefore difficult to characterize. Through a modelling approach, Branstator (1985) demonstrated that extratropical response can vary greatly depending on the nature of the tropical temperature anomaly and that this response is especially sensitive to sea surface temperature near Indonesia.

Much less examined are the influences of extratropical sea surface temperature anomalies on middle latitude flow.

Namias (1978) attributed the unusual North American winter of 1976-77, which featured amplified ridging over western North America, to an abnormally cold pool of water in the northeastern and north-central Pacific. These observations are supported by the modelling studies of Frankignoul and Molin (1988) and Pitcher et al. (1988), who demonstrated a weak association between sea surface temperature in the North Pacific and middle tropospheric flow over North America. Although these relationships are weak and inconsistent, similar sea surface interactions may be associated with ridge development and amplification over the Gulf of Alaska during southwestern trough development.

Split Flow Associations

The occurrence of troughing over the southwestern United States is, in some cases, associated with middle tropospheric split flow over western North America. This conclusion is consistent with the views of Reitan (1974) and Parker et al. (1989), who described associations among surface cyclogenesis, upper air closed low development, and split flow over the western United States. My analyses indicate that split flow is most apparent during spring southwestern troughing events but that it occurs to a lesser extent in other seasons, as well. During these events, the high latitude wave train over western North America is very meridional and out-of-phase with the lower latitude flow. The two branches diverge over the Gulf of Alaska, where the northern stream flows northeastward into Canada and the southern branch flows southeastward toward the southwestern United States. The two branches rejoin over eastern North America. This arrangement resembles the type 8 synoptic category depicted by Barry et al. (1981), in which a surface low is centered over the southwestern United States and a strong anticyclone is situated to its north, over southern Canada.

The role of split flow in the development and maintenance of southwestern troughs is intriguing, especially in light of the potential significance of localized wave influence over the eastern Pacific. Klein (1957), in his discussion of cyclogenetic pattern in the western United States, noted that spring patterns were more variable than those during other seasons and postulated that this variability may be the influence of more frequent episodes of middle tropospheric blocking. A similar notion was formulated by Pyke (1972). The causal energetics associated with the development of blocking are poorly understood; however, climatological studies of their temporal and spatial characteristics have indicated that the high latitude regions over the Pacific, between 120°W and 180°W longitude, are preferred locations for the development of blocking (Rex, 1950a,b; Shukla and Mo, 1983). These features are very persistent and develop most often during April. Blocking episodes are sometimes characterized by the development of a high latitude ridge, with a cut-off or nearly cut-off trough to the south or southeast (Pyke, 1972). Air moving into the blocked region is split between a northern branch, around the blocking ridge, and a southern branch, through the low latitude trough.

Climatic Impacts

The climatic influence of southwestern troughing is expressed in many ways, and includes their effects on surface cyclogenesis and related meterological elements. Previous surface cyclone climatologies, such as those of Klein (1954), Reitan (1974), and Whittaker and Horn (1981), noted an increase in surface cyclogenesis throughout the western and southwestern United States during the transition seasons, especially in spring. Although upper air mechanisms were not directly examined in these earlier studies, increased spring and autumn cyclogenesis in the western United States, which is an area normally dominated by ridging and weaker dynamics, implies more frequent troughing and associated upper air divergence. During most months, cyclones develop primarily over the lee side of the Rocky mountains in Colorado and Alberta, and move in an easterly direction. This pattern is a result of the combined influence of orography, decreased stability, and the modal dominance of ridging over western North America. During the transition seasons, when the tendency for the western United States to be dominated by ridging weakens and southwestern trough occurrence increases, as noted in this study, upper level divergent mechanisms shift southwestward. As a result, cyclogenesis in the southwestern United States becomes more common during spring and autumn. Winter southwestern trough occurrence is related to cyclogenesis along the western Gulf coast, which is the location of a strong land/sea temperature gradient (Harman, 1990). During winter trough events, the upper air divergent field associated with positive vorticity advection east of the trough axis and a resultant downstream flow trajectory that places the region of highest wind speeds near the Gulf coastal baroclinic zone make this a favored cyclogenetic region.

Through surface cyclogenesis and moisture advection, southwestern troughs provide a large proportion of the total precipitation received throughout the central United States. During the twenty-four year record, in which precipitation data were available, southwestern troughs provided some regions with close to 70 percent of their monthly total precipitation. Furthermore, during southwestern trough days, many stations received 120 to 180 percent of that received during an average precipitation day.

The pattern of southwestern trough precipitation influence varies seasonally, and is a function of trough axis location, downstream flow trajectory, and moisture availability. For example, regardless of month, southwestern troughs bring little precipitation to the northwestern United States. The composite southwestern trough axis is located between 110°W and 120°W longitude during each month. Therefore, the northwestern states are west of the trough axis and under the influence of negative vorticity advection and upper air convergence. Sellers (1968), in his factor analysis of precipitation patterns in the western United States, noted a similar tendency for portions of the Northwest to be dry when areas in the Southwest are wet.

The influence of trough-derived precipitation is more difficult to establish throughout southern California, Nevada, Arizona, New Mexico, and Texas. These regions are some of the most arid in the study area and exhibit a high degree of month-to-month variability in their precipitation density and percentage of total precipitation patterns. Furthermore, considerable variability exists among individual stations within this area. Pyke (1972) noted similar precipitation variability in the southwestern United States and attributed its occurrence to regional variations in topography. With the trough axis positioned near 110°W longitude, dynamic uplift mechanisms are not lacking; therefore, the resultant patterns should be more consistent. This variability may be a partial function of the convective nature of precipitation in this region. The density calculations are especially sensitive to this problem. The availability of moisture may also contribute to pattern inconsistencies throughout the Southwest. Although composite trough location is essentially constant during all months, the source of moisture and processes by which it is advected may vary. A slight westward adjustment in tilt of an individual trough event can provide access to Pacific moisture. Furthermore, synoptic conditions over the central United States preceding trough development may influence the amount of water vapor available for the southwestern trough to operate on. If much of the moisture is removed by an antecedent event, it will take longer for the southwestern trough to reestablish a Gulf of Mexico moisture flow. As a consequence, southwestern trough precipitation production may be small in these cases.

East of the trough axis, precipitation influence becomes more clearly defined and appears to vary as a function of stationary wavelength, the latitude of maximum baroclinicity, and resultant surface storm track. During winter trough events, when the polar vortex is at its maximum southward extent and stationary wavelength is greatest, surface cyclones form along a more southerly baroclinic zone. As a result, the highest percentage of total precipitation amounts associated with southwestern troughing occurs in the south-central states, near Kansas and Oklahoma. During the transition seasons, the zone of greatest baroclinicity shifts northward and wavelengths decrease. Composite flow downstream from the trough axis is more southwesterly, pushing the precipitation influence into the north-central states.

Southwestern troughs are clearly key contributors in the precipitation climatology of the central United States. Precipitation density values indicate that southwestern events are capable of producing daily precipitation amounts much greater than average. On the longer term, year-to-year variations in the number of such events can have a significant impact on the hydrological balance of a large portion of the United States.

Of the annual and seasonal southwestern trough frequency time series, only spring possesses statistically significant trends during the forty-two year data period. Throughout the period 1975-1986, the mean annual spring southwestern trough frequency (9.6 events per year) was less than the earlier thirty year period (11.2 events per year). A similar, but not statistically significant, decrease is visible in the annual, autumn, and winter time series, also. The Wolf-Waldowitz runs test, performed on the spring trough frequency time series, further supported an underlying tendency for non-random clustering of years in which above average and below-average trough frequencies occurred. The periods 1952-1960 and 1965-1974 were characterized by above-average years, whereas the period 1961-1964 had below-average spring trough occurrence. In fact, the time series appears to exhibit a weak periodic behavior; however, spectrum analysis revealed no significant spectral peaks.

Although my precipitation analysis considered southwestern trough precipitation influence west of the Mississippi River, only, southwestern trough-derived precipitation may have a strong influence on the hydrological budget of the eastern states, as well. Because of the possible relationships between southwestern trough precipitation and other environmental and socio-economic factors, such as Great Lake water level, I performed an additional analysis in which the Lake Michigan annual water level (LaMoe, 1987) was examined to determine whether the annual or seasonal frequency of southwestern trough events can explain a significant proportion of lake level variability. A stepwise multiple regression equation was constructed in which annual lake level was the dependent variable. The independent variables consisted of the annual and seasonal frequencies of southwestern trough events. Because lake level measurements contain a strong two year autocorrelation, cumulative seasonal and annual southwestern trough frequencies were included in the regression model, also. Therefore, the equation was able to account for the possibility that lake level in any particular year might be a function of the cumulative number of troughing events during the antecedent years.

Results indicate that only cumulative autumn and winter southwestern trough events, during the current year and the preceding year, account for a significant proportion of the variance. However, an r-squared value of .264 indicates that this relationship is quite weak. The individual correlation coefficient is strongest for the autumn events (r=.441). The cumulative winter events explain a much smaller proportion of the variance.

Several factors might account for the lack of strong relationship between southwestern trough frequency and Lake Michigan water level. A key problem is the statistical modelling of the lake level time series. The lake level data represent average annual values and carry with them a significant serial correlation. Not only are the lake levels during a given year responding to current inputs and outputs, but they also reflect the conditions of preceding years. A simple regression equation, such as I have performed, cannot adequately capture the complexity of the actual system.

Nonetheless, the equation does indicate a weak causal relationship between autumn trough events and Lake Michigan water level. Although the Great Lake catchment basin is largely outside of my precipitation study region, precipitation density and percent of total precipitation patterns offer some explanation for these results. During spring, the region of greatest southwestern trough precipitation influence is located over the north-central United States. Therefore, these regions are likely to experience the higher precipitation amounts during springs with more frequent trough events. During autumn, the region of maximum trough influence shifts toward the southeast, closer to the Great Lakes area. As a consequence, the Great Lakes receive higher moisture inputs during autumns in which higher frequencies of troughing occur. Furthermore, because autumn is normally a dry period in the upper middle western states, such increases in moisture might have a more significant impact on the regional hydrologic balance than during other seasons.

Eddy Heat Flux Climatology

A large proportion of the northward transfer of sensible energy in the middle latitudes is accomplished by quasi-stationary and transient eddies (van Loon, 1979). The individual significance of these eddies varies seasonally and latitudinally. Zonal averages presented in past climatologies indicate that total eddy heat flux, which is the combination of quasi-stationary and transient eddies, is greatest during winter. Above 55°N latitude, contributions by each eddy type are similar; however, below 55°N, transient eddies are the dominant form of eddy sensible heat transfer (van Loon, 1979).

Interpreting the results of this climatology in light of past eddy transfer climatologies is difficult. These results are regionally specific, whereas earlier studies were not. Because the western United States is modally dominated by broad ridging, with negative v-component winds and relatively warm middle tropospheric temperatures, zonally averaged quasi-stationary eddy heat flux values in this region are much different from those based on total hemispheric data. Whereas zonally averaged quasi-stationary eddy flux values calculated over the entire hemisphere are essentially positive at all latitudes, quasi-stationary flux in the western United States is largely negative.

Although my energy transfer calculations use 500 mb data and do not represent the level at which maximum heat transfer usually occurs (850 mb - 700 mb), the general pattern of the resultant values should be similar at this higher level. Compared to sensible heat transported by quasi-stationary eddies, non-trough and southwestern trough transient eddy flux is much larger during all seasons. As expected, quasi-stationary flux values throughout the study region are mostly negative in all seasons; however, the pattern and magnitude of flux do appear to vary as a function of seasonally-induced changes in flow meridionality and ridge location. The weakly defined quasi-stationary eddy heat flux pattern during autumn is a response to weak dynamics throughout the study area. In early autumn, geopotential height gradient in the Southwest is still quite weak. In contrast, during winter, when wind speed and wave amplitude are greatest, quasi-stationary eddy flux increases negatively through the entire study area. The weaker spring pattern again reflects decreased dynamics and increased zonality. The emergence of positive flux values throughout southern California, Nevada, Oregon, and Washington in spring may be a response to a seasonally induced eastward realignment in the modal ridge position.

The regional patterns and magnitude of the flux values indicate that, in relative terms, transient eddies are far more efficient mechanisms of northward sensible heat transport. Southwestern trough transient eddy heat flux is especially large and reflects the strongly meridional flow and large latitudinal temperature departures associated with these events. During spring and autumn, the overall transient flux patterns are similar for both non-trough and trough periods. The largest values occur in the northeastern corner of the study area, where positive v-components are coupled with large positive temperature departures. During winter, the southwestern trough transient eddy flux values exhibit a slightly different pattern. Whereas the largest flux values are found in the northeast corner of the study area in spring and autumn, the largest winter values are split into two separate centers over the north-central and south-eastern portions of the region. Values over Montana and Wyoming are in excess of 24 °C m/s and reflect large negative latitudinal temperature gradients and moderately weak negative v-component winds. Over Arkansas, values are also large but in this case reflect a large positive v-component wind and a positive latitudinal temperature departure.

Addressing the Research Questions

In Chapter 1, four research questions were posed regarding the temporal climatology, teleconnective associations, and climatic impacts of southwestern troughing. The temporal distribution of southwestern troughs presented in this study generally matches expectations based on earlier middle tropospheric climatologies. Most interesting is the bimodal monthly distribution, with maxima during the spring and autumn. This distribution suggests causal mechanisms that are specific to the transition seasons, such as changes in zonal wind speed, wave movement, and wave number. Although such factors contribute to the dominance of southwestern events during spring and autumn, a large number of troughs occur during the winter, also, implying that additional factors may be leading to their development.

The seasonal wave train composites, Asian coastal analyses, and split flow analyses indicate that trough development, although seasonally consistent, is quite complex and involves an interaction of several processes. Clearly, the most dominant feature that emerges from the trough genesis analyses is the development and amplification of ridging over the Gulf of Alaska. Other features, such as the short wave triggering perturbation in the western Pacific that may provide a source of energy for wave amplification over the Gulf of Alaska, and eastward wave train movement, contribute to trough development. However, wave amplification over the eastern Pacific and downstream teleconnection provide the strongest signal during trough development and serve as a telltale indicator of trough onset for forecasters. Furthermore, the importance of regional wave processes over the Gulf of Alaska may be enhanced by episodes of blocking, also, especially during spring.

The climatological significance of southwestern troughing is illustrated by its influence on precipitation and energy transfer processes. Southwestern events provide large proportions of the total precipitation throughout much of the central and west-central United States. In addition, during these events, average precipitation amounts far exceed those occurring during average precipitation days, stressing the dynamic intensity and moisture advective capacity of these systems. The vigor of southwestern troughs can be linked to their large amplitude and consequent ability to transport large quantities of eddy sensible heat. As compared to other transient eddies and quasi-stationary eddies, southwestern trough transient eddy heat flux is much larger.

Chapter 5

SUMMARY AND CONCLUSIONS

Summary

This study comprises the first extensive climatological evaluation of regional-scale troughing over the southwestern United States and provides information regarding the temporal distribution of these events, the sequence of associated wave changes throughout other parts of the westerlies during trough development, and the influence of these events on precipitation and meridional sensible heat flux. Based on the resultant climatology, wave train composites, split flow analyses, precipitation analyses, and energy transfer assessments, this study reveals that:

1. Southwestern troughs occur most frequently during the spring (April-May) and the late autumn months (October-November). Somewhat fewer events occur during winter and very few southwestern troughs develop during July and August. The year-to-year frequency of annual and seasonal events is quite variable; however, the time series of spring events exhibits a small degree of statistically significant non-random clustering behavior. This

clustering is particularly noteworthy between 1975-1987 when the mean number of spring southwestern events was smaller than that of the earlier period of record. Because of the strong influence southwestern troughs have on the precipitation climatology of the central and west-central states, changes in the seasonal frequency of these events undoubtedly have significant impacts on related meteorological and socio-economical factors.

2. The development of southwestern troughing, although consistent for each season, is complex. During trough onset, wave changes over the Atlantic Ocean, Europe, and Asia are generally weak, with most occurring over the Pacific Ocean and North America. As implied by the increased frequency of troughing during spring and autumn, trough development appears to be enhanced by, but not dependent on, transition season wave dynamics. Troughing appears to be a teleconnective response to ridge development over the Gulf of Alaska, which in itself may be a response to other factors. These factors include: (1) the development and eastward movement of a triggering short wave in the western and central Pacific; (2) localized amplification in the eastern Pacific; and (3) split flow over western North America. The development of a western Pacific triggering short wave fits the conceptual modal for winter RPNA development posed by Yarnal and Diaz (1986). However, the formation of southwestern troughs during the

early autumn, when baroclinic instability over the maritime continent and southern Asian coast is small, indicates that energetics in this region may play only a small role in trough development. Furthermore, these results indicate that associated energetics near Asia are concentrated over the northwestern Pacific and appear to be to far north to linked with instability over the south Asian coast. The association between split flow over western North America and southwestern trough development is most apparent during spring and may be related to blocked flow over the north Pacific. As ridging becomes established over the Gulf of Alaska and heights fall sharply over the southwestern United States, overall wave number increases; however, the lysis composites indicate that the wave number increase is only temporary.

3. Southwestern troughs, through their influence on surface cyclogenesis and moisture advection, provide much of the west-central United States with large proportions of their monthly precipitation totals. In some cases, southwestern trough-derived precipitation provides nearly 70 percent of the total. Furthermore, the southwestern trough average daily precipitation amount is often in excess of 100 percent of that occurring on an average precipitation day. The pattern of trough influence changes seasonally and is largely a function of flow trajectory downstream from the trough axis. During winter, when

stationary wavelength is at it maximum, flow east of the trough axis stretches through the south-central and Gulf states. As a result, winter southwestern trough precipitation influence is greatest in these areas. During the transition seasons, stationary wavelength shortens and the zone of greatest trough influence shifts northward into the north-central states.

4. As compared to the average daily meridional sensible heat transported by quasi-stationary eddies and non-southwestern trough transient eddies, southwestern trough transient eddy heat flux is much larger. Whereas quasi-stationary flux over the western United States is predominantly negative, transient flux is largely positive, maximizing over the northeastern portion of the study area. The large values of eddy sensible heat transfer associated with southwestern troughs is related to the highly meridional character of these events. Strong v-component geostrophic winds, coupled with large latitudinal temperature departures, result in significant transfers of energy.

Conclusions and Recommendations

By virtue of their influence on surface cyclogenesis, moisture advection, precipitation, and energy transfer, southwestern troughs are of considerable meteorological and socio-economical interest. The influence of southwestern troughing on the climate of North America is directly linked to their geography. These events not only differ significantly from those associated with the modal upper air configuration, which by itself would result in unusual weather conditions if persistent over the long term, but they also are capable of generating large temperature and moisture gradients through their access to Gulf of Mexico heat and moisture.

Hawes and Colucci (1986) and Parker et al. (1989) noted a deficiency in the ability of National Meteorological Center models to accurately predict the timing and amplitude of southwestern troughs. The impact of such error can be especially significant when heavy precipitation or severe weather are produced by these systems. Modelers and forecasters can profit by the increased knowledge of the temporal and spatial climatology of southwestern troughs revealed by this analysis, as such knowledge provides direction for future research and modelling efforts.

During trough genesis, associated wave train processes appear to be focused over the Pacific, with very little wave activity over the Atlantic, Europe, and Asia. Unfortunately, data coverage is sparse throughout this region, placing a heavy burden on spatial interpolation. Because most interpolation schemes are initiated using numerically generated information in the data sparse areas, they may not always capture or adequately define those features that are critical to trough development.

The composite results revealed by this study focus the primary southwestern trough developmental impetus on three factors. These are: (1) the development and eastward movement of a western Pacific short wave; (2) the rapid development and amplification of ridging over the Gulf of Alaska; and (3) transition season long wave variability. Especially important from a forecaster's viewpoint is the degree to which ridging over the Gulf of Alaska amplifies during trough development, as its amplitude is strongly related to the strength of pressure height fall in the southwestern trough. The failure of NMC models to accurately predict southwestern trough amplitude may be a reflection of their inability to handle the energy characteristics of the Gulf of Alaska ridge.

The rapid development and amplification of ridging over the Eastern Pacific, coupled with inability of NMC models to adequately assess the strength of this feature, indicate a need to examine the cause of this amplification further. Some form of instability near the Asian coast, as Yarnal and Diaz (1986) suggested, might provide one possible source of momentum and energy transfer. As shown by the composite results, such a disturbance does occur in association with trough development and is especially strong during spring. Although this triggering disturbance appears to be most directly related to the initiation of a slightly progressive Pacific wave train, a condition needed for trough development and probably enhanced by transition season variability, its influence on wave addition and amplification over the eastern Pacific needs to be further examined.

Greater attention must be given to localized energy inputs near the Gulf of Alaska. The wave train composites clearly indicate that the wavelength and strength of the Gulf of Alaska ridge far exceed any upstream teleconnection. The influence of sea surface temperature offers a potential source of localized energy. Several authors have noted a positive association between warm equatorial eastern Pacific sea surface temperatures and PNA circulation modes (Wright, 1978; Horel and Wallace, 1981; Trenberth and Paolino, 1981; van Loon and Madden, 1981). Yarnal and Diaz (1986) envisioned a link between RPNA flow and cold phases of ENSO. Although most of the influence that tropical sea surface temperature exerts on middle latitude flow is thought to occur during winter only, when the westerlies reach their maximum southward expansion, similar sea surface temperature relationships might occur during other seasons, as well, and should be further investigated (Horel and Wallace, 1981).

Another form of regional wave modification over the eastern Pacific is blocking. During the development of some southwestern troughs, especially in spring, the meridional split flow tendencies over the eastern Pacific and western North America suggest that blocking might be involved. By its perturbing, and often persistent, influence on the westerly wave train, blocking can result in unusual weather conditions over North America. Unfortunately, regional wave modifications caused by blocking are poorly understood, difficult to objectively characterize, and poorly handled by numerical models (Quiroz, 1987).

The non-random behavior exhibited by the southwestern trough time series is significant in terms of its influence on surface climate change. Climate change studies have traditionally focused on climatic trends revealed by temporal and spatial averages using measured variables such as temperature and precipitation. Even though these studies do provide indication of climate change, they offer little information regarding associated changes in the controlling elements, such as the frequency and nature of travelling disturbances. Because of the influence that southwestern troughs have on the precipitation and energy transfer budgets of the central and western United States, an understanding of how the frequency of these events has varied during the data record provides valuable insight into the relationship between middle tropospheric phenomena and surface impact. With this information, global climate model output, which can be used to assess changes in the future frequency of southwestern troughs, can be better interpreted in terms of actual surface climate response. These interpretations are important when directed at the social and economic implications of southwestern troughs, especially as they relate to agriculture, water supply, and shipping.

Based on these conclusions, future research should concentrate on four questions. These are:

1. To what degree are air-sea interactions related to the development of southwestern troughing? This question should focus on the influences of tropical and extratropical sea surface interactions, with particular emphasis in the North Pacific. Although modelers have demonstrated a link between colder water surfaces in the central and northern Pacific and PNA flow, the association is weak and cause and effect questions are yet to be answered. Closer attention needs to be given to the influence of sea surface interactions near Indonesia, also. Branstator (1985) recognized the importance of air-sea interaction in this region as an influence on extratropical flow. Furthermore, sea surface interactions within this region may offer greater insight into the RPNA conceptual model proposed by Yarnal and Diaz (1986).

2. What influence do cold air outbreaks over the Asian coast have on southwestern trough development? As these

cold air masses move over a warmer water surface, enhanced convection might produce downstream adjustments in wave location and amplitude. Furthermore, these events, which are most common during winter, might provide a southwestern trough developmental mechanism during winter that differs from that of spring and autumn.

3. How is blocking related to trough development over the southwestern United States? Flow distortion can be significant and quite persistent during blocked periods. The climatological tendency for blocking to develop over the eastern Pacific during spring and its ability to produce low latitude cut-off or open troughs may be related to some cases of southwestern trough development.

4. How would climate change, as portrayed by general circulation model output, influence the frequency of southwestern troughing? Furthermore, how might these changes interact with the surface climate and related socio-economic functions of the United States? Southwestern troughs play an important role in the precipitation climatology of the central United States. Any increase or decrease in their future frequency can produce significant agricultural and social impacts.

LIST OF REFERENCES

LIST OF REFERENCES

Barnston, A.G. and R.E. Livezey, 1987. "Classification, seasonality and persistence of low-frequency atmospheric circulation patterns." Monthly Weather Review 115:1083-1126.

Barry, R.G., G. Kiladis, and R.S. Bradley, 1981."Synoptic climatology of the western United States in relation to climatic fluctuations during the twentieth century." Journal of Climatology 1:97-113.

Bell, G.D. and L.F. Bosart, 1989. "A 15-year climatology of Northern Hemisphere 500 mb closed cyclone and anticyclone centers." Monthly Weather Review 117:2142-2163.

Bolin, B., 1950. "On the influence of the Earth's orography on the westerlies." Tellus 2:184-195.

Branstator, G., 1985. "Analysis of general circulation model sea-surface temperature anomaly simulations using a linear model. Part I: forced solutions." Journal of the Atmospheric Sciences 42:2225-2241.

Carleton, A.M., 1988. "Meridional transport of eddy sensible heat in winters marked by extremes of the North Atlantic Oscillation, 1948/49-1979/1980." Journal of Climate 1:212-223.

Colucci, S.J., 1976. "Winter cyclone frequencies over the eastern United States and adjacent western Atlantic." Bulletin of the American Meteorological Society 57:548-553.

Cressman, G.P., 1948. "On the forecasting of long waves in the upper westerlies." Journal of Meteorology 5:44-57.

________., 1959. "An operational objective analysis system." Monthly Weather Review 87:367-374.

Dole, R.M., 1986. "Persistent anomalies of the extratropical Northern Hemisphere wintertime circulation structure." Monthly Weather Review 114:178-207.

Douglas, A.V., 1974. "Cutoff lows in the southwestern United States and their effects on the precipitation of this region." Final Report on Project Entitled "Dendroclimatic History of the United States," Department of Commerce Contract 1-35241-No.3, Laboratory of Tree-Ring Research, University of Arizona.

Duquet, R.T and J. Spar, 1957. "Some statistical characteristics of cyclones at 500 millibars." Journal of Meteorology 14:251-260.

Eagleman, J.R., 1980. Meteorology: the atmosphere in action. New York: D. Van Nostrand Co.

Frankignoul, C. and A. Molin, 1988. "Response of the GISS general circulation model to a midlatitude sea surface temperature anomaly in the North Pacific." Journal of the Atmospheric Sciences 45:95-108.

Haines, D.A. and J. Winston, 1963. "Monthly mean values and spatial distribution of meridional transport of sensible heat." Monthly Weather Review 91:319-328.

Hamilton, K., 1988. "A detailed examination of the extratropical response to tropical El Nino/Southern Oscillation events." Journal of Climatology 8:67-86.

Harman, J.R., 1990. Synoptic climatology of the westerlies: process and patterns submitted to the Association of American Geographers Resource Paper Series.

Hawes, J.T. and S.J. Colucci, 1986. "An examination of 500 mb cyclones and anticyclones in NMC prediction models." Monthly Weather Review 14: 2163-2175.

Hoard, D.E. and J.T. Lee, 1986. "Synoptic classification of a ten-year record of 500 mb weather maps for the western United States." Meteorology and Atmospheric Physics 35:96-102.

Horel, J.D. and J.M. Wallace, 1981. "Planetary-scale atmospheric phenomena associated with the Southern Oscillation." Monthly Weather Review 109:813-829.

Hosler, C.L. and L.A. Gamage, 1956. "Cyclone frequencies in the United States for the period 1905-1954." Monthly Weather Review 84:388-390.

Jenne, R., 1975. "Data sets for meteorological research." Atmospheric technology division, National Center for Atmospheric Research, Boulder Colorado, Technical note 111.

Joung, C.H. and M.H. Hitchman, 1982. "On the role of successive downstream development of East Asian polar air outbreaks." Monthly Weather Review 110:1224-1237.

Klein, W.H., 1957 "Principal tracks and mean frequencies of cyclones and anticyclones in the Northern Hemisphere." Research Paper No. 40, U.S. Weather Bureau, U.S. Government Printing Office, Washington, DC.

Klein, W.H. and J.S. Winston, 1958. "Geographical frequency of troughs and ridges on mean 700 mb charts." Monthly Weather Review 86:344-358.

Knox, J.L. and J.E. Hay, 1984. "Blocking signatures in the Northern Hemisphere: rational and identification. Atmosphere-Ocean 22:36-47.

Knox, J.L., K. Higuchi, A. Shabbar, and N.E. Sargent, 1988. "Secular variation of Northern Hemisphere 50 kPa geopotential Height." Journal of Climate 1:500-511.

LaMoe, J.P., 1987. "Nearshore wave energy and bluff recession rates along Lake Michigan's southeastern shorezone." Masters Thesis, Michigan State University Geography Department.

Lau, N. and K. Lau, 1984. "The structure and energetics of midlatitude disturbances accompanying cold-air outbreaks over East Asia." Monthly Weather Review 112:1309-1327.

Lahey, J.F., R.A Bryson, E.W. Wahl, L.H. Horn, and V.P. Henderson, 1958. Atlas of 500 mb wind characteristics for the Northern Hemisphere. University of Wisc. Press.

Namias, J., 1978. "Multiple causes of the North American abnormal winter 1976-77." Monthly Weather Review 106:279-295.

______, J., 1986. "Persistence of flow patterns over North America and adjacent ocean sectors." Monthly Weather Review 114:1368-1383.

North, G.R., F.R. Moeng, T.L. Bell, and R.F. Cahalan, 1982. "The latitude dependence of the variance of zonally averaged quantities." Monthly Weather Review 110:319-326.

O'connor, J.F., 1969. "Hemispheric teleconnections of mean circulation anomalies at 700 millibars." U.S. Weather Bureau Technical Report No. 10, U.S. Department of Commerce, Silver Spring, Maryland.

_______., 1961. "Mean circulation patterns based on 12 years of recent northern hemispheric data." Monthly Weather Review 89:211-227.

Palmen, E. and C.W. Newton, 1969. Atmospheric circulation systems: their structure and physical interpretation Academic Press: New York.

Parker, S.S., J.T. Hawes, S.J. Colucci, and B.P. Hayden, 1989. "Climatology of 500 mb cyclones and anticyclones, 1950-85." Monthly Weather Review 117:558-570.

Petterssen, S., 1941. "Cyclogenesis over southeastern United States and the Atlantic coast." Bulletin of the American Meteorological Society 22:269-270.

Pitcher, E.J., M.L. Blackmon, G.T. Bates, and S. Monoz, 1988. "The effect of North Pacific sea surface temperature anomalies on the January climate of a general circulation model." Journal of the Atmospheric Sciences 45:173-188.

Pyke, C., 1972. "Some meteorological aspects of the seasonal distribution of precipitation in the western United States and Baja California." University of California Water Resources Center Contribution No. 139.

Quiroz, R.S., 1987. "Traveling waves and regional transitions in blocking activity in the Northern Hemisphere." Monthly Weather Review 115:919-935.

Reinhold, B.B. and R.T. Pierrehumbert, 1982. "Dynamics of weather regimes: quasi-stationary waves and blocking." Monthly Weather Review 110:1105-1145.

Reitan, C.H., 1974. "Frequencies of cyclones and cyclogenesis for North America, 1951-1970." Monthly Weather Review 102:861-868.

Rex, D.F., 1950a. "Blocking action in the middle troposphere and its effects upon regional climate. I. An aerological study of blocking action." Tellus 2:196-211.

________., 1950b. "Blocking action in the middle troposphere and its effects upon regional climate. II. The climatology of blocking action." Tellus 2:275-301.

Rossby, C.G. et al., 1939. "Relationships between variations in the intensity of the zonal circulation of the atmosphere and the displacement of semi-permanent centers of action." Journal of Marine Research 2:38-55.

Sands, R.D., 1966. "A feature-of-circulation approach to synoptic climatology applied to western United States." Publications in Geography, Technical Paper No. 66-2, Department of Geography, University of Denver.

Sellers, W., 1968. "Climatology of monthly precipitation patterns in the western United States, 1931-1966." Monthly Weather Review 96:585-595.

Shukla, J. and K.C. Mo, 1983. "Seasonal and geographical variations of blocking." Monthly Weather Review 111:388-402.

Stark, L.P., 1965. "Positions of monthly mean troughs and ridges in the Northern Hemisphere, 1949-1963." Monthly Weather Review 93:705-720.

Treidl, R.A., E.C. Birch, and P. Sajecki, 1981. "Blocking action in the Northern Hemisphere: a climatological study." Atmosphere-Ocean 19:1-23.

Trenberth, K.E. and D.A. Paolino, 1981. "The northern hemisphere sea level pressure data set: trends, errors, and discontinuities." Monthly Weather Review 108:858-872.

van Loon, H., 1979. "The association between latitudinal temperature gradient and eddy transport. Part I: Transport of sensible heat in winter." Monthly Weather Review 107:525-534.

van Loon, H. and R.A. Madden, 1981. "The Southern Oscillation I: global associations with pressure and temperature in northern winter." Monthly Weather Review 109:1150-1162.

van Loon, H and J. Williams, 1980. "The association between latitudinal temperature gradient and eddy transport. Part II: Relationships between sensible heat transport by stationary waves and wind, pressure and temperature." Monthly weather Review 108:604-614.

Wahl, E.W., 1972. "Climatological study of the large-scale circulation in the Northern Hemisphere." Monthly Weather Review 100:553-564.

Winkler, J.A., 1988. "Climatological characteristics of summertime extreme rainstorms in Minnesota." Annals of the Association of American Geographers 78:57-73.

White, G.H., 1980. "Skewness, kurtosis, and extreme values of Northern Hemisphere Geopotential Heights." Monthly Weather Review 108:1446-1455.

Whittaker, L.M. and L.H. Horn, 1981. "Geographical and seasonal distribution of North American Cyclogenesis, 1958-1977." Monthly Weather Review 109:2312-2322.

Wright, P.B., 1978. "The Southern Oscillation." in Pittock, a.b., et al. (eds) Climate change and variability Cambridge University Press: London, pp. 180-184.

Yarnal, B. and Diaz, H.F., 1986. "Relationships between extremes of the Southern Oscillation and winter climate of the Anglo-American Pacific coast. Journal of Climatology 6:197-219.

Yarnal, B. and Leathers, D.J., 1988. "Relationships between interdecadal and interannual climatic variations and their effect on Pennsylvania climate. Annals of the Association of American Geographers 78:624-641.

Zishka, K.M. and P.J. Smith, 1980. "The climatology of cyclones and anticyclones over North America and surrounding ocean environs for January and July, 1950-77." Monthly Weather Review 108:387-401.