# A SYNOPTIC ANALYSIS OF MT. McKINLEY WINDSTORMS

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## SUMMARY

Multi-day Mt. McKinley wind storms are investigated using upper air and reanalysis data sets, as well as select surface observations. After a brief historical review, three wind storm cases are presented. These three wind storms highlight the life-threatening conditions climbers occasionally have to contend with while on the mountain. Using upper air data from the years 1958-1997, and limiting the time period between 15 April and 30 June (climbing season), a climatology of Mt. McKinley windstorms is developed. A total of 26 cases were selected for analysis based on a minimum 500 mb wind speed of 17 $ms^{-1}$ and a duration of at least 60 hours. Synoptic analysis of these 26 cases shows the importance of quasi-stationary ridges located over the Gulf of Alaska and northwestern Canada. These ridges slow the movement of eastward propagating disturbances, as well as help produce very large gradients in the height field. Due to the passage of jet streaks up the west side or over the top of quasi-stationary ridges, free atmospheric and surface wind speeds vary considerably during the majority of Mt McKinley wind storms. Frequency analysis of these storms indicates a steady decrease in occurrence from mid-April through June, in large part due to the seasonal weakening of the polar jet stream over the North Pacific.

## 1. Introduction

Mt McKinley* (6194 m) is unique among the world's great mountains not because it is North America's highest point, or because of its 4500 m of relief; Mt. McKinley's uniqueness is derived from its geographic position at 63° N. This high latitude location translates into colder temperatures then would be experienced at the same elevation on a mid-latitude mountain. More importantly, due to the lowering of the tropopause with increasing latitude, climbers on the upper slopes of Mt. McKinley are at times in close proximity to the polar/arctic jet stream(s). With some 1100 climbers attempting to climb the mountain during the mid-April through late June climbing season, prolonged periods of high winds or fresh snow can create major loss of life. This is especially true when 300 to 400 climbers are on the mountain during the late May-early June period.

The mid-April through June climbing season corresponds to months in which the surrounding lowlands experience the driest and most cloud free weather of the year. At higher elevations however, anytime of the year when relatively moist air is advected from the Bering Sea or the Gulf of Alaska, precipitation in some form is probable. Virtually all precipitation that falls above 3000 m, irregardless of the time of year, is in the form of snow. It is common during the climbing season for the mountain to receive several major snow storms, depositing as much as a meter of snow per storm at lower elevations. Deep snow is only one consideration

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* The mountain is still officially called Mt. McKinley, although the park was renamed Denali National Park in 1985. However, many people refer to the mountain by its Athabascan name: Denali- which means "the great one."

that climbers have to contend with. Strong winds are the principal concern due to their intensity, duration and frequency. Poor visibility, caused by blowing snow or by clouds that envelop the mountain, is an additional concern to mountaineers.

Nearly 100 people have lost their lives on Mt. McKinley since people started to climb the mountain at the beginning of the 20th century. It is interesting to note that a significant number of those deaths can in some way be attributed to extreme weather (strong winds, deep snow, low visibility). Climbing literature is replete with epic tales of life and death on Mt McKinley. In *Minus 148°* , Davidson (1969) gives an account of the first winter ascent of the mountain. Shortly after reaching the summit, during the first week of March 1967, this expedition was hit with a five day storm that pinned them to the upper mountain. Wind gusts were estimated well above 45 $ms^{-1}$ (100 mph), combined with ambient temperatures near -40° C (-40° F), inspiring the wind chilling title.

During July of 1967 a large 12 man expedition climbed the mountain via the Muldrow Glacier route (northeast side). The first summit team reached the top of the mountain, and had returned to its camp located at 4573 m by the afternoon of 17 July. During the early hours of 18 July, while the second summit team approached the apex of North America, a major weather system enveloped the mountain. This storm brought high winds and fresh snow that continued until 22 July. This initial period of stormy weather was followed by three days of intermittent high winds and fresh snow. The seven members of the second summit team were never seen alive again. This expedition inspired two books: *White Winds* (Wilcox, 1981) and *The Hall of the Mountain King* (Synder, 1973).

Between 11-18 May 1992 another major storm lashed the mountain with high winds and large amounts of fresh snow, causing most of the climbing to be suspended. Kocour recounts this storm in her book: *Facing the Extreme* (1998). In reality, between 11-31 May the mountain was hit with a series of storms, with short periods of reasonably good climbing weather in between. The death toll for the May 1992 storms was 11, although several of these deaths were not weather related. Frequently climbers, wanting to take advantage of the improving conditions make a summit attempt during one of these windows of opportunity, only to be caught high on the mountain as the next storm develops.

Since 1983 the National Weather Service's Fairbanks forecast office has been providing a general synoptic weather forecast for Denali National Park. The Park Service routinely relays these forecasts to the climbing ranger camp located at 4268 m as well as to base camp (2134 m). These daily forecasts are made available to climbers who are on the West Buttress route. The Fairbanks Forecast Office in return receives daily weather reports (during the climbing season) from the ranger's camp, as well as from base camp. The data from the camps consists of estimates of wind speed and direction, max/min temperatures, snowfall and current weather. These observations were initiated during the 1983 climbing season, and have continued during subsequent climbing seasons. Unfortunately the data from the mountain is sporadic, as well as subjective, and therefore can only be used in a qualitative fashion.

The goal of this paper is to answer the following three questions: 1) What synoptic pattern(s) are responsible for Mt. McKinley wind storms? 2) What role does the jet stream play? and; 3) What are the frequency and duration of these events? The outline of this paper is as follows: Three well documented case studies are presented in section 2, while a synoptic climatology of 26 wind storm is discussed in section 3. The frequency of occurrence of Mt. McKinley wind storms is presented in section 4. Section 5 consists of a discussion on quasi-stationary ridges and the movement of jet streaks through these ridges, while the results of this paper are summarized in section 6.

**2. Case Studies**

Our wind storm analysis relies on upper air data from McGrath (MCG), Fairbanks (FAI), and Anchorage(ANC), the twice-daily NCEP/NCAR reanalysis data set, as well as observations from climbers who were on the mountain at the time. The location of the three primary upper air sites surrounding Mt. McKinley as well as several additional upper air stations are displayed in Fig.1.

*2.1 1-6 March 1967*

The first winter ascent of Mt. McKinley occurred in late February of 1967. The team made it to the summit on 29 February, but had the misfortune of starting their decent in a developing wind storm. Half of the team was able to make it back to their high camp at 5240 m, while the second half of the team were trapped high on the mountain, in the vicinity of Denali Pass (5549 m). Fig. 2 shows 500 mb and 200 mb geopotential heights (referred to as heights) for 12 UTC on 2 March and 4 March. The high amplitude ridge over the Gulf of Alaska, extends from the surface into the lower stratosphere. Between 1-3 March the members of the climbing team who were pinned down near Denali Pass, estimated wind speeds on the order of 50 $ms^{-1}$. At 00 UTC 2 March, sounding data indicates that free atmospheric wind speeds near Mt. McKinley were 25 $ms^{-1}$ at 500 mb (5400 m) and 42 $ms^{-1}$ at 400 mb (7000 m).

By 00 UTC 2 March the ridge had moved into the eastern Gulf of Alaska, allowing a trough in the Bering Sea to move northeast over the top of the ridge and advect considerable amounts of moisture into the state. Precipitation was widespread over western and central Alaska. At Talkeetna for example, 5 cm of water equivalent was measured between 2-4 March, while McGrath received 2.3 cm over the same period.

Despite the strong winds and periods of snow, on 3 March the group that had been at high camp were able to struggle down to a new camp at 4390 m, while the other members of the team remained trapped at Denali Pass. The climbers at 4390 m noted that the wind direction was variable as they made their descent. Since the geostrophic winds were from the southwest, this report of variable wind direction is due to local mountain effects. Fig. 3 shows 500 mb wind speeds at 00 UTC 4 March, note the elongated jet streak centered at the top of the ridge. The 00 UTC FAI upper air data indicates winds of 48 $ms^{-1}$ at 500 mb and 86 $ms^{-1}$ at 400 mb. In Figure 4, 200 mb temperatures valid at 00 UTC 4 March are displayed. The large temperature gradient over Alaska and to the northwest is noteworthy.

By 00 UTC 6 March the ridge over the Alaska-Canada border had moved far enough east to allow a deep trough to develop in the southern Bering Sea (not shown). This weakened the height gradient on the west side of the ridge, effectively terminating the high wind event on Mt. McKinley. The climbers who had been stranded near Denali Pass were able to move down the mountain during the day of 6 March.

*2.2 19-26 July 1967*

At the beginning of this event a weak cut-off low was positioned over the northern Bering Sea, with a ridge of high pressure to the south of the Aleutian Islands (not shown). In addition, warm air at the 200 mb level was located over northwest Alaska, with cooler air over the Aleutian Islands (not shown). Over the course of the next three days this trough-ridge pattern slowly moved eastward as depicted in Fig.5. By 12 UTC 22 July the flow pattern became zonal (Figure 5b) and remained so for the next 72 hours. On the mountain, Snyder (1973) reported that at the expedition's camp (4575 m), winds reached maximum intensity on 21 July. He estimated sustained speeds of 25-30 $ms^{-1}$, and gusts of 40-45 $ms^{-1}$ at that time. Fig.6 shows the 500 mb reanalysis winds at 12 UTC 22 July. The areas of strongest winds were located to the east of the Bering Sea low, and to the south of the Arctic trough. As seen in Fig.7, cold 200 mb air was located over the Gulf of Alaska with warm air north of the Brooks Range (>70°N). The north-south 200 mb temperature gradient across the state at this time was on the order of 2.2° C $(100\ km)^{-1}$.

Between 22-25 July, the ridge and associated temperature pattern continued to move slowly eastward, allowing a developing low over Kamchatka to move into western Alaska on 26 July (Figure 5d). This change in flow pattern signaled the end of high winds over the interior of Alaska, as energy for this new system was concentrated over the Alaska Peninsula.

Due to the presence of the low in the southern Bering Sea and the trough in the Arctic during this event, considerable amounts of moisture was advected into the state with the southwesterly and westerly flow. In the vicinity of Mt. McKinley, 7-15 cm of rain was recorded at a number of climate stations (below 1000 m elevation) during the 19-26 July period. On the mountain considerable amounts of fresh snow fell between 19 and 22 July.

*2.3 11-18 May 1992*

As noted in the introduction, during the last three weeks of May 1992, climbers on Mt. McKinley experienced some of the worst weather in many years. Fig. 8 shows a sequence of 500 mb heights beginning at 00 UTC 12 May. At the start of this event a high amplitude ridge was positioned over the western Gulf of Alaska, with a low over northeast Siberia. Over the next four days the low/trough pattern moved over the top of the quasi-stationary ridge, producing a large gradient in the height field. Between 12-18 May, three jet streaks passed directly over the interior of Alaska, as they moved through the trough-ridge couplet.

On Mt. McKinley during this period, sustained winds on the upper half of the mountain were estimated at 20 $ms^{-1}$ with gusts in the 30-40 $ms^{-1}$ range. For comparison, the average of the MCG, FAI and ANC sounding winds at 12 UTC 12 May, were 32 $ms^{-1}$ at 500mb and 38 $ms^{-1}$ at 400 mb. On 13 May base camp (2134 m) reported 1.5 m of new snow with winds between 10-15 $ms^{-1}$. Reports from Kocour (1998) and the National Park Service climbing rangers, suggested that during this wind storm, there were periods (6-12 hours) in which wind speeds temporarily diminished.

As in the previous two case studies, the 200 mb heights as shown in Fig.9, indicate a strong ridge over the Gulf of Alaska, with a gradient on the order of 600 m $(1000\ km)^{-1}$. During this event the 200 mb temperature gradient (not shown) was on the order of 1.4° C $(100\ km)^{-1}$. The first in a series of wind storms concluded on 19 May, as a building ridge over the Bering Sea moved well into the Arctic, reducing the gradient in the height field over the Interior of Alaska.

## 3. Synoptic Climatology of Mt. McKinley Wind Storms

In order to gain an understanding of the type of synoptic patterns that produce multi-day winds storms on Mt. McKinley, a climatology of these events was constructed. Our first step in constructing this climatology was to determine a minimum criteria for wind speeds and duration. We subjectively determined that the movement of climbers would be very limited when sustained winds were 17 $ms^{-1}$ or higher, as a result we selected this value as our minimum criterion. Since the objective of this study is to analyze multi-day (persistent) wind storms, we only considered events that had a duration of 60+ hours. In addition, we limited the analysis period from15 April to 30 June, in order to correspond to what in the last two decades has become the 'normal' climbing season. 500 mb wind speeds were derived by a simple average of the MCG, FAI, and ANC upper air data. For the 40 year period from 1958 to 1997, we found 26 events that exceeded the established criteria. Due to a lack of data from Mt. McKinley, we made no attempt to verify that all of these storms had produced high winds on the mountain.

The next step was to conduct synoptic pattern analysis of these 26 cases using the NCEP/NCAR reanalysis data set, provided through the Climate Diagnostic Center (http://www.cdc.noaa.gov). Using daily averaged 500 mb heights, we were able to identify four synoptic patterns that produce Mt. McKinley wind storms (Fig.10).

The pattern that had the highest frequency is shown in Fig.10a (type-1 with 18 occurrences). In these cases a high amplitude ridge is positioned over the Gulf of Alaska with a deep trough over Kamchatka and the Bering Sea. This ridge-trough pattern was common to the three case studies already discussed in this paper. The second most common pattern is shown as

Fig.10b (type-2 with 6 occurrences), where a deep cut-off low positioned over the Alaska Peninsula produces strong south-to-southeast winds over Mt. McKinley. Cut-off lows and deep troughs are common in the southern Bering Sea and Gulf of Alaska in April and May. For most of these storms the polar jet is typically located to the south and southeast of the low-center. With a quasi-stationary ridge blocking the eastward movement of the low/trough however, strong upper-level winds can be produced over the interior of Alaska as the height gradient increases along the western boundary of the ridge.

The third synoptic type is shown as Fig.10c, in which an anticyclone is located over the southern Bering Sea, with a jet positioned over the Chukchi Sea (70° N). This pattern is rare and hence it appeared in only one out of the 26 cases. From time to time ridges do form over the southern Bering Sea in spring and early summer (Fig. 10d), however, in general these ridges do not produce strong winds as the gradient in the height field is minimal. On occasions, as cool lower stratospheric air (200 mb) moves northward and collides with warm air over the Arctic, very large height gradients and associated strong winds are produced on the east side of the ridge (type-4 with 1 occurrence).

Multi-day wind storms frequently consist of more than one synoptic type, primarily those displayed in Fig.10a,b. The May 1992 event presented in section 3, and shown as Fig. 8, was essentially a composite of two synoptic patterns. The initial pattern was type-1, with the ridge axis located over central Alaska. After several short-wave troughs moved over the top of the ridge, the event concluded as a type-4 pattern.

The critical synoptic element that consistently appears during multi-day Mt. McKinley wind events, is a quasi-stationary ridge located over the Gulf of Alaska or western Canada, as indicated by type-1 and type-2 patterns, which compose 24 of the 26 analyzed wind storms. These ridges are important because they impede the eastward movement of troughs and lows; and secondly, when the ridges move poleward from the North Pacific, they create very large height gradients over Alaska, helping to intensify jet stream winds.

**4. Frequency and Duration of Wind Storms**

In order to obtain some insight into the frequency and duration of Mt. McKinley wind storms, we examined the 1958-1997 upper air data between the dates 15 April and 30 June, and categorized wind speeds into bins of $\geq 15$, $\geq 20$ and $\geq 25$ $ms^{-1}$ (Fig.11). The vertical bars in this figure give the seasonal maximum and minimum frequency of occurrence. For example, during the 1986 climbing season wind speeds were $\geq 15$ $ms^{-1}$ only 4% of the time, while in 1958 they were $\geq 15$ $ms^{-1}$ about 36% of the time. The horizontal line through each vertical bar is the 40 year mean; wind speeds $\geq 20$ $ms^{-1}$ have a frequency of occurrence of 7.6% for example. Note that there is roughly a three-fold decrease in the mean frequency of occurrence from one category to the next.

The next step was to catagorize wind storms based on the month in which they occurred as well as the duration (Fig.12). It is important to note that the data for April, includes only the second-half of the month. Month-to-month comparisons indicate that the highest frequency of wind storms occurs in April, after which storm frequencies steadily decrease. Wind storms with a duration of 60+ hours occur about once every three seasons in April, compared with once every five seasons in May and once every 11 seasons in June.

The decrease in wind storm frequency from April to June stems primarily from a decrease in the intensity of the Aleutian Low and weakening of the polar jet stream. In other words, due to a decrease in the thermal contrast between East Asia and the North Pacific, there is a pronounced decrease in baroclinicity in the North Pacific by early summer. These changes are reflected in a general decrease in the north-south height gradient over Alaska by June.

## 5. Discussion

### *5.1 Ridging*

It has been demonstrated that quasi-stationary ridges located over the Gulf of Alaska and western Canada are a key element in Mt. McKinley wind storms. Tibaldi *et al* (1994) studied Northern Hemisphere blocking and noted that in the Pacific Basin, blocking is primarily a winter phenomena. The data however, also showed a weaker secondary blocking maximum occurring in the summer. Austin (1980), in his study of Northern Hemisphere blocking, noted the association of wave numbers two and three with blocking over the Pacific Ocean. In our analysis of 26 wind storms, we found that the Northern Hemisphere wave number ranged from two to four during these events.

As discussed by Bluestein (1993), high amplitude ridges can become quasi-stationary depending on the amount of temperature advection and diabatic heating that occurs within the ridge. Inspection of the reanalysis data for our 26 cases shows that most ridges form over the central North Pacific between 180° and 160° W, and then move northeast into the Gulf of Alaska. Once these ridges move north of 60° N, they collide with Arctic air (cool tropospheric and warm stratospheric), frequently producing large height gradients. Of equal importance are troughs and lows which move up the west side or directly over the top of a ridge. The concept that very strong jet stream winds are produced at the confluence of a trough (to the north) and a ridge (to the south), was highlighted by work of Namias and Clapp (1949).

As a result of strong temperature advection, temperature changes of 15-20° C over periods of 36-48 hours are common in the upper troposphere over Alaska during periods of ridge building. In a study of anticyclone development over northern Canada, Fleagle (1947) noted that maximum temperature advection occurred in a layer 2-3 km thick which was located just above the tropopause. During the typical type-1 wind storm, cold air at 200 mb over the North Pacific is advected northward where it collides with warm air over the Arctic, producing a large temperature gradient. Temperature advection at 500 mb is reversed, with warm air over the North Pacific moving into cooler Arctic air. For the 26 events analyzed, we found that the mean 200 mb temperature gradient over Alaska was on the order of 1.7° C $(100\ km)^{-1}$.

The preceding discussion suggests that significant changes in mid-tropospheric height fields during Mt. McKinley wind storms are controlled primarily by temperature advection in the upper tropopause and lower stratosphere. Fig.13 presents two examples of height changes taken through a north-south transect (151°W), for the May 1992 event. Fig.13a indicates a large increase in heights near the tropopause, to the south of the mountain. This corresponds to a period where the winds were increasing (numbers to the right in Fig.13). In Fig.13b both upper level heights and winds are decreasing. It is apparent that the greatest change in the height field occurs in the 400-200 mb layer.

### *5.2 Jet Streaks*

We know from climber reports that during multi-day wind storms, wind speeds can either remain relatively constant or vary widely, two examples of which are shown in Fig.14. The 11-19 May 1992 event is shown as Fig 14a. As was noted earlier, during this particular event three jet streaks moved across the interior of Alaska, producing significant speed fluctuations. The 18-26 May 1997 event is displayed as Fig.14b. During this storm, once the initial jet streak moved up the western side of the ridge, wind speeds in the vicinity of Mt. McKinley remained relatively constant for the following five days. In Fig.14a,b note that not only is the magnitude of the 500 mb winds lower than those at 300 mb, but the amplitude of fluctuations are considerably smaller at 500 mb as well.

## 6. Conclusion

This study suggest that multi-day Mt. McKinley wind storms are synoptically controlled, and occur when either the polar or arctic jet stream is located near the mountain. Most of these events occur when a ridge of high pressure is positioned over the Gulf of Alaska or northwest Canada. Quasi-stationary ridges slow the eastward movement of lows and troughs as well as produce large height gradients over Alaska. Many wind storms also occur in association with significant precipitation events, as disturbances move up the western side or over the top of a ridge. Southwesterly flow in particular advects large amounts of moisture into the interior of Alaska from the North Pacific.

Mid-tropospheric wind speeds can vary considerably during wind storms, in large part due to the passage of jet streaks through the ridge. A frequency analysis of wind storms has shown a steady decrease of these events from April through June, in association with the seasonal decrease in baroclinicity in the North Pacific, and the subsequent weakening of the polar jet stream.

There are two outstanding problems concerning our understanding of Mt. McKinley windstorms: the presence of tropopause folds, and the amplification of free atmospheric winds by the complex terrain of Denali National Park. The role which tropopause folds might possibly play in these wind storms is open to speculation since the upper air network over Alaska is in general too course to detect these features (Danielsen 1968, Danielsen & Hipskind 1980). However, due to the relatively low elevation of the polar tropopause over Alaska (Hoinka 1998), and the strength of upper-level temperature gradients, we suspect that on occasions tropopause folds transport high momentum air from the lower stratosphere into the middle troposphere during Mt. McKinley wind storms.

As the modeling work of Olafsson & Bougeault (1996) has indicated, wind speeds experienced by climbers on the upper-half of a mountain like Mt. McKinley, could be substantially higher than free atmospheric winds due to the funneling of air between the mountain and surrounding terrain (gap type winds), or between the mountain and stable layers located in the upper-troposphere. Many Mt. McKinley climbers report considerable wind amplification as air is funneled through Windy Corner and Denali Pass, which are essentially gap features. In the future we hope to use a mesoscale model to simulate air flow around over Mt. McKinley, in hopes of gaining some understanding of these local-scale amplifications.

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**Figure Captions**

Fig. 1 Geographic setting of Mt. McKinley. Three letter identifiers are upper air stations: ANC- Anchorage, BET- Bethel, BRW- Barrow, CDB- Cold Bay, FAI- Fairbanks, KOD- Kodiak, MCG- McGrath, OME- Nome, OTZ- Kotzebue, YAK- Yakutat

Fig. 2 Geopotential heights (m) for March 1967 event, all times at 12 UTC. (a) 500 mb on 2 March (b) 200 mb on 2 March (c) 500 mb on 4 March (d) 200 mb on 4 March

Fig. 3 500 mb winds ($ms^{-1}$) at 00 UTC 4 March

Fig. 4 200 mb temperatures (K) at 00 UTC 4 March

Fig. 5 500 mb geopotential heights (m), all times at 12 UTC for: (a) 20 July (b) 22 July (c) 24 July (d) 26 July

Fig. 6 500 mb wind speeds ($m\ s^{-1}$) at 12 UTC 22 July

Fig. 7 200 mb temperatures (K) at 12 UTC 22 July

Fig. 8 500mb geopotential heights (m), all times at 00 UTC for: (a) 12 May (b) 14 May (c) 16 May (d) 18 May

Fig. 9 200 mb geopotential heights (m) at: (a) 12 UTC 12 May (b) 12 UTC 15 May

Fig. 10 Four types of synoptic patterns common to multi-day Mt. McKinley wind storms. (a) Type 1- Ridge over Gulf of Alaska and western Canada (b) Type 2-Low over Alaska Peninsula (c) Type 3- Anticyclone over southern Bering Sea (d) Type 4- Ridge over Bering and Chukchi Seas

Fig. 11 Frequency of occurrence for three wind speed categories. Vertical bars represent maximum and minimum seasonal frequencies, while thin horizontal lines are 40 year means.

Fig. 12 Number of wind storms events between 1958-1997 categorized by duration and month of occurrence

Fig. 13 Vertical cross-section of north-to-south geopotential height change (m) taken through 151° W, for the May 1992 wind storm. Solid lines indicate increasing heights, dotted lines decreasing heights. Numbers to the right of each figure are the change in winds ($ms^{-1}$) in the vicinity of Mt. McKinley. Arrows point to latitude of Mt. McKinley. a) 12 UTC 12 May minus 12 UTC 10 May b) 00 UTC 14 May minus 12 UTC 12 May

Fig. 14 300 mb and 500 mb wind speeds computed from a three-way average of MCG, FAI, and ANC soundings. (a) 11-19 May 1992 (b) 18-26 May 1997

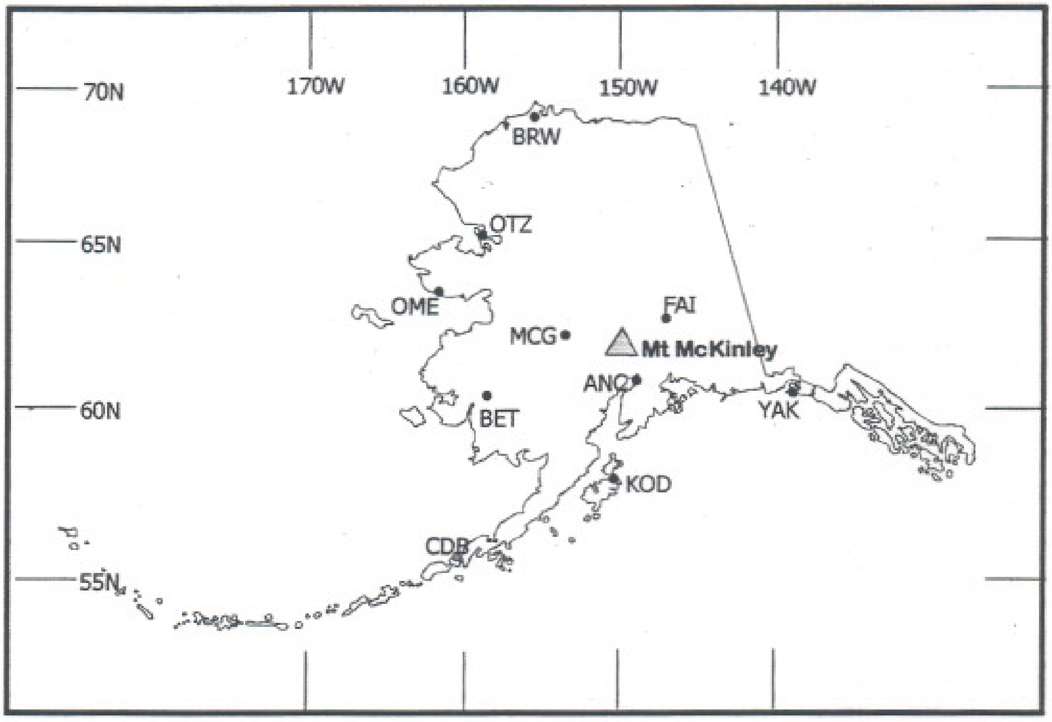

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Fig 1

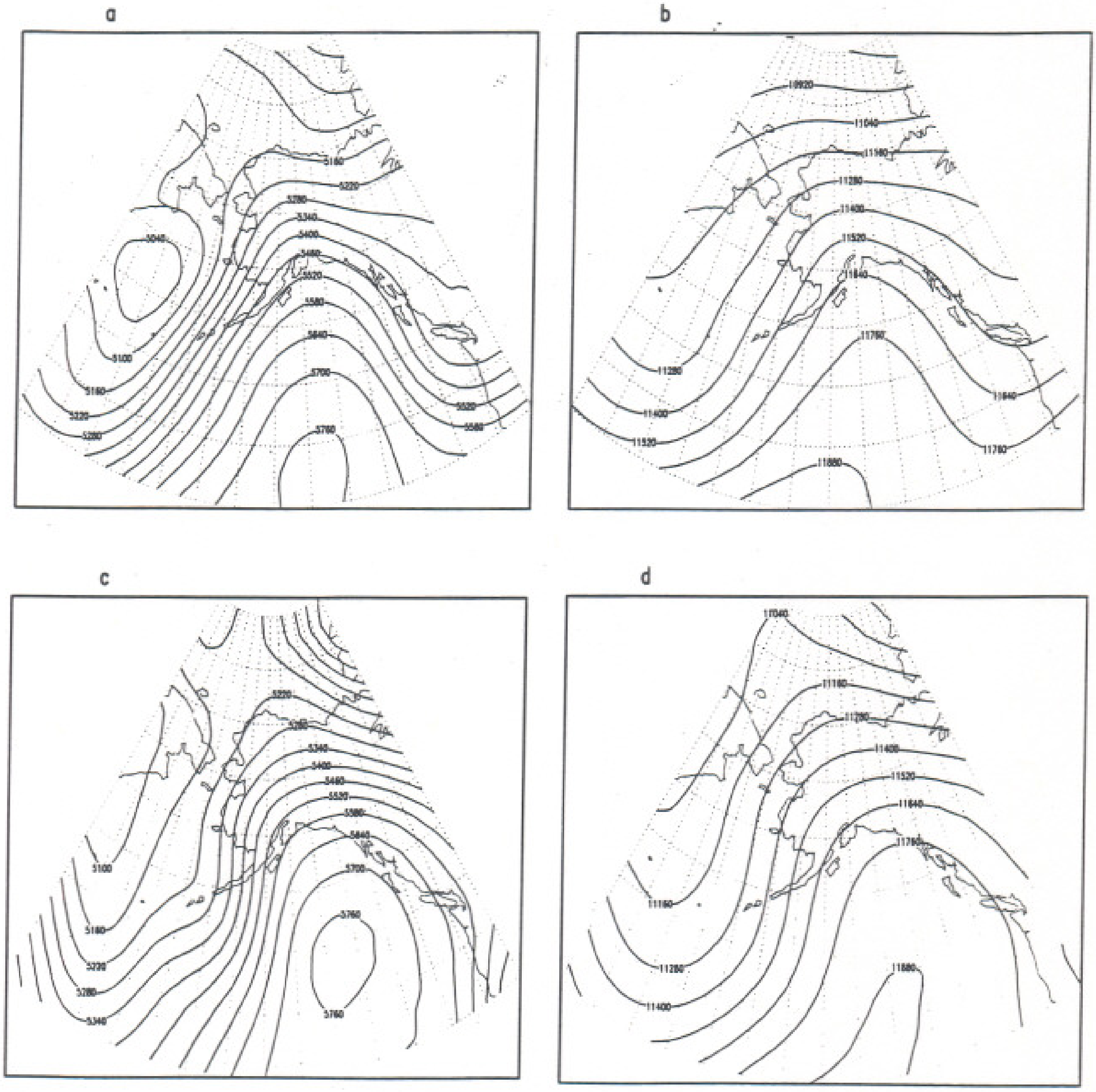



Fig 2

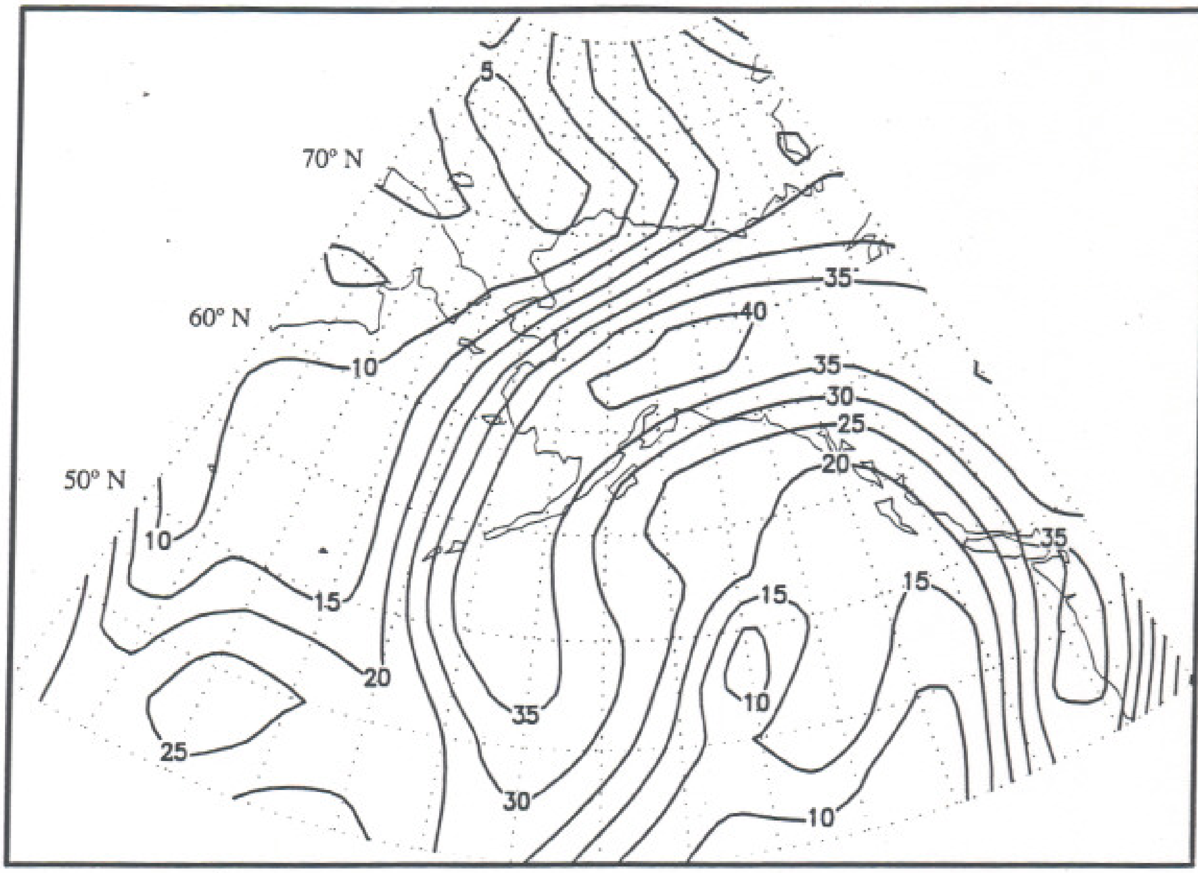



Fig 3

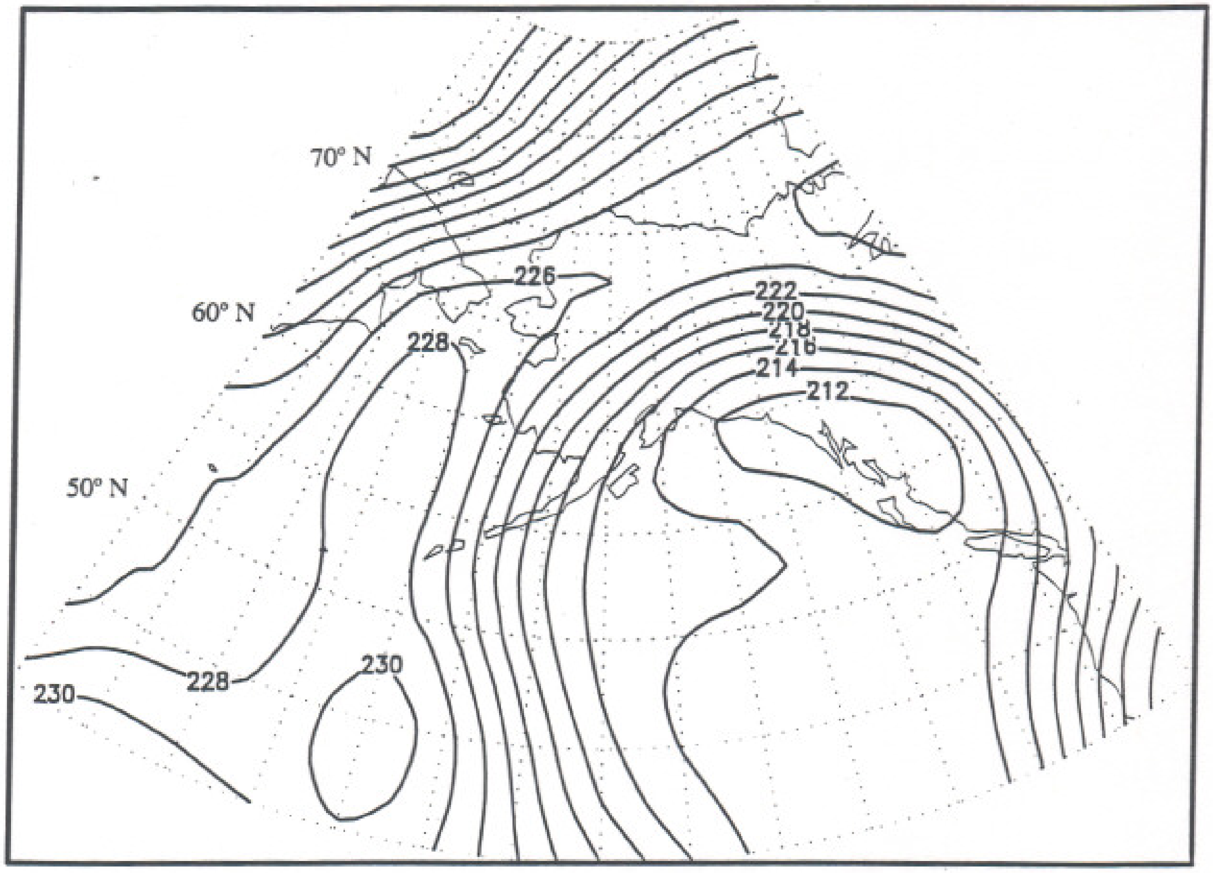
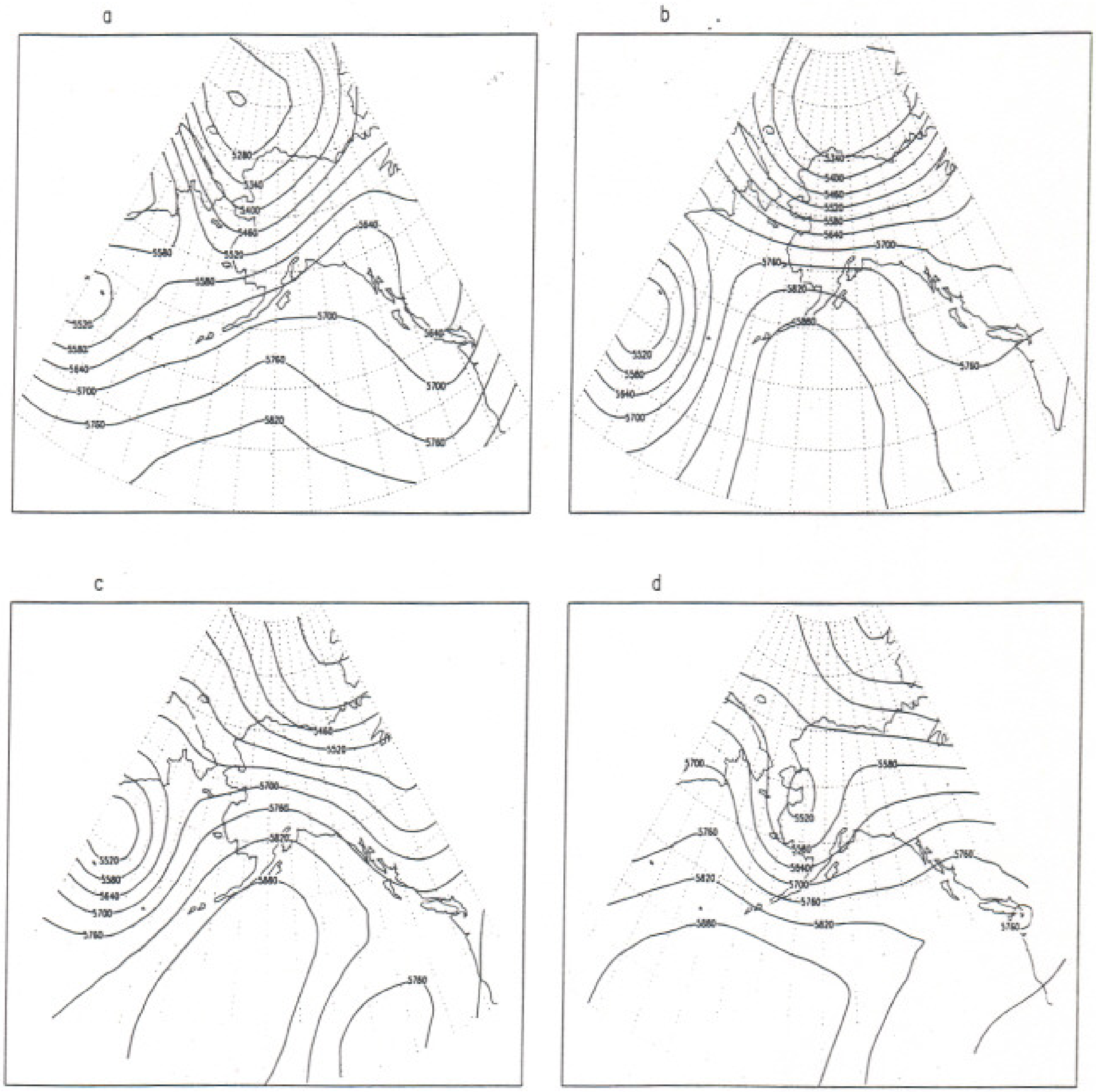



Fig 4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5880

Fig 5

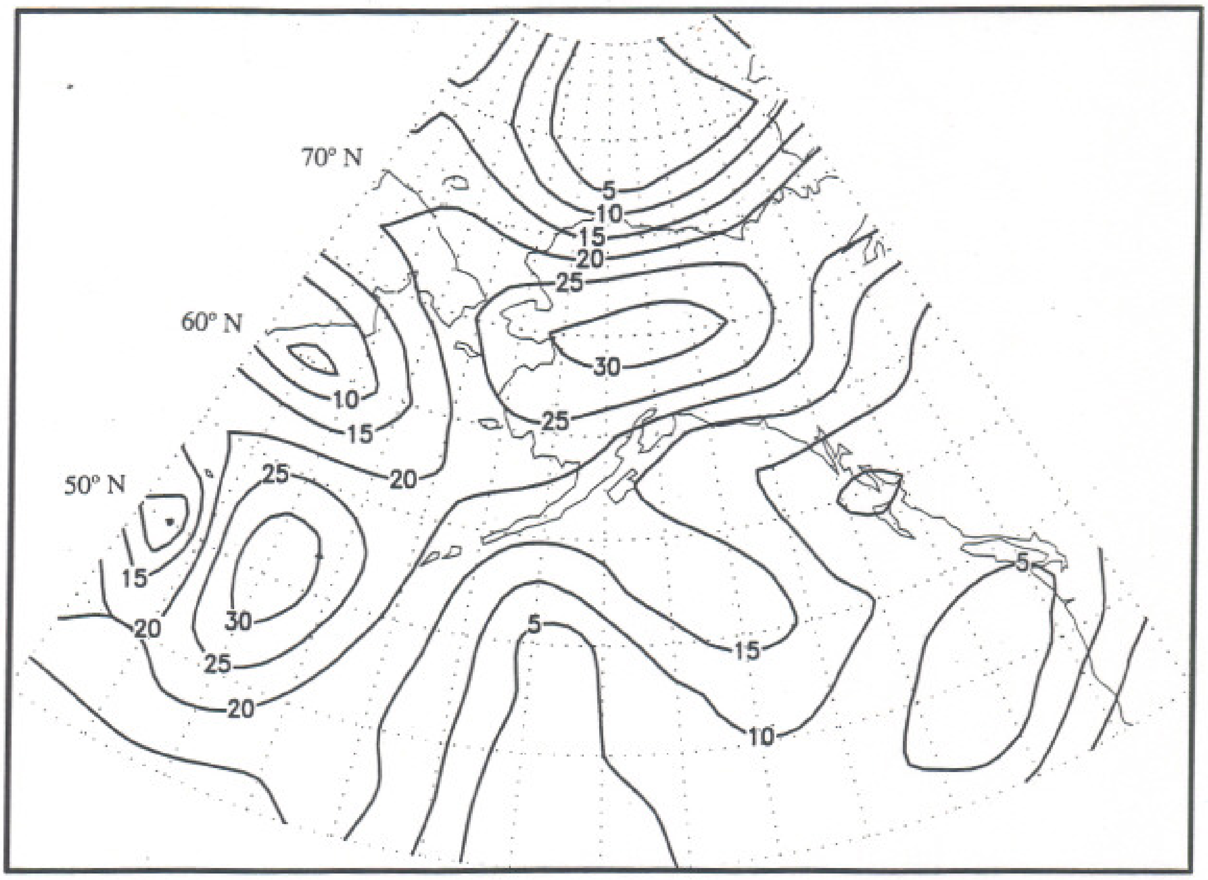



Fig 6

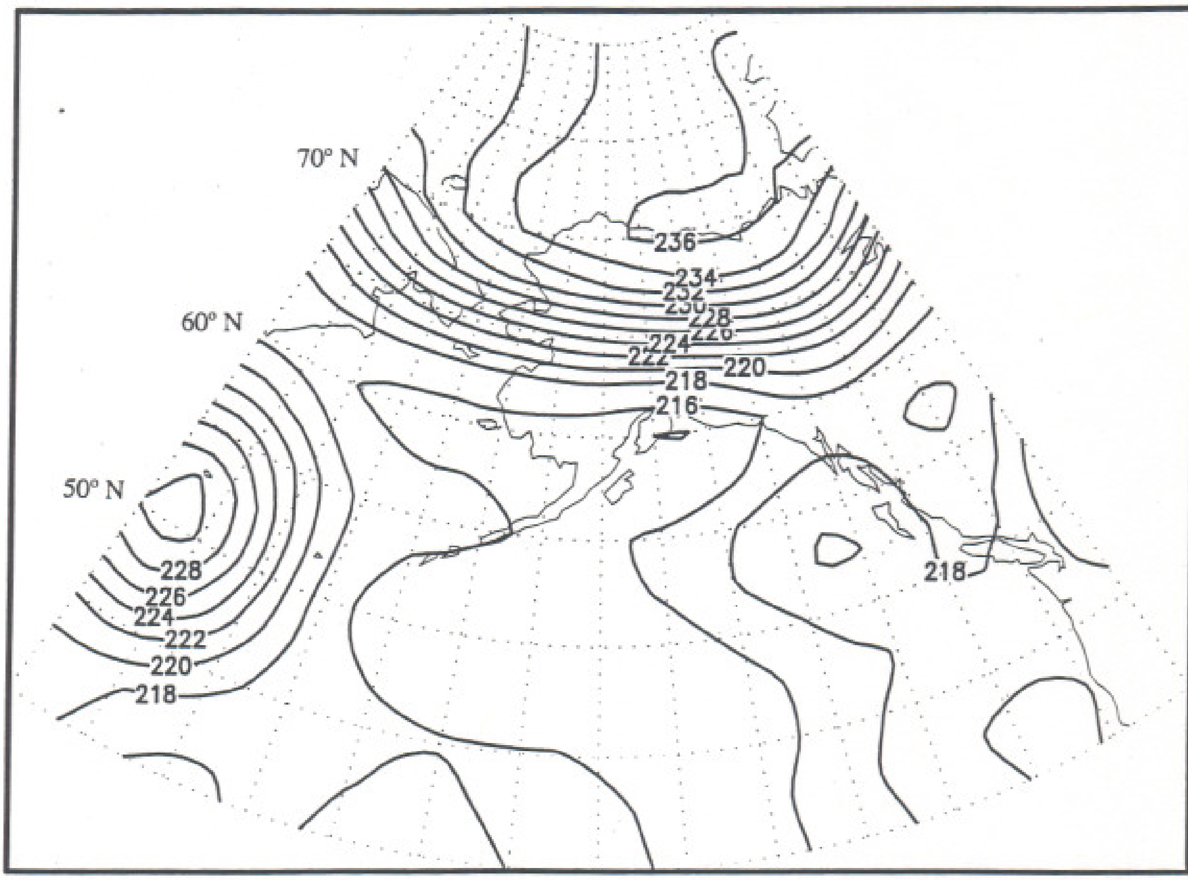

70° N
60° N
50° N
236
234
232
230
228
226
224
222
218
220
216
228
226
224
222
220
218
218

Fig 7

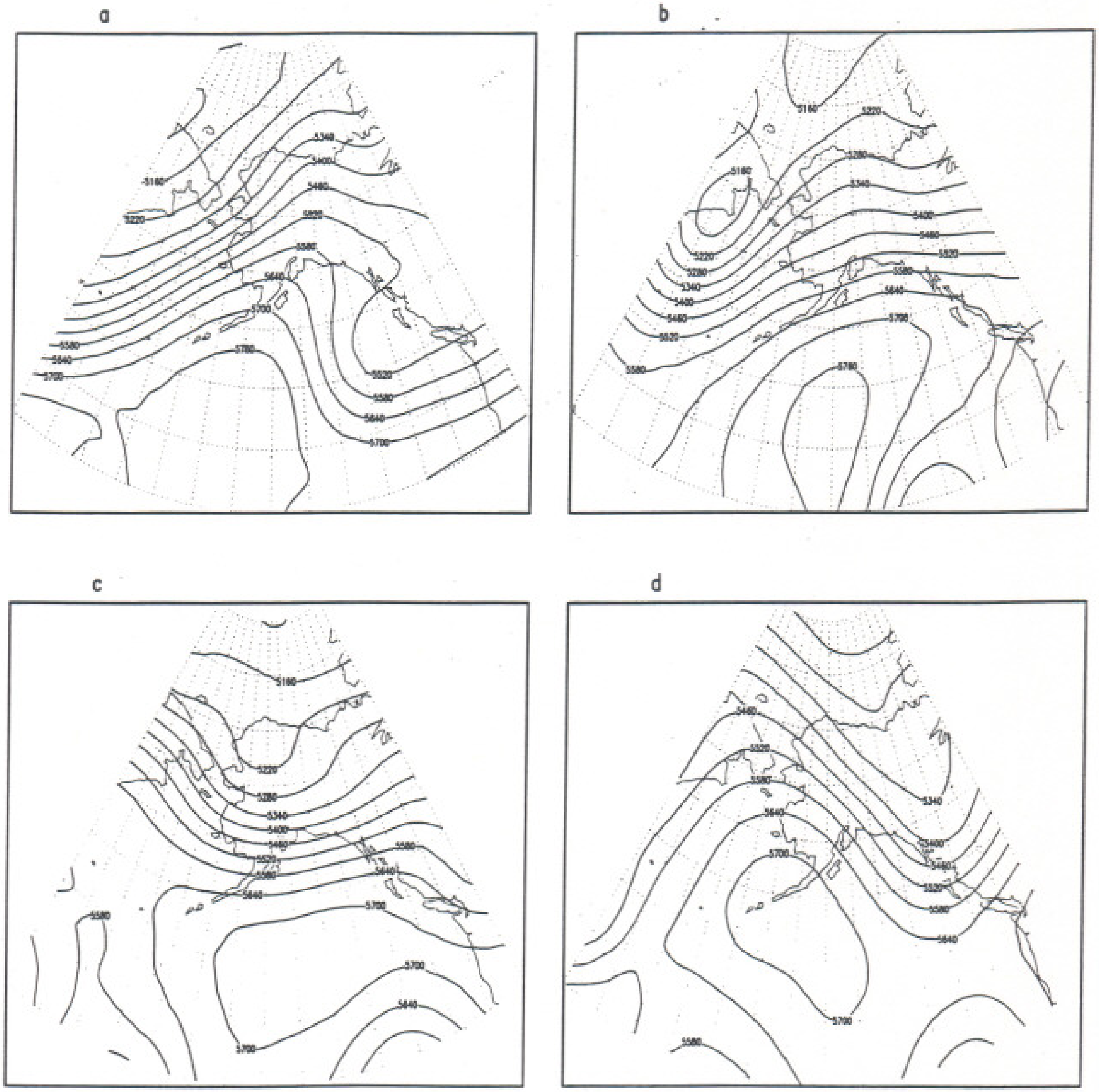

a
5160
5220
5340
5400
5460
5520
5580
5640
5700
5760
b
5160
5220
5280
5340
5400
5460
5520
5580
5640
5700
5760
c
5160
5220
5280
5340
5400
5460
5520
5580
5640
5700
d
5340
5400
5460
5520
5580
5640
5700

Fig 8

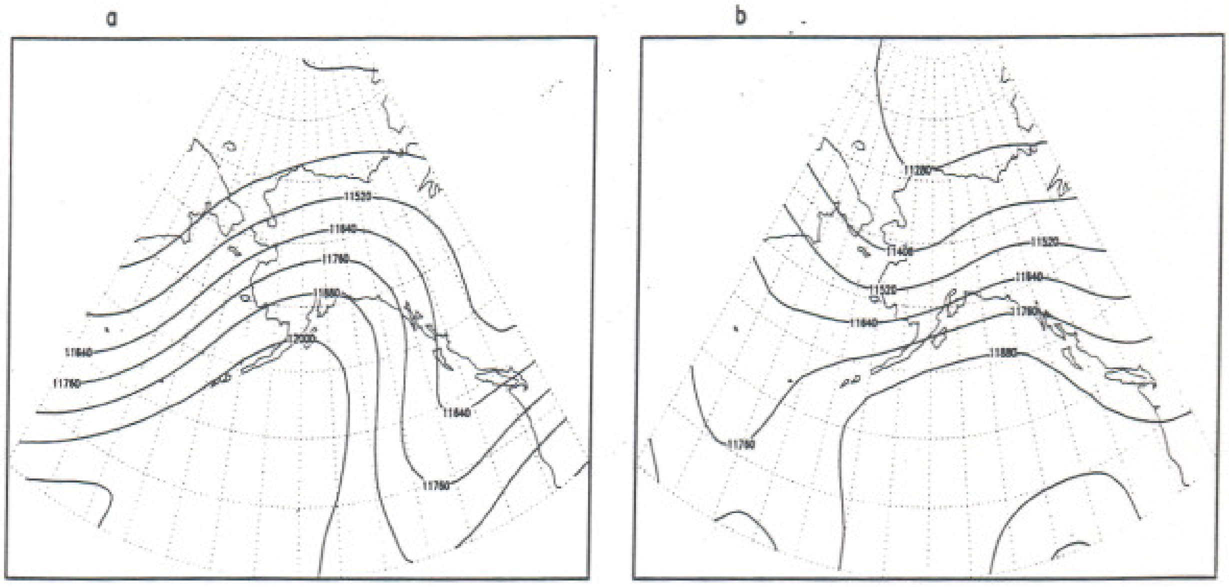
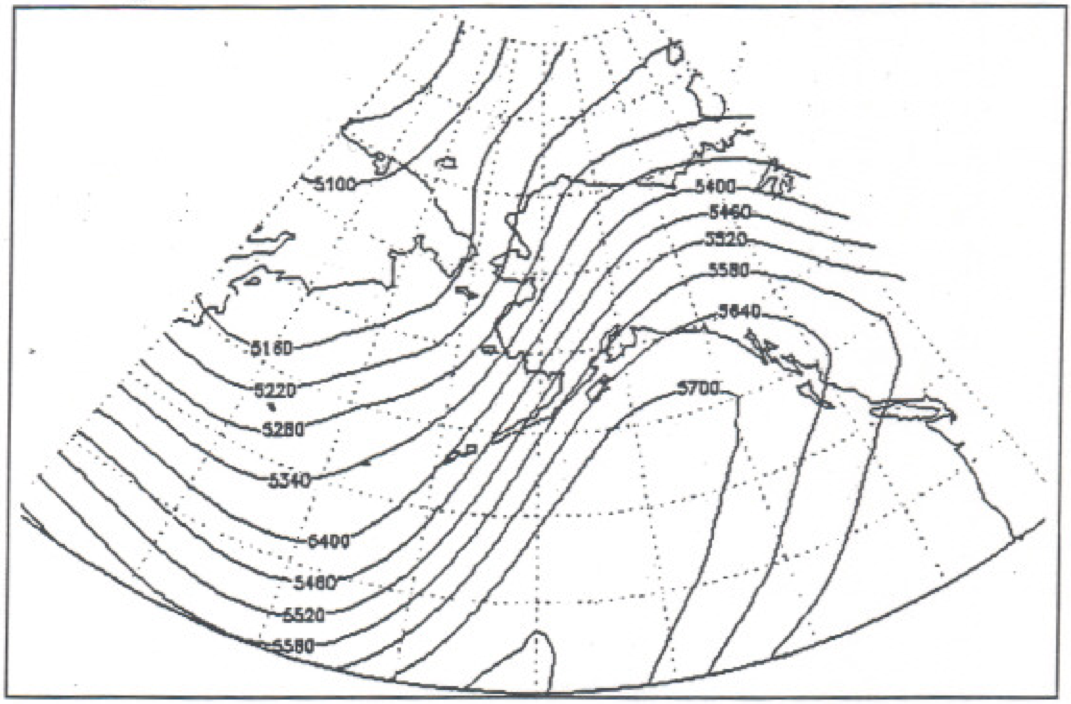

a
11520
11640
11760
11880
12000
11640
11760
11640
11760
b
11280
11400
11520
11520
11640
11640
11760
11880
11760

Fig 9

a




b

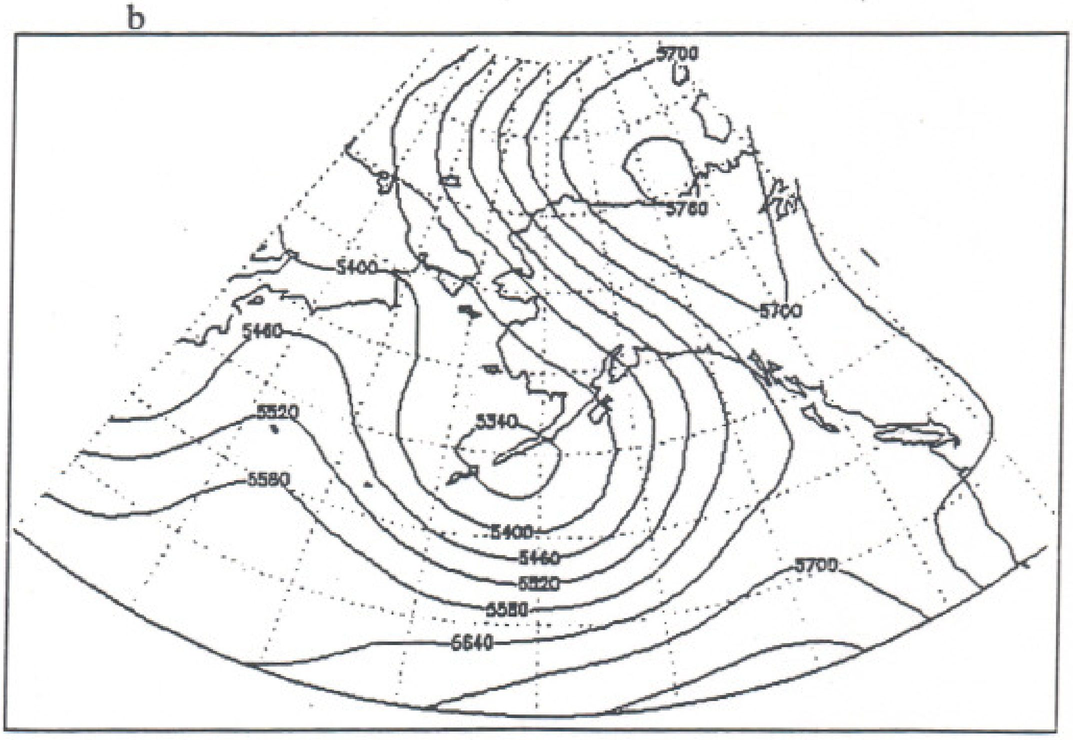
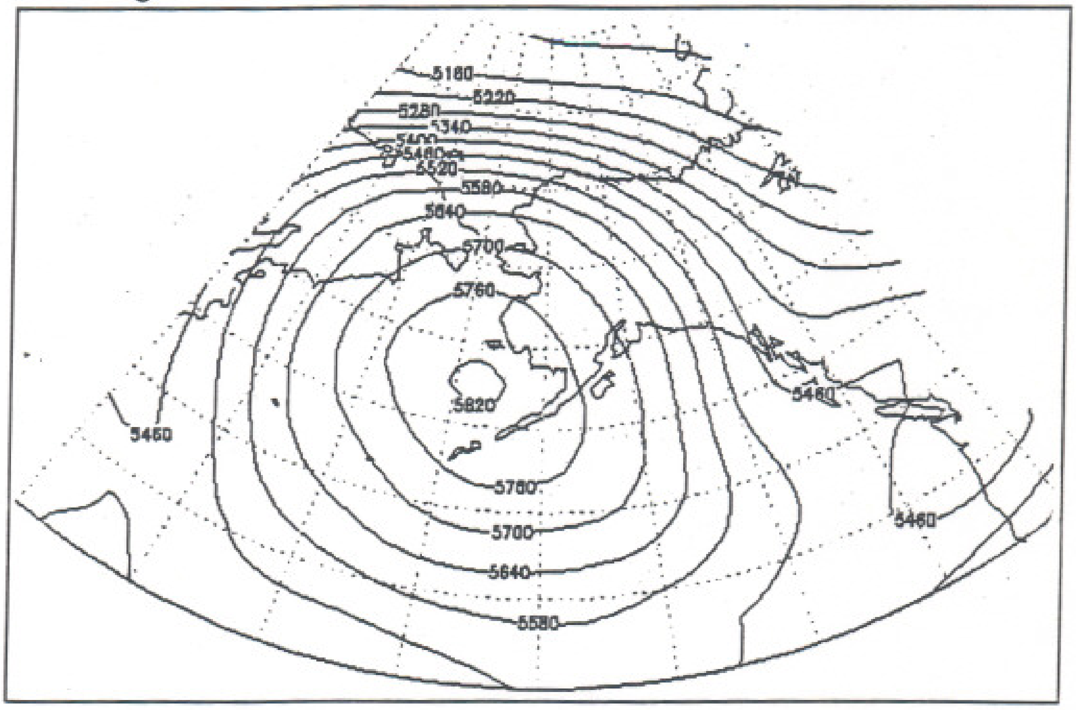



Fig 10

Fig 10

c


5160
5220
5280
5340
5400
5460
5520
5580
5640
5700
5760
5820
5460
5460
5760
5700
5640
5580
5460

d

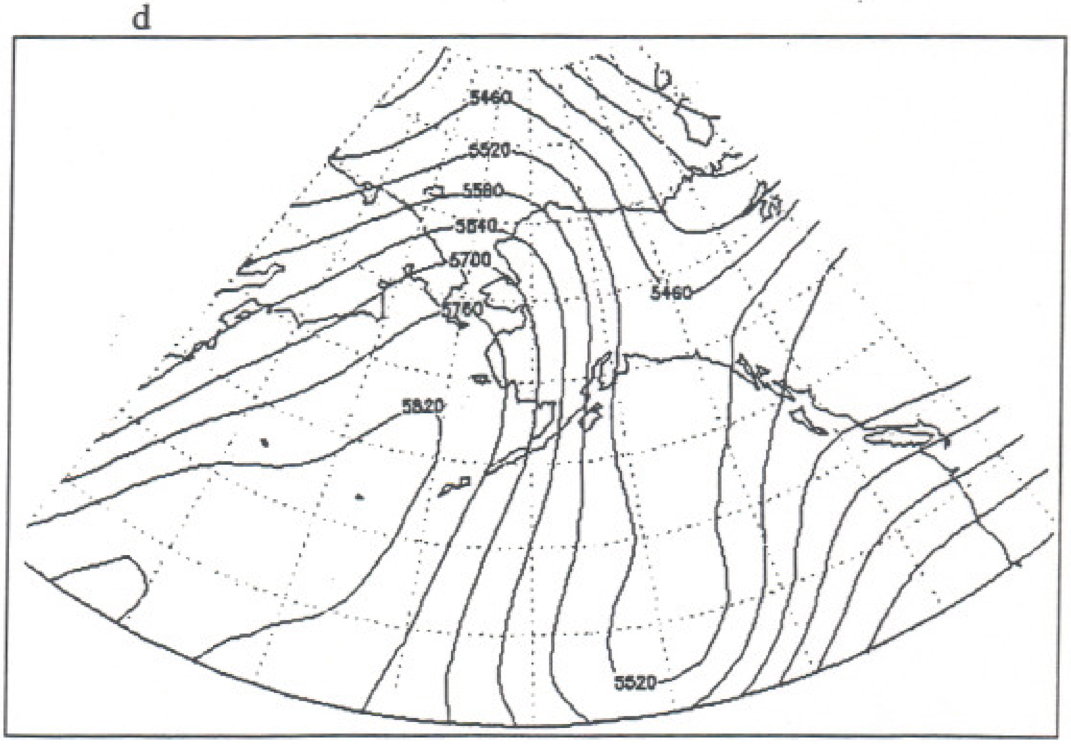
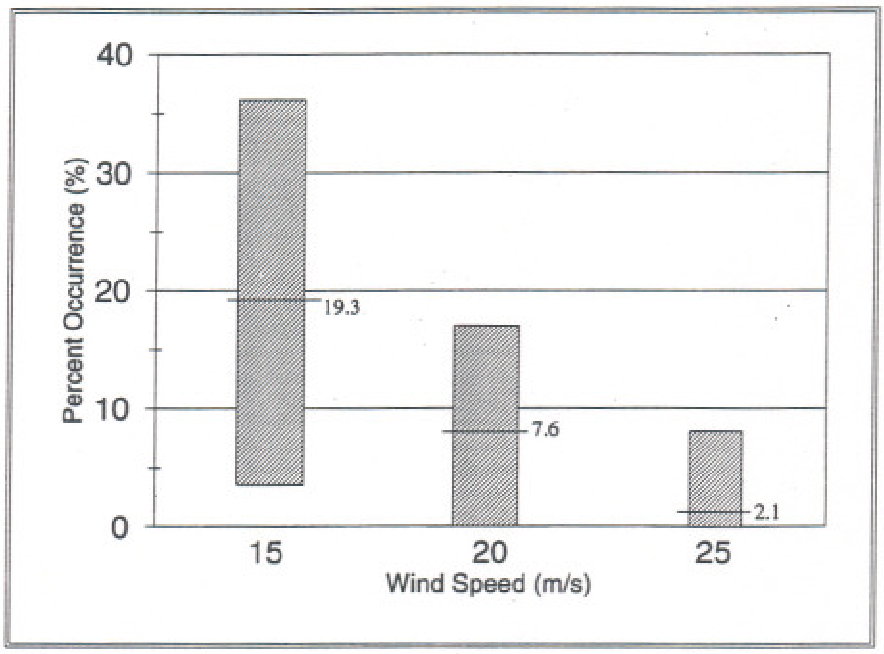

5460
5520
5580
5640
5700
5760
5460
5820
5520

Fig 10 con'



40
30
20
10
0
Percent Occurrence (%)
19.3
7.6
2.1
15
20
25
Wind Speed (m/s)


Fig 11

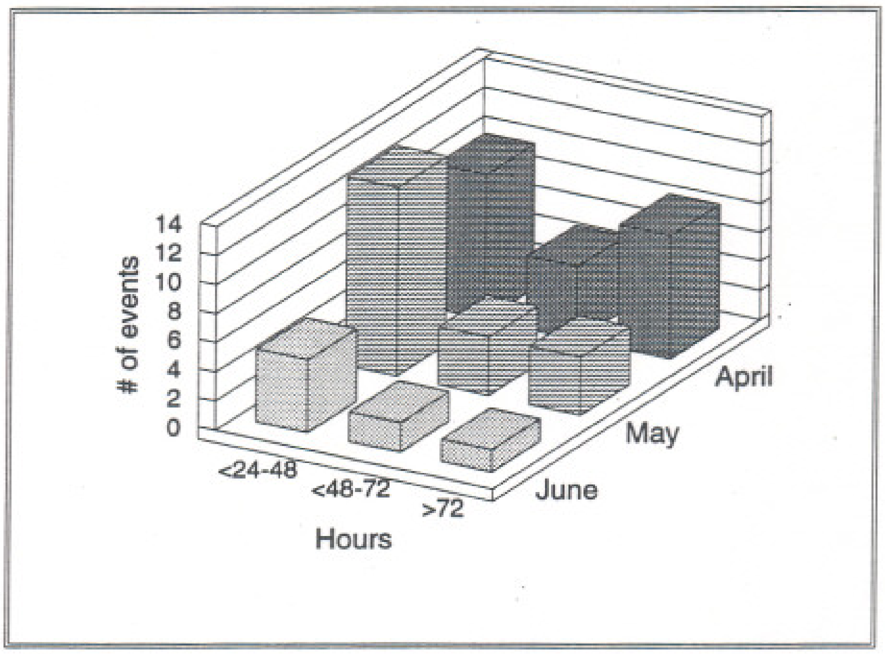



Fig 12

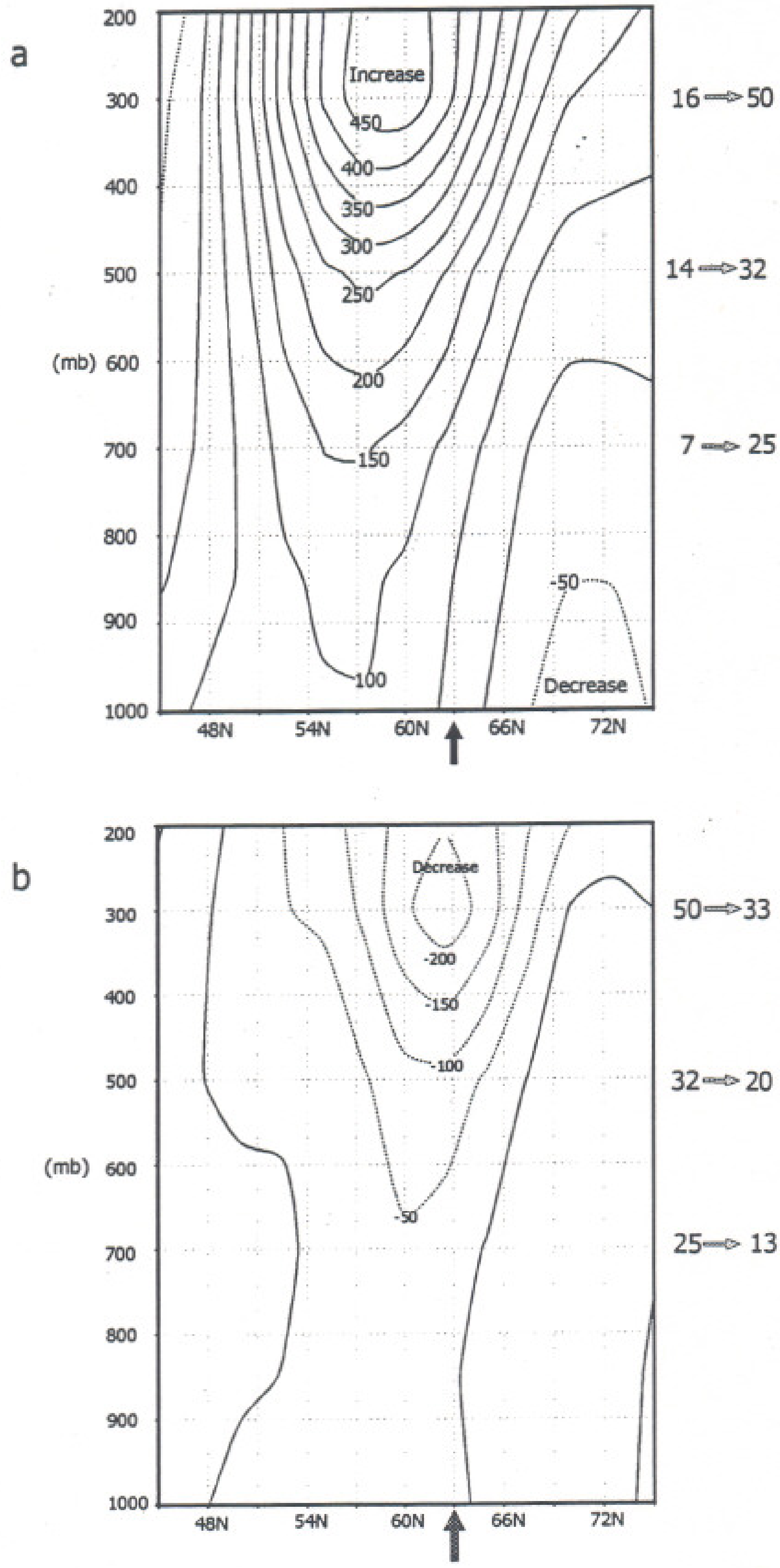
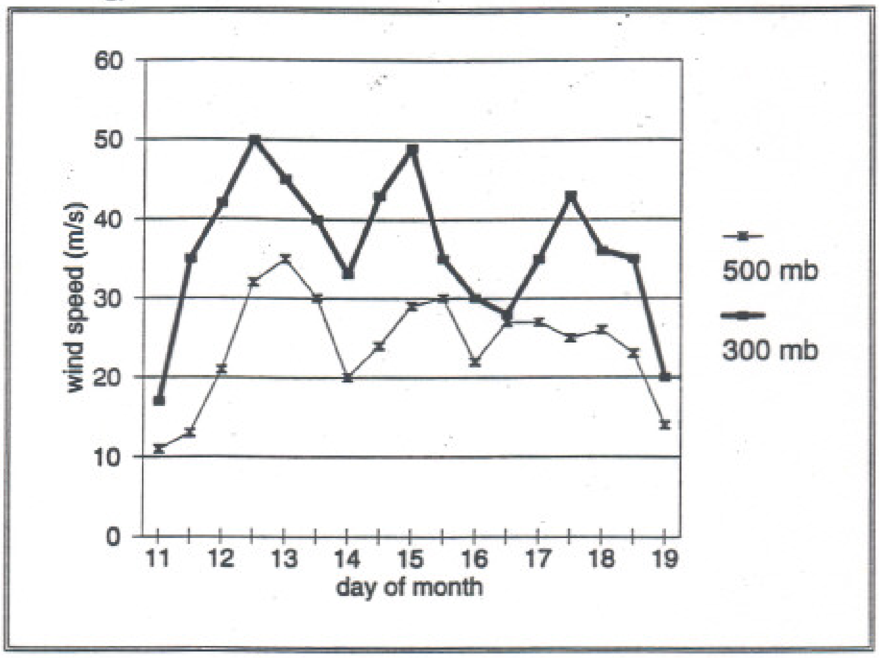

a
Increase
450
400
350
300
250
200
150
100
-50
Decrease
16 ⇒ 50
14 ⇒ 32
7 ⇒ 25
b
Decrease
-200
-150
-100
-50
50 ⇒ 33
32 ⇒ 20
25 ⇒ 13
(mb)
200
300
400
500
600
700
800
900
1000
48N
54N
60N
66N
72N

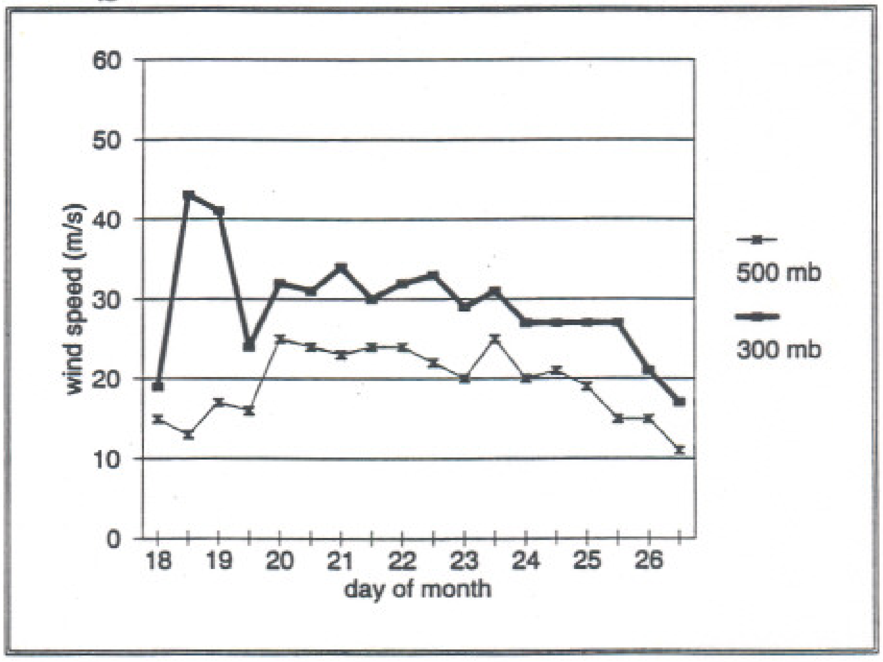
Fig 13

a



60
50
40
30
20
10
0
wind speed (m/s)
11
12
13
14
15
16
17
18
19
day of month
500 mb
300 mb


b



60
50
40
30
20
10
0
wind speed (m/s)
18
19
20
21
22
23
24
25
26
day of month
500 mb
300 mb


Fig 14