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ANALYSING COLD FRONTS FOR FORECASTING OPERATIONS

by

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CONTENTS

	page
LIST OF FIGURES	iv
1. INTRODUCTION	1
2. PROBLEMS AND STRATEGIES	2
3. CASE 1 – OCTOBER 1996	6
4. CASE 2 – MAY 1994	8
5. CONCLUDING REMARKS	9
REFERENCES	11

LIST OF FIGURES

	pages
1. Schematic illustration of the “hidden trough”	12
2. Curved or broken fronts as a result of topography	12
3. Methods of cold front analysis	13-14
4. Positions of the pressure gradient front in relation to the isobaric pattern	15-16
5. Surface re-analysis of a cold front and a pre-existing trough in May 1994	17-19
6. A collection of fronts and troughs	20
7. Schematic illustration of the curvature of isobars across a cold front	21

摘要

在清涼季節分析影響香港的冷鋒，對於富有經驗的預報員而言，也是一個頗為棘手的問題。進侵華南的冷空氣往往是相當淺薄，南下過程容易受到地勢阻撓。在氣團差異不明顯的情況下，鋒面位置的連貫性更是難於掌握。此項檢討的目標，除落實一些基本分析策略外，更為分析過程中所經常碰到的難題及模稜兩可情況提供輔助指引。傳統的等壓分析，低壓槽的位置通常是處於最低氣壓的軸線上。在華南出現廣闊低壓槽或「隱槽」的形勢下為冷鋒定位，除了盡量考慮風、氣溫、露點的變化，一個較為可取的策略是將冷鋒位置靠向北面，貼近緊密氣壓梯度的前沿。處理具備強烈斜壓特性的槽，彈性地多用靜止鋒，有助維繫分析的一致性與連貫性。良好的分析手段，不但要實事求是，最終的分析目標，是透過對觀測數據的仔細評估、氣象知識的充分應用、數值預報的恰當理解，帶出一個合理的天氣故事，為預報的製定提供不可或缺的基礎。

Abstract

The analysis of cold fronts affecting Hong Kong is a rather tricky problem in the cool season, even for the more experienced forecasters. The layer of cold air over southern China is often shallow and its southward march is susceptible to topographical influences. At times, the air mass differences are too weak for continuity in the frontal position to be reliably maintained. The objective of this review is to reinforce some basic analysis strategies and to provide various supplementary guidelines in dealing with difficult and ambiguous situations often encountered in the course of frontal analysis. While a trough tends to be analyzed along the axis of minimum pressure in conventional isobaric analysis, the preferred strategy in placing a cold front within a broad pressure trough or a “hidden trough” pattern over southern China is to shift it towards the leading edge of the pressure gradient on the northern side, taking into account changes in wind, temperature and dew point wherever possible. More flexible use of stationary fronts, as a form of troughs with strong baroclinic characteristics, is recommended for maintaining consistency and providing better continuity. Apart from good analysis practices guided by pragmatic considerations, the ultimate analysis target, through close monitoring of observational data, sound application of meteorological knowledge, and prudent interpretation of numerical prognoses, is to convey a logical weather story that can be used as an essential platform for forecast formulation.

1. INTRODUCTION

The analysis of cold fronts affecting Hong Kong is a rather tricky problem in the cool season, even for the more experienced forecasters. The layer of cold air over southern China is often shallow and the air mass differences at times so weak that continuity in the position of the front is difficult to maintain. The rugged terrain over southern China, particularly as the cold air negotiates the Nanling ranges, also complicates the analysis.

Standard textbook approaches are mostly derived from experience in the temperate latitudes with a strong bias towards the classical Norwegian school of frontal analysis. However, problems peculiar to southern China pose additional challenges in operational analyses (e.g., Chin 1969, Zhu *et al.* 1992). In view of the high turnover rate of personnel in the Central Forecasting Office (CFO), it is even more important to have a common understanding on how these problems should be tackled. The objective of this note is to reinforce some basic strategies in frontal analyses and to provide supplementary guidelines in dealing with difficult and ambiguous situations often encountered in the course of frontal analysis.

The first draft was prepared in the summer of 1996 and comments were collected from CFO forecasters. After some minor alterations, the feasibility and practicality of the proposed procedures were tried out during the cool seasons in the past several years. In the process, operational practices in the CFO have continued to evolve. Changes arising from new services, e.g., increasing exposure of the weather maps on the web and via the media, also create new (or aggravate old) dilemmas in operational chart analyses, particularly in terms of maintaining good continuity and consistency.

Frontal features and characteristics over central and southern China are discussed in Section 2 and analysis strategies suggested. The finer points are illustrated by selected cases in Sections 3 and 4. The former case describes the merits of various methods in a typical cold front passage scenario. The latter case is a not-so-typical case which demonstrates the need for a vigilant and critical approach in the analysis. Concluding remarks, including operational considerations at the Hong Kong Observatory, related issues in frontal analysis and other possibilities within the meteorological community, are given in Section 5.

2. ANALYSIS PROBLEMS AND USEFUL STRATEGIES

2.1 Follow pressure gradient instead of pressure trough

In the majority of cases, cold fronts over central and southern China run parallel to the isobars. This is often referred to as the “hidden trough (隱槽)” pattern, e.g., Zhu *et al.* 1992. In conventional surface weather charts, a number of weather elements such as wind, pressure, temperature, dew-point and weather can be used to locate the cold front. From the practical handbook by Lu *et al.* (1984), the recommended steps are to make a general synoptic assessment, do a continuity analysis, locate areas of significant weather, study the latest 3-hour pressure change patterns, and pencil in a tentative position of the front. Final adjustment of the front, based to a certain extent on subjective judgment, is then made after the isobars are drawn.

Fundamentally, the front should be placed along the air density discontinuity of two contrasting air masses. But as density is not directly measured and reported, the next best thing is to use either temperature or dew-point. Between the two, dew-point tends to be the more conservative option unless there is significant precipitation. Temperature can be affected by radiation conditions and surface characteristics.

Weather and pressure also have their limitations given that the cold air over southern China is often shallow. Weather tends to lag behind in tandem with the upper troughs. Pressure measures the net effect within the whole column of air and not just the thin layer of cold air near the surface.

Wind, in terms of directional shear, is not obvious because of the “hidden trough” pattern which gives northerly winds ahead of the front. Cyclonic shear in terms of differential wind speeds, though present, may well be masked by the terrain effect, an underlying complication that afflicts all other elements.

In general, temporal changes in the meteorological elements, particularly 24-hour changes to reduce the diurnal effect, are more useful and representative. But the inherent limitations associated with each element still cannot be entirely removed.

An operational constraint is that isobaric analysis is still the main tool used in the delineation of surface weather systems. As such, the position of cold front cannot be totally divorced from the pressure pattern and the isobaric contours even if pressure may not be the best indicator of the air mass characteristics. The practical solution is to look for a suitable pressure-related alternative. In view of the frequent “hidden trough” patterns and the close relationship of pressure gradient with other air mass parameters such as temperature and dew-point, the best option is to place the cold front just ahead of the first isobar of the region with higher value of pressure gradient. Based on this approach, a schematic illustration is given in Fig. 1 showing

the typical "peeling-off" pattern of the isobars away from the gradient towards the eastern end of the front.

2.2 Stand-alone cold front in the absence of frontal depression or warm front

Frontogenesis over central and southern China does not necessarily require cyclogenesis at the same time. In other words, a cold front can be analyzed in the absence of a frontal depression. A typical sequence of event is the strengthening of an anticyclone over northern China representing a mustering of cold air, the deepening of a pre-existing east-west orientated surface trough over central China (or the rejuvenation of a weakening stationary front), the packing of pressure gradient north of the trough, frontogenesis with or without the emergence of a depression over eastern China or East China Sea, and a gradual southward march of the newly formed cold front towards the South China Sea.

By the same token, a cold front going into a frontal depression does not necessarily require the company of a warm front. A warm front can be separately included if and when supported by data and observation. The current intransigent CFO practice of including an obligatory warm front for every cold front/frontal depression analyzed, in accordance with the classical Norwegian school of frontal analysis, reflects our loyalty to conventional wisdom rather than adherence to scientific evidence. Many operational meteorological centres have since abandoned or are in the process of relaxing such restrictive practices (e.g., Santurette and Joly 2002).

2.3 Stay away from the mountain

Another point of contention is whether to extend the cold front westwards into the quasi-stationary low over southwestern China. Some would argue that a frontal zone on the east side of a low pressure system, in view of the prevailing southerly geostrophic flow, should be analyzed as a warm front and not as a cold front. In practice, the compromise is very often to draw in a trough for that sector. But if we bear in mind that the low in this case is very much a terrain-hugging feature over the Yunnan Highland, the argument becomes academic and irrelevant. Given that the cold air over southern China is hardly more than 2 km in depth and that the Yunnan highlands and mountains are in general over 1 km in height, there is little point in extending the surface cold front west of 105°E. For the depth of cold air commonly found over southern China, the western extent of the front becomes blocked by terrain near 110°E at some latitudes.

It really serves no meaningful purposes to be too dogmatic in insisting that a cold front should not be extended all the way into the quasi-stationary low over southwestern China. At times, for the sake of completeness and continuity, there could well be some merits in retaining an artistic license within an essentially scientific exercise. But a word of caution here: if the low over southwestern China is a developing weather system (cyclogenesis), then there will be active southwesterlies feeding into the east side of the low. In such cases, a trough or a stationary front through the low appear to be the more flexible alternatives, at least as an interim

measure before the vortex moves eastwards and eventually evolves into a frontal depression over the East China Sea (also see section 2.7).

2.4 Curved or broken fronts around topography

For shallow cold air of no more than 1 km in depth (check upper-air data!), the physical barrier posed by the Nanling ranges becomes a major consideration. Cold air passage tends to be easier over the mountain passes, e.g., outbreak channels towards Beibu Wan and the Pearl estuary are two of the most popular routes. Such localized effects are best dealt with by doing an in-depth analysis using the zoom-in box on the top left corner of the large scale surface charts. For the drawing of cold front as a synoptic system, it is acceptable to have the small scale terrain-related irregularities along the front smoothed over. But for major terrain effects such as the easterly surge down Taiwan Strait and the blockage of the Taiwan ranges, the cold front can be sharply curved or broken (Fig. 2).

The handling of the front over Nanling and the Fujian mountains can create further problems in continuity and interpretation. In Zhu *et al.* (1992, pp. 335-336), the trapped front over the Fujian mountains is taken to be “occluded” due to orographic blocking. However, there is often a tendency for forecasters to leave a “stationary” cold front over Nanling and the Fujian mountains while a narrow ridge continues to extend towards the coast of Guangdong. As the cold air finally reaches Hong Kong in the form of freshening easterlies, an undesirable situation develops in which there is evidently a change of air mass over Hong Kong and yet the cold front is still analyzed to the north over southern China.

A better strategy is to maintain the frontal continuity over Nanling and the Fujian mountains as far as possible in a typical sequence of A to D as shown in Fig. 2 (akin to Chin 1969). Effectively, the “occlusion” over the Fujian mountains between the continental cold air and the modified cold air down the coast of southeastern China is implicitly assumed, with only the active part of the cold front explicitly analyzed and tracked to mark the continuing advance of cold air towards the South China Sea.

Once over the northern part of the South China Sea and less inhibited by terrain, the front can become smoother and, if supported by observations, may even be linked up again with the front over the Pacific sector. If the cold air does not have the momentum to reach the South China Sea, then certain sectors of cold front can be re-analyzed as a stationary front (or a trough as may be the case when baroclinicity is weak but convection is active). This tactic can be especially useful in monitoring warm air intrusion in spring time when maritime airflow increasingly encroaches upon the coastline, typically over western Guangdong (i.e. the cold front in Scenario C in Fig.2 will effectively evolve into a stationary front with cooler air generally retreating inland).

2.5 Make better use of stationary fronts

It is undesirable to have the cold front retreating back towards the cold air.

If the southward advance of the cold air becomes hesitant, the front may evolve into a stationary front if baroclinicity is maintained. For some reasons, the stationary front is not a very popular option in CFO practices. There is certainly a case for it being used more often. Otherwise, unless a cold front is analyzed, all shear lines are presented as troughs irrespective of whether there are contrasts in air mass characteristics on both sides. In effect, this can at times lead to an under-representation of the developing weather situation and may impact on the forecast formulation.

2.6 Drop fronts when gradient slackens and frontal clouds become diffuse

With weakening frontal characteristics (i.e. frontolysis) and no marked wind shear, pressure gradient slackens and the front becomes indistinct. Frontolysis usually happens when the front moves to the northern part of the South China Sea where the cold air mass becomes sufficiently modified and mixed. Depending on the season and the prevailing synoptic conditions, the trough will either dissipate in time or cyclogenesis (occasionally tropical cyclone formation) will take place along the remnant trough. At times of uncertainty, a useful tactical move is to put in a dissipating front. Depending on subsequent development, the front can then be dropped, replaced by a stationary front or trough, or taken over by a full-blown low pressure system.

2.7 Retain multiple fronts/troughs if situation warrants

If conditions are favourable, frontogenesis may become active again along pre-existing troughs and stationary fronts. The sequence of events very often starts off with a remnant trough or stationary front over central or southern China and a developing cold front over northwestern China heralding a fresh outbreak of cold air. In most cases, the two systems will eventually merge into one before reaching the south China coast as an active cold front. On rare occasions, the two systems may retain their separate identities throughout their southward march and their progress need to be carefully monitored if changes in local weather conditions are to be accurately captured (see example in Section 4).

3. CASE 1 – OCTOBER 1996

The history of a cold front in early October 1996 was used as an example to illustrate the differences arising from the various analysis approaches. Frontal analysis based on surface data over China from 00 UTC 5 October 1996 to 00 UTC 8 October 1996 were re-analyzed using the following definitions:

	Methodology	Notations in Fig. 3
(a)	The pressure gradient front (as defined in Fig.1)	Conventional cold front symbol
(b)	The pressure front (24-hr pressure change contour of +2 hPa)	Dashed line labelled “P” (----P-----P-----)
(c)	The temperature front (24-hr temperature change contour of -2°C)	Dashed line labelled “T” (----T-----T-----)
(d)	The dew-point front (24-hr dew-point change contour of -2°C)	Dashed line labelled “D” (----D-----D-----)
(e)	The wind front (organized northerly winds, say ≥ 10 knots)	Wind barbs
(f)	The weather front (organized frontal precipitation)	Precipitation symbols

Allowing for discrepancies in interpolation among different data fields, it was found that the frontal boundaries as given by the analysis of various parameters were in reasonable agreement at the beginning of the period (Fig. 3(a)), with the temperature and dew-point fronts slightly behind the pressure gradient front. The notable exception was the pressure front which lagged behind by about 200 km as the cold air emerged from northwestern China.

By 6 October (Fig. 3(b)), the fronts had reached central China. Judging from the wind, dew-point and temperature fields, the cold air appeared to be breaking out in small pockets ahead of the pressure gradient front. The push was most noticeable between the longitudes of 110°E and 114°E. This was also the sector where precipitation was enhanced ahead of the front. The pressure front, meanwhile, still lagged behind but was fast catching up. Precipitation was generally located behind the various fronts except along the western sector.

By 7 October (Fig. 3(c)), the pressure front had succeeded in overtaking the rest, particularly along the western sector where it reached as far as Hainan Island and the Vietnam coast. However, it was obvious that the front edge of the cold air mass was still very much over Guangdong. As a result, there were hardly any significant changes in the weather in Hong Kong. The wind and weather fronts, however, started to lag behind the rest. The wind surge effect was probably dampened by the physical blockage of the Nanling ranges. Localized outbreak of northerly winds was most evident over Beibu Wan.

The surge crossed the south China coast early on 8 October (Fig. 3(d)).

The temperature and dew-point fronts in general kept in step with the pressure gradient front. The relative position of the pressure change contour of +4 hPa, labelled “P*” in Fig. 3(d), was also examined. Lagging slightly behind, the +4 hPa contour, a commonly adopted threshold among the forecasters, was shown to be more representative than the +2 hPa contour. Uninhibited by terrain, wind effects became more conspicuous as reported by the coastal stations. The weather front, meanwhile, retreated back towards central China in association with the upper troughs.

In summary, this example of typical frontal analysis demonstrates that the pressure front (unless adopting a more stringent criterion of +4 hPa), the wind front and the weather front were in general less reliable. The pressure gradient front, on the other hand, correlated well with temperature and dew-point changes. Positions of the pressure gradient front in relation to the isobaric analyses from 00 UTC 5 October to 00 UTC 8 October are shown in Fig. 4(a)-(d). Timing of frontal passage based on the pressure gradient consideration was also consistent with the observed changes of weather in Hong Kong, with the frontal clouds arriving on 8 October and bringing patches of light rain to the territory; temperatures and dew point started to fall and the drop became even more pronounced the next day as the full impact of the cool air was felt:

Date	Mean Pressure (hPa)	Maximum Temperature (°C)	Mean Temperature (°C)	Minimum Temperature (°C)	Mean Dew- Point (°C)	Duration of sunshine (hours)	Mean Cloud Amount (%)	Total Rainfall (mm)
6 Oct	1012.3	29.3	27.3	25.1	24.3	7.4	71	4.1
7 Oct	1013.8	30.3	28.0	26.4	24.6	10.1	42	Trace
8 Oct	1014.8	29.2	27.0	25.2	23.2	5.0	64	1.9
9 Oct	1014.9	26.6	25.2	23.9	20.5	0.3	85	0

4. CASE 2 – MAY 1994

A trough crossed the south China coast on the night of 3 May. Weather in Hong Kong deteriorated earlier in the day as the trough approached. In the aftermath of trough passage, temperature dropped from a high of 28.8 degrees on 3 May to a low of 21.1 degrees in the early morning on 5 May. There was also a sharp fall in dew point during that time, from 24°C to 13°C. With a mean relative humidity of 51% on 5 May, the sky cleared for a brilliantly sunny day. Even though a front was never analyzed on the working charts, the whole weather sequence was reminiscent of a clearing surge in winter. The change in air mass during the event was quite marked.

With hindsight, a trough and a cold front could both be depicted in the post-analyses of the surface charts. The trough was characterized by weak wind shear and active convective clouds along a pressure trough. The front was characterized by strong temperature and dew point contrast just ahead of the pressure gradient. Early on 2 May, the synoptic situation was dominated by a deep low over southwestern China with a broad trough extending northeastwards across central China. When first analyzed at 12 UTC on 2 May, the cold front was about 600 km north of the trough along the western sector. The gap was generally narrowed down to about 300 km by the time the trough reached the coast of Guangdong at 12 UTC on 3 May. Continuity showed that the trough and the front crossed the coast as two separate systems, the latter arriving about 24 hours later. The surface re-analyses at 12-hourly interval during the period are shown in Fig. 5(a)-(f).

The response time of various weather elements in Hong Kong as shown in the table below was consistent with this scenario. Falling pressure and a deterioration in weather normally associated with a trough scenario occurred as early as 3 May. However, clearance of clouds and a significant drop in dew point normally associated with a change of air mass did not take place until 5 May. If the event was represented solely by either a trough or a front, the effects due to the other system could well be overlooked or under-estimated. The timing of onset and clearance of weather would also be severely compromised.

Date	Mean Pressure (hPa)	Maximum Temperature (°C)	Mean Temperature (°C)	Minimum Temperature (°C)	Mean Dew-Point (°C)	Duration of sunshine (hours)	Mean Cloud Amount (%)	Total Rainfall (mm)
1 May	1008.8	31.1	28.0	26.4	23.3	5.5	67	0
2 May	1006.3	30.3	28.6	27.3	23.8	3.9	83	Trace
3 May	1005.0	28.8	26.2	23.9	23.9	0	94	86.8
4 May	1007.1	25.9	21.7	21.4	21.4	0	95	19.4
5 May	1011.3	28.2	24.0	21.1	13.0	8.3	64	0

5. CONCLUDING REMARKS

Trials during the past several cool seasons support the use of pressure gradient for the location of cold front over central and southern China. In practice, while a trough tends to be analyzed along the axis of minimum pressure, the preferred strategy in placing a cold front within a broad pressure trough is to shift it towards the leading edge of the pressure gradient on the northern side, taking into account, of course, changes in wind, temperature and dew point wherever possible. This means that the spacing of isobars and hence careful interpolation between station values become very important in operational analysis. As a corollary, computer analysis of surface isobaric charts, which tends to smooth over such fine details, should be treated and interpreted with care.

When to start (or drop) a front and where to locate a front can be problematic at times, particularly as continuity needs to be maintained in the sequence of weather maps issued for the public on the internet or through the mass media. The guiding principles here are: (a) on working charts, the existence and locations of fronts on earlier analyses should always be re-evaluated and refreshed in the light of latest information; and (b) on weather maps for the public, the current thinking and assessment should always be accurately and faithfully reflected with due considerations given to continuity and consistency as far as possible.

Apart from synoptic observations, satellite information and NWP guidance should also be referred to in analyzing and placing a front. Sometimes, a remnant front or a pre-existing trough may lie dormant for days before becoming active again in terms of weather development, often heralding an imminent change in air mass. The satellite images would provide a useful indication of such developments. For potential cyclogenesis and frontogenesis, the forecasters can also consult the numerical prognoses for the next 12 to 24 hours to determine whether the feature in question is developing or merely transient in nature. Once a front is analyzed, it should be located and tracked to the extent the observations allow. Nowadays, NWP prognoses can also provide reasonably accurate depictions of frontal movements in the short range. These provide useful frames of reference in determining how far forward a front should be placed, especially when interpretation of surface observations is complicated by orographic influences (e.g., cold front passage over Japan). Similarly, as a front degenerates, surface observations, satellite analysis and NWP guidance should all be taken into consideration before dropping a front from the charts. The danger here, and a bad practice as such, is to underestimate its impact or to become lax in analysis when a front is judged to be of no further threat to Hong Kong (e.g., after the cold front has moved southwards to the South China Sea).

A combination of trough and fronts along an air mass boundary (e.g., a cold front over the Ryukyu Islands gradually evolving into a trailing trough in the South China Sea) is not uncommon. But over a spatial scale of 30 degree longitudes between the eastern slopes of the Tibetan Plateau and Japan, complicated combinations of multiple transitions along one single boundary (say from trough to

stationary front to cold front and to occluded front) may be regarded as an over-interpretation, especially considering the lack of observations over the oceanic areas to justify such differentiations. A family of frontal depressions with alternating warm and cold fronts in tow can be analyzed at times, but the number of depressions is usually no more than two or three. Any significant changes in analysis should also be consistent with the synoptic development. For instance, it would look extremely odd if a trough is re-analyzed as a cold front when there is apparently no fresh outbreak of cold air from the north! For stationary fronts that are normally lodged over weak flow region, their placement across or ahead of regions of high pressure gradient would be difficult to rationalise in the face of strong southerly (warm advection dominant) or northerly (cold advection dominant) flow.

There is always a fair degree of subjective judgment in frontal analysis and pragmatic considerations cannot be totally ignored. In other parts of the world, the approach can be much more liberal and diversified (see Fig. 6). Given the prevailing conservative tendency in Hong Kong in leaning heavily towards the classical mode, forecasters should be wary of including a frontal feature that cannot be found in Fig. 6! For example, a common pitfall is the temptation to conveniently link up “O5” with “C1” right through the centre of “L3” when “L4” is hovering over the Sea of Japan and “L3” is developing south of Japan (see also legend for “O5” in Fig. 6).

Apart from pragmatic considerations, common sense based on sound meteorological understanding is indispensable. For example, it should be remembered that the frontal zone is a narrow strip of finite width, typically about 100 kilometres across in order of magnitude, and not a line of discontinuity as often suggested by the “kinked” (i.e. with an angular bend) isobars across the front. So to have isobars crossing the front at a sharp and pointed angle can be regarded as a gross aggravation of an already misleading situation and an unnatural departure from the real world (Fig. 7(a)). Such a discontinuity is mathematically not differentiable and would be a problem in any numerical simulation! The weaker the front, the more obtuse should be the angle the isobars make across the front (Fig. 7(b) and (c)). Along the same argument, the isobars should become highly curved rather than “kinked” if the front is replaced by a trough.

Ultimately, while an endless discussion on what is acceptable and what is not permissible can often lead to a cul-de-sac, a return to the first principles is never wrong and may even turn out to be more enlightening and beneficial in the practical sense:

- all analyses and annotations, frontal or non-frontal, are there to tell a weather story;
- the story has to be based on sound meteorological knowledge and reasoning, with a logical flow and good continuity;
- good reasoning and continuity stem from close monitoring and prudent interpretation of observational data (past and current), satellite information, as well as NWP analyses and prognoses.

And when we have done that, not only is good analysis ensured, we are probably more than half-way towards a good forecast as well!

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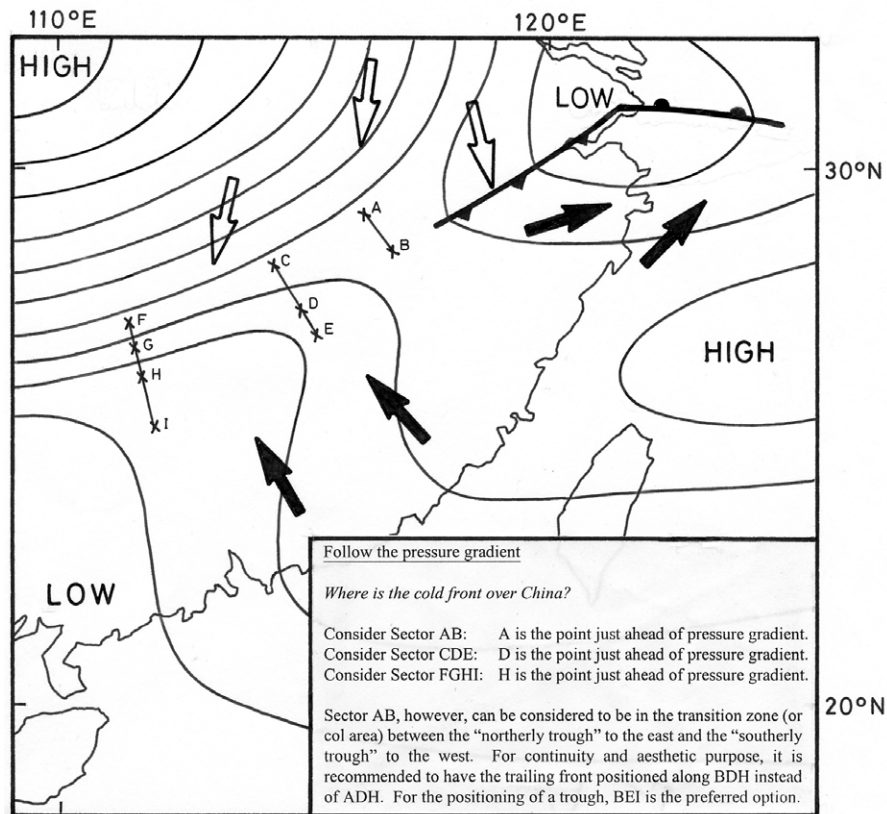


Figure 1 – Schematic illustration of the “hidden trough”. While the eastern portion of the cold front is lodged in the pressure trough of the developing frontal depression over eastern China, its trailing portion, to be extended westwards across China, should be placed just ahead of the pressure gradient rather than along the axis of minimum pressure within the pressure trough.

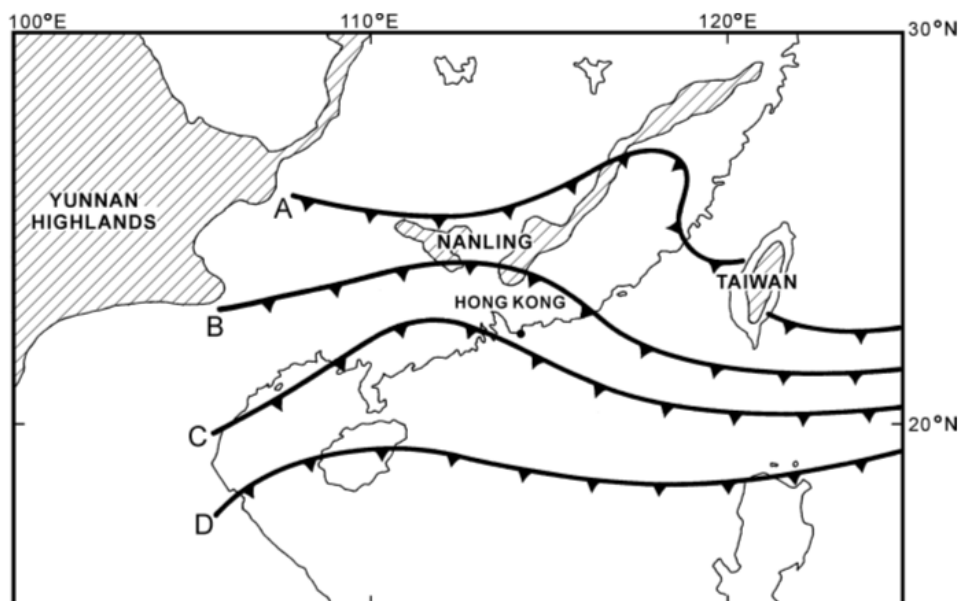
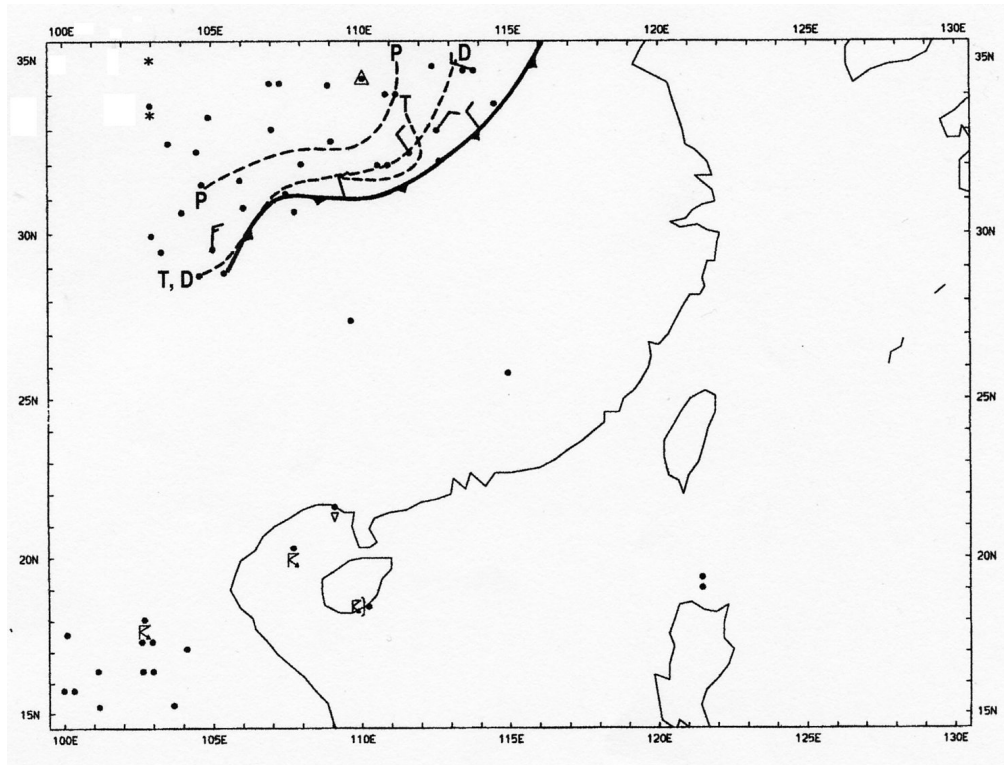
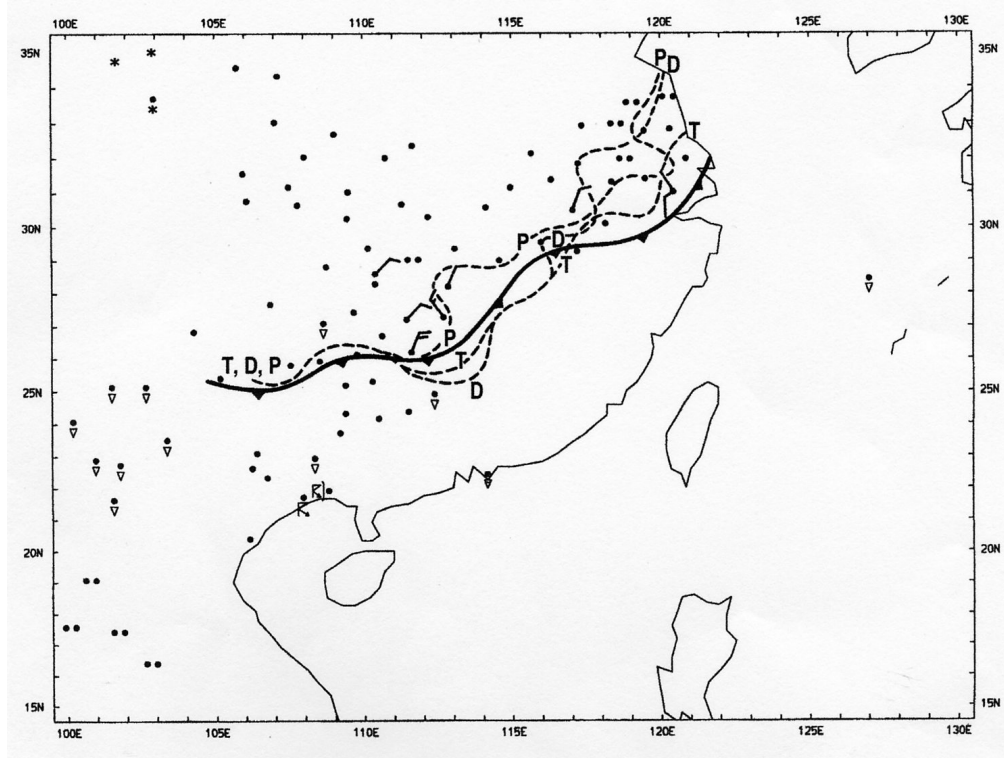


Figure 2 – Curved or broken fronts as a result of topography. Shaded areas are terrains of 1 km or higher.

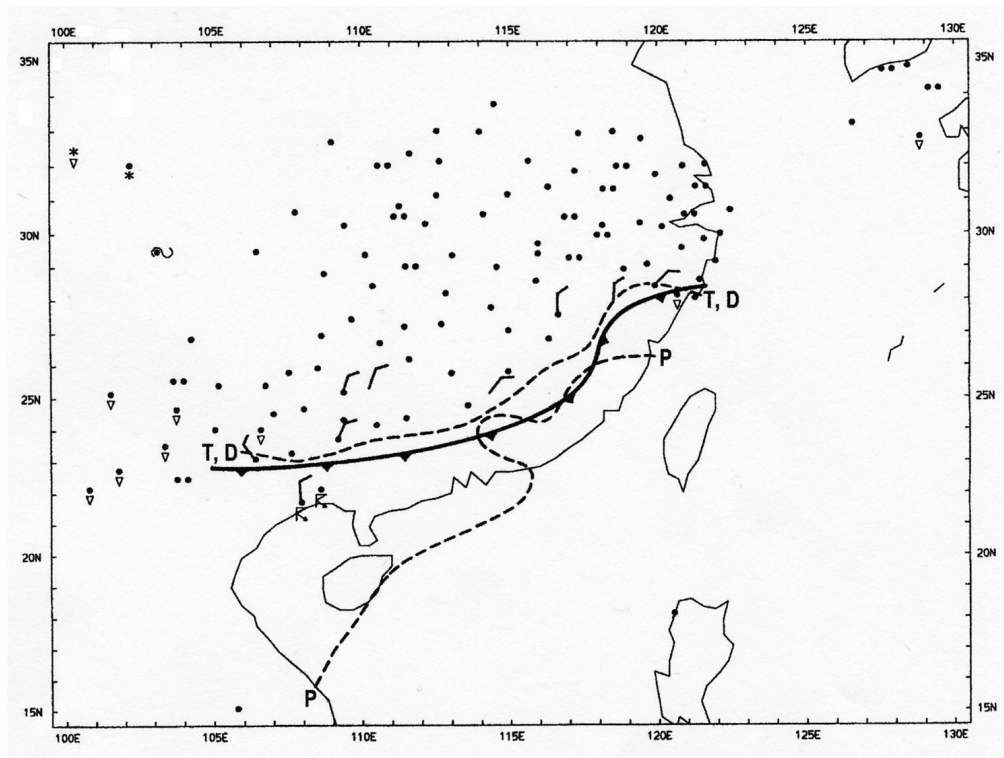


(a) 00 UTC on 5 October 1996

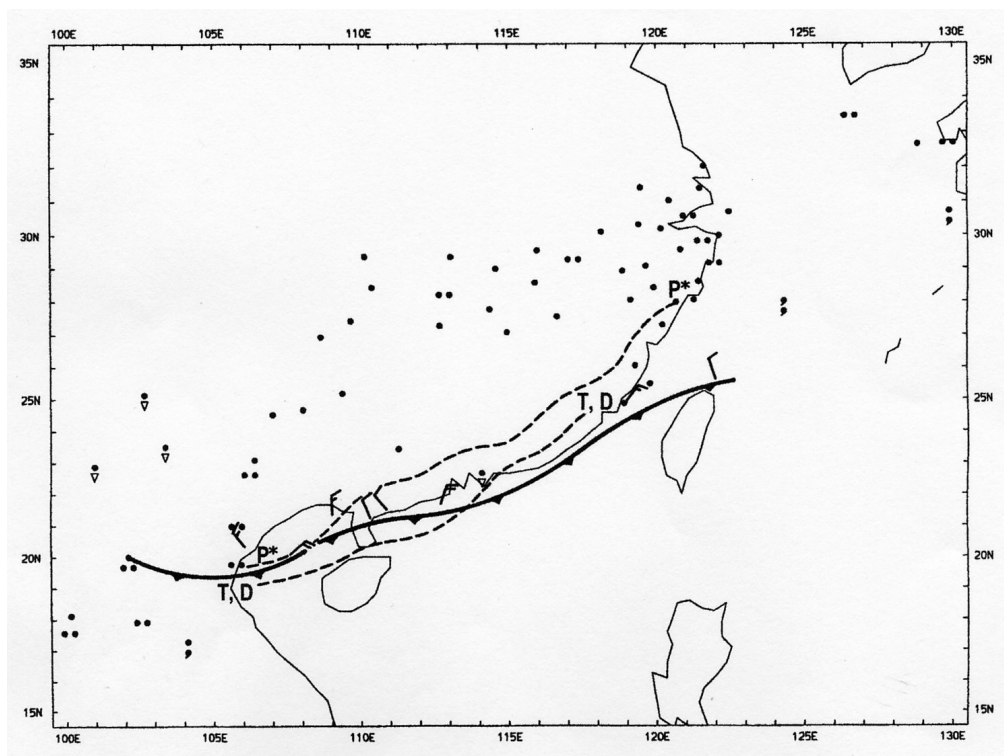


(b) 00 UTC on 6 October 1996

Figure 3 – Methods of cold front analysis based on pressure gradient, wind, precipitation, and 24-hour changes of pressure, temperature and dew point (see Section 3, page 6 in text, for legend).

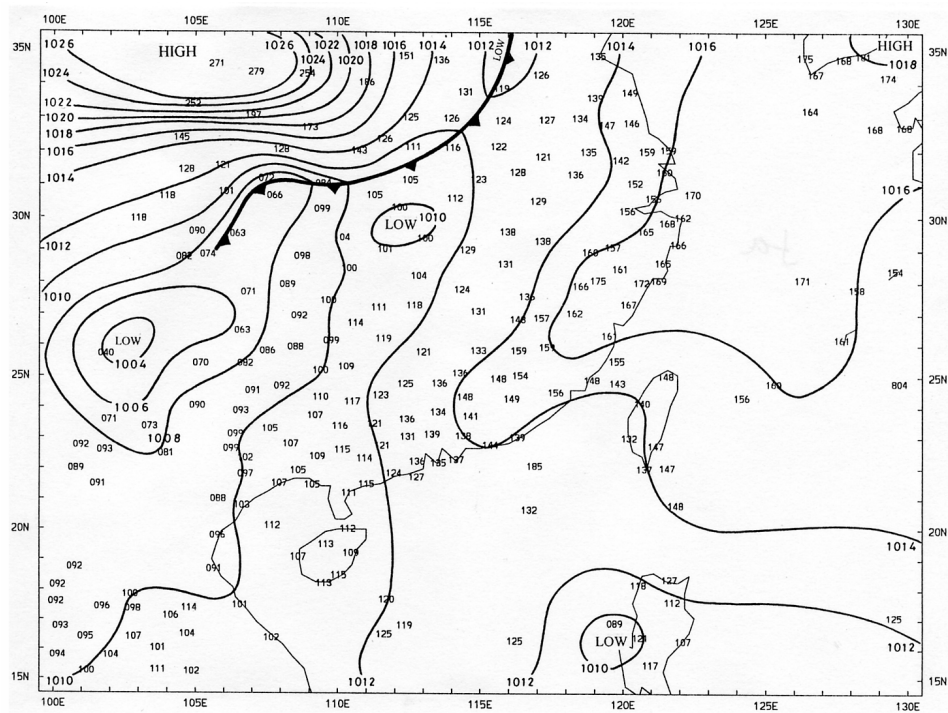


(c) 00 UTC on 7 October 1996

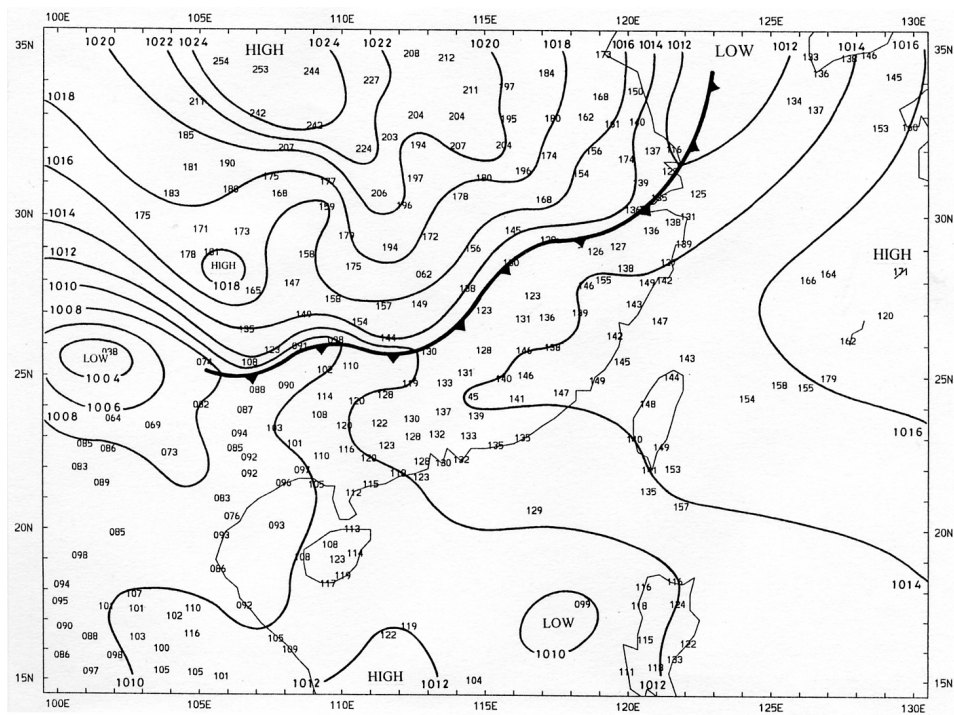


(d) 00 UTC on 8 October 1996

Figure 3 (cont'd)

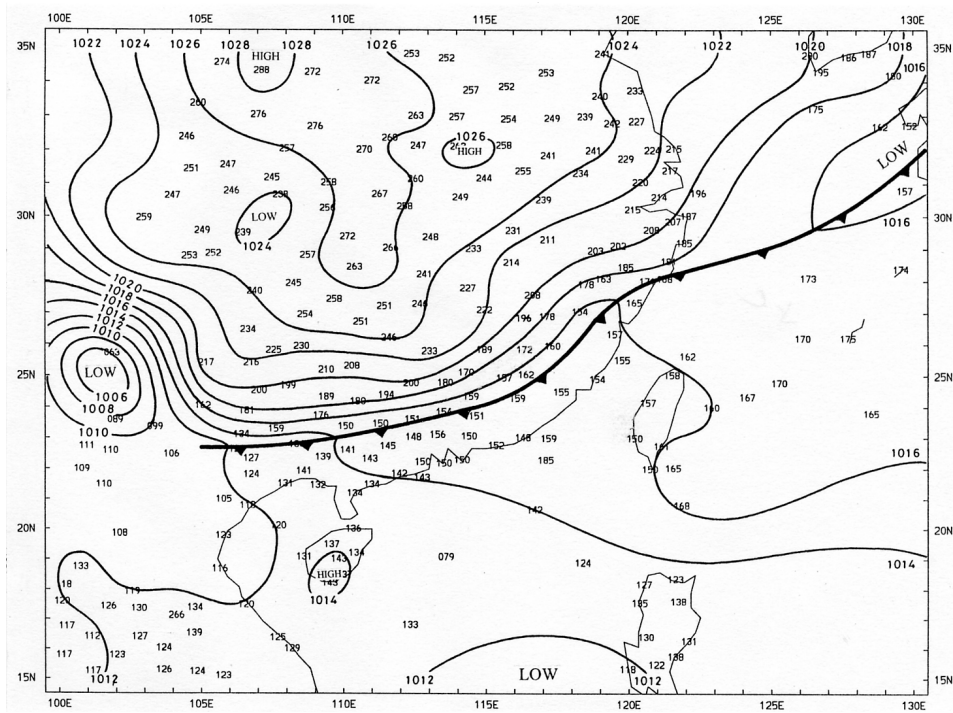


(a) 00 UTC on 5 October 1996

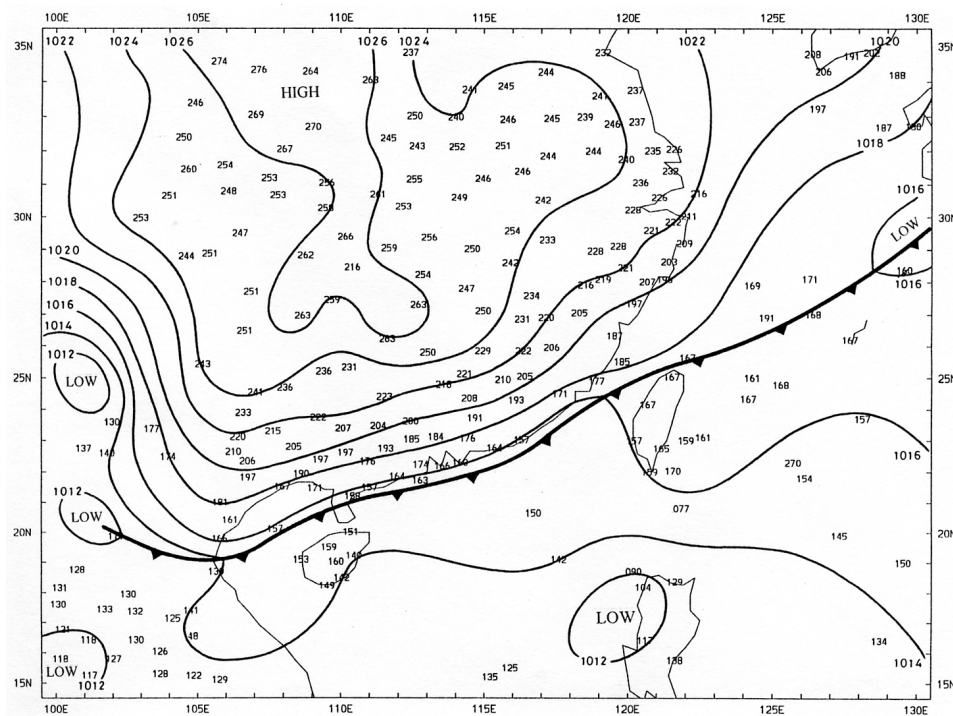


(b) 00 UTC on 6 October 1996

Figure 4 – Positions of the pressure gradient front in relation to the isobaric pattern.

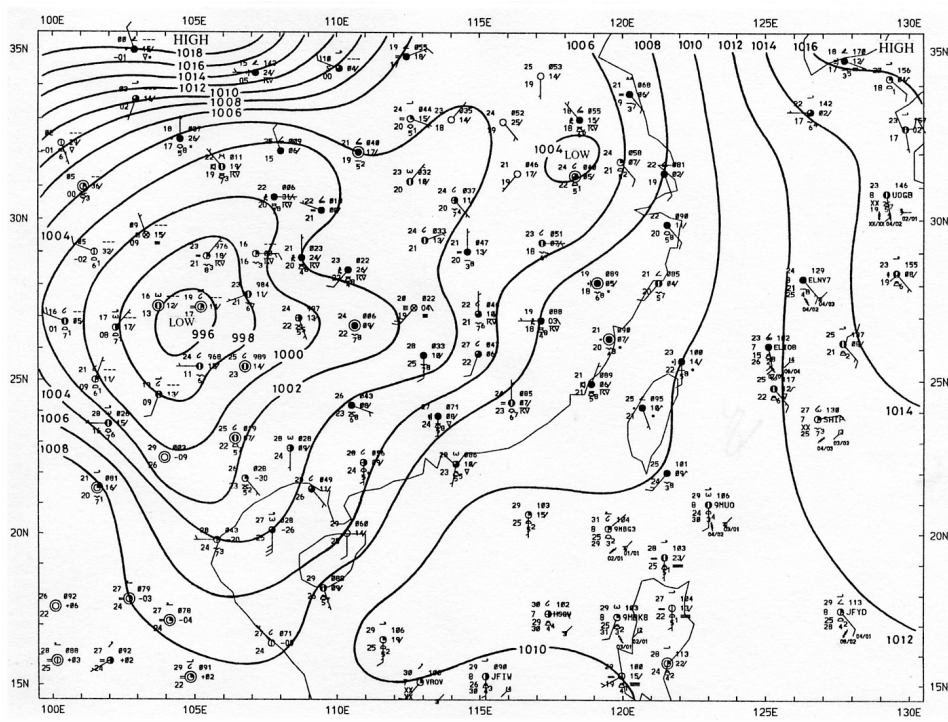


(c) 00 UTC on 7 October 1996

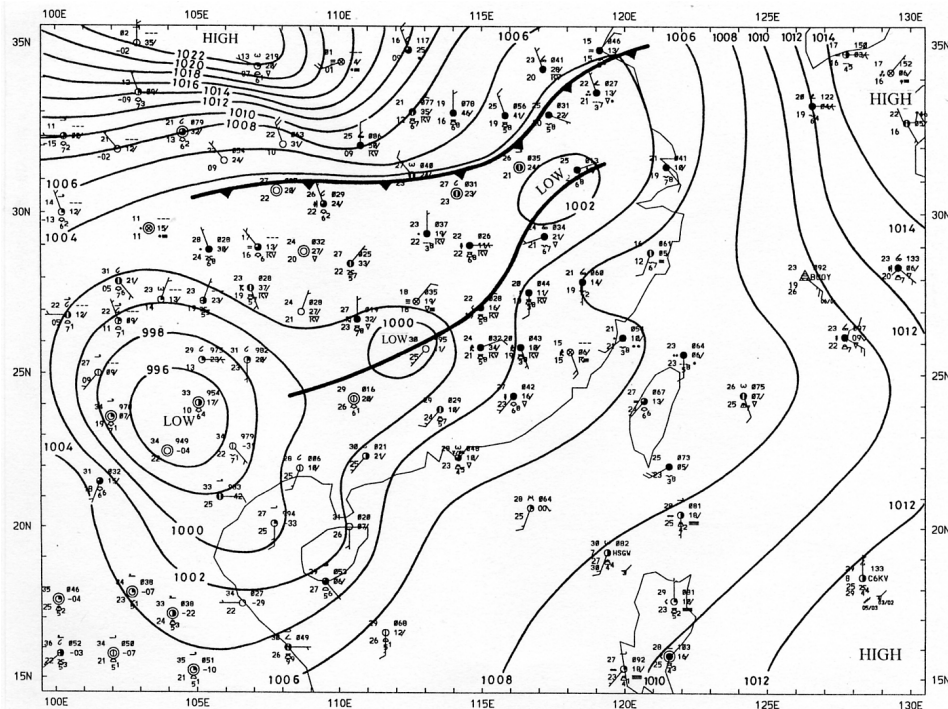


(d) 00 UTC on 8 October 1996

Figure 4 (cont'd)

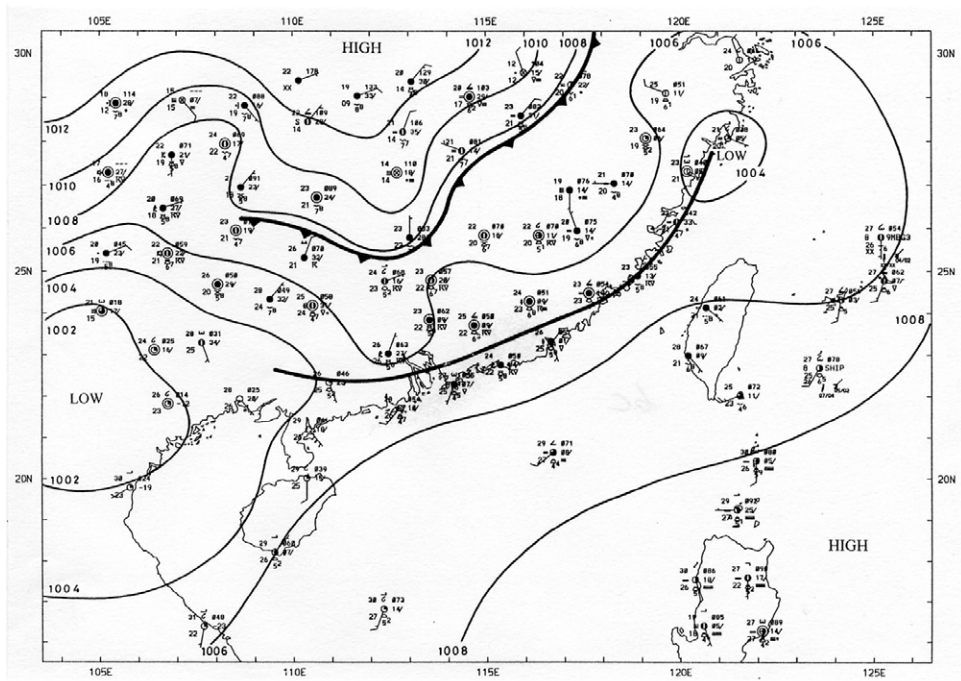


(a) 00 UTC on 2 May 1994

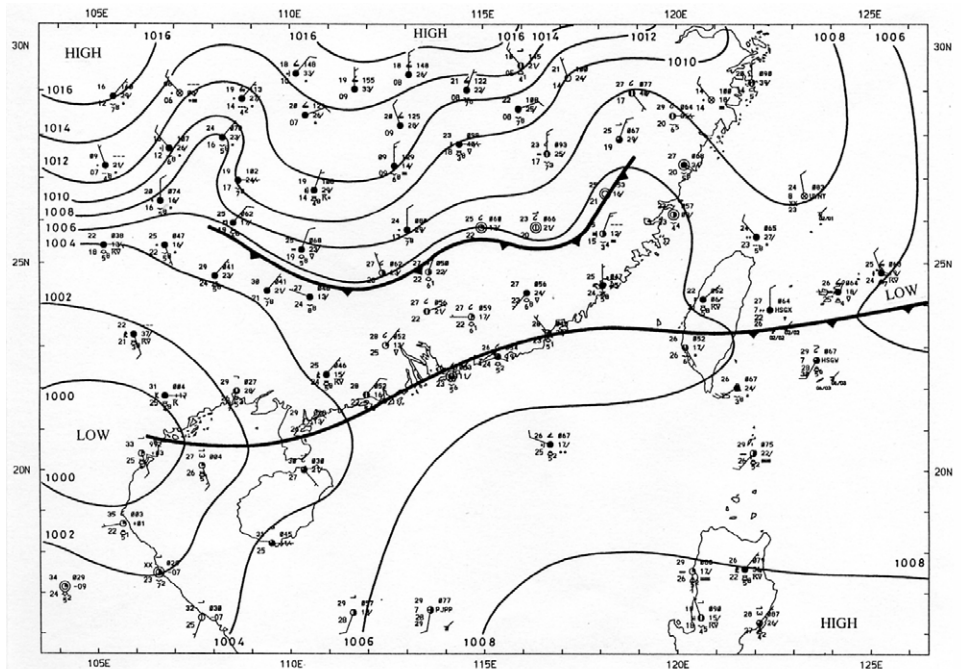


(b) 12 UTC on 2 May 1994

Figure 5 – Surface re-analysis of a cold front and a pre-existing trough in May 1994.

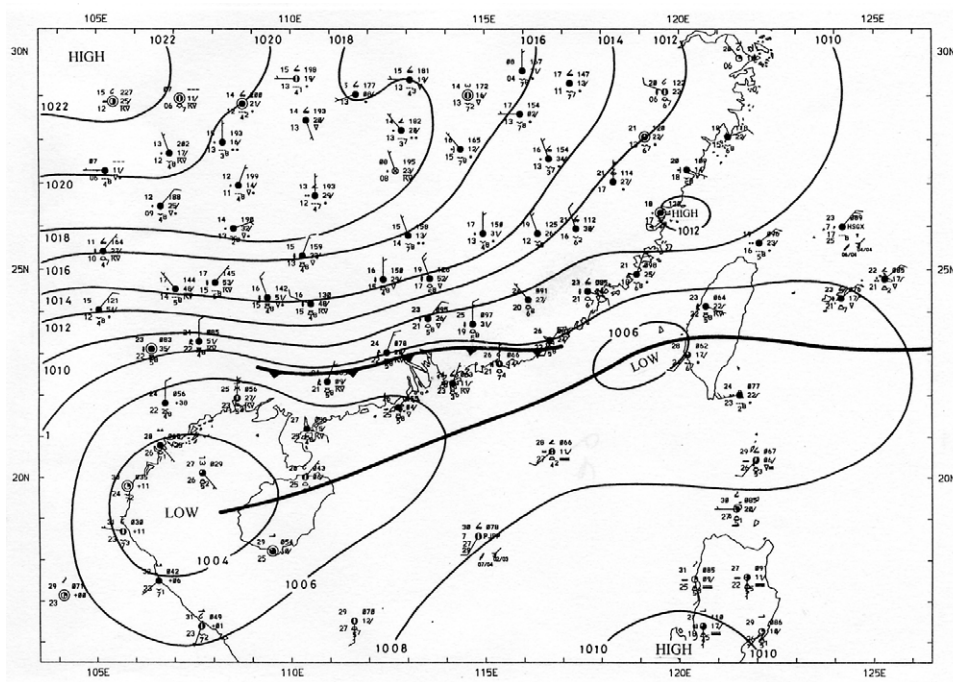


(c) 00 UTC on 3 May 1994

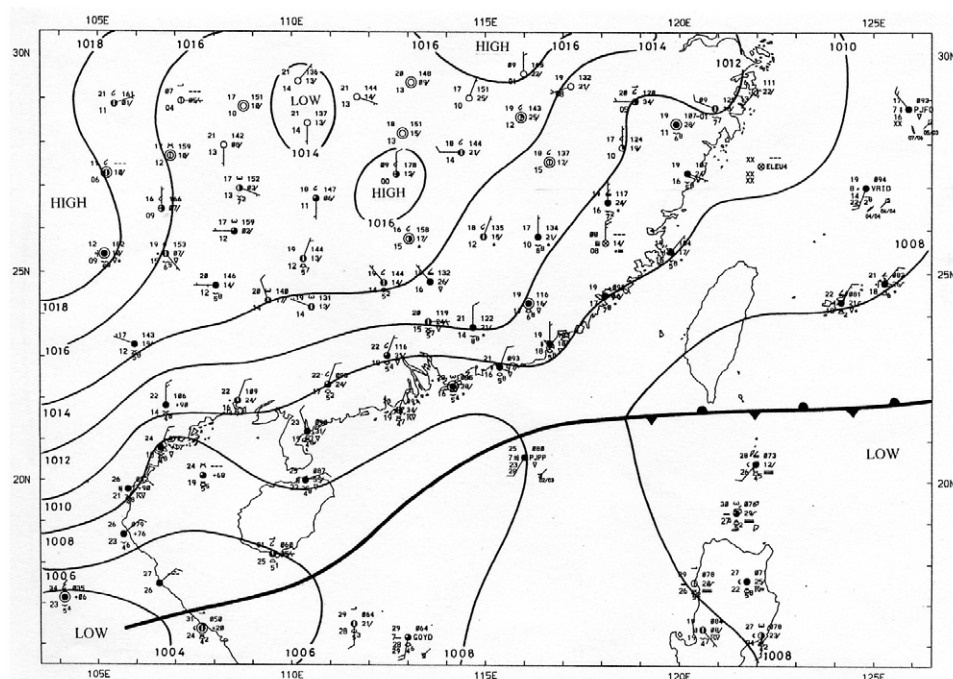


(d) 12 UTC on 3 May 1994

Figure 5 (cont'd)



(e) 00 UTC on 4 May 1994



(f) 12 UTC on 4 May 1994

Figure 5 (cont'd)

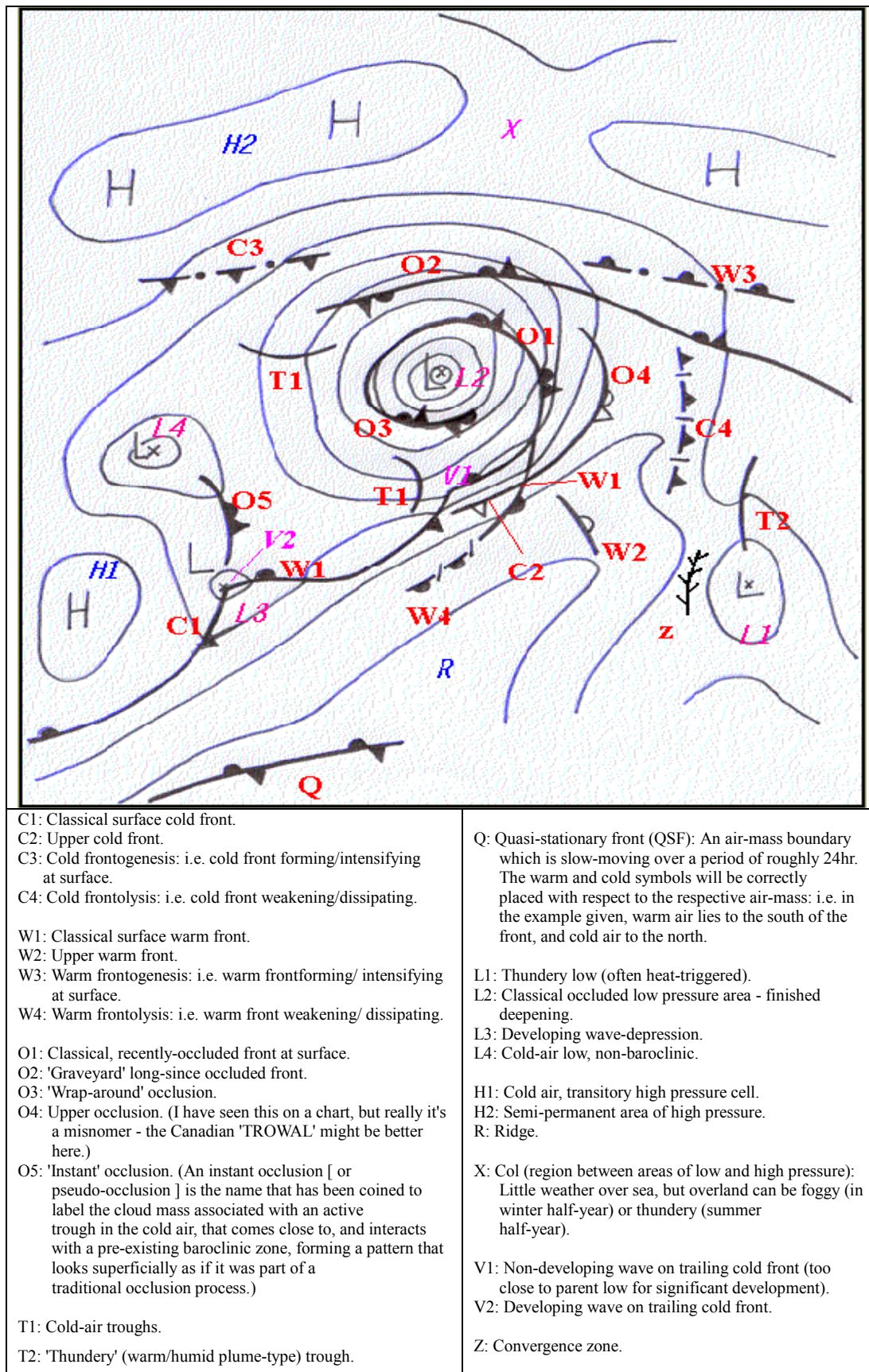
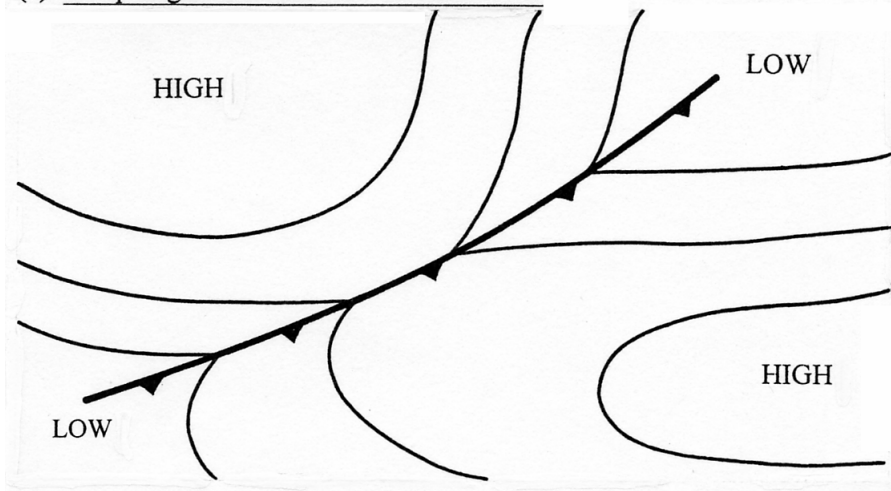
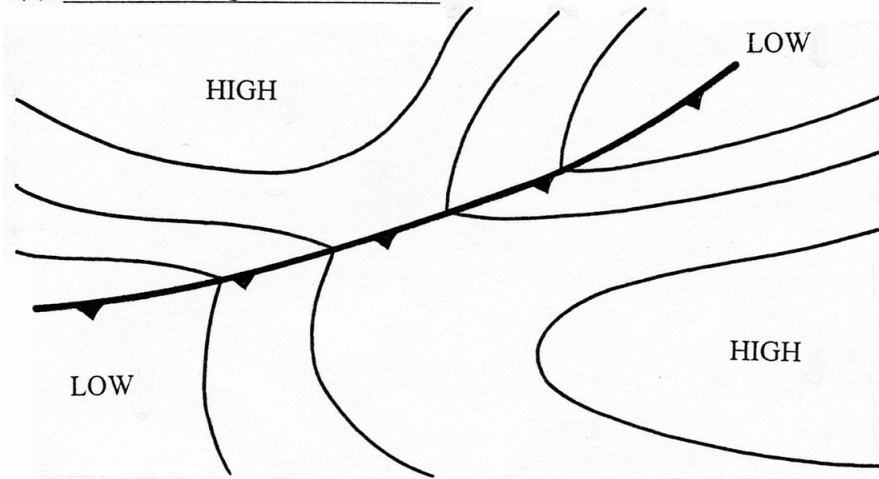


Figure 6 – A collection of fronts and troughs (source: Martin Rowley of UKMO at www.booty.demon.co.uk/metinfo/frontal_ex.htm)

(a) Sharp-angled curvature not recommended



(b) More acute angle for active front



(c) More obtuse angle for weak or dissipating front

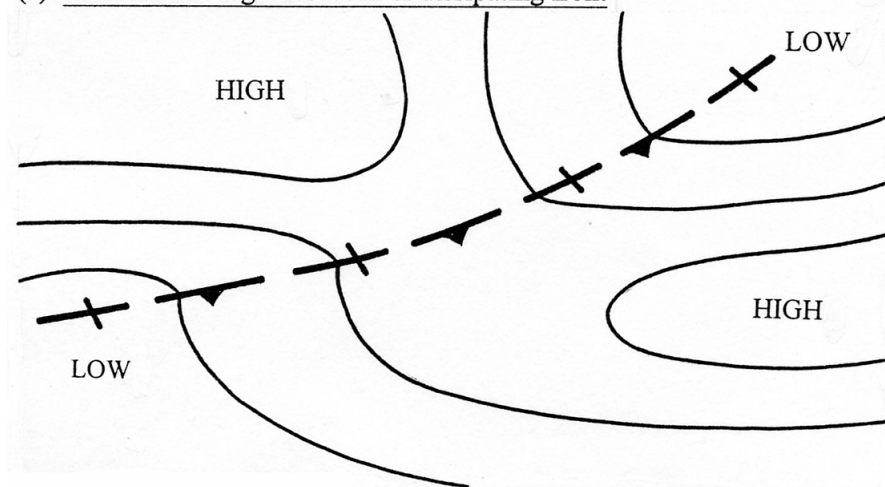


Figure 7 – Schematic illustration of the curvature of isobars across a cold front.