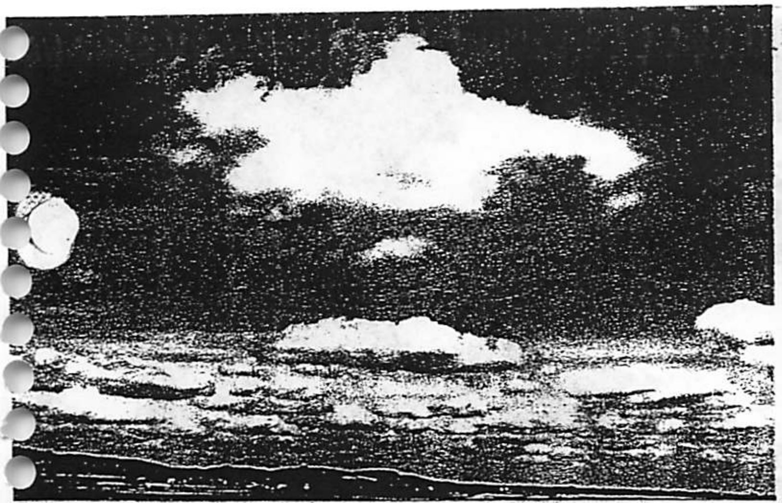
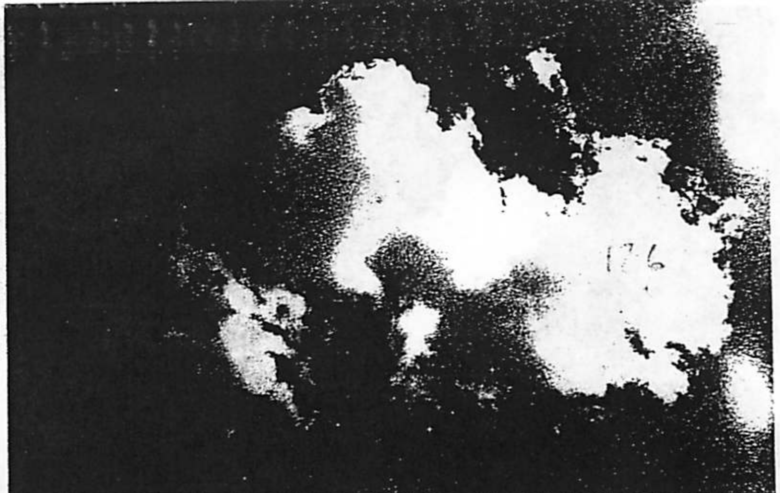




Both Photo A (left) and Photo B (right) show the decay of a very shallow cu under an inversion. All the photos and drawings are by Tom.

GROWTH AND DECAY O

TOM BRADBURY

No cumuli last for ever and some have a very brief life. It is worth watching for the first signs of change, especially in the cloud you are heading for. If a small cu decays it is usually easy to divert to an active cloud nearby. A developing cu-nim is much more serious. It may end up overshadowing a whole county.

Shallow cu

Photos A and B show the demise of a flat cu on a perfect day with high based shallow clouds under a solid inversion. A shows a decaying cloud nearby with active ones further away. B shows a cloud from directly below taken with a 24mm very wide angle lens. There was not a wisp of it left five minutes later. Shallow cu can become a mile wide or more and, although lacking in depth, persist at least a quarter of an hour. A cloud this size survives because the small area of lift feeding it moves about constantly refreshing it. When the lift fails holes appear and the cloud soon evaporates. From high up it is hard to spot the start of holes but looking at the shadows on the ground is a help.

Stages in the life of a cumulus

1. The initial thermal. Almost as soon as a thermal leaves the ground it begins to be weakened by mixing with its environment. This process, known as "entrainment", starts at the edge of the thermal. Most thermals have their maximum lift in the core. The core speed is faster than the ascent of the summit. As the faster rising air nears the top it usually curves outwards and begins to fall back when it reaches the side of the dome.

One can see this in time lapse films of large cumuli. The central dome surges upwards almost vertically but turrets on its edges tend to slip back relative to it. To begin with the little bulges at the side merely rise slower than the central dome but later on they actually descend.

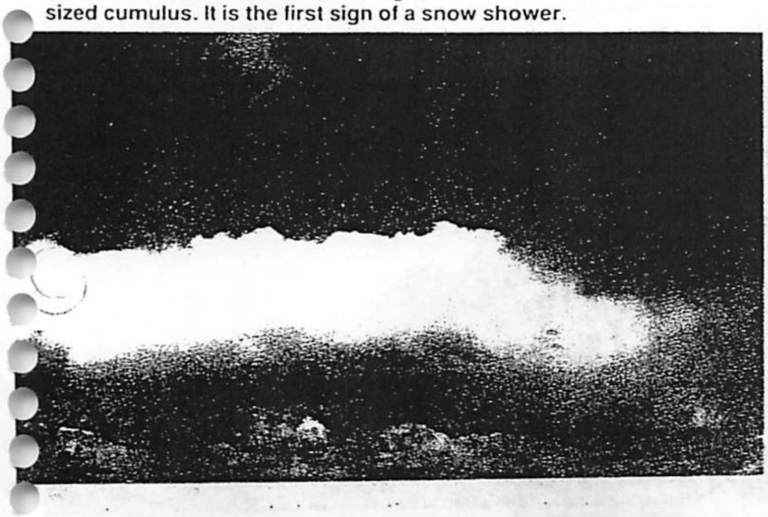
2. At first entrainment of outside air into the thermal occurs chiefly at the leading edge of the rising dome. Later outside air is drawn into the side of the cloud and some may curl round and enter near the base. One can often see that the surface of a large dome is covered with lots of lesser bulges. These engulf outside air as they rise, so diluting the thermal. Large wide domes take longer to become diluted than small ones and can rise further before they lose lift. A clump of cumuli lasts longer and grows larger than an isolated cloud because the inner clouds are protected from erosion until they emerge into clear air higher up.

The sheltered inner core sometimes builds up such a speed that it shoots out of the cloud mass as a long thin column. Thin columns offer less drag and can rise faster than the usual blunt dome of cumulus. Being narrow makes them vulnerable to erosion from the surrounding cooler and drier air so they have a short life. Any wind sheer tends to blow them over and the column is apt to break leaving only a dissipating bubble at the top with sink beneath it.

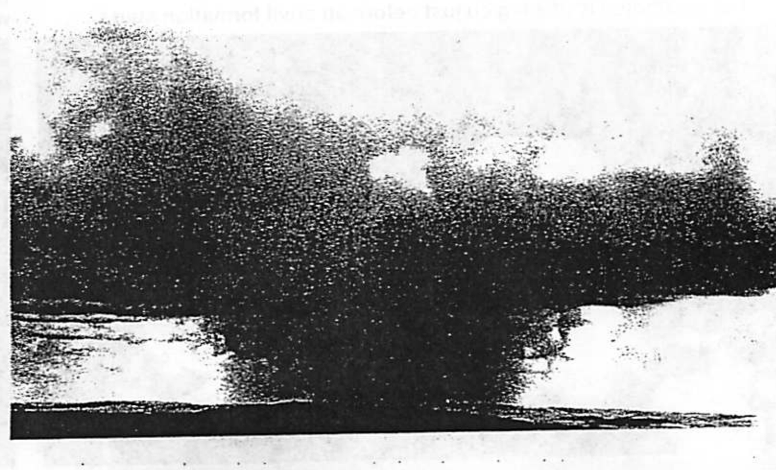
Photos C and D show two varieties of big cu. C looking east shows a good looking sky with no threatening features but D, looking SW at almost

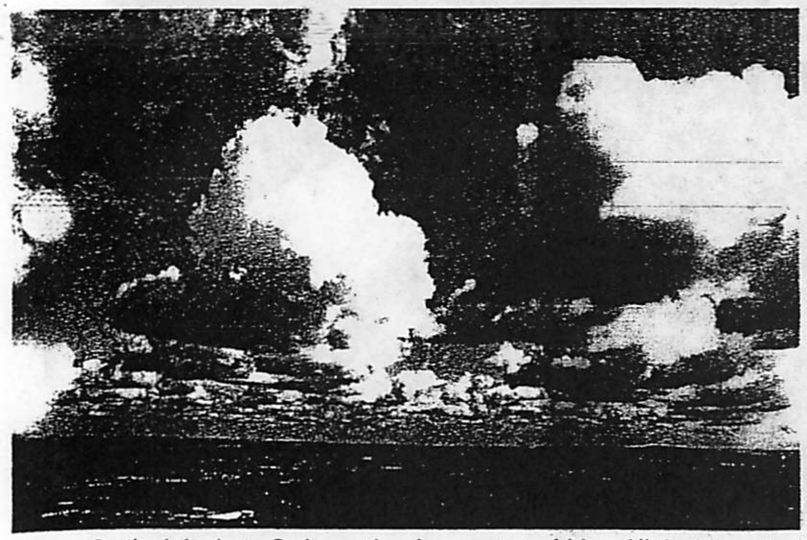
Photo E shows active cu with strong lift. The ne r right, but a new turret on the left shows where th f

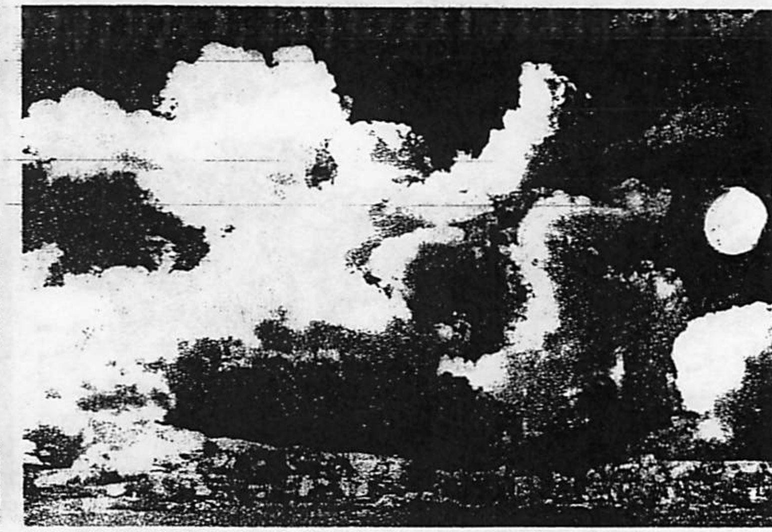
Below: Photo G. Glaciation blurring the outline of a moderate sized cumulus. It is the first sign of a snow shower.



Below: Photo H of a snow shower from an area of spread out.







On the left photo C shows the view east at midday. All the big cu look good ahead. Photo D (on the right) was taken looking SW at the same time as photo C. Over energetic cu are throwing up long narrow turrets which isn't a good sign for the afternoon.

CUMULUS

as begun to tilt and develop an overhang on the ved to.

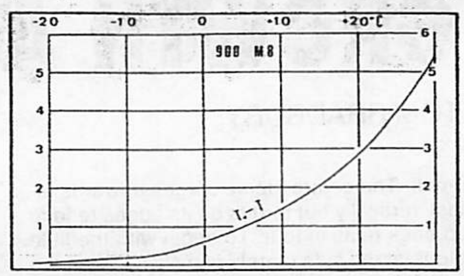


Fig 1. Graph showing the difference between actual and virtual temperature at the 900mb pressure level assuming 100% humidity.

the same time as C, is an early warning of changes for the worse. These clouds are altogether too energetic, throwing off narrow tilted columns in their haste to grow tall.

3. Moisture as a factor in lift

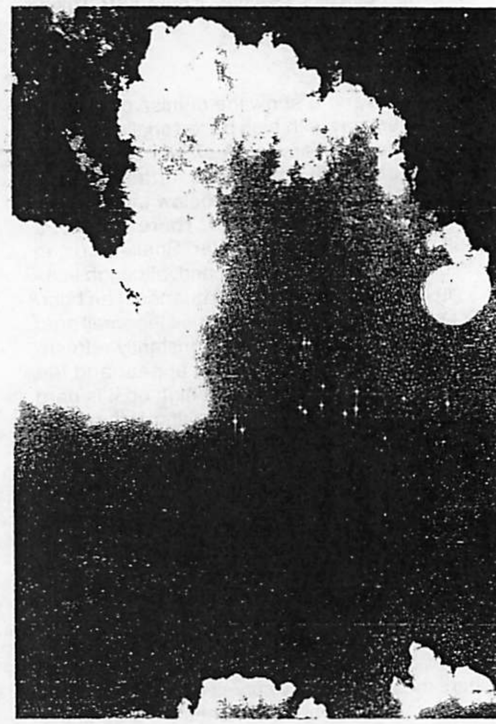
Water vapour is less dense than dry air at the same pressure and temperature. When calculating lift in a thermal it is convenient to work with the "virtual temperature". This a fictitious temperature at which completely dry air would have the same density as the saturated air. For example if the air at 900 millibars (3243ft in a standard atmosphere) had a temperature of 15°C and a relative humidity of 100%, the virtual temperature would be two degrees higher at 17°C.

The difference between virtual and actual temperatures is negligible below -20°C but increases to more than 5°C at a temperature of 0°C. Fig 1 shows a graph of this difference between virtual and true temperature. If the air is not saturated the virtual temperature is less than the value shown on the graph. For example with a relative humidity of 50% the value is halved.

Moisture becomes important when entrainment draws drier air into the thermal. The mixing both cools and dries the thermal and the original density difference is rapidly reduced.

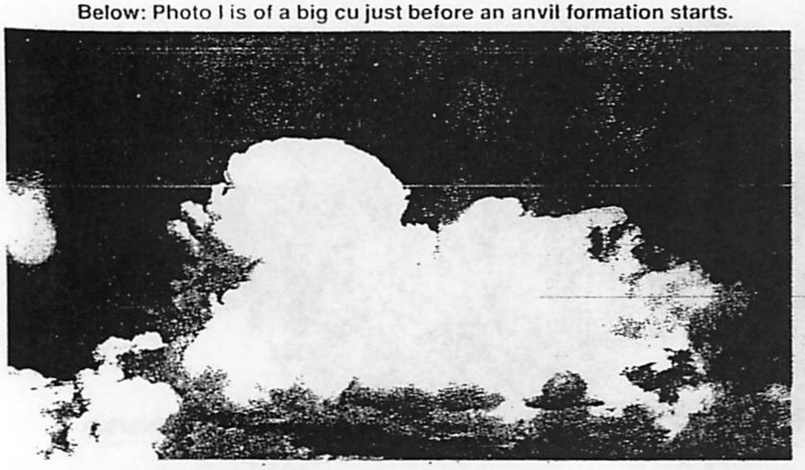
Condensation

The air can only hold a limited amount of water vapour and the colder it is the less it can hold.



Above - Photo F is looking up at an overhanging turret. Lift has moved to the far side where the base is still clear. (Taken with a 24mm very wide angle lens.)

Below: Photo I is of a big cu just before an anvil formation starts.



Below: Photo J was taken 15 minutes later when the small anvil was well developed

GROWTH AND DECAY OF CUMULUS

While unsaturated a rising thermal cools at 3 C/1000ft. When the temperature falls below the dewpoint, condensation begins and the water vapour forms cloud droplets. Condensation releases latent heat which increases the energy of the cloud. This usually allows the thermal to rise much higher. Entrainment of dry air from outside the cloud reverses the process.

Many traverses of cumuli made by aircraft with fast response temperature and humidity sensors showed that tiny pockets of dry air became engulfed by the growing cloud. With time these grew into sizeable volumes of air which had been cooled by evaporation as well as mixing. Volumes of denser air developed within the cloud; this first reduced the thermal strength and eventually stopped all the lift.

Visible signs

The first effects of entrainment are seldom visible to an approaching pilot; the process takes time to reveal itself. From the air it is difficult to watch how a cloud is developing; one is usually travelling too fast to be able to observe the changes and the altering angle of view affects one's impression of the cloud. Indeed rounding a TP and setting off in the new direction often seems to make clouds look better (or worse) than on the previous leg.

enforced grounding provides opportunity centrate on a single cloud. Stop watch. pad and camera are useful here. One soon finds problems. It is rare to be able to time a cloud from the moment it first forms and it requires patience to follow it to final extinction.

Some small cu form and disperse in a couple of minutes, especially early in the day. Such very short-lived puffs of cu often form just above the base of the inversion when momentum makes the thermal penetrate the stable layer above. Finding itself suddenly too dense to stay up the thermal quickly flops back and its marker puff vanishes.

Most medium sized cu go through a cycle of growth, decline and revival which makes timing frustrating. Clearly fresh pulses of lift come up to revive a moribund cloud. (How often do you look back and see the cloud you spurned five minutes ago has just grown a new turret and now looks better than the one you are under?)

Photo E shows a collection of cu on a day of strong lift. The right hand (downwind) side of the nearer cloud has begun to tilt indicating that the lift is failing there but the new turret poking up on the left marks where a fresh pulse of lift is active. Photo F was taken looking up at a turret when it had only recently started tilting. The top still looks active but is actually just starting to overhang (as in E). Approaching such a cloud one usually doesn't find any lift until the far edge is reached.

Bright clouds are best

A growing dome of cu has a sharply defined and usually looks a bright white if the sun is behind you. It is bright because the newly formed droplets are small and very close together so that they reflect sunlight particularly well. A dulling of the cloud can mean it is aging; the tiny droplets are merging into larger and less reflective elements.

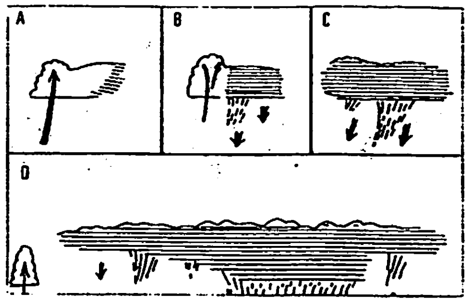


Fig 2. A to D - cold springtime cumulus becoming glaciated and producing a snow shower. Horizontal lines show where ice crystals had become dominant.

Look of the cloudbase

A sharply defined dome to a cumulus usually shows the upper part of the cloud is still active. Unfortunately the dome is often the last part of the cloud to decay.

It may keep growing for some minutes after the lift has ended below cloudbase. If the thermal starts to die out the first signs of decay show up at cloudbase. A ragged and uneven cloudbase usually means the lift has failed under that section. However there may be a new surge of lift further upwind and this will produce an inviting flat base. The new dome will appear a little later.

Decaying turrets

Soon after the turret has stopped rising the crisp outline starts to blur. Selective evaporation slowly changes the rounded dome into thin filaments of cloud and it ends up as a hairy mess. This affects even small cu but it is most noticeable with some cu-nim. The text books call it "Capillatus" which is Latin for having hair. The hairy appearance is often, but not invariably, a sign that the water droplets have changed to ice crystals.

Glaciation

This is the technical term for the transformation of supercooled water droplets into ice crystals. The process usually marks a fundamental change as a big cu grows into a cu-nim. The veil of ice crystals gives the cloud a misty appearance (see photo G), the domes and turrets start to blur and the first signs of anvil cloud may appear. This often starts near the downwind end of the cloud and takes very few minutes to transform the appearance. A shower quickly follows. On cold days in spring the precipitation often starts as snow which falls so slowly one can watch the trails sinking down and expanding outwards as the shower grows.

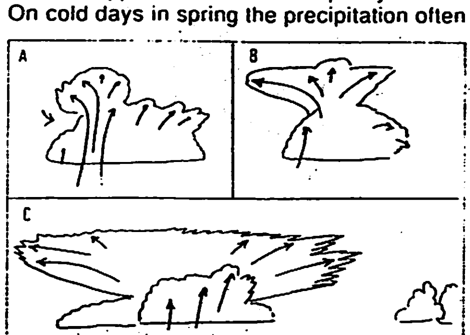


Fig 3. A to C - warmer cu developing a small anvil.

Spread out of showers

Showers vary greatly in the area they cover. Some cu-nim have a life time as brief as half an hour from start to finish. These are usually small enough to fly round without much waste of time or loss of height. Cu-nim which form wide anvils are a serious problem. The actual shower may only cover a small area but the anvil can grow to overshadow an enormous distance. Photo H illustrates an early stage in the spread out.

Fig 2 shows four stages in a cold springtime cu-nim. At (A) only the extreme downwind end has begun to glaciate and a new turret composed of super cooled water droplets is growing on the left (upwind) end.

In (B) the glaciation has spread more than half way through the cloud and the first trails of falling snow begin. By (C) the entire cloud has lost its crisp shape and a second trail of snow has begun. (D) shows the last stage when a vast sheet of cloud (still producing snow) extends across some thirty miles. When this happens in mid or late afternoon the cloud persists for two or three hours.

Anvil formation

Fig 3 shows a deeper cloud changing into the typical anvil of a cu-nim. The first stage (A) is a large swelling dome with the beginning of an overhang on the left. The anvil has developed in (B) and is nearing its full size in (C).

This kind of development is shown in photos I and J. Photo I shows a large dome of cloud with a notch cutting into it on the left hand (upwind) side. The subsequent change was quite rapid. Within a quarter of an hour the cloud looked very different.

An anvil had spread out in all directions and the cumulus base had degenerated into a rather small supporting column. The volume of air entering the cloud was probably much less than in I and the anvil did not grow much wider.

TOM BRADBURY

EVOLUTION OF CUMULUS CLOUDS

To get the best out of a promising sky it is vital to understand just how clouds are formed

Cumuli evolve into many different shapes depending on the stability of the atmosphere. the distribution of moisture, the variation of wind velocity at different levels and how the air is heated. This article describes some of the patterns which appear.

Basic thermals

Fig 1 illustrates five stages in an idealised thermal. The initial stage (A) consists of a shallow layer of air resting on a flat area about the size of an airfield which has been warmed by sunshine. The air in contact with the ground takes up heat and becomes less dense. At first the heat is distributed upwards by small scale turbulence.

This process can sometimes be seen as a shimmer in the air which makes distant objects blurred, especially when viewed through binoculars. The shimmer is due to variations in refraction of light where different densities of air lie along the line of sight. The effect is common over tropical deserts but may also be seen over England on hot days.

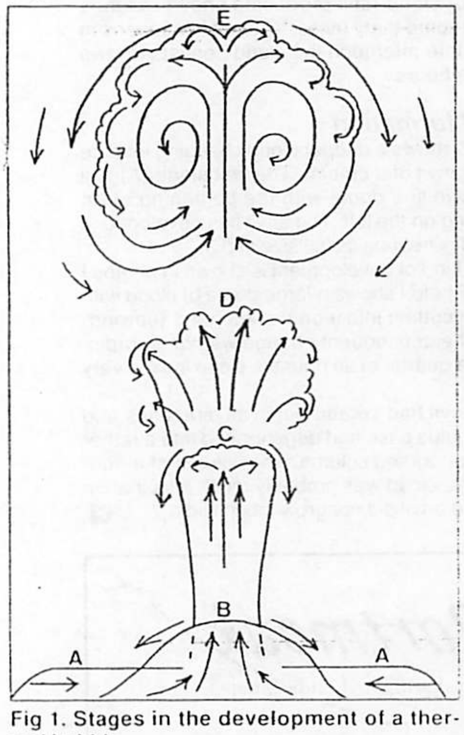


Fig 1. Stages in the development of a thermal bubble.

Small scale turbulence is inadequate to distribute the heat fast enough so eventually a large mass of air breaks away from the surface. The whole mass of air cannot rise simultaneously. the drag would be enormous. Instead a part rises into a dome (B). As the heated dome rises the air above it is pushed aside while near the surface a horizontal inflow starts. On a calm day this inflow may be shown by windsocks or smoke trails.

A broad dome of rising air still produces too much drag so the lift becomes concentrated in a relatively narrow column (C) and (D) which soon develops its own circulation (E). This circulation is often called a thermal bubble.

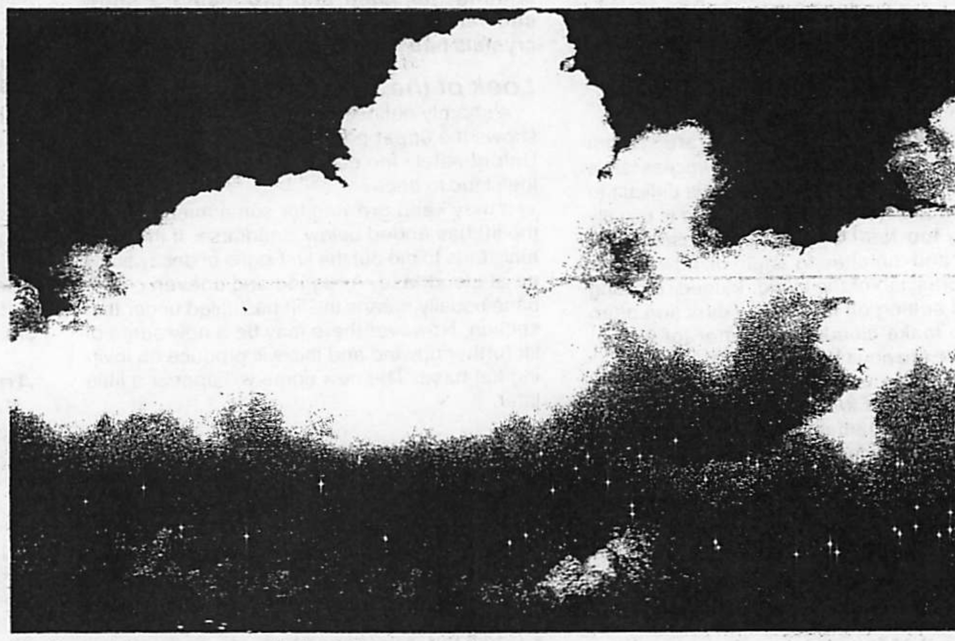


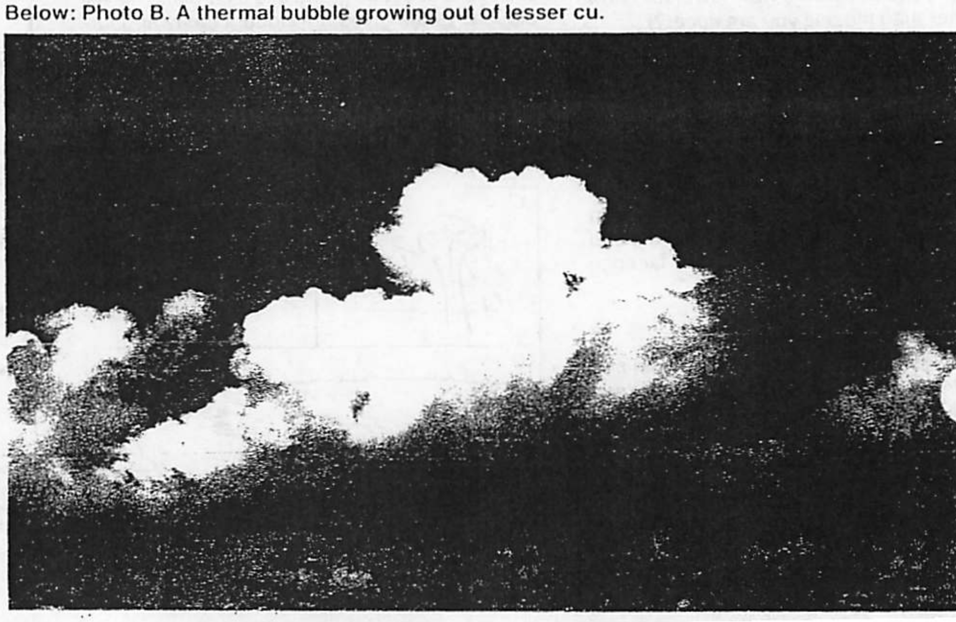
Photo A. A heavy cu consisting of several bubbles.

Circulation in a thermal bubble

As the thermal rises the top and sides are slowed down by the drag from its passage through the environment. The central core is protected and usually rises at twice the speed of the summit.

The difference in ascent speeds sets up a circulation rather like a vortex ring. Fig 2 illustrates the direction of flow round the side of the rising bubble. Underneath the bubble there is an inflow with some of the air from outside dragged into the circulation.

Below: Photo B. A thermal bubble growing out of lesser cu.



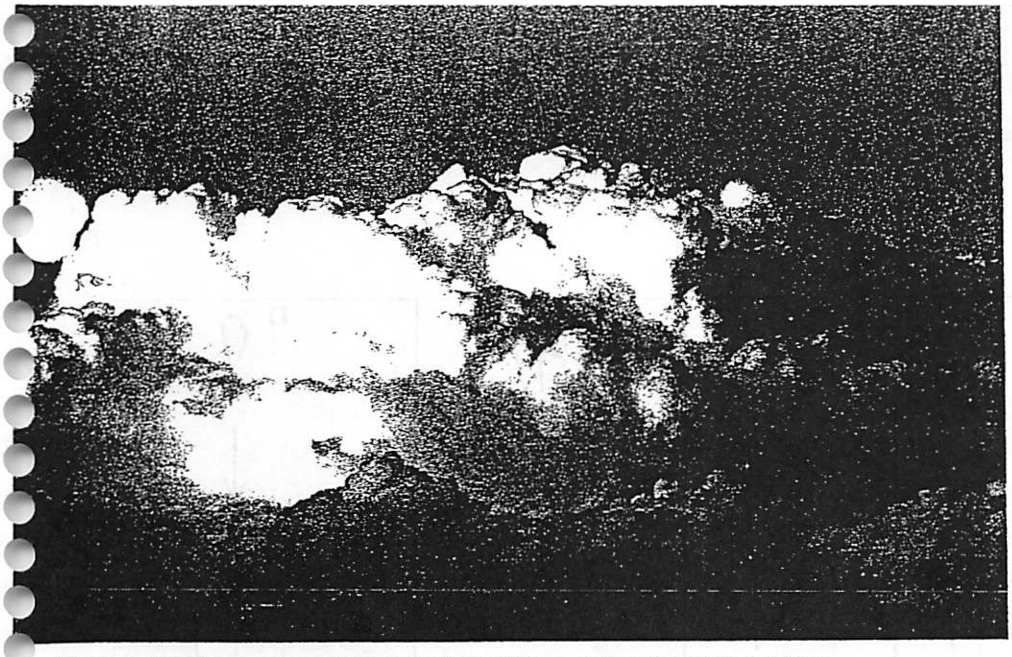
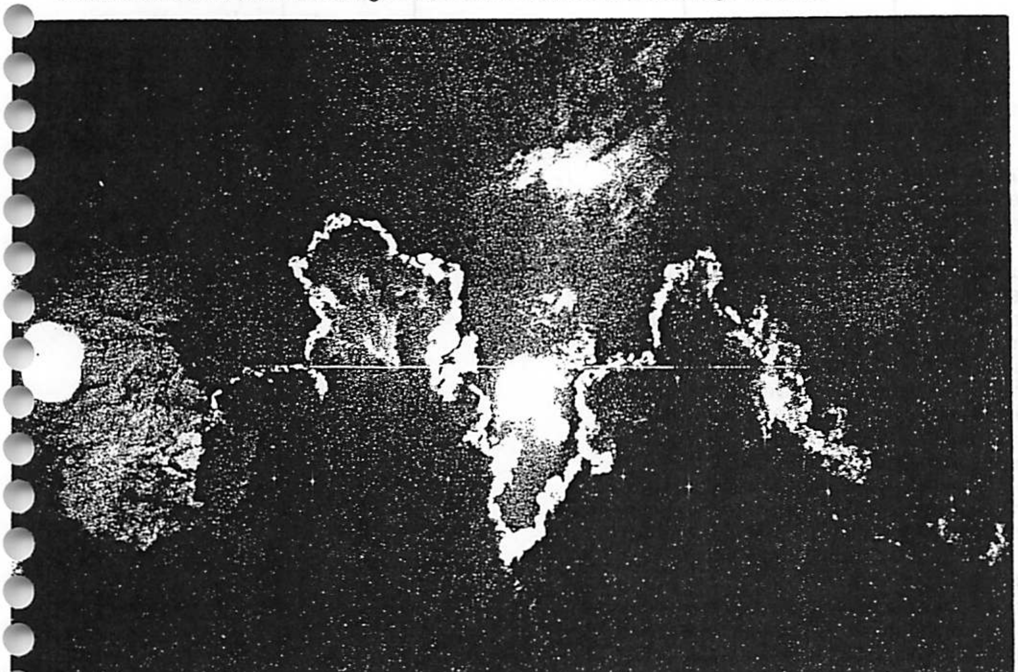
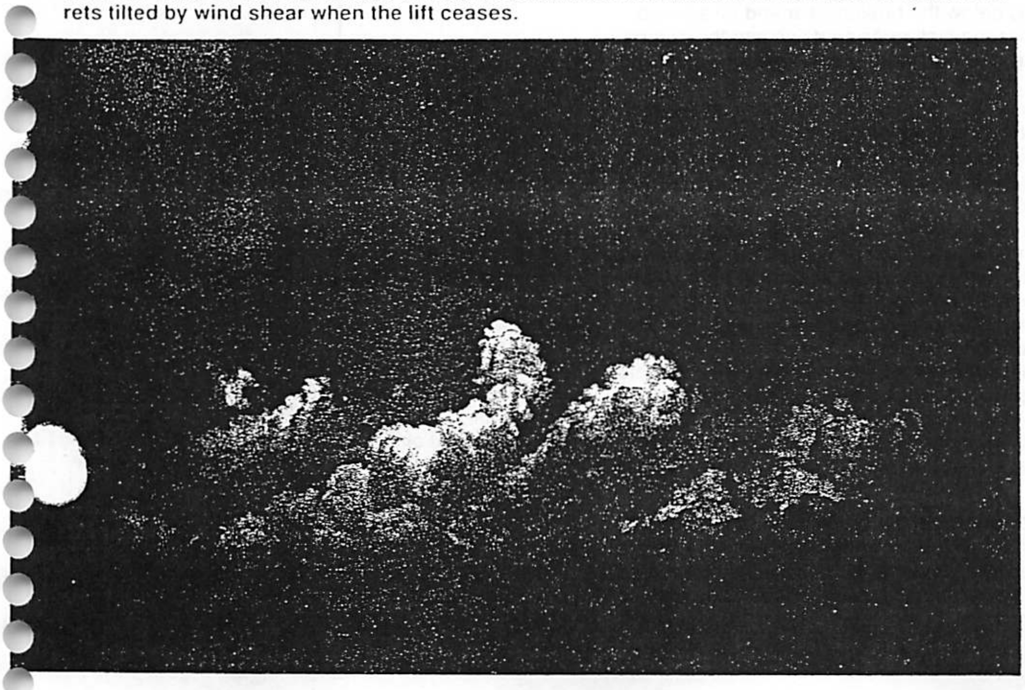


Photo C. Massive cumulus congestus formed from numerous large bubbles.



Above: Photo D. Tall and narrow turrets of short lived thermals. Below: Photo E. Narrow turrets tilted by wind shear when the lift ceases.



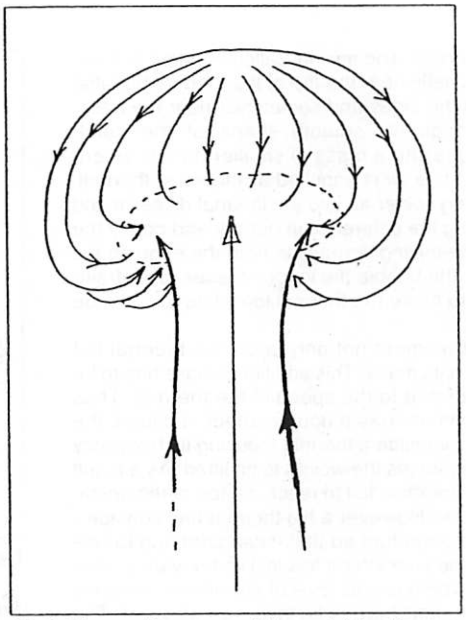


Fig 2. Flow pattern round the outside of a very powerful thermal bubble.

Size of thermal bubbles

In recent years people have noticed that clouds have no natural scale length. Clouds and their constituent parts come in many sizes; clouds (like coastlines and mountains) can be represented by fractals whose outline looks the same at many different scales.

When satellite pictures became available it was found that the cloud patterns had the same fractal dimensions over seven orders of magnitude. The swirls and eddies associated with thermals range in size from centimetres, when modelled in a water tank, to kilometres in a cunim.

Thermals do not invariably form bubbles. Weak or sluggish thermals never seem to develop the full circulation. A well formed thermal bubble usually needs vigorous ascent with a big initial difference of density between the bubble and the outside air. Winter thermals are often too weak to develop a proper bubble; their feebleness is revealed by a lack of proper domes on the cu tops and a general tendency for fuzzy edges to the clouds.

Great contrasts of temperature seem to produce the best shaped bubbles. Some of the finest examples can be seen in early atomic bomb photos. (Fig 2 was based on such a photo.) Bangs caused by smaller ground explosions, for example a petrol tank blowing up, sometimes produce a perfect vortex ring with a clear centre in the rising cloud of smoke.

The smoke and ash from a volcanic eruption generally circulates like thermal bubbles. Eruptions often produce a mass of clouds consisting of numerous overlapping bubbles churning over and over. The motion looks very similar to a time lapse film of a big bank of cumulus.

Entrainment

Thermals normally expand as they rise. This is partly due to the reduced pressure aloft but mostly due to outside air becoming mixed with the thermal. The mixing, called entrainment, occurs chiefly near the top of the thermal but also round the sides and sometimes near the base. The originally smooth shape of the dome changes into a mass of smaller domes where the outside air is engulfed by the rising thermal. Drawing colder air into the thermal dilutes it and reduces the difference in density and hence the lift. The mixing spreads in from the edge so the larger the bubble the longer it takes for entrainment to make the thermal too dilute to continue rising.

Entrainment not only cools the thermal but adds to its mass. This additional mass has to be accelerated to the speed of the thermal. Thus entrainment has a double effect: it dilutes the warm air inside a thermal reducing its buoyancy and increases the weight to be lifted. As a result many thermals fail to reach the top of the unstable layer. However a big thermal has considerable momentum so that it can continue to rise for some time after it has lost its buoyancy. How far it overshoots its level of equilibrium depends on whether there is an inversion above it. The top of an overshooting thermal is colder than its environment and very ready to sink when the momentum has been expended.

Multi-cored thermals

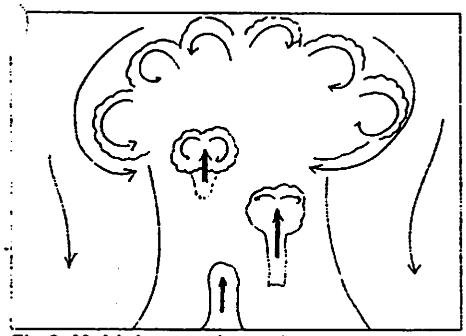


Fig 3. Multiple core thermal.

In the early morning, when there is only just enough heat to set off a thermal, there is usually only a single core of lift and this is drawn up into the bubble as soon as the limited amount of warm air near the surface is exhausted. Such thermals are generally short lived. Unless the air is very unstable and moist any cu dissolves rapidly. Later in the day, especially in hot continental areas, thermals can draw on a large supply of hot surface air. Then they become big and broad and long lasting. These thermals may have several cores. Fig 3 illustrates a broad thermal with several much smaller bubbles moving up inside. The pattern in Fig 3 is based in part on the behaviour of smoky bonfires. These often produce surges of activity sending beautifully formed thermal bubbles shooting up within the main smoke column. The bonfire bubbles are of course tiny compared to real thermals and being so small are rapidly eroded. Their whole lifetime is over in a matter of seconds but their circulation looks identical to that of full sized thermals.

Photo A shows a big cu with several domes formed by separate bubbles. Photo B is a shorter lived cloud with a thermal bubble rising out of the centre. C shows a bank of cumulus congestus consisting of a great many bubbles

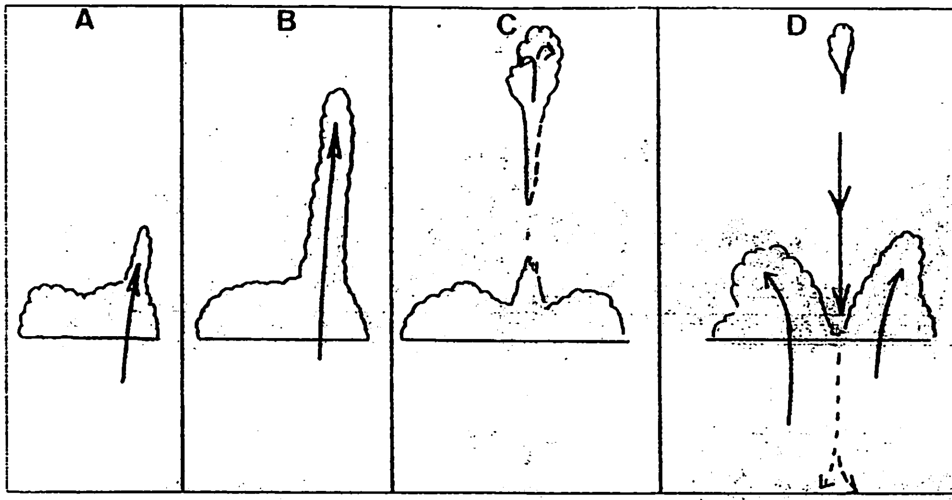


Fig 4. A very narrow thermal shooting up as a short lived tower and changing into a column of sink.

Cloud profile and rates of ascent

The rate of rise of a thermal depends on the difference in density between it and the environment and the drag due to its passage through the surroundings. A wide blunt dome of cu has to push more environmental air out of its way than a thin narrow thermal. Fig 4 shows a very thin thermal rising out of a clump of cu. It quickly grows into a tall column (B) which ascends much faster than the fatter clouds. Unfortunately this process has its own defects. A tall thin column of cloud suffers from severe erosion at the edges, especially if the cloud shoots up into much drier air. Erosion is often so rapid that several thousand feet of cloud evaporate in five minutes or so (C). The bubble at the top, which is often the widest bit, lasts longest but the stalk quickly vanishes.

Now the brief surge of lift changes to sink (D). Formation of cloud released latent heat which added to the energy. Evaporation takes back this latent heat leaving the air colder and denser than its environment. A column of sink soon develops below the broken pillar and on some occasions the sink goes on down into the original clump of cloud and eventually out below the base.

Even wide domes of cumulus lose lift and start to subside but not as rapidly as the narrow towers. Descent results in evaporative holes developing which increase the sink. Unless further bubbles rise up to maintain the cloud it starts to degenerate. One cannot always see this when looking at a clump of cumuli but the cloud shadow often reveals these holes before they show in the profile of the cloud.

Photo D shows two narrow towers which shot up from the smaller cu. The translucence near the cloud top shows how thin it became. In photo E the two tall turrets had stopped rising and the wind shear began to topple them over. The fatter cloud on the far right was too massive to respond to the wind shear.

Inversions and bubbles

On many good soaring days cumulus tops are limited by an inversion. When the thermal bumps into the warmer air it quickly stops rising and the upward flow in the core is deflected sideways

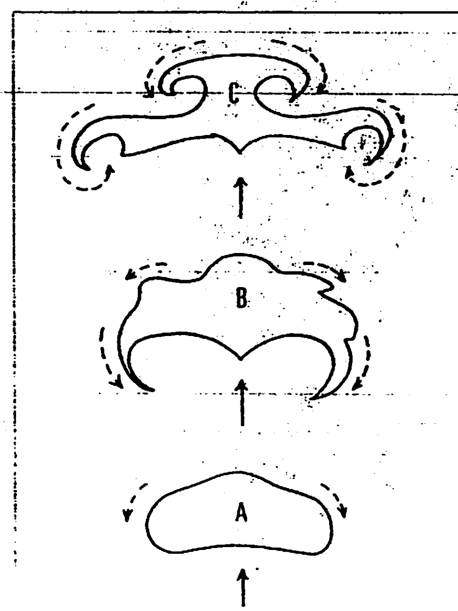


Fig 5. Hooks developing on the top of bubbles which were stopped by the inversion.

This sideways deflection may produce a temporary wind shear at cloud top. The effect of such a shear has been modelled mathematically: one result is shown in Fig 5. A is the original bubble. B shows how the outward shear starts to distort the bubble and C shows how continued shear produces hooks. The model traces the moisture in the bubble but does not allow for evaporation in regions of descent. In real life one may see such small hooks on the cloud top but they usually dissolve in strong sink at the edges. If there is already a wind shear above the inversion the hook pattern loses symmetry and only one side shows the curl over

LIDAR flow patterns

LIDAR works on the same principle as radar except that it uses a laser beam. It can detect motions along the line of sight by the doppler principle and can often follow minute particles in cloud-free air. Fig 6 shows the flow under lines

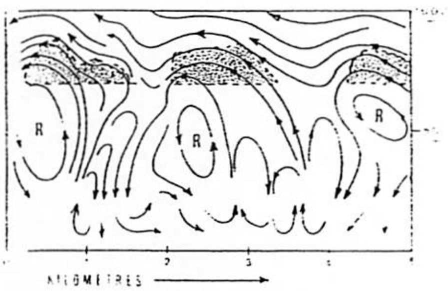


Fig 6. Lidar pattern of flow below lines of shallow cu.

of cu at an inversion. It is much less detailed than the mathematical model in Fig 5 but gives a more comprehensive picture. Above the cloud tops there was a wind shear from right to left so the flow did not form thermal bubbles. Instead a kind of wave motion occurred above the cloud tops while below the up and down flow was separated by regions of rotation marked R.

Influence of moisture

The water vapour in the atmosphere can provide much extra energy once the thermal has cooled enough to start condensation. Condensation releases latent heat which makes the thermal warmer. The added energy allows cloudy thermals to rise further and faster. Too much moisture makes thermals harder to use, partly because the cloudbase lowers if the air becomes more moist. An approximate rule is that the base of cumulus (in feet) is 400 times the difference between dew point and surface temperature in Celsius. Thus with a dew point of 10 C and an air temperature of 20 C one should find the cloudbase at about 4000ft. The cloudbase usually rises during the day reaching its maximum in mid afternoon when the surface temperature is highest.

Entrainment of outside air into a cloud dilutes the thermal. If the environment is very dry the edges of the cloud start to evaporate while it is still building. This is usually a good thing for soaring pilots because evaporation produces gaps for the sun to come through and keep thermals going. When the air aloft is very moist the cloud from old thermals persists and the sky becomes full of decayed cumuli which provide no lift but restrict the sunshine.

Spread out

On most fine days there is a temperature inversion with its base several thousand feet above the surface. The warm air aloft acts as a lid preventing thermals rising much beyond the base of the inversion. The rising cu spreads out into a layer when it bumps into the inversion. Provided that the air is fairly dry the sky becomes dotted with well spaced flat cumuli. Each little cu evaporates in the dry air before it can spread far. Unfortunately air which has had a long sea crossing tends to become progressively moister. The British Isles and parts of NW Europe are often covered by such moist air.

Each thermal carries extra moisture from the surface up to the inversion. There it merges with the moist air already aloft. The flattened cumuli spread out to form an almost continuous sheet of cloud which eventually cuts off the sun and halts the production of thermals. Sometimes the cloud develops gaps through which the sun penetrates to start up more thermals, but on a bad day the gaps are quickly filled in again by fresh thermals. Ireland is even more troubled by spread out than England. Not only is it nearer the Atlantic but the land is greener and moister so that thermals carry up extra moisture to thicken the cloud layer. Photo F, from Dundee University, shows an example of spread out. It was taken at 1538 on August 13, 1994, a day when most of the British Isles was under a cool northerly airflow with a high centred south-west of Ireland. Ireland was almost completely covered with the spread out stratocu which consisted of large cells with hardly any cracks between them.

Photo F. Dundee University's satellite picture of August 13, 1994, showing variations in spread out. Printed by kind permission of the University.

Over central and southern England the cloud cells were much smaller with better gaps between them making it possible to go cross-country. Clear areas over the SW of England and Wales, Norfolk and inland of the Cheshire Gap show where the sea air did not warm up enough to form cu.

The Soaring Forecast at a Glance

In a nutshell, four weather factors affect cross-country soaring. 1) winds aloft, 2) lapse rate, 3) height of thermals, 4) moisture content of air.

http://nimbo.wrh.noaa.gov/Reno/rnosafrno.htm

1 Date of forecast. Issued once a day at 0900.

2 Winds— directional shear, or speed shear of more than 3 kts per 1000' tends to break up thermals. Winds greater than 25 kts aloft may make out and return flights difficult, but may also produce wave.

3 Trigger temp and trigger time— point at which thermals begin to release from ground

4 Max altitude of thermal convection— Higher is better.

5 K— moisture index

6 Lapse Rate— Larg lapse rates and lower Lifted Indicie signal strong thermals. Lapse rates of 3 degrees per 1000' are ideal while lifed indices c 0 are ideal. Check for inversion layers high clouds, and overdevelopment which may weaken thermals or cut the day short.

7 Trend— lastly, look at the changes since yesterday and tomorrows outlook. Note how the Soaring Index and K index has changed since yesterday. Be aware of the large scale synoptic weather pattern.

```
ZCZC RNOSAFRNO
ÅeTTAA00 KRNO 111345
PREPARED BY THE RENO NATIONAL WEATHER SERVICE FORECAST OFFICE
...SOARING FORECAST WORKSHEET...INCLUDING EASTERN SIERRA
AND WESTERN NV.      DATE: 5/11/99      FORECASTER:DONALDSON

FCST WINDS/TEMPS ALF                 THERMAL DATA    (F/C)         PDT
MSL  (FT) FD WND FORMAT              TRIGGER TEMP: 50 / 10 TIME:1000
10,000...3022/+03                    MAXIMUM TEMP: 69 / 21 TIME:1500
12,000...3123/+01                    MAXIMUM ALT  15150 FT
14,000...3129/+05
16,000...3135/+09                                    YSTDY/ TDA
18,000...3140/+13                    SOARING INDEX       419 / 477 FPM
20,000...3046/-17                    "K" INDEX........   -13 /  15
24,000...3055/-24                    SHOWALTER........    14 /  12
30,000...2961/-40                    LIFTED...........     7 /   7
34,000...2961/-50                    VERTICAL TOTALS...   16 /  19
39,000...2957/-58

WAVE EXPECTED: WK ISOLD              MTN TOP COMPARATIVE DATA (07 PDT)
RIDGE LIFT EXPECTED: NO              SLIDE MTN...33/27/0101
                                             1/-3/0101

AFTERNOON WIND (IN KNOTS) FORECAST:
MINDEN..NW 5-10        TRUCKEE...NW 10-15    AIR SAILING...NW 10-15

WEATHER SYNOPSIS: WK UPR LVL RDG OVR THE SIERRA.

SIGNIFICANT CLOUDS/WEATHER/WINDS/ISOTHERMAL OR INVERSION LAYERS:
BKN-SCT090-110 BKN130-150 HYR MTNS LCL OBSCD. INVERSIONS 090-100
120-140.

SOARING OUTLOOK FOR 05/12: UPR LVL RDG OVR THE SIERRA WILL CONTINUE
TO WKN AS UPR LVL TROF SLOLY MOVS INTO THE PACIFIC NORTHWEST.
LGT-MOT WRLY FLOW FOR WK WAVE CONDS. THE AMS OVR THE SIERRA WILL
REMAIN DRY AND STBL. GUSTY NW SFC WNDS WILL DVLP IN THE AFTERNOON.

THIS PRODUCT IS ROUTINELY PREPARED BY ABOUT 730 AM PDT AND
DISTRIBUTED TO THE RENO FLIGHT SERVICE STATION AND THE RENO NATIONAL
WEATHER SERVICE WORLD WIDE WEB HOMEPAGE AT
(HTTP://NIMBO.WRH.NOAA.GOV/RENO/). NOTE THIS ADDRESS SHOULD BE TYPED
IN SMALL CASE IN YOUR WWW BROWSER. THIS FORECAST IS NOT UPDATED. FOR
CURRENT FLIGHT CONDITIONS FORECAST AND ADVISORIES ACCESS YOUR LOCAL
BRIEFING OUTLET OR FAA FLIGHT SERVICE STATION.
/
NNNN
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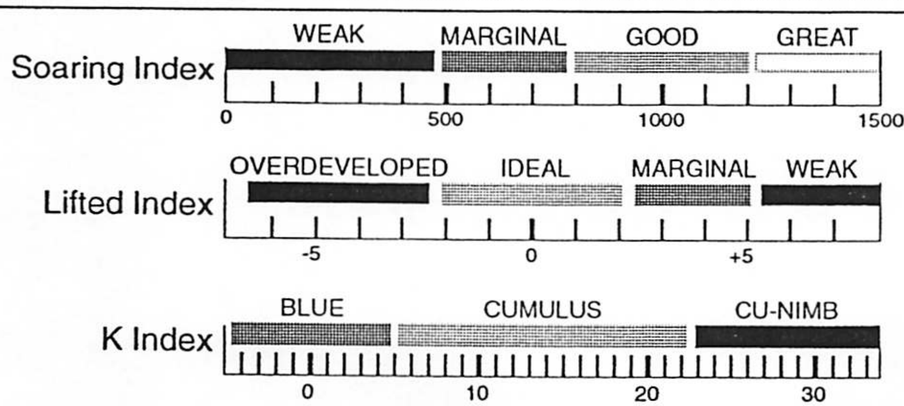
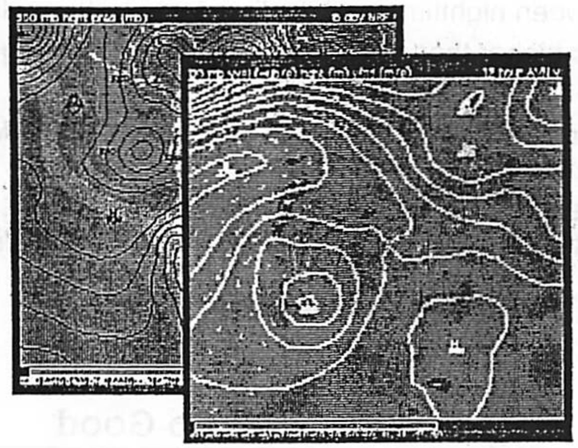


Indicies— The SI, LI, and K give a good rule of thumb for the day's soaring, but they don't tell the whole story. In theory, the SI is the storongest lift a soaring pilot will experience during the day. The Showalter and Vertical Total Indicies are measures of instability. Very high numbers signal the potential for violent thunderstorms.

The Complete Weather Briefing

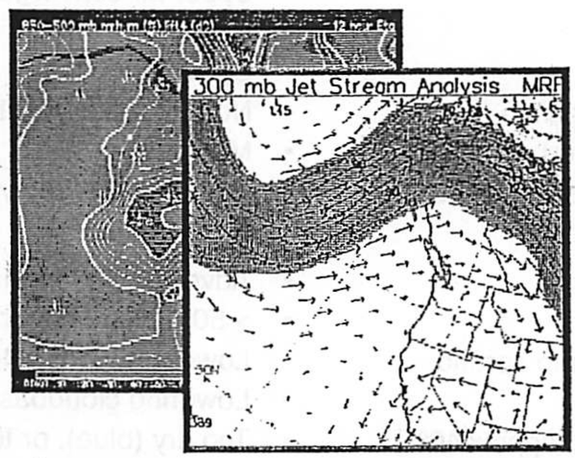
The forecast for a good flight starts days ahead of time. Track conditions and trends, and digest the information day by day. When you flight comes, you will have a more thorough understanding of the conditions presented to you.

Synoptic Scale/Long term—
These look 2-10 days ahead and give you the large scale weather patterns (fronts, jet streams, pressure areas). They also create the setting in which to interpret the meso scale and micro scale forecasts.



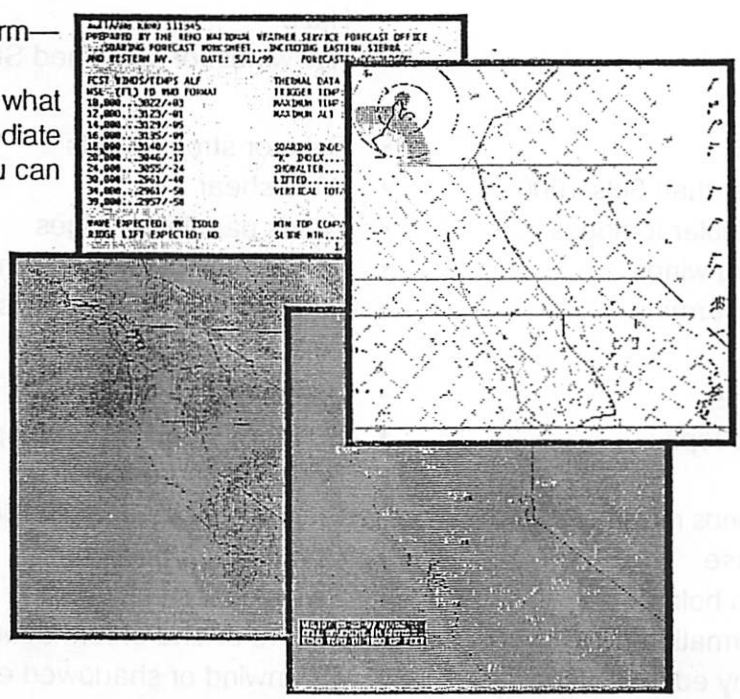
Climate records and averages
9 and 3 day 500 mb charts
3 day 700 mb charts
3 day RH and LI charts

Meso Scale—
These look 1-2 days ahead and give you the large scale weather patterns, but with better accuracy. This is where satellite photograph come into play, as well as more detailed forecasts.



4 panel aviation charts
surface prognostic charts
Infrared satellite images
Jet stream forecasts
Technical weather discussion
Winds aloft forecast
Sea level pressure and precip forecast
850mb forecast chart
700 mb forecast chart
300 or 500 mb forecast chart

Micro Scale/Short term—
This is essentially a "nowcast". It tells you what the present and immediate conditions are so you can better read the day.



Surface observations
Soaring forecast
RAOB (weather balloon) data/ pseudoadiabatic chart
Winds aloft
Technical weather discussion
Radar images
Visible satellite images
High res 1km visible satellite image
Water vapor satellite images
Aviation forecasts

Rules of Thumb & Tidbits

While it pays to know the technical ins and outs of soaring forecasting, there are a few simple correlations that can be useful.

- The greater the difference between nighttime and daytime temperatures, the stronger the lift will be
- If todays max temperature was higher than yesterdays max temp, soaring should be better.
- Lift begins in the higher terrain before it begins in the valleys
- In the late afternoon, thermals rarely reach from the ground to cloudbase. Most of the thermals seem to originate at altitude and continue to cloudbase.
- In the high desert, the sun is responsible for more thermals than the wind.
- Hills facing the sun most directly are often the most likely area for thermals.
- The higher the lift goes to, the stronger the thermals.
- Launch earlier than normal if clouds form in the morning hours.

	Good	Not So Good
Synoptic Weather	• Cool air aloft	• Warm air aloft
	• Upper air divergence	• Upper air convergence
	• Rapid lapse rate	• Lazy lapse rate
	• Upper level trough	• Upper level ridge
	• South of polar jet stream	• North of polar jet stream
	• Continental or modified marine air	• Marine air
	• No strong H or L pressure aloft	• Strong pressure system aloft
Weather	• Radiative heating	• Advective/Latent heating
	• < 50% cloud cover	• > 50% cloud cover
	• Higher temps and temp spread	• Lower temps and temp spread
	• Rising cloudbases	• Lowering cloudbases
	• Just enough moisture (approx 40%)	• Too dry (blue), or too moist (OD)
	• No cirrus clouds	• Cirrus clouds
	• Good visibility	• Haze
	• SW winds	• NW winds, or sustained SE winds
Winds	• Moderate winds	• Calm or strong winds
	• No shear greater than 3kts/1000'	• Wind shear
	• Winds perpendicular to ridges	• Winds parallel to ridges
	• No early morning winds	• Early morning winds causing mixing
	• Wave induced thermals	• Stable upper air dynamics
Clouds	• Dark, flat bottoms	• White, rounded bottoms
	• Hard edges and tops	• Soft ragged edges and tops
	• Vertical growth	• Horizontal spreading
	• Whisps and strands moving upward	• Fractal strands hanging down
	• Concavity of base	• Convexity of base
	• Solid clouds, no holes	• Swiss cheese clouds
	• Beginning of formation cycle	• Mature or end of formation cycle
	• Upwind or sunny edge of cloud	• Downwind or shadowed edge of cloud

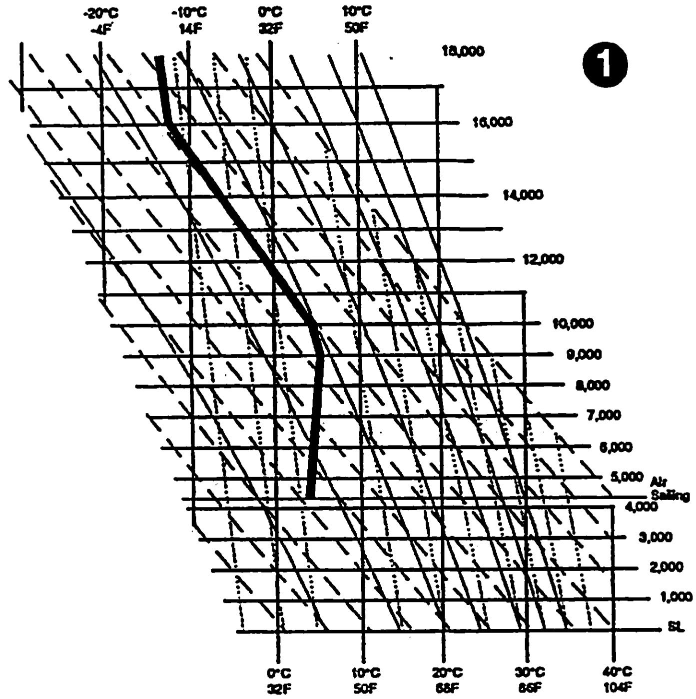
Calculating Thermal Conditions— Chad Moore

The pseudoadiabatic chart— that tangle of lines that eludes understanding and seems to reside only in the realm of meteorologists and physicists. Most pilots shrug it off and are thankful that it wasn't on the glider pilot practical exam. Hopefully, I can shed a little light on calculating thermal conditions using this tool that should be in every XC pilot's toolbox.

Air is not heated directly by the sun, but is heated indirectly by contact with the Earth's surface. As air near the surface rises in temperature, it becomes buoyant, lifts upward, and is eventually mixed with the surrounding air, transferring heat to the atmosphere. As the sun rises at dawn, the preexisting condition of the air, also known as **the environmental lapse rate**, is cool. There is usually a shallow inversion near the surface, but above the inversion the air cools rapidly with increased altitude. The environmental lapse rate is measured each morning at one of several weather balloon sites around the US. This radiosonde data is available on the web by 0800 am.

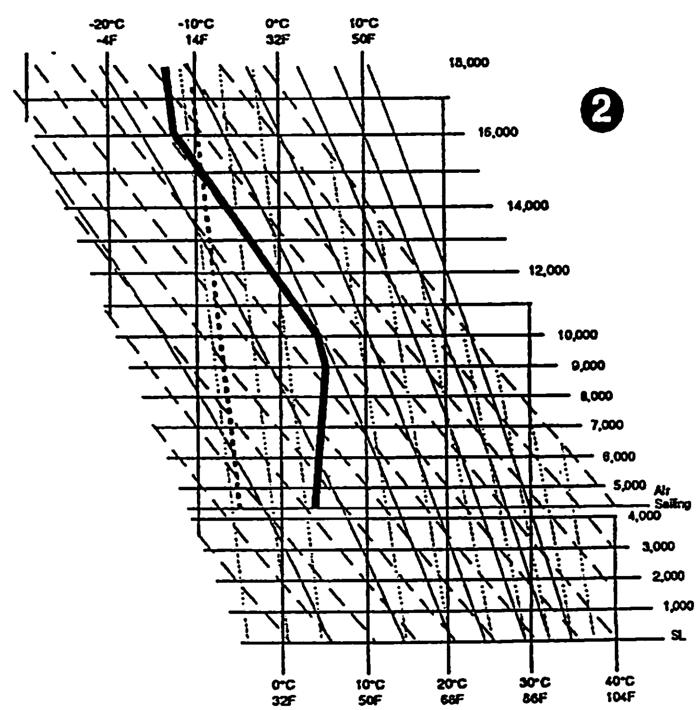
As the sun rises and heats the ground, heat is transferred to the shallow layer of air at the surface. Warmer air is more buoyant, and thus has a tendency to rise. The rising action is limited at first by the shallow inversion that developed overnight, and also the tendency for warm air to "stick" to the land's surface. Eventually, the warm bubble of air lifts away from the surface forming a thermal. Rising air is termed "adiabatic", and behaves either as a **dry adiabatic** parcel or a **wet adiabatic** parcel. Dry air cools rapidly as it rises and reduces pressure, about 3°C per 1000'. Moist air cools less rapidly due to the latent heat of condensation, about 1.5°C per 1000'.

So let's turn our attention to the pseudoadiabatic chart. Horizontal lines indicate altitude in MSL, vertical lines show temperature. The first step is to plot the environmental lapse rate (1). Using the morning sounding data, plot and connect the dots. You may also want to add in the overnight low temperature to represent the ground level data. The plotted data show a typical nighttime inversion up to 9,000, which should quickly



dissipate by midday. It also shows a moderate inversion at 16,000. Note that we must remember that the field elevation is 4300' in the case of ASI.

With the environmental lapse rate plotted, we then need to plot the forecasted **cloudbase**. This is the point at which the rising dry adiabatic parcel will become a wet adiabatic parcel. Cloudbase marks this transition, the **saturation line** is not necessarily the upper limit of thermals. Plot the dewpoint at ground level and extend a line parallel to the light gray dotted lines (2).



The Pseudoadiabatic Chart—Example

Here is an example of a thermal soaring plot. Sounding data is filled in on the left, the bold line represents the environmental lapse rate. Dewpoint is -5°C (23), max temperature is 26°C (78). Data is typical of a good spring soaring day.

Sounding Data (°C)

-14

-13

-7

-1

4

5

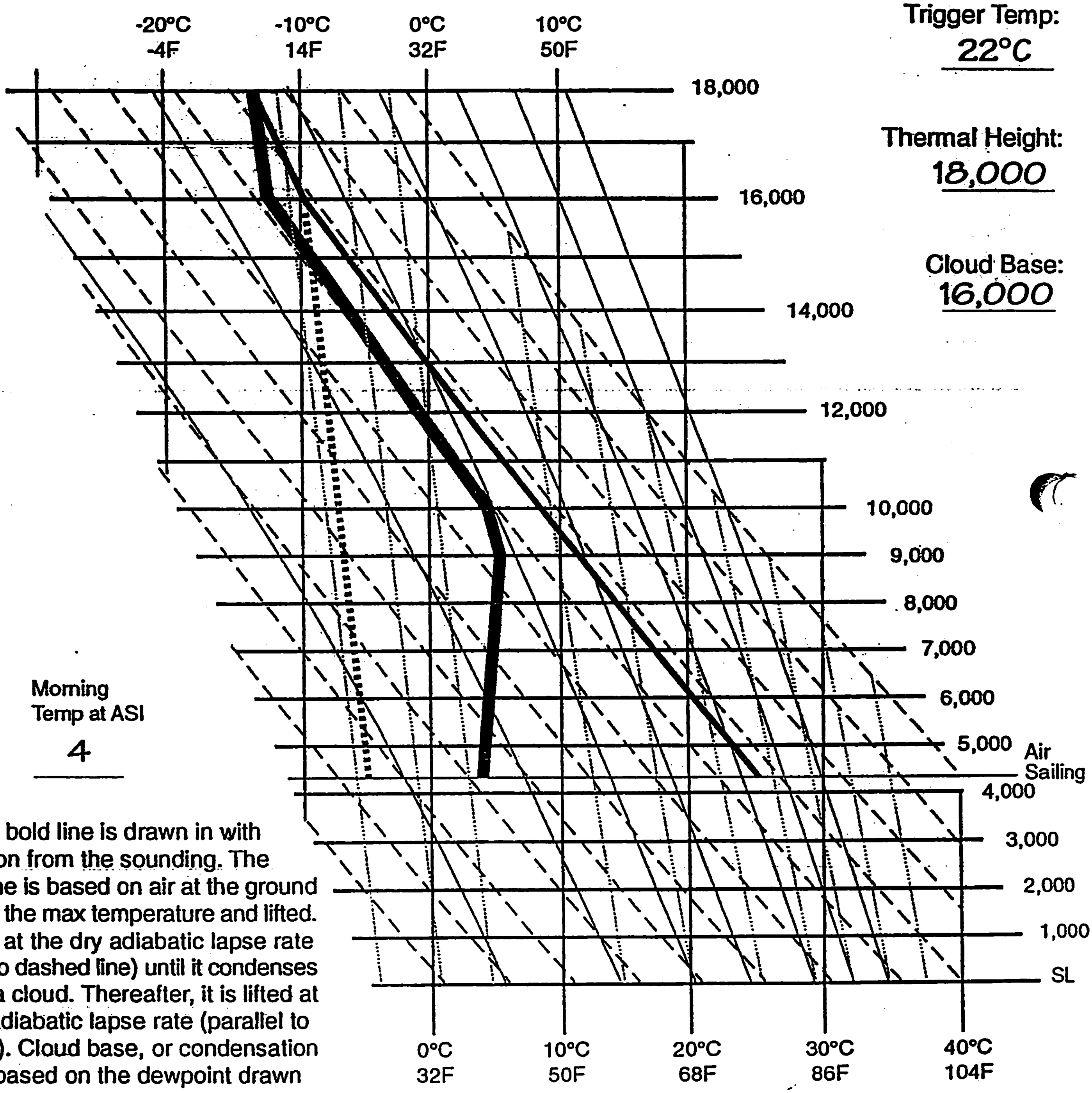
Morning Temp at ASI

4

Trigger Temp: 22°C

Thermal Height: 18,000

Cloud Base: 16,000



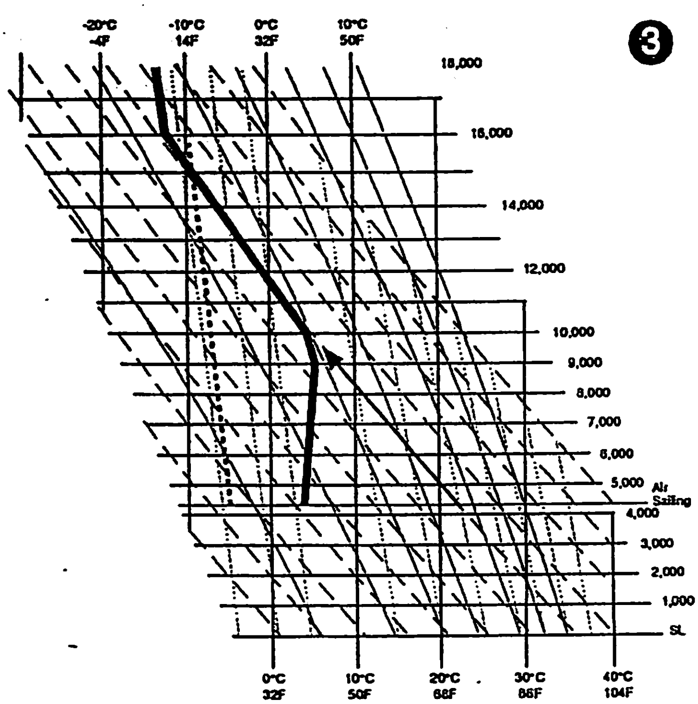
Dry Adiabats

Wet Adiabats

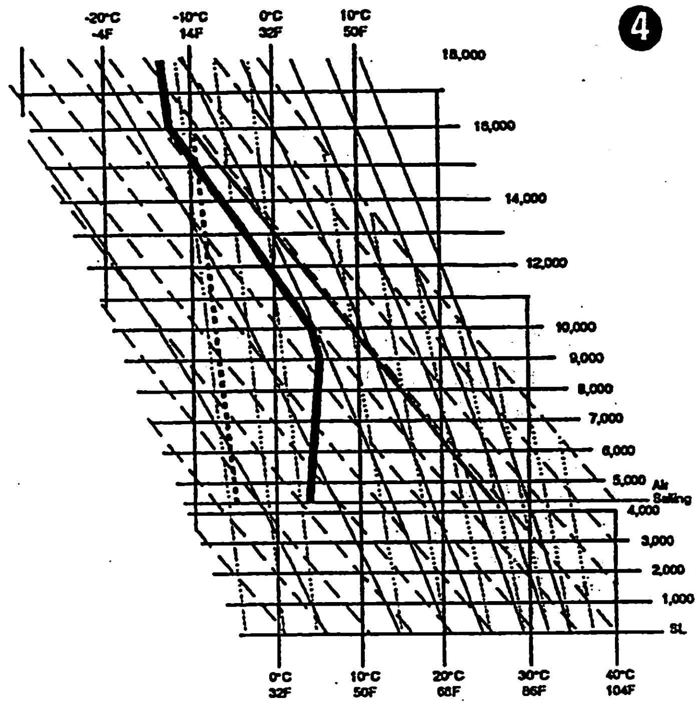
Equal satura lines

The thick bold line is drawn in with information from the sounding. The thinner line is based on air at the ground heated to the max temperature and lifted. It is lifted at the dry adiabatic lapse rate (parallel to dashed line) until it condenses for form a cloud. Thereafter, it is lifted at the wet adiabatic lapse rate (parallel to solid line). Cloud base, or condensation point, is based on the dewpoint drawn out parallel to the gray dotted saturation lines lines until it intersects the lifted parcel of air. The thermal height is the point at which the lifted parcel of air is the same temperature as the environmental lapse rate.

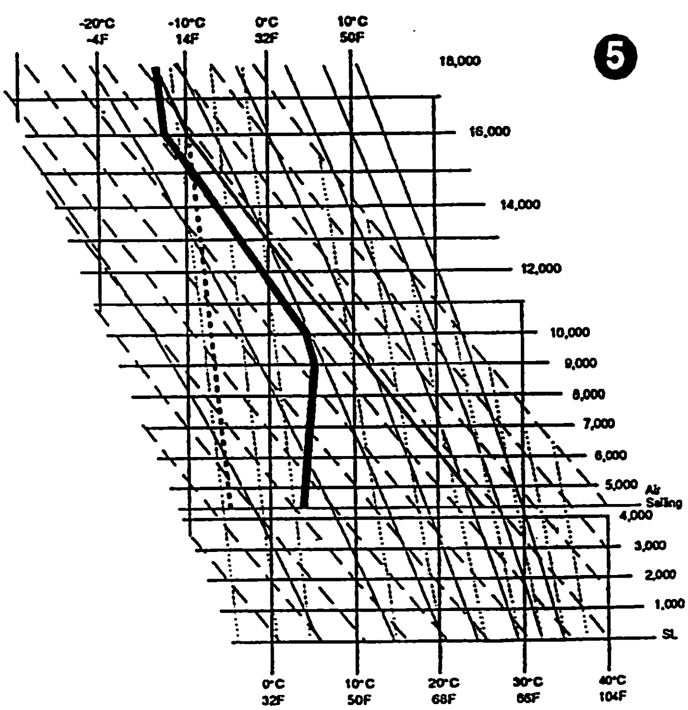
Now lets trigger our thermal! A thermal will trigger and release off the ground when it has a good chance of breaking through the nighttime inversion. Using the dashed black lines (the dry adiabatic lines), we can estimate that the trigger temperature is 22° C (3). Anything above this temperature and the thermals are expected to rise to a considerable height. The time of day where the temperature first achieves 22° C is called the trigger time. The Trigger Time is usually 10am-12noon in the valleys and a bit earlier in the higher terrain.



Using the highest expected daily temperature, plot the thermal height. Start at 4300' and 26° C. Extent the line upward parallel to the dry adiabats until cloudbase is reached— where the adiabatic line crosses the saturation line (4). Cloudbase occurs at 16,000'— in theory. In actuality, the thermal incorporates drier air from mid altitudes as it rises, making the cloudbase somewhat higher than the pseudoadiabatic chart indicates. So on you flight, expect cloudbases to be higher during the warmest part of the day, say 17,500'. For now, lets ignore these real world considerations.

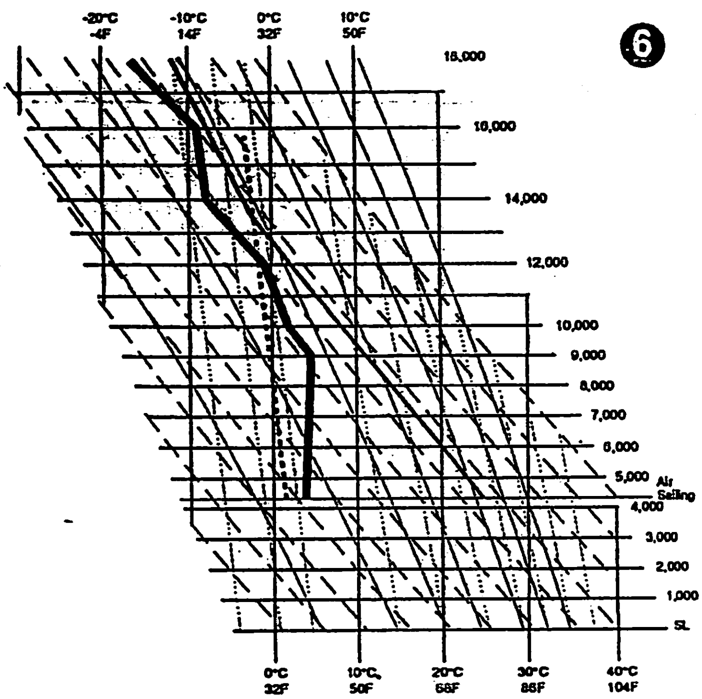


Finally, lets change the adiabatic line from dry to wet at 16,000'. Follow the solid black wet adiabats until the rising parcel of air is at the same temperature as the environmental lapse rate (5). This is the upper limit of lift. Note that lift continues about 2,000' into the cloud before topping out at 18,000'. On the next page is the chart in full size.



Lets look at another example. This time, we have a strong, but overdeveloped day. The air is more moist at the surface and aloft, and the chance for thunderstorms is high.

The saturation is shifted farther right than our last example. The environmental lapse rate has a different shape, and our expected high temperature is 25° C (5). Cloudbase is reached at a lower level, 13,500. The wet adiabatic line never intersects the environmental lapse rate below 18,000'. If we could see the rest of the chart, we may see the line continue upward to 30,000 or 40,000 feet! These are the conditions that create strong thunderstorms— moist air, strong surface heating, and cold unstable air aloft.



The pseudoadiabatic chart is a good place to begin to analyze the day. As the day progresses and your flight begins, other signs such as the terrain, cloud formation, and the way thermals "feel" will take precedence over the chart you drew at 9am. But having drawn that chart, you will be better able to interpret the day.

Try the next three examples if you are still rusty on this primary skill.

Much of this material has been borrowed from luminaries in the field of soaring weather. Peter Kelly has a great website going into detail on weather forecasting and has numerous links. His web page is at www.community.net/~soaring. Charlie Hayes also has some quality weather links at www.soar-palomino.com. Kempton Izuno has written extensively about suitable weather for long distance flights in the Great Basin. Dan Gudgel gave a great presentation at the PASCO 1998 Soaring Seminar on soaring weather. And finally, Carl Herold for all of the ideas and pointers. Also check out SOARING METEOROLOGY FOR FORECASTERS, and METEOROLOGY FOR GLIDER PILOTS, by C. E. Wallington.

The Pseudoadiabatic Chart—Exercise 1

Here a chance to plot data yourself. Data is for a typical summer day at ASI. Dewpoint is -1°C (30), max temperature is 30°C (85). Answers are at the bottom.

Sounding Data (°C)

-7

-5

-3

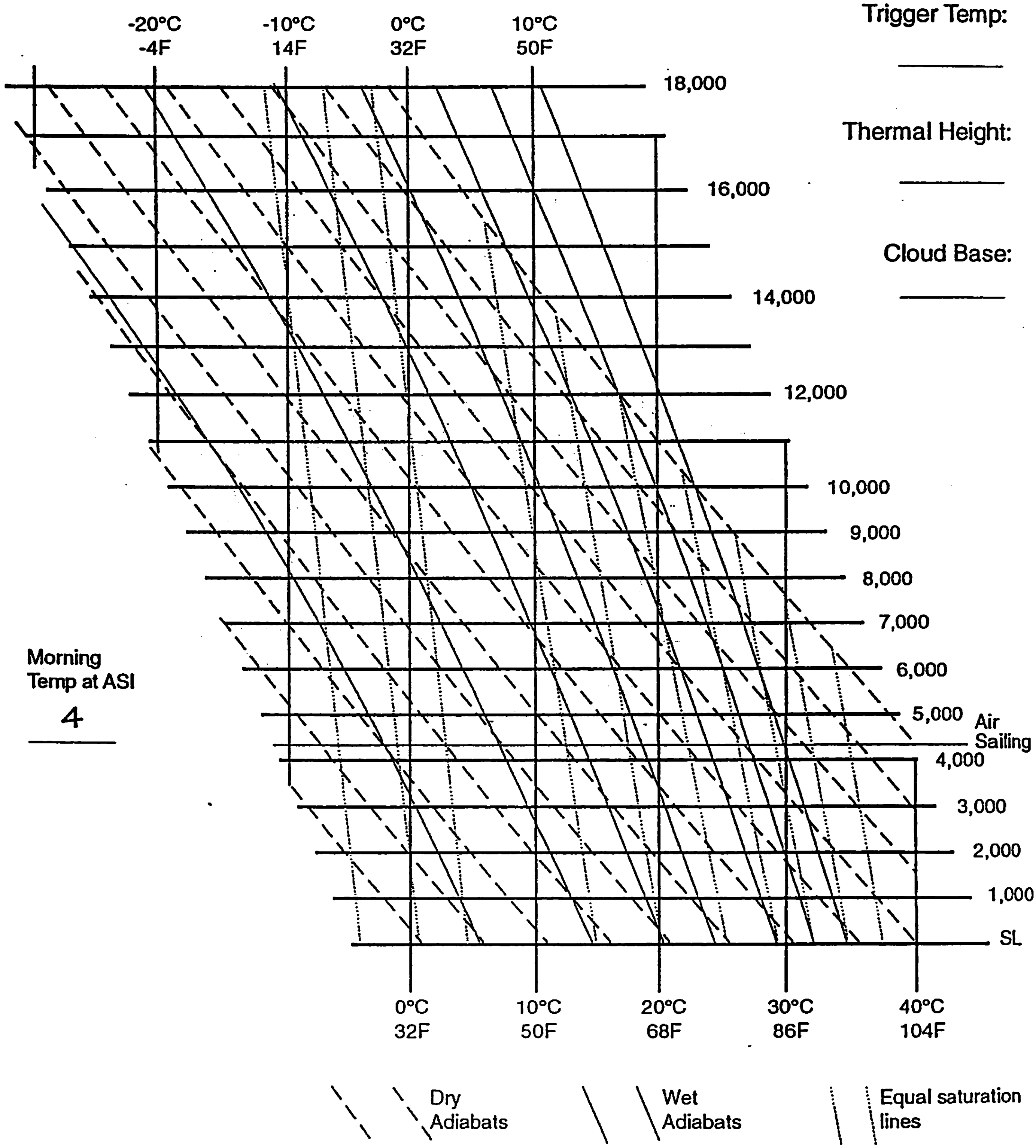
3

3

5

Morning Temp at ASI

4



Trigger Temp: ______

Thermal Height: ______

Cloud Base: ______

Trigger Temp 27°, Thermal Height 16,000, No cloudbase (blue day), Inversion at 10,000-12,000, Mild inversion above 14,000.

The Pseudoadiabatic Chart—Exercise 2

Here a chance to plot data yourself. Data is for a typical summer day at ASI. Dewpoint is 3°C (38), max temperature is 30°C (85). Answers are at the bottom.

Sounding Data (°C)

-14

-6

-4

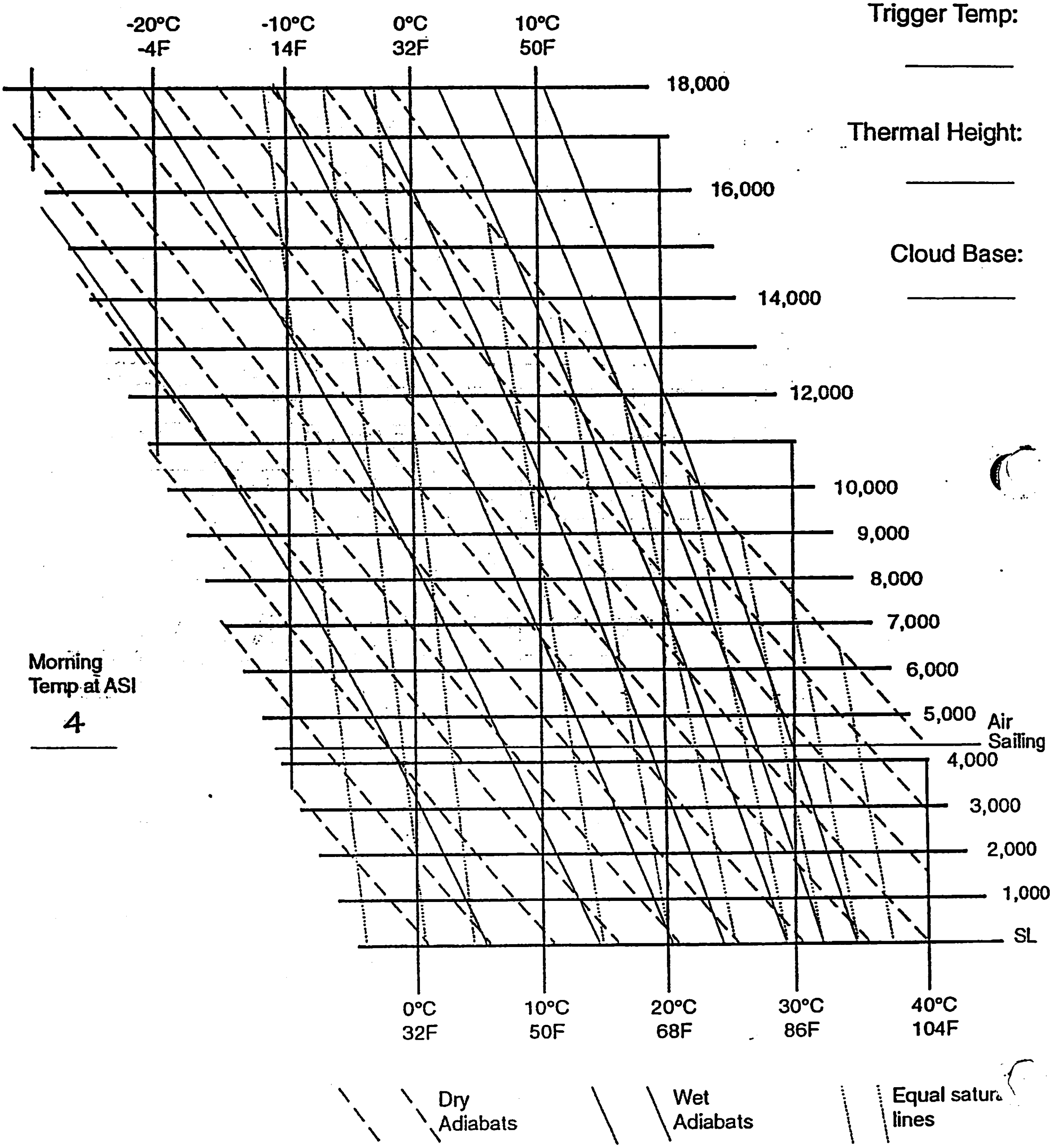
0

3

6

Morning Temp at ASI

4



Trigger Temp: ______

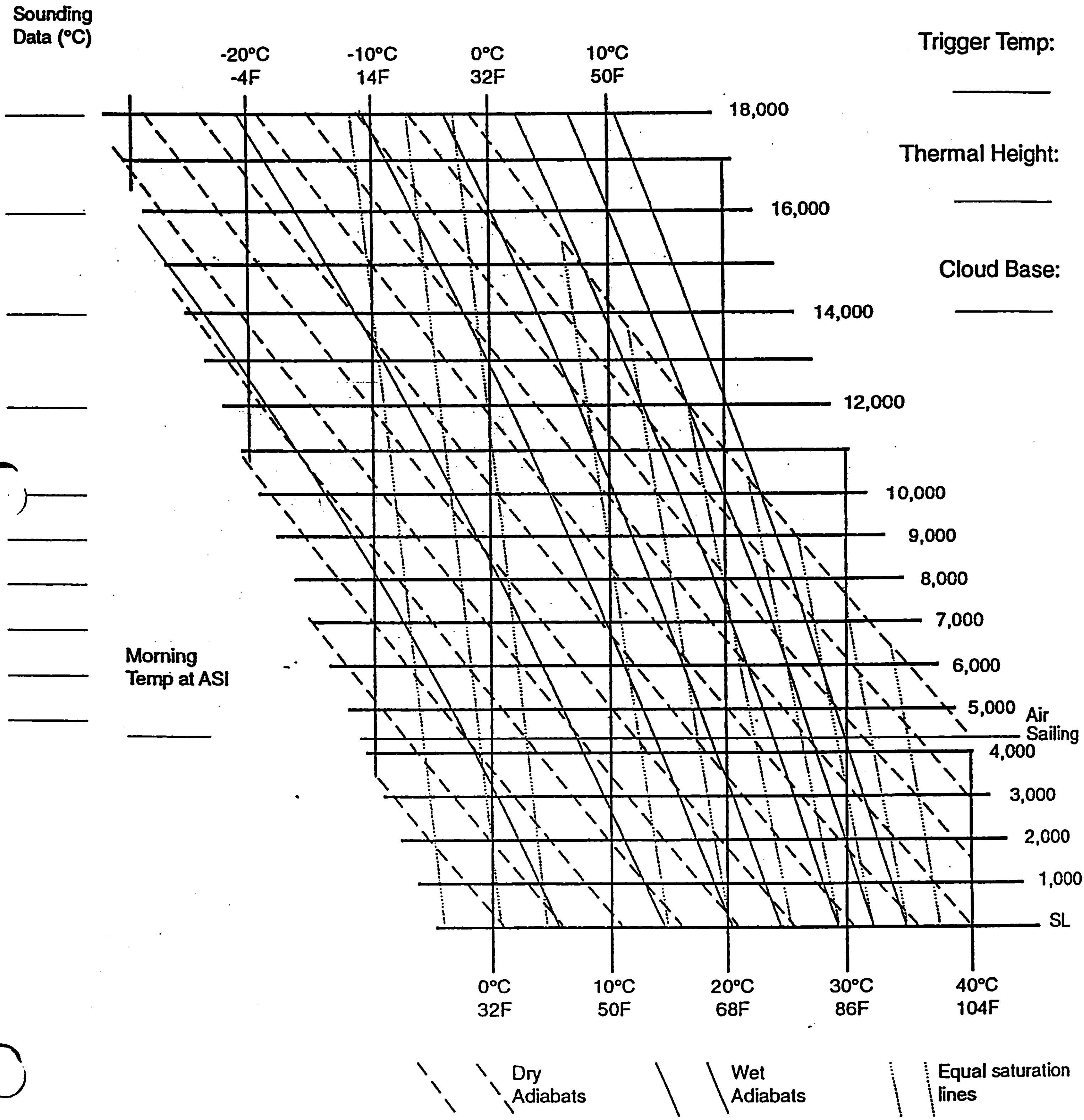
Thermal Height: ______

Cloud Base: ______

Trigger Temp 21°, Thermal Height 18,000+ (overdeveloped), Cloudbase 14,500.

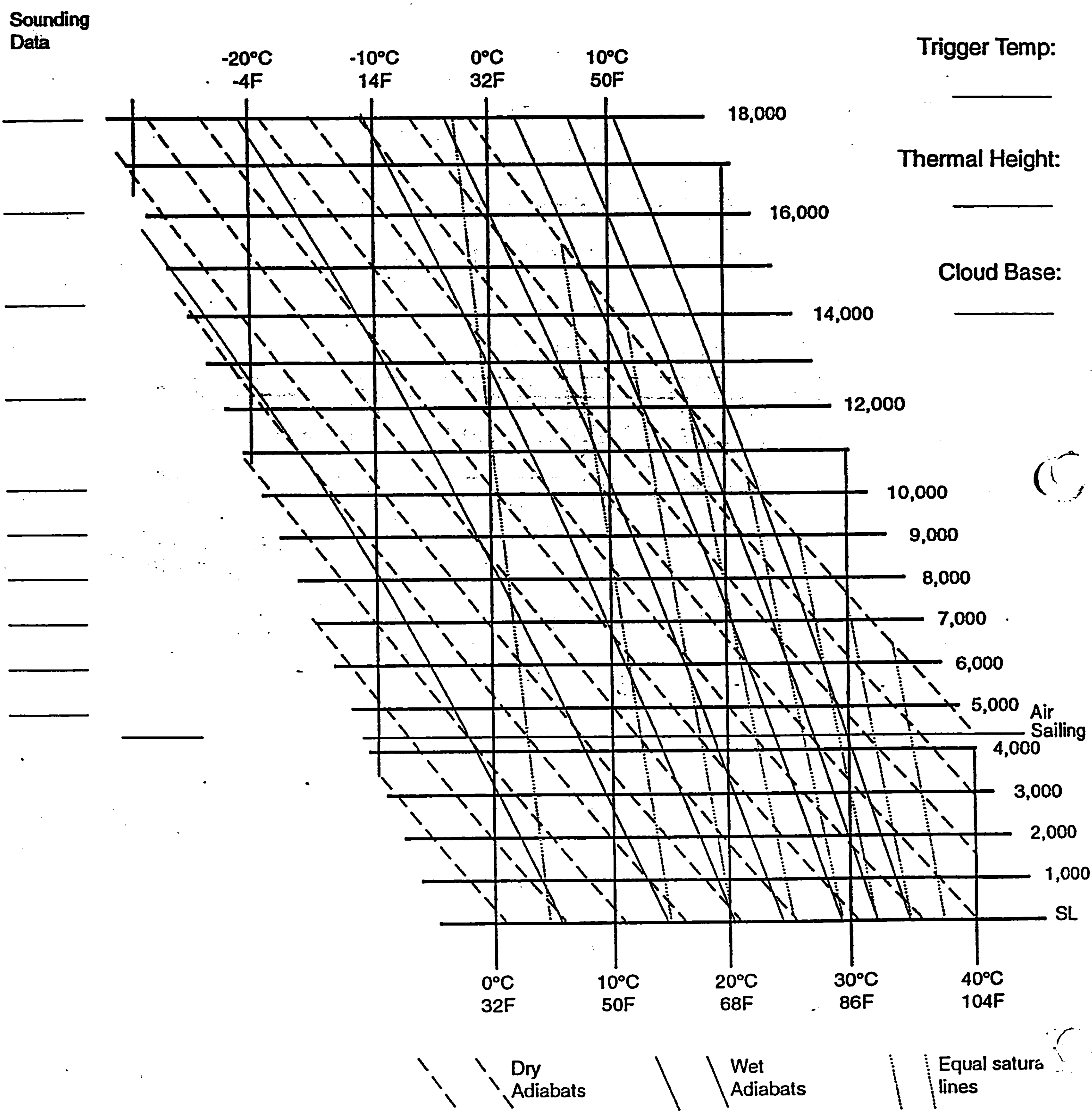
The Pseudoadiabatic Chart—Exercise 3

Plot today's sounding data.



The Pseudoadiabatic Chart

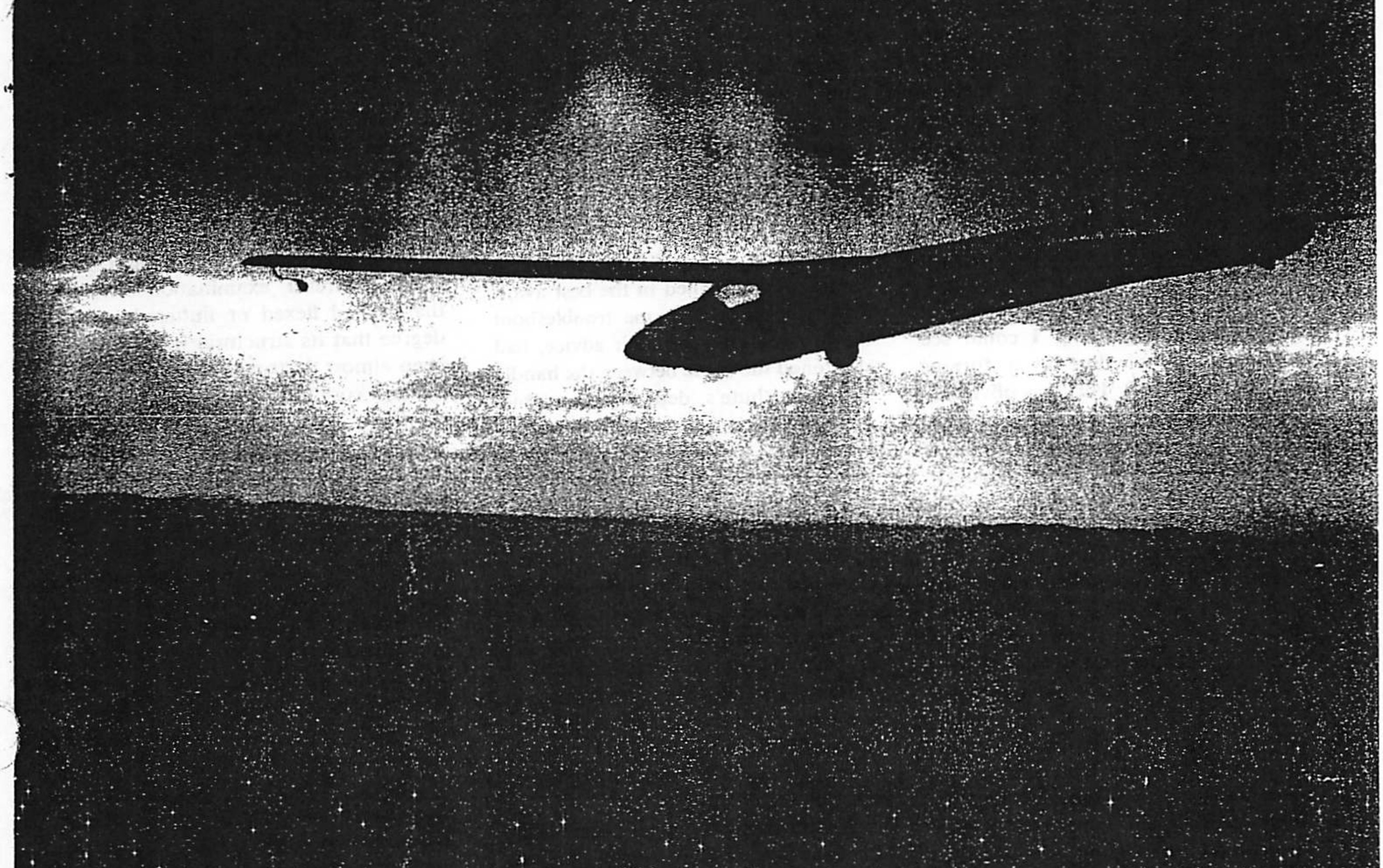
Here's a blank chart. Keep this one clean for copying.



Better pay attention! A cu-nim can be a scary teacher—

Dunderhead's Thunderhead

by GEORGE WORTHINGTON



On the next-to-last day of the National Soaring Championships at Liberal, I had photographed the final turnpoint and was headed for homebase in my AS-W 12. A hugh cumulonimbus thunderhead with rain gushing out its bottom lay between me and the finish gate. I was 4000 feet above ground; the storm had seemed to suck all normal lift out of the area for miles around.

From past experience I decided my best bet lay in flying directly toward the rain in the hope of using the updrafts of the storm itself. This stratagem had been successful several times on other days of the Kansas contest. Inherent was the danger of being drawn up into the storm cloud, something which could tear a glider apart and endanger its pilot's life (blind flying instruments are outlawed by contest rules).

I had thought of that danger many times and had considered what actions I would take: By lowering the wheel, using flap position #3, and flying at 125 mph redline, the sailplane would have a descent capability of 1050 ft./min. In the event that the upcurrent exceeded that figure and I found myself being sucked into the cloudbase, I had a last resort—I could deploy the sailplane's drag chute. (In order to obtain optimum aerodynamic performance, the AS-W 12 has no spoilers or landing flaps but has a jettisonable drag chute instead.)

I had written the manufacturers asking for all available information regarding the deployment of the chute at redline speeds. Their answer was that they were sorry but that they didn't know and couldn't predict what could happen. I optimistically decided that the chute would withstand the high-speed shock and would do the job. However, I felt that it would never come to that because the danger of involuntary entry into a cloud can nearly always be overcome by flying away from the storm at the correct time. I based this on my more than 20,000 cross-country miles in the AS-W 12 during the preceding three years, with dozens of transits under and through similar storms. I had deep respect for the power and dangers of the storm, but I felt that I could overcome the problem.

I flew two miles toward the rain under a black cloud shelf whose base lay about 7000 feet above the ground. When I reached the edge of the rain I was down to 3000 feet above the ground. But I found 300-fpm lift.

The cloud's black bulk darkened the area: I caught glimpses of other ships nearby and consequently paid great attention to keeping them in sight as I circled. By the time I reached 4000 feet AGL, lift had increased to

500 fpm. My mood became excited and hopeful as it can during such a race. I was expecting to achieve 7000 feet where I would be able to glide out of the storm's lift-killing influence and into the sunshine where normal lift conditions could be expected. At 5000 feet, lift had increased to 700 fpm and my feeling of well-being was increasing. An overdevelopment standing square in the middle of one's path on a cross-country flight is never a welcome sight—I've been stopped by them dozens of times. So it's pleasurable to fly up to them, dip into their power, and get help in circumnavigating them.

About this time my attention was attracted to the ground. I could see large curtains of dust in a furious dance beneath me. This was obviously an area where the storm's churning currents were touching the ground in their circle from downdraft to updraft. I welcomed this sign because it promised strong lift and it was fascinating to watch from my vantage point.

The AS-W 12 was being carried up even faster now, and I suddenly became aware of the cloud mass overhead. Its distance was about right—the base was still high enough above that it shouldn't give me any trouble, and besides, it sloped upwards from my position to the outer edge two miles away. I had gone as high as safely possible so I banked quickly and turned away from the storm at redline speed. It was not enough. The clouds were getting closer. I lowered the landing wheel and set the flaps in position #3. I felt confident that this action would keep me below the clouds.

It did not.

With stunning suddenness I was inside the dark vapors. I reached for the drag chute release handle, then paused. Deployment could rule out any chance of making the finish line and require an off-field landing. If I had to jettison it at altitude there was a strong probability of losing it and having to spend $300 for a replacement. There still remained one thing I hadn't tried.

Many years ago during instrument flight training in the Navy, I had been taught an emergency cloud-flying procedure using only the compass and airspeed indicator. I had entered the cloud in level flight and the turbulence was only mild. If I could hold a heading I would eventually break out in the clear. However, I had entered the cloud at redline and the compass was dancing and swinging to the degree that it was unusable. Speed was building. I applied careful back pressure on the stick. In spite of this, the speed passed 140 mph and kept slowly rising. I knew the ship was in a turn; I would have to use the drag chute.

I pulled the release handle. No response. The absence of even a momentary tug convinced me the chute had inadvertently jettisoned. (This was not a surprise. The same thing had happened the day before during a landing. I had called in the best available experts to help me troubleshoot the problem and, on their advice, had shortened the cable between the handle and the chute's deploy/jettison mechanism. Now I knew this shortening had made the situation worse, not better. However, I'm a poor mechanic, there is never enough time at a contest, and I am to blame.)

The airspeed continued to build. I knew the ship must be in a nose-down turn. To increase the back pressure on the stick would only aggravate the problem. However, something had to be done because the airspeed needle was now approaching 160 mph. I kept thinking, "How could this possibly have happened? What can I do now to save the ship?"

A loud chattering noise began. Were the flaps fluttering? It seemed a prelude to the total disintegration of the AS-W 12. I expected a wing to come off at any moment. In desperation I pulled back more firmly on the stick. I began to black out from the *g* forces. That wouldn't do. I eased off on the stick. Nothing to do now but wait . . . the needle crept toward 200 mph . . . the chattering grew still louder. It seemed inevitable that I would at least lose the ship.

A few more seconds had passed when abruptly I caught sight of a patch of ground. The ship was in a right turning dive of perhaps 40 degrees. Just as suddenly the clouds closed in again. I waited. Ten seconds passed. The ground appeared again, but this time the sailplane's flight path had cleared the bottom of the clouds.

The controls were rock stiff. It seemed to take a long time to bring the ship to a level attitude. When the speed dropped back through 150 mph the chattering noise ceased. Was the ship damaged? All my senses were critically focused on its responses. These seemed normal and I turned my attention to getting back to home-base. On the way a strong feeling welled up inside me: I had been very lucky. It was overwhelming at the moment; it was to be a mood that would persist for days and weeks.

After the landing, the only visible damages to the ship were a few "wrinkle lines" on the top and bottom outer skins of the horizontal stablizer which otherwise appeared quite normal. But further careful examination showed that it had flexed or fluttered to the degree that its structural integrity had been almost destroyed. Repairs of this damage cost $600.

As serious as this incident was, I find that its prevention in the future seems simple. Now that I know more intimately that lift in this area of a thunderhead can exceed 2000 fpm, I can allow more clearance and be more alert for telltale signs. It is obvious that I allowed the prospect of mid-air collision to assume too high a priority to the detriment of my concern for the cloud danger. I also allowed myself to be too distracted by the awe-inspiring dust spectacle below. In effect, I "went to sleep" near a danger that should have received more attention and respect. The very thing that should have helped—my considerable experience with overdeveloped cu-nim situations—lulled me into a dangerous false sense of security.

It is important to mention in retrospect that the plan to fly in under the cloud shelf toward the rain still seems valid. The mistake occurred as I was nearing cloudbase when I should have been monitoring rate-of-climb and proximity-to-cloudbase more carefully. Had this been done, I would have turned toward the outer edge of the shelf much earlier. I could then have resumed circling upon reaching an area of diminished lift so that the original goal of gaining maximum safe altitude could still have been achieved.

This method would have taken more time, of course, and racers must begrudge this. The lesson I learned is that this particular type of delay is worth the extra safety.

unjustifiably precise predictions. Usually it is more justifiable (and useful to the glider pilot) to try to convey some idea of the overall "soarability" of the thermals than to make superficial predictions of the speed of thermal lift. This "soarability" is assessed as a tentative by-product of the forecast intensity of sunshine, depth of convection, wind shear, the observed state of the ground, the nature of the countryside and the current accounts of thermal soaring experiences.

CHAPTER 16

Lee Waves

Have you ever watched the ripples in a shallow brook as the water flows over a submerged rock? The water rises over the rock, dips sharply on the downstream side and, if the rock is in the form of a ridge placed across the stream, the water surface will rise and fall a second, third or several more times downstream. The crests of the ripples form a series of bars parallel to the rock and, with water flowing through them, these bars remain in almost stationary positions in the stream.

Substitute an airstream for the brook, a mountain for the rock and we begin to visualise the form of lee waves in the atmosphere. But before trying to visualise too much let us get a few basic features of wave flow fixed in our minds. These features are illustrated in Figure 16.1 by the airflow across a very long isolated mountain ridge lying at right angles to the airstream. Of course, mountain ridges do not always happen to be at right angles to the wind direction; they are often short rather than very long; they are seldom isolated from other mountains, and they rarely have the smooth symmetrical profile shown in this illustration. But we can consider more complicated shapes later. First the basic features and the terminology used to describe them.

The flow pattern may be dissected into three zones. The first zone contains the undisturbed flow—too far upstream to be diverted far from its steady horizontal course. Then comes the mountain sector wherein the streamlines at low levels tend to follow the high ground profile, and finally we have the lee wave flow with its regular undulating stream bearing little apparent relationship to the flat terrain below.

It is this lee wave flow that merits detailed discussion and the two dimensions most appropriate to such discussion are wavelength and amplitude.

The lee wavelength is a measure of the distance from one wave crest to the next—or from trough to trough. Usually between 2 and 20 nautical miles, this lee wavelength is determined almost entirely by

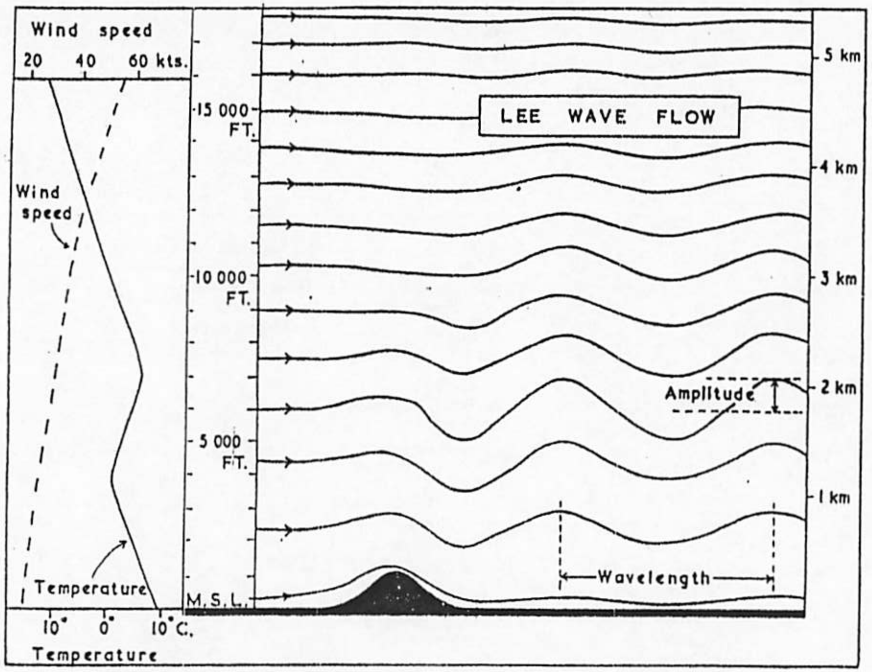


Fig. 16.1. In lee wave flow the air usually dips sharply down in lee of a hill ridge before undulating up and down for some considerable distance downstream. The wavelength of the lee waves is determined entirely by wind and temperature conditions in the upstream flow while the lee wave amplitude depends on both airstream conditions and the size, shape and surface nature of the ridge.
Lee waves are often associated with a stable layer sandwiched between air of lesser stability together with an increase with height of wind components across the ridge.

winds and temperatures at various levels in the undisturbed flow. It is not normally the same as the distance between the summit of the ridge and the first lee wave crest.

The lee wave amplitude is half the vertical distance from wave trough to crest. Notice that the amplitude varies with height. Negligible close to the ground and at very high levels, it attains a

maximum at about 6,000 ft. in the illustration of Figure 16.1. The streamline at this level in the undisturbed, upstream flow is displaced from 1,000 ft. below to 1,000 ft. above this level in the lee wave part of the stream, i.e. the lee wave amplitude is 1,000 ft. at the 6,000 ft. level.

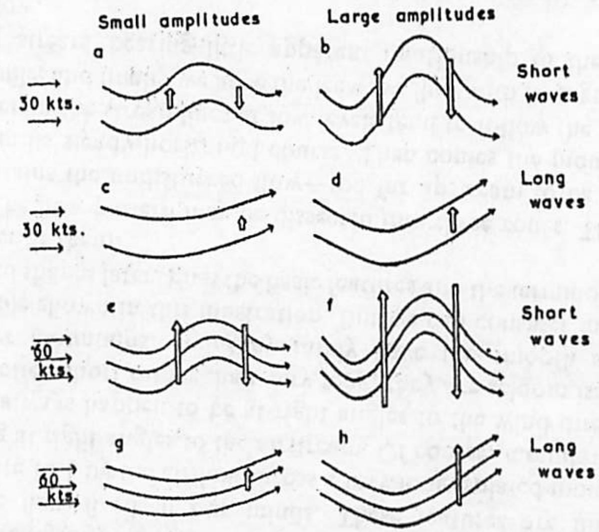


Fig. 16.2. Vertical currents (represented by the broad arrows) in wave flow depend upon the wavelength, the wave amplitude and the wind speed through the waves. Strong up- and downdraughts are favoured by large amplitudes, short wavelengths and strong winds.

Either one or both of these dimensions are bound up with almost every feature of wave flow to be discussed.

Vertical currents in the wave flow depend on the amplitude, the wavelength and the wind speed. As shown in Figure 16.2, strong up- and downdraughts are favoured by:

1 large amplitudes—the larger the amplitude the farther the air moves up and down;

2 short wavelengths—the shorter the wavelength the steeper the ascents and descents in the undulating airflow;

3 strong winds—the stronger the wind the faster the air moves through the wave pattern.

The distribution of vertical speed throughout a wave flow is illustrated in Figure 16.3.

The lee wave flow illustrated was evidenced by variations in the rate of ascent of a radio-sonde balloon released from Leuchars on 21 December 1953, and the detailed structure of this flow was calculated approximately on an experimental but justifiable theoretical basis. In this particular flow it is apparent that a glider

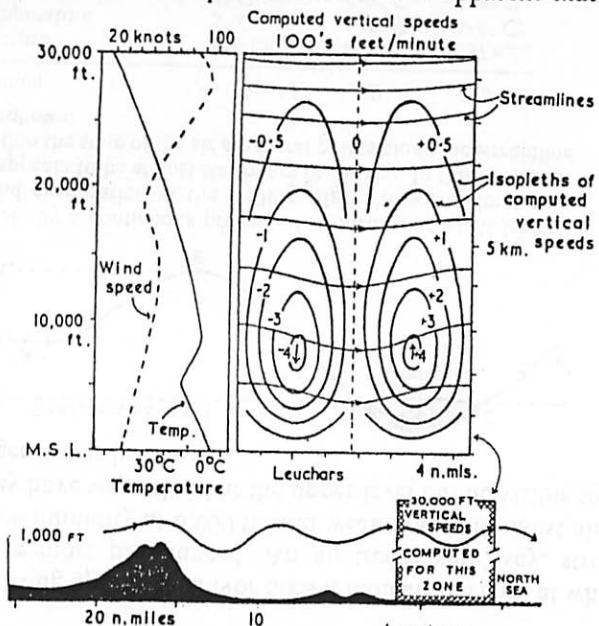


Fig. 16.3. On 21 December 1953 waves were evident in lee of the Sidlaw Hills, Scotland. Vertical speeds in the neighbourhood of Leuchars were calculated approximately on an experimental but justifiable theoretical basis. Wind direction was approximately 290 degrees at all heights.

with a minimum sinking speed of, say, 180 ft./min. (about 60 m./min.) could have maintained or gained height in the updraught of the wave between 3,000 and 17,000 ft. Above and below this height interval the vertical wave currents were too small for soaring.

The egg-like structure representing vertical speeds is characteristic of many a lee wave flow. Of course, details vary from one wave situation to another but it is useful to have the basic pattern in mind.

Wave cloud is another phenomenon linked closely to lee wave amplitude. Air rising in the updraught of a wave cools adiabatically, and if this cooling is sufficient to cause condensation then cloud will form. Subsequent warming in the downdraught causes the

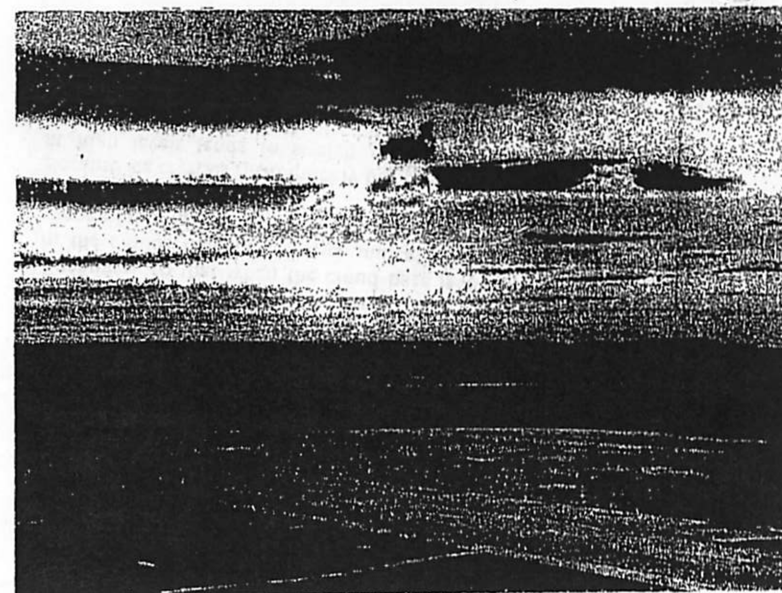


Plate 19 LEE WAVE CLOUDS *P. Lane*

The view towards the west-south-west from R.A.F. Leeming, Yorks, showed a series of wave clouds in lee of the Pennines in the late afternoon of 19 April 1958. The wind at 2,000 ft. was 250 deg. 25–30 knots. The smooth bars of wave cloud lying across the wind were between 8,000 and 12,000 ft. while the relatively ragged patches of wave cloud between 3,000 and 5,000 ft. indicated the tendency for rotor flow to develop at low levels.
(Reproduced by courtesy of H.M.S.O.)

condensed water to evaporate and so by a continuous process of condensation at its leading edge and evaporation at the trailing edge the cloud as a whole appears to be stationary in the sky. As illustrated in Figure 16.4, wave cloud owes its existence to two principal factors: the wave amplitude and the humidity of the air before it enters the wave flow. Because condensation of water vapour in the atmosphere is a very rapid process the formation of wave cloud does not depend upon the speed of the vertical currents. Therefore the only certain fact implied by the presence of a wave cloud is that near the level of the cloud the wave amplitude is big enough to lift the air to its condensation level. This in turn indicates anything from small amplitude undulations in humid air to large amplitude waves with low humidity, and remembering that the vertical currents are dependent not only on the amplitude but also on the wavelength and wind speed it becomes apparent that a wave cloud is not an absolutely

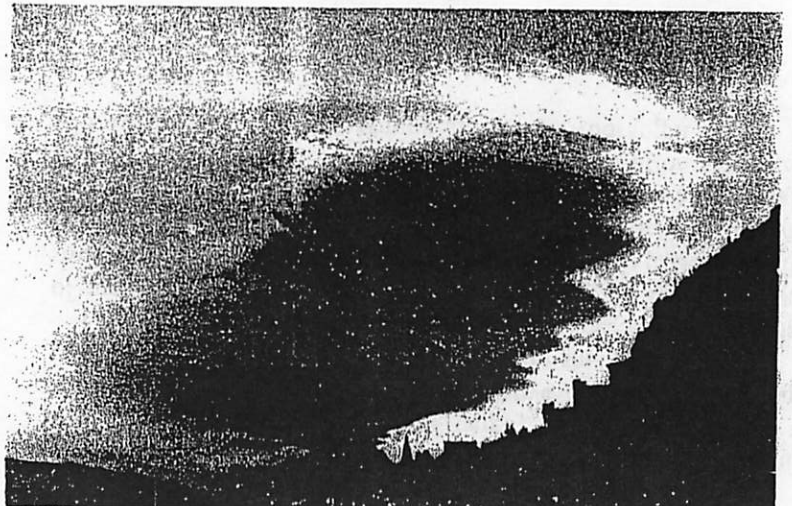


Plate 20 WAVE CLOUD IN SICILY *R. K. Pilsbury*

This wave cloud in the vicinity of Taormina, Sicily, shows a small scale globular form of cloud at its trailing edge. A westerly wind was blowing (from right to left in this photograph) at the time.

sure sign of strong updraughts. Nor does it indicate the level at which the waves are most pronounced. An airstream with, say, strong waves but low humidity at 6,000 ft. and weak waves in moist air at 10,000 ft. may have wave cloud at the upper level but no visible signs of the stronger waves below.

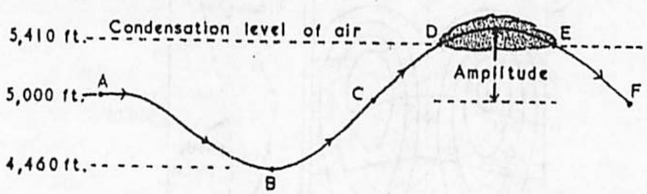


Fig. 16.4. By a continuous process of condensation at its leading edge and evaporation at the trailing edge, the wave cloud as a whole appears to be almost stationary in the sky. In this particular illustration the state of the air at several points along the streamline are as follows:

Position	*A, C and F*	*B*	*D and E*
Pressure	850 mbs.	867 mbs.	837 mbs.
Temperature	5° C.	6·6° C.	3·8° C.
Dewpoint	4° C.	4·2° C.	3·8° C.
Water vapour content	6 gm./kg.	6 gm./kg.	6 gm./kg.
Relative humidity	94%	85%	100%

Humidity can and often does vary considerably with height; some of the more detailed variations can occasionally be deduced from the shapes of isolated wave clouds. In Figure 16.5*b*, for example,

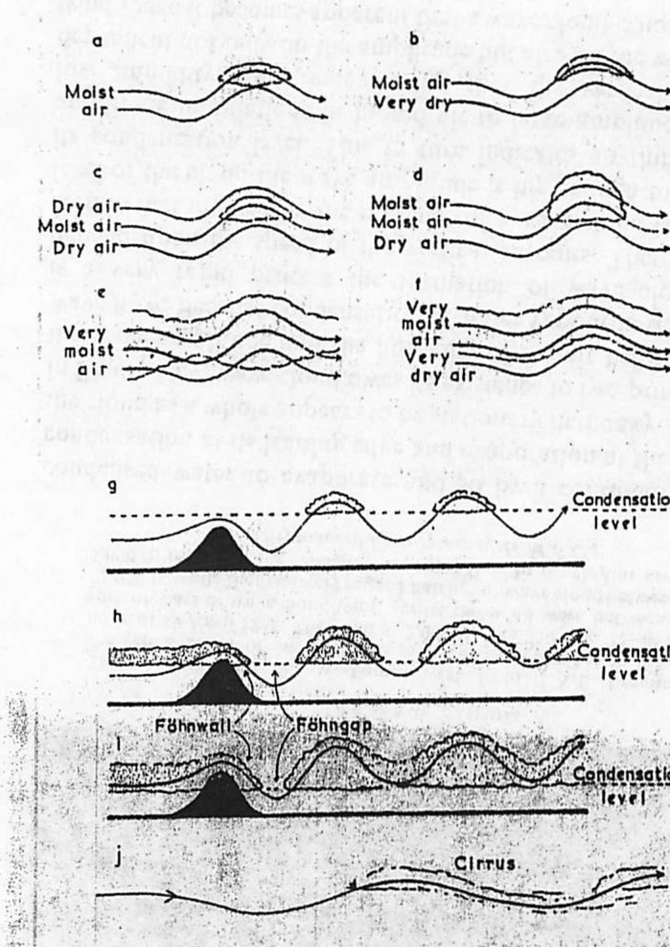


Fig. 16.5. The shape of the wave cloud depends not only upon the streamlines but also on the vertical variation of humidity.
Quite often the streamlines reach their lowest levels in the Foehngap, so that when the cloud base is low this stationary gap in the clouds may be a better indicator of wave flow than the shape of the wave cloud itself, which, as in *i*, may have a deceptively flat base.
Because ice crystals form quickly but evaporate slowly, wave cloud at high levels tends to stretch out some way downstream, as illustrated in *j*.

the concave base of the lenticular cloud denotes an abrupt increase of humidity with height, while a convex base betrays a more gradual vertical variation of humidity. Figures 16.5*c* and *d* show that the streamlines are as steep as the cloud face only when the humidity decreases sharply just above the wave cloud level.

The lenticular (lens shaped) form of wave cloud is most commonly observed at medium levels—between 6,000 ft. (2,000 m.) and 20,000 ft. (6,000 m.) in temperate regions. At lower levels the wave cloud is often torn into ragged patches by low level turbulence. The patches as a whole remain more or less stationary but their detailed outline changes quickly and erratically.

At high levels cloud is usually composed of ice crystals and because these crystals form quickly but evaporate slowly high level wave cloud forms readily in the updraught of a wave but does not always disappear on the descent; it tends to stretch out some way downstream.

Wave conditions

Another way of dissecting the airflow across a ridge is to regard it as a lee wave pattern, typified by the streamline in Figure 16.6*a*, superimposed on the more common type of flow depicted in Figure 16.6*b*. The main problem in planning to soar in waves is that of deciding whether or not the lee wave part of the flow can exist in

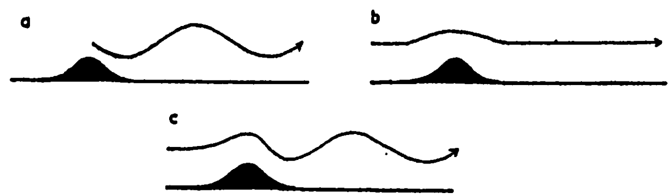


Fig. 16.6. Wave flow may be considered as a flow typified by the streamline in *a* superimposed on the more common flow depicted in *b*. The result is illustrated by *c*.

the prevailing or predicted atmospheric conditions. Experience suggests that the conditions favourable for waves with appreciable vertical currents comprise:

1 a layer of low stability (high lapse rate) at low levels,
2 a stable layer (e.g. isothermal layer or inversion) above the lower layer, and
3 an upper layer of low stability in the troposphere.

Supplementary conditions are that the geostrophic wind, or wind at about 1,500 ft. (500 m.), should be at least 15 knots across whatever mountain ridge is being considered and that the wind

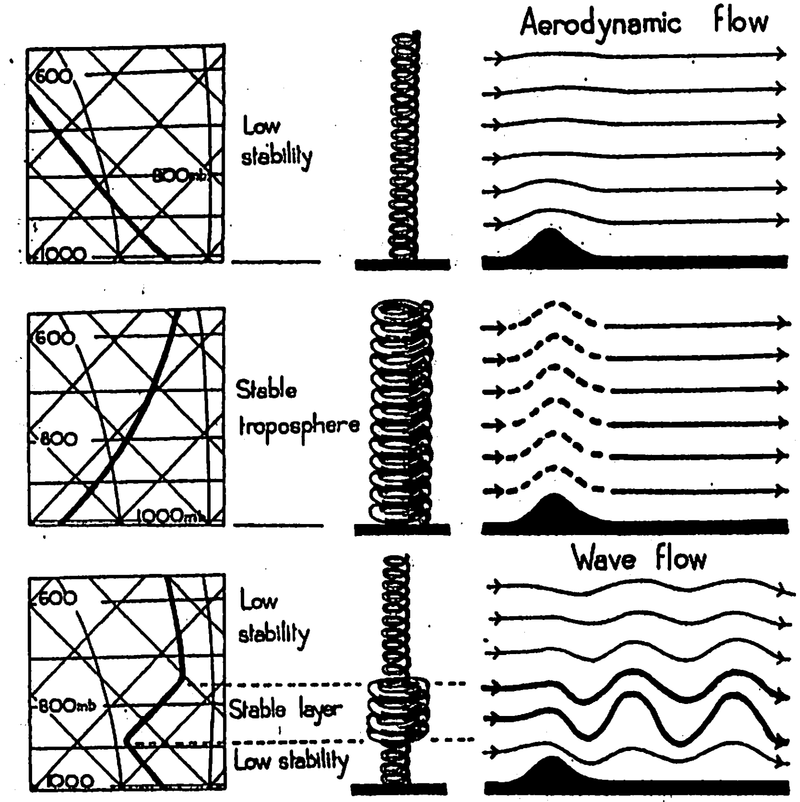


Fig. 16.7. The atmosphere may be likened to a vertical coiled spring. An unstable airstream can be compared with a weak, flimsy spring because it offers little resistance to vertical motion within it, and a stable atmosphere can be likened to a tough, heavy spring which tends to suppress internal vertical motion. The best structure for persistent oscillation is a sandwich of a few strong coils between two weaker springs.

direction should be almost constant with height up to the top of the stable layer. These conditions are illustrated in the left-hand sides of Figures 16.1 and 16.3.

To understand why stable air sandwiched between two layers of lesser stability favours the formation of significant lee waves it may be helpful to resort to an analogy. The atmosphere may be likened to a vertical, coiled spring. An unstable airstream can be compared with a weak, flimsy spring because it offers little resistance to vertical motion within it, and a stable atmosphere can be likened to a tough, heavy spring which tends to suppress internal vertical motion. With the aid of Figure 16.7 it is not difficult to imagine that although the lower coils of the flimsy spring would move easily up and over a mountain ridge the jolt received at ground level would not be transmitted far upwards. Nor would it stretch the imagination too far to suppose that if the heavy spring were forced over a ridge it would be too tough for oscillations to be set up.

But consider now a few strong coils sandwiched between two weaker springs—as depicted in the lowest section of Figure 16.7. With this arrangement it is conceivable that the tough coils will continue to bounce up and down for some time after the structure has crossed a mountain ridge.

The atmosphere works in a somewhat similar fashion. Neither a completely unstable nor a uniformly stable airstream can produce appreciable lee waves but a stream containing stable air between layers of lesser stability is both flexible enough to be set in vertical motion and resilient enough to maintain this motion as a series of vertical oscillations.

The spring analogy has many flaws and we must be cautious in drawing conclusions from it. Nevertheless it does illustrate several features of lee wave flow. Considering Figure 16.7, for example, it seems reasonable to suppose that the heavy coils dominate the leeward oscillations, and indeed lee waves in the atmosphere usually do have their maximum amplitude in the stable layer which contributes so much to their existence. (See Figures 16.1 and 16.3.)

The amplitude and the frequency with which the coils bounce up and down is related in some close but complicated way to the precise depth and resilience of each part of the spring and the lee wavelength is determined by the speed with which these vertical oscillations are propelled downstream. It should be no surprise, therefore, to learn that lee wavelength and amplitude in the atmosphere are determined by the winds and temperatures at various levels in the undisturbed flow. Out of the intricate relationships between winds, temperatures, lee wavelength and amplitude, two deductions which emerge as useful though not infallible supplements to the wave flow conditions already listed are that:

1 the stable layer associated with the wave flow produces larger amplitudes when it comprises a shallow layer of great stability than when only moderate stability extends over some considerable depth;

2 long waves are associated more with strong upper winds than with light winds aloft.

Diurnal variation of lee waves

In the neighbourhood of Cross Fell in the Pennines the local folk assert that "the bar never crosses the Eden," and if you appeared no wiser for this odd piece of information they would explain that the bar refers to a cigar shaped cloud (the Helm bar) sometimes observed downwind of and parallel to the steep escarpment of Cross Fell, and that the Eden is the river in the leeward valley. During the mornings the bar usually moves slowly downwind, towards the south-west, but later in the day, just as the cloud seems about to cross the river, it apparently changes its mind and retreats back towards the escarpment. Thus "the bar never crosses the Eden," or translating the story into meteorological English: there is a tendency for lee wavelengths to increase during the morning and decrease during the late afternoon. An explanation of this diurnal effect starts with insolation, or heat from the sun, which warms the ground, which warms the air at low levels. Any low level inversion present is reduced in depth, or even eaten away, by the convection set up, and it is one of the intricate relationships between temperature and wavelength that links such a reduction with an increase in wavelength. In a complementary manner the subsequent decrease in wavelength stems from the low level cooling which occurs in the late afternoons and evenings of fairly clear days.

Lee wave amplitude is also affected by diurnal heating and cooling. Its variation is such that, in the British Isles,* the wave history of many a day can be classified into three periods:

Early morning in which a sudden and quite early onset of wave flow is often followed by good wave soaring conditions at their best between about one and three hours after sunrise.

The middle of the day is the least likely period for soarable waves. Waves are suppressed or even obliterated by convection.

* The variation being described does not apply to regions where diurnal heating is more intense; in the Owens Valley, California, heating tends to increase the lee wave amplitude in the mid-afternoon.

Late afternoon and evening. Increasing amplitude and a shortening of lee wavelength combine to produce appreciable vertical currents which are often at their strongest from about one to three hours before sunset. If a 15-knot gradient wind is maintained the wave flow may persist until well after dark, but there is a tendency for the wave amplitude to decrease again and when it does so the collapse is often sudden.

Although these diurnal effects are important they play only a subsidiary rôle in the creation of lee wave conditions. It is the synoptic situation that can provide the upper wind and temperature conditions suitable for wave flow. The diurnal heating and cooling, which is itself under partial control of the synoptic situation, superimposes significant but not necessarily dominant variations on these conditions.

Synoptic situations

A synoptic situation favourable for lee waves is simply one in which the airstream conditions required for wave flow are satisfied in the locality being considered. These conditions can be fulfilled in a variety of ways.

Warm sectors over the British Isles often include fresh west to south-west winds whose variation with height shows an increase in speed but little or no change in direction. The well stirred air at low levels usually has little stability from ground level up to between 2,000 and 6,000 ft., and above this layer the stability increases sharply before falling off with height. So warm sectors are likely to promote many a wave flow in lee of mountain ridges whose axes lie across the flow. But it is unlikely that these waves are fully exploited; warm sectors often bring a complete cover of low cloud which not only conceals its own wave top from the observers below cloud but may also mask the hill tops with drizzle and fog.

Anticyclones with their subsidence aloft usually have a temperature structure made to measure for lee waves; a shallow, extremely stable layer centred somewhere between 4,000 and 10,000 ft. is a common feature of high pressure systems in temperate regions. But the centre of an anticyclone also features light and variable winds, so that to locate the wave flow conditions we must search towards the outer fringes—far enough from the centre to pick up winds of 15

knots or more, but not so far that the stabilizing effect of subsidence is lost.

Warm fronts are often preceded by wind and temperature conditions which, for limited spells during the pre-frontal changes, are suitable for wave flow. The nature of this wave flow ahead of a

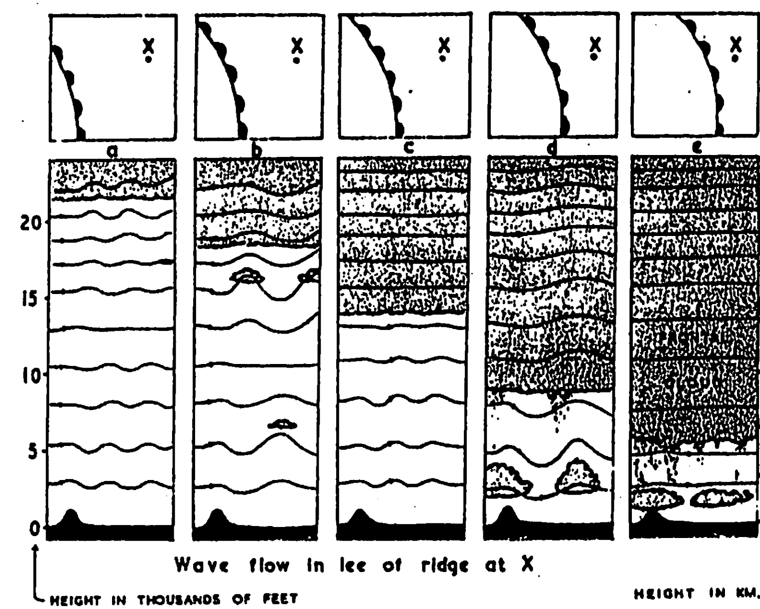
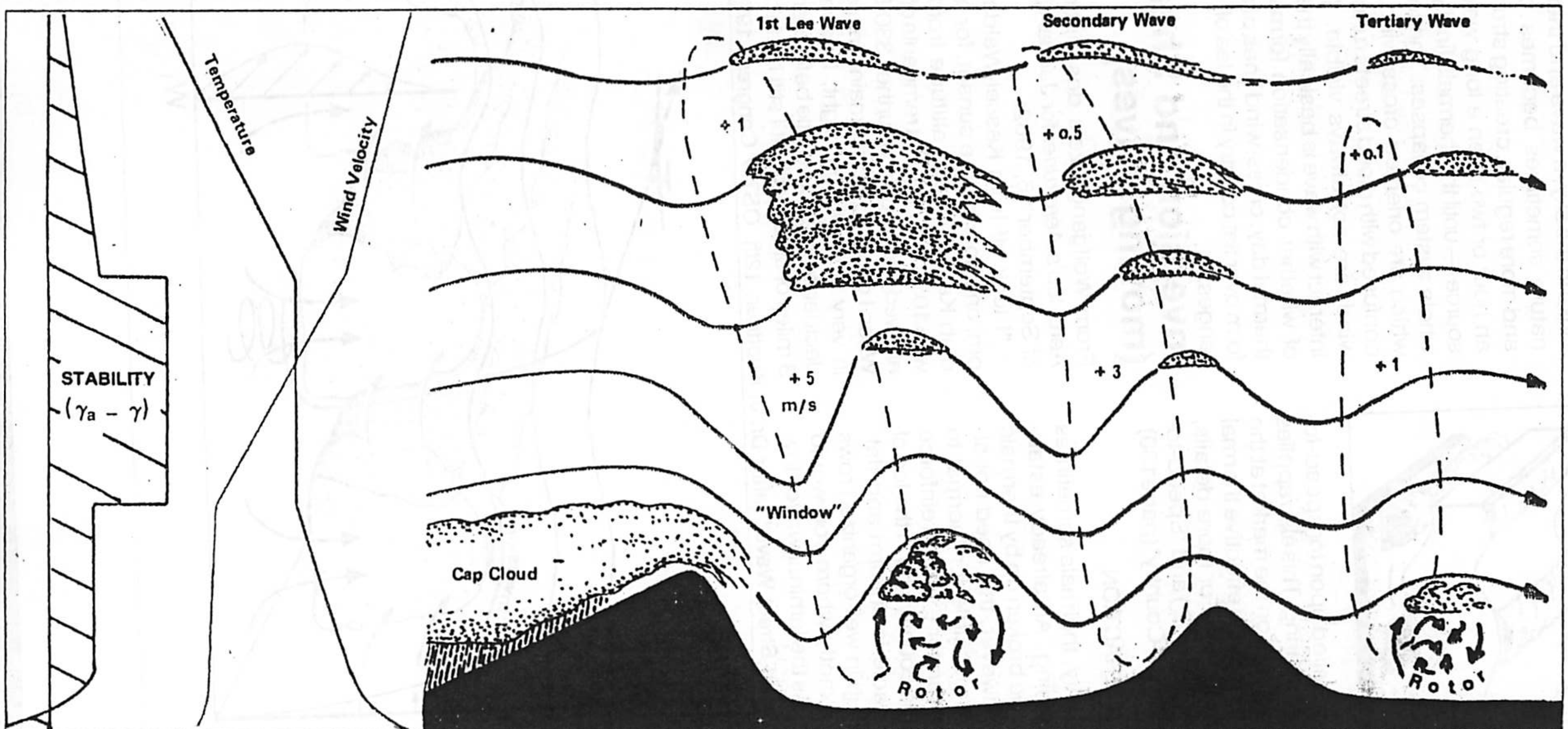


Fig. 16.8. During the approach of a warm front there occur one, two or possibly three spells during which the steadily changing winds and temperatures aloft favour the formation of soarable waves. In this illustration there are two soarable spells, depicted in *b* and *d*.

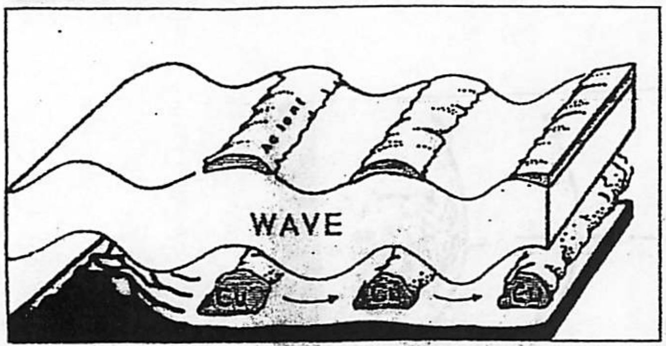
well marked warm front is illustrated by the sequence of events depicted in Figure 16.8.

The approach of the warm front is accompanied by increasing and lowering cloud and also by changes in the upper winds and temperatures. In practice it is impossible to reason out precisely where or when the airstream conditions will be suitable for wave flow. However, experience and lengthy calculations suggest that some distance ahead of the front (16.8*a*) there are likely to be rather short waves of only mediocre amplitudes, and in noting the effective heights of these waves we meet a new phenomenon—a wave which has amplitude maxima at two distinct levels. Between these levels

Mountain Lee Wave



Wave and thermals sometimes interact and reinforce each other.



the speed ring cannot be relied upon for speed-to-fly information when wave soaring. This also applies to all the flight data computers on the market at the end of the 1980s, even those with effective thermal soaring altitude compensation. For more details, see "30 Training Tasks" (page 82) and "Speed-to-Fly When Wave Soaring Cross-Country" (page 130).

WAVE AND THERMAL INTERACTION

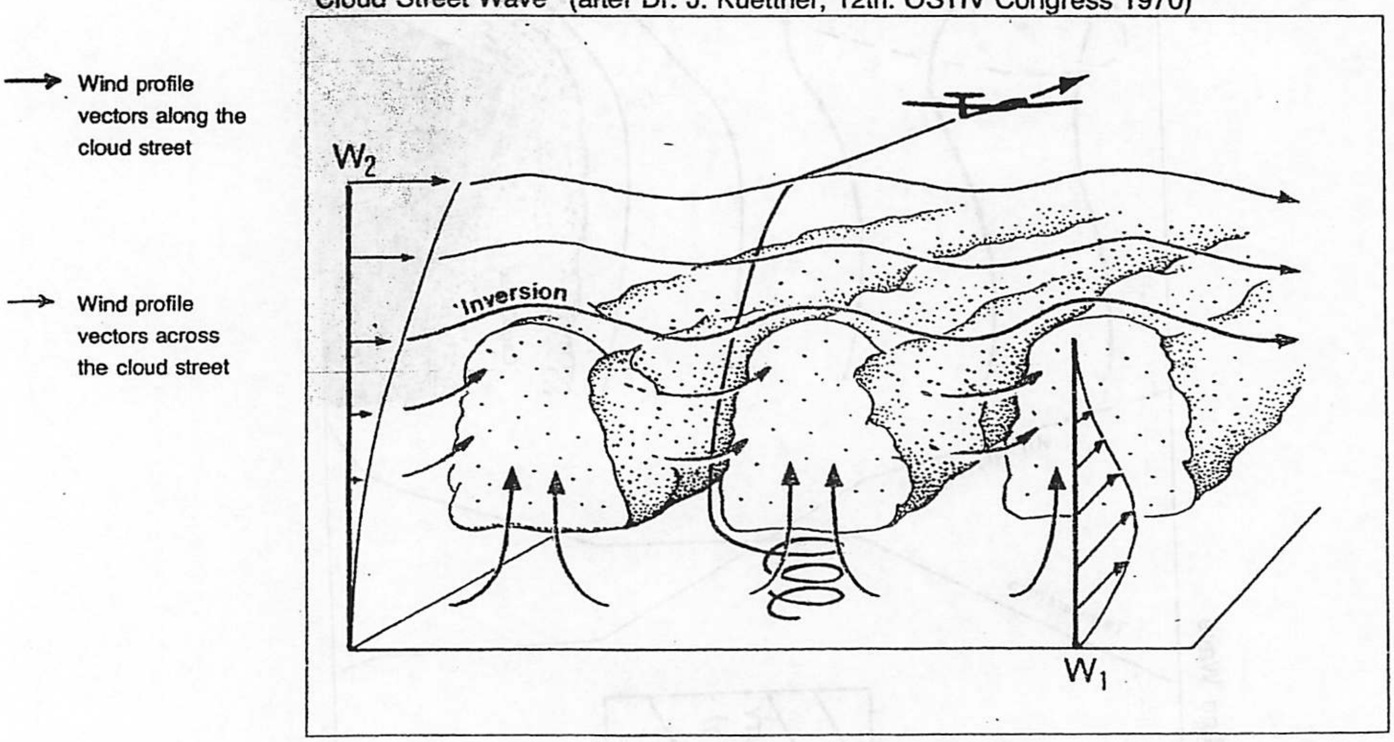
Because of their irregularity, thermals sometimes prevent waves from forming. An already established wave system can be broken up by thermals as the day advances. However, this need not always happen. It is quite possible for thermal to coexist with wave, and even for each to reinforce the other. In particular, if the countryside in the lee of the wave-triggering obstacle is uniform and flat, thermals over it may form up in well-organized rows under the wave-crests, exactly where you would also expect to find rotors. As the laminar wave-flow sweeps over these thermal barriers it can be boosted, and sometimes persist further downwind from the source than would have been the case without thermal influence. In the evening, as the sun sinks in the sky, a wave and thermal system of this nature sometimes becomes better harmonized and more regular, creating stronger conditions for an hour or two even a long way downwind of the source — until the thermals finally peter out, and the whole system collapses. These bars of thermals, which are oriented cross-wind and must not be confused with cloud streets running up- and down-wind, are not always visible. The way thermals interact with wave is basically the same regardless of whether condensation forms. Even on a blue thermal day, cross-wind lines of convective lift can form over flat country in the lee of, and parallel to hill-ranges.

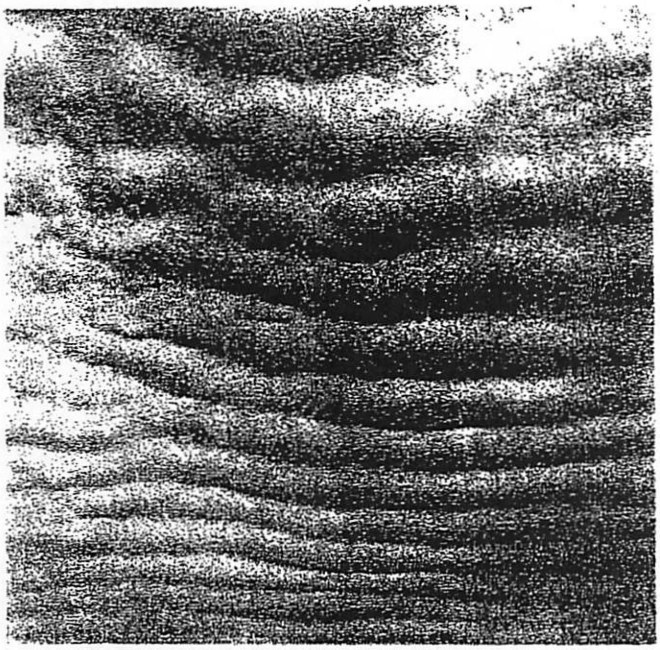
Inversion and Shear Waves (moving waves)

From Wolfgang Itze's description (in Deutscher Aeroklub's *Aerokurier* for January, 1963) of his flight of September 16, 1962:

"I took off from Kassel-Waldau airport at 5:35 pm, one hour before sunset, for a local flight in the club Ka-8. Release altitude from a winch launch was 1050 feet. The last remnants of evening thermals allowed me to gain a further 330 feet in 50-fpm lift. When I could no longer maintain more than zero sink in very slow straight flight, I gave up circling and decided to fly about a little before landing. After about 3 miles of straight flight I still hadn't lost any altitude.

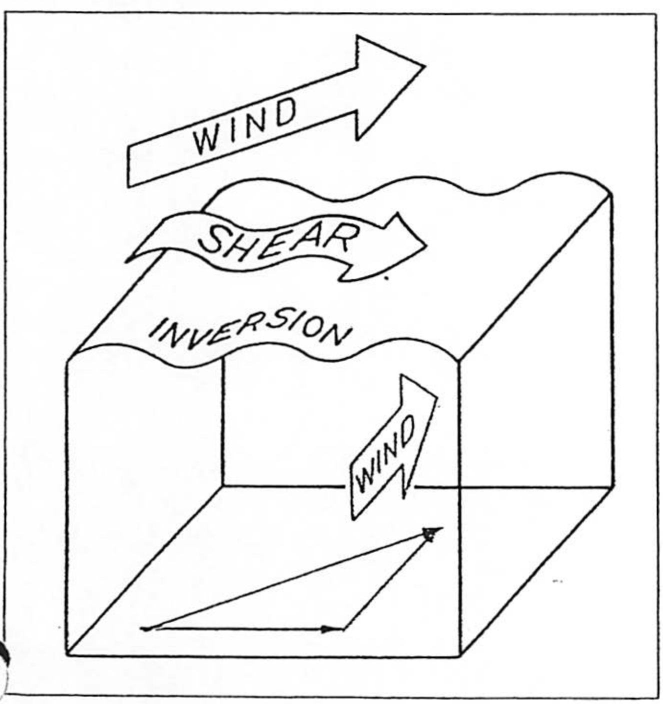
"Cloud Street Wave" (after Dr. J. Kuettner, 12th. OSTIV Congress 1970)





I continued to fly S-turns to determine the direction of the inversion wave and by about 6:00, when the air had become completely stable after the last evening thermal, I was still climbing at a good 200 fpm, flying back and forth for about six miles as if I were flying a ridge. When I reached 2200 feet, the bottom of the inversion, the lift reduced to zero sink. I could have remained aloft indefinitely, and I suppose I could also have flown for long distances, but the approach of darkness forced me to land. Some 3½ miles away, parallel to the wave I was flying, I discovered the next very intense inversion wave. I landed after determining the direction of this second wave." Itze had remembered the theoretical representation of an inversion wave in Georgii's book, "*Meteorological Sailplane Navigation*," and had used the information in flight.

Inversion Waves



Direction and strength of the wind shear are obtained by subtraction of the wind vectors.

Inversion waves are formed if there is a strong wind shear at the inversion altitude. They are independent of any obstacle, whether terrain or convective, just like waves at sea; their direction is across the wind shear. Itze provides the following data for the day of his flight: Surface wind 210° at 5 kt, wind at the 850-mb surface 270° at 15 kt. Assuming that the shear occurred fairly abruptly at the inversion, it would have a resultant of 110° at 13½ kt, in which case the waves would have been aligned 20°-200°. Itze's inflight estimate of 10°-190° tallies closely with this. At the same time the waves must have moved in the shear direction — that is, 100° — since they travel like waves on the water surface.

The description of 3½ mile wave spacing is difficult to understand, though, since inversion (or Helmholtz) waves could only develop such wavelengths under extreme conditions. (Wavelength increases with the abruptness of wind shear and decreases with the strength of the inversion. Since strong shears and strong inversions usually go hand in hand, wavelengths are usually less than 3000 feet.)

A flight made in 1960 by Kolde and analyzed by H. Jackisch seems to fit the model more exactly as far as wavelength is concerned.

Inversion waves are limited to a shallow layer, are difficult to locate (since they move), tend to "break" like water waves, and hence usually exist only for short periods. It is doubtful that they'll ever have much practical use for cross-country soaring.

Dynamic Soaring

Inspired by the splendid flight performance of the Albatross, a large sea bird whose refined use of horizontal wind shear near the surface allows it to cross entire oceans without updrafts, several theoretical explanations have been advanced in the last decades which have attempted to make these sources of lift available to sailplanes as well. Since these have remained only theoretical until now, many of these hypotheses have gotten the reputation of pointless physical and mathematical problems with no practical application.

However, Ingo Renner, a four time World Champion, has actually made dynamic soaring flights, thus proving that long flights are possible even without lift as we know it, as long as a wind shear of sufficient strength exists.