Direct Evidence of "Sheets" in the Atmospheric Temperature Field

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ABSTRACT

This paper presents experimental evidence showing the ubiquitous presence in the lower atmosphere (at least up to 25 km) of very strong (positive) temperature gradients within very thin layers. The presence of such "sheets" in the temperature field of the free atmosphere was frequently hypothesized in order to account for the aspect sensitivity of VHF radar measurements. Owing to their high vertical resolution (20 cm) and to the fast-response thermometers used, in situ balloon measurements discussed in this paper constitute the first direct evidence of their true existence. Statistical study of the properties of the sheets results in the following typical values: thickness 3–20 m, temperature increase 0.2–0.8 K, gradient 30–100 K/km. The sheets are frequently observed in groups, associated with and taking part in regions of high static stability. Local measurements using two pairs of sensors one meter apart indicate that the sheets are not flat and horizontal. Sometimes, clear evidence of ongoing or recent mixing, despite the strong local static stability, can account for such distortions. Observations of the same sheets by two thermometers 65 m apart (vertically) indicate vertical distortions of the sheets up to 10 m and horizontal extensions larger than 100 m. The possible contribution of the observed sheets to the VHF radar vertical reflectivity is estimated and compared with simultaneous reflectivity profiles measured by the PROVENCE radar. Without any adjustment, these profiles compare favorably, both in shape and in level, thus suggesting that the sheets can account for a significant fraction of the VHF radar vertical echoes.

1. Introduction

High vertical resolution (20 cm) atmospheric temperature profiles, obtained from the ground up to the middle stratosphere (27 km) by in situ measurements using fast-response cold wire thermometers, revealed a large number of very strong (positive) temperature vertical gradients within very thin layers (typically less than 10 m). This unexpected finding has potentially important consequences for the theoretical understanding of small-scale atmospheric dynamical processes and also has practical consequences for all the propagation phenomena (light beams, radio waves, sounds . . .) within the atmosphere.

This kind of structure has been observed in the stably stratified part of the ocean (Gregg 1980; Dugan 1984; Luck 1988) or in lakes (Thorpe 1977; Imberger and Ivey 1991). In the atmosphere, similar observations have been reported in the stable planetary boundary layer; see, for example, Gossard et al. (1985). To our knowledge, however, the present work, thanks to the high resolution of the measurements, constitutes the first report of the ubiquitous presence of such strong gradients in the free atmosphere, up to 27 km. In the present report, following the oceanic and boundary-layer terminology, we use the word "sheets" to name these thin regions with very strong temperature gradient (Woods 1968, 1969). However, the use of the same name does not imply that the observed structures correspond to identical physical mechanisms. As an example, a mechanism specific to the ocean, known as "salt fingers," can lead to the formation of density staircases, with a succession of "sheets" and "layers" (strong and weak density gradients, respectively). See, for example, Marmorino (1987) or Marmorino and Greenewalt (1988). This kind of process is clearly excluded in an atmospheric context and the use of the word "sheet" simply refers to the morphology of the observed gradients.

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We first tried to determine if the gradients observed within these sheets constituted a distinct population in the histogram of the vertical gradients. But we found that nothing special distinguishes them from any other gradient, and that they merely constitute the upper tail of the gradient distribution that is monotonic (and strongly decreasing) in this region. This conclusion implies that the distinction between a sheet and another gradient is somewhat arbitrary, as discussed further below. The same conclusion was reached by Desaubies and Gregg (1981) on the basis of oceanic high-resolution temperature measurements. Their Fig. 4, showing the (finite difference) temperature gradient distributions for various vertical spacings, illustrates quantitatively this point. However, the observed characteristics of the sheets cannot be accounted for only by the properties of the gradient distribution. For example, their thinness is an independent (and important) characteristic, as well as their spatial and temporal distribution.

We will present below some characteristics of the sheets that we could deduce from the dataset analyzed, and we will discuss their potential impact on propagation phenomena. We intentionally avoid any theoretical speculation about their nature or their generation mechanism, this question being a separate, and perhaps controversial, subject. However, the interested reader can find a good discussion of some possible mechanisms (for the oceanic case) in Desaubies and Gregg (1981).

**a. Examples of stratospheric sheets**

Before giving a more precise definition of what we call a sheet, we will look at some examples in order to get an intuitive idea of what they are. Figure 1 displays a section of temperature profile with a high vertical resolution (0.2 m), as observed with a balloonborne gondola, just above the tropopause. On this profile, some regions with strongly positive (vertical) temperature gradients are labeled with letters (“a”...”g”). These regions are examples of what we call sheets; we will explain below how they were selected. Figure 1 also contains two close-ups of gradients “b” and “c” where the profiles observed by three temperature sensors one meter apart (one pair horizontal and one pair vertical, as indicated on the upper left corner of Fig. 1) are shown. The comparison of the three profiles gives important clues about the structure of the sheets. Note that, owing to the wind differences between bal-
loon and gondola, the path of the sensors is not vertical so that the profiles obtained by the vertical pair are measured with some (variable) horizontal separation in the range 0.3 to 1.2 m.

The gradient b, despite its strong static stability, displays clear evidence of ongoing mixing: inside this sheet, the temperature increases by $\Delta T = 0.39$ K within a thickness $\Delta z = 8.5$ m, this corresponds to an average gradient of 47 K/km. The maximum thickness of the mangled layer, estimated by the altitude range, observed on the three profiles for a given temperature is 4.7 m.

The gradient “e” is still stronger, since the temperature increases by $\Delta T = 1.36$ K within a thickness $\Delta z = 10.7$ m, corresponding to an average gradient of 127 K/km. The close-up of the three temperature profiles shows that no mixing is present here, but indicates nevertheless a smooth altitude variation of the isothermal surface between 0 and 60 cm. This separation of the three profiles strongly proves that the local temperature gradient is not purely vertical.

b. Consequences for propagation phenomena

The existence of very strong temperature gradients in the atmosphere has important consequences for propagation phenomena, both electromagnetic and acoustic. Depending on the wavelength of the propagating field, compared with the characteristic thickness of the sheet encountered, the interaction will be described in terms of refraction or diffraction. For example, visible light propagating along a quasi-horizontal path, will experience downward refraction, localized within the sheets. On the other hand, clear-air radars operating in the VHF range can obtain strong echoes from such structures in the vertical direction.

Much work and debate has been devoted to the question of the physical mechanism underlying the radar aspect sensitivity. Discussions of these questions can be found in Tsuda et al. (1988) or in Woodman and Chu (1989) and in references therein. A review paper written by Gage (1990) discusses many possible mechanisms. In a recent paper, Salathé and Smith (1992) present in situ observations (from an airplane) of temperature microstructure above and below the tropopause, supporting the idea that stratospheric radar echoes are produced by very sharp temperature gradients. Independent of any theoretical debate, a statistical description of the observed sheets will be an important element for the quantitative understanding of this physical mechanism. Such a description should include the occurrence frequency as a function of altitude and meteorological conditions, the thickness $\Delta z$ and amplitude $\Delta T$ distributions, indications about the spatial and temporal extension of such a phenomenon, and an appropriate description of their geometric structure, such as characteristic wavelengths and amplitudes of the isothermal surface distortions.

2. Experimental setup

All the experimental data used in this paper were obtained during the field experiment RASCIBA, held at the CNES balloon launching site of Aire sur l’Adour (43°42’N, 0°15’W) at the end of February and beginning of March 1990. The scientific objective of this campaign was the detailed study of the small-scale dynamics in the troposphere and the lower stratosphere. Measurements were conducted using three complementary experimental techniques: RASCIBA stands for radar, scidar, balloon. The 45-MHz S-T radar, known as PROVENCE, was operated by the LSEET and allowed continuous monitoring of the radial wind speed and echo power in a vertical direction and two oblique (15°) ones. The antennas of the radar were located just beside the balloon launching site. The spatial resolution used for this study was 600 m and the time resolution was 6.5 minutes (the integration time in each direction was 2 minutes). The scidar, operated by the Université de Nice, deduced the altitude and intensity of turbulent layers by monitoring their effect on the scintillation of a double star. Data from this instrument will not be used in the present study. The balloon instrumentation included two gondolas. The main gondola was operated by Service d’Aéronomie and included three high-resolution (5 ~ 7 mK), fast-response (time constant < 10 ms at all altitudes) temperature sensors (AIR Inc.), a laboratory-built ionic anemometer, a high-resolution (0.15 ~ 0.45 Pa) pressure sensor (ParoScientific), and a magnetometer in order to reconstruct the gondola attitude. The sampling frequency was 32 Hz for the temperature sensors and the ionic anemometer and 1 Hz for the pressure sensor. A second gondola that hung 65 m below the main one, operated by the Université de Nice, was devoted to the estimation of the $C_T^2$ parameter within the turbulent layers. It also included a fast-response thermometer sampled, after convenient filtering, every 1.5 s (or more) through the standard Vaisala meteorological package. These thermometric data were available during the second and the third flights. All balloon flights were performed during the night in order to avoid radiative contamination and to match with the stellar observations of the scidar.

The absolute position of the gondola was measured each minute using the Omega radio positioning system. The altitude of the gondola was computed by integration of the hydrostatic equation. The random altitude error grows nearly exponentially with altitude from 3 cm at the ground level up to 50 cm at 27 km. The ascent velocity of the balloon being ~5–7 m s⁻¹, the vertical resolution of the profiles is ~20 cm. In order to avoid the problem of conversion between time and space scales when the vertical velocity is not constant, the temporal temperature profiles were spatially resampled with a constant vertical step of 20 cm using a cubic spline interpolation.
The distance between the balloon and the main gondola was 175 m. Owing to the ubiquitous wind shears, a relative wind occurs between the balloon (that follows the airflow) and the gondola, with observed magnitudes $\sim 4 \pm 2$ m s$^{-1}$. The gondola includes a large vane in order to point all the sensors upwind. In view of the maximum diameter of the balloon (21 m) and the relative wind distribution, the balloon-gondola distance is sufficient to avoid perturbations by the turbulent wake of the balloon most of the time (Barat et al. 1984).

3. Selection procedure

The selection of the sheets for their statistical study is a two-step process. The first step is entirely automatic and consisted of listing all the regions where the squared Brunt–Väisälä frequency ($N_{BV}^2$) rises above a given threshold. A high-resolution profile (vertical sampling: 20 cm) of potential temperature $\theta(z)$ was computed, starting with temperature and pressure measurements. Since the local value of $N_{BV}^2$ strongly depends on the (spatial) frequency range taken into account in the differentiation process [for an illustration of this point, see Fig. 1 in Desaubies and Gregg (1981)], this profile was first carefully low-pass filtered in order to suppress all scales smaller than 10.8 m, and the resulting series was undersampled with a step of 5.4 m (new Nyquist frequency = cutoff frequency). This series was then differentiated, using a 32-point McClellan–Parks differentiator (McClellan et al. 1973), and the local value of $N_{BV}^2 = \theta^{-1} g (d\theta/dz)$ was computed. The threshold used for the selection process was $N_{BV}^2 > 2 \times 10^{-3}$ (rad s$^{-1}$)$^2$ in the stratosphere. In the troposphere, the threshold was lowered to $N_{BV}^2 > 1 \times 10^{-3}$ (rad/s)$^2$ to increase the selected population.

By contrast, the second step of the selection procedure is essentially a “manual” one. The high-resolution temperature profile is examined again for each region selected after the first step. In some cases, the high value of $N_{BV}^2$ was only a consequence of local mixing but did not correspond to a net increase of temperature. In other cases, the profile was spoiled by the turbulent wake of the balloon, producing spurious values of $N_{BV}^2$. An example of such contamination can be seen in Fig. 4 on the “ascent” profile around 20.8 km. All these cases were excluded from the final list. However, sections where mixing occurred simultaneously with strong “background” gradient (such as the region “b” in Fig. 1) were kept. After this manual rejection process, a list of sheets was established for each balloon ascent. For each sheet, a bottom and a top were chosen manually, thus allowing us to determine its thickness $\Delta z$ and its amplitude $\Delta T$. Usually, this manual choice was done in order to emphasize the steepest part of the gradient. However, in some cases, a rapid succession of “small” sheets was also considered as a “large” sheet. In such a case, the mean gradient $\Delta T/\Delta z$ is smaller than the local values, but both $\Delta T$ and $\Delta z$ are much larger.

This manual part introduces some subjectivity in the selection procedure. However, the range of reasonable choices is rather narrow, and it seems likely that the statistical properties, as presented below, are essentially independent of the precise individual choices. Another problem is the arbitrary choice of a threshold on $N_{BV}^2$, and to a lesser extent, the choice of the cutoff frequency. The cutoff frequency was chosen to improve the signal to noise ratio on $N_{BV}^2$, while keeping the best possible spatial resolution. The choice of the threshold was essentially made to get a number of sheets sufficient for a statistical study, but still manageable for the manual part of the selection process. This choice is not based on physical considerations, and some tentative sheets were automatically excluded despite their close resemblance to others that were selected.

4. Observed characteristics

a. Altitude distribution

Figure 2 displays the four temperature profiles measured during the rapid ascent of the balloons (for legibility, profiles are offset by steps of 20 K). On each profile, the positions of the sheets are shown as small ticks. The wind speed profiles, obtained by meteorological rawinsondes launched from Bordeaux (44°50'N, 0°35'W, 128 km northward to Aire sur l’Adour), are shown in a small box for the four measurement nights. A simple examination of Fig. 2 allows us to draw general conclusions about the vertical distribution of sheets.

On each profile, most of the sheets are observed in the lower stratosphere (typically up to 20 km). However, some sheets are also observed in the troposphere and in the middle stratosphere. The number of observed sheets seems to depend on the meteorological conditions. The first two flights (leftmost) occurred during quiet conditions (light winds). The third flight occurred during very quiet conditions and we observe that the number of sheets is rather small, both in the troposphere and in the stratosphere. By contrast, the last flight (rightmost) occurred during strong wind conditions and a large number of sheets is observed up to 25 km.

Another characteristic that is easily observed in Fig. 2 is that the sheets tend to occur in groups. Figure 1 displays with high resolution such a group of seven sheets from the first flight within a 300-m altitude range. However, some sheets can appear isolated and, more generally, no specific rules could be found for the distances between successive sheets. Regions where the sheets are packed together correspond to a net increase of the temperature. There is an interesting question (similar to the “chicken and egg” one) related to this property: Is it the mere packing of the sheets that produces the net increase of temperature, or are the sheets more likely to develop in regions where the mean gradient is large already? The answer to this question re-
quires that the generation mechanism of the sheets be understood.

If we restrict attention to regions where the temperature increases with altitude (the gradient being calculated as for $N^2_{Bv}$), the contribution of the sheets to this increase is between 16% and 46% in the troposphere and between 22% and 50% in the lower stratosphere. By contrast, the contribution of the sheets to the altitude increase (in the same regions where $dT/ dz > 0$) is only between 2% and 14% in the troposphere and between 3% and 17% in the lower stratosphere. In other words, the sheets occupy a small fraction of the profiles, but they contribute to a large fraction of the temperature increase.

b. **Thickness and amplitude distribution**

Figure 3 represents, in log-log coordinates, the thickness $\Delta z$ of the sheets (for the four flights) versus their amplitude $\Delta T$. Three different markers were used to distinguish three atmospheric regions: the stable boundary layer, the troposphere, and the stratosphere. Four oblique lines indicate constant values of the average gradient, from top left to bottom right $\Delta T/ \Delta z = 10, 30, 100, 300$ K/km. Most stratospheric sheets are steeper than 30 K/km and all tropospheric ones are steeper than 10 K/km, these lower limits being consequences of the selection process. This can be regarded more or less as a definition of the sheets. As already noted in the Introduction, the distribution of atmospheric temperature gradients is continuous, and we look here only at its upper tail.

More informative is the fact that stratospheric sheets can reach 300 K/km, while tropospheric ones reach 200 K/km. However, it should be noted that such extreme values are reached only by the thinnest (less than 2 m) ones. Another characteristic that distinguishes tropospheric and stratospheric sheets is their maximum amplitude: in the stratosphere, it can exceed 2 K, while in the troposphere it is smaller than 1 K and even 0.5 K for most of them. The sheets observed in the stable boundary layer seem to behave exactly like strato-
spheric ones, suggesting that the only significant parameter is the large-scale static stability of the surrounding region.

As suggested by Fig. 3, the large range of observed thickness and amplitude of the sheets are best described in logarithmic coordinates, each variable being characterized by a typical value and by an amplitude range (corresponding, respectively, to the mean and the standard deviation of the logarithm's distribution).

Table 1 gives the "typical" values observed for all the sheets (central columns) as well as an interval of variation (±1 σ in log).

From this table, it appears that the typical thickness Δz does not change dramatically within the altitude range studied. On the other hand, the typical amplitude ΔT varies by a factor 2.7 and appears directly connected with the general stability of the embedding region. We also note that tropospheric sheets are significantly weaker (in ΔT and ΔT/Δz) than stratospheric ones.

This effect is probably connected with the lower limit on $N_a \gamma$ that was used for their selection in order to increase their population.

c. Presence of mixing within the sheets

Another rather surprising characteristic of these sheets is that their strong local stability does not prevent overturning. A characteristic example was given in Fig. 1 by the sheet b, but this kind of situation is not exceptional. Among the 189 sheets selected on the four profiles, 54 (29%) show evidence of ongoing or recent mixing, as suggested by the presence of small-scale fluctuations. Five among these sheets can be described as strongly mixing (presence of overturning). In a few cases, the strong temperature inhomogeneities are observed just above or below a sheet, but it is not clear whether this association is fortuitous or not. In the above description, we intentionally avoided the word
“turbulence” since it usually conveys supplementary (and here unwanted) meanings, especially in terms of associated velocity fluctuations.

d. Some constraints on the associated wind environment

As mentioned in section 2, the local structure of the wind field was measured by a two-axis ionic anemometer (pointed upwind by a large rigid vane) and a magnetometer in order to reconstruct the wind vector relative to the gondola. Horizontally, this wind vector is the difference between the horizontal winds at balloon and gondola levels (since the balloon is expected to follow the wind at its own level), while vertically, it is the local vertical wind minus the gondola vertical velocity.

Careful (visual) examination of these wind data (amplitudes, orientations) in the sheet areas did not allow us to detect any characteristic structures at the same vertical scales. This observation does not imply the lack of dynamical link between the sheets and the local wind environment, but does constitute, by itself, a result that gives important experimental constraints on any physical model proposed to interpret the existence of “sheets.”

e. Some constraints on the sheets’ shapes and lifetimes

It is very difficult to obtain information about time and space extension of any structure when it is observed with only one in situ instrument. In order to obtain reliable information about the vertical structure, the balloon vertical velocity is maximized. Consequently, any measurement at a given altitude contains no information about the horizontal or temporal extension. Using the main gondola alone, with its three temperature sensors one meter apart, we can only assert that the observed structures always have a horizontal extent larger than 1 m and last for at least 0.2 sec. This information is nearly useless and is more or less contained in the selection procedure used. More useful information can be deduced from recognizing that the three temperature profiles are usually significantly different within each sheet. If we consider the sheet “e” in Fig. 1, for example, we see that the altitude difference observed with the horizontal and vertical pair of sensors can reach, respectively, 15 and 60 cm. This behavior is typical of what is observed within all the sheets. We thus can draw the following partial conclusion: the sheets are not static and horizontal structures. They move with, and are distorted by, the surrounding medium and the local slopes observed can reach tens of degrees.

During the second and the third flights, we used the temperature profile measured by the gondola of the Université de Nice. Despite its spatial resolution (9 m or more) and its temperature resolution of 0.1 K, the comparison of the temperature profiles from the two gondolas allowed us to draw important conclusions. The two stratospheric profiles measured during the second flight, including both rapid ascent and descent of the balloon, are shown in Fig. 4. In this figure, the (small) instrumental drift of the temperature sensors was corrected and the various profiles are offset in order not to overlap. The profiles observed by the two gondolas are nearly identical except for small details (which we will examine below). On the other hand, the temperature profile observed during ascent and during descent are clearly distinct, even if some portions (between 13 and 20 km, for example) show a striking resemblance to each other.

Each sheet listed during the two rapid ascents was searched for on the profile of the second gondola. In short, we can state that each sheet with an amplitude $\Delta T$ larger than 0.4 K was found but only one (among seven) with an amplitude smaller than 0.2 K. This nondetection may result either from the coarser resolution of the meteorological profile or (more probably) because the time and space extension of small amplitude sheets are smaller than that of stronger ones, as can be expected.

When a given sheet was visible on both profiles, an altitude difference $\Delta h$ was estimated along with an horizontal distance $\Delta h$ (with respect to the airflow at the altitude of the sheet) between the measurement position of the two gondolas. Since the gondola displacements are identical to the balloon one, $\Delta h$ is estimated by a time integration of the smoothed wind profile calculated from the anemometric data, as in Barat (1982). The result of these estimates is shown in a small graph within Fig. 4 with one marker for each sheet (crosses for the second flight and circles for the third). Since the ascent velocity was slightly variable around 6 m s$^{-1}$, the observed time separation between the two profiles (at any given altitude) is 12 ± 2 s.
From this study using two gondolas, we conclude the following points:

- The "small" sheets (with an amplitude $\Delta T < 0.3$ K) have a time extension smaller than 12 s and/or a horizontal extension smaller than a few tens of meters.
- The "large" sheets have a time extent longer than 12 s and a typical horizontal extent larger than 50–100 m.
- Within their space/time extent, the sheets are distorted (they are definitely not flat). However, the vertical distortion $\Delta a$ is typically smaller than 10 m.
- The horizontal scales associated with these vertical distortions can be rather small (some tens of meters). This point is confirmed by the rather large angles deduced from the three sensor measurements and that the altitude difference $\Delta a$ does not seem to increase with the horizontal separation $\Delta h$.
- Since we have only two measurement points on each sheet, it is not possible to elaborate further on the horizontal structure of the vertical distortion. In particular, our observations cannot distinguish between regular (corrugated) or random structures.

5. Contribution of the sheets to the radar echoes

Since $S-T$ radar measurements were available simultaneously with the balloon experiments, it is interesting to investigate the possible contribution of the sheets to the radar echoes, especially in the vertical direction. However, the uncertainties about important characteristics of the sheets, such as their horizontal extension and structure, as well as the relatively large distance between the balloon and the radar beam, do not allow us to try a direct calculation of such a contribution. Instead, our goal here is to show that, using reasonable hypotheses and approximations, the fraction of the incoming electromagnetic power that such structures are able to reflect (or backscatter) toward
the radar antenna can constitute a significant part of the echoes observed in the vertical direction.

a. Hypotheses and approximations

From the balloon observations, we know that the measurement volume of the radar may contain some sheets. These sheets may cover only a part of the surface illuminated by the radar (because of their finite horizontal extension) and their surface is probably distorted. The scattering of the radar energy by such refraction structure is a complicated phenomenon and the interferences between all the scattered waves, along with the focusing and defocusing due to the sheet distortions, will produce a highly inhomogeneous backscattered energy pattern at the ground level. Because of the horizontal advection of the sheets within the measurement volume and their probable distortion (change of the refraction profile within each individual sheet and change of their relative distances), the inhomogeneous backscattered pattern will change and move accordingly.

However, if we consider the average energy (over a sufficient time) received by the radar, we expect that all the interferences and focusing phenomena will be averaged out. This average energy can then be estimated by the sum of the contributions of each individual sheet, ignoring any distortion or interference. In order to estimate the individual reflectivity, we then apply the analytical formula for a flat and infinite layer (see below), using the high-resolution temperature profile measured by the balloon to provide a realistic refraction profile.

This model of flat (and horizontal) sheets provides a reasonable estimation of the average energy backscattered toward the ground; however, the distortion of the surfaces and their finite horizontal extension can also produce a broadening of the solid angle within which this energy is backscattered. Since this broadening is not taken into account by the analytic formula, the calculated result can be overestimated. On the other hand, the partial coverage of the illuminated surface is accounted for by the fact that the balloon profile is assumed to be representative (in a statistical sense) of any line of sight within the radar measurement volume in the same altitude range. It is also worth noting that, because of the weak number of sheets that are observed within each radar resolution range, we can expect large statistical fluctuations in the estimated average backscattered energy.

The refractive index (and its gradient) are computed using only the “dry air” formula because of the lack of simultaneous high-resolution humidity measurements. However, the possible effects of humidity can only be significant in the troposphere, below 8 km.

b. Calculations and comparisons

The profiles of radar reflectivity $\rho^2(z)$ are computed from the measurements using

$$\rho^2 = \frac{P_r}{P_t} \frac{4r^2 \lambda_R^2}{A^2} \quad (\text{Gage and Balsley 1980}),$$

where $P_r$ and $P_t$ are, respectively, the received and transmitted powers, $r$ is the radial distance from the antenna $(r = z - z_{\text{radar}})$, $\lambda_R$ is the radar wavelength, and $A$ is the effective area of the antenna.

The reflectivity for an individual sheet $\rho^2_i$ is numerically computed as (Gage and Balsley 1980)

$$\rho^2_i = \frac{1}{4} \int \frac{dn}{dz} e^{-2ikz} dz \quad \text{with} \quad k = \frac{2\pi}{\lambda_R},$$

where $n$ is the local (dry) refractive index. The integral is taken over the altitude range where the sheet contributes to the variation of the refractive index. The estimated contribution of the sheets to the radar reflectivity is computed as a weighted average of individual reflectivity. The weighting function, representative of the sensitivity of the radar within a given measurement gate, is a symmetric triangle with a width at half-maximum equal to the radar resolution (600 m).

Figure 5 displays, for the four measurement nights, the comparison of the reflectivity profiles observed by the radar (dotted lines) and the estimated contribution (without any normalization) of the sheets to this reflectivity (small diamonds connected by thick solid lines). In some altitude ranges, the lack of sheets with a sufficient gradient caused the thick line to be interrupted. For each night, the dispersion of the individual radar reflectivity profiles is representative of the variability of this parameter.

The goal of this paper is not to discuss the possibility of interpreting completely the VHF vertical reflectivity as the result of partial reflections on the refractivity sheets. However, Fig. 5 strongly suggests that this phenomenon can account for a significant fraction of the vertical radar echoes. Further, the positions of maxima and minima on the observed reflectivity profiles are in good agreement with the corresponding extrema of the computed profiles. This observation suggests that the statistical properties of the sheets in a given altitude range do not change significantly over horizontal distances going from 10 to 25 km for the first three flights and up to 130 km for the fourth. If the partial reflection of radar waves on the refractivity sheets is a major contribution to the echo power obtained in the vertical direction, the known proportionality of these echoes to $N_{\text{HV}}^2$ (Tsuda et al. 1988) could be related to the observed tendency for the sheets to group in regions with high stability (see Fig. 2) and to their observed larger amplitude $\Delta T$ in these regions (see Table 1).

6. Summary, discussion, and conclusions

This paper presents experimental evidence for the ubiquitous presence in the lower atmosphere (at least up to 25 km) of very strong (positive) temperature gradients within very thin layers. This kind of structure
is described as “sheets” in the oceanic and boundary-layer literature, most frequently as part of steplike (or stair) structures. The presence of such sheets in the free atmosphere was frequently hypothesized in order to account for the aspect sensitivity of VHF radar measurements. Owing to its high vertical resolution, this work constitutes (to our knowledge) the first direct evidence of their true existence. The definition of what
is a “sheet” is partly subjective, since it is based on the histogram of the low-pass filtered vertical temperature gradients (cutoff wavelength = 10.8 m) that is monotonically decreasing for large gradient values. The sheets described here constitute the upper tail of this histogram, above some arbitrary limit and after the exclusion of strong gradients resulting only from local ongoing mixing. A possible effect of this partly subjective selection procedure can be the exclusion of small-scale sheets and a subsequent bias in the statistical properties deduced above. Obviously, this potential exclusion cannot change our main conclusion about the very existence of atmospheric temperature sheets.

The sheets are frequently (but not exclusively) observed in groups (up to ten sheets within 400 m), associated with, and contributing to, the regions of high static stability. The number of observed sheets seems also to increase when the meteorological conditions are disturbed (strong jet stream).

Because of the experimental setup, the horizontal and time extensions of the sheets were difficult to observe. On the very local scale (1 m) the gradients appear distorted and tilted. Sometimes, clear evidence of ongoing or recent mixing, despite the strong local static stability, can account for such distortions. However, most of the sheets appear to be laminar and the observed small-scale distortions are probably a consequence of larger-scale motions. This distortion at larger scales was observed (12 s later and with a horizontal separation going up to ≈100 m) by a second gondola with a maximum vertical amplitude of ≈10 m. Though our two-point measurements do not allow definite conclusions, these distortions are reminiscent of those encountered in the ocean and are beautifully illustrated by two-dimensional measurements (Dugan & Marmorino 1984; Marmorino 1987; Marmorino and Greenewalt 1988). The kind of distortions observed in an oceanic context would conveniently account (after appropriate scale change) for our atmospheric observations.

The possible contribution of the observed sheets to the VHF radar echoes obtained in the vertical direction was investigated. The lack of relevant information about the horizontal structure of the sheets, as well as the expected complexity of any realistic simulation, leads us to limit our objective to an order-of-magnitude estimation. However, the comparison of these crude estimates with simultaneous radar measurements suggests that the contribution of the sheets to the radar vertical reflectivity is significant (and may be dominant). Further, the statistical properties of the sheets involved in this radar reflectivity, such as their number within a given altitude range or the amplitude of the temperature “step,” seem to be (nearly) independent of the horizontal distance, at least up to 100 km. This last property is consistent with the general observation that the characteristics and the number of sheets are mainly determined by the general static stability of the embedding region.

In a previous work (Dalaudier et al. 1989), three of us tried to interpret the VHF radar echoes in the vertical direction as the result of backscattering by anisotropic temperature fluctuations with one-dimensional vertical spectrum proportional to $N_{by}k_z^3$. The shape of the reflectivity profile was successfully reconstructed, but the calculated level was much too large and no consistent interpretation could be found. The calculations described in the present paper account conveniently for the observed vertical VHF reflectivity profiles (both in shape and in level) and the contribution of the sheets to the temperature (3D) spectrum is expected to be strongly anisotropic. Future work in this field should try to model properly the 3D temperature spectrum in the atmosphere, taking into account the (scale dependent) anisotropic contributions from the sheets in order to produce a consistent theoretical interpretation of both balloon and radar observations.

Further investigation of the “sheet and layer” structure in the free atmosphere is necessary in order to gather more information about their structure, their properties, and their mutual relations. Future experiments should answer important questions about their horizontal extension, their time evolution, and their vertical distortions. Theoretical questions about the mechanisms underlying their generation, their evolution, and their destruction, and more generally their relation to other small-scale and mesoscale phenomena, should also be investigated.

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