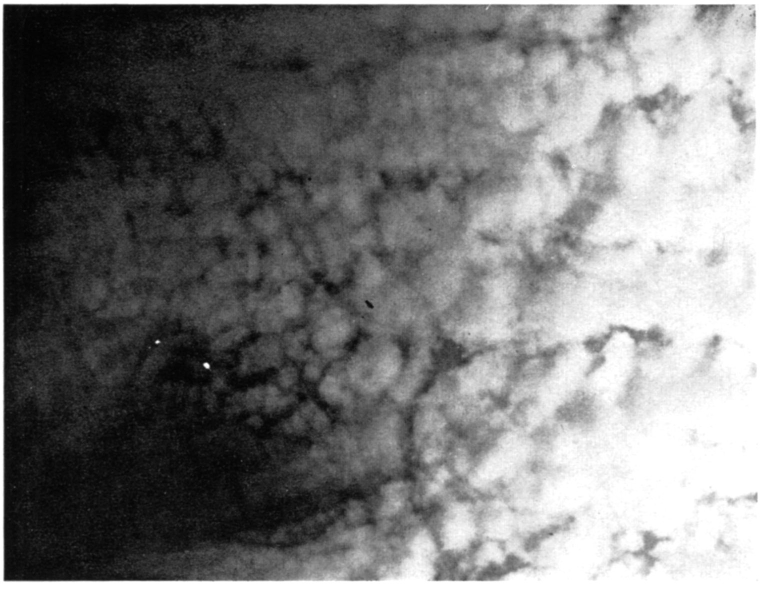
DISCUSSION.

Queney. — Je désirerais dire quelques mots au sujet d'un paramètre que je considère comme assez important dans l'étude de la turbulence, c'est l'*échelle*. M. Scorer nous a décrit deux sortes de turbulence, qu'on peut appeler turbulence dynamique et turbulence thermique. La turbulence dynamique est celle qui se forme dans les couches stables comme conséquence d'une certaine variation verticale du vent. La turbulence thermique est au contraire celle qui se forme dans les couches instabilisées par le chauffage à partir du bas, ce qui se produit en général dans la journée au-dessus des continents. Ce qui est intéressant à mon avis, c'est que la turbulence dynamique a une échelle qui peut être très petite, notamment si elle prend naissance près du sol; par exemple, si l'on enregistre le vent au voisinage du sol avec un anémomètre très sensible on a un diagramme indiquant une échelle de temps qui peut être plus petite que 1/100^{e} de seconde. Pour un vent fort, on peut avoir apparition d'oscillations d'assez grande période, par exemple des rafales de vent qui peuvent atteindre plusieurs secondes comme plusieurs minutes. En général, plus on s'élève dans l'atmosphère plus l'échelle augmente. Il est intéressant de voir ce qui se passe au niveau du jet-stream car on se fait sans doute une idée assez fausse de ce qu'est un jet-stream, et quelle est la turbulence qui peut en résulter. En général, conformément à la figure que j'ai montrée hier (*fig.* 20) donnant une coupe verticale à travers un jet-stream (le mot *jet* est d'ailleurs assez mal choisi), la tropopause est interrompue du côté polaire de l'axe, et le jet-stream est généralement associé à un courant descendant à travers la brèche dans la tropopause. Ce courant descendant n'est pas très rapide — de l'ordre de 10 cm/s —. En conséquence il y a stabilisation de l'air au-dessous du jet-stream, et l'on a en même temps un gradient de vitesse très grand. Conformément à ce qu'a dit le Professeur Scorer, cela favorise la formation de turbulence, mais c'est une turbulence qui est essentiellement formée de tourbillons horizontaux, à cause de la grande stabilité, ces tourbillons étant plus ou moins irréguliers, avec une étendue moyenne de l'ordre de 100 km alors que la largeur du jet-stream est de l'ordre de 1000 km. Cette turbulence est essentiellement dynamique, mais elle dégénère en tourbillons de plus en plus petits, et qui sont d'autant moins horizontaux que leur échelle est plus petite; donc, finalement, on a toutes les échelles de turbulence à partir des tourbillons les plus grands. En général, dans une couche stable, plus l'échelle est grande, plus les mouvements tendent à être horizontaux.



(*a*) The edge of a layer of *Altocumulus* which is extending. The cells are small at the edge but increase inwards. They represent inhomogeneities of humidity in the clear air in which the cloud is formed (R. S. Scorer).

(*b*) ***Fallstreaks*** of ice crystals, which evaporate into the air, producing variations in humidity (R. S. Scorer).

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(*a*) Small *Cumulus*, which by evaporation produce inhomogeneities of humidity (R. S. Scorer).

(*b*) *Castellanus* clouds, which have the same effect as cumulus (*plate* VI *a*) but are not the result from convection currents from the ground. They may occur at all heights in the troposphere and at any time of day or night (R. S. Scorer).

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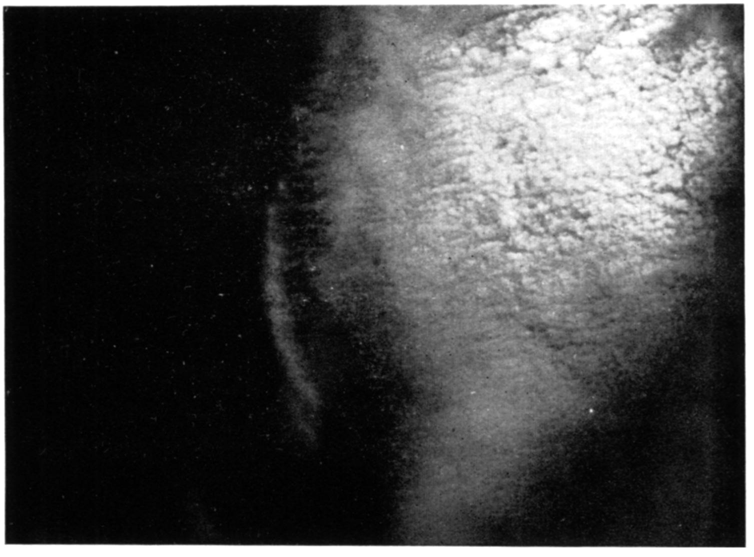
(a) *Allocumulus billows* showing a roll-type distribution of humidity (R. S. Scorer).



(b) A *wave-cloud* in which the cloud forms on the left, but by the time the air reaches the right hand edge it has become cellular. The wind blows from left to right through the stationary cloud (Ann Welch).

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(*a*) A *wave-cloud* composed of several layers (H. Klieforth).

(*b*) *Wave-clouds* formed in a thin layer of high humidity (R. S. Scorer).

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Les grands tourbillons intéressent surtout les météorologistes, parce qu'ils expliquent les échanges horizontaux de grande échelle; les tourbillons plus petits intéressent les aviateurs parce qu'ils constituent des dangers pour les avions, et la turbulence de petite échelle intéresse les astronomes, probablement, parce qu'elle *peut* créer des fluctuations de densité. Mais je dis *peut*, car je vais justement montrer qu'elle ne donne pas nécessairement des effets optiques importants.

Donc dans la turbulence dynamique toutes les échelles sont possibles. Au contraire, dans la turbulence thermique l'échelle de temps est en général assez grande. M. Scorer nous a parlé d'une sorte de bulle d'air chaud qui monte; dans ce cas, l'échelle de temps du phénomène est de l'ordre de plusieurs minutes en général. Cette turbulence thermique peut d'ailleurs dégénérer en tourbillons plus petits, mais ce qui domine, c'est tout de même une échelle relativement grande. Or en ce cas il y a très peu de chances pour qu'il se produise une action optique importante si la turbulence n'est pas localisée dans les basses couches, et si les rayons lumineux sont peu inclinés, ceci en vertu de l'équation hydrostatique. En effet supposons qu'il se produise ce que M. Scorer appelait un « thermique », c'est-à-dire une bulle d'air relativement légère incluse dans de l'air plus lourd. S'il s'agit d'une turbulence de grande échelle, limitée en altitude à une certaine couche, il est impossible qu'on n'ait pas de perturbations en dessous en vertu de l'équation hydrostatique, qui exige un déficit de pression au sol au-dessous de chaque bulle d'air relativement léger. Donc s'il y a une turbulence en altitude, on a aussi des fluctuations jusqu'au sol, car il y a nécessairement compensation, et à chaque bulle d'air léger doit être associée une bulle d'air lourd de façon à ce qu'au sol il n'y ait pas de variation de pression. Or, si l'on étudie ce qui se passe au point de vue optique (ce que j'avais fait à la suite d'une question que m'avait posée M. Danjon) on trouve qu'il y a compensation rigoureuse s'il s'agit de rayons verticaux, et compensation partielle s'il s'agit de rayons obliques. Mais il est bien entendu que cela n'est vrai que pour une turbulence dont l'échelle de temps est assez grande (supérieure à 1 s environ). 'Cest le cas de la plupart des perturbations des jet-streams, justement. Je crois qu'il est assez important de tenir compte de ce résultat; car on s'imagine que cette turbulence des jet-streams doit produire des effets énormes, et ce n'est pas exact.

Rösch. — Dr. Lynds has shown extremely interesting results of his temperature records all the way up a 75-foot tower. It is very important to have this proof of the change in microthermal phenomena with elevation above the ground, and to know that the temperature fluctuations are much smaller at 75 feet than near the ground. But I would like to come back again to this question : what will happen when you have your dome and telescope at 75 feet above the ground ? Because, after all, you want to set up a telescope, not a thermistor on a tower. May I present some wind-tunnel patterns on various models of domes with smoke streaks showing how the distribution of the turbulence around the dome differs from one to another. This is just a first attempt but I think it may be of some interest. First is a conventional spherical dome with two types of shutters (*plate* IX). With two cylindrical shutters moving away from one another as usual and the opening of the dome facing the wind, there is some turbulence behind the dome but not in front. When you observe at right angle to the direction of the wind, there is a tremendous effect of the shutters : they operate just like an airplane wing. Also when you observe in a direction away from the wind you have turbulence in front of the opening. For the same dome, but with a spherical shutter just as in the case of the 120-inch at Lick Observatory, for instance, the turbulence is much less than with a pair of cylindrical shutters. At the Pic du Midi we have built a dome of another type which we have called the " Lyot dome " (*plate* X). The tube of the instrument is surrounded by an outer protecting tube and the objective is just at the front end of these tubes. The wind tunnel tests, for various directions, indicate that the depth of the turbulent zone can definitely be reduced. These examples were just intended to show that there may exist important effects around the dome; anyhow, we need a dome and a telescope !

Now, I would like to give you an example of the effects of a front arriving above the observatory and, at the same time, of some typical deteriorations of a telescopic image by the atmosphere during daytime (*fig.* 27). These are two short exposures (about 2 ms) of a sunspot taken 1/20th of a second apart. This gives you the time-scale of the changes in the atmosphere in which we are interested : on the edges of the bright bridge across the spot the details are completely different from one exposure to the next, in spite of the short interval. Another point is that these pictures were taken towards the South-East at a medium elevation, just when a cloud system associated to a cold front was arriving from the West, so that the sky became covered shortly after the exposures. What I want to show you is that the sharpness of the image is not affected by the arrival of this front. Some details can be recognised which do not exceed half a second in size, almost the theoretical resolving power for the 23-centimetre objective used.

This means that the wave-front arriving on the objective was nearly flat over 23 cm, but the tilt of the normal to this flat wave-front not only fluctuates rapidly but is different from one point to another of the field, because the light has not travelled through the same masses of air in the atmosphere. The result is that only very contrasted details, such as a bright bridge across the dark umbra of the spot, can be seen; whereas in the surroundings, in the penumbra of the spot and in the photosphere itself, there is a complete blending of theimages of neighbouring points of nearly equal brightness. This is a type of deterioration due to distant turbulence, about which I hope the meteorologists will give us their opinion.

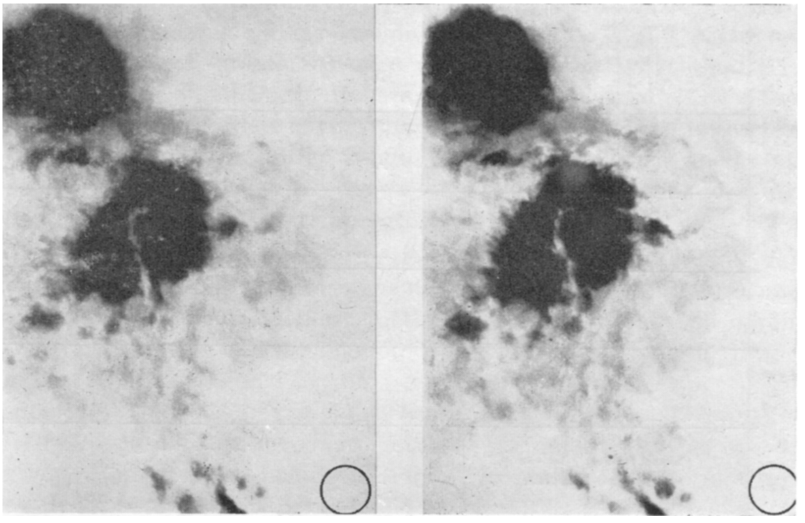

Fig. 27. — Effets de distorsion de l'image d'une tache solaire par une région inhomogène éloignée. Noter les formes différentes, à 1/20^{e} de seconde l'intervalle, des images du pont brillant qui se projette sur l'ombre. Le diamètre du cercle représente 5″.

Dommanget. — I just want to add a very important point concerning the effect of the wind on the dome : the best position of the opening of a conventional dome to give the minimum effect of turbulence is facing the direction of the wind. But, then, if the wind is rather strong, the telescope is shaked and this situation is finally a bad one.

Siedentopf. — At Tübingen we have made some experiments similar to those just described by Dr. Lynds. As an example, figure 28 shows the condensed results of some records in the ground layer for one whole day. The records and their reduction were made by Dr. U. Mayer. The two lowest curves show the mean wind velocity and the solar radiation. The wind velocities measured at 12 m above ground were generally small; the radiation was disturbed in the afternoon by cumulus clouds. The next curves give the results of temperature observations made with thermocouples. These thermocouples were of a differential

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type : one free junction consisting of thin wires with a time-constant smaller than 0.1 s, the other junction of thick wires shielded and with a time-constant of more than 10 s. This arrangement has the advantage, that the slow changes of temperature are not recorded, while great sensitivity to the quick fluctuations of temperature can be obtained. In the third curve, we see the differences of temperature between two

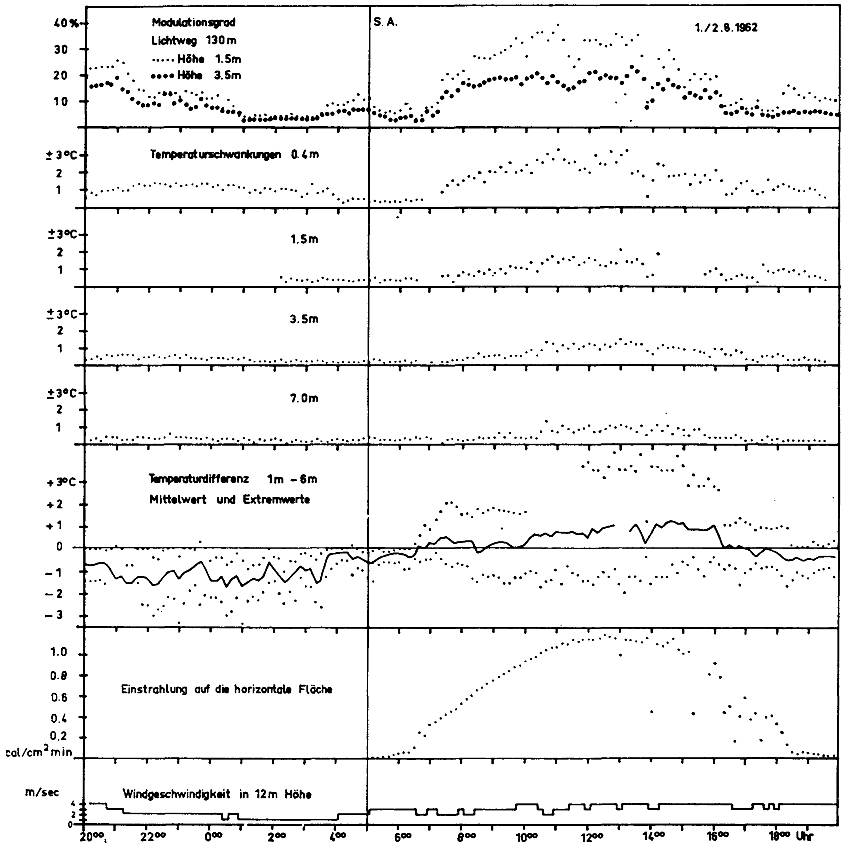

Fig. 28. — Wind and insolation, temperature gradients, temperature fluctuations and light ray modulation for a 24 h period.

such differential thermocouples at 1 and 6 m above ground. Mean values and extremes are shown, each value corresponding to an average over 5 mn. The difference is positive and fluctuates considerably during day-time when the insolation is greater than about 0.4 cal/cm^2.mn. From one hour and half before sunset till one hour after sunrise the difference is negative with smaller fluctuations. The temperature fluctuations at four different heights above ground were found from the differences in temperature between two differential thermocouples 6 cm apart, so that the influence of the smallest eddies predominated. The fluctuations during day-time are considerably greater than during the night; the decrease of the fluctuations with height is also very conspicuous. In the two uppermost curves the results of optical observations are given. The scintillation of a nearly parallel light beam of 1.5 cm diameter at the source was recorded by a photoelectric photometer with 1.5 cm aperture. The distance between source and photometer was 130 m; two light-beams at 1.5 and 3.5 m height above the ground (grassland) were used. This optical method is very sensitive to the small fluctuations in refractive index caused by temperature fluctuations. The curves show the same behaviour as the temperature curves : the resulting modulation decreases with height above ground and increases during daytime roughly proportional to the insolation or the gradient of temperature.

The number of bits of information recorded during one full day in these experiments is so enormous that the data handling becomes a major problem. The quickest method is probably the use of digital voltmeters printing the results on paper tape or magnetic tape and handling them with an electronic computer. We have since obtained a great deal of data on light beam modulation and temperature fluctuations up to about 20 m height. We also intend to use these methods for the site-testing work of European Southern Observatory (E. S. O.) in South Africa.

Stock. — I would like to add something to Dr. Scorer's explanation of the effect of an inversion. The development of a temperature inversion and its effect on optical observations are particularly marked in desert or semi-desert climates. When the water vapour concentration is very low, radiation cooling of the surface is very effective and this means that the air close to the ground also cools off and eventually builds up during the night a layer of cold air lying under the warmer free atmosphere. In a mountainous area, the effect becomes even more pronounced because the entire surface cools off and during the night you get a downward stream of cold air which fills up the valleys, while at the tops of the mountains the air is continuously replaced by the warmer air of the free atmosphere. Thus you have practically constant temperature throughout the entire night at the mountain top, provided the inversion does not rise to its level. On the valley floor there may be rather a steep temperature drop during the entire night. To give you an example from Chile, we have observed on a mountain, about 2 000 m above the valley floor, a maximum of 60° and a minimum of 50°F, while at the valley floor the maximum was 80° and the minimum 40°F. The diurnal range is about four times larger in the valley than on the mountain top. In addition the air current flowing downhill is subject to friction and develops turbulence. So when you observe on the valley floor, you notice that the seeing deteriorates almost immediately after sunset. If you go a little above the floor, you may have a short period with good seeing until the temperature drops and a slight breeze starts coming downhill and the seeing deteriorates, let us say from a fraction of a second to the order of one minute of arc. The effect is particularly noticeable when the weather is calm over the entire range. The moment you have some wind, it mixes the cold and warm air and you do not get good seeing at the bottom at all; but neither do you get drastically poor seeing. So it appears that the higher the temperature increase at the inversion layer, or the larger the gradient is, the worse the seeing gets. This is practically independent of the mechanism that is producing the turbulence. I will not attempt to explain this. So much for inversions and turbulence effects in desert climates. I may add one thing : moisture acts as a stabiliser by absorbing the radiation from the ground so that the air in the valleys remains warmer. Furthermore moist air is itself capable of radiating and thus reducing its temperature. On the other hand, it is capable of absorbing more radiation during daytime than dry air. So in a moist climate you generally get less drastic temperature variation between day and night. Now, in respect to the experiments Dr. Rösch has made : when I talked about turbulence I intentionally used the words " optically effective turbulence ". The experiments made by Dr. Lynds and by other meteorologists during the past few decades show that turbulent elements exist of almost any size. There is no upper limit. However, our optical experiments show that we are dealing with turbulent elements of, let us say, a few metres or less. Dr. Lynds' recordings were beginning to capture these small elements. However, when you make wind tunnel experiments with a dome, and you show this turbulence, you must also prove that it is optically effective. How this is to be done is a different matter; I have innumerable observations which show that wind passing over an obstacle at up to 30 or 35 km/h has no measurable effect on the seeing. From a theoretical point of view this is to be expected. You need near-sonic velocities in order to produce the temperature differences which would cause the kind of seeing we observe.

Scorer. — Perhaps I could comment on Dr. Stock's remarks first since they are fresh in our memories. This of course is, in my view, the correct interpretation of what is going on, but, with all due respect, this is well known to meteorologists and I think that any difference that there might be between what you have found in Chile and what might be found somewhere else would be very readily intelligible to meteorologists. There may be differences due to the shape or to the height of the mountain which would cause these phenomena not to be repeated exactly on another site. For example, I believe that Dr. Lynd's observatory is on a small promontory on a larger hill; now, suppose there were a small extension of the hill sticking out on one side; this might turn out to be just as good a place a the top in certain circumstances.

Now when we come to the question of moisture, I cannot accept your argument about its effect. When the ground becomes cold there is a radiative exchange between the ground and a shallow layer of air due to the water vapour present, because the water vapour is the only component which absorbs the infrared radiation to any extent. In European climates the depth of this layer would be perhaps 2 or 3 m and above that there would be a gradual re-emission which would be involved in any heat transfer higher up. In very dry climates the lower layer might be 10, 20 or even 50 m thick, but it is still a relatively shallow layer and the moisture content does not have any important effect on the motion. On the other hand, in a wet climate where there is vegetation and where the ground is wet, then the conductivity of the ground will make a great deal of difference to the temperatures range between day and night. For instance, as we all know, sand becomes too hot to walk on with bare feet, but grassland in the same sunshine does not. This has nothing to do with the moisture in the air; it is the result of the evaporation from the vegetation and of conduction in the ground.

Now Dr. Rösch and his wind tunnels. This is a well known technique in studying the emission of smoke from buildings to see whether the smoke will go in the windows. The difference in this case, as Dr. Stock mentioned, is that the turbulence will not cause any optical effect unless there are temperature gradients in the air impinging on the dome. If you have air of uniform temperature impinging on it, then the turbulence will not matter optically; if you have extremely stable air impinging on the dome, then you get the kind of turbulence that Dr. Lynds talked about, but in that case the experiments are not correct because there are no density gradients in the wind tunnel and therefore you are not revealing the kind of flow that will take place when there will be an optical effect. The only people, to my knowledge, who have made any wind tunnel experiments with temperature gradients are at New York University. Dr. Strom has made some tests in stably stratified air on buildings which were designed to be placed on the snow at the South Pole. But there are very great difficulties in representing an atmosphere which is stably stratified.

Finally one comment about Prof. Queney's remarks. Perhaps I would like to add one or two zeros to his time-scale, then I would agree that his conclusions are correct, but I think that 1 s is not large enough. As Dr. Rösch said, the hydrostatic equation is not satisfied when the fluctuations are so rapid and the vertical extent so large, and I agree with his conclusions about this. On the other hand, in the jet-stream these large eddies which Prof. Queney mentioned, of the order of 100 km, produce smaller fluctuations. If we plot wind and temperature as functions of height we will find that in the jet-stream there will be many fluctuations; in the temperature likewise there will be many thermal fluctuations, but not quite so severe as in the wind. Such fluctuations are due to very flat eddies which, if they are 100 km in horizontal dimension, are of very much less vertical extent. They cause, particularly if the air goes over a mountain, some instability on a very much smaller scale. So that these things in the jet-stream cannot be ignored simply because they are of large scale (*see* Scorer, 1963).

RÖSCH. — First, I am very glad that Prof. Scorer has suggested one or two zeros after the 1-second time scale given by Prof. Queney, because this gives a still better explanation of what we call accidental refractions, which are deviations of seconds of arc lasting for some time, for tens of seconds or minutes. Now, about the wind tunnel experiments, I am well aware that they do not reproduce exactly the real case, because of the stratification. I know that some Japanese physicists have tried to study the turbulence and orographic clouds around mountains by using, not a wind tunnel, but a water flow with a channel profile such as to introduce in the equations the equivalent of the gradients. But this is too complicated for us at the present time. Anyhow, the fact is that from the observational point of view we know quite surely that, as Dr. Dommanget mentioned, we have the best conditions when the wind is arriving straight on the instrument, not coming over the dome; for instance, it is quite usual, when the wind is blowing only from time to time from behind the dome, to observe very sharp stellar images with nice diffraction rings and suddenly to hear some noise because a gust is hitting the dome : immediately after, the image " explodes " and becomes completely fuzzy. So although I agree that the wind tunnel experiments are not correct, they are not entirely misleading because the type of things they show confirm exactly what we know from optical observations. This is also an answer to Dr. Stock when he said that there would be no optical effects : they *do* exist.

VAN ISACKER. — The influence of humidity on refractive index, as Prof. Scorer said, may be as important as temperature fluctuations. Some measurements have been done in the course of a study of tropospheric propagation of radio waves, using a refractometer which measures directly the refractive index and simultaneously a thermometer and an hygrometer (although hygrometers are not sufficiently fast). The result obtained shows that for a temperature of about 20°C, the effect of humidity variation is of the same order as that of temperature variation itself. A second point related to what Prof. Scorer said : I think that stability depends also on the gradient of humidity; with cold humid air below and warm dry air above, an inversion may not be stable at all. As for the experiments of Dr. Lynds, they are very different from those done by meteorologists, because generally the latter take great care to have very homogeneous and very isotropic surfaces in order to have a simple phenomenon to study. Observations made near a mountain with a very inhomogeneous surface may be representative of this place only, I think, and not at all of other places.

COURTÈS. — I think both Drs. Scorer and Rösch are right about the dome effects, because the main phenomenon you observe is probably " pumping " : when the wind is coming from the back, there is a depression like on the back of an airplane wing and it is the effect of pumping of air situated inside the dome which has quite a different temperature.

RÖSCH. — I agree completely with you. We shall have a conclusive experiment when using our completely closed dome.

COURTÈS. — For the dome of the 193-centimetre telescope of Haute Provence, Dr. A. Couder has chosen the same type of shutter as that of the dome of the Lick 120-inch telescope, because of the effects you mentioned, which can be important. We have made certain experiments on this question; you know that this dome can be arranged with a very small opening, just a little larger than the diameter of the telescope; some fans at the back of the dome are used to produce a certain depression inside the dome; an aerodynamical profile has been given to the aperture of the dome and also to the aperture of the telescope itself so as to get a laminar flow of the air which is sucked through the dome and then blown away on the opposite side. Of course, there is also a laminar flow inside the tube, owing to small fans located between the two tubes of the telescope. This system works well when the wind is light, but when the wind is strong we are unable to produce a depression sufficient to get the air circulating in a laminar flow.

I have another point about a question raised by Dr. Lynds. In the case of the rim of a flat hill, I think that if the flat part of the mountain is very small you may consider it as something like a tower; but if the flat area is very large there are very different microclimates and I think it is dangerous to be in the discontinuity caused by the rim. In our experiments in South Africa we have always noticed very poor seeing just at the rim of the cliffs.

STOCK. — Concerning turbulence around the dome, all the " boiling ", I think, is essentially due to a temperature difference between the inside and the outside of the dome. In other words, if we would keep the temperature equal inside and outside — and I think this is attempted in any modern dome — we have solved our problem.

CIALDEA. — The optical effects of the atmosphere depend only on the gradient of the refractive index; in the experiments of Dr. Rösch, the turbulence produces a gradient of pressure, not a gradient of temperature, but the effect is the same, I think.

MEINEL. — With regard to wind turbulence around domes, the velocities involved are low enough, so that no optical inhomogeneities will result. This remark is confirmed by the observed absence of Schlieren effects at sub-sonic velocities in wind tunnels. In addition, I do not think that the proposed test by Dr. Rösch with the enclosed dome-telescope is conclusive unless one can demonstrate the microthermal homogeneity of the air arriving in the vicinity of the dome.

RÖSCH. — Of course. My point was that, by using a closed dome, you discard the possible effect of pumping warm air from inside the dome. I would like also, after Dr. Cialdea's remark, to emphasize again that we astronomers are not interested in either temperature or pressure gradients, but in refractive index gradients. The point is : are these gradients produced by gradients of temperature, or by gradients of pressure ? My guess was that generally we are dealing with temperature gradients. A very crude explanation : due to the fact that the velocity of the sound is expressed by a much larger number than the conductivity of the air, an excess of density vanishes much more rapidly by sound waves than by thermal equalizing, so that the pressure gradients should remain much smaller than the temperature gradients. I am glad that the meteorologists confirm this point by a more correct analysis.

KIEPENHEUER. — It is also possible to construct instruments that do not need a dome. I described such an instrument in the *Proceedings of the Symposium on Solar Seeing*, which have been presented to you at the opening of this meeting.