SOME COMMENTS ON THE USE OF INFRARED RADIOMETRY FOR REMOTE ATMOSPHERIC PROBING

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ABSTRACT

This report represents primarily a critique of the lead paper by L.D. Kaplan on infrared radiometry. The following topics are analysed - the extent to which the desirable thermal resolution of the lower troposphere can be achieved, the effects of complex cloud structure on infrared data, the effective weighting function if linearisation is possible, remote sounding from below the atmosphere, first-guess fields and operational techniques to blend satellite infrared data into a mix of data from various meteorological systems, a simple inversion procedure for thermal structure, and problems arising from cloud and haze layers of variable amount and emissivity.

1. KEY PROBLEMS ACCORDING TO KAPLAN

Kaplan, in his lead paper on infrared radiometry, considers that two key problems in meeting the needs of numerical weather prediction are: "the necessity of obtaining soundings of temperature and water vapor content of the lower troposphere with sufficient vertical resolution to determine the exchange of heat and moisture between the surface and the atmosphere; and the necessity of obtaining these soundings even under the usual conditions of at least partial cloud cover".

To permit flux determinations, we need at least meso-scale resolution, which could be possible only by infrared probing from below. This could be both automated and remoted by using satellite interrogation of radiometric buoys or radiometric automatic land stations. However, we must bear in mind that the fluxes are needed in the numerical procedures not only at the moment of initial data, but for the next three or four weeks inside the computer as it races well ahead of the atmospheric evolution. Within the computer, fluxes in the vertical near the ground will have to be parameterized. The divergence of these fluxes, plus advective and radiative processes, will then be used to modify local gradients over deep layers, from which new fluxes will again be calculated by parameterization. If this procedure is not possible, extended-range prediction for several weeks cannot be successful, and initial data on even a micro-scale will not contribute to the numerical prediction. Expressed in another way, meso-scale and micro-scale information decays rapidly in the atmosphere and must continually be re-synthesized by a numerical model. It therefore makes little or no difference whether such information is available initially or not.

The problem of a partial cloud cover is indeed a very complex one, to which we will return a little later. Essentially, the number of degrees of freedom associated with broken stratified clouds (amount and temperature for each distinct layer) is such that virtually no degrees of freedom will be available to specify either the tropospheric temperature or moisture fields. In other words, the radiative data do carry considerable information, but, relative to an informed first-guess field, such information deals almost entirely with the clouds themselves. Unfortunately, it may be very difficult to make an initial guess of the cloud characteristics, so that the method of solution will be slow and sensitive to errors. Moreover, space averages will certainly be involved and since the horizontal variability can be relatively great (clouds being sub-synoptic scale phenomena) there will be problems of non-linear averaging.

2. USE OF HIGH FREQUENCY INFORMATION

As Kaplan points out, in his lead paper, the upward intensity depends on the integral, over pressure, of the product of black-body intensity and the pressure derivative of the transmission function. If the problem can be solved by the use of a good initial guess-field the subsequent linearization replaces the black-body intensity by its temperature derivative. This derivative is also very sensitive to both frequency and temperature and behaves quite differently at high and low frequencies. At 2000 cm^{-1}, for example, the ratio of this derivative at 300°K to that at 200°K is about 53, whereas at 667 cm^{-1} the ratio is only 2.2. This means that the weighting functions for the 4.3 micron and 15 micron bands of CO_2 will be quite different, so that the information from a second band will not be redundant and can permit an improved resolution of the thermal structure of the atmosphere.

If broken clouds are present, the use of two widely-separated spectral windows can also be very helpful. As an example, consider the case of a single layer covering one-half the sky at a temperature 20°C colder than the ground at 260°K. The effective radiating temperature at 2500 cm^{-1} will exceed that at 900 cm^{-1} by 2.0°C, with a standard error of about 0.5°C, assuming intensities have standard errors of one per cent. We thus have two relatively independent pieces of information, but unfortunately there are three unknown quantities. In the daytime one might be able to estimate the cloud amount from data at visible wavelengths, or we may be able to guess the surface temperature from other meteorological data (especially over oceans for which this is a moderately conservative element).

Kaplan, in his lead article, suggests the use of a wide-band narrow-angle sub-scan over each element of area to determine intensity maxima (presumed to be clear skies) and minima (presumed to be overcast cloud). If true, both the ground and cloud temperature would be known, and narrow-band wide-angle window data would yield the effective average cloud amount. Knowing these three parameters, the effects of the broken clouds could be removed from non-window data. It is unlikely that this procedure would really be effective, but at least it could be checked if two pairs of wide-band and narrow-band windows were used. If both spectral regions yielded the same value for effective cloud amount, one would have considerably more confidence in the technique. If they did not agree, a more complex model would be needed, or else auxiliary information from non-infrared sensors. The correction technique suggested is very sensitive to the cloud-ground temperature difference, so that it would be necessary to be certain that truly overcast and truly clear areas were those of minimum and maximum intensity. If the two windows agreed on the effective radiating temperature of only one of these limits, the problem would still be soluble, however.

3. SOUNDING FROM BELOW

In his lead article, Kaplan draws attention to the information derivable from infrared sounding from below, and it is clear that microwave techniques are also effective in this mode. In both cases, resolution is good for layers for which sounding from above yields the least information. It is rather surprising that little serious attention appears to have been paid to the automating and remoting of a surface sounding system, using interrogating satellites and oceanic buoys plus automatic land stations in difficult or unpopulated areas. It is certain that radiosonde releases from unattended oceanic buoys are virtually impossible, while an unattended radiometric unit could well be feasible. Particularly over oceanic areas where conventional data have minimum density, such complex systems seem particularly attractive, especially in view of the fact that the platform itself and the telemetering capability, required for even the simplest observations, constitute a major expense, together with installation and subsequent inspection.

With a sun seeker added to the equipment, daytime observations of total aerosol, total water vapor and total ozone would seem feasible, and these may well be parameters of great significance for complex numerical models of the atmosphere. Total liquid water should be an extremely valuable parameter (perhaps from microwave observations) in addition to total vapor, since the sum of water in all phases would be an element whose careful budget inside a computer could greatly improve precipitation forecasts.

4. INCORPORATION OF INFRARED DATA INTO AUTOMATED ANALYSIS

If infrared data are to be used primarily in real time, all techniques and details should be based on this premise - with respect to both selection of channels and methods of processing. For both GARP and the eventual complete WWW, one can visualize two computer installations at a World Meteorological Centre. One will operate on a slowly advancing but quite complex model of the atmosphere at about real time, and will fit in all input data at their actual times by a very frequent objective analysis. At specified intervals, this computer will output complete observations and analyses for archiving, dissemination and input to the second computer which will do prediction, only, at very high speed and for variable time periods (e.g., once every few days to 30 days, but generally for much shorter periods). Both computers will deal, either directly or else indirectly by parameterization, with all significant processes and parameters, whether observed frequently (temperature, wind, etc.), infrequently (ozone distributions) or not at all (vertical motions). Both computers will have products that can be degraded by poor or insufficient initial data, but both can also operate in the absence of frequent specific data (by manufacturing synthetic data internally and/or carrying forward earlier data as the atmosphere would). After such an operation has run for a week or so in pseudo-real time, gathering in vast amounts of varied data, poor data will do more harm than no data.

We may conclude that at any time we will have available relatively good first-guess fields for temperature, water vapor and ozone - particularly if we have a full mix of data flowing to the computer: conventional surface and upper air data, merchant and fixed ship surface and upper air data, buoys and automatic stations, aircraft data (including dropsondes), floating balloon data and satellite radiometric observations. There will be no purpose in squeezing crude information from infrared sensors - such as ozone data or tropospheric temperatures and vapor concentrations under complex cloud conditions. In the latter case one would concentrate instead on deducing cloud information plus stratospheric temperatures.

Since the infrared data processing will require the products of the analysis computer and will feed data back in, all intermediate steps (on other computers) should be eliminated and the infrared data should go as directly as possible into the World Meteorological Centre. Not only should the frequencies be selected to provide maximum useful information to the analysis routine, but the processing must also be done in an optimum manner, fully consistent with the treatment of all other data. This implies space smoothing to remove sub-grid scale variance and prevent aliasing. Fortunately, this should simultaneously subdue random experimental and computational errors, but care will be needed to avoid degrading high-accuracy clear-sky data by averaging with lower-accuracy cloudy-sky data. Such problems will not be as severe as might be imagined in areas of persistent cloudiness, since the analysis routine will be able to produce, for such areas, relatively good estimates of cloud parameters.

With a good first-guess field for temperature, represented by a cap superscript, the governing equations become

$$\delta T_j = T_j - \hat{T}_j \; ; \; \delta I_i = I_\nu - \hat{I}_\nu = \tau_I(p_B) \cdot \frac{\partial B_\nu}{\partial T} \cdot \delta T_B - \sum_j \delta T_j \int_j \frac{\partial B_\nu}{\partial T} \cdot \frac{\partial \tau_I}{\partial p} \cdot dp ,$$

where we have an overcast cloud or ground surfact at (p_B ,T_B), and each of the j layers is a standard layer for the numerical model being used, for which δT_j is assumed effectively constant - since no finer resolution of temperature information is either achievable or desirable, in view of the vertical grid scale implied by the model. In any event, it would be quite reasonable to assume slow variations of δT in the vertical, uncorrelated with the weighting function in an individual layer. This would not be true for T_j or $\hat{T}_j$.

One problem that arises is how to ensure a stable solution yet extract maximum information from the infrared data, or how to match up the number of linearly independent frequency equations with a reasonable number of temperature departure parameters, to minimize errors in computed isobaric heights at all levels. If one uses frequencies from two bands to capitalize on significantly different behaviours of ($\partial B_\nu / \partial T$), the number of frequencies may easily exceed the number of standard layers (perhaps about ten up to the 10 mb level). For some systems the number of frequencies may be less than ten and in any event one suspects that the number of degrees of freedom for a temperature departure field should be less than the number of standard layers. In other words, prior knowledge of an approximate temperature structure decreases the information content of the infrared data.

One possible procedure would be to treat as the unknowns smoothed temperature departures at a small number of selected pressure levels, and interpolate linearly between them to obtain the departures appropriate to each of the j standard layers. The i frequency equations could then be solved by a straightforward least-squares technique, and the final values of δT_j reformulated subsequently as the output. Such a procedure is statistically sound since the first-guess field can be assumed to be of roughly equal accuracy at all levels, and since any apparent loss in information due to under-resolution is compensated by increased accuracy of the set of departures deduced. The window frequency (or frequencies) would be used for the first guess of T_B , and p_B would be obtained from the assumed (p,T) relationship; the window frequency equations would also participate in the least-squares solution.

5. THE HAZE PROBLEM

The haze problem is largely an unknown one but may often be serious near the ground. It is certain that aerosol absorption of solar radiation is comparable to that by water vapor - although this fact has not been appreciated in the past. If this is the case, infrared attenuation is also inevitable, and will cause trouble in the inversion procedures. It may well be that aerosol data will have to be incorporated into future atmospheric numerical models, requiring good initial data as well as information on sources and sinks. If so, a combination of emission and backscatter sounding techniques (from above and/or below) may be required, and it might then be possible to correct infrared intensities for haze effects.

In the case of haze or cloud layers (whether black radiators or not), the key parameters are the temperature of the layered material and the product of emissivity and fraction of sky coverage for that layer (these two parameters cannot be separated, and need not be separated for the inversion problem). Further complications arise, particularly in the interpretation of window intensities, associated with the spectral variations in infrared emissivities of ground, cirrus cloud and haze. It is, nevertheless, quite apparent that two window spectral regions will be needed to minimize ambiguity (and permit an inversion solution) whenever the effective window temperature does not agree with a reasonable estimate of the ground temperature (after correction, of course, for radiative effects of atmospheric gases). It is to problems such as these that greatly increased attention appears to be warranted.