Nimbus Weather Satellites: Remote Sounding of the Atmosphere

Since their inception in 1959 weather satellites have made a vast impact on meteorologists and meteorology. Cameras in orbit initially provided pictures of clouds from which air movements could be determined. These pictures are now a standard feature of weather forecasting. Shortly thereafter infrared maps were constructed from satellite data. These maps reveal temperature variations on the earth's surface. They can be used to study, for example, the meandering of the Gulf Stream for about 1000 miles across the Atlantic. But meteorologists and atmospheric scientists are now most excited over the results from the latest two satellites in the Nimbus series.

Instruments aboard Nimbus 3, launched in 1969, and Nimbus 4, launched in 1970, are capable of yielding the vertical profile of the temperatures in the atmosphere between the satellite and the earth. Since these satellites pass over most of the earth's surface in a 12-hour period, they sound out the global distribution of temperature in three dimensions. Global distributions of ozone and of water vapor can also be measured by equipment on Nimbus. Quantitative estimates of these properties are necessary to test models of atmospheric circulation and energy exchange. The ultimate goal is long-range weather forecasting.

Prior to Nimbus, meteorologists used rockets and balloons to sound the atmosphere. But these conventional techniques are not suitable for scanning remote corners of the earth, as is attested by the fact that very few measurements had been made in the Southern Hemisphere. Nonetheless they are still important because satellite techniques are not sufficiently developed to monitor some properties of meteorological interest, such as wind velocity, that can be measured by weather balloons. Nimbus 4 circles the earth every 107 minutes at a height of almost 1100 kilometers. The satellite is in a polar orbit that allows it to scan the whole globe twice daily as it rotates on its axis. The effectiveness of the satellite as a data-gathering technique is impressive; if balloons and rockets were to monitor weather phenomena as comprehensively, they would have to be launched every 12 hours over every 500 km^2 of the earth's surface.

The vertical temperature profile is determined from measurements recorded by infrared detectors. Nimbus 3 carries the satellite infrared spectrometer (SIRS) and a Michelson infrared interferometer spectrometer (IRIS). Improved versions of these two detectors are aboard Nimbus 4, together with a British detector called the selective chopping radiometer (SCR). They all supply data for the atmospheric temperature from radiometric measurements of infrared emission due to transitions between vibrational levels of carbon dioxide molecules. The vibrational band is centered at 15 μm, or 667 reciprocal centimeters (the inverse of the wavelength is called the wave number; its unit is the reciprocal centimeters) and spans a region from 600 to 800 cm^{-1}.

Carbon dioxide in the atmosphere absorbs and reemits infrared radiation emitted from the earth's surface. Because of the transmission characteristics of the atmosphere, each part of this spectral band corresponds to radiation originating from carbon dioxide at a particular height above the earth's surface. For example, with the appropriate calculations it is possible to predict that the infrared radiation with a wave number of 710 cm^{-1} predominantly comes from carbon dioxide at a height of 5 km (corresponding to a pressure of about 450 millibars), whereas the spectral feature at 685 cm^{-1} mostly originates at a height of about 15 km (or at a pressure of 100 mb). The fact that vertical temperature profiles could be obtained in this way from remote infrared measurements was independently realized by a number of meteorologists in the late 1950's but was best expounded by L. D. Kaplan in 1959 when he considered 5 cm^{-1} bandwidths.

These calculations depend on detailed knowledge about how absorption coefficients vary with frequency and with pressure and on the assumption that the carbon dioxide is uniformly mixed with a known mixing ratio. The need for narrow bandwidth posed severe experimental problems which led to three different instrumental solutions. The consistency between all three types of orbiting radiometers and their impressive agreement with temperatures measured by radiosondes (instruments carried aloft by weather balloons) bodes well for this meteorological technique.

David Wark and Donald Hilleary of the U.S. National Oceanographic and Atmospheric Agency (NOAA) are the experimenters in charge of SIRS. They obtained their first temperature profile from the instrument on Nimbus in April 1969 (*1*). Rudolph Hanel and Barney Conrath, Goddard Space Flight Center, successfully initiated their remote experiments with IRIS at the same time (*2*). SIRS is a conventional diffraction-grating spectrometer with special detectors and electronics. It is designed to measure simultaneously the intensity of the emitted radiation (the radiances) from seven narrow intervals in the carbon dioxide band. An eighth channel in the 11.1-micrometer atmospheric window is used to measure the radiance from the earth's surface (or from cloud tops if they are present). A knowledge of this boundary condition is essential for a satisfactory solution to the equations representing the vertical temperature distribution.

The Michelson interferometer IRIS records the entire infrared spectrum over a wide interval. The version on Nimbus 4 handles the atmospheric emission spectrum from 400 to 1500 cm^{-1} which of course includes the 667 cm^{-1} carbon dioxide band. It also includes distinctive features due to water vapor, ozone, and methane. The other minor constituents of the atmosphere have not been detected by IRIS so far. IRIS is similar to the interferometer originally designed by Michelson. It consists of a beam-splitter and a moving mirror which changes the phase of one beam relative to the other. The recombined beams form an interference pattern, the intensity of which is measured by a thermistor balometer. The infrared spectrum can be obtained from the signal by means of a Fourier transformation. The moving mirror travels 0.2 cm in 10 seconds while recording one complete spectrum. IRIS can monitor the three-dimensional distribution of water vapor as well as the temperature distribution. Ozone profiles are not so easily obtained because of the limitation on the instrument resolution and noise in the region on the 1042 cm^{-1} ozone band (*3*).

The SCR experiment is led by Dr. J. T. Houghton of Oxford University and Professor S. D. Smith of Heriot-Watt University, Edinburgh. Their main objectives have been to extend the altitude range of the remote sounding upward to 50 km (1-mb level)—the Nimbus 3 results showed the temperatures up to 30 km (10-mb level)—and to "design a simple, robust radiometer of high performance for remote sounding of the lower atmosphere." The SCR views the atmospheric carbon dioxide radiance in six channels having maximum responses that vary in about 10-km intervals from the earth's surface to 50 km. Initial results showed a resolution of about 5 km in altitude, with an uncertainty of at most a few kelvins (*4*).

The British radiometer relies on interference filters which, the English team believes, give resolution comparable to that provided by the much larger grating spectrometer, and on a spectroscopic technique known as selective chopping. The incoming radiation is alternately blocked by a mechanical chopper and allowed to pass through a gas cell containing carbon dioxide before it reaches the detector. The gas cell serves as an effective filter for strongly absorbed frequencies. Thus the pertinent radiation is modulated at the detector and distinguished from unchopped radiation by a phase-sensitive detector. This system selects parts of each absorption line at regions of similar absorption, thus giving better height resolution. The British team showed that one cell is sufficient for measurements of the lower atmosphere, but that two selective absorbing cells of carbon dioxide are needed to adequately sound the atmospheric region from 30 to 50 km. The effective spectral resolution of the radiometer depends on the pressure of the carbon dioxide in the cell and the length of the cell. For one of the channels on the Nimbus 4 apparatus the resolution is one cm^{-1}. It is this feature that enables the SCR to reach greater heights.

In order to measure temperature with any radiometer to an accuracy of at least 1°K, the radiance must be measured with a maximum error of 0.5 percent. This means that the instrument must be capable of gathering a substantial amount of radiant energy. As always seems the case in instrument design, this need for large energy-gathering capabilities is offset by another condition—namely, good spectral resolution. The good spectral resolution is necessary to distinguish the radiation arising from different altitudes. But unfortunately, resolution is sacrificed for energy-gatherng power and vice versa. If a low resolution element is restricting the "energy grasp," the effectiveness of a radiometer can be maximized by increasing the apertures and allowing a higher flux of radiation to enter into the radiometer. Other trade-offs are also important in radiometer design. For the SCR instrument, the limiting element is the auxiliary filters rather than the gas cells.

Now that the experimenters have shown that their respective instruments give reasonable values for the temperature profiles, data can be accumulated rapidly and maps of global temperature patterns put to practical use. The SCR, for example, takes 5000 temperature profiles per day, and these are transmitted, along with the other Nimbus data, to receivers in Fairbanks, Alaska. Data from SIRS have been used in weather analysis by NOAA scientists since 1969. Compared to the conventional techniques of launching rockets or balloons, a Nimbus temperature sounding is relatively inexpensive.

One of the major problems encountered by the experimenters is that cloud cover obscures the radiation emitted by the earth's surface. If the height of the clouds above the earth's surface and their density are known, they cause no inconvenience since either the earth's surface or cloud tops can provide the boundary condition needed to solve the temperature equations. Unfortunately, the cloud height cannot always be deduced, and the surface temperature is needed. Over the water-covered areas of the earth the problem is not so great because the surface temperature is fairly constant and can be statistically estimated from the usual weather conditions for that seasonal time and place. However, dry land surfaces have temperatures which fluctuate considerably from day to night and which often make the equations impossible to solve accurately.

It has been suggested that soundings taken at frequencies where clouds are transparent (such as microwave frequencies) may circumvent the problem of cloudy areas. Two such microwave experiments are scheduled for flight on Nimbus E in 1972. Nimbus E will also carry two infrared vertical sounders—an improved British instrument, SCR II, and ITPR (infrared temperature profile radiometer) managed by NOAA. Both of these devices will use interference filters.

The constant surveillance by Nimbus of the global temperature patterns provides a unique opportunity to thoroughly analyze familiar weather patterns and to spot previously unknown phenomena. The selective chopping radiometer's good resolution at 40 to 50 km makes possible observations of stratospheric events which are not reflected at lower altitudes. Early results indicate, for example, that the 1970 winter South Pole had two distinct cold regions at 45 km where only one was expected. At present there is no explanation for this behavior.

Recently the British team and others have published observations of "sudden warmings" in the stratosphere over the winter North Pole (*5*). In these sudden warmings, the temperature over a small area may rise by as much as 50°K in a few days. These seemingly local phenomena are actually parts of a global weather pattern. They are accompanied by major changes in air circulation. Earlier measurements of stratospheric warmings taken with rockets and radiosondes are rather sparse, and the cause of these sudden warmings is not yet known.

At wavelengths that are not strongly absorbed by the atmosphere—the so-called "atmospheric windows"—it is possible to study direct emissions of the earth's surface for remote identification of its components. Hanel, Conrath, and their colleagues at NASA believe that, once the atmospheric effects are removed, the IRIS spectra will provide some information, although the present precision needs to be improved.

In any event, remote sounding of the atmosphere is likely to be an increasingly important source of data for meteorologists and others. At present, one year's highly successful operation has been achieved.

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References

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