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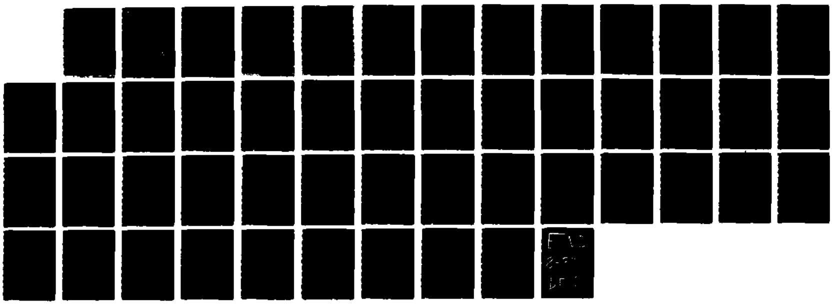

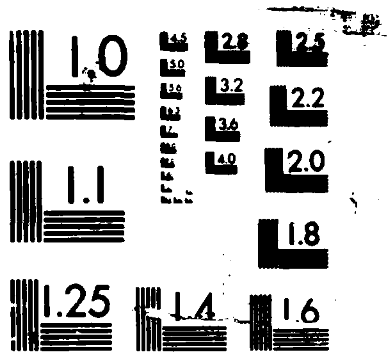

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A RAND NOTE

New Weather Sensing and Forecasting Capabilities for Ground-to-Space Operations

C. Schutz, F. W. Murray

February 1987

RAND

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Certain weather variables exercise an important control over space operations, either by making a launch infeasible or by adversely affecting the space vehicle and its trajectory. Climatological studies and standard National Weather Service observations show that the normal range of variability with location and season, even from day to day, precludes the forecasting of these variables sufficiently accurately for precise trajectory control. Several new systems are now becoming available for measuring wind and density (or variables from which density can be computed) continuously and automatically: VAS, PROFILER, WINDSAT, and the next generation of weather satellites. Together these systems offer the promise of continuous real-time monitoring of winds and air density throughout that part of the atmosphere that exercises the greatest influence on space operations.

A RAND NOTE

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New Weather Sensing and Forecasting Capabilities for Ground-to-Space Operations

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Prepared for
The United States Air Force

RAND

PREFACE

As part of the study effort "Advanced Weaponry" under Project AIR FORCE, the authors of this Note address the requirement for accurately predicting the trajectory and speed of a space-bound vehicle as it moves through the atmosphere from the launch pad to space.

Such weather conditions as the surface temperature and wind, the amount and type of clouds, and the occurrence of precipitation mainly determine whether launching is feasible. These conditions are readily observable from the ground and can be forecast in the short term (up to a few hours) with considerable accuracy. Other conditions that might affect the trajectory or its precise determination from the ground are atmospheric density and winds aloft. For one reason or another, the standard methods of observing these variables for space launches--namely, the balloon-borne radiosonde and the rocket-launched "Jimsphere" (a radio-reflective balloon designed to measure wind shear)--are not adequate.

This Note examines a few of the new weather sensing and forecasting capabilities now coming into use, or expected to be developed in the next few years, to fill this need.

SUMMARY

Certain weather variables have been identified as exercising an important control over space operations, either by making the launching infeasible or by adversely affecting the space vehicle and its trajectory as it moves through the atmosphere. In the latter category, atmospheric density and winds from ground level up to about 12 km are the most important. Climatological studies and standard National Weather Service observations show that the normal range of variability with location and season, and even from day to day, precludes the forecasting of these variables with a sufficient degree of accuracy for precise trajectory control.

Several new systems now coming on line for measuring wind and density (or variables from which density can be computed) continuously and automatically over the desired altitude range are VAS, PROFILER, WINDSAT, and the next generation of weather satellites. VAS is based on a visible and infrared spin-scan radiometer carried aboard a geosynchronous weather satellite. It assigns simultaneous heights and velocities to winds inferred by means of a cloud tracking system using CO_2 absorption. The PROFILER, a ground-based system, uses clear-air Doppler radar to measure winds and passive microwave radiometers to derive temperature, moisture, and, by extension, air density. WINDSAT is a pulsed CO_2 coherent laser radar (lidar) system that is carried aboard polar-orbiting satellites. It determines winds by sensing the motion of natural aerosols. The satellites, including both the next-generation polar-orbiting and geostationary systems, will be upgraded dramatically and will carry in their payload new microwave "sounding" sensors. With accuracy comparable to the conventional balloon-borne sounding devices, these sensors will penetrate most clouds and transmit temperature and moisture data continuously for a grid pattern covering the entire globe. Together these systems offer the promise in the near future of continuous real-time monitoring of winds and air density throughout that part of the atmosphere that exercises the greatest influence on space operations.

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Thanks are extended to Ralph Huschke for his review of this Note and for the important contributions he made to it.

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I. INTRODUCTION

Although the operating environment of both manned and unmanned space vehicles is mainly outside the atmosphere and not subject to weather conditions, the weather often plays an important role during launch and reentry. This was made tragically clear by the failure of the Challenger shuttle, which has been attributed in large part to unusually cold conditions on the launch pad. In another case, surface winds were a consideration for the first Strategic Defense Initiative laser test using the orbiting Discovery space shuttle on 22 June 1985. It appeared for a while that the experiment would have to be delayed because of 36 m s^{-1} (80 mph) wind gusts on Mount Haleakala, a volcano on the island of Maui with an observatory at the 3034-m (9954-ft) level. Typically, an experiment of this nature is cancelled with winds over 13 m s^{-1} (30 mph) because when the astronomical dome that houses the laser gun's array of optical systems is opened, high surface winds buffet the device and make precise aiming or tracking more difficult.

Other weather variables, including clouds and precipitation, can have a direct effect on space operations. It is easy to determine the surface temperature and wind, the type and amount of clouds, and the current or recent occurrence of liquid or solid precipitation at the launching site in order to take precautions or delay the launching. However, other less readily observable conditions may also pose an equal threat to the mission.

Winds aloft and air density are especially important. Changes in density along a trajectory alter the trajectory, and refraction through atmospheric layers of varying density make the tracking of a space target more difficult. Winds aloft can have a particularly great influence. Wind shear (changes in direction or speed over short distances) in upper winds can also add structural stress to a space vehicle and its control systems, endangering its operation. For that reason, another shuttle flight recently was delayed because a Jimsphere*[1] wind profile taken just before launching time indicated

[1]Asterisks denote terms explained in the Appendix: Definitions and Acronyms. See also the *Glossary of Meteorology* [1].

strong winds between 16 and 18 km above the launch site (near the top of the troposphere* at that latitude). The mechanical turbulence that strong wind shears create in the upper atmosphere often produces optical turbulence that distorts the laser tracking beam.

The emphasis in this Note will be on current and future capability to measure and forecast upper wind and density in a time frame that is useful for space operations and research. If it is operationally feasible, special observations of the pertinent meteorological variables are made at the launch pad immediately before launching. Otherwise it may be necessary to use forecast values, which must be based on many observations taken over a wide area. Most of the effect of wind and density, as indicated by the problems cited, is in the lower atmosphere, or troposphere. The zone of interest for this study is a three-dimensional band of the mid-latitudes from 30°N to 60°N and to an average altitude of about 12 km, but with some consideration of higher altitudes.

Above the ground surface layer, wind is observed directly by tracking a sensor or a tracer lofted by balloon or rocket. Density, however, must be computed from the observed pressure and temperature, except that between 30 and 90 km it is determined from observing the drag on a falling sphere that was lofted by rocket. The standard operational tool that currently measures wind direction and speed, along with pressure, temperature, and humidity in the troposphere and the lower stratosphere* is the rawinsonde*, and the observation made with it is called a RAOB* or a RAWIN*. A radio telemetering instrument is attached to a rising balloon, and pressure, temperature, and humidity observations are transmitted to a ground station, where corresponding heights are computed using the hydrostatic equation. The position of the balloon is tracked either by radio direction-finding, using the same telemetering signal, or by radar, in which case a radar target is also attached to the balloon. Wind direction and speed are then found by trigonometric computation.

RAWINs are recorded twice daily by the National Weather Service (NWS*) and by the corresponding services of other nations at 0000Z[2] and 1200Z at approximately 70 stations in the Continental United States (see Fig. 1) and at hundreds of other stations around the world. These

[2] "Z" indicates Greenwich Mean Time.

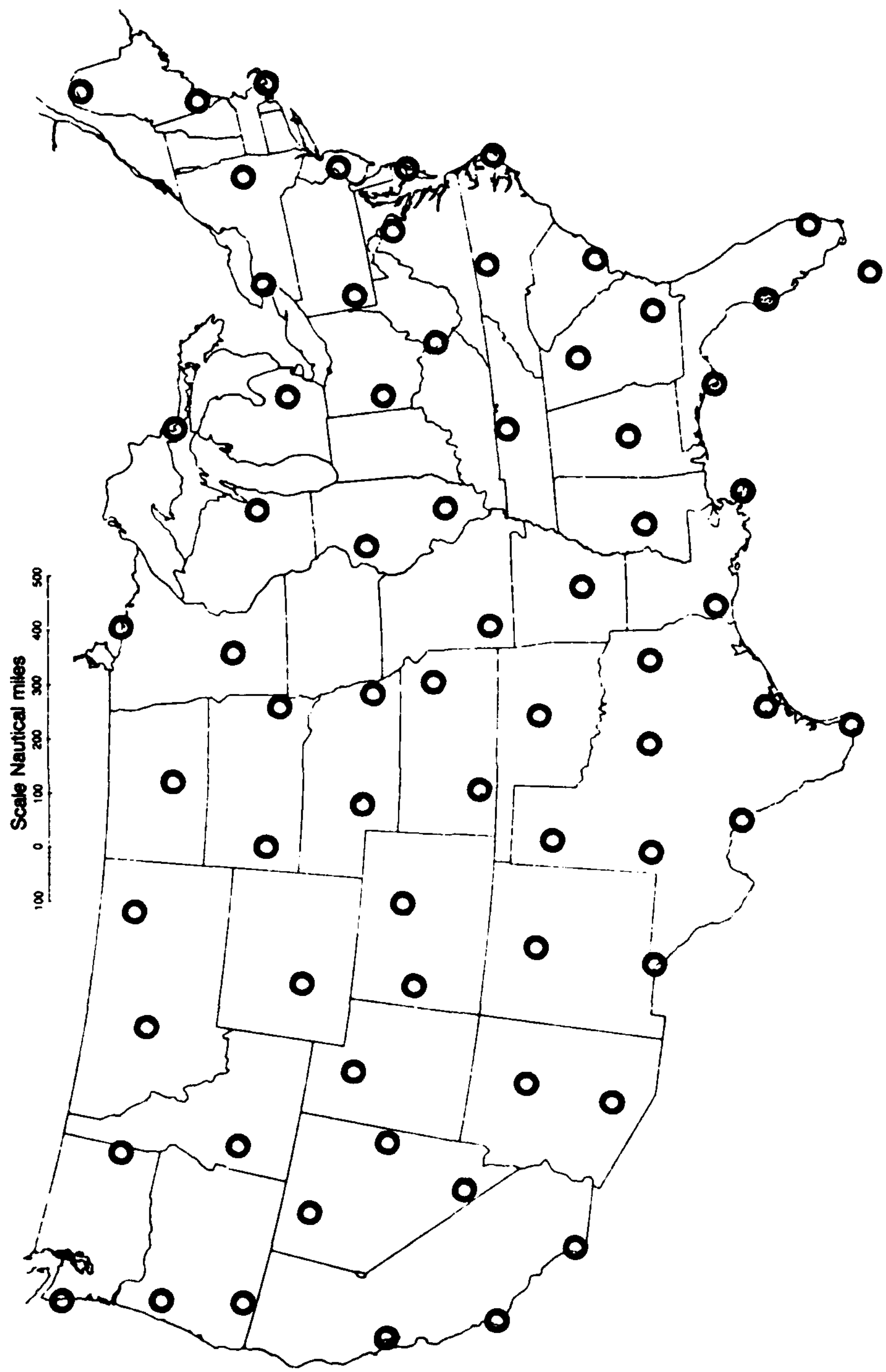


Fig. 1—Rawinsonde stations in the Continental United States

observations are freely exchanged among nations over high-speed communications nets. Station spacing in densely populated parts of the world is typified by that in the United States. Over the oceans and sparsely populated land areas there are very few stations. Some radiometric observations from operational weather satellites help to fill in the gaps, but with poor accuracy. The low frequency and sparse spacing of rawinsonde observations are two major flaws in the current upper-air system. Many "special interest" groups take their own RAWINs, sometimes with especially accurate instrumentation, and they may also use non-operational research-type equipment (such as the Jimsphere for wind shear) that is specifically designed to observe accurately a weather variable.

The operational synoptic maps* used for wind, height (pressure), and temperature forecasts are constant-pressure maps*. The NWS, using automated computer procedures, plots on maps the observed values taken from RAWIN data each day at the synoptic times*, 0000Z and 1200Z, around station locations over most of North America. The plotted data include:

- Height of constant-pressure surface* (m).
- Temperature (°C).
- Dewpoint depression (°C) (a measure of moisture content)
- Wind direction (to the nearest 5°) and speed (to the nearest 1.5 kt).
- Twelve-hour height changes (m).

Values are then interpolated to a regular grid, and isopleths* of the height of the constant-pressure surface and temperature on that surface are constructed, again by automated procedures. A map constructed for each of the standard pressure surfaces is made available over facsimile circuits to weather forecasters at private and governmental offices around the world.[3]

---

[3]In the near future, a new procedure will be instituted under which the data generated by the NWS will be made available only to their own regional stations through a computer network and to private distributors, who can tap on to the computers in Washington, further process the data, and transmit them to the ultimate users.

The NWS uses numerical weather prediction (NWP*) models based on automated analyses to produce a series of forecasts or prognostic maps* for each of the standard pressure surfaces. These forecasts are valid at 12-hour intervals from 12 to 72 hours after observation time. They are made available to the public in the same way as the analyses. Concurrently, the Air Force Global Weather Central (GWC*) at Offutt Air Force Base, following similar procedures, produces analyses and forecasts that are transmitted to Air Weather Service stations around the world. The GWC product can be made available to anyone having need of it for Department of Defense work. The value of the product of this elaborate system is directly dependent on the quantity, quality, and timeliness of the upper-air observations.

The problems of the present RAWIN system for meteorologically sensitive operations are being addressed by the National Oceanic and Atmospheric Administration (NOAA*), which is the parent organization of the NWS, and by the U.S. military weather services. Four new systems for measuring wind and density continuously and automatically are in the testing phase. They are: (1) VAS*, (2) PROFILER*, (3) WINDSAT*, and (4) a new generation of satellites.

The Visible Infrared Spin-Scan Radiometer (VISSR*) Atmospheric Sounder (VAS) aboard the Geosynchronous Operational Environmental Satellites (GOES*) first started relaying information in 1982. NOAA's National Environmental Satellite Service is currently evaluating the operational utility of the system [2].

The complete ground-based PROFILER system is being studied at NOAA's Aeronomy Laboratory of the Environmental Research Laboratories (ERL*) in Boulder, Colorado [3]. The PROFILER has the potential of direct readout of high-altitude wind and density information every 5 minutes. This system is being installed at the National Aeronautics and Space Administration (NASA) Kennedy Space Center to test its usefulness in supporting space shuttle launches [4]. The PROFILER could be used along with the Jimsphere [3]. By using both systems for wind information before launch, load calculations could continue to be based on the high-resolution Jimsphere data while the PROFILER would monitor winds aloft continuously to detect any unexpected change.

WINDSAT is a global wind measuring system that will fly aboard polar-orbiting satellites some time in the future. It is being developed by NOAA's Wave Propagation Laboratory (WPL*) in conjunction with the U.S. Air Force Space Division Defense Meteorological Satellite Program (USAF-DMSP*) [5,6].

Finally, the next generation of weather satellites [7], beginning with GOES-NEXT* in 1989 and the polar-orbiting NOAA-K in 1990, will revolutionize vertical sounding techniques for obtaining temperature and moisture information. Their new microwave sensors will not be degraded by most clouds, and high-quality data will be available at all times of the day, worldwide.

These systems are discussed briefly in Sec. IV. The impact of these systems cannot be overstated as a data source for more accurate NWP model products, wind and density measurements, and forecasts.

II. AIR DENSITY

There are three possible sources of air density values. In decreasing order of accuracy, they are currently measured values, forecast values, and climatological averages. In some circumstances (e.g., if the observed values are sparse or if the valid time is long after the observation time) climatology is superior to a forecast. Whichever source is selected, the usefulness of the data depends on the accuracy with which density can be measured and the natural variability of density. If forecast values are to be used, then one must take into consideration the accuracy with which density can be forecast. The choice of sources depends on the availability of data and on the requirements of the application.

MEASUREMENT OF DENSITY

Whether currently computed density, climatological averages, or forecasts are to be used, the process starts with observation. In the lower atmosphere (up to about 30 km), density is not directly measured. Instead, it is computed from $\rho = p/RT$, where ρ is the density, p is the pressure, R is the gas constant for dry air, and T is the absolute temperature. A small correction for humidity may be included, but except for extremely low altitudes it is negligible. The magnitudes of T and p and of their observational errors are such that the error in density should closely parallel the error in pressure.

Rawinsonde ascents commonly attain altitudes of about 30 km. For reasons of economy and speed in reporting, however, the operational, near-real-time dissemination of these observations is limited to data for the lowest 16 km, and the detail reported is defined by requirements of operational NWP models. The complete, detailed data are available at their points of origin and, after the fact, can be obtained from the National Climatic Data Center. At missile ranges density is also measured directly between 30 and 150 km by ejecting a special sphere, known as the Robin Falling Sphere PWN-12A, from a lofted rocket and measuring the drag as it falls [8]. Such observations, however, are less accurate than the RAOBs at lower levels. Typical accuracies of all three systems are shown in Table 1 [9]. The values in the lower part of Table 1 are taken from the U.S. Standard Atmosphere* [10], which has been adopted internationally as a standard reference to be used primarily for design purposes.

Reliance on NWS observations has several drawbacks. In the first place, the accuracy may not be as good as is required, and the maximum altitude reported may not be high enough. More serious is the fact that observations are not usually available at the exact time and place that they are needed. That is why special observation systems have been installed at the ranges. But even with special dedicated observation systems there may be a problem of response time. It takes on the order of two hours to prepare a rawinsonde for release and to complete the ascent, and even with computerization, there is additional time involved in processing the telemetered data. With rocket-borne falling spheres there are similar lags. Hence, even with dedicated equipment it might be necessary to rely on frequent fixed-time observations.

Table 1

OBSERVATIONAL ERRORS IN PRESSURE, TEMPERATURE, AND DENSITY

	Surface	30 km	90 km
Range radiosonde			
Pressure	0.1 %	0.5 %	
Temperature	0.1°C	0.3°C	
Density	0.1 %	0.5 %	
NWS radiosonde			
Pressure	0.1 %	1.0 %	
Temperature	0.7°C	1.5°C	
Density	0.1 %	1.5 %	
Robin Falling Sphere			
Density		3.0%	7.0%
Standard Atmosphere			
Pressure (mb)	1013.25	11.97	0.0018
Temperature (K)	288.15	226.65	186.87
Density (kg m^{-3})	1.225	0.018	3.416×10^{-6}

NATURAL VARIABILITY

In order to consider natural variability, reference points must be established. The simplest reference is the U.S. Standard Atmosphere, which is roughly the climatological average for mid- latitudes for the entire year. The Standard Atmosphere, however, is too crude an approximation to use directly for the present purpose. The actual density varies both with season and latitude and may differ considerably from the standard value.

The horizontal arrows in Fig. 2 show the estimated systematic changes (combined seasonal and latitudinal) in the mean monthly densities as percentage departure from Standard. The systematic departure is least around 8 km altitude. The 1 percent maximum and minimum in months with the highest and lowest values at the extreme locations, indicated by the dashed lines, may differ from the Standard by 20 percent at ground level and as much as 80 percent at 80 km. The actual density at 80 km, however, is five orders of magnitude smaller than at ground level, so a large percent variation is small in absolute terms.

Table 2 [11] gives seasonal climatological averages for density, broken down by latitude and month, and expressed as percentages of the Standard Atmosphere values. The $\pm$ increments are estimated 95 percent range variabilities. The values shown here are excerpted from a more extensive table.

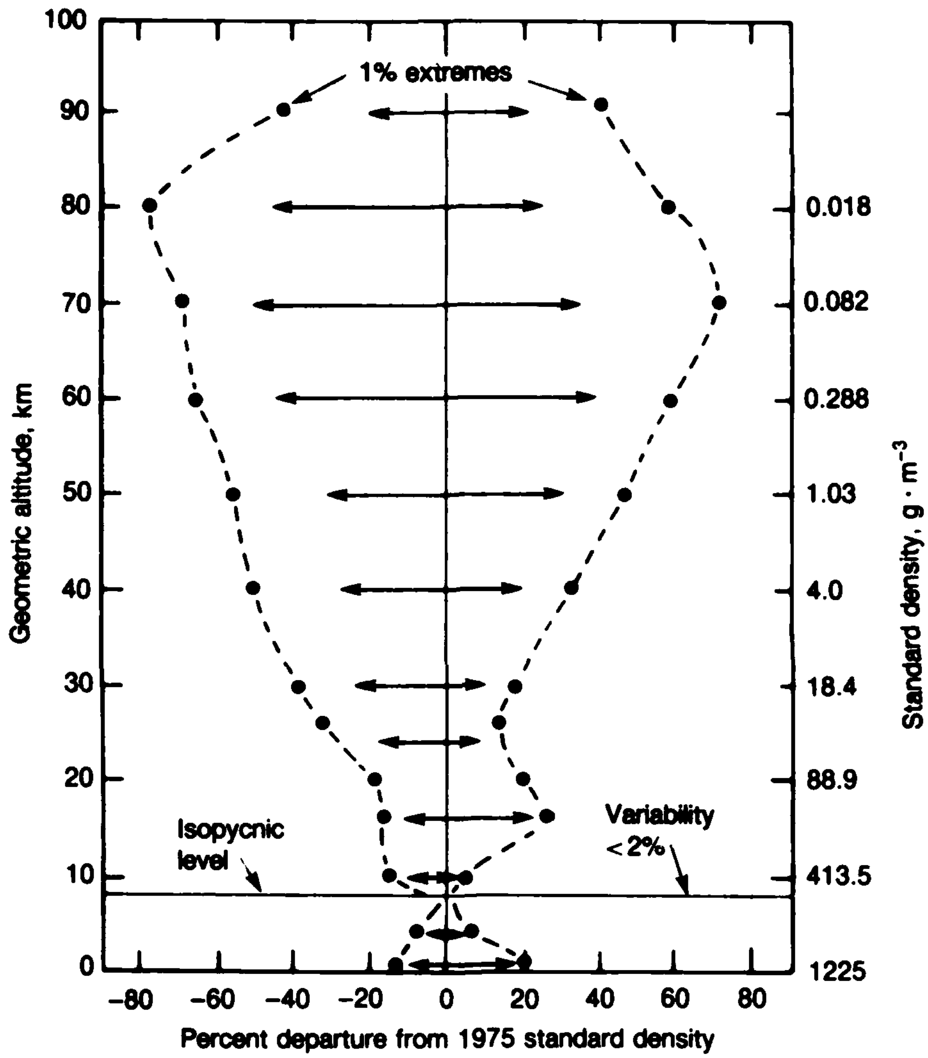


Fig. 2—Range of systematic variability of density around the U.S. standard atmosphere

Density varies not only with location and season, but also from day to day at each location. An indication of this kind of variability is shown in Table 3 [12], which shows standard deviations of departures from the monthly mean expressed as percent of the monthly mean.

Table 4, from the same source, shows the range, in percent, of mean monthly density.

Table 2

ATMOSPHERIC DENSITIES AS PERCENTAGE OF DENSITY AT CORRESPONDING HEIGHT IN U.S. STANDARD ATMOSPHERE, 1962

Height (km)	Standard (kg m^{-3})	January		
		60°	45°N	30°N
3.048	9.0477 -1	103 ± 5	102 ± 4	98 ± 2
6.096	6.5312 -1	100 ± 3	100 ± 2	100 ± 2
9.144	4.5904 -1	98 ± 5	100 ± 2	101 ± 1
12.192	3.0267 -1	91 ± 9	96 ± 9	105 ± 6
15.240	1.8756 -1	91 ± 6	97 ± 7	108 ± 6
18.288	1.1628 -1	90 ± 5	97 ± 5	105 ± 5
21.336	7.1742 -2	93 ± 4	98 ± 4	101 ± 3
24.384	4.4173 -2	93 ± 4	98 ± 4	98 ± 3
27.432	2.7392 -2	92 ± 5	97 ± 4	96 ± 4
30.480	1.7101 -2	89 ± 6	96 ± 6	96 ± 4
33.528	1.0647 -2	87 ± 6	95 ± 6	96 ± 5
36.576	6.6486 -3	85 ± 7	93 ± 7	97 ± 6
39.624	4.2213 -3	84 ± 8	92 ± 7	100 ± 7
42.672	2.7222 -3	82 ± 8	89 ± 8	100 ± 7
45.720	1.7811 -3	80 ± 9	89 ± 9	100 ± 8
48.768	1.1968 -3	76 ± 10	87 ± 9	100 ± 9
51.816	8.1948 -4	74 ± 10	87 ± 10	100 ± 9
54.864	5.6990 -4	72 ± 10	87 ± 10	100 ± 10
57.912	3.9506 -4	70 ± 10	87 ± 10	100 ± 10
60.960	2.7163 -4	69 ± 10	86 ± 10	100 ± 10

[continued]

Table 2 (continued)

Height (km)	Standard (kg m^{-3})	July		
		60°N	45°N	30°N
0	1.2250 +0[a]	100 ± 4	97 ± 3	95 ± 2
3.048	9.0477 -1	99 ± 2	98 ± 2	95 ± 1
6.096	6.5312 -1	97 ± 2	97 ± 2	97 ± 1
9.144	4.5904 -1	100 ± 3	100 ± 2	100 ± 1
12.192	3.0267 -1	97 ± 8	106 ± 5	107 ± 1
15.240	1.8756 -1	100 ± 5	108 ± 6	111 ± 3
18.288	1.1628 -1	102 ± 3	107 ± 3	110 ± 3
21.336	7.1742 -2	104 ± 2	106 ± 2	106 ± 2
24.384	4.4173 -2	106 ± 2	106 ± 2	104 ± 2
27.432	2.7392 -2	108 ± 2	107 ± 2	103 ± 2
30.480	1.7101 -2	108 ± 2	107 ± 2	104 ± 3
33.528	1.0647 -2	108 ± 3	109 ± 3	104 ± 3
36.576	6.6486 -3	110 ± 3	111 ± 3	106 ± 3
39.624	4.2213 -3	114 ± 3	114 ± 4	109 ± 4
42.672	2.7222 -3	116 ± 4	114 ± 4	111 ± 4
45.720	1.7811 -3	118 ± 4	116 ± 4	111 ± 5
48.768	1.1968 -3	120 ± 5	117 ± 5	111 ± 6
51.816	8.1948 -4	120 ± 6	119 ± 6	112 ± 7
54.864	5.6990 -4	122 ± 7	120 ± 7	112 ± 7
57.912	3.9506 -4	122 ± 8	123 ± 8	112 ± 8
60.960	2.7163 -4	124 ± 8	120 ± 8	111 ± 8

[a] Power of 10 by which number is multiplied.

Table 3

STANDARD DEVIATIONS OF OBSERVED DENSITIES AROUND THE MONTHLY MEAN AT WALLOPS ISLAND, 38°N

Altitude (km)	Density (% of Monthly Mean)			
	Jan	Apr	July	Oct
20	2.6	2.2	1.6	1.9
25	2.1	1.5	1.4	2.0
30	2.3	2.1	1.7	2.2
35	2.8	3.4	2.1	2.6
40	3.4	5.1	2.8	4.2
45	4.3	5.2	3.3	4.9
50	4.5	5.4	3.7	6.0
60	6.0	6.3	6.0	3.2
70	8.0	5.0	7.0	4.3
80	9.0	7.7	7.2	6.2

FORECASTING OF DENSITY

Because density is so variable with location and time as well as with latitude and season, use of a Standard Atmosphere or even of climatological means is not likely to be satisfactory. Even the most recent routine observation from the nearest NWS RAWIN station may not be good enough. And logistical problems may limit or preclude the use of observations on demand using local dedicated equipment. Hence the use of forecast values might be considered.

Density is not normally forecast by the NWP models of the NWS. Instead, the models turn out heights for various pressure levels, together with some temperature values, that can be mapped. The product that is disseminated to users consists of forecast height contours* on constant-pressure maps at 850, 700, 500, and 250 mb* (about 1.5, 3, 5.6, and 10.4 km, respectively.) The forecasts are valid at 12-hour intervals out to 72 hours from the time of observation. Temperatures are disseminated with the 12-hour winds-aloft forecasts for 3, 6, 9, 12,

Table 4

RANGE OF MEAN MONTHLY DENSITY AT DIFFERENT LATITUDES

Altitude (km)	30°N Mean Annual Density (kg m^{-3})	30°N Range (‰)	45°N Mean Annual Density (kg m^{-3})	45°N Range (‰)
10	4.1816 -1[a]	-0.7 to +0.8	4.1183 -1[a]	-1.3 to +1.2
20	9.3875 -2	-2.4 to +3.6	8.9751 -2	-4.5 to +5.1
30	1.8436 -2	-3.7 to +3.4	1.8500 -2	-5.2 to +6.2
40	4.1722 -3	-5.2 to +4.2	4.0473 -3	-9.5 to +10.5
50	1.1031 -3	-6.1 to +5.4	1.0573 -3	-14.0 to +13.2
60	3.2877 -4	-7.8 to +7.1	3.1601 -4	-16.9 to +16.7
70	8.7289 -5	-9.9 to +9.8	8.3932 -5	-18.4 to +20.7
80	1.8970 -5	-6.8 to +7.9	1.8898 -5	-13.7 to +18.9
90	3.6276 -6	-7.6 to +7.3	3.5888 -6	-8.7 to +12.7

[a]Power of 10 by which the number is multiplied.

18, 24, 30, 34, and 39 thousand feet. Temperature-pressure pairs for a given location, altitude, and time can be obtained by interpolation among these various forecast charts, and finally density can be obtained using the equation of state.

If done in the field using using the standard upper-air forecast products produced and disseminated by the NWS, the prediction of atmospheric density is a cumbersome, inefficient, and inaccurate process. However, it could be done much more expeditiously by the Global Weather Central (GWC) at Offutt AFB as a part of their package of user-oriented forecast products. GWC is capable of pulling out values of pressure and temperature valid at any given location, altitude, and time from their NWP models, and from these values, computation of density is a trivial task. Although this procedure would give far better results than could be obtained from the NWS standard output, any forecast procedure will introduce so much uncertainty that there would be no need to be concerned with observational accuracy. It is therefore questionable whether any use of current forecast densities would be at all satisfactory, especially if the valid time is long after the RAWIN observation times.

III. WIND, WIND SHEAR, AND TURBULENCE

The principal wind-related hazards to space launch and recovery are the dynamic effects of wind shear and turbulence on vehicle stability. In general, there are three major causes of highly disturbed wind fields:

1. Surface effects--a broad category of turbulence-inducing phenomena whose effects are generally, except for category (b) below, confined to the lowest kilometer or so of the atmosphere. These include (a) friction-induced turbulence near the ground in high-wind situations; (b) mountain-induced "waves," shears, and turbulence, often in the lee of orographic barriers; (c) accelerated and channeled downslope winds in rugged terrain, like the "Santa Ana" of Southern California, the "chinook" of the Rockies and the Cascades, and the "foehn" of the Alps; and (d) thermal turbulence over strongly heated surfaces, at times exacerbated by terrain.

These surface-effects phenomena are dominated by local geographic features, are fairly predictable in areas where they are known to occur, and, as far as we know, pose no significant threat to space launch and recovery facilities. They are, therefore, ignored in this Note.

2. Deep convection--thunderstorms and related severe weather phenomena, usually perceived as vertically developed cellular cloud systems embodying strong updrafts and downdrafts and associated wind shears and turbulence, all on relatively small space and time scales (a few tens of kilometers and tens of minutes per individual convective cell).

Convective storms are, indeed, a major threat to space launch and recovery operations: such operations would not be conducted if there were any significant risk of a convective cell encounter. These phenomena, however, also pose an enormous threat to aviation and to public safety in general, making convective storm detection and prediction very-high-priority capabilities of the weather services. These capabilities and future improvements are and will be applied in the space program. Recent disastrous "microburst" aircraft accidents related to low-level wind shear have generted a great deal of new interest and money to address the convective storm problem.

3. Vertical shear of horizontal winds aloft--the most common cause of "clear-air turbulence," and usually associated with large vector differences in horizontal winds over small vertical distances in the vicinity of high-altitude jet streams*. This type of disturbed upper-air wind field can extend over thousands of square miles and persist for hours over a given location.

Present-day capabilities for both measuring and predicting upper-level wind shear and turbulence are, respectively, poor and bad. Measurement of wind shear aloft currently depends on the accurate determination of strong winds at high altitudes every 12 hours at rawinsonde stations hundreds of miles apart. There are problems with both the instrumentation and the space-time resolution. Turbulence is not directly measured at all except by aircraft that encounter it. Neither can be reliably predicted, given such a poor base of observational data.

Our discussion of wind measurement and prediction will focus on the problem of upper-level wind shear and turbulence.

MEASUREMENT

The rawinsonde (a term derived from the combination of radiosonde* and radar or radio wind sounding techniques) is the standard method of obtaining pressure, temperature, humidity, and wind data from the surface to altitudes of about 30 km. The ascending radiosonde balloon and instrument package is tracked by radar or radio direction finder; wind vectors are determined geometrically (and automatically) from successive balloon positions and recorded for every minute of the balloon ascent. This set of wind calculations is known as a "RAWIN" observation. A sounding to 30 km altitude takes about 100 minutes to complete.

The troposphere is the region of the atmosphere where the combination of air density and spacecraft speed make potential wind shear and turbulence problems the most acute. Maximum wind shears most often occur near and just below the core of a jet stream, which in turn is usually located a few thousand meters below the tropopause*. Hence, such wind shears are normally found at altitudes of 6 to 12 km in regions of strong jet-stream winds.

Strong winds carry a sounding balloon rapidly away from the ground observing site, resulting in decreased accuracy in the radar tracking of the balloon as slant range increases. The very weather situation that breeds strong wind shear and turbulence, therefore, often makes accurate wind measurement more difficult.

The worst problem in wind-shear detection, however, is the low density of rawinsonde stations and the low frequency of observations. Figure 1 shows the locations of upper-air stations over the United States. Observations are made at 12-hour intervals, all stations launching their balloon-borne packages at about 1100Z and 2300Z (for their "1200Z" and "0000Z" observations). These data, collected worldwide, are transformed into upper-air analyses (synoptic maps*), as previously described. The large-scale jet streams and their wind speeds and, by inference therefrom, areas of potentially strong wind shear and turbulence are identified on these maps. In addition, the one-minute wind velocity data of the RAWIN observations are scrutinized by specialists whose main concern is the detection and prediction of hazardous wind conditions aloft.

Overall, the upper-air measurement and analysis system does as good a job as possible in detecting wind shears every 12 hours in a coarse spatial network of observations. This is a far cry from continuous monitoring or pinpoint detection.

Turbulence is not directly detected at all in this system. It is inferred as a probable result of wind shear. The only direct detection of turbulence is through pilot reports of chance aircraft encounters with turbulent air. These "PIREPs*" constitute an important additional source of information for aviation weather service specialists, but the frequency and location of such reports are uncontrollable and unpredictable.

FORECASTING

At present, winds aloft are operationally measured with the rawinsonde, as are temperature, humidity, and height of standard pressure surfaces. In the "free atmosphere"*, which lies above 1 or 1.5 km above ground, the winds are geostrophic*; in other words, they are parallel to the contours of constant-pressure charts and have speed inversely proportional to the spacing of the contours. Thus, winds aloft can be used in the analysis of the contour patterns of constant-pressure surfaces, and conversely, forecast contour patterns are used to infer the forecast winds aloft. The contours represent the changing pattern of "high"* and "low"* pressure systems.

In former times, analysis was done manually by plotting the observations on a map and visually interpolating among them. Now the process is completely automatic, with the raw data entering the computer from transmission lines and being processed numerically. The 12-hour prognostic chart prepared 12 hours previously is taken as a first guess and then modified in accordance with current observations. The analyzed charts are the basis from which the prognostic (forecast) charts are made. Analyses and forecasts are made at several levels in the free atmosphere, the lowest being 850 mb (about 1.5 km ASL*). Some other standard levels are 700 mb (about 3 km ASL), 500 mb (about 5.6 km ASL), and 250 mb (about 10.4 km ASL).

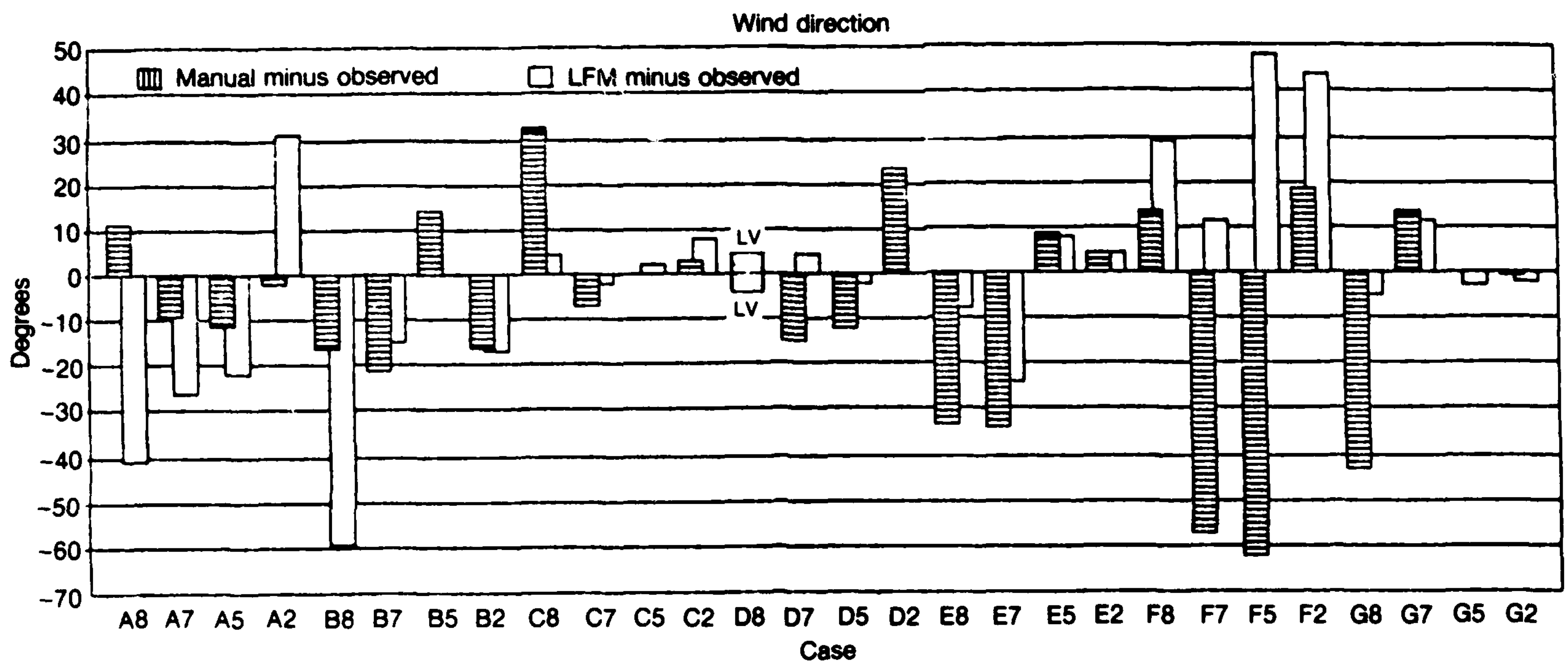
Again, in former times the process of prognosis was manual, consisting of extrapolation from a series of observations. Now, numerical weather prediction models are used to make the prognoses. Several different types of NWP models are in use, each having its own strengths and weaknesses. Depending on the synoptic* situation, one type of model is likely to be better than another, and the forecaster must make a considered choice among them. He may also use manual extrapolation in making his final decision. Three different NWP models are currently in use to forecast the contour patterns from which the winds can be inferred. They are:

1. LFM* with analysis and prognoses at 12-hour intervals out to 48 hours, at 850 mb, 700 mb, 500 mb, and 250 mb.
2. Barotropic* with analysis and prognoses at 12-hour intervals out to 48 hours, at 500 mb.
3. Baroclinic* with analysis and prognoses at 12-hour intervals out to 48 hours, at 500 mb and other levels.

The prediction of upper-air wind shear and turbulence (as distinguished from wind speed and direction) is currently highly subjective and follows two approaches. The first is a triply inferential approach in which horizontal wind speed and direction forecasts are inferred, as described above, from the direction and spacing of predicted height contours of constant-pressure surfaces in the upper air. Wind shear is then manually inferred from the vertical differences in the inferred wind fields, and turbulence is inferred from the magnitude of the inferred wind shear. The second approach is to monitor pilot reports for indications of turbulence, and, when turbulence is reported, issue advisories for possible turbulence encounters over areas of similar upper wind conditions. In practice, these two approaches are jointly employed.

The upper-wind forecast is, then, the basic ingredient of a wind shear and turbulence forecast. A recent case study compared the accuracies of the upper-wind forecast by numerical weather prediction and manual techniques [13]. Wind speed and direction were predicted for four constant-pressure levels in the atmosphere--850 mb, 700 mb, 500 mb, and 250 mb, corresponding approximately to altitudes of 1.5 km, 3 km, 5.6 km, and 10.4 km, respectively. Predictions were made for two days in summer, two in winter, and three in spring; the location was Pittsburgh, Pennsylvania. Although this sample is far from large enough for statistical inference, some results are presented here as an indication of the accuracies possible.

A summary of results from one NWP model (the limited-area fine mesh, or LFM, model) and the manual method is given in Figs. 3 and 4. Relevant results for the present study are the apparent increases in wind-speed prediction errors with increasing altitude and the larger wind-direction errors at the lower altitudes. Both types of error could reduce the accuracy of wind shear forecasts, but the high-altitude wind-speed errors are the more important in the present context because they are committed in the critical region for occurrence of severe clear-air turbulence.



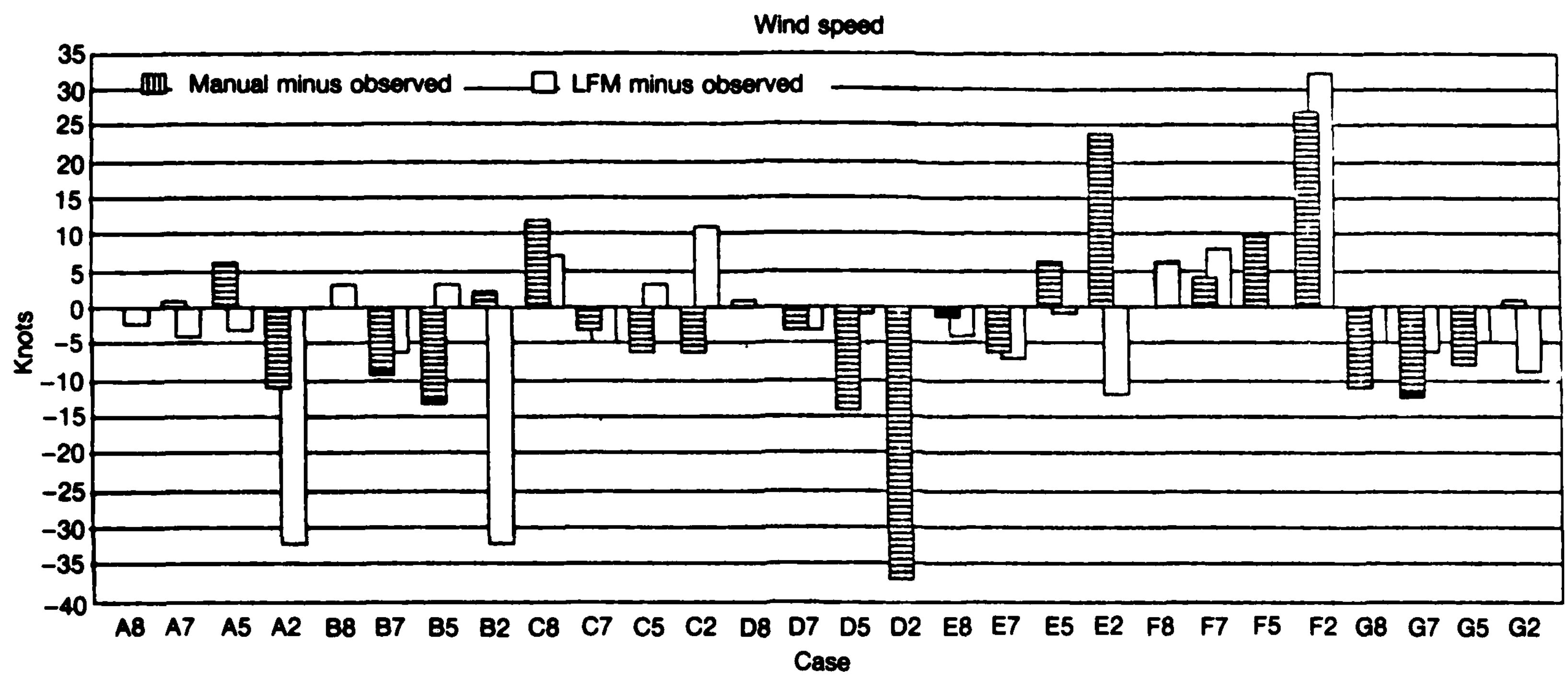
Key

A = 10 June 1982
B = 29 July 1982
C = 27 January 1983
D = 10 February 1983

E = 6April 1983
F = 19 April 1983
G = 27 April 1983
LV = Light variable

8 = 850 mb
7 = 700 mb
5 = 500 mb
2 = 250 mb

Fig. 3—Manual vs. LFM 12-hour wind direction errors
(departure from observed)



Key:

A = 10 June 1982	E = 6April 1983	8 = 850 mb
B = 29 July 1982	F = 19 April 1983	7 = 700 mb
C = 27 January 1983	G = 27 April 1983	5 = 500 mb
D = 10 February 1983	LV = Light, variable	2 = 250 mb

Fig. 4—Manual vs. LFM 12-hour wind speed errors
(departure from observed)

IV. RESEARCH

As mentioned in the Introduction, VAS, PROFILER, WINDSAT, and the new satellite sensors are in the test phase and, except for WINDSAT, may soon supplement current RAWIN data.

VAS

VAS data from the NOAA GOES weather satellites are used to automatically assign simultaneous heights and velocities to winds inferred by means of a cloud tracking system using CO_2 absorption [2]. Two important features of the VAS system are:

- CO_2 slicing, which enables accurate vector discrimination in multi-cloud layers by means of animated CO_2-channel imagery.
- CO_2 absorption, which uses the VAS CO_2-channel radiometric values to provide quantitative heights of cloud vectors.

The CO_2 slicing method uses sequences of half-hourly CO_2-channel images (spectral bands 3, 4, and 5 at 14.2, 14.0, and 13.3 μm) to track clouds at high (100-349 mb), middle (350 to 649 mb), and low (650 mb to ground) levels. Good agreement with RAWIN data at 200, 400, and 700 mb was found. Also, the CO_2 heights were found to be reliable within about 50 mb rms* deviation from other available height determinations.

Since VAS wind data are dependent on the existence of clouds, their areal coverage will be somewhat limited and variable, and their vertical resolution will be poor, determined by the vertical distribution of clouds. Hence, VAS measurements will rarely directly detect strong wind shears and turbulence. Their greatest value, not to be underestimated, will be in supplementing the global rawinsonde network over the vast data-sparse regions.

PROFILER

The ground-based PROFILER is a new NOAA device for measuring wind, temperature, and moisture aloft that will become operational through the midwest in 1989 [14]. This automated system provides accurate high-temporal-resolution data that promise to have a major impact on real-time and forecast information for ground-to-space operations.

A complete PROFILER consists of two parts. The wind profiler uses clear-air Doppler radar for measuring winds. The thermodynamic profiler employs passive radiometers for deriving temperature and moisture [3].

Wind Profiling

Natural atmospheric turbulence produces a spatial spectrum of variability of the atmosphere's temperature and moisture fields. These variations of temperature and humidity result in a refractive-index change that scatters a portion of an incident electromagnetic wave. Some of this energy is received at the original point of transmission and will be Doppler shifted in proportion to the radial component of the wind velocity in the scattering volume.

Height coverage of the wind profiler is a function of wavelength for a given radar sensitivity. For example, the higher-frequency (10-cm wavelength) radars appear to be effective clear-air wind-measuring devices only within the earth's turbulent boundary layer (up to 3 km). On the other hand, the low-frequency (6-m wavelength) systems show good results to altitudes of between 17 and 20 km.

Most wind profilers are monostatic; i.e., transmitter and receiver use a single antenna. Thus the measured Doppler shift is along the radar beam and represents only one component of the total wind. The simplest wind profilers project one beam 15° off vertical and a second beam 15° off vertical in an orthogonal plane. Under the assumption of no vertical velocity, the radial components measured along these two beams can be rotated to the horizontal and combined to give horizontal wind speed and direction of good quality if averaged for one hour. Greater temporal resolution (about 30 minutes) can be provided by three or more beams per system. A three-beam wind profiler is fully adequate for the vast majority of practical applications and can be confidently used.

Thermodynamic Profiling

Passive radiometric techniques are used in the thermodynamic profiler, which provides basic measurements of temperature and moisture, as opposed to the active radar employed in the wind profiler. The atmosphere radiates at every altitude as a function of temperature and moisture content. Some of this energy can be detected by passive radiometers whose output is quantitatively expressed as "brightness" temperatures. Because the atmosphere has different temperatures at different altitudes, and because radiometer frequencies can be selected to emphasize the emitted radiation from a limited range of altitudes, a multi-frequency radiometeric system can be used to infer good estimates of true temperature profiles.

Temperature profiles from satellites are derived in a similar manner from information collected by radiometers that operate at infrared and microwave frequencies. Only microwave radiometers are now used for the thermodynamic profiler. Frequencies between 50 and 60 GHz* are used for temperature profiling and frequencies between 20 and 30 GHz for moisture measurements.

The PROFILER has the potential for detecting a number of parameters that are not measured routinely. For example, present temperature sounding systems do not provide a direct readout of density or of total liquid water and total water vapor. The true power of this new technique does not, however, lie with its promise of detecting hitherto unmeasured parameters. Rather, its advantage is in making routine wind, temperature, and moisture measurements continuously and automatically. Data from a PROFILER network added to the synoptic-scale data now taken only twice per day by RAWINs should constitute a major step toward the desired highly reliable short-range (2 to 12 hour) weather forecasts necessary for ground-to-space operations. The installation and use of a dedicated PROFILER at each space launch and recovery site would be particularly advantageous [4].

WINDSAT

WINDSAT is the newest measuring concept, and it is the furthest from realization. It is a satellite-borne lidar* (laser radar) device that uses as targets natural aerosols carried by the wind. The system scans conically about the nadir as the platform (space shuttle or polar-orbiting weather satellite) moves in orbit. A given volume of space is interrogated many times from widely separated viewing angles, allowing representative along-track and across-track velocity vectors to be determined. Average velocity profiles can thus be generated for each given volume over the entire globe. Global coverage is achieved by choosing different orbital and conical scan parameters and by using different angles to measure the total wind vector.

WINDSAT is a pulsed CO_2 coherent lidar* system. It includes a very stable single-frequency CO_2 TEA (transverse excited atmospheric) laser, an interferometer, transmit-receive optics with appropriate scanning, an IR detector, a velocity-frequency analyzer, and a data processer and display [5]. The laser beam is directed to the point of interest in the atmosphere. Aerosol particles in the earth's atmosphere scatter some of the transmitted radiation in all directions. Since the particles move with the wind, the frequency of the backscattered light is Doppler shifted from the frequency of the transmitted beam. Receiving optics collect the backscattered radiation, which is coherently detected by an IR detector. The detector output contains a beat frequency that is a measure of the radial component of the wind velocity at the point of interest [5].

The Wave Propagation Laboratory studies analyzed the feasibility of obtaining wind measurements from satellites in circular orbits of 300 km and 800 km altitude. Analysis of simulated performance resulted in the conclusion that it is indeed feasible to measure the global wind field using a satellite-borne pulsed coherent lidar. The National Academy of Science Select Committee on the NWS concluded that WINDSAT is the only concept now in sight that promises to provide truly global wind coverage for operational use in the future [5].

In a special study [6], wind fields were measured from the planetary boundary layer* to the lower stratosphere using the NOAA pulsed infrared (CO_2) Doppler lidar and compared with the results of measurements by sonic anemometers on a 300-m tower, RAWINs, Jimspheres, and a PROFILER. The results show that when a backscatter signal exceeds the lidar system noise by 10 dB, wind measurement is accurate to within a small fraction of a meter per second.

SATELLITES

Several new developments in the next generation of polar-orbiting and GOES weather satellites will also be of primary importance in ground-to-space operations [13].

The next generation of atmospheric soundings from polar- orbiting satellites (aboard NOAA-K, -L, and -M in 1990 through 1992) will be accomplished with an Advanced Microwave Sounding Unit (AMSU*). The satellites will provide the first all-weather temperature soundings from space with an accuracy equivalent to that achieved in clear air today (within 2°C of radiosonde* measurements). Such soundings through clouds will enable much improved analyses and should lead to better forecasts in the active regions of the atmosphere. The AMSU will also provide improved water vapor measurements for three layers of the atmosphere, estimates of precipitation, and even estimates of soil moisture and liquid-water content of the snow pack.

The next geostationary satellites (GOES-NEXT, to fly in 1989) will carry a simultaneous imaging and sounding capability. The images will be accurately registered to the ground to further improve their utility in studying mesoscale* weather phenomena. The soundings, while more sensitive to cloud interference than those from the next-generation polar-orbiting satellites, will be available at all times of the day, not just twice a day as with the polar orbiter. A new 1000-spectral-channel High-resolution Interferometer Sounder (HIS*) is also under development for future GOES. This instrument, which has already been tested on high-altitude aircraft, will enable vertical temperature and moisture soundings to be achieved with greatly improved vertical resolution.

High data rates and the need to combine data from several sources will drive NOAA to new communication techniques and new data management schemes. Management of vast quantities of data for weather forecasting and scientific purposes will be among NOAA's greatest future challenges.

OTHER FUTURE EXPECTATIONS

Forecast inputs from VAS, PROFILER, WINDSAT, and the new satellites were highlighted in this brief Note because of questions recently raised within Project AIR FORCE. These "systems" are only part of a major revolution now taking place in operational meteorology. Historically, two of the biggest barriers to better weather forecasts have been an insufficiency of atmospheric data and an inability to process data fast enough. But automatic measurement systems like those discussed and supercomputers like the Cray and the Cyber 205 are rapidly changing things. For example, Beran [3] discussed a possible network of PROFILERS for automatically detecting and tracking storms approaching a launch pad.

Graff [15], from an interview with Dr. Alexander E. McDonald, Director of NOAA's Program for Regional Observing and Forecasting Services (PROFS*), discusses automatic "mesoscale" sensing and forecasting techniques, which makes the authors, as two old weather forecasters, stare with envy. The PROFS test area is a region 125 miles in diameter centered at Boulder, Colorado. Twenty-two ground-based automated weather stations have been scattered throughout the region. At each station, instruments measure wind speed and direction, temperature, pressure, dew point, and solar radiation. Every 10 seconds a microprocessor transmits the data from the sensors to a central facility in Boulder. This network is supplemented by the new Doppler radar and lightning detection systems as well as by data from GOES. PROFS also receives the scheduled transmissions of surface and RAWIN data for the entire western United States.

The resulting mass of data is sorted out by computer and presented as color-enhanced images for the area or as graphics indicating wind, temperature, and moisture at each of the 22 ground-based stations. Since these displays are available virtually in real time, a forecasting meteorologist can follow the movement of storm cells on the screen and can extrapolate where the storms are heading. This enables him to issue warnings of severe local storms up to 30 minutes in advance.

The NWS has plans to deploy 113 short-range forecasting systems very similar to the experimental PROFS all around the country in the 1990s. The net result should be a dramatic improvement in the accuracy of launch-pad short-range (2 to 12 hours) forecasts, especially when nearly continuous upper-air data from PROFILER and GOES-NEXT are added and more powerful computers are used for analysis in operational systems.

V. CONCLUSION

Our discussion has given some insight into the present and (to the meteorologist) exciting new sensing and forecasting capabilities being sponsored by NOAA. Their VAS, PROFILER, and new satellite sensors are well past the drawing board and have been supplementing RAWINs as the source of wind and density measurements since 1982. WINDSAT is close to becoming useful.

At present, upper-air forecasts are hampered by the timing and infrequency of RAWINs as well as by their limited global number. Oceanic areas and sparsely populated land areas are hardly covered at all.

The new wind, temperature, pressure/height, and moisture sensing capabilities of VAS, PROFILER, WINDSAT, and the next generation of weather satellites will help answer the resolution question. These state-of-the-art systems have the ability potentially to feed continuous and automatic wind and density information at all levels of a fine-mesh global grid directly into weather centers and NWP models, greatly improving the data base from which the forecasts are developed. High-resolution wind data are particularly important. A recent report of the National Academy of Sciences Select Committee on NWS [5] concluded that "there is a consensus among modelers, whether doing operational forecasting or research, that wind information is critical to continued improvement in forecasting."

Because this kind of data set has never before been available, NOAA has been hampered in its efforts to develop and test highly reliable mesoscale models. Once the network is in place and operating, this kind of numerical weather prediction research could begin in earnest, with the hope that the desired very accurate short-range (2 to 12 hours) forecast would evolve [3].

Appendix

DEFINITIONS AND ACRONYMS

AMSU - Advanced Microwave Sounding Unit

ASL - Above sea level

barotropic and baroclinic models - Numerical models used for predicting pressure-height distribution on a global scale. The barotropic model considers the atmosphere as a single layer, whereas the baroclinic model has many layers and can also predict temperature distribution.

constant-pressure chart (or **map**) - A map showing the distribution of the height of a specified pressure level at a given time. Point data may be plotted on the map, and contours of equal height are drawn to delineate the constant-pressure surface*.

constant-pressure surface - A surface along which the atmospheric pressure is everywhere equal at a given time.

contour - A curve drawn on a map connecting points of equal height of some property; an isopleth* of height.

Coriolis acceleration - The apparent acceleration of a body or parcel of air moving inertially in a fixed frame of reference when viewed from a rotating frame, such as the surface of the earth.

DMSP - Defense Meteorological Satellite Program

Ekman layer - The layer of transition between the surface boundary layer, where the shearing stress is constant, and the free atmosphere, where the atmosphere is treated as an ideal fluid in geostrophic* equilibrium.

ERL - Environmental Research Laboratories, an agency of NOAA*

free atmosphere - That portion of the earth's atmosphere, above the planetary boundary layer*, in which the effect of the earth's surface friction on the air motion is negligible, and in which the air is usually treated (dynamically) as an ideal fluid. The base of the free atmosphere is usually taken as the geostrophic wind* level.

geostrophic balance - A state of the atmosphere in which the actual wind has the same direction and speed as the geostrophic wind*.

geostrophic wind - That horizontal wind velocity for which the Coriolis acceleration* exactly balances the horizontal pressure force. The geostrophic wind is thus directed along the contour lines on a constant-pressure surface*, with low elevation to the left in the Northern Hemisphere. The geostrophic wind is usually taken to be a good approximation to the actual wind in the free atmosphere*, particularly in middle and high latitudes, but in some contexts, this is not a good assumption.

GHz - Gigahertz (10^9 cycles per second)

GOES - Geosynchronous Operational Environmental Satellite. A meteorological satellite that observes clouds and other atmospheric phenomena from a point in space that is fixed relative to the surface of the earth.

GOES-NEXT - The new version of GOES* now being developed

GWC - Global Weather Central

high - In meteorology, elliptical for "area of high pressure," referring to a relative maximum (in two dimensions) of atmospheric pressure (closed isobars) on a surface-level chart, or to a maximum of height (closed contours) on a constant-pressure chart*. The term is used interchangeably with "anticyclone".

HIS - High-resolution Interferometer Sounder

isopleth - A curve on a chart representing equal values of some property. A contour is an isopleth of height; an isobar is an isopleth of pressure; an isotherm is an isopleth of temperature; an isopycnic is an isopleth of density; an isogon is an isopleth of wind direction; and an isotach is an isopleth of wind speed.

jet stream - Relatively strong winds concentrated within a narrow stream in the atmosphere. Specifically, a quasi-horizontal band of maximum winds imbedded in the mid-latitude westerlies and concentrated in the high troposphere*.

Jimsphere - A roughened radar-reflective balloon two meters in diameter, developed by NASA's Marshall Space Flight Center to measure wind shear that might affect spacecraft launches.

LFM - Limited-area Fine Mesh prognostic chart*. It is a refinement of the primitive-equation baroclinic* numerical weather prediction model and is designed to produce higher resolution in areas of particular interest.

lidar - A ranging device that operates on the same principle as radar, but at optical or infrared frequencies, using a beam generated by a pulsed laser.

low - In meteorology, elliptical for "area of low pressure," referring to a relative minimum (in two dimensions) of atmospheric pressure (closed isobars) on a surface-level chart, or to a minimum of height (closed contours) on a constant-pressure chart*. The term is used interchangeably with "cyclone". It is sometimes called a "depression".

mesoscale - A scale of atmospheric phenomena and processes with horizontal extent from about 10 km to about 1000 km. It lies between the microscale and the synoptic scale*.

mb - Abbreviation for **millibar**, a unit of pressure customarily used in meteorology; equal to 100 Pascal. Standard sea-level pressure is 1013.25 mb or 101,325 Pa.

NOAA - National Oceanic and Atmospheric Administration

NWP - Numerical Weather Prediction. The process of solving the hydrodynamic and thermodynamic equations that govern the state and motion of the atmosphere using numerical methods in order to forecast the future condition of the atmosphere. The term is slightly misleading in that pressure, temperature, humidity, and winds are forecast, not "weather" per se.

NWS - National Weather Service. The branch of NOAA* formerly known as the "Weather Bureau."

PIREP - (PIlot REPort.) A report of meteorological conditions encountered by an air crew in flight.

planetary boundary layer - (Also called friction layer, atmospheric boundary layer.) That layer of the atmosphere from the earth's surface to the geostrophic wind* level, including the surface boundary layer* and the Ekman layer*. Above this layer lies the free atmosphere*.

PROFILER - A ground-based device for measuring wind, temperature, and moisture aloft, using Doppler radar and passive radiometers.

PROFS - Program for Regional Observing and Forecasting Services

prognostic chart or **map** - A map showing conditions forecast to oc at a specified future time. In particular, a map showing the expected height pattern of a given synoptic chart* at a specified valid time.

radiosonde - A device containing sensors for atmospheric pressure, temperature, and humidity, together with a radio telemetering system. It is sent aloft by balloon, and the data from it are received and processed at a ground station.

RAOB - (RAdiosonde OBservation.) An evaluation in terms of temperature, relative humidity, and pressure aloft of radio signals received from a balloon-borne radiosonde*. The height of each mandatory and significant pressure level of the atmosphere is computed from these data.

RAWIN - A method of winds-aloft observation; that is, the determination of wind speed and direction at many levels above the station. It is accomplished by tracking a balloon-borne target by radar or radio direction-finder. The term is frequently used to indicate the set of data produced by a rawinsonde*.

rawinsonde - A method of upper-air observation combining the radiosonde* and the RAWIN*. The wind speed and direction, temperature, pressure, and relative humidity are determined by tracking a balloon-borne radiosonde by radar or radio direction finder.

rms - Root mean square

stratosphere - The atmospheric shell above the troposphere* and below the mesosphere. It extends from the tropopause* to the level (about 20 to 25 km) where the temperature begins to increase with height. It is characterized by great stability with respect to vertical displacement.

surface boundary layer - (Also called surface layer, friction layer, atmospheric boundary layer, ground layer.) That thin layer of air adjacent to the earth's surface, extending up to the so-called anemometer level (the base of the Ekman layer*). Within this layer the wind distribution is largely determined by the vertical temperature gradient and the nature and contours of the underlying surface; shearing stresses are approximately constant.

synoptic - In general, pertaining to or affording an overall view. In meteorology, this term has become somewhat specialized in referring to the use of meteorological data obtained simultaneously over a wide area for the purpose of presenting a comprehensive and nearly instantaneous picture of the state of the atmosphere.

synoptic chart or **map** - A meteorological chart on which all data refer to a single specific time.

synoptic scale - A scale of atmospheric processes and phenomena with horizontal extent greater than about 1000 km.

synoptic time - A specific time of day at which by international agreement weather observations are made simultaneously everywhere. The standard synoptic times for upper-air observations are 0000Z and 1200Z.

tropopause - The boundary between the troposphere* and the stratosphere*. It varies from about 8 km altitude in the polar regions to 15 km in the tropics, and it also varies with the seasons. It is usually characterized by an abrupt change in lapse rate, that is, the rate of change of temperature with height.

troposphere - That portion of the earth's atmosphere from the earth's surface to the tropopause; roughly the lowest 10 to 20 km of the atmosphere. It is characterized by decreasing temperature with height, appreciable vertical wind motion, appreciable moisture content, and weather.

U.S. Standard Atmosphere - A hypothetical vertical distribution of atmospheric temperature, pressure, and density which, by agreement, is taken to be representative of the atmosphere for purposes of pressure altimeter calibration, aircraft performance calculations, aircraft and missile design, ballistic tables, and so forth.

VAS - VISSR* Atmospheric Sounder

VISSR - Visible Infrared Spin-Scan Radiometer

WINDSAT - A satellite-borne lidar (laser radar) device for measuring winds

WPL - Wave Propagation Laboratory

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