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WEATHER ASSESSMENT AND FORECASTING

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16. ABSTRACT

In FY-77 the Marshall Space Flight Center Data Management Program activities centered around the analyses of selected far-term Office of Applications (OA) objectives, with the intent of determining if significant data-related problems would be encountered and if so what alternative solutions would be possible. Three far-term (1985 and beyond) OA objectives selected for analyses as having potential significant data problems were Large-Scale Weather Forecasting, Local Weather and Severe Storms Forecasting, and Global Marine Weather Forecasting. MSFC Data Management personnel scheduled overview analyses of these objectives in FY-77 -- primarily as fact-finding studies to allow MSFC to gain adequate background information to perform subsequent data system analyses. ECOsystems International, Incorporated, provided a significant part of this background information. The first part of this report, "Weather Assessment and Forecasting," by ECOsystems presents an overview of general weather forecasting activities and their implications upon the ground based data system. The second part of this report describes selected topics specifically oriented to the use of satellites (e.g., Vertical Temperature Profiling of the Atmosphere from Satellites).

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WEATHER ASSESSMENT AND FORECASTING

Purpose

The objective of meteorological activities is to predict the atmospheric parameters which influence human activities with maximum precision, as far in the future as possible and over as many areas as are of interest.

The objectives include the general weather forecasts, the prediction of severe storms and warning of their impact, forecast of weather over the seas, several specialized forecasts. The differing set of ultimate users, their diverse geographic location, and the different techniques currently employed bring about the specialization of weather forecasting into distinct "Services." Nevertheless, these apparently diverse activities are highly interrelated. For one, all use as a basis the Large Scale Weather Forecasting, also known as Basic Meteorological Service. On the other hand, the Basic Service uses as inputs several of the data gathered by the specialized activities.

In addition, the science of meteorology is fostered by a significant research activity, whose fruits eventually enter the main stream of operational services: some of the data gathered by research activities are also used as inputs by operational services.

Because of this high degree of interrelationship, it is best to present the "weather picture" in its entirety; the separate roles of important specialized services, such as Marine Weather and Severe Storm Warning and Forecast, will then acquire their proper perspective, meaning and scale.

Overview of Currently Operational Meteorological Services

The functional subdivision of the weather forecast field is:

- o Basic Meteorological Services
- o Function-oriented Services
  - Aviation
  - Marine
  - Severe storms
  - Agriculture
  - Forestry (Fire Weather)
  - Military
  - Atmospheric pollution
  - Other

Figure 1 depicts their interrelationships.

The objectives of the Basic Meteorological Services are to: a) provide uniform weather forecasts to the public; b) provide the data and information base for the Function-oriented Services. Thus, the Basic Meteo Service underlies the entire structure of weather forecasting. In the U.S. civilian sector basic meteo services are provided operationally by the National Weather Service of NOAA. In the U.S. military sector, by the Air Force Global Weather Central (AFGWC), Offutt AFB, Neb., and the Fleet Numerical Weather Center, (FNWC), Monterey, California.

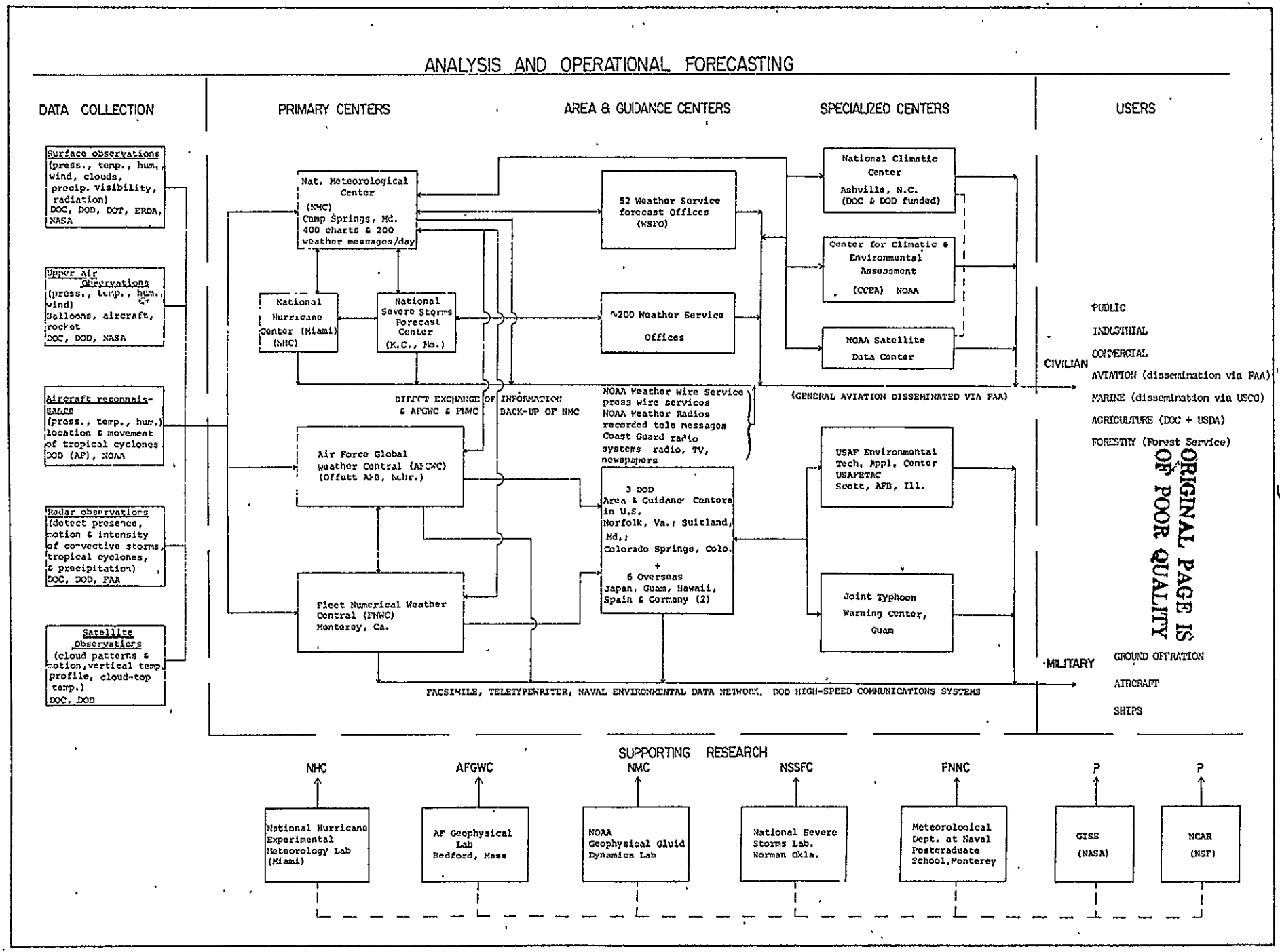
The principal U.S. Function-Oriented services (also known as "Specialized Services") are categorized following by title, function, responsibilities and cognizant agency:

- Aviation Meteorological Service

  Supplies current and forecasted weather information to pilots, dispatchers, air traffic controllers.

  Subfunctions and responsibilities:

FIGURE 1 INTERRELATIONS BETWEEN METEOROLOGICAL ACTIVITIES



ORIGINAL PAGE IS OF POOR QUALITY

= Provision of basic met-service-DOC/NOAA

= Dissemination of information to users - DOT/FAA

= Supply of information to global military aviation - DOD/USAF

- Marine Meteo Service

Supplies current and forecasted weather information to ship's captains, port authorities, ship routing dispatchers.

Subfunctions and responsibilities:

= Provision of basic met-service; issuance of forecasts and warnings; dissemination of information - DOC/NOAA

= Collection of weather data; dissemination of warnings - DOT/U.S. Coast Guard

= Provision of marine met. information to military forces; cooperative gathering of data from ships and coastal installations; provision of data and information to other agencies interested in maritime service - DOD/U.S. Navy

- Agricultural Meteo Services

Supplies current and forecasted weather information and warnings of weather events affecting crops

Subfunctions and responsibilities:

= Provision of specialized observations (frost); issuance of forecasts; provision of advisories; dissemination of warnings; assessment of impact of weather and climate on agriproduction - DOC/NOAA and USDA.

- Forestry Meteo Services

Supplies current and forecasted weather-affected indices of propensity to fire.

Subfunctions and responsibilities:

= Gathering of data; generation of advisories and warnings for fire weather - DOC/NOAA, USDA/FS, DOI/Bureau of Land Management.

- Severe Storms Warning

Provides forecast and warning of potentially damaging weather events

Subfunctions and responsibilities:

= Gathering of data; generation of severe storm warnings - DOC/National Severe Storm Forecast Center

= Gathering of data; generation of hurricane advisories - DOC/ National Hurricane Center

= Gathering of data; generation of forecasts and advisories of major storms -DOC /Joint Typhoon Warning Center

- Military Meteorological Service

  Provides weather information as required by the tactical and strategic needs of the U.S. military forces.

  Subfunctions and responsibilities:

  Gathering of data; exchange of data with other agencies; development of forecasts and advisories, world-wide - DOD/AFGWC, DOD/FNWC

- Other Specialized Services

  = Air Pollution Potential Warning - DOC/NOAA

  = Air Pollution Monitoring - EPA, State, Local Governments

  = Weather advisories to plan and conduct space launches - DOC for NASA

  = Weather and climate forecasts for major civil projects - DOD/U.S. Corps of Engineers

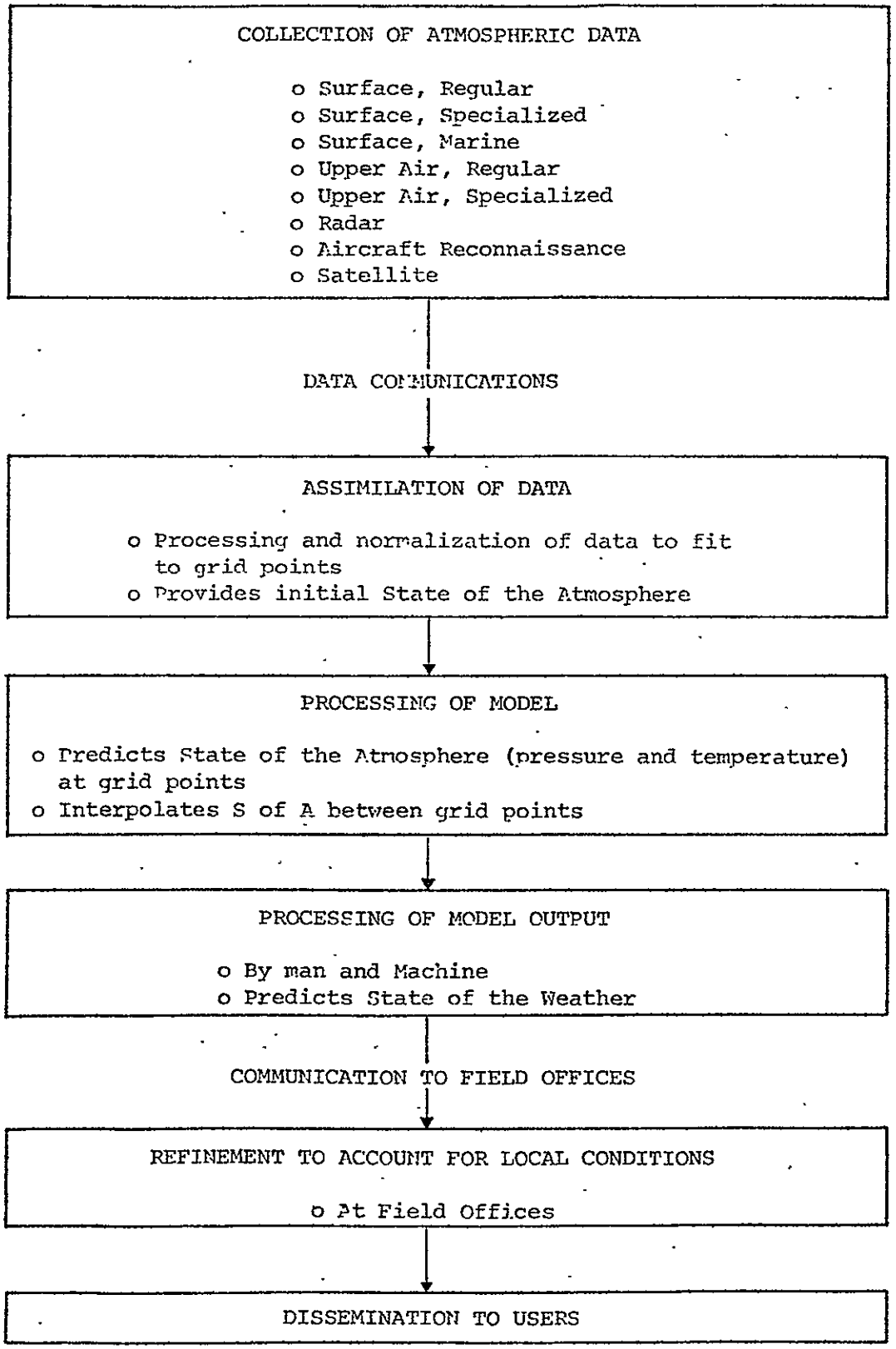
  = Weather synopses and forecasts for energy consumption - ERDA

The process underlying weather forecasts is presented schematically in Figure 2. The next section addresses the components of the process;

- Gathering of atmospheric data
- Transfer of this data to analysis locations (data communications)
- Extraction of information from the data, by generation of analyses (synopses of current situation) and forecasts (prediction of future situation)
- Dissemination of the information to users
- Archiving of the information for ready retrieval

FIGURE 2

SCHEMATIC DEPICTION OF BASIC WEATHER SERVICE (GLOBAL FORECAST)



The Data Gathering Function

Data gathering activities are divided into the following categories:

- Surface Observations
- Upper Air Observations
- Aircraft Reconnaissance Observations
- Radar Observations
- Satellite Observations

Surface Observations

The observed parameters are:

Pressure

Temperature

Humidity

Wind speed and direction

Cloud coverage and type

Precipitation

Visibility

Solar radiation

Surface observations are collected by five "networks:"

1) Regular observations to support basic and specialized meteorological services are taken by DOC, DOD, DOT, ERDA and NASA at approximately 1,400 land locations.

2) Specialized observations are taken for NOAA by citizen volunteers to support climatological needs.

3) Specialized observations are taken by employees of USDA and DOI to support agriculture and forestry needs. These two specialized networks together comprise approximately 13,000 stations.

4) Marine surface observations are gathered from ships at sea. More than 2,500 vessels of the merchant fleet provide cooperative observations in a program operated by DOC. DOT's Coast Guard operates 82 ships and 190 shore and island stations, including the Ocean Weather Station HOTEL located off the U.S. East Coast for which DOC provides the meteorological staff. Marine surface observations are also routinely taken by DOD Vessels. At most of the marine stations, the additional observable of sea state is included.

Some of the observing stations are designated as *benchmark* stations. They provide especially detailed observations to establish a reliable record for early detection of climatic fluctuations and trends.

5) Dense networks of surface observing stations are established occasionally to support small-scale meteorological research. Some of their data are used to support the Basic Meteo Service. Currently, the principal networks are:

DOC's network near Normal, Okla., supporting the National Severe Storms Laboratory.

EPA's network around St. Louis, Mo., supporting air pollution research.

DOD's network at the Air Force Geophysical Laboratory, Bedford, Mass., in support of small-scale meteorological research.

Upper Air Observations

The observed parameters are:

Pressure

Temperature

Humidity

Wind

They are measured from balloon, aircraft, or rocket platforms.

Data from the upper air observing network provide the basic input to numerical analysis and forecasting. Their principal sources are:

DOC supports or operates 120 U.S. and overseas stations.

DOD operates 42 fixed and shipboard stations, plus nine mobile stations. These support special DOD projects, but are deployed also, within assigned mission priorities and capabilities, to support other Agencies' programs.

Upper Air observations are also available from NASA's Marshall Space Flight Center: they are added to the basic network during severe weather situations.

DOC makes special upper air soundings to three kilometers at seven locations in support of air pollution responsibilities of the EPA. These soundings are too abbreviated to be of much use in large-scale analysis and forecasting, but are distributed over the Service C network for use in local forecasting, especially for severe storm warnings.

NASA and DOD use rocketsondes to obtain temperature and wind measurements from 30 to 100 kilometers at 13 locations in North and Central American and the surrounding ocean areas. These data support special high-altitude operations and contribute significantly to improving scientific knowledge of the outer atmosphere.

Aircraft Reconnaissance Observations

The observed parameters are:

Pressure

Temperature

Humidity

They are measured by dropsonde between flight level and the surface at a few points along the flight path. Primary performer is DOD.

DOD's aircraft reconnaissance program provides valuable fill-in data from large areas of the oceans where island and ship observations are scarce. Its major objective is to obtain precise information on the location, movement, and physical characteristics of tropical cyclones in the western Atlantic, Caribbean, Gulf of Mexico, and the Pacific; and of winter storms off the U.S. east coast. Aircraft reconnaissance is requested only after a thorough evaluation of other data sources (satellites, radar, and ground stations) indicates that additional information from an aircraft mission is essential to the protection of U.S. lives and property.

Operational aerial weather reconnaissance is accomplished by a fleet of 20 USAF WC-130s.

Special flights also are conducted by the Air Force to support meteorological research programs. On occasion aircraft of NOAA's Research Facilities Center perform reconnaissance in the North Atlantic, Caribbean, and Gulf of Mexico, although these are normally operated for support of research programs. In early 1977, an USAF WC-130 containing special reconnaissance equipment was loaned to NOAA to augment its research program.

Radar Observations

The observed parameters are:

= Detection of presence of convective storms and tropical cyclones

= Their motion

= Their intensity

= Amount of precipitation

These are used for: short-term warnings of severe weather (that contribute heavily to saving lives and property in many areas of the Nation); remote identification and tracking of squall lines, tornadoes, and other destructive storms; estimating the precipitation rates and amounts for use in flash-flood warnings and in managing water resources.

Radar observations contribute to the Basic Meteorological Service by measuring the intensity and motion of large areas of precipitation. In the specified role of detector and tracker of small-scale severe weather phenomena, radar observations are passed rapidly in a dedicated communications network to those who need to take quick action to avert a disaster.

The Basic Weather Radar Network uses DOC's and certain DOD radars. In the Western Mountain States air traffic control radars of the FAA supply observations in locations where normal weather radar units would be very expensive to install and operate.

Satellite Observations

The observations performed by metsats are:

Cloud patterns

Cloud motion

Cloud-top temperatures

Vertical temperature profiles of the atmosphere

Relay of remote observations (DCS)

The Defense Meteorological Satellite Program (DMSP) managed by the USAF, is an operational polar-orbiting system capable of obtaining high-resolution meteorological data under low light level conditions. DMSP acquires data essential to satisfy special military requirements: its data are also available to NOAA for operational applications as required. NOAA archives some of these data and makes them available to the national and international meteorological community for use in research and studies.

The weather satellites of DOC/NOAA and DOD provide cloud photos of the globe, and information on the three-dimensional temperature structure of the atmosphere. These partially satisfy civilian and military requirements for upper air data over the remote ocean areas. The Geostationary Operational Environmental Satellite (GOES) series provide near continuous high resolution surveillance of the birth and growth of hurricanes and major storms as well as of other weather events over the U.S. and the adjacent waters.

GOES also provides the capability to collect and relay data from remote observing platforms relay of facsimile products, and determination of upper-level winds from cloud-top motions.

Over the last decade, satellites have provided increasing amounts of significant data for meteorological and oceanographic analysis and forecasting, and information on severe weather.

The Information Extraction Function

It is useful to address this function before that of data communications, to make clearer what data are relayed where. Specifically, this section addresses *what* functions are performed by the principal players in meteorology. The methods of extraction, or *how* these functions are performed are presented later.

The extraction of information is performed at the Analysis and Forecast Centers and Offices.

These are of three major types: Primary Centers, Area and Guidance Centers, and Specialized Centers. (See Figure 1)

Primary Centers produce basic analyses and forecasts and provide basic warning services.

Area and Guidance Centers (and Offices) supplement and adapt the products of primary centers to their local regions.

Specialized Centers serve unique requirements of special user groups or provide services unavailable from other Centers, such as climatological support.

The U.S. participates in the international World Weather Watch program under the auspices of the World Meteorological Organization. Under this program: 1) the National Meteorological Center (NMC), the National Environmental Satellite Service (NESS), and the National Climatic Center (NCC) collectively form one of the World Meteorolo-

gical Centers with global responsibilities for collection and retrieval of data, analyses and forecasts; 2) the Regional Center for Tropical Meteorology collocated with the National Hurricane Center in Miami provides analyses and forecasts for the tropical latitudes to supplement the mid- and high-latitude products of the NMC.

Primary Centers

DOC operates three primary centers:

the National Meteorological Center (NMC) at Camp Springs, Md.

the National Hurricane Center (NHC) at Miami, Florida.,

the National Severe Storms Forecast Center (NSSFC) at Kansas City, Mo.

NMC provides basic weather analyses and forecasts for the Northern Hemisphere and for portions of the Southern Hemisphere. On the average, NMC processes daily more than 40,000 surface observations, 2,000 ship reports, 1,500 upper air soundings, 2,800 aircraft reports, several hundred vertical soundings derived from satellite data, and global cloud-cover data from weather satellites. NMC produces daily more than 400 charts for facsimile transmission and 200 messages for teletypewriter distribution to users, primarily in North America, some overseas.

NHC provides basic forecasts and hurricane warnings in the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico for Federal agencies and users. NHC performs research to improve the timeliness and accuracy of hurricane warnings, assisted by NOAA's National Hurricane and Experimental Meteorology Laboratory at Miami, and by NMC.

NSSFC issues convective outlooks and severe thunderstorm and tornado watches to support civil needs. Severe weather watches are issued as needed: they designate areas where the occurrence of severe thunderstorms and/or tornadoes is most likely. Outlooks of thunderstorm possibilities are issued twice daily, thrice from February to August.

Methods of severe weather forecasting have improved over the past 20 years; yet there is still need to improve techniques and applications. For example, NSSFC needs to reduce the size of watch areas (current average is approximately 70,000 km^2) to refine the timing and location of severe weather occurrences, and to increase the watch lead time.

All national centers are programmed for early installation of Automation of Field Operations and Services (AFOS) equipment, described later in this report, for more effective operation of the entire NWS field structure.

DOD operates two primary Centers.

The USAF Global Weather Central (AFGWC) at Offutt AFB, Nebr. provides basic analysis and forecast products to support worldwide defense aerospace and ground operations. AFGWC products are distributed globally to DOD facilities and forces by facsimile, teletypewriter, high-speed communications. AFGWC provides severe weather warnings to DOD installations and facilities.

AFGWC identifies areas within the conterminous U.S. which potentially can produce weather phenomena hazardous to aircraft and ground operations. It provides point warnings to a large number of military locations.

The Navy Fleet Numerical Weather Central (FNWC) at Monterey, Calif. provides analysis and forecast products to support global naval requirements over, on, and within the world's oceans. FNWC products are disseminated over the Naval Environmental Data Network to Fleet Weather Centrals and Naval Weather Service Environmental Detachments throughout the world, and to naval ships by fleet facsimile and teletypewriter broadcasts. Products are exchanged among DOD processing centers via computer-to-computer high-speed data links.

Cooperative DOD-DOC arrangements provide continuous service in the event of power shortages, computer outages or other incidents. In the event of NMC operations failure, AFGWC will provide selected meteorological charts to the National Facsimile Network at Kansas City; FNWC will back up the Forecast Office Facsimile Network and simile Network and provide backup guidance material to support the NMC forecast operation. AFGWC will provide NMC's aviation winds forecasts and NDDFC's severe local storms forecasts if those centers are out of operation for an extended period.

Area and Guidance Centers

These Centers use the products of the Primary Centers to provide forecasts, warnings, guidance and support to civil or military Weather Service Offices within their areas, which comprise one or

more states or portions of larger states.

DOC operates 52 Weather Service Forecast Offices (WSFO). Each WSFO develops principal forecasts three times daily for periods up to 48 hours, updated when required. Based on NMC guidance material received via facsimile, each WSFO provides extended outlooks once daily for its area of responsibility.

Designated Offices also function as warning coordination centers for hazardous conditions.

Forecast Offices also provide the main field support for all specialized forecast services such as marine, aviation, agriculture, air pollution, and forestry weather.

Several WSFOs have additional forecast functions:

1) in coordination with NHC, the WSFOs at Boston, Mass., Washington, D.C., and San Juan, P.R., are responsible for hurricane warnings in their respective areas.

2) following international agreements, the Eastern Pacific Hurricane Center at WSFO San Francisco, and the Central Pacific Hurricane Center at WSFO Honolulu, provide tropical storm forecast and warning for the eastern and central Pacific Ocean. Similar services are provided by NHC for the Atlantic, Caribbean Sea, and Gulf of Mexico. Hurricane advisories for the general public and marine interests contain the position, intensity, direction rate of movement, and other significant characteristics of the storm.

3) the WSFOs at San Francisco, Calif., Salt Lake City, Utah, Denver, Colo., Forth Worth, Tex., Chicago, Ill., Washington, D.C., Boston, Mass., and Miami, Florida, are Storm Coordination Centers, responsible for the preparation of storm summaries for the media on significant non-tropical storms and coastal flooding.

All WSFOs also assist in disaster preparedness by cooperating with Federal, State, and local agencies in areas where destructive storms are likely. Nineteen of the WSFOs service 22 states have specialists assigned for this activity.

To assist Primary Centers and WSFOs in applying satellite data to the preparation of short-term forecasts and warnings, 6 Satellite Field Service Stations (SFSS) are collocated with NMC, NHC, NSSFC, and with the WSFOs at San Francisco, Anchorage, and Honolulu. High-resolution weather pictures from the geostationary operational satellites are distributed over specially conditioned lines to SFSS and WSFO photorecorders twice hourly (more frequently, if needed). Satellite meteorologists at each SFSS analyze the pictures and assist all WSFO staffs in interpreting and using the data.

Plans are to equip all WSFOs with AFOS equipment, described later in this report, over the next four to five years. The objective is to introduce modern methods of data handling, display, and distribution to provide for an improved and much more responsive field forecast and warning system.

DOD operates three Area and Guidance Centers in the U.S. and six overseas to meet global military requirements: Norfolk, Va., Suitland, Md., Colorado Springs, Colo., Japan, Guam, Hawaii, Spain, and two in Germany. These Area and Guidance Centers receive products from DOD's two Primary Centers in the U.S. and, in turn, prepare forecasts, warnings, and planning guidance oriented to the area of responsibility and type of operations (air, sea, or ground) being conducted by the supported military command.

Specialized Centers

Specialized Centers meet the unique requirements of specific users.

DOC, with NASA support, provides small, highly specialized services to support the space program.

DOD operates two specialized centers:

1) the USAF Environmental Technical Applications Center (USAFETAC), Scott AFB, Ill., with a subunit at Asheville, N.C. conducts climatological studies for operational planning, quality control of data taken by DOD units, archiving of specialized military observations.

2) the Joint Typhoon Warning Center on Guam prepares typhoon warnings for the North Pacific west of longitude 180°, the Bay of Bengal, and for the Arabian Sea west of 62.5° east longitude.

NOAA operates two specialized centers:

1) The NOAA Center for Climatic and Environmental Assessment (CCEA) relates the impact of climate and climate variation to national and international socioeconomic problems such as food production, demand/distribution of energy, and availability of living marine resources. The Center's Headquarters and Computer Modeling Division are at the University of Missouri, Columbia, Mo.; the Assessment Division is located in Washington, D.C.

2) The NOAA National Oceanic and Atmospheric Satellite Data Branch consolidates satellite data services. It is collocated with NESS, but is a subelement of the National Climatic Center.

The Weather Data Communication Function

Communications are essential to the functioning of all meteorological services. Because the weather is changing constantly, communications facilities must be able to relay meteorological data and information rapidly for timely centralized processing and for dissemination to users.

The two principal methods of meteorological communications in current use are digital data and facsimile transmission.

Digital communications provide collection and distribution of alphanumeric weather data and information.

Facsimile networks and broadcasts transmit graphical weather information from selected centers to civil and/or military weather offices and users.

Three Agencies are responsible for Meteo digital data communications.

DOT/FAA provides: 1) the basic national digital data system to collect and distribute weather observations and forecasts common to the other agencies; 2) the radio transmitting facilities for the 60 and 100 WPM distribution-only circuits for transmitting data (by NWS) on the World Meteorological and Caribbean meteorological broadcasts.

DOC/NWS provides: 1) internal communication systems; and 2) the basic national teletypewriter system to distribute day-to-day observations, forecasts, and severe weather warnings to the public through radio and TV stations, daily newspapers, etc., via NOAA Weather Wire Service which has over 2,500 private subscribers. NWS is also responsible for certain international circuits required to support the World Meteorological Center at Camp Springs, Md.

DOD supports and maintains systems unique to military requirements.

Table 1 synopsizes the nomenclature and principal characteristics of corresponding networks.

Their detailed description is presented in Appendix A.

Dissemination of Weather Information to Users

Dissemination is the final link in the forecast and warning process. For effective use, warnings must reach all affected members of the public and responsible officials with minimum delay and must convey maximum understanding, to allow adequate lead time for decisions and for taking protective actions to mitigate the effects of weather events. The time requirement varies from a few minutes in the case of a tornado warning to several days for snowmelt-type flood warnings. To serve the large variety of users and effectively meet the wide range of delivery time requirements, a mix of dissemination methods is used.

Radio, television, telephone, teletypewriter systems, newspapers are all used to varying degrees for disseminating environmental forecasts and warnings. They are all designed to serve multi-mission roles. Each routinely provides general weather information, warnings, and forecasts to the public and special user groups.

Although the dissemination system performs well in routine situations, there are periods of severe weather when it is inadequate. This was dramatically illustrated in the widespread tornado outbreak of April 3-4, 1974, where the need for improvements in warning dissemination was brought out strongly. Other previous disaster reports and

TABLE 1

METEOROLOGICAL DATA COMMUNICATIONS NETWORKS

RESPONSIBLE AGENCY	NOMENCLATURE	NUMBER OF CIRCUITS	TYPE AND CAPACITY	PRIMARY USAGE
DOT/FAA Digital	Service A Area Circuits	64	100-wpm multipoint half duplex	Dedicated to FAA, NWS for routine distribution
	" " " "	18	100-wpm " " "	Dedicated to NWS, routine distribution.
	Service A Request/Reply	45	100-wpm " " "	Flight Briefings
	Service A Low Speed	16	100-wpm " " "	Extra capacity for private, mostly airlines
	Service C Area Circuits	12	100-wpm " " "	Collect/distribute basic data gov't & private
	Service O Area Circuits	67	100-wpm " " "	Collect/distribute international data - gov't & private
	DOD Circuits	15	100-wpm " " "	Distribute civil data to military users
		2	100-wpm point/point " "	" " "
	WSFO Point-to-Point	53	100-wpm point/point full duplex	Transmit/Receive to/from WMSC and WSFO's
	Nongovernment medium-speed circuits		1,200 & 2,400 bps multipoint receive only	Distribute A, C, O data to special users
	Hi & Medium Speed Links	1	2,400 bps point-to-point full duplex	Computer/computer: exchange of A, C, O data between NMC & WMSC

TABLE 1 (cont'd)

METEOROLOGICAL DATA COMMUNICATIONS NETWORKS

RESPONSIBLE AGENCY	NOMENCLATURE	NUMBER OF CIRCUITS	TYPE AND CAPACITY	PRIMARY USAGE
	Hi & Medium Speed Links	1	1,200 bps point-to-point full duplex	Same, between WMSC and USAF AWS
		1	1,200 bps point-to-point full duplex	"Notice to Airmen" between WMSC & National Flight Data Center
		1	1,200 bps point-to-point full duplex	Distribute A, C, O data to FAA Central Flow Control
		1	2,400 bps point-to-point full duplex	Computer/computer: exchange A, C, O data between NMC and NSSFC
		1	2,400 bps point-to-point full duplex	Computer/Computer: exchange A data between WMSC & Aviation Service
		1	2,400 bps point-to-point full duplex	To develop pilot self-briefing technique
DOC/NOAA Digital	RAWARC	5	1,200 bps point-to-point full duplex	Distribute radar data between Radar An. & Dev't. Unit KC and Suitland
	Special Link	1	2,400 bps point-to-point full duplex	Alphanumeric & graphic computer link between NESS & NSSFC
	International Circuits	11	various	Exchange meteo data with Canada, USSR, Cuba, UK, Japan, Mexico, Brazil, Central America, Argentina, Bahamas, Jamaica, South Africa

TABLE 1 (cont'd)

METEOROLOGICAL DATA COMMUNICATIONS NETWORKS

RESPONSIBLE AGENCY	NOMENCLATURE	NUMBER OF CIRCUITS	TYPE AND CAPACITY	PRIMARY USAGE
	Radio Circuits		Mostly Morse Code	Receives Marine data from ships at sea
	Alaska VHRR & GOES circuit	1	Microwave 50 Kpbs	Connects NESS & Gilmore Creek
			Satellite link	Connects Anchorage & Juno.
DOD Digital	Automated Weather Network	4	3,000-wpm point-to-point full duplex	Computer-Computer from-to Carswell AFB, Croughton RAF, Fuchi, Clark.
			100-wpm multipoint full duplex	Distribution to DOD users
			3,000-wpm point-to-point full duplex	To-from AFGWC, FNWC, NMC, WMSC
	COMET I		100-wpm multipoint half-duplex	Collect & disseminate airways data
	COMET IIA & IIB	2	100-wpm " " " "	Collect & disseminate data & products
	COMET III		300-wpm broadcast" " "	Disseminate synoptic and customized data
	COMEDS	19	1,200-wpm multipoint full-duplex	To replace COMET
	Naval Environment Data Network			Disseminates FNWC products to special U.S. & overseas locations

TABLE 1 (cont'd)

METEOROLOGICAL DATA COMMUNICATIONS NETWORKS

RESPONSIBLE AGENCY	NOMENCLATURE	NUMBER OF CIRCUITS	TYPE AND CAPACITY	PRIMARY USAGE
DOC Facsimile	NAFAX		Long-line graphics net	U.S. Domestic disseminates to 250 NWS, 450 civil/military Offices, 350 non-government users
	NAMFAX		Long-line graphics net	Disseminates graphics to support aviation
	FOFAX		Long-line graphics net	Distributes NMC, NESS satellite pix to WSFO's
	TROPRAN		Long-line graphics net	NMC products to NHC; NESS sat data to users
	Intra-Alaska Facsimile Net		Microwave, troposcatter, cable, radio, Sat. links	Distributes graphics throughout Alaska
OTHER Facsimile	Facsimile Radio Broadcasts		Leased commercial HF radio broadcasts	Caribbean, South America, Central America, NW Pacific
	Satellite Broadcasts		From ATS, SMS/GOES	to all equipped users
	Marine Broadcasts		HF radio	To ships at sea, incl. tuna fleet.
DOD Facsimile	Strategic FAX Network		Landline & microwave	Specialized military-oriented data from AFGWC.
	Overseas FAX Networks		120 to 240 scans/min.	Specialized products to European & Pacific locations
	Fleet Weather Broadcast		CW radio, TTY, FAX	Between Naval Facilities

surveys have identified similar unmet needs in the dissemination system. Improvements are being made to meet these needs and more are planned. The AFOS program promises to significantly improve the dissemination of forecasts and warnings internally to the meteorological services and more importantly to the public and specialized users.

The major links in the dissemination process are:

Weather Service Offices

NOAA has approximately 200 Weather Service Offices (WSO) throughout the country that prepare and disseminate local forecasts and short-period warnings to the general public and to responsible state and local officials. Heavy reliance is placed upon radio and TV broadcasting, for rapid warning and forecast dissemination. WSO's also provide dissemination of hurricane and tornado warnings, with key dissemination nerve centers at the National Hurricane Center and the National Severe Storms Forecast Center. Some WSO's have been supplemented with specially trained personnel who provide weather information for agricultural and forestry users. A few WSOs are operated solely to provide weather information for specialized users, as necessitated by technical or economic considerations.

DOD operates over 300 WSO's on land and aboard ship that provide forecasting, briefing, climatological, and consultant services in support of military weapons systems, facilities, and installations. DOD mobile units provide weather support for maneuvers, exercises, and special military and contingency operations.

Flight Service Stations

The FAA network of 326 Flight Service Stations (FSSs) provides

weather information to aviation interests at civil airports. Many FSS facilities also provide weather-briefing services by telephone to pilots at smaller airports that have no other weather information source.

Message Transmitting Systems

Voice communications methods have a major role in disseminating meteorological information to the general public through telephones, telephone answering recorders, NOAA Weather Radio, and other radio broadcasts. Use of recorders for distributing weather information to public, aviation, marine, and other specialized groups allows a growing number of users to be served at minimum expense. For aviation users, FAA broadcasts recorded weather observations and NOAA-provided forecasts and warnings.

NOAA operates a continuous weather broadcast service consisting of over 80 NOAA Weather Radio stations. These broadcasts, transmitted on frequencies of 162.40 MHz, 162.475 MHz (in selected areas where interference is a problem), and 162.55 MHz, provide continuous weather forecasts and warnings and other pertinent weather information directly from weather offices to the local community consisting of the general public, mariners, safety officials, news media, utility companies, schools, and anyone else having need for up-to-the-minute information. Through a warning-alert device, specially equipped radio receivers can be demuted by the NOAA transmitter, thus giving an immediate alert to anyone having this special receiver. This alert would be followed by the warning information. Because of the demonstrated need for extending this warning system as seen during the widespread tornado outbreak of April 3-4, 1974, work is underway to expand the coverage of NOAA Weather Radio stations nationwide.

The U.S. Coast Guard provides long-range weather broadcasts in the maritime regions by voice, radiotelegraph and facsimile from five stations in the Atlantic and Gulf of Mexico and seven stations in the Pacific. Additionally, there are 37 Coast Guard stations making weather broadcasts in the coastal regions. This system is a vital part of the maritime weather dissemination program. The FM radio systems are also being used as emergency communications to link essential Department of Commerce facilities with news media and public agencies in areas where hurricanes and severe storms frequently disrupt normal communications. DOD operates 101 two-way radio facilities in the United States for direct voice contact between weather personnel and airborne pilots.

The NOAA Weather Wire Service (NWWS) is a system of statewide teletypewriter circuits used to distribute consumer-oriented weather warnings, forecasts, and data from WSFOs to the news media for relay to the public and various specialized users. It provides on an optional basis visual and audio capability to alert all users to critical incoming messages. WSFOs and WSOs have direct entry on these circuits. The WSFOs furnish forecast and warning information, the WSOs enter local information. The Service also includes four 100-wpm teletypewriter overlay-relay circuits which enable state relay centers to obtain and further distribute the required information from other States. There is a need to expand this service from the present 35 states to all conterminous states so that the mass media will have available timely warning information on potential disasters for immediate relay to the public. Expansion plans are not completed at this time.

Telescriber systems are used at many civil and military airfields to disseminate observations, forecasts, and warnings to air traffic controllers, aircraft operations offices, and other users. Closed-circuit television is used extensively by DOD to distribute weather information and to brief pilots and operational control personnel on the weather.

There are over 100 cable television systems that automatically receive their local forecast from NWWS and continuously display this information on a special channel. Forecasts and warnings are automatically changed upon receipt over NWWS.

The National Weather Service is experimenting with an audio-visual weather service program over a channel of the Great Falls, Mont., cable television system. All information originates at the Weather Service Forecast Office and is sent to the cable office over coaxial cable for distribution to the television customers.

The Department of Commerce, U.S. Coast Guard, State and local governments, and private interests cooperate in a Coastal Warning System to warn pleasure boaters and other marine interests that lack radio receiving equipment of impending weather conditions on coastal and inland waters. More than 400 flag or light displays are operated along the seacoasts, the shores of the Great Lakes, and on the inland waterways.

Archiving of the Information

All cognizant Centers and Offices maintain local archives, albeit for a limited time.

The NOAA National Climatic Center at Asheville, N.C., operated jointly with DOD, is the central archival, processing, and service center for weather records collected by all Federal Agencies.

The NOAA National Oceanic and Atmospheric Data Branch, collocated with NESS, provides a dedicated satellite data bank and is the central source of meteo satellite data for the user community.

NOAA publishes periodic and yearly synopses, maps and charts from past records. USDA publishes weekly Crop Weather Bulletins. USGS publishes yearly streamgage records for approximately 17,000 points throughout the U.S.

How the Basic Meteorological Service is Performed

We have seen that the information provided by the Basic Meteo Service, also known as Global Weather Forecast, is the data base which supports all other specialized services. This section addresses the technique by which the Basic Service is performed. We will concentrate on the civilian aspects of the service as performed by NMC. The DOD procedure is similar: much of the basic data are in fact provided to NMC by the DOD services, and vice-versa.

Synopsis of System Operation

Operational use of numerical, or computerized, methods at the NMC began in 1958. Its introduction had to await the development of: 1) sufficiently rapid communications to make the first hemisphere barotropic prognoses available in time for their use in preparing routine daily forecasts, and 2) the availability of sufficiently fast machines.

The current operational models used by NMC for forecasting the state of the atmosphere are: 1) a northern-hemispheric six-layer baroclinic model, known as the PE model, introduced in 1966, which uses the primitive equations on a 380 x 380 Km grid; 2) a regional Limited-Area Fine-Mesh (LFM) model introduced in 1971, which also uses the primitive equations on a 190 x 190 Km grid, and which covers the continental USA and northern Mexico.

The LFM was run to 24 hr. advance forecast until early 1976; since then, the program was expanded to run to 48 hrs.

The U.S. meteorological community currently receives the following advance forecasts:

24, 36 and 48 hours from the PE and LFM models, generated twice daily from data gathered at 0000 and 1200 GMT.

84 hours from the PE model, generated once daily from 0000 GMT data.

NMC forecasts and data are disseminated to the approximately 53 Weather Service Forecast Offices (WSFO's). Thus local forecasters obtain immediate displays of data (from surface, high altitude radar and satellite observations) and of their synopses made at NMC.

The WSFO's issue local forecasts at least three times daily, in a format that can be used by news media as a local forecast for any point within the zone.

The NMC basic data and information are also disseminated to other Specialized Centers, described in the previous section.

The Forecast Procedure at NMC

As shown in Figure 2, the collected data are first processed to provide "initial conditions" for subsequent entry into the atmospheric model. The purpose of this step, known as *assimilation,* is to provide an accurate initial state of the atmosphere at the locations and times required by the model. Typical processes are:

- Reduction of data to standard model altitudes: because most data are taken at altitudes other than the model's standard levels, interpolations, regressions and similar operations are used to "normalize" them.
- Reduction of data to standard grid points: for the same reason, and using similar techniques.

After the state of the atmosphere is initialized, the model is run. Its detailed explanation, as well as that of more complex models currently under research, is left for a subsequent section. The general features of the NMC models, common to all current atmospheric models, are:

A system of *conservation laws* for

(i) mass

(ii) momentum

(iii) thermodynamic energy

supplemented by *diagnostic relationships* such as

(i) the equation of state

(ii) the hydrostatic equation

The whole system is solved numerically by finite difference methods.

The model produces a forecast of the *state of the atmosphere,* over the area of interest, defined as the calculation of the future expected *pressures and temperatures* at the mesh points, and a map which interpolates in between the mesh points. The model does not produce sea-level forecasts, because the boundary-layer effects are too imperfectly known to be solved by purely automatic techniques. The levels at which the model produces these forecasts are varied from time to time: they are located generally at even pressure altitudes, within the six layers indicated in Table 2. Note that the altitudes are barometric, not physical.

From the computer output depicting the state of the atmosphere, the NMC forecaster prepares the forecasts of the *state of the weather* (e.g. rain) and the sea-level forecast. These are then transmitted over the National Facsimile Circuit to the WSFO's.

TABLE 2

THE SIX ALTITUDE LAYERS OF THE PE AND LFM MODELS

LAYER	PRESSURE ALTITUDE RANGE, mbars	NOMENCLATURE
0	950 - 1000	Planetary Boundary Layer (not computed by models)
1	720 - 950	Tropospheric Level
2	490 - 720	
3	260 - 490	
	260	Standard Tropopause Level
4	180 - 260	Stratospheric Levels
5	100 - 180	
6	0 - 100	Constant Potential Temperature Level

NOTE: Model altitude nodes are generally located at even pressure altitudes within each range.

There are three methods in use to perform the function of conversion from State of the Atmosphere (computer output) to State of the Weather (final product).

1) The Classical Statistical methods use regressions of past *observed* data and extrapolate then into the future. No account is taken of the current numerical forecast. This method leads to only short-term forecasts and is rapidly falling in disuse in the U.S.

2) The so-called "Perfect Prog." method employs regressions of long period of past *observed* data: but, when projecting into the future, it correlates the past observations with the *forecast produced by the model*.

3) The Model Output Statistics (MOS) method, erstwhile known as the "imperfect prog" method, introduced operationally in 1968, also uses regression of past data. These, however, *are not observed* data, but data *computed by the model* in the past. The advantages of the method are: a) it automatically takes into account model biases; b) it can correlate variables which are never observed, but which are computed from other variables, such as vertical velocities.

The MOS is currently the most widely used method for converting the State of the Atmosphere produced by the computer model into a State of the Weather required by the users.

The production of the sea-level weather prognostic packages is particularly important. It is a continuous process by which NMC forecasters update their prognoses by modifying the latest available numerical prognoses via, e.g. the MOS, and by subjective evaluation of the latest data.

The forecaster examines the latest sea-level and upper-air analyses and weather patterns: he emphasizes current relationships between low-level circulation patterns and circulations aloft, in preference to the history of the weather systems. He must diagnose the existing 3-dimensional structure of the atmosphere: thus, he compares the structure and evolution of the real atmosphere against that simulated by the numerical model.

He isolates the systematic errors between past and already verified prognostic charts, and considers how they might be factored into the prognoses. Most systematic errors in NMC's models fall into two categories: 1) those associated with truncation errors in the model, which show up as slowness in system displacements; and 2) those resulting from failure to forecast baroclinic developments with sufficient accuracy or rapidity. The second class of errors shows up in the model as failure to include rapidly developing storms and as insufficient amplitude in upper-air troughs and ridges.

The product thus produced by NMC is further modified as appropriate by the local WFSO's, using similar techniques to those described, to take into account local weather patterns, correlations and peculiarities.

It is clear that at the present state of the art the computer model does not in and by itself provide a State of the Weather forecast, nor does it provide a perfect State of the Atmosphere forecast. Man's judgement is needed to augment the computer's product. For this reason, numerical or computerized meteorological methods are also known under the name of *numerical guidance*.

Accuracy of NMC's Forecasts

Experience at NMC since the introduction of Numerical Weather Forecasting in 1958 indicates the following:

Better forecasts are introduced by careful and systematic use of numerical guidance as opposed to independent forecasting in competition with the computer product.

The forecast skill improves in direct proportion to the improvement in numerical forecast guidance.

The better the numerical prognoses, the more difficult it is to improve manually with any degree of success.

Two questions often asked are: how good is the weather forecast? How much did it improve as a function of the introduction of more sophisticated techniques? To properly answer these questions, one needs to specify just which weather parameter or parameters are of interest.

A quantification of the improvements achieved is offered by "skill score" records, which take various forms. The so-called S_1 score for pressure (or equivalent atmospheric height) is given by:

$$100 \frac{\Sigma e_G}{\Sigma G_L}$$

Where:

e_G is the error in the difference of forecasted pressure between grid points

G_L is the observed difference of forecasted pressure between grid points

Σ extends over all meshes in the area being scored

It is clear that if the pressures are all forecasted correctly, the error e_G will become zero; thus a zero skill score is equivalent to a perfect forecast (in this case, of pressure).

Figure 3 shows the history of skill scores of sea-level and 500 mbar prognoses for the U.S. as a whole.

It is clear that the 500-mb prognosis is considerably better than that at sea-level. This is due to the inability to correctly model the complex effects of terrain on the atmosphere.

Figure 4 exemplifies the behavior of the pressure skill score as a function of length of prognosis: the longer the forecast period, the worse the forecast.

It also indicates the advantage to be gained by using a smaller grid size.

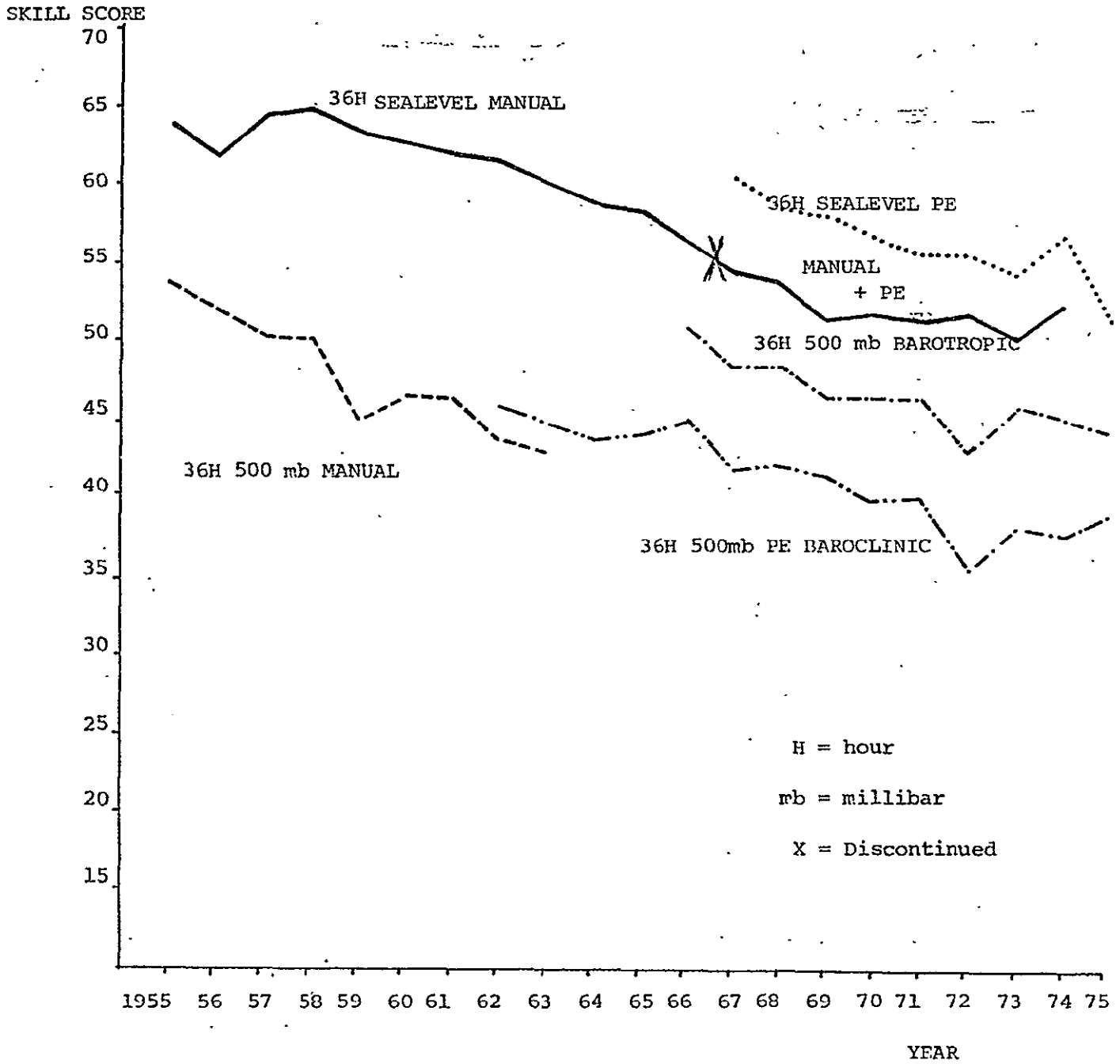
Table 3 shows that models are less skillful over the Western U.S. This is attributed partly to the more difficult terrain, partly to the scarcity of observations over the Pacific.

Figure 5 shows the improvement in the average forecast of temperatures.

The contribution of numerical methods to the forecast of rainfall occurrence and amount, thunderstorms, clouds, ceilings, and visibility is difficult to specify because most numerical forecasts of these weather elements have only become available in the last two or three years. Precipitation has proven to be one of the most difficult; numerical forecasts of precipitation have been the least useful of all the output from numerical models. Precipitation forecasts depend on personal skill and experience in interpreting the numerical guidance. This is particularly true for forecasts of precipitation amount. Figure 6 illustrates a 10-year NMC record of accuracy of precipitation

FIGURE 3

HISTORICAL EVOLUTION OF YEARLY MEAN S, SKILL SCORES (atmospheric pressure)



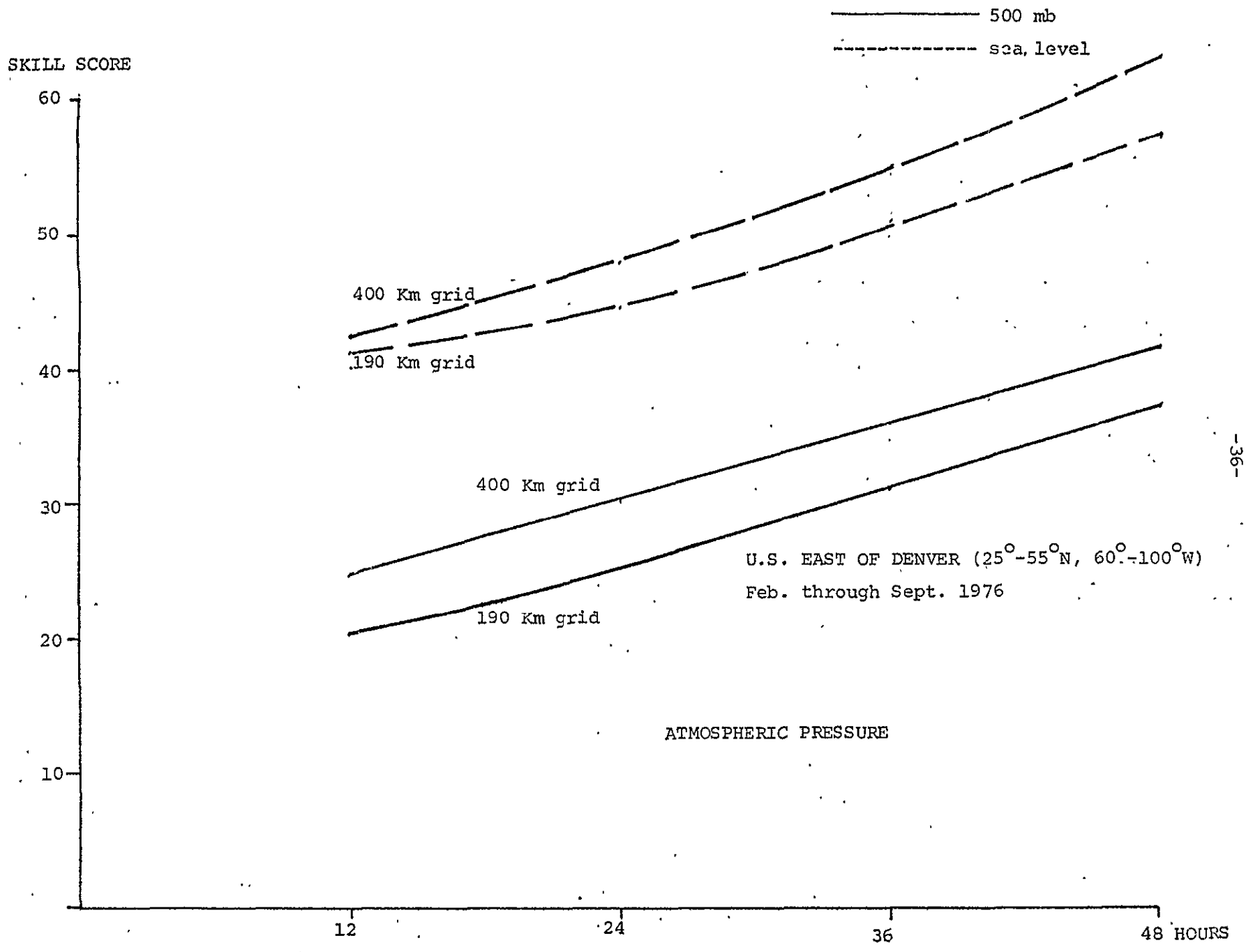


FIGURE 4 SKILL SCORES AS A FUNCTION OF FORECAST PERIOD AND OF GRID SIZE

TABLE 3

Mean S_1 scores for large-mesh and fine-mesh models, and their differences over the eastern and western United States (February through September 1976).

	East of Denver (25°-55°N, 60°-100°W)			West of Denver (25°-55°N, 105°-140°W)		
	L	S	L - S	L	S	L - S
12 h forecast						
sea level	42.7	41.3	+1.4	43.8	43.5	+0.3
500 mb	24.8	20.1	+4.7	27.1	25.7	+1.4
24 h forecast						
sea level	48.0	44.8	+3.2	51.7	50.7	+1.0
500 mb	30.4	25.1	+5.3	32.7	30.1	+2.6
36 h forecast						
sea level	55.3	51.2	+4.1	58.8	57.4	+1.4
500 mb	36.0	31.3	+4.7	39.3	38.4	+0.9
48 h forecast						
sea level	63.7	57.7	+6.0	64.5	63.2	+1.3
500 mb	42.0	37.7	+4.3	45.7	45.2	+0.5

L = Large Mesh (PE model)

S = Small Mesh (PE-LFM model)

L-S = Improvement

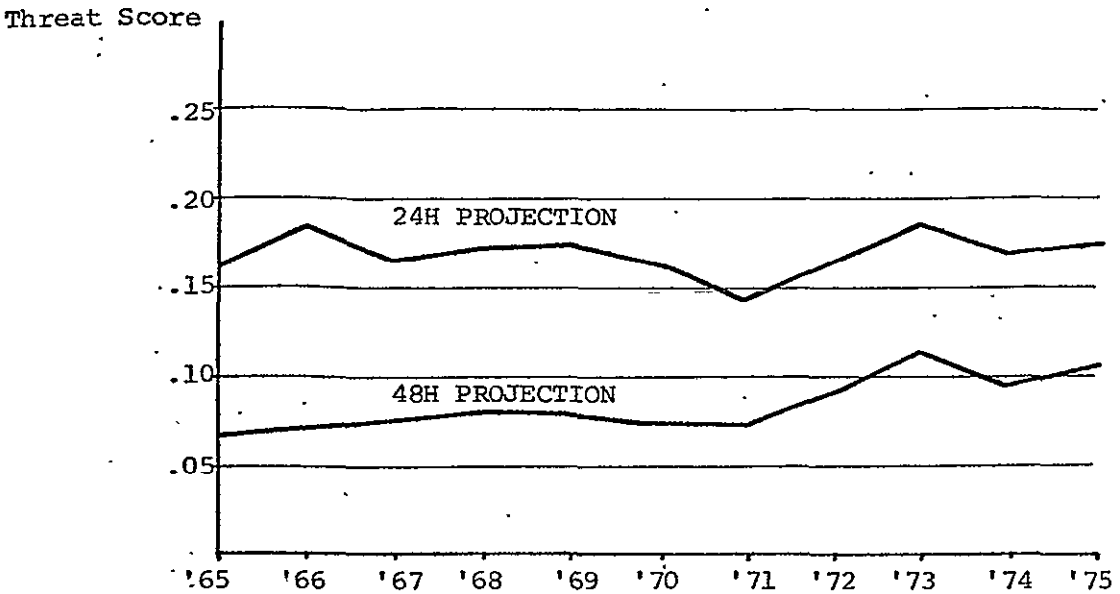
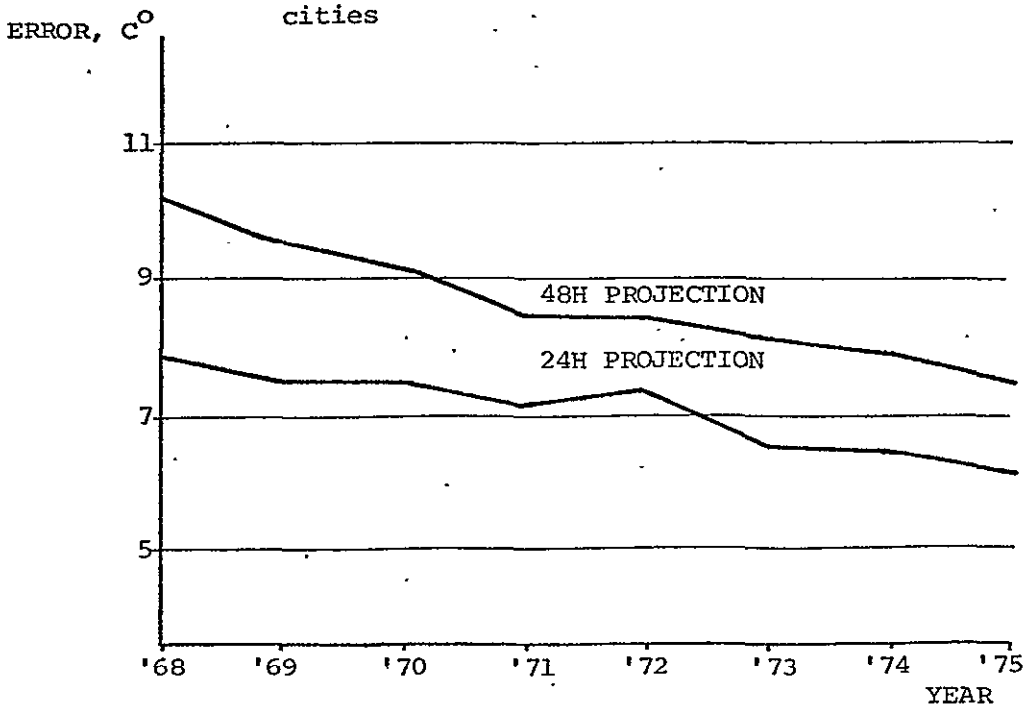


FIG. 6 Mean annual threat scores for manual NMC forecasts for areas of 1 inch or more of precipitation during a 24H period

FIG. 7 Evolution of mean absolute errors of temperature forecasts (combined maximum and minimum) for 126 cities



forecasting in the U.S. which uses the so-called "threat score" (where 100 is perfect, 0 is completely erroneous forecast). There is some evidence of slight improvement in the 48 h projections, but this record certainly shows less increase in skill with time than the temperature or the pressure prognoses.

The Current Operational Models and Their Utilization

The purpose of the current operational models used by NMC is to provide a prediction of the future atmospheric parameters of pressure and temperature, at specified mesh points, over certain areas:

The U.S. for domestic purposes

The Northern Hemisphere for U.S. marine and overseas interests

From this prediction of temperature and pressure, forecasters produce forecasts of other parameters of interests, such as rainfall.

The model is based upon five vector and scaler equations which are:

1. The equation of motion, or the momentum equation, which is just the mathematical statement of:

Acceleration =	Coriolis force +	pressure gradient force +	effective gravitational force	+ frictional forces

$$\frac{d\vec{V}}{dt} = -2\,\vec{\Omega} \times \vec{V} - \frac{1}{\rho}\,\vec{\nabla}p + \vec{g} + \vec{F} \qquad (1)$$

Where:

$\vec{\Omega}$ is the earth's angular velocity

$\vec{V}$ is the velocity vector of an atmospheric particle

ρ is the atmospheric density

$\vec{\nabla}$ is the vector "del" operator, $\vec{i}\,\frac{d}{dx} + \vec{j}\,\frac{d}{dy} + \vec{h}\,\frac{d}{dz}$

p is the pressure

g is the effective gravity, $\vec{g}^{\,*} + \Omega^2\,\vec{R}$

(where $\vec{g}^{\,*}$ is the acceleration force due to gravity, $\Omega^2\,\vec{R}$ is the centrifugal force; Ω being the angular speed of rotation of the earth, $\vec{R}$ the position vector of the atmospheric particle as measured from the origin at the earth's center)

$\vec{F}$ represents the frictional forces

2. The equation of state, which describes the relationship between pressure, density and temperature. The ideal gas law is assumed;

$$\frac{p}{\rho} = RT \tag{2}$$

where:

R is the gas constant for air

3. The thermodynamic equation, which expresses the conservation of energy. For a perfect gas the first law of thermodynamics is:

$$\dot{H}\, dt = c_v dT + p d\alpha$$

where:

H is the rate of external heat addition per unit mass

c_v is the specific heat at constant volume

$\alpha = \frac{1}{\rho}$ is the specific volume

Using the equation of state (2) and the relationship

$$c_p = c_v + R$$

where c_p is the specific heat at constant pressure, we obtain:

$$\dot{H}dt = c_p dT - \alpha dp$$

Dividing through by T we obtain the *entropy* form of the law,

$$\frac{\dot{H}dt}{T} = dQ = c_p \frac{dT}{T} - \alpha \frac{dp}{T}$$

or again using the equation of state,

$$\frac{\dot{H}}{T} = \frac{dQ}{dt} = c_p \frac{d \ln T}{dt} - R \frac{d \ln p}{dt} \tag{3}$$

The entropy change, dQ/dt, is often expressed in terms of the change of potential temperature following the motion. Potential temperature is defined as the temperature which a parcel of dry air at pressure p and temperature T would have if it were expanded or compressed adiabatically to a pressure of 1,000 mb. Clearly, the relationship between pressure and temperature for an adiabatic expansion is given by setting $dQ/dt = 0$ in (3) resulting in

$$c_p \, d\,(\ln T) = R\, d\,(\ln p)$$

which can be integrated to give an expression for the potential temperature Θ:

$$\Theta = T \left(\frac{1,000}{p}\right)^{R/c_p} \tag{4}$$

Finally, taking the log of this equation we obtain

$$c_p \frac{d\ln\Theta}{dt} = c_p \frac{d\ln T}{dt} - R\frac{d\ln p}{dt}$$

and comparing this with (3) we arrive at the equation

$$\frac{dQ}{dt} = c_p \frac{d\ln\Theta}{dt} \tag{5}$$

This is the form of the first law of thermodynamics used in the NWP models.

4. The continuity equation

$$\frac{1}{\rho}\frac{dp}{dt} + \vec{\nabla} \cdot \vec{v} = 0 \tag{6}$$

Here $\frac{d}{dt}$ denotes the "total" derivative

$$\frac{dp}{\alpha t} = \underbrace{\frac{\partial p}{\alpha t}}_{\text{local part}} + \underbrace{u\frac{\partial p}{\partial x} + v\frac{\partial p}{\partial y} + w\frac{\partial p}{\partial z}}_{\text{Advective part}}$$

where u, v, w are the components of $\vec{V}$ (eastward, northward and vertical velocities).

Thus for dry air (1), (2), (5) and (6) comprise a complete system of six scaler equations in six unknowns u, v, w, p, α, Θ. The additional equation (4) relates Θ to T. The friction force $\vec{F}$ and heating rate dQ/dt are assumed to be known functions, or expressible in terms of the other variables. Hence, in principle, if we know the initial state of the atmosphere, all future states can be determined by solution of this system.

Since the Earth is spherical, this system of equations is written in spherical coordinates (λ, ϕ, z) where λ is the longitude, ϕ is the latitude, and z is the vertical distance above the earth's surface. Denoting the radius of the earth by "a," the three component equations of (1) are:

$$\frac{du}{dt} - \frac{uv \tan\phi}{a} + \frac{uw}{a} = -\frac{1}{p}\frac{\partial p}{\partial x} + 2\Omega\, v \sin\phi - 2\Omega\, w \cos\phi + F_x \tag{7}$$

$$\frac{dv}{dt} + \frac{u^2 \tan\phi}{a} + \frac{vw}{a} = 1\,\frac{1}{p}\frac{\partial p}{\partial y} - 2\Omega\, u \sin\phi + F_y \tag{8}$$

$$\frac{dw}{dt} = \frac{u^2 + v^2}{a} = -\frac{1}{p}\frac{\partial p}{\partial z} - g + 2\Omega\, u \cos\phi + F_z \tag{9}$$

which represent the eastward, northward, and vertical component momentum equations, respectively. The other equations are unaffected by the sphericity of the earth.

An approximation made in current models is the so-called hydrostatic approximation. The rationale for this becomes apparent by rewriting (9), which expresses the vertical component of the momentum equation, and

comparing with the order of magnitude of the quantities involved:

z-Component momentum equation	$\frac{dw}{dt}$	$-2\Omega\ u \cos\phi$	$-\frac{u^2+v^2}{a}$	$= -\frac{1}{\rho}\frac{\partial p}{\partial z}$	$-g$
Scales of individual terms	$\frac{UW}{L}$	$f_o U$	$\frac{U^2}{a}$	$\frac{P_o}{\rho H}$	g
Magnitudes of the terms (cm sec^{-2})	10^{-5}	10^{-1}	10^{-3}	10^{3}	10^{3}

The scaling indicates that *to a high degree of accuracy the pressure field is in hydrostatic equilibrium,* that is, the pressure at any point is simply equal to the weight of a unit cross-section column of air above that point. Thus under the hydrostatic approximation the vertical component of the momentum equation is simply

$$\frac{\partial p}{\partial z} = -\rho g$$

Under the assumption of hydrostatic approximation, the primitive equations are used conveniently in pressure coordinates. This is because some of the terms in the fundamental equations take a simpler form, particularly the continuity equation. This system is called the (x, y, p, t) coordinate system and in it the vertical velocity w is replaced by the "vertical" velocity $\omega = dp/dt$. These are then the primitive equation (PEs) is currently employed.

It is worth reiterating that both the PE and the LFN modelo use these equations: the principal difference being in the finer grid interval of the LFN.

Relationship between Length and Accuracy of Forecast and Processing Speed

Assessment of the Speed of Processing of Current Models

Models based upon primitive equations require approximately 10,000 360-equivalent computer instructions per grid point. Let us see what this amounts to for the currently used largest operational model, i.e., the hemispheric PE model. The number n of grid points is:

$$n = \frac{2\pi R^2}{a^2} \ell \qquad (1)$$

Where:

R = mean earth's radius = 6,370 Km

a = grid separation

ℓ = number of levels

If the iterations reoccur with a cycle τ hours, and the forecast period is T hours, the total number of instructions N is:

$$N = \frac{2\pi R^2 \ell}{a^2} \frac{T}{\tau} \times 10^4 \qquad (2)$$

If it is desired to generate the T-hour forecast in h computer hours, the speed of the machine S in Mips must be:

$$S = \frac{Nh}{3{,}600 \times 10^6} = \frac{2\pi R^2 \ell Th \times 10^4}{3.6 \times 10^9 \, a^2 \tau} \cong \frac{\ell Th}{a^2 \tau} \times 710 \qquad (3)$$

Another useful and equivalent way to express this relationship is to introduce the "time acceleration factor," $\alpha = \frac{T}{h}$, which expresses how many times faster than real time is the forecast desired (for example, if one wishes a 24-hour forecast in one hour, $\alpha = 24$).

This yields:

$$S(\text{MIPS}) \cong 710 \cdot \frac{\ell T^2}{a^2 \alpha \tau} \qquad (4)$$

For the current PE hemispherical model:

$$a = 380 \text{ Km}$$
$$\ell = 6 \text{ levels}$$
$$\tau \cong 0.1 \text{ hours}$$

The computer speed equation becomes:

$$S(\text{MIPS}) \cong 0.3\ T\ h \cong 0.3\ \frac{T^2}{\alpha} \qquad (5)$$

For example, a 24-hour State of the Atmosphere forecast (T=24) in one hour (h=1) will require a machine speed of approximately 7.2 MIPS.

This is the approximate speed of the 360/195 used at NMC for weather-type code: one hour is also approximately the time required to complete a 24-hour forecast.

To the computer processing time must be added:

1) the time required for the assimilation of data, which is approximately constant regardless of the length of the forecast, and which is of the order of one hour on the 360/195; 2) the time required for generating the State of the Weather forecast at NMC. This is dependent upon the difficulty of the weather situation and on the skill of the human meteorologist. It ranges from one to two hours; 3) the transmission time to the WSFO's, which is small; 4) the time required for the WSFO's to adapt the NMC information to the local conditions, which can range from one-half to two hours; 5) the time required for dissemination, which is also relatively small, of order minutes to specialized user for severe weather phenomena to one-half hour for public dissemination.

The computer processing time for the basic State of the Atmosphere forecast is thus not a critical element with the current PE model. It is in fact most critical for the 24-hour forecast, gradually losing criticality for the longer forecasts.

This apparent balance between computer speed and model complexity is, however, brought about by force of circumstances: the model is approximately as complex as the best available computer can handle. To obtain a perspective of the actual situation, let us look at what are the critical items apt to improve the State of the Atmosphere forecast.

Factors of Improvement of State of the Weather Forecast, and Their Impact on Processing Speed

It is difficult to determine exactly the relative importance or priority of the many causes of error in numerical predictions. This is partly because the sources of error are not independent of one another; partly, because their relative importance depends on model details, on the forecast range and region in question, and on the particular verification measures employed.

In fact, a considerable divergence of opinion did exist in the past within the meteorological community: whether it was more efficacious to devote resources to gathering more and more exact data, or to improving models. The proper answer is: both are important; in fact, one will not work without the other. The listing of Table 4, compiled partly by computation, partly by experience and from experimentation is reasonably accepted. It should be considered as indicative rather than exact. Note that the principal improvements, in order of descending priority, are attributed to:

TABLE 4

FACTORS CONTRIBUTING TO THE IMPROVEMENT OF THE 24-HOUR WEATHER FORECASTS AT THE 500 mb LEVEL

PRIORITY	ITEM	CORRESPONDING ESTIMATED ERROR VARIANCE, %
1.	Horizontal resolution: fine mesh vsus. 390 Km. mesh	35%
2.	Accounting for mountains vsus. smooth earth	27%
3.	Accounting for precipitation vs. no precipitation	18%
4.	High vertical resolution vs. six vertical levels	15%
5.	Improvement of observing system	13%
6.	Addition of horizontal eddy viscosity vs. no viscosity	11%
7.	Addition of surface drag vs. no surface drag	8%
8.	Convective adjustment vs. no adjustment	6%
9.	Correction of initialization errors	4%
10.	Accounting of radiation vs. no radiation	3%
11.	Inclusion of rough mountains vs. smooth mountains	3%
12.	Abrupt vs. gradual precipitation	2%
13.	Artificial boundaries	2%
14.	Sophisticated vs. crude surface drag	1%
15.	Nonlinear vs. linear viscosity	1%
16.	Time integration schemes	1%

1) Tightening of the horizontal and vertical grid: approximate improvement: 38%

2) Improvement of the model: approximate improvement: 36%

3) Improvement of the observation system: approximate improvement: 13%

Reduction of the grid dimensions has major impact on the computer speed. Suppose in fact that the horizontal grid is reduced by a factor of k. To fully benefit from this finer mesh, the vertical grid spacing need also to be reduced: not in direct proportion, but approximately as $\sqrt{k}$. Likewise, the time steps need be reduced to match the finer spatial structure: this reduction is also of order $\sqrt{k}$.

From (3), we see that the required computer speed then increases by:

$$k^2 \text{ (horizontal grid)} \times \sqrt{k} \text{ (vertical grid)} \times \sqrt{k} \text{ (time cycle)} \cong k^3$$

A reduction of the horizontal space grid by a factor of 2 thus requires a machine speedup of a factor of 8.

From (3), maintaining the computation time constant, we see that this involves computer speeds of the order of $7 \times 8 \cong 50$ to 60 Mips. Or conversely, the processing time for data assimilation and model run would climb to approximately 8 hours each (a total of 16 hours), which when added to the other lead times would essentially invalidate the 24-hour forecast.

Note that: 1) improvements of the observation system are less significant than tightening of the grid; 2) improvements in the model act likewise; their introduction would, however, further increase the processing speed requirements. It is in this sense that computer

performance is critical to future improvements of the weather forecast procedure.

Prospects for Higher Speeds

From 1950 to 1972, the speeds of the fastest (Top of the Line, or TOL), commercial computers speeds increased on the average by $\sqrt{2}$ yearly, or, equivalently, doubled every two years. Since 1972, this trend has slowed down considerably.

a. IBM's TOL, the 360/195, running at approximately 7 Mips on weather code, has not been topped in IBM's line. In fact, the fastest machine of the 370 series is somewhat slower, 4 to 5 Mips. IBM has not indicated any plans to produce faster machines in the near future.

b. CDC's classical high speed line has also stopped with the 7,600, capable, on weather code, of up to 8 Mips. No announcements have been made of any faster general-purpose product.

c. CDC's STAR is somewhat of an anomaly: in that it runs at very high speed (100 Mips) for "perfect" code composed of only additions: on complex, high-entropy code its speed drops to approximately 3 to 4 Mips. On weather code, it has been rated at approximately 15 Mips: however, the difficulties of programming have slowed its introduction.

d. The TI ASC is capable, on weather code, of up to approximately 20 Mips. No announcements have been heard as to faster machines.

e. The ARPA-funded ILLIAC IV is capable of approximately 40 to 50 Mips on weather code: it is, however, a one-of-a-kind device: no plans have been forthcoming for its introduction to the market.

f. Foreign machines are even slower than these: for example, the nearest potential competitor, the Soviet BESM-10, which was indicated to be capable of 10 Mips and projected to begin operations in 1973, has not yet appeared.

A basic commercial reason for this slowdown is the sparseness of the market for these high speed applications, and the current preference to use preprocessors whenever possible. These devices can operate very fast, up to several hundred Mips, on low-entropy code.

A major task for the Surveys and/or the Trades effort is thus to investigate the major manufacturer's plans for producing high-speed machines; should this prove disappointing, to investigate the applicability of preprocessors to weather code and the current efforts in this direction.

Efforts of Model Improvement

The principal organizations active in the development of improved State of the Atmosphere and Weather models are shown in Table 5.

The principal Models under development are:

Group I

a) GFDL Global 9-level Atmospheric Model
b) GFDL Global 18-level Atmospheric Model using Modified Kurihara Grid
c) GFDL Global Joint Ocean-Atmosphere Model
d) GISS Global 9-level Model
e) NCAR Global Multi-Level Model
f) RAND Global 2-Level Model

Group II

a) HRC Global 5-Level General Circulation Model
b) MO Global 5-Level General Circulation Model

TABLE 5

PRINCIPAL U.S. AND INTERNATIONAL ORGANIZATIONS ACTIVE IN THE DEVELOPMENT OF IMPROVED STATE OF THE ATMOSPHERE AND STATE OF THE WEATHER MODELS

Geophysical Fluid Dynamics Laboratory (GFDF), NOAA, USA

Goddard Institute for Space Studies (GISS), NASA, USA

National Center for Atmospheric Research (NCAR), USA

World Meteorological Centers (WMCs) - Part of the World Weather Watch (WWW) program. Three Centers at: Washington, DC; Melbourne, Australia; Moscow, USSR

Rand Corporation, USA

MIT, USA.

UCLA, USA.

Lehigh Univ., USA

Hydrometeorological Research Center (HRC), USSR

Meteorological Office, UK

Universities Modelling Group, UK

Electronic Computation Center, Japan

Institute of Meteorology, Sweden

Meteorological Research Institute, Japan.

Novosibirsh Computer Center, USSR

Commonwealth Meteorology Research Center, Australia.

Institute for Theoretical Meteorology, Denmark

National Hurricane Research Lab, NOAA.

c) UMG 5-Level General Circulation Model

Group III

a) LU Global Short-Term 2-Level Prediction Model Using Telescoping Grid

b) ECC Hemispheric 4-Level Model

c) IM MISU Hemispheric 10-Level Model

d) MRI Global 3-Level Model

Group IV

a) NCC Hemispheric Extended-Range Prediction Model Using A Priori Known Climatology

b) CMRC Global 5-Level Spectral Level

c) HRC Hemispheric 4-Level Spectral Model

d) ITM Hemispheric Spectral Model

A brief description of the principal characteristics of these models follows:

Group I models use primitive equations; number of vertical levels ranges from 2 to 18; integration is made over the global domain. All use finite-difference techniques and possess various degrees of parameterization of the atmospheric boundary layer, cumulus connection, radiation and topography. The water vapor equation is also incorporated to compute the large-scale precipitation and release of latent heat. Few models treat ground hydrology and ocean coupling (joint atmosphere - ocean model), which are important for climate simulation. They have generally been well tested and used for short-and extended-range weather prediction, four-dimensional assimilation, observing system simulation experiments, and several circulation and climate studies.

Group II models use primitive equations, solved by finite difference techniques. They possess five vertical levels and are global and/or

hemispheric in scope.

Group III models employ primitive equations, hemispheric or global, with varying vertical resolutions. They differ considerably in their way of treating physical processes. Most are aimed at 1 to 5 day forecasts.

Group IV models use the primitive equations. Three models are hemispheric; one is global, but is used mainly for hemispheric experiments. The salient feature of these models is the utilization of spectral techniques: for three of the models, in the horizontal dimension, and for one, in all three space dimensions. The physical processes are incorporated in a rather simple manner - a few models do not treat physical processes at all. Large-scale water vapor transfer is not included in any of these models.

As a gross indication, the requirements imposed on machine speeds by greater modeling sophistication, within the current state of knowledge, amount to approximately doubling or tripling the number of computer instructions per grid point. As has been shown, however, the largest improvement in weather forecasting derives from tightening the spatial and temporal grid. This presents the major impact upon machine speed.

APPENDIX A

DESCRIPTION OF THE METEOROLOGICAL DATA COMMUNICATIONS NETWORKS.

1. FEDERAL AVIATION ADMINISTRATION DIGITAL DATA COMMUNICATIONS

The FAA's Modernized Weather Digital Data Communications System consolidates the circuit control and relay functions of Services A, C, and O into a single Weather Message Switching Center (WMSC) at Kansas City. These functions are performed automatically by computers combined to operate as a real-time store and forward communications switch. All Service A and C circuits extend directly into the computer switch: others from overseas points pass through the Aeronautical Fixed Telecommunications Network switch which is collocated and interconnected with WMSC. Computer-to-computer links provide for the exchange of data between WMSC and the National Meteorological Center (NMC) at Suitland and between WMSC abd the Air Force Automated Weather Network switching facility at Carswell AFB, Tex.

The circuits of the Modernized Weather Digital Data Communications System are:

o *Service A Area Circuits:*

(a) Sixty-four 100-words per minute (wpm) multipoint half-duplex circuits dedicated to meet the collection and routine distribution requirements of the FAA and NWS user. Users whose needs are compatible with those of FAA and NWS may obtain receive-only drops on these circuits.

(b) Eighteen 100-wpm multipoint half-duplex polled circuits dedicated to meet NWS's collection and routine distribution requirements. Users with compatible needs may obtain receive-only drops.

o *Service A Request/Reply Circuits:*

Forty-five 100-wpm half-duplex circuits parallel the Service A Area Circuits to enable Government flight briefing facilities to obtain information not routinely transmitted on these circuits.

o *Service A Low-Speed Nongovernmental Circuits:*

Sixteen 100-wpm multipoint circuits for distributing data to nongovernment users whose needs are not satisfied by the area circuits, principally airlines.

o *Service C Area Circuits:*

Twelve 100-wpm multipoint half-duplex circuits for collecting and distributing basic meteorological data to serve both government and nongovernment users.

o *Service O Area Circuits:*

67- and 100-wpm multipoint half-duplex circuits for collecting and distributing international meteorological data to government and non-government users.

o *Depart of Defense Circuits:*

Fifteen 100-wpm multipoint circuits and two 100-wpm point-to-point circuits for distributing selected civil environmental data to military customers in the continental U.S.

o *Weather Service Forecast Office Point-to-Point Circuits:*

Fifty-three 100-wpm full-duplex circuits to the WSFOs transmit forecast products to WMSC and receive supplementary weather data by WSFOs.

o *Nongovernment Medium-Speed Circuits:*

1,200 bits per second (bps) and 2,400-bps multipoint receive-only circuits for distributing Service A, C, and O data to very high volume airline and other nongovernment users whose needs cannot be satisfied by low-speed circuits.

o *High- and Medium-Speed Links:*

2,400-bps full-duplex computer-to-computer circuit for exchanging Service A, C, and O data between WMSC and NMC.

1,200-bps full-computer-to-computer circuit for exchanging Service A, C, and O data between WMSC and the Air Force Air Weather Service.

1,200-bps full-duplex "Notice to Airmen" circuit between WMSC and the National Flight Data Center.

1,200-bps full-duplex point-to-point circuit for distributing Service A, C, and O data to the FAA's Central Flow Control Facility.

2,400-bps full-duplex computer-to-computer circuit for exchanging Service A, C, and O data to the NSSFC.

2,400-bps full-duplex computer-to-computer circuit for exchanging Service A data between the Aviation Weather and NOTAM System and WMSC.

2,400-bps full-duplex computer-to-computer circuit for use in developing pilot self-briefing techniques.

2. DEPARTMENT OF COMMERCE's DIGITAL DATA COMMUNICATIONS

o *Radar Report and Warning Coordination (RAWARC) Teletypewriter Network:*

Collects and distributes radar reports and storm warning information. RAWARC comprises five circuits terminating at the Radar

Analysis and Development Unit in Kansas City and at the automated relay center in Suitland, Md. The only regularly scheduled operation on RAWARC is an hourly collection of radar reports which is relayed to other circuits as required. Otherwise, RAWARC traffic is basically unscheduled and is handled according to a priority system.

o *NOAA Weather Wire Service:*

Described under the section on Dissemination of Weather information to users.

o *Special Communications Links Between Guidance Centers:*

High-speed alphanumeric and graphic computer link between NMC/NESS and NSSFC.

o *International Circuits:*

Eleven international circuits augment FAA's Service O circuits to exchange meteorological data among the U.S. and Canada, the USSR, Cuba, Great Britain, Japan, Mexico, Brazil, the Central American nations, Argentina, the Bahamas, Jamaica, and South Africa. These include a Washington-Toronto high-speed circuit, a Washington-Moscow circuit for exchange of satellite information, a Washington-Central American loop, a Washington-Mexico low-speed circuit, a Washington-Buenos Aires low-speed circuit, a Washington-Bahamas low-speed circuit, a Washington-Jamaica low-speed circuit, a Washington-South Africa high-speed circuit, and three other circuits--Washington-Bracknell (England), Washington-Tokyo, and Washington-Brasilia - that are part of the World Weather Watch main trunk circuit. The Washington-Bracknell circuit is also used to exchange facsimile charts.

o *Radio Circuits* -- Weather messages and observations from ships at sea are transmitted by radio, primarily by Morse code, to shore-based radio stations and thence relayed to NMC via the Teletypewriter Exchange Service, international communications carrier facilities, and Coast Guard circuits. More than 1,000 Marine observations are automatically processed, separated geographically and consolidated into bulletins each day for distribution on domestic and international meteorological communications facilities.

o *Alaska VHRR and GOES Satellite Distribution Circuit:*

Microwave circuit from the NESS site at Gilmore Creek, Alaska furnishes satellite pictures to the WSFOs at Fairbanks, Anchorage; it then continues onward via satellite to furnish the signal to WSFO Juneau, Alaska.

3. DEPARTMENT OF DEFENSE DIGITAL DATA COMMUNICATIONS

o *Automated Weather Network:*

This network, operated and maintained by the Air Force, is the backbone of the military weather communications system. It comprises four real-time communications switching computers at Carswell AFB, Tex., RAF Croughton, England, Fuchu Air Station, Japan, and Clark Air Base, Philippine Islands, linked by high-speed data circuits. The overseas Automatic Digital Weather Switches collect data from radio intercept sites and low-speed feeder circuits. These data are transmitted at 3,000 wpm to the continental U.S. switch at Carswell AFB where the information is examined, sorted, edited, compiled into specific weather messages, and switched to military and civil customers. Besides low-

speed distribution to DOD weather units, data are transmitted by high-speed circuits to the AFGWC the Navy's FNWC, NMC, and the WMSC at Kansas City. All circuits are full-duplex, permitting a total exchange of data that include reports from field units to military and civil processing centers and products from these centers to the field units.

o *Continental United States Meteorological (COMET) Teletypewriter System:*

This is currently the primary communications system for collecting, editing, and disseminating environmental data at military stations in the U.S. It consists of three teletypewriter networks, each subdivided into eight geographical areas. The COMET I network consists of half-duplex 100-wpm loop circuits used for collecting and disseminating airways data. The COMET II network consists of two half-duplex 100-wpm loop circuits. One circuit (COMET IIA) is used for collecting data, while the other (COMET IIB) is used for disseminating operational weather products and data. The COMET III network consists of half-duplex 300-wpm broadcast circuits used for disseminating synoptic and customer tailored data. Polling for data collection on COMET I and COMET IIA and for disseminating data over COMET IIB and COMET III are controlled by the 1108 computer at Carswell AFB.

o *Continental United States Meteorological Data System (COMEDS):*

This network is being implemented as the primary communications system for the collection and dissemination of environmental data at military stations in the U.S. COMEDS should soon replace the existing COMET. COMEDS will consist of 19 regional loop circuits operating at

1,200 words per minute, full-duplex, with approximately 25 terminals each. The circuits will be controlled by the on-line 1108 computer at the Air Force Automated Digital Weather Switch at Carswell AFB, Tex.

o *Naval Environmental Data Network:*

Provides the dissemination of meteorological and oceanographic computer products from FNWC at Monterey to specially equipped locations in the U.S. and overseas. The network provides for rapid collecting, processing, disseminating, and displaying of environmental data and consists of on-line telecommunications equipment, automated display devices, digital computers, and associated circuitry.

4. DEPARTMENT OF COMMERCE FACSIMILE COMMUNICATIONS

DOC is responsible for the basic facsimile circuits, including those that fulfill international commitments. DOC 's facsimile networks serve different users in different geographical areas; they include long-line and radio systems.

National Facsimile (NAFAX) Network:

This long-line network which extends throughout the U.S. distributes a comprehensive set of charts depicting analysis, forecast, and selected observational data to civil and military WSO's and to various other users. Basically a graphics network, NAFAX serves approximately 250 NWS offices, 450 military and civil governmental offices, and nearly 350 nongovernmental users -- more than 1,000 drops overall.

Exception for the radar summary charts prepared by the NSSFC and digitized cloud pictures prepared by NESS, all materials originate at NMC.

National Aviation Meteorological (NAMFAX) Network:

A long-line network which provides selected civil and military weather offices with graphic guidance materials, including satellite products, to support international high-altitude aviation operations. The network operates at 120 and 240 scans per minute with automatic selection of speed and mode as a function of the type of product being transmitted. The network extends to the U.S. borders, and carries products to Alaska for relay to the Intra-Alaska facsimile network. The network also extends selectively to Canada, Mexico, San Juan, Curacao, and Nassau.

Forecast Office Facsimile (FOFAX) System:

A long-line network which distributes 1) NMC forecast guidance materials and NESS satellite products to the WSFOs; 2) NESS-prepared SMS pictures and digital mosaics obtained from satellite pictures. FOFAX operates at 120 or 240 scans per minute and has automatic selection of speed and mode.

Tropical Regional Analysis Facsimile Circuit (TROPRAN):

A long-line network which distributes tropical area analyses and prognoses. It carries: 1) NMC products for use by the NHC; 2) NESS tropical-area satellite data to all users on the circuit; 3) charts manually prepared by NHC to NMC for relay to the Caribbean HF radio broadcast from Brentwood, N.Y., and to FOFAX.

Intra-Alaska Facsimile Network:

A system of microwave, troposcatter, satellite links, cable, and high-frequency radio facilities used to distribute graphic materials throughout Alaska. Charts prepared by WSFO Anchorage, and charts received from NMC are switched automatically into the Network. At present the Intra-Alaska Facsimile Network serves 11 NOAA, one Coast Guard, three FAA, 13 DOD Offices, plus private users. FAA and NOAA fund the portion of NAMFAX which connects to Alaska, via a satellite channel from Valley Forge, Pa., to Talkeetna, Alaska. NOAA provides approximately 90% of the funds for circuitry within Alaska, and DOD the remainder. Portions of the backside of the intra-Alaska facsimile network are employed to deliver tsunami and tide gage information to the Palmer Observatory in Alaska.

5. OTHER FACSIMILE BROADCASTS

International radio facsimile meteorological broadcasts are transmitted via leased commercial HF radio facilities. These broadcasts are beamed primarily toward the Caribbean, Central America, South American, and southwest Pacific areas.

Several facsimile broadcasts are relayed through the NASA satellites ATS 1 and 3, and the SMS/GOES systems.

Marine HF radio facsimile meteorological broadcasts, intended primarily for reception by ships at sea, are transmitted from the U.S. West Coast via Coast Guard facilities. A special HF radio facsimile service is provided to the Pacific coast and high seas tuna fleet by

by NOAA-Scripps Institution of Oceanography, Radio Station WWD, at La Jolla, California.

Real-time reconstructed radar images consisting of weather echoes with added handwritten annotations and geographical overlay are transmitted in facsimile from the 35 WSR-57 radar sites currently equipped with transmitters. The two operational modes employed are hard-wire private line circuits leased from common carriers and direct-distance dialing. Either service is available to interested government and non-government users on a cost-basis.

6. DEPARTMENT OF DEFENSE FACSIMILE COMMUNICATIONS

DOD is responsible for circuits filling unique military requirements.

Strategic Facsimile Network:

A landline and microwave net that extends to selected DOD users at approximately 70 U.S. locations. AFGWC at Offutt AFB is the transmitting facility. The Strategic Facsimile Network supplements DOC's facsimile system by providing specialized graphical data oriented to military operations. It is used primarily to support the readiness of U.S. strategic weapons forces and secondarily to support airlift and tactical forces. The Network operates at 120 or 240 scans per minute. Most products are computer-generated and introduced into the system through digital-to-analog converters.

Overseas Facsimile Networks:

To satisfy the needs of military customers overseas, AFGWC transmits specialized products to European locations over the European Facsimile Network (EURFAX) and to the Pacific over the Pacific Facsimile Network. The Pacific network operates at 120 or 240 scans per minute while EURFAX operates at 120 scans per minute. The Air Force has a program to upgrade the EURFAX system with modernized recorder hardware. Most products are generated by AFGWC; a limited number of specialized, manually prepared products are injected into EURFAX by the European Tactical Forecast Unit at Kindsbach, Germany, and into the Pacific network by the Asian Tactical Forecast Unit at Yokota Air Base, Japan.

Fleet Weather Broadcasts:

The Naval Communications System supports the Naval Weather Service in its requirements for specialized operational communications. Meteorological traffic is handled in the same manner as other Navy traffic; no center or unit is dedicated exclusively to meteorological communications. Meteorological information is transmitted to Naval operating forces via radio (CW, teletypewriter, and facsimile) broadcasts. Designated Fleet Weather Centrals are responsible for contents of these broadcasts which include observations, analyses, forecasts, and warnings. In preparing broadcasts, the centrals and facilities make use of their own specialized products, those from FNWC, and, to the extent possible, products from the Basic Meteorological Service and data from DOD's Automated Weather Network.

ESTIMATION OF DATA LOADS FOR 1985 ERA WEASATS

This report is in presentation format.

ESTIMATION OF DATA LOADS FOR 1985 ERA WEASATS

CONSIDER THE 3 PRINCIPAL FUNCTIONS:

- BASIC ATMOSPHERIC PARAMETER MEASUREMENTS - SIMILAR TO THAT PERFORMED BY CURRENT POLAR SATS, BUT EXPANDED TO REFLECT TECHNICAL IMPROVEMENTS

- CLOUD COVER MEASUREMENTS - SIMILAR TO THAT PERFORMED BY GOES, BUT IMPROVED

- SEVERE STORM MONITORING AND TRACKING - NOT CURRENTLY PERFORMED

ESTIMATE DATA LOAD FOR EACH.

DETERMINE DRIVERS -

CHECK DATA LOAD OF SECONDARY FUNCTIONS FOR SIGNIFICANCE - ADD ONLY IF SIGNIFICANT.

1985 BASIC WEASAT DATA LOAD MODEL

CHARACTERISTICS: 90 KM MESH, HEMISPHERICAL COVERAGE, 12 LEVELS, RE-INITIALIZATION INTERVAL 1 HOUR.

MEASUREMENTS: PRESSURE AND TEMPERATURE

NO. BANDS: 8 (USED CURRENTLY)

DATA CONTENT: 12 BITS PER MEASUREMENT PER POINT PER BAND, PLUS 2 BITS FOR IDENTIFICATION (SYNCH.) - TOTAL 14 x 2 = 28 BITS; x 8 BANDS = 224 BITS/POINT

TOTAL # BITS PER DUMP (1 HOUR) (R = EARTH'S RADIUS = 6,370 KM):

$$\frac{2\pi R^2}{\overline{90}^2} \text{ X 12 LEVELS x 224 = 84.6 M BITS}$$

IF DUMPED CONTINUOUSLY:	23.5 KB/SEC
ADD MISSION-RELATED LOAD:	$\simeq$ 2.5 KB/SEC
TOTAL DATA RATE:	$\simeq$ 26 KB/SEC

ISSUES:

1. SENSORS ARE ASSUMED TO HAVE PROGRESSED TO CAPABILITY OF ROUTINE MEASUREMENT OF TEMPERATURE, PRESSURE - ONLY PARTIALLY PERFORMED NOW FROM POLAR SATS.
2. NO PROBLEM IN SPACE-TO-GROUND LINK IF SAT IS SYNCHRONOUS
3. ONBOARD STORAGE IF SAT IS OF THE POLAR TYPE (OPERATIVE NOW) - STORAGE SIZE (APPROXIMATELY 10 HOURS OF DATA):

   $$26 \text{ KB/SEC X } 36{,}000 \cong 10^9 \text{ BITS}$$

4. SAT-TO-GROUND LINK FOR POLAR SAT BECOMES:

   $$\frac{10^9 \text{ BITS (STORAGE FOR 10 HOURS)}}{800 \text{ SEC (TIME OF VIEW)}} = 1.25 \text{ M BITS/SEC}$$

5. TDRS RELAY PROBLEM IF SAT. IS POLAR

6. GROUND DATA TRANSMISSION OF POLAR SAT DATA FROM STATION TO CENTRAL (NOW $\simeq$ 48 KHZ) MUST GROW FOR POLAR SAT TO ALLOW DUMPING TO CENTRAL WITHIN APPROXIMATELY 15 MINUTES TO ALLOW TIMELY INITIALIZATION

$$\text{DUMP TO CENTRAL: } \frac{10^9 \text{ BITS}}{15 \times 60 \text{ SECS}} \cong 1.1 \text{ M BIT/SEC.}$$

7. THERE IS AN IMPACT ON THE ASSIMILATION SYSTEM AT CENTRAL - BECAUSE THE SAT. DATA DUMP GROWS FROM 48 KHZ TO 1.1 M BIT/SEC. THE IMPACT IS HOWEVER NOT LINEAR (OR PROPORTIONAL) BECAUSE THE NON-SAT DATA ARE STILL BEING COLLECTED.

8. THE WWW DATA, IF SATELLITES REACH THESE CAPABILITIES, NEEDS TO BE COLLECTED IN BULK AND REAL-TIME RATHER THAN SUMMARIZED AND DELAYED. IMPACT ON INTERNATIONAL GROUND LINES.

9. POTENTIAL TDRS RELAY PROBLEM FROM OTHER 2 (POSSIBLY NON-U.S.) SYNCH. SATS.

CLOUD COVER DATA REQUIREMENTS - HYPOTHESIZED 1985 SYNCHRONOUS SYSTEM - EVOLUTION OF CURRENT GOES

REQUIREMENT FOR PRECISION OF CLOUD COVER MEASUREMENT: ±5% DOWN TO 20% COVER, OVER A CELL SIZE OF 1,000 KM^2

$$e\% = \frac{200k}{\sqrt{h}}$$

k = INTERPRETATION CONSTANT $\cong$ 1

h = RATIO OF TOTAL CLOUD AREA TO RESOLUTION ELEMENT AREA

e%= PERCENT ERROR IN MEASURING CLOUD COVER

HENCE:

$$h = \frac{4 \times 10^4 k^2}{(e\%)^2};$$

IF k $\cong$ 1, e% = 5 DOWN TO 20% CLOUD COVER:

h = 1,600

LINEAR RESOLUTION REQUIRED, $r = \sqrt{\frac{200(KM^2)}{1,600}} = 0.35$ KM

1985 RESOLUTION REQUIREMENTS;

r AT VISIBLE $\cong$ 0.35 KM

r AT IR $\simeq$ 4 KM

(CURRENT 0.8 & 8 KM)

SATELLITE COVERS $\simeq \frac{1}{4}$ OF EARTH'S SURFACE IN 10 MIN (NOW IT COVERS $\simeq$ 1/4 EARTH SURFACE IN 18.2 MIN.)

NOTE: 10 MIN REACTION TIME IMPROVES KNOWLEDGE OF WINDS AND IS CONSISTENT WITH ASSUMED 90 KM MESH IN MODEL.

NO. LEVELS: 16 $\cong$ 4 BITS

AREA OF 1/4 EARTH'S SURFACE: 127×10^6 KM^2

NO. OF RESOLUTION ELEMENTS: $\frac{1.27 \times 10^8}{(0.35)^2} \cong 6.38 \times 10^8$

NO. OF BITS: $6.38 \times 4 \times 10^8 = 2.55 \times 10^9$ BITS

DATA RATE: $\frac{2.55 \times 10^9}{(10\text{MIN}) \times (60\text{ SEC})} = 4.25$ MB/SEC.

ISSUES:

1. NO PROBLEM SPACE-TO-GROUND LINK EXCEPT MORE SYSTEM ERP.
2. IF MORE THAN 1 SYNCH. SATELLITE, COMMUNICATIONS VIA TDRS MAY PRESENT PROBLEM.
3. INCREASE GROUND DATA RATE (OR PREPROCESSING AT GROUND SITE).
4. IF SATELLITE IS USEFUL ONLY FOR INITIALIZATION: IMPACT ON ASSIMILATION SYSTEM -
5. IF SATELLITE IS USEFUL ALSO FOR RAIN ANNOUNCEMENTS, GROUND SYSTEM MUST OPERATE IN REAL TIME - I.E. 0.5 TO 1 HR MAX. END-TO-END FROM PROCESSING TO DISSEMINATION.

HYPOTHESIZED 1985 SYNCHRONOUS STORM SAT.

TORNADO ADVISORY

NO. OF TORNADOES IN U.S. AVERAGE: 630/YR.

NO. OF TORNADO-DAYS U.S. AVERAGE: 158/YR.

THEORETICAL ALERT STATUS: 43% OF THE TIME - HOWEVER SINCE OCCURRENCE IS RANDOM, ESSENTIALLY 100% OF THE TIME.

TEMPORAL DISTRIBUTION OF TORNADOES OVER U.S. (ROUNDED):

JANUARY	2%
FEBRUARY	4%
MARCH	10%
APRIL	15%
MAY	23%
JUNE	18%
JULY	10%
AUGUST	5%
SEPTEMBER	5%
OCTOBER	3%
NOVEMBER	4%
DECEMBER	2%
TOTAL	103% (ROUNDOFF ERROR)

SPATIAL DISTRIBUTION OF TORNADOES OVER U.S.:

AREA 1:	TX, OKLA, ARK., KAN., MO., NEB., IOWA:	53%
AREA 2:	LA., MISS., ALA., GEO., TENN., FLA.,:	15%
AREA 3:	SO.D., MINN., WISC., MICH., ILL., IND.,:	14%
AREA 4:	KY., OHIO, PA., VA., W. VA., N.C., S.C., MD., NY., DEL.,:	9%
AREA 5:	MONT., N.D., WYO., COLO., N.M.,:	5%
REMAINDER:		4%
TOTAL		100%

TEMPORAL DISTRIBUTION DURING DAY: PEAKS BETWEEN 3 TO 7 PM

HENCE: PEAK ALERTS MARCH THROUGH SEPTEMBER, AFTERNOONS.

TORNADO SPEED, MEAN: 48 TO 64 KM/HR (AVERAGE 56 KM/HR)

PEAK: 112 KM/HR.

TORNADO SIZE: 100M TO 1.5 KM

PATH LENGTH: AVGE.: 26 KM

MAX.: 352 KM

TORNADO PERMANENCE TIME: AVGE. $\frac{26\text{KM}}{56\ \text{KM/HR}} \cong 28$ MIN.

MIN.: $\frac{26\text{KM}}{112\ \text{KM/HR}} \cong 14$ MIN

DETECTION-TO-WARNING TIME: $\simeq 5'$

SCAN TIME TO DETECTION: $\simeq 2.5'$

AREA OF IMPORTANCE: 80% OF U.S., 6.4×10^6 KM^2

RESOLUTION: $\simeq$ 300 M (POSSIBLE WITH 16 LEVELS = 4 BITS)

DATA RATE: $\frac{6.4 \times 10^6}{0.3^2} \times \frac{1}{(2.5\text{MIN}) \times (60\ \text{SEC})} \times 4$ BITS = 1.9 M BITS/SEC

ISSUES:

1. NO GROUND SYSTEM IS IN EXISTENCE FOR RECEPTION, PROCESSING, IMPACT PREDICTION, DISSEMINATION
2. GROUND SYSTEM TURN-AROUND TIME
3. COST/BENEFIT OF DAMAGE VERSUS WARNING TIME MAY HELP IN RELAXING SPECS
4. PROBABILITY OF SEEING SMALL TORNADOES IS QUESTIONABLE (CLEAR AIR FORMATION).

OTHER WEATHER REQUIREMENTS

(SATELLITE OBSERVATIONS)

SURFACE WINDS.

NOW EXTRAPOLATED FROM: CLOUD MOTION;

FREE TRANSPONDER BALLOONS (FRENCH EOLE SYSTEM)

DATA RATES RELATIVELY SMALL

SOIL MOISTURE

2 REQUIREMENTS:

1. FOR IMPROVED WATERSHED MODELING: SEE WATER AVAILABILITY
2. FOR CROP FORECASTING: RESOLUTION COMMENSURATE WITH ABOVE

DATA RATES AND IMPACT ARE LESS SIGNIFICANT THAN THOSE FOR IMPROVED CLOUD COVER, OR TORNADO WARNING.

INSOLATION

IN CLEAR AIR, INSOLATION IS THE COMPLEMENT OF CLOUD COVER.

IN TURBID AIR, AEROSOL MODEL NEEDED.

DATA RATES RELATIVELY SMALL

SOIL TEMPERATURE

2 REQUIREMENTS:

1. FOR IMPROVED WATERSHED MODELING, TO PERFECT COMPUTATION OF EVAPOTRANSPIRATION BY ITSELF OR IN CONJUNCTION WITH SOIL MOISTURE
2. FOR CROP FORECASTING, TO IMPROVE ESTIMATION OF CONDITION AND FORECAST OF YIELD.

RESOLUTION REQUIREMENTS ARE RELATIVELY BROAD (ORDER OF SEVERAL KM). THUS DATA RATES LESS THAN THOSE FOR THE BASIC WEATHER FUNCTIONS.

AIR STAGNATION

DERIVED FROM BASIC WEATHER DATA.

ESTIMATION OF DATA LOADS FOR 1985 ERA WEASATS RECAP OF DATA SYSTEM MAJOR IMPACTS

1. THE POSTULATED BASIC WEASAT IMPACTS DATA SYSTEM *ONLY IF POLAR* - 2.5 MB/SEC DUMP RATE, CORRESPONDINGLY HIGH GROUND RATES .

   PROBABILITY IS THAT THEY WILL REMAIN POLAR - BECAUSE OF METHODS USED

2. CLOUD COVER MEASUREMENT WILL CONTINUE SYNCHRONOUS - 4.25 MB/SEC DUMP RATE - BIGGEST IMPACT.

3. TORNADO SAT (STORM SAT) NEEDS TO BE SYNCHRONOUS - 1.9 MB/SEC DUMP RATE.

4. THE MAJOR DATA RATE DRIVERS ARE RESOLUTION AND AREA COVERAGE; NEXT IS TIME INTERVAL OF DUMP; NEXT IS GROUND TURN-AROUND TIME.

5. OTHER SYSTEM DRIVERS: GROUND PREPROCESSING AND PROCESSING; TDRS DATA RELAY.

6. OTHER IMPACTS ARE SMALLER

VERTICAL TEMPERATURE PROFILING OF THE ATMOSPHERE FROM SATELLITES

VERTICAL TEMPERATURE PROFILING OF THE ATMOSPHERE FROM SATELLITES

This report discusses the physics of the methods in current use and proposed sounding of atmospheric pressure from satellites. It provides empirical results to allow comparing satellite-derived measurements with those from radiosondes and rocketsondes.

1. BASIC CONSIDERATIONS

Uncooperative passive satellite sounding techniques measure radiation leaving the earth's atmosphere in particular regions of the electromagnetic spectrum. The layer of atmosphere from which the radiation arises (and which thus is "sensed") depends on the molecular absorption characteristics for the wavelength employed, the optical characteristics and the viewing geometry of the sensor. The radiant energy can be interpreted in terms of the average temperature of the sensed layer through Planck's law.

Figure 1 depicts the spectral regions which have been found most useful for sensing from satellites.

The three major atmospheric windows (regions of minimum molecular absorption) can be used to sense surface temperature.

The three major absorption bands due to constituents with a uniform distribution in the atmosphere, can be used for sensing the vertical temperature profile.

Both windows and absorption bands occur in the near and intermediate infrared and in the microwave range of the spectrum.

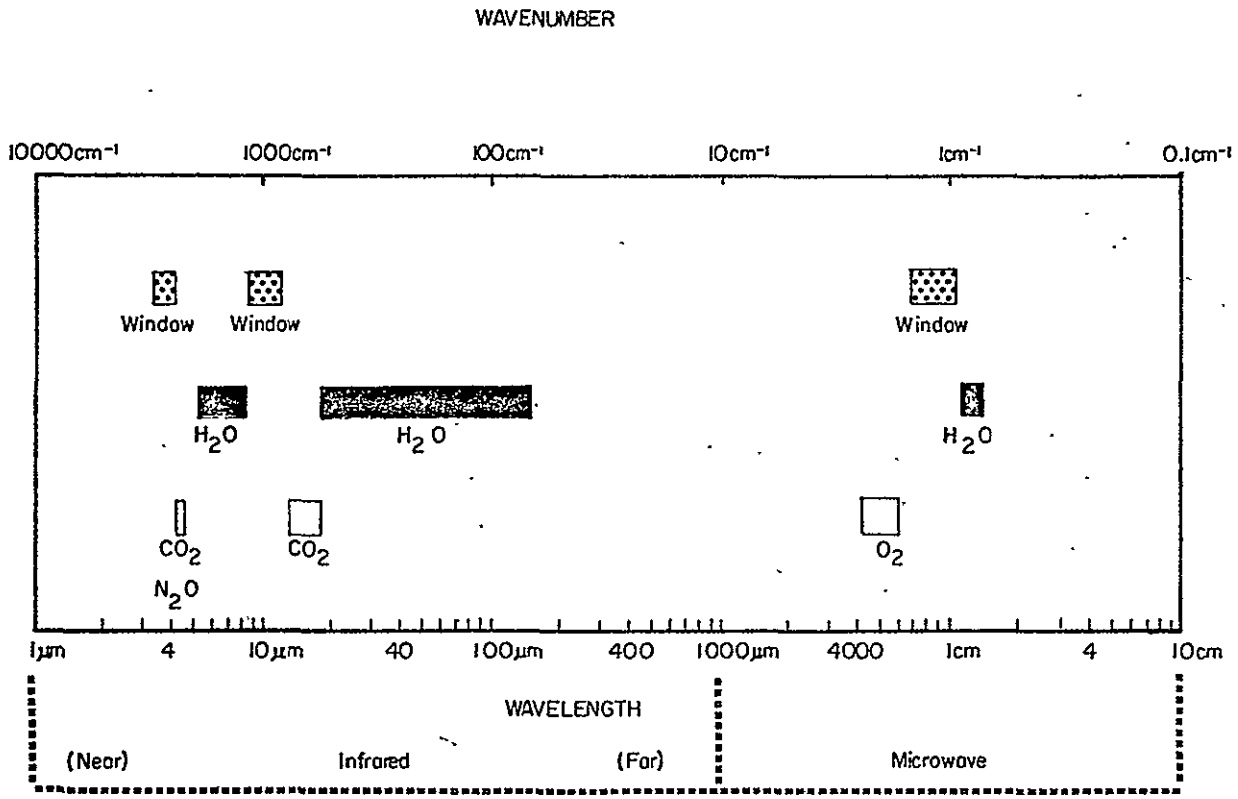


FIGURE 1

SPECTRAL REGIONS FOUND USEFUL FOR INDIRECT SENSING FROM SATELITIES

The top row indicates the location of atmospheric windows.

The bottom row indicates the location of absorption bands from distributed constituents.

Windows are usable to measure surface temperature.

Absorption bands are usable to measure vertical temperature profile.

The wavenumber is the number of wavelengths contained within one centimeter. For example, 1,000 cm^{-1} means 1/1,000th of 1 cm, or 10 microns.

Figure 2 compares the relevant characteristics of these three spectral regions.

From the standpoint of available thermal energy, the 15-μm region has a distinct advantage over the 4.3-μm and 5-mm spectral regions. Thus, if the detector sensitivity were the same for all spectral regions, the 15-μm region would be superior to the other two.

The performance of currently available detectors within each spectral region, and the required spectral bandwidths and optical fields of view are such that the 4.3-μm region is best for sensing the relatively warm regions of the atmosphere: it is inferior to the 15-μm region for sensing the cold portions. This is because the radiance at 4.3 μm depends upon temperature more strongly than the radiation emitted at 15 μm or 5 mm. At low temperatures, however, the energy at 4.3 μm is much closer to the detector noise level than is the case for the other two regions. Consequently, in clear atmospheric conditions the 4.3-μm and 15-μm regions are superior to the 5-mm region for sensing atmospheric temperature.

The presence of clouds forces consideration of the cloud penetration capability of each spectral region. The microwave region has an overwhelming advantage in this regard, especially for cirrus (ice) clouds.

In summary, all three spectral regions possess basic advantages and disadvantages for atmospheric sounding. Consequently, instruments operating in all three spectral regions have been tested aboard spacecraft during the first half of this decade.

ENERGY (Relative Planck Radiance)

	200°K	300°K
4.3μm	1.25	200
15.0μm	5000	15000
5.0μm	1	1

TEMPERATURE SENSITIVITY (Relative to Detector Noise*)

	200°K	300°K
4.3μm	1	20
15.0μm	10	6
5.0mm	4	1

*(0.002, 0.2 erg/cm^2 s str cm^{-1}, 0.7°K)

CLOUD TRANSMISSION

	Water	Ice
4.3μm	6%	1%
15.0μm	1%	1%
5.0mm	96%	99.98%

FIGURE 2 - COMPARISON OF CERTAIN CHARACTERISTICS OF THE 4.3-μm, 15.0-μm and 5.0-mm SPECTRAL REGIONS

2. DOWNWARD VIEWING SPECTRAL METHODS

A. The Satellite Infrared Spectrometer (SIRS) Approach

This technique measures the radiation emerging from the top of the atmosphere in several spectral intervals ranging from the center out to the wing of an absorption. Thermal energy measured near the opaque band center arises from higher altitudes because the atmosphere absorbs the energy emitted at lower heights. Energy measured in the wing of an absorption band arises from lower altitudes because of the higher transparency of the upper atmosphere at the bands edges. If the distribution of the absorbing gas is known, the variation of the sensed outgoing radiation with wavelength can be interpreted in terms of the variation of atmospheric temperature with altitude.

Figure 3 illustrates spectra of outgoing radiation equivalent blackbody temperature near 15-μm as measured by the Infrared Radiation Interferometer Spectrometer (IRIS) from the Nimbus-4 Spacecraft. Note that the radiation temperatures decrease as the center of the band is approached. This corresponds to the decrease of tropospheric temperature with altitude. The minimum at $\sim 690\ cm^{-1}$ is associated with the cold tropopause: the subsequent increase to a maximum at the band center is due to the increase of temperature with altitude in the stratosphere. The entire spectra need not be measured to infer the temperature profile; just several (five to seven) carefully selected spectral intervals (cf. those shown by arrows, chosen for the SIRS sounder). This is because the energy measured at any wavelength arises from a relatively deep layer (8-12 km) of the atmosphere so that the measurements at adjacent frequencies are highly redundant, i.e. strongly correlated.

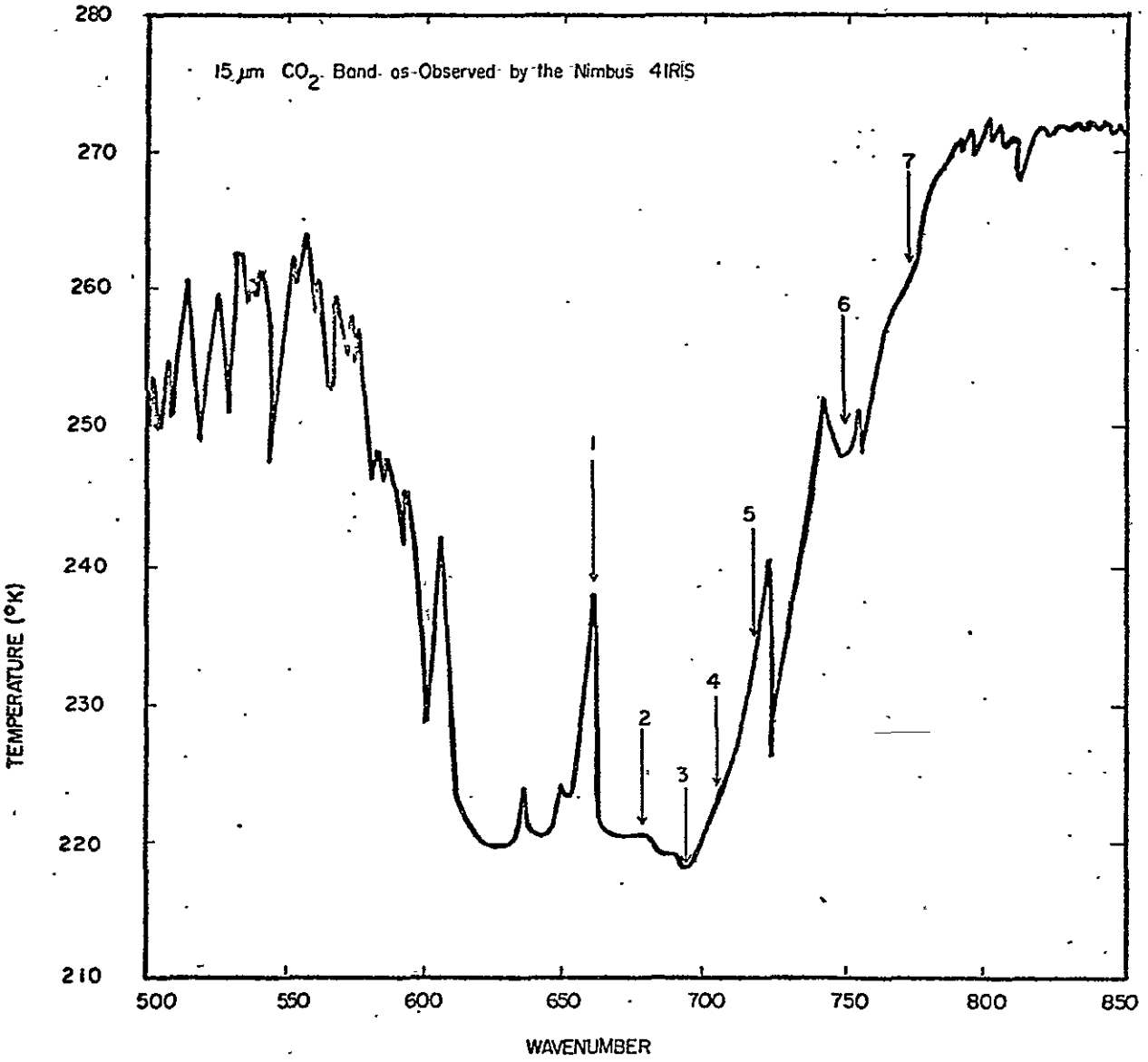


Fig. 3. Spectra of outgoing radiation equivalent blackbody temperature near 15-μm observed by the IRIS on Nimbus 4 (the arrows denote the spectral regions sampled by the SIRS instrument).

Figure 4 indicates the altitude of the vertical layers sensed by the eight 5-cm^{-1} spectral channels of SIRS. The curves, usually referred to as weighting functions, depict the layers of atmosphere most vividly sensed by the particular spectral channels. The complete temperature profile of the atmosphere is obtained from all the spectral measurements using one of the several available numerical solutions. For a discussion of these methods see report No. 6, "Meteorological Observations via Satellites," pp. 11-14, appended.

Figure 5 exemplifies a SIRS sounding. Note the inability to resolve small-scale vertical structure from this type of radiance data. This problem is dramatized by the failure to resolve the sharp tropopause feature. Nevertheless, the SIRS has proven to be able to diagnose large-scale temperature features with an accuracy of 1° to $2^{\circ}C$.

It should be emphasized that the derived temperature soundings are highly sensitive to instrumental noise. Evidence of this is contained in Figure 6, which shows a SIRS profile derived when a spurious error of 10% existed in a single channel. For this reason the measurement noise on all downward viewing infrared sounders is kept below 0.5%.

B. The Selective Chopping Radiometer (SCR) Approach

The SIRS spectral resolution (5 cm^{-1}) is inadequate for measuring the upper stratosphere. To observe these high altitudes with a downward viewing instrument one must sense the outgoing radiation with extremely high spectral resolution at the center of the absorption band.

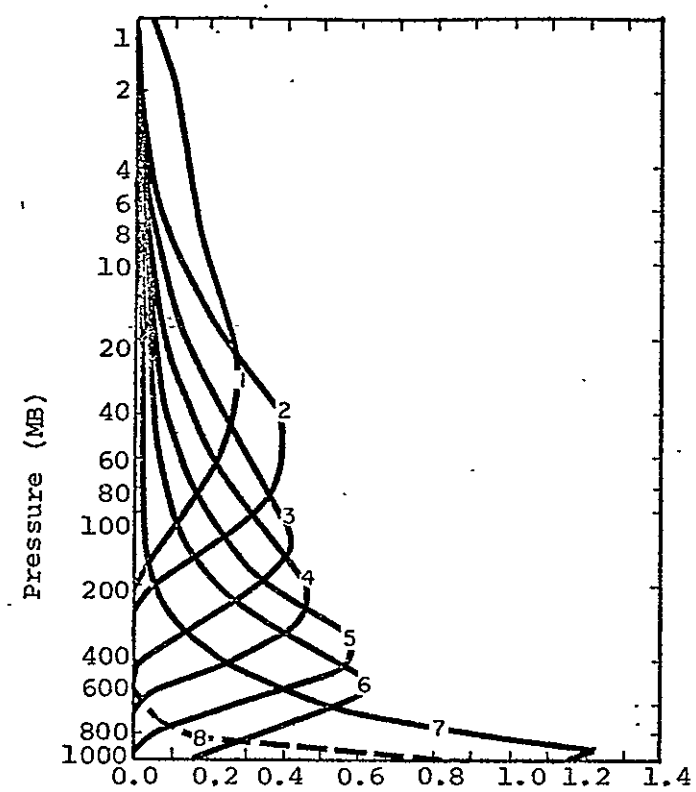


Fig. 4. Vertical layers sensed by the 5-cm wide spectral channels of the SIRS instrument on Nimbus 3.

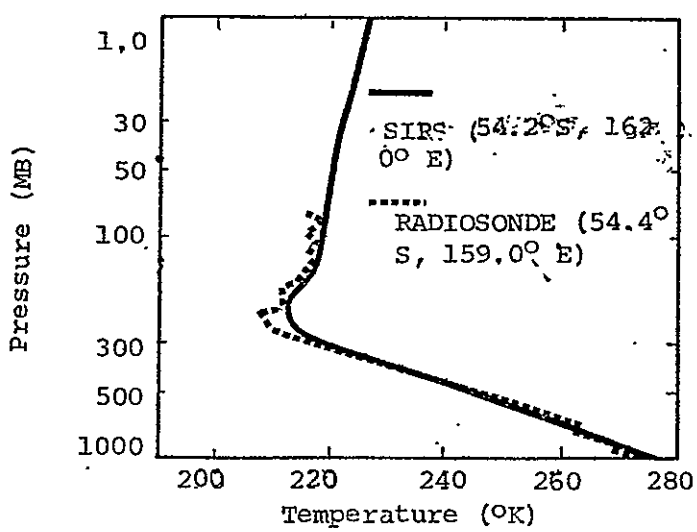


Fig. 5. Comparison of a SIRS derived temperature profile with a radiosonde observed temperature profile at latitude 54S.

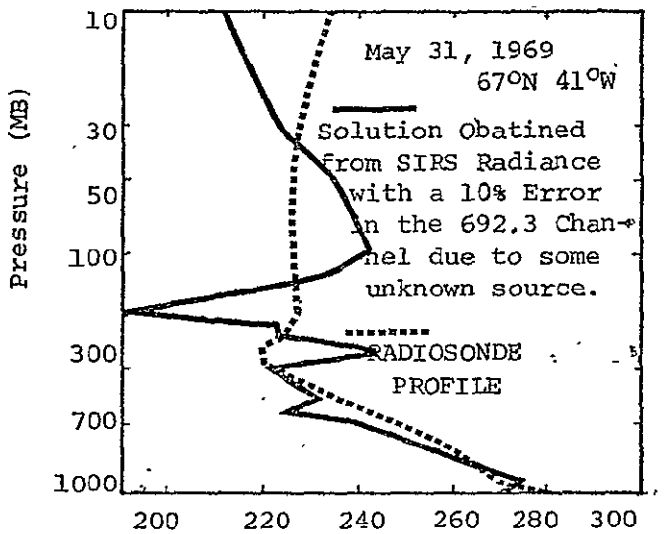


Fig. 6. Comparison of a radiosonde observed temperature profile with a SIRS derived temperature profile when a spurious telemetry error of 10% existed in a single channel.

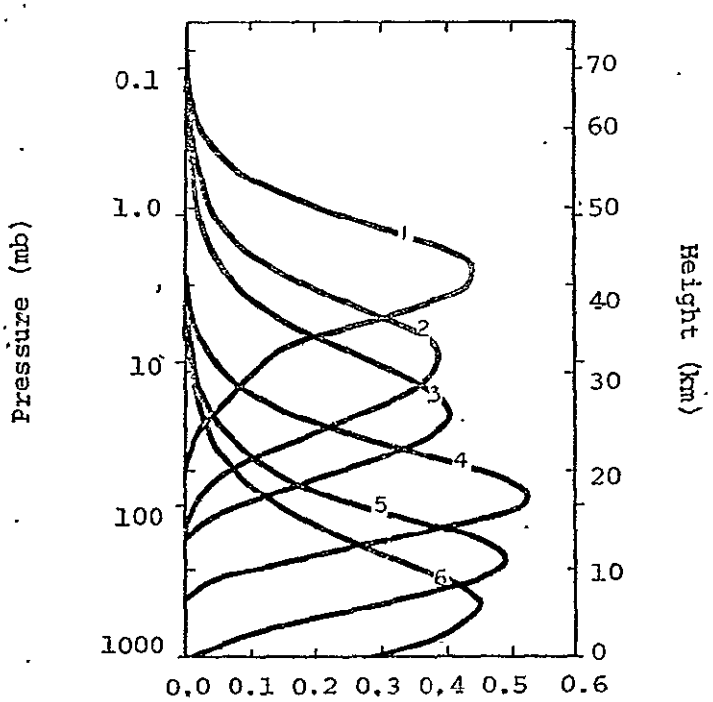


Fig. 7. Weighting for the six spectral channels of the SCR instrument on Nimbus 4.

This instrument periodically places cells containing CO_2 gas in the path of the incoming radiation. The path through the CO_2 cells is selected to be equivalent to the normal path traversed by the radiation in the corresponding layer of the atmosphere. Thus significant atmospheric absorptions causes the incoming radiation to be modulated at the "cell insertion frequency."

Figure 7 depicts the Nimbus 4 SCR channel weighting functions. As shown, this technique is capable of observing temperatures to the 45-km level. The comparison shown in Figure 8 indicates good agreement, in the range from 100 to 2 mb, between the SCR-derived and rocketsonde-observed profiles.

Figure 9 exemplifies an SCR sounding during an event of stratospheric warming, a situation very difficult to retrieve directly from SIRS data. Good evidence of the warming trend appears in the SCR-derived temperature profile: yet the absolute accuracy still leaves much to be desired.

To infer upper stratosphere temperatures with better accuracy requires the measurements of radiance using weighting functions which peak in the mesophere. Such weighting functions are characteristics of an advanced version of the SCR tested aboard the Nimbus-F satellite during 1974.

C. The Multi-Band Infrared Approach

As indicated eralier, 4.3 μm CO_2 band offers advantages over the maximum energy 15 μm CO_2 band:

a) Greater dependence of the Planck radiance upon temperature makes measurements more sensitive to vertical and horizontal temperature gradients, except at the low temperatures near the tropopause;

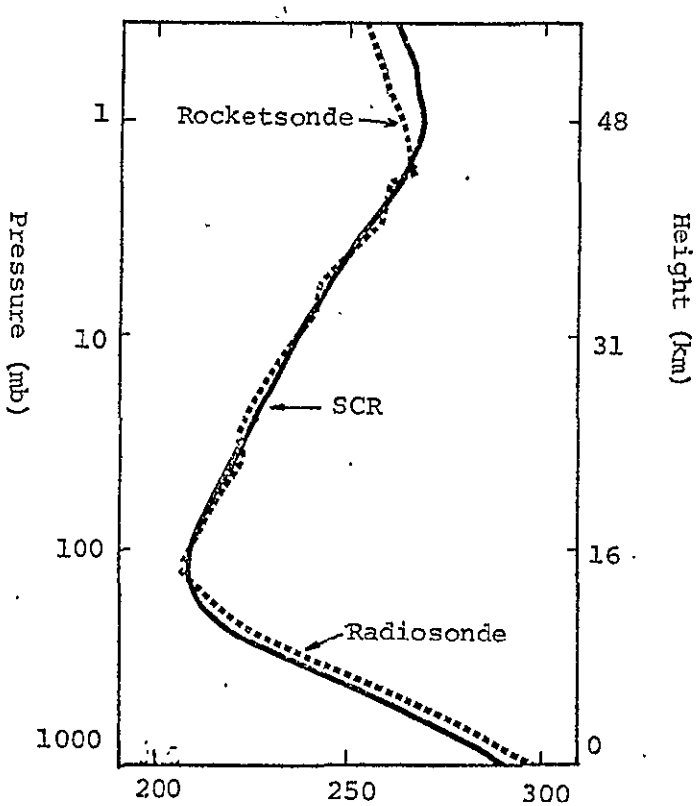


Fig. 8. Comparison of a SCR derived temperature profile with a radiosonde/rocketsonde observed temperature profile.

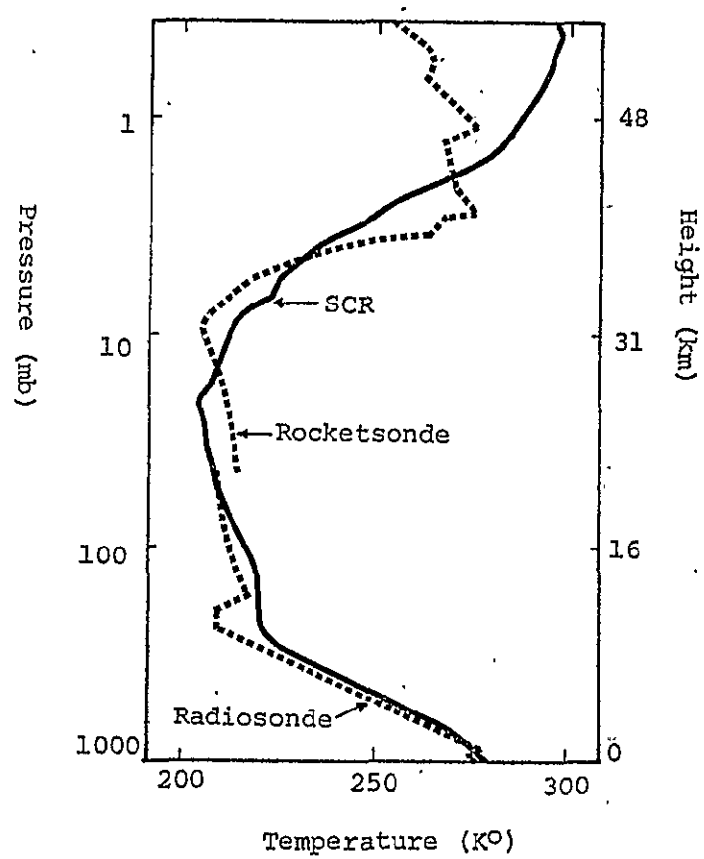


Fig. 9. Comparison of a SCR derived temperature profile with a radiosonde/rocketsonde observed temperature profiles at West Gerinish and Stornoway, during a stratospheric warning

b) The absorption of CO_2 is greater, allowing the probe of higher altitudes.

A high-resolution Infrared Sounder (HIRS) on Nimbus-F will sense simultaneously several spectral intervals of the 4.3 μm and 15 μm CO_2 bands to improve temperature profiling accuracy.

Figure 10 shows the HIRS weighting functions. Note the high vertical resolution in the lower atmosphere in the 4.3 μm CO_2 channels: and the visibility of the tropopause region, made possible because the Planck radiance is small in this cloud layer of the atmosphere. The 4.3 μm channels exhibit greater sensitivity to the upper stratosphere near the 1-mb level as compared to the 15 μm CO_2 band measurements.

Figure 11 compares temperature profiles derived from synthetic, essentially error-free HIRS radiance data, using a) combined 4.3 μm and 15 μm CO_2 observations and b) only 15 μm CO_2 observations. Note that the frontal inversion displayed by the radiosonde was not captured well by the 15 μm data only it did appear with the combined 4.3 μm and 15 μm observations. The errors of the combined-band method are smaller throughout most of the atmosphere. The errors using only the 4.3 μm band measurements (not shown) are larger than those using only the 15 μm band measurements, especially in the tropopause region. The HIRS aboard Nimbus-F will determine whether such improvements can be realized in practice.

The downward viewing sounding radiometer on the operational TIROS-N satellite and its successor will take advantage of the multiband approach of HIRS as well as the selective chopping technique.

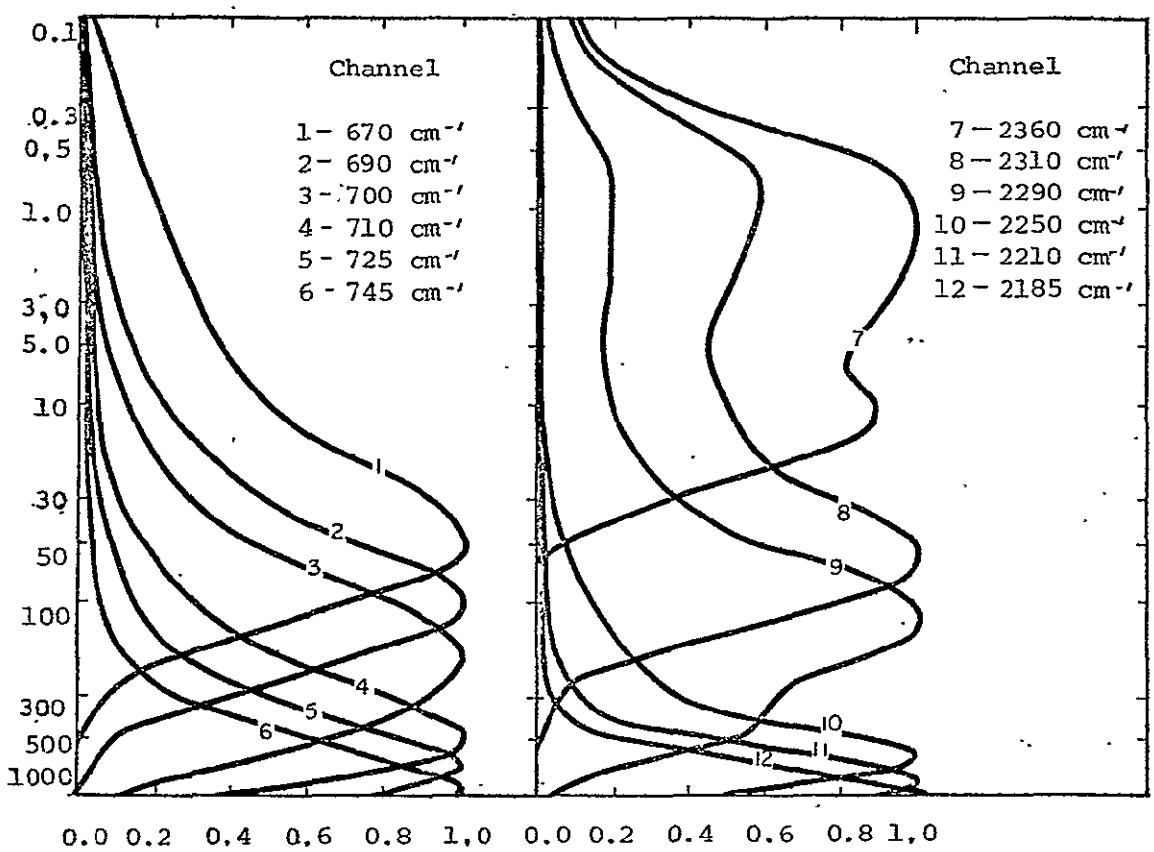


Fig 10 Weighting functions for the twelve spectral channels of HIRS.

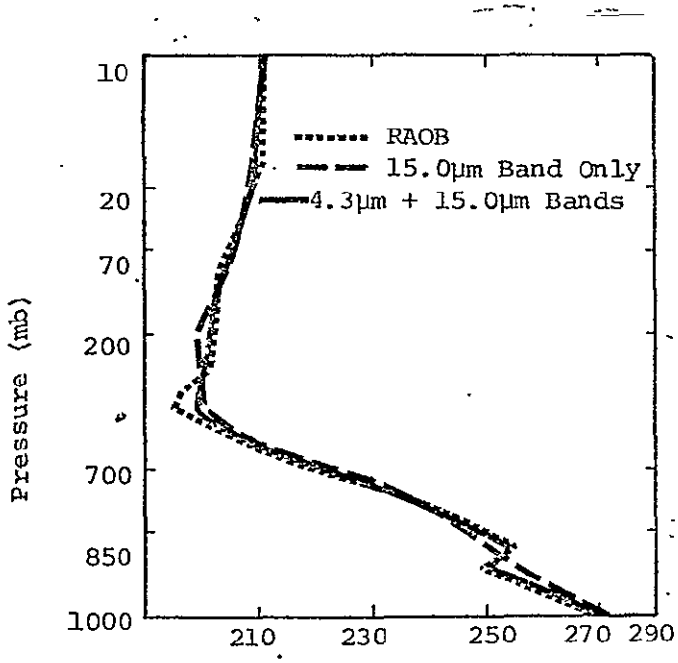


Fig 11 Comparison of HIRS 4.3-μm plus 15μm CO_2 derived temperature profile with a 15-μm CO_2 derived temperature profile and a radisonde observed temperature profile.

D. Medium Resolution Scanning Improvements

The limitation of infrared spectral regions for atmospheric sounding is caused by the high absorptivity of clouds. When a cloud completely fills the field of view of an infrared sounding instrument, no thermal information can be sensed below the cloud level. When a partial cloud cover exists, it is difficult to differentiate the cloud condition from the thermal structure; that is, high clouds in a warm troposphere are visualized in the infrared similarly to low clouds within a cold troposphere.

The problem of sounding the troposphere in the infrared in the presence of partial cloudiness can be alleviated using instruments which contiguously scan the atmosphere with medium spatial resolution (30-60 km). Given numerous spatially independent observations of radiance over a broken cloud regime, the major variation will be due to a variation of the amount of cloud within the instruments field of view. This property can be utilized to determine the radiance propagating from the cloudless regions contained within a partially cloudy area.

Figure 12 shows an example of Infrared Temperature Profile Radiometer (ITPR) data obtained from a high altitude NASA aircraft over a broken cloud regime. Shown plotted is the radiance measured in a relatively transparent CO_2 channel at 750 cm^{-1} as a function of the radiance measured in a window channel at 899 cm^{-1}, both observed simultaneously from the high altitude aircraft. As shown, the variation, which is due to a variation in cloud amount, is linear. Consequently, if the clear sky window radiance is known, the clear sky radiance for the CO_2 channel can be inferred by linear extrapolation. The clear sky window radiance can be observed from satellite by the very high spatial resolution scanning radiometers used for cloud mapping. This technique has been demonstrated by its application to radiance data obtained while flying at 33,000 ft over a Pacific cold front. Figure 13 shows a cross-section, through the front, of the radiance-derived temperature profiles and an analysis of the departures from their level mean values. As shown, even though some cloudiness existed above 18,000 ft, the variation of temperature across the front could still be diagnosed. However, it must be emphasized that in areas of extensive overcast (which did not exist in this case), infrared sounding information terminates at the cloud-top level.

E. Microwave approach

It is hoped that sounding through most types of clouds can be accomplished using microwave sensors, since the absorption by clouds and aerosols in this spectral region is usually orders of magnitude less than that in the infrared.

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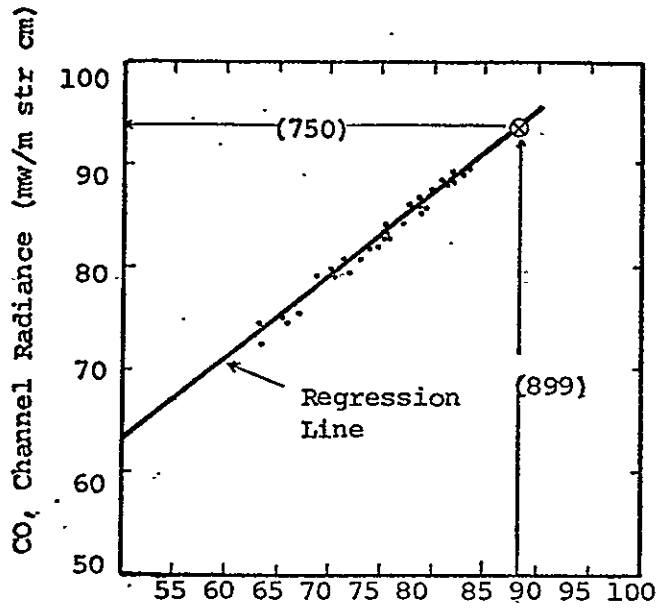

Fig. 12. Aircraft ITPR measured radiances over a cloudy region. Data for a CO_2 channel (750 cm) are plotted as a function of data measured in a window channel (899 cm).

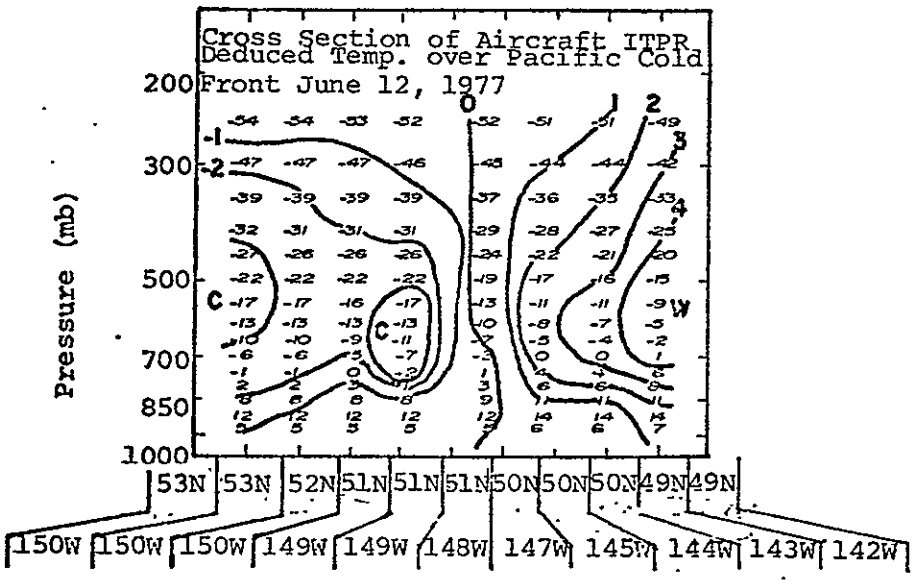

Figure 13

Figure 14 shows theoretical calculations of the ratio of the transmissivity of the atmosphere with clouds to that without clouds. As shown, cirrostratus is completely transparent to microwave radiation and nimbostratus is only partially absorbent. Although thunderstorm clouds are fairly opaque, these will never fill the 200-km field of view of a microwave instrument.

One of the problems of using microwave observations for sounding the lower atmosphere is due to the variation of surface emissivity over a considerable range (0.4-1.0), as a function of surface composition, surface roughness, and soil moisture. It appears that the determination of the surface emissivity will require the combined and simultaneous use of resolution infrared and medium resolution microwave observations performed within their respective windows. The combined use of infrared and microwave radiation for sounding the lower stratosphere and troposphere was initiated with the launch of Nimbus-E.

The microwave region can also be used to sound the stratosphere and lower mesosphere. This is accomplished by within very narrow spectral intervals centered on the peaks of the most absorbing oxygen lines.

3. LIMB SCANNING METHODS

Another technique for probing the atmosphere is called the "Limb Scanning Method." An instrument possessing a very small optical field of view scans across the limb of the earth. At any time, such an instrument receives radiation emanating from a relatively narrow in height layer of the atmosphere.

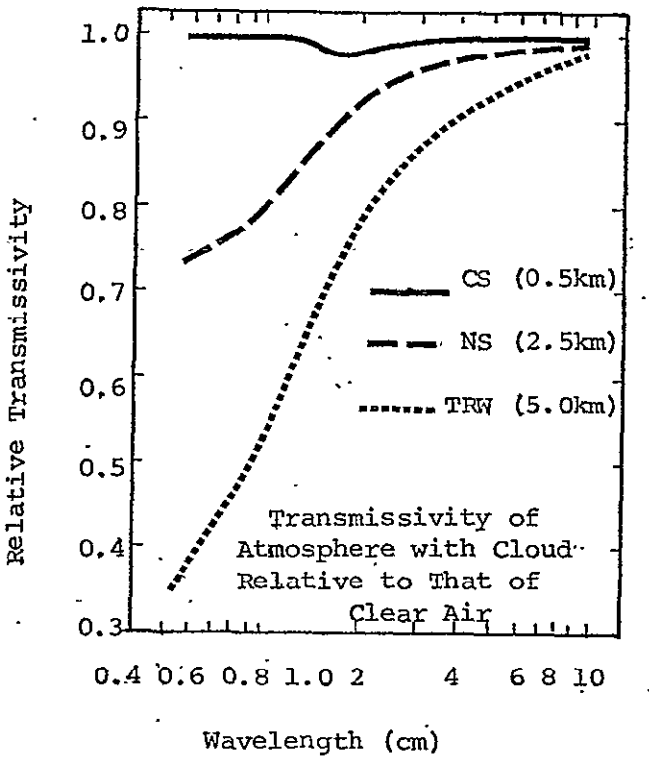

Fig. 14. Radio of transmissivity of the atmosphere with clouds relative to that of clear air (after Westwater, 1972).

CS= Cirrostratus
NS= Nimbostratus
TRW= Thunderstorm Cloud

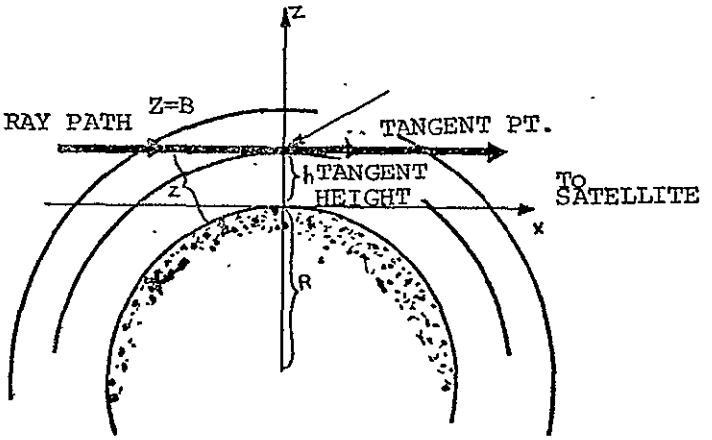

Fig. 15. Limb viewing geometry.

Figure 15 presents the limb-viewing geometry. The satellite-borne radiometer receives radiation emitted by the atmosphere along a ray path that may be identified by the tangent height, the point along the ray path that is closest to the surface. The instrument scans along the tangent height vertical plane. Because of the viewing geometry, none of the signal originates below the tangent point. Because atmospheric density and pressure fall off exponentially with height, most of the sensed radiation originates in the few kilometers of atmosphere above the tangent point.

Figure 16 shows the limb radiance weighting function within a spectral interval covering most of the 15 μm CO_2 band. For tangent heights above 25 km most of contribution is within 3 km of the tangent point. Below 25 km, the weighting functions take on the broader shape of the downward viewing instruments, although a spike still exists at the tangent point.

The limb scanning method was tested on 7 February 1970 by flying an infrared radiometer aboard an aerobee rocket launched from White Sands Missile Range, N. Mex. The radiometer scanned the earth's horizon in the 15 μm CO_2 band. Figure 17 illustrates a smoothed measured limb radiance profile. The measured radiance decreases with tangent height because of the increasing transparency and decreasing emissivity of the atmosphere with altitude. Since the emissivity of the atmosphere as a function of altitude is known for the 15 μm CO_2 band, the temperature profile can be obtained from the limb radiance profile. Figure 18 com-

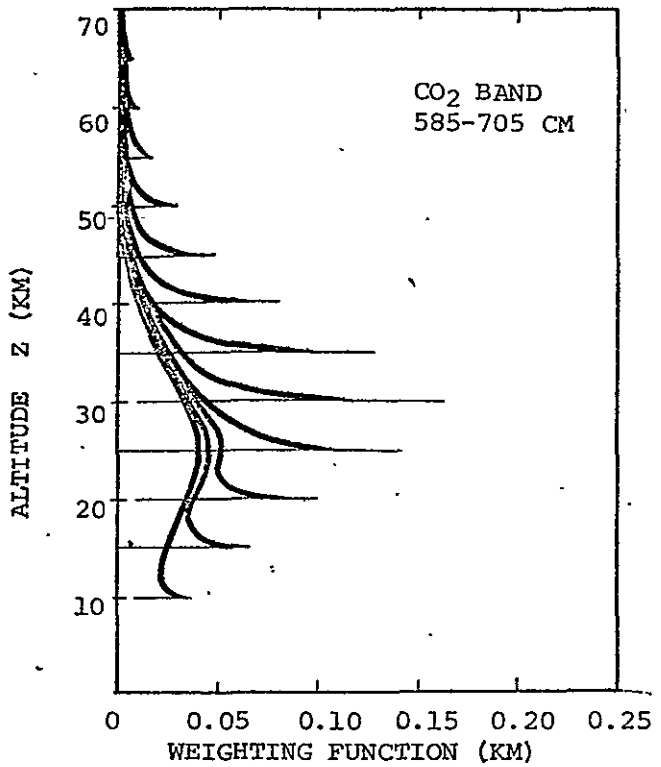

Fig. 16. Limb radiance weighting functions for a broad spectral region of the 15μm CO_2 band.

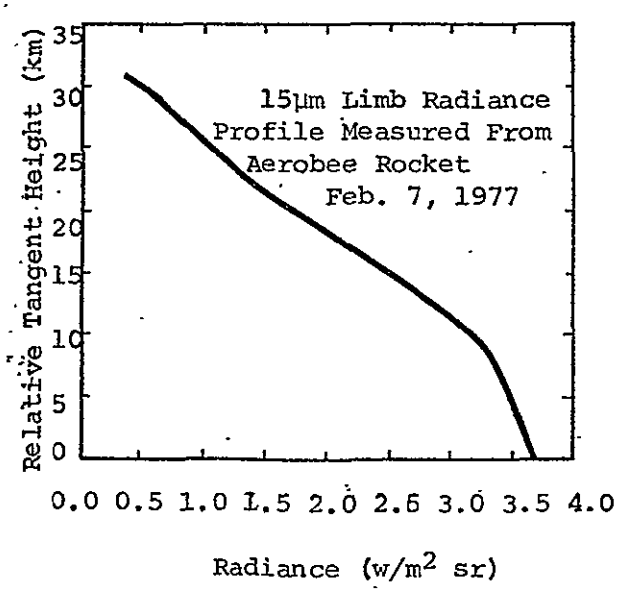

Fig. 17. 15μm limb radiance profile measured from an Aerobee rocket (after McKee, 1972).

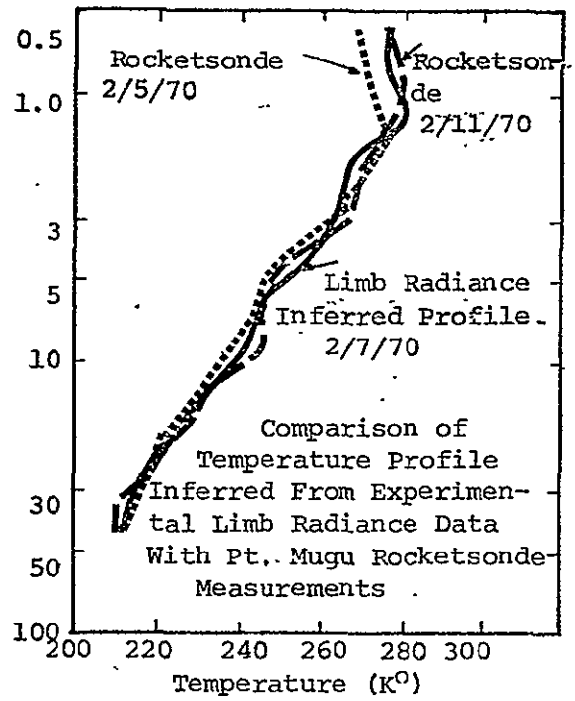

Fig. 18. Comparison of a limb radiance inferred temperature profile with a rocketsonde temperature profile (after) McKee, 1972).

pares the temperature profile derived from the limb radiance profile with available rocketsonde temperature data. As can be seen, relatively small-scale features can be resolved by this technique - for example, the abrupt change in temperature lapse rate near 4 mb. The technique is necessarily limited to the stratosphere because of the likely interference by clouds of a ray traversing through the troposphere. It was implemented during 1974 with a sophisticated Limb Radiance Infrared Radiometer (LRIR) aboard the Nimbus-F satellite.

PRESSURE MEASUREMENTS VIA SATELLITES

PRESSURE MEASUREMENTS VIA SATELLITES

There do not exist currently operational techniques to measure surface atmospheric pressure from satellites. Several schemes have been advanced and are the subject of feasibility studies. This report discusses the two methods most likely to bear fruit in the near future.

GARP specifies a surface pressure measurements accuracy of $\pm 0.3\%$ or ± 3 mb, which corresponds to an altitude difference of only 20m. Thus the height of the surface must be known to great accuracy: this may restrict the usefulness of passive satellite techniques to oceans where the mean height is known. This is not necessarily a limitation: pressure measurements are most needed over ocean areas where they are very sparse.

I. Peckham's Method. This method was advanced by G.E. Peckham at the NASA-sponsored Active Microwave Workshop, Houston, Texas, 1974, and again in the 1975 meeting at GSFC. Its basis is to simultaneously measure the intensity of electromagnetic energy reflected from the surface in an absorption band and at a nearby wavelength. Since scattering by intervening clouds and surface reflectivity are slowly varying functions of wavelength, the ratio of the intensities at the two wavelengths is a measure of the absorption due to the absorption band itself. This yields information on the total amount of gas in the atmosphere and hence the surface pressure.

Phenomena which contribute to the received signal and which might lead to errors in the pressure measurement are ocean surface reflectivity, temperature, water vapor and absorption by clouds. One requirement needed

to attain the GARP ± 3mb specification is knowledge of the surface temperature to within 1 K and $\gamma - 1/\gamma$ to within 0.006, where γ is the ratio of specific heats of air. The temperature measurement could be determined by a passive satellite-borne system: however, this high level of accuracy is not yet attainable. Further the partial pressure of water vapor is a significant part of the total pressure: the presence of water vapor affects the oxygen absorption coefficient (Peckham proposes to use the oxygen 5 mm band). Therefore an integral part of this method of measuring surface pressure is a simultaneous measurement of water vapor.

II. "Optical Path" Methods. The basis of these methods is that the difference between the time for a radio wave to travel from a satellite through a vertical column of dry atmosphere and the time for travel in vacuum is proportional to the pressure at the base of the atmosphere, independent of the pressure-temperature profile. This follows from the proportionality of refractivity to density. Thus the time difference is proportional to $\int_0^\infty \rho dh = \frac{P}{g}$. Clearly, insensitivity to pressure-temperature profiles is a unique advantage of this technique. Its disadvantage is that it requires extremely accurate timing measurements and/or determination of path geometry.

a) Single satellite methods. When only a single satellite is used, the dispersion between two different wavelengths must be measured. This leads to the necessity for measuring very small time differences because even the maximum difference in velocity is only about 0.003 percent. To achieve the GARP accuracy of ± 3 mb requires timing accuracies of about 10^{-12} sec. (10^{-3} nanosec).

b) Dual satellite methods. In these methods the pressure determination is to be made using both the direct and the specular-angle surface-

bounce between two satellites. The bounce-path is greatly advantageous primarily because the relevant time differences are some 2 to 3 orders of magnitude greater than for the single satellite method. An additional factor of about 5 beyond the times which arise in single satellite methods can be achieved because of the longer (slant-range) path. Thus it turns out that timing to about 1/3 10^{-9} seconds would be adequate. However, this method involves a more complex path geometry.

CONTRIBUTION OF SATELLITE DATA TO IMPROVEMENT OF THE NWP FORECASTS

CONTRIBUTION OF SATELLITE DATA TO IMPROVEMENT OF THE NWP FORECASTS

This report addresses the question "How much of the improvement in NWP forecasts is due to satellite data?" Following is a summary of the current status in this area.

In conjunction with the GARP Data Systems Test (DST), the NMC is conducting a series of tests designed to assess the impact of satellite-derived soundings upon the NMC analysis and forecast system.

Forecasts through 84 h are generated from analyses produced with and without the soundings obtained from the operational VTPR instrument aboard NOAA-4 and the experimental infrared (HIRS) and microwave (SCAMS) instruments aboard Nimbus-6. The "first guess" for these analyses provided by the NMC nine-layer global model: subsequent forecasts are made with the NMC six-layer PE model. Differences between analyses, and the overall gain or loss in forecast skill resulting from the satellite data, are assessed via several objective and subjective procedures. These include "numerical" evaluation of standard skill scores and "judgement" by operational meteorologists.

Indications thus far are that during the first test period August - September 1975, satellite soundings had little if any consistent positive or negative impact upon analyses and forecasts. The extent to which these inconclusive results reflect: a) inherent errors in the satellite data; b) deficiencies in the prediction model; c) the method of data

assimilation and analysis; d) others, is under investigation. The results of tests in the meteorologically more active period 1 Feb. - 4 March '76, are being analyzed.

A definitive conclusion is premature: yet several factors are worth considering:

(1) These studies are new and subject to error. For instance Dr. Tracton of NMC indicated in a personal communication to ECOsystems Dr. Sigillito that his earlier paper on the subject, "Preliminary Evaluation of Nimbus-6 Sounding Data," Sixth Conference on Weather Forecasting and Analysis, 1976, was totally useless because the NESS programs used to process the satellite soundings contained *errors which completely invalidated the results.*

(2) Satellite data is generally available at times other than the standard synoptic times and thus must be assimilated into the NWP initialization process (the so-called four-dimensional data assimilation problem). It is by no means clear that this problem has been satisfactorily solved. The current feeling is that much progress remains to be done in the area: *Thus satellite data is probably not being used to its full potential.*

(3) There appears currently to be a standoff between the spare but more accurate radiosonde VTP data and the much more dense but less accurate satellite-derived VTP's. This should change as the inevitable improvements in satellite VTP's occur.

The above treats only VTP's and says nothing about the relative values of satellite-derived winds, cloudiness and imagery. The usefulness of this type of data is ever more difficult to quantify than that of the

VTP data: in some cases, usefulness may only show indirectly, over a period of time.

From the literature and personal discussions, it is unquestionable that meteorologists are convinced that satellite data are useful to better understand the atmosphere and to measure some of the parameters needed to forecast future states of the atmosphere and hence the weather.

The process of quantifying the usefulness of satellite data has only recently begun: a definitive assessment must await the results of these studies.

METEOROLOGICAL OBSERVATIONS VIA SATELLITES

History, Theory, Methods to measure cloud cover, ice, precipitation.

METEOROLOGICAL OBSERVATIONS VIA SATELLITES

1. General Comments.

The principal reason for the importance of remotely sensing the atmosphere is the need to collect data on a scale which is either prohibitively expensive or virtually impossible by conventional or direct means. The atmosphere is an enormous three-dimensional fluid (more than 2 million tons of air for every inhabitant of the earth), the majority of which lies over the oceans. Provision of an adequate network of conventional sensors would be quite impractical; advanced conventional sensors (balloons) would be unacceptable because of their hazard to air transportation.

Table 1 presents the historical sequence of recent meteorological space missions.

Table 2 summarizes principal physical characteristics of spacecraft with missions directly or indirectly related to meteorology.

2. Use of, and Problems Induced by Clouds in Sounding the Earth's Atmosphere

Infrared radiance measurements of dense clouds are used to estimate the cloud heights. This is accomplished by computing a temperature from the observed radiance and finding where this temperature prevails in the vertical temperature profile for the subject geographical position and time. The normally valid underlying assumption is that the cloud is at the same temperature as its surrounding air. The presence of thin clouds or even appreciable haze above the target cloud distorts the radiance

TABLE 1

METEOROLOGICAL SATELLITE FLIGHTS AND FUNCTIONS 1977

SATELLITE	PURPOSE[1]	LAUNCH	ORBIT[2]	FUNCTIONS[3]	REMARKS
NOAA	O	10/15/72	S/1460	Image, Sounding, Space	Deactivated
NIMBUS 5	R	12/12/72	S/1110	Image, Sounding, Relay	
ITOS E	O	07/16/73	S/1460	Image, Sounding, Space	Failed to orbit
DMSP	O	08/17/73	S/830	Image, Sounding	Low light level image
NOAA 3	O	11/06/73	S/1510	Image, Sounding, Space	Standby
DMSP	O	03/16/74	S/830	Image, Sounding, Lightning detection	
SMS 1	R/O	05/17/74	G/35700	Image, Relay, Space	Standby 105°W
DMSP	O	08/09/74	S/830	Sounding, Auroral, Electron count	Imagery sensors failed 11/'74
NOAA 4	O	11/15/74	S/1460	Image, Sounding, Space	Primary
SMS 2	R/O	02/06/75	G/35700	Image, Relay, Space	135° W
DMSP	O	05/24/75	S/830	Image	Auroral sensor failure
NIMBUS 6	R	06/12/75	S/1110	Image, Sounding, Relay	
GOES 1	O	10/16/75	G/35700	Image, Relay, Space	75° W., Note 4
DMSP	O	02/19/76	S/830	Image, Sounding, Auroral	Failed to orbit
ITOS E2	O	9/76	S/1460	Image, Sounding, Space	Former ITOS C Spacecraft
DMSP	O	Mid 76	S/830	Image, Sounding, Auroral Electron count	Initial Block 5D
ITOS H	O	Late 77	S/1460	Image, Sounding Space	

TABLE 1 (cont'd)

SATELLITE	PURPOSE[1]	LAUNCH	ORBIT[2]	FUNCTIONS[3]	REMARKS
GOES B	0	Early 77	G/35700	Image, Relay, Space	
GOES C	0	Late 77	G/35700	Image, Relay, Space	

[1] R - Research, 0 - Operational, R/0 - Operational Prototype.

[2] S - Sun-synchronous, G - Geosynchronous/altitude in kilometers

[3] Image - TV-like picture of cloud patterns or sea-surface temperature patterns.
Sounding - Vertical profile of atmospheric temperature, water vapor, ozone.
Relay - Relay and tracking of surface or balloon-borne sensors.
Space-Measurement of space radiation or solar emissions.

[4] Replace SMS 1.

TABLE 2

EARTH SATELLITE SPECIFICATIONS

	ORBIT	SPACECRAFT WEIGHT (POUNDS)	PAYLOAD WEIGHT (POUNDS)	SPACECRAFT SIZE (FT^3)	PAYLOAD POWER (WATTS)	COMMUNI-CATIONS POWER (WATTS)	SOLAR PANEL OUTPUT (WATTS)
Nimbus	Circular Near-Polar Sun-Syn-chronous Noon Equa-tor Cros-sing 1000 Km Alt	1716	490	40	156	104	550
ITOS	Circular Near-Polar (78°) Sun-Syn-chronous 9 am Equator Crossing 1500 Km Alt	875	250	50	125	50	400
TIROS-N	Circular Near-Polar (81°) Sun-Syn-chronous 8 am or 3 pm Equator Crossing 833 Km Alt	1200	270	60	125	65	400

TABLE 2 (cont'd)

	ORBIT	SPACECRAFT WEIGHT (POUNDS)	PAYLOAD WEIGHT (POUNDS)	SPACECRAFT SIZE (FT^3)	PAYLOAD POWER (WATTS)	COMMUNI-CATIONS POWER (WATTS)	SOLAR PANEL OUTPUT (WATTS)
ERTS	Circular Near-Polar (82°) Sun-Synchronous 9 30 am Equator Crossing 912 Km Alt	2080	450	52	271	104	550
ATS	Geostationary 37,000 Km Alt	2950	520	48	400	200	600
SMS	Geostationary 37,000 Km Alt	1256	165	150	33	80	140
SKYLAB	Circular 50° inclination	200,000	8,700	90,000	500	7,000	22,000

measurements through emission and scattering from the intervening materials. The resulting errors in computed cloud altitude can be reduced by corrections based on multifrequency observations, but may still be significant.

More serious is the interference of clouds in deriving the vertical temperature profile of the atmosphere from infrared radiance measurements. (See later section of this report for theory). Successful application of the method depends critically on the degree to which the portion of the observed radiance emanating from clouds and aerosols can be evaluated and subtracted in order to produce a "clear column radiance." If the clouds are solid and opaque, the soundings can be extended only down to the top of the cloud. These limitations have led to an active interest in the microwave region of the electromagnetic spectrum for making or augmenting such observations. In the microwave region the wavelength - 0.5 to 10 cm - is large compared to the dimensions of aerosol and cloud particles - $\simeq$ 1 to 20 μm - so that scattering is orders of magnitude less than in the infrared region. This enhances the transparency of clouds in the microwave region: nevertheless, cloud effects are still not zero. Effective quantitative measurements still depend upon the magnitude of cloud effects and the degree to which corrections can be applied. Combinations of infrared and microwave systems are expected to possess synergistic advantages: their joint use in future satellite-borne sensors is almost assured.

3. Methods of Measuring Winds

There are several methods where with winds can be directly measured from satellites. The only one in current operational use is the observation of cloud motion vectors from sequential geostationary satellite

images. The method assumes that the cloud and the volume of air containing it move together. Cloud motion vectors can be measured with an accuracy of 2-3 knots. Error components are the resolution of the image, the registration accuracy between successive images, changes in form of the cloud. The principal output error lies in the specification of the altitude corresponding to the wind derived vector. After the launch of the SMS-T1 on May 17, 1974 - which produces an IR and a visible image - cloud top heights could be deduced by placing the cloud where its indicated temperature matches that of the local temperature profile. Good results are found for cumulus clouds which are dense and sharp-topped (i.e., the observed radiance emanages only from the cloud top and represents its local temperature). Large errors result from tenuous clouds such as cirrus where a considerable portion of the observed radiation comes from below the cloud yielding a too-warm and hence too-low indication.

Winds derived from cloud motions observed from Geostationary Satellites prior to SMS-1 (ATS 1 and 3) have shown an average deviation of 5 to 8 knots compared to the winds measured by rawinsondes. Both natural variability and fundamental accuracy are involved in this deviation: this is because the rawinsondes and the satellite observations are never simultaneous and exactly collocated. Thus time and space variations in the wind field are included in the reported discrepancies.

From SMS images winds are operationally determined using a semi-automated machine which stores successive images on disks, displays them on vidicons, and automatically tracks cloud features to determine their vector velocity.

Another method of inferring surface wind fields from satellites is to observe the brightness distribution in the sun glitter pattern on the

ocean. A perfectly calm water surface will display a bright disk 0.5° in diameter; a disturbed surface will show a large, diffuse spot whose dimensions and brightness distribution are related to the surface wind which disturbs the surface. The technique has been shown to be sufficiently useful to be of interest, but the limited area of the surface which can be so observed detracts considerably from its general applicability.

4. Methods of Estimating Rainfall

Satellite cloud images have been used to estimate average daily rainfall over subsynoptic areas in the tropics and subtropics. The procedure determines the percentage of the subject area covered by each of three rain-producing cloud types (cumulonimbus, nimbo-stratus, and cumulus congestus) and applies an empirically-determined coefficient to each to arrive at a total rainfall prediction. Figure 1 shows the results of the method applied to the area of Zambia, Africa, for the period of January, 1970.

5. Theory of Atmospheric Profiling

5-1. Temperature Profiling

The thermal radiation emitted by the atmosphere contains information on the vertical distribution of temperature and on the concentration of the emitters: these are either optically active gases or nongaseous components (aerosols, clouds and hydrometeors).

To measure the temperature profile of the atmosphere one must observe the radiation emitted by an atmospheric constituent whose vertical distribution (concentration) and radiating properties are known so that

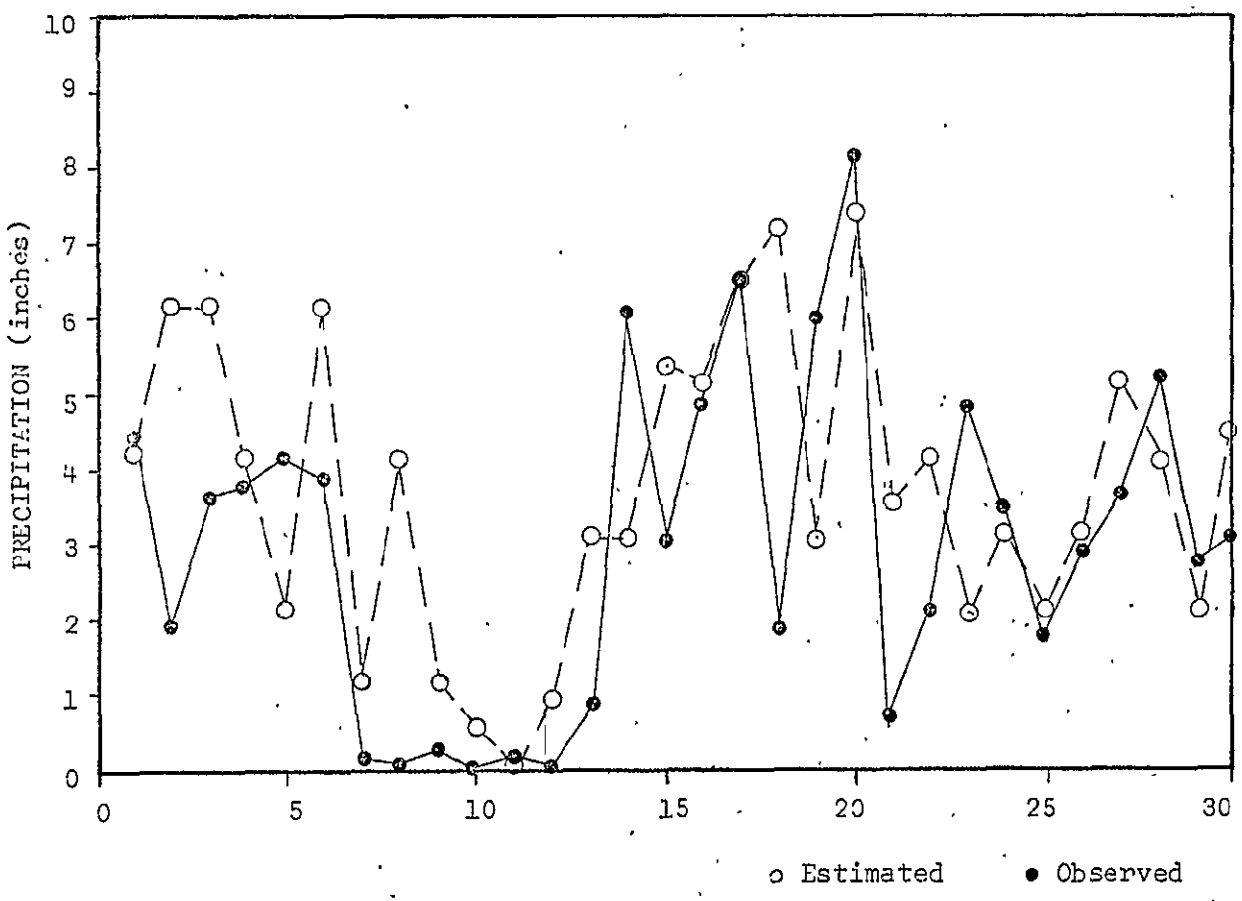

FIGURE 1 - ESTIMATED AND OBSERVED AVERAGE RAINFALL, ZAMBIA, AFRICA, JANUARY, 1970

τ (transmissivity) and $d\tau/dP$ are calculable. This requires that the radiation emanate from a gas which has a known, stable concentration; and further that its radiation be separable from all other sources, gaseous or aerosol. The gases useable for temperature profiling are CO_2 in the 2325 cm^{-1} (4.3-μm) or the 668 cm^{-1} (15-μm) band and O_2 in the 60-GHz microwave band. It is assumed that CO_2 is uniformly distributed throughout the atmosphere at 316 ppm: and that O_2 is uniform below 100 km. Local diurnal, and hemispheric seasonal variations of tropospheric CO_2 range up to 5 ppm ($\sim$ 1.5%). There are also indications of a small discontinuity between the troposphere and the stratosphere. These effects are, however, small and easily compensated.

The relationship between the vertical temperature profile and the infrared emission spectrum can be expressed quantitatively as follows. Consider a satellite which measures the monochromatic intensity emitted from directly below. The amount of radiation contributed by each incremental layer dz is given by

$$dL_\lambda = L_\lambda^* \, \tau_\lambda \, da_\lambda \qquad (1)$$

Where:

L_λ = radiance per unit wavelength interval at wavelength λ

L_λ^* = blackbody monochromatic radiance specified by Planck's law

τ_λ = transmissivity of the layer of gas lying above the level z

a_λ = fraction of the radiance along a particular path length which is absorbed by the layer in question

Equation (1) can be integrated over height to obtain the total radiance impinging on the satellite sensor from below:

$$L_\lambda = \tau_{\lambda o}\, a_{\lambda o}\, L^*_{\lambda o} + \int_o^\infty + \tau_\lambda\, L^*_\lambda\, k_\lambda\, \rho\, dz \qquad (2)$$

where we have used $da_\lambda = -k_\lambda\, \rho\, dz$, with ρ the density of the gas and k_λ its absorption coefficient.

The subscript o refers to the earth's surface.

The integral can be approximated as the sum of the contributions of N layers of finite thickness, each of them isothermal (thus L^*_λ is constant in each layer), so that L^*_λ can be taken outside the integral. With this approximation, (2) can be written in the form:

$$L_\lambda \cong \alpha_o\, L^*_{\lambda o} + \alpha_1\, L^*_{\lambda 1} + \alpha_2\, L^*_{\lambda 2} + \cdots + \alpha_N\, L^*_{\lambda N}$$

where

$$\sigma_o = \tau_{\lambda o}\, a_{\lambda o}$$

and

$$\alpha_i = \tau_{\lambda i} \int k_{\lambda i}\, \rho\, dz,\ i = 1, 2, \ldots, N.$$

The integration is carried out from the bottom to the top of the layer in question. The term $\alpha\, \tau_{\lambda i}$ is the transmissivity of the atmosphere lying above the i-th layer. It is also possible to write the coefficient in the form:

$$\alpha_i = \tau_{\lambda i}\, \sigma_{\lambda i}$$

where $\sigma_{\lambda i}$ is the optical thickness of the i-th layer. The α_i can be determined quite accurately from data or average atmospheric composition as a function of height.

Now for each of the layers the L_λ^* in various wavelength bands are related by Planck's law. Therefore, if measurements of L_λ are available at N different wavelengths, it should be possible, in principle, to solve the resulting set of simultaneous equations to obtain L_λ^* in each layer: the temperature corresponding to these blackbody radiances can then be determined from Planck's law. In practice, accurate solutions can be obtained only if each of the N equations contains a sufficient amount of information that is not redundant with the other equations (i.e., the equations are truly independent). Thus there is an upper limit to the amount of vertical resolution that can be obtained with remote sensing. Even with this limitation it is usually possible from radiance measurements in cloud-free areas to infer temperatures over layers a few kilometers thick to within about 1°C.

Another procedure is to "guess" at the temperature profile, calculate the radiances which would be observed if the guess were perfect (an exact process) and then employ one of several regression solutions to the differences between the observed and "first guess" radiances. The better the first guess, the better the answer so that in operations the last forecast is used as each first guess. As satellite data influences this forecast, however, it results in a dependence and feedback that may be dangerous. A safer approach is to use an invariant first guess based on climatology. The result, however, is not as good as the measure which, of course, is closer to the real profile.

Comparison of satellite-retrieved temperature profiles with radiosonde data reveals rms differences ranging from 1.5° to 4.0°C between

10 mbar and the surface, compared with differences between adjacent pairs of radiosondes ranging from 1.5° to 2.5°C. The largest differences between satellite and radiosonde temperatures occur around the tropopause and near the surface; the smallest differences are in the middle troposphere.

5-2. Constituent Profiling

Consider now the radiation exchange equation:

$$I_v = \varepsilon_v B_v(T_o)\ \tau_v\ (O,\ P_o) - \int_o^{P_o} B_v(T_p)\ \frac{d\tau_v(O,P)}{dP}\ dP$$

$$+ (1 - \varepsilon_v) \int_{P_o}^{o} B_v(T)\tau_v(O,P_o)\ \frac{d\tau_v(P_o,P)}{dP}\ dP \qquad (1)$$

where

I_v = measured radiance at wavenumber v

ε_v = emissivity of surface of earth at v

$B_v(T)$ = Planck blackbody radiance at v and temperature T

T_p = temperature of air at level where pressure is P

T_o = temperature of surface of earth.

$\tau_v(a,b)$ = transmission of atmosphere between pressure levels a and b.

The first term is the energy emitted by the surface of the earth and transmitted by the overlying atmosphere. The second term is the energy emitted by the atmosphere in the upward direction. The third term is the energy emitted downward by the atmosphere, reflected by the surface (reflectivity = $1 - \varepsilon_v$) and transmitted by the atmosphere

on the way up. In the infrared region $\varepsilon_v \cong 1$ and the last term is 0. In the microwave region $0.4 < \varepsilon_v < 1.0$ and this last term is significant.

In the preceding section it was pointed out that if τ and $d\tau/dP$ in the radiative transfer equation were known, B could be computed from the observed radiance I_v. Conversely, if the temperature profile is known, we can use the measurements to calculate transmittances and from these, distribution and total amount of the emitters.

Early studies of the distribution of tropospheric relative humidity on a quasi-global basis used measurements in the 6.3-μm water vapor absorption band, i.e. the IR "window" usable with satellite-borne radiometers.

Formulations have been developed for obtaining information on tropospheric relative humidities and total water vapor content, as well as temperatures, from high spectral resolution satellite measurements such as those from the Nimbus-3 and -4 Infrared Interferometer Spectrometer (IRIS) or the Nimbus-4 Satellite Infrared Spectrometer (SIRS) experiments.

Nimbus-3 and -4 IRIS measurements have been used to study techniques for estimating atmospheric ozone. Good correlations between the satellite ozone determinations and tropospheric weather systems have been shown in these studies, suggesting that ozone observations from future satellites may aid in weather prediction.

A totally different means of remotely sensing ozone has been afforded by the Backscattered Ultraviolet (BUV) experiment flown on

Nimbus 4. The BUV instrument consists of a double monochromator that is stepped every 32 s through 12 discrete wavelengths between 2500 and 3400 Å in the Hartley-Huggins ozone absorption band.

6. Measurement of Surface Parameters

6-1. Surface Temperature

The surface temperature of the solid or liquid earth can be determined by measuring the blackbody radiation emitted in the infrared or microwave region. Since the observed radiation is equal to the emissivity multiplied by a function of the temperature, it is necessary to know the emissivity. In the infrared the emissivity of most surfaces, including water, is essentially unity: in the mocrowave region the emissivity varies. For example, the microwave emissivity of water lies between 0.4 and 0.6. This uncertainty renders quantitative microwave measurements somewhat questionable. However, the insensitivity to most clouds makes the microwave region very desirable: research is underway to develop methods of tightening the emissivity ranges and correcting for the reflected contamination. The NOAA operational satellite scanners produce infrared images, which are used to infer temperature. They employ the "thermal" infrared window - 8 to 14 μm - for most surface temperature measurements. The accuracy of sea-surface temperatures thusly derived is constrained by the extent of the possible corrections to compensate for water vapor, haze, and thin clouds. Dense clouds obscure the surface and no measurements are possible.

The absolute accuracy of the measurement of sea-surface temperatures from satellites is estimated to be 1.5-2.00 K. The relative accuracy is of order 1.0 K.

6-2. Sea Ice

Ice is gradually being recognized as possessing more influence upon weather than had heretofore been thought. Ice strongly influences albedo and hence affects the heat and mass budgets of the polar regions. It is a major factor in the exchange of heat between oceans and atmosphere. For example, it is estimated that the heat flow into the atmosphere from a newly formed "hold" is approximately 100 times greater than through the surrounding ice. Thus extent, location, and movement of ice are important to meteorology.

Ice is readily observed in the visual channels of satellite images. These, however, are not available during winter because of insufficient illumination. Infrared images alone are not conclusive since land, ice and low clouds are often not separable. Microwave radiometry is particularly powerful for observing ice because it is all-weather, all-season, and can provide information on the condition of the ice.

The Nimbus 5 spacecraft carries an Electronically Scanning Microwave Radiometer (ESMR) which has been used to obtain maps of polar ice fields. It consists of a Dicke-type radiometer with a temperature sensitivity of 2, K^{o} fed by a phased-array antenna which step-scans across the sub-satellite track in 78 beam positions via of ferrite phase shifters contained in the antenna elements. The total swath covered is $\pm 50^{o}$ from nadir. The radiometric data along with internal calibration data are telemetered every orbit and are computer-processed into maps. Approximately one day's worth of data are accumulated for one polar projection, redundant data in a given map cell, resulting from orbit swath overlap, are averaged

for that time period. The resolution cell size in the processed image is ∿32 km.

The brightness temperatures observed with the ESMR depend on the physical temperature and emissivity of the surface and the opacity and temperature profile of the intervening atmosphere. However, the atmospheric contributions in the polar regions are generally negligible due to the low humidity and near absence of liquid water droplets. The cloud cover generally consists of low-altitude stratus clouds, whose liquid water content is too small to affect the microwave emission: for example, the ice crystals contained in cirrus clouds are quite transparent to 1.55-cm radiation.

The surface emissivity accounts for the largest signal contrast observed in the polar regions; however, variations in the physical temperature of the surface are observed also. At 1.55 cm, the emissivity of sea water is $\simeq$ 0.4, of first-year ice $\simeq$ 0.95, and of multiyear ice $\simeq$ 0.8.

Maps of polar ice in both the arctic and antarctic regions have been produced from Nimbus 5 ESMR data and compared to ice boundaries given in oceanographic atlases. A typical comparison is shown in Figure 2. The Atlas indicated that the Ross Sea was not open to the South Pacific; yet the ESMR data of January 30, 1973, showed that it was, and further showed that the atlas over-estimated the ice cover elsewhere, particularly in the Weddell Sea, seen in the upper right-hand quadrant of Figure 2.

The ability of the ESMR to remotely sense sea ice through clouds makes it extremely valuable for research studies, for updating climatic information, and for operational use. ESMR images are now being used

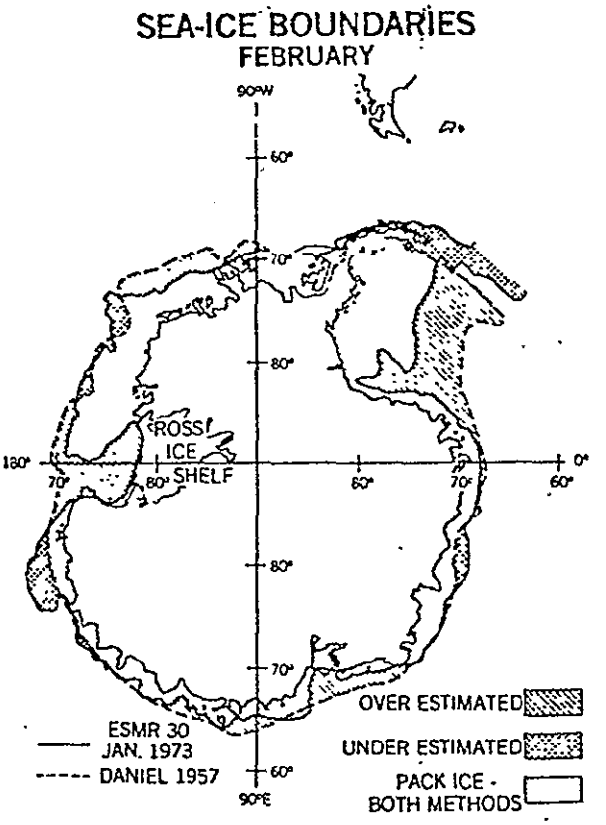

Fig 2. South polar ice pack prediction and satellite measurement.

operationally by the U.S. Navy Fleet Weather Facility as an aid to navigation in polar waters.

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