NOAA Satellite Programs

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A description is given of current National Oceanic and Atmospheric Administration (NOAA) programs involving Landsat as well as the METSAT polar-orbiting and geostationary satellites. These include the use of NOAA satellites as data collection platforms and the use of NOAA satellite radiometers in monitoring meteorologic, oceanographic, hydrologic, and agricultural phenomena. Configuration of the next generation of NOAA satellite sensors and spacecraft is included along with a final section on research directions and results.

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I. INTRODUCTION

The meteorological satellites operated today have evolved from a long line of experimental and operational satellites beginning with TIROS-1 launched on April 1, 1960. Since then over 40 environmental satellites have been successfully placed into orbit. The Earth has been under continual surveillance since the first operational meteorological satellite, ESSA-1, was launched in February 1966. Land remote sensing has also evolved from research efforts which began in the early 1960s. The first Landsat (ERTS-1) was launched in 1972 and was equipped with two experimental sensors providing multispectral data on soil, water, vegetation, and minerals.

The technical evolution of these satellites has led to the highly sophisticated systems we operate today. The first views of cloud patterns shrouding the Earth, though remarkable, were crude by today's standards. Now we can view the Earth's surface with instruments having 30 m resolution with the Landsat 4 satellite, see the Earth's surface and cloud layer tops with up to 1 km resolution with the geostationary operational environmental satellites (GOES)[1] and the National Oceanic and Atmospheric Administration (NOAA) environmental satellites, and obtain temperature and moisture profiles of the atmosphere from the surface to 65.5 km with multichannel infrared and microwave radiometers. The data presentation has evolved from crude oblique television picture data to a digital data stream of almost 300×10^9 bits per day from the combined land and meteorological satellites.

II. GEOSTATIONARY METEOROLOGICAL SATELLITES

NOAA operates two operational geostationary satellites (three others are maintained with varying degrees of capability in a standby mode) which orbit the Earth above the equator at an altitude of 35 000 km with an orbital period synchronous with the Earth's eastward spin to remain stationary at a fixed longitude position relative to the Earth. The fixed locations are at 75°W and 135°W and provide continual coverage of the North and South American continents and the adjacent oceans.

The satellites view the Earth with visible and infrared sensors providing an image every 30 min and occasionally as frequently as 5 min to allow near-continuous monitoring of the development of significant weather systems. These data are distributed over telephone circuits to 7 National Weather Service Satellite Services Units where additional communication facilities allow further distribution to subscribers over a "GOES-Tap" system. Currently, over 215 users outside NOAA receive GOES image data (140 Federal users and 75 private industry and university users).

The instrument that provides images also has 4 infrared channels whose data are used to derive vertical temperature and moisture profiles (soundings). Atmospheric soundings derived from these data are currently being tested as an additional data source for the National Meteorological Center (NMC) forecast models.

Some of the applications currently provided from the geostationary satellite data include the following:

(1) Cloud motion wind vectors are automatically computed for low level winds and are manually processed for mid and high level winds. Over 1200 vectors are generated each day.

(2) Quantitative precipitation estimates are computed and manually edited to estimate precipitation amounts resulting from convective storm systems and hurricanes.

(3) Fruit frost freeze monitoring is performed by defining surface temperature patterns associated with rapid radiative cooling in the normal temperate citrus and vegetable growing areas. The near real-time continuous monitoring allows farmers to delay the start of preventative measures until a freeze is imminent, thus saving thousands of dollars.

(4) Snow cover analyses are used to predict the snow melt runoff potential in river basins across the nation. Analyses are derived from both the meteorological satellites and from Landsat imagery. Landsat images of snow cover over the Lake Tahoe, Calif., area are shown in Figs. 1 and 2 for the years 1976 and 1983. The heavy snow in 1983 resulted in excessive runoff which was predicted and evaluated using such data.

(5) Hurricane classification is performed using a semiobjective method of classifying the stage of development and wind intensity from cloud patterns. Fig. 3 shows Hurricane Alicia in August 1983 when its center is about to make landfall at the Texas–Louisiana border. Fig. 4 shows Hurricane Iwa approaching the Hawaiian Islands in November 1983.

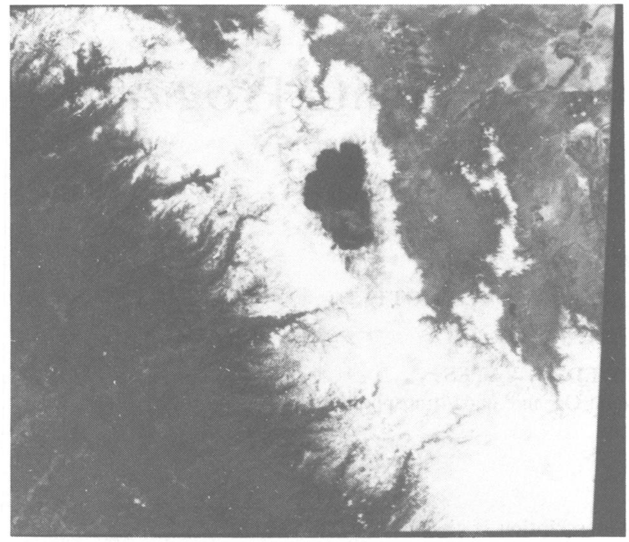


Fig. 2. Lake Tahoe, Calif.; April 15, 1983.

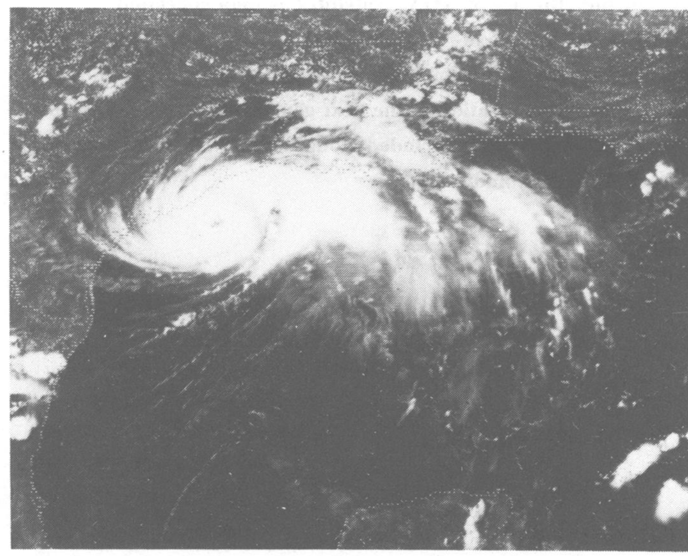


Fig. 3. Hurricane Alicia, August 17, 1983; Galveston, Tex.

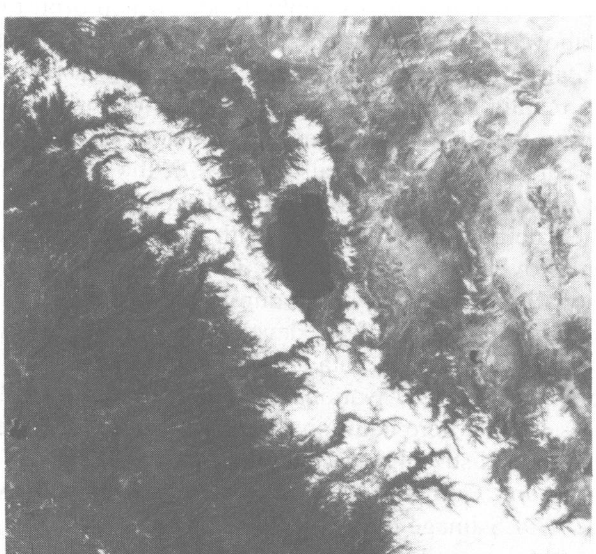


Fig. 1. Lake Tahoe, Calif.; April 23, 1976.

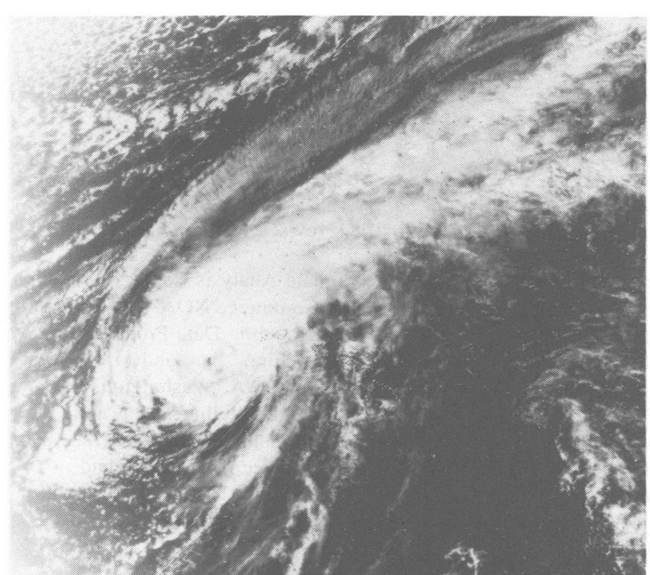


Fig. 4. Hurricane Iwa, November 1983, Hawaii.

(6) Satellite interpretation messages describing weather systems and features interpreted from satellite imagery are prepared and distributed over the National Weather Service (NWS) communications links at regular intervals throughout each day.

(7) The 30 min image sequences are combined to form animated cloud imagery. The animation reveals the dynamics associated with the cloud development providing the analyst with an added dimension for interpreting the data.

(8) Severe convective storm development is monitored using cloud top temperatures combined with cloud motions at different layers to describe and classify the events in terms of severity and to anticipate where severe weather will eventually develop. Fig. 5 is an enhanced infrared GOES image showing a severe weather outbreak over the midwestern states from which tornadoes occurred in April 1982. The enhancement scheme reverses the grey scale at key temperatures to accentuate important features and results in the coldest clouds with the deepest convection showing up as black.

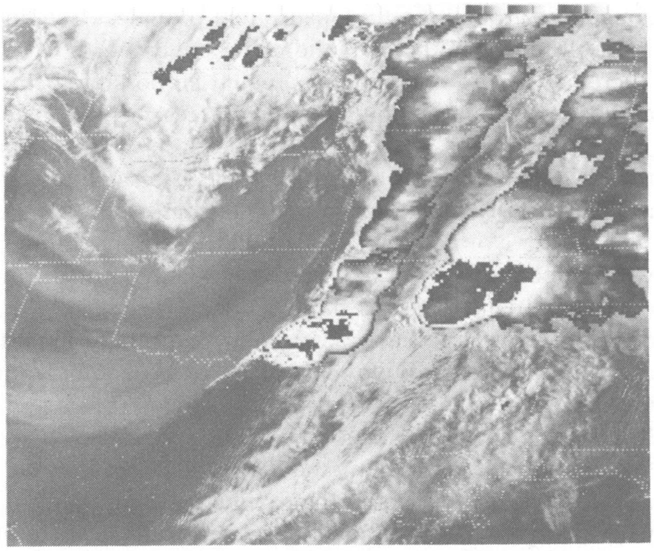


Fig. 5. Severe weather outbreak over eastern Arkansas and Southeastern Oklahoma; April 2, 1982.

(9) Detection of fog and the rate of dissipation are determined in support of shipping, fishing, and aviation interests.

In addition, there is a data collection system (DCS) on GOES which is a communications system to monitor and collect messages from instruments on remote platforms. Currently, there are over 4600 platforms in the system. Ninety percent of them report river stages and rainfall data for water resource management and hydrological applications.

A weather facsimile system on GOES allows the retransmission of GOES image sectors and conventional NWS meteorological charts to receivers located anywhere within view of three GOES satellites operated for WEFAX transmission (a central standby GOES satellite is the third). Over 435 WEFAX charts are broadcast via the 3 satellites each day.

The geostationary satellites also carry a space environment monitor (SEM) which detects solar X-ray activity to monitor and predict solar flares and energetic particle sensors to measure the energetic particle flux at orbit altitude.

III. POLAR-ORBITING METEOROLOGICAL SATELLITES (NOAA)

NOAA operates 2 polar-orbiting satellites in sun synchronous orbits at an altitude of 850 km. One crosses the equator at 0730 and 1930 local Sun time and the other at 1400 and 0200 local Sun time. Each satellite orbits the Earth 14 times per day viewing both the night and day sides of the globe for 2 global views each day. Data are recorded on tape recorders on the spacecraft and transmitted to Earth while the spacecraft is within view of the two NOAA command and data acquisition (CDA) stations located in Wallops Island, Va., and Fairbanks, Alaska.

The primary instruments are the advanced very high resolution radiometer (AVHRR) and the TIROS operational vertical sounder (TOVS). The SEM and the DCS are secondary sensors.

The AVHRR has 5 channels in the visible near-infrared and infrared, each with 1 km resolution on the surface of the Earth. However, because the onboard recorder capacity is not sufficient to contain a whole orbit of 1 km data, only 15 percent of the 1 km scale data can be recorded. For fully global coverage the data are compressed and recorded at a 4 km resolution.

In addition to recording the 4 km global area coverage (GAC) data and the 1 km local area coverage (LAC) data for eventual relay to the CDA ground stations, the NOAA satellites broadcast both data sets in real time. Two channels, the visible and thermal infrared, are specially treated to eliminate panoramic distortion and are broadcast at VHF to more than 1000 inexpensive ground stations worldwide. All 5 channels of LAC data, plus the TOVS data, are broadcast at *S*-band to more than 80 stations worldwide.

Products derived from the AVHRR instruments include the following:

(1) Global cloud images are recorded for both the day and night side of the Earth each day.

(2) Between 20 000 and 40 000 sea surface temperature observations are made each day with the number of observations varying with cloud cover. Surface temperature patterns derived from the NOAA satellites reveal many ocean features including the Gulf Stream wall and associated eddies, cold water upwellings off the United States west coast, the Gulf of Mexico loop current, and changing flow patterns in the equatorial ocean currents. Fig. 6 shows the thermal patterns of the Gulf Stream and eddies in April 1983. Fig. 7 is a computer-drawn thermal analysis of the same area showing the fine structure of the Gulf Stream and other small thermal features.

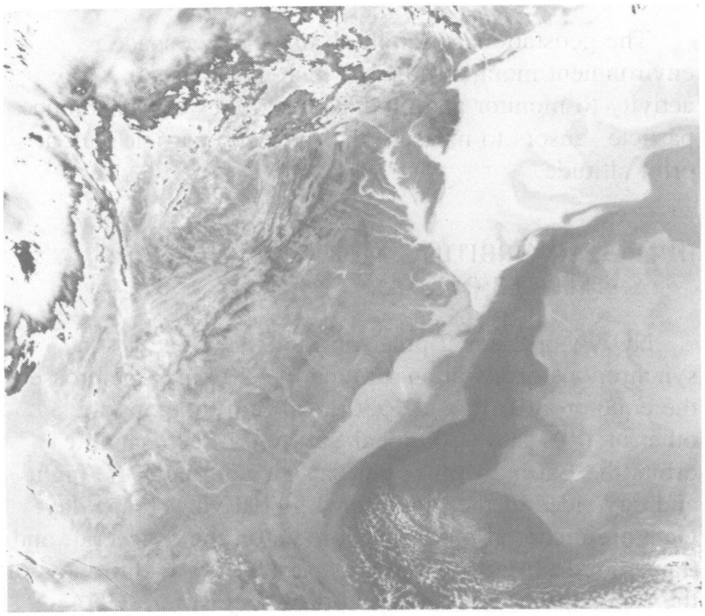


Fig. 6. East Coast United States and Gulf Stream, April 29, 1983.

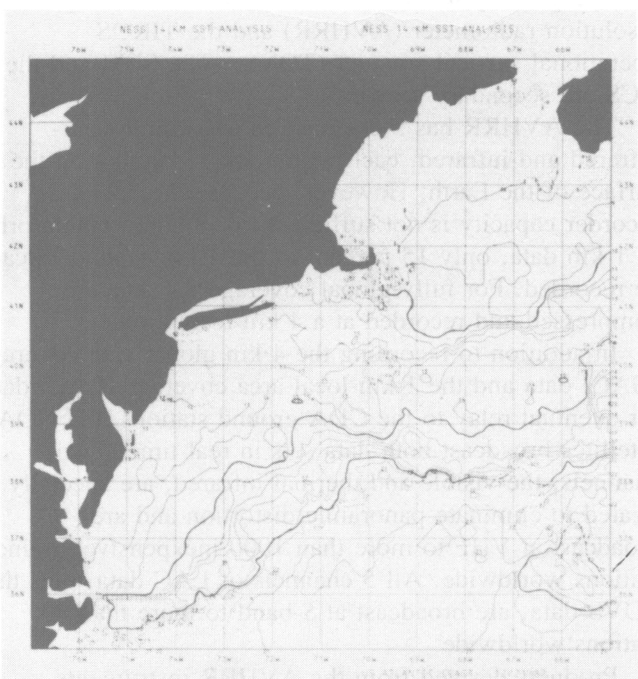


Fig. 7. Sea surface temperature analysis, East Coast United States, December 29, 1982.

(3) Vegetation Index (VI) maps are produced from the visible and near-infrared channel data depicting the general health of vegetation. These data (see Section VI, Research Directions and Results) are being evaluated for operational use and are proving to be very useful indicators of crop condition throughout the growing season and of the impact of land use in developing countries.

(4) The high resolution image data are used to define sea/ice conditions, ice flow boundaries, and ice leads in support of Great Lakes shipping, Arctic resupply, and oil rig safety. It is also used to detect subtle surface water thermal differences useful to the fishing industries.

(5) The lower resolution image data are used for monitoring global weather on a daily basis to evaluate abnormal weather events in other parts of the world and for providing a climatological record for analyzing long-term trends which could affect the United States and the rest of the globe.

The TOVS system consists of a high resolution infrared sounder (HIRS/2), a stratospheric sounding unit (SSU), and a microwave sounding unit (MSU). The HIRS/2 provides vertical temperature profiles, primarily in the troposphere, water vapor content at three levels of the atmosphere, and the total ozone content. The SSU instrument, funded and supplied by the British Meteorological Service as part of a United States/United Kingdom cooperative program, provides temperature information in the stratosphere. The MSU improves the soundings around the tropopause and provides soundings in the troposphere below solid cloud cover. Without microwave data, no soundings would be possible below clouds, which are opaque to the infrared. Approximately 16 000 soundings globally are output each day as input to the NMC's numerical forecast model. The satellite data are particularly important in the data sparse ocean areas such as the Northeastern Pacific. Since the prevailing wind direction is from the west at the latitude of the continental United States, knowledge of weather conditions over the Pacific Ocean are especially important and the satellites provide most of it. The sounding data are also disseminated worldwide over the World Meteorological Organization (WMO) global telecommunication system and are used extensively by meteorological services in the Southern Hemisphere where very few conventional data are available. Satellite data have had a profound impact on the accuracy of weather forecasting in that part of the world.

The NOAA satellites also carry an SEM which measures solar proton flux, electron flux density, and total particulate energy distribution at spacecraft altitude.

A data collection system, called ARGOS, is provided by the French Centre National d'Etudes Spatiales (CNES) for locating and collecting data from up to 2000 moving platforms, such as buoys or balloons. The data are collected by NOAA and transmitted to the ARGOS Center in France for processing and dissemination.

The most recent NOAA satellite carries a search and rescue instrument which receives and relays signals from emergency transmitters to local user terminals and to a central processing center operated by the Air Force at Scott Air Force Base, Ill. This system in combination with a similar system on the Russian COSPAS satellite has, at this writing, been credited with the rescue of over 137 lives at a current rate of 10 or 12 per month.

IV. LANDSAT

In January 1983 NOAA took over from NASA the operational responsibility for the land remote sensing satellites. The Landsat spacecraft orbits the Earth in a

Sun synchronous 700 km polar orbit crossing the equator southbound at 1030 local Sun time. There is a multispectral scanner (MSS) with four channels having 80 m resolution and a thematic mapper (TM) instrument with six 30 m resolution channels and one 120 m infrared channel. Both scanners view only a 185 km swath on Earth along the satellite subpoint track. Because of the narrow swath, a 16 day repeat cycle is required for coverage continuity.

The spectral bands in the MSS and TM allow the measurement of sediment laden water, delineation of shallow water areas, man-made (cultural) features, vegetation reflectance, chlorophyll absorption, vegetation moisture, and soil/rock differentiation. Applications vary from geologic mapping, forest type delineation, vegetation monitoring, water resource management, demographic studies, and land use analyses. Users are divided into two major categories: (1) "renewable resources" for agriculture and water management and (2) "nonrenewable resources" for geologists.

There are 12 foreign ground stations that pay an access fee to receive directly broadcast Landsat data when the spacecraft is within view. Data can only be collected when the spacecraft is within view of a readout station because the spacecraft has no onboard recording capability. In addition, there are three direct readout stations operated by the United States Government.

With the implementation of the tracking and data relay satellite system (TDRSS) in late 1984, the Landsat will have the capability to transmit worldwide data through the TDRSS for direct reception in the United States. This capability has already undergone successful testing with the one TDRSS satellite in position.

The component failures in the present Landsat 4 satellite have limited operations primarily to MSS data coverage. We currently operate the spacecraft for about 200 MSS scenes per day which includes about 75 scenes each day over the United States readout facilities. Over 6600 TM scenes were collected before the failures in the spacecraft limited TM acquisition.

A second Landsat spacecraft is planned for a March 1984 launch and will once again provide both TM and MSS operations. NOAA will take over the TM product responsibility from NASA in January 1985 and expects to process up to 50 TM scenes each day in addition to the current MSS workload. Fig. 8 is a photographic enlargement of a TM scene of Washington, D.C., recorded on November 2, 1982.

V. FUTURE SYSTEMS

NOAA plans to continue both the geostationary and polar-orbiting spacecraft into the foreseeable future in essentially the present orbits but with added and improved instruments. The Landsat system is scheduled for assumption by a commercial operator and a request for proposals (RFP) was issued in January 1984. The future of the United States land remote sensing system will depend upon the response received to this RFP.

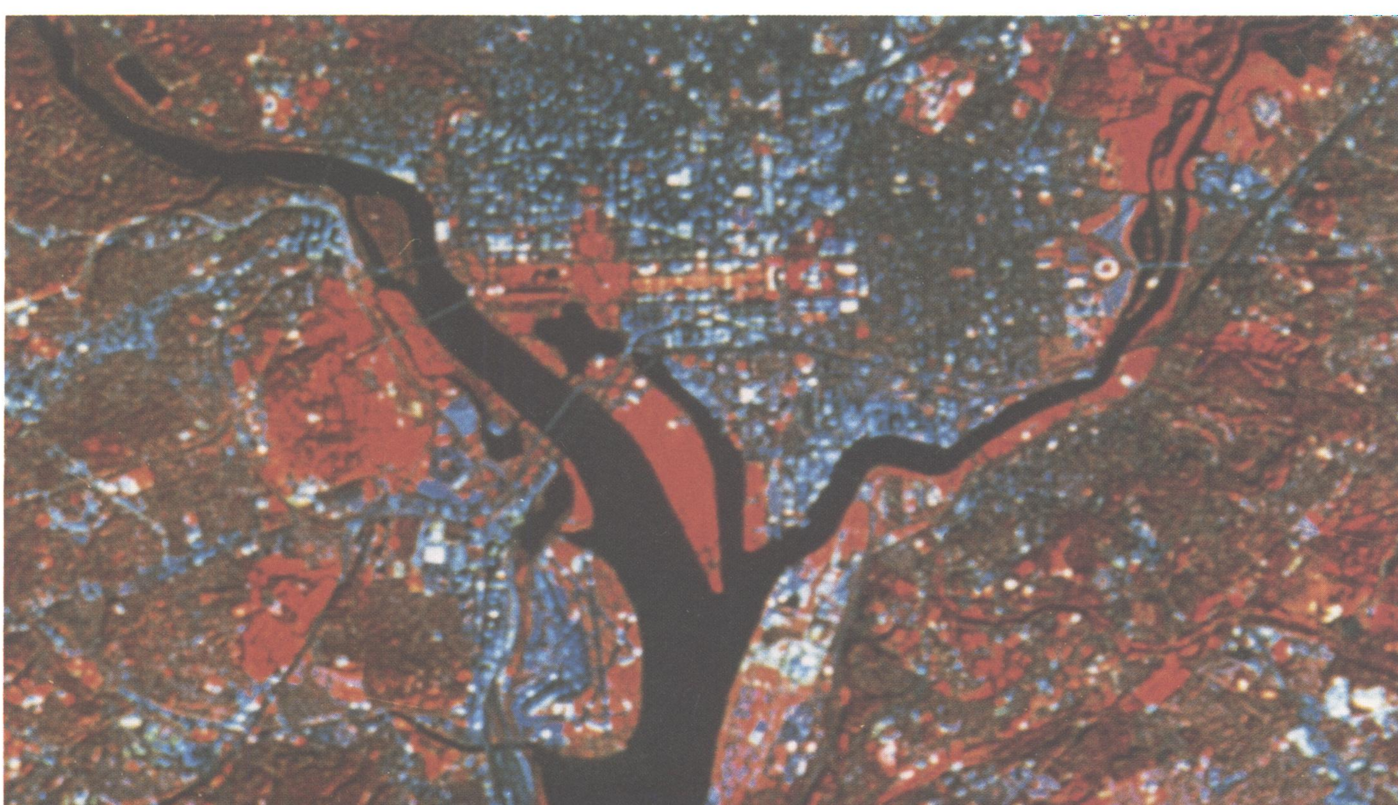


Fig. 8. Enlarged Landsat thematic mapper view recorded November 2, 1982, over District of Columbia.

(1) *NOAA-Next.* The instrument complement of the current NOAA series of satellites is shown on Table I. The advanced TIROS-N (ATN) spacecraft has reserve capacities for additional payload, and two uses are planned. Solar backscatter ultraviolet (SBUV) ozone sounder instruments will be flown on the satellites in an afternoon orbit from NOAA-F (1984) to NOAA-J. Also, NOAA will fly NASA's Earth radiation budget experiment instruments on NOAA-F and NOAA-G as part of the NASA research program. No other firm commitments have been made for the small reserve remaining in the series.

The primary mission of the NOAA spacecraft is to provide vertical profile of atmospheric temperatures (soundings), sea, and Great Lakes surface temperatures, and the nature and distribution over the globe of storms, clouds, ice, snow, and vegetation. The most significant improvement planned for NOAA-Next is an advanced microwave sounding unit (AMSU) which will replace the current SSU and MSU. Improved soundings in the presence of total cloud cover is the primary objective, with the detection and quantification of precipitation below clouds a secondary object. In the present system, the primary instrument has been the HIRS, an infrared

TABLE I
Standard Instruments, Services, and Direct Data Broadcasts of the Current NOAA Series

Instruments

A. Advanced Very High Resolution Radiometer (AVHRR/2) (1 km resolution)

Channels	*Wavelengths* (μm)	*Primary Uses*
1	0.58–0.68	daytime cloud/surface mapping
2	0.725–1.10	water delineation, ice, and snow melt
3	3.55–3.93	sea surface temperature, nighttime clouds
4	10.30–11.30	sea surface temperature, day/night clouds
5	11.50–12.50	sea surface temperature, day/night clouds

B. TIROS Operational Vertical Sounder (TOVS) (three-sensor system)

1. High Resolution Infrared Radiation Sounder (HIRS/2) (17.4 km resolution)

Channels	*Wavelengths* (μm)	*Primary Uses*
1–5	14.95–13.97	temperature profiles, clouds
6–7	13.64–13.35	carbon dioxide and water vapor bands
8	11.11	surface temperature, clouds
9	9.71	total O_3 concentration
10–12	8.16–6.72	humidity profiles, detect thin cirrus
13–17	4.57–4.24	temperature profiles
18–20	4.00–0.69	clouds, surface temperatures under partly cloudy skies

2. Stratospheric Sounding Unit (SSU) (147.3 km resolution)

Channels	*Wavelengths* (μm)	*Primary Uses*
1–3	15	temperature profiles

3. Microwave Sounding Unit (MSU) (105 km resolution)

Channels	*Frequencies (GHz)*	*Primary Uses*
1	50.31	temperature soundings through clouds
2	53.73	
3	54.96	
4	57.95	

C. Space Environment Monitor (SEM) (measures solar particle flux at spacecraft)

1. Total energy detector (TED): Solar particle intensity from 0.3 to 20 keV
2. Medium energy proton and electron detector (MEPED): Protons, electrons, and ions in 30 to 60 keV range

Services

A. SARSAT. Satellite-aided search and rescue system: Cooperative international program to locate downed aircraft and ships in distress. Participants are the United States, Canada, France, the U.S.S.R., the United Kingdom, Sweden, and Norway.
B. ARGOS. Data collection and platform location system: French system; hardware provided by France and flown by NOAA. Data relayed by NOAA to the Toulouse Space Center for ARGOS processing.

Direct Data Broadcasts (continuous; available to any receiving station)

A. Automatic picture transmission (APT): Visible and infrared imagery at 4 km resolution. VHF broadcasts at 137.50 or 137.62 MHz.
B. High resolution picture transmission (HRPT): Visible and infrared data at 1 km resolution. *S*-band broadcasts at 1698.0 and 1707.0 MHz.
C. Direct sounder broadcast (DSB): TOVS data transmitted at 136.77 or 137.77 MHz and in the HRPT stream for use in quantitative programs.

radiometer. The MSU was a secondary instrument. With the AMSU, the roles will be reversed. The microwave instrument will be primary and the infrared HIRS will become secondary.

The AMSU will consist of two independent components. The larger component, AMSU-A, will consist of 15 channels in the 20–90 GHz range and provide the principal data for temperature soundings. The other component, AMSU-B, will have 5 channels in the 90–183 GHz range and provide the data for tropospheric humidity profiles, delineation of sea ice and open water, and information about snow thickness and soil moisture. The United Kingdom has offered to fund and provide the AMSU-B as a continuation of the highly successful cooperative arrangement by which they now provide the SSU.

The AMSU will provide temperature sounding data at about 50 km resolution, humidity sounding data at about 15 km resolution, and the locations of precipitation cells, weather fronts, and sea ice. The greater emphasis on microwave radiometry means that more reliable data and coverage will be collected in cloudy areas.

The AVHRR/2 now in operation provides timely, reliable information about sea surface temperatures, ice, snow, and clouds. The instrument will continue on NOAA-Next in essentially its present form with some technical improvements to the filter and electronic systems and possibly an additional channel at 1.6 μm to aid in snow/cloud discrimination. The channel 2 spectral response will be made more symmetrical, yielding higher spectral purity and easier interinstrument comparison needed for effective vegetation monitoring. Suggestions that one or more channels be at resolutions close to 0.5 km have been made, based on the advantages to various users. Implementation would depend upon a design that offers selectability, data compression, or another technique to make tractable the space and ground communications problems resulting from the larger data volume.

The data provided by the detectors of the SEM contribute to the safety of space missions, high altitude aviation, and the efficient operations of terrestrial communications links. The expectation is that the instrument will be continued essentially unchanged.

The search and rescue instrument flown on NOAA-8 was provided by Canada and France under an understanding with NASA covering a 15 month demonstration. NOAA will enter an operational agreement with them covering an additional four instruments. Discussions about the search and rescue instrument cooperation in the NOAA-Next era have not been initiated, but it is unquestioned that this function will continue to be served by the new satellites.

France designed the ARGOS system and is providing six flight instruments, the last of which will fly on NOAA-J. Formal agreement to continue this relationship for NOAA-Next satellites has not been entered, but neither party has present reservations about doing so.

NOAA-Next will continue the present direct data broadcast program. Most direct sounder broadcast and high resolution picture transmission users probably will want to have access to any new or improved data of the types they use in their operations. They will be provided with a richer data stream. Automatic picture transmission stations are band and equipment limited; enhancements on their behalf will be in terms of quality and stability improvements in the derivation and broadcast of the imagery information they receive.

(2) *GOES-Next.* The visible and infrared spin scan radiometer (VISSR) was the standard GOES instrument for obtaining Earth–atmosphere measurements until September 1980. VISSR provided imaging data at 1 km resolution in the visible, 8 km nominal in infrared. GOES-D (1980), GOES-E (1981), and GOES-F (1983) were equipped with the replacement VISSR atmospheric sounder (VAS) instrument. VAS is capable of providing both multispectral imaging and atmospheric sounding data from GOES. The two remaining satellites of the current GOES series, GOES-G and GOES-H, will use VAS instruments, continuing this space capability through 1989–1990. A VAS demonstration program has been conducted that proved the VAS concept and unequivocally confirmed all expected advantages as well as demonstrating some unexpected advantages. A program to develop and implement the operational potential of this instrument is underway. However, although VAS has demonstrated the practicability and utility of soundings and additional spectral image channels, improvements in sensitivity and coverage in time are required to satisfy proven objectives. Therefore, a significant upgrade in performance is sought for GOES-Next.

Today's VAS has 8 visible channel detectors and 6 thermal detectors that sense infrared radiation in 12 spectral bands. A filter wheel effects channel selection over the infrared bands, which have central wavelengths between 3.9 and 15 μm. Resolution is 1 km visible and 7 or 14 km infrared, depending on detector selection. VAS operates in either an imaging mode or a dwell sounding mode; "dwell" sounding because multiple observations of the same atmospheric column are used to improve the signal-to-noise ratio. A mixed mode, dwell imaging is possible and allows tropospheric temperature and humidity soundings, as well as imagery, to be obtained over a 35° band of latitude at the operational half hourly frequency.

The minimum characteristics of the GOES-Next instrument are shown in Table II.

Space environment monitor detectors similar to those being flown currently (Table III) will be carried by GOES-Next. A need of the community concerned with solar events and conditions is a solar X-ray imager suitable for geostationary satellite use. The option to include such an imager on GOES-Next is being pursued. It will be included if it proves to be technically feasible at an acceptable cost.

TABLE II
Instrument Characteristics: GOES-Next Imaging and Soundings

1. General
   a. Provide imaging and sounding services round the clock.
   b. Imaging and sounding functions can be conducted in parallel.
   c. Full resolution data are disseminated to the NOAA Suitland Facility.
2. Imaging
   a. At least 5 channels.
   b. Full disc coverage in 20 min.
   c. Coregistration of successive images within 2 km.
   d. Channel-to-channel registration within 11 rad (one-tenth FOV).
   e. Required spectral bands and subpoint resolutions:

Spectral Bands (μm)	*Resolutions* (*km*)
0.55– 0.75	1
3.80– 4.00	4
6.50– 7.00	8
10.20–11.20	4
11.50–12.50	4

3. Soundings
   a. At least 14 channels, each with an 8 km × 8 km field of view.
   b. Coverage of 3000 km × 3000 km areas (60°N to 60°S) within 40 min.
   c. Channel-to-channel registration within 2 percent of the field of view.
   d. Required central wavenumbers, bandwidths, and wavelengths:

Central Wavenumber (cm^{-1})	*Bandwidth* (cm^{-1})	*Wavelength*
679	10	14.73
691	12	14.47
700	10	14.29
710	10	14.08
735	13	13.61
748	16	13.37
787	20	12.71
892	50	11.21
1365	50	7.33
1467	140	6.82
2213	35	4.519
2520	100	3.968
2671	100	3.744
14367	1000	0.696

TABLE III
Space Environment Monitor (SEM): Current Detectors

1. X-ray sensor: Measures solar X-rays at 0.5–3.0 Å and 1.0–8.0 Å.
2. Energy particle sensor: Measures charged particle flux of
   a. Protons (0.8 to 500 MeV) over 7 log ranges
   b. Alphas (3.2 to 400 MeV) over 6 log ranges
   c. Electrons (≥ MeV) over 1 log range.
3. High energy proton and alpha detector (HEPAD): Detects protons in the 379 keV range.
4. Magnetometer: Monitors the magnitude and direction of the ambient magnetic field, the parallel field ($\pm 1200\ \gamma$), and the transverse field (selectable in the ranges $\pm 50\ \gamma$, $\pm 100\ \gamma$, $\pm 200\ \gamma$, or $\pm 400\ \gamma$).

The GOES DCS will be continued, unchanged for users, during the GOES-Next era. Compatibility within the international geostationary environmental satellite array will be maintained for this service.

WEFAX broadcasts from GOES-Next, the relayed transmissions of processed environmental data in facsimile format at 1691.0 MHz, will be identical to those of today.

The direct broadcast of GOES-Next sensor data also will be unchanged. Stations equipped to receive these *S*-band (1687.1 MHz) transmissions, and to process the ingested data, will remain able to do so.

Geostationary satellites offer the opportunity to detect instantaneously and to report distress signals from downed aircraft or ships in trouble. NASA is funding two experimental search and rescue transponders for flight on GOES-G and GOES-H late in the decade. This capability will be supplemental to the search and rescue function of the polar system providing up to 6 hours of added alert time. The polar system will still be required to determine location. If this experiment proves successful, an operational search and rescue capability will be established on GOES-Next as well as NOAA-Next.

VI. RESEARCH DIRECTIONS AND RESULTS

The first meteorological satellites 25 years ago were limited to gathering images, and the first developments in satellite meteorology were image interpretation. Gradually, along with greater sophistication in the design and operation of the satellites themselves, the sensors have produced more quantitative information and, even in the case of imaging instruments, digital data streams have replaced analog signals. There continues today a stream of research both to improve upon the quantitative products being delivered to our customers and to develop better tools and insights for interpreting the imagery that flows in great quantity from the polar orbiting and geostationary meteorological satellites.

Research and Development in Quantitative Satellite Products from Operational Spacecraft

(*1*) *Atmospheric Soundings—Polar.* The processing of satellite-measured radiances to produce atmospheric temperature profiles has been routine for over a decade. The current operational method for deriving temperature and water vapor soundings from the TOVS data is a multiple regression statistical scheme that relies on a set of nearly coincident radiance observations and radiosondes gathered over prior days. The quality of the operational soundings is measured in the same way—direct comparisons of satellite retrievals with radiosonde observations at nearly the same place and time. (Radiosonde observations are themselves subject to error, and the atmosphere sometimes has large spatial and temporal variations; so this comparison includes differences that are not wholly attributable to the satellite retrievals.) Table IV shows how these comparisons have fared in recent years. For clear scenes there has been little or no change, but under cloudy and partly cloudy conditions the improvements are significant.

Improvements in the algorithms by which the radiative transfer equations are solved, as well as

TABLE IV
Squared Differences Between Satellite Retrievals and Radiosondes

Layer (mb)	Squared Difference from Radiosonde (K^2) Clear 79–80	Clear 80–81	Clear 81–82	Partly Cloudy 79–80	Partly Cloudy 80–81	Partly Cloudy 81–82	Cloudy 79–80	Cloudy 80–81	Cloudy 81–82
100– 70	4.65	4.16	4.06	4.66	4.22	4.31	5.04	5.25	4.58
200–100	4.27	3.59	3.88	4.80	3.87	3.97	5.42	4.87	4.93
300–200	5.23	4.54	4.57	6.11	5.36	4.62	8.01	5.98	6.06
400–300	5.18	4.97	4.68	5.62	5.83	5.32	8.80	8.49	7.01
500–400	5.35	4.95	4.88	5.80	5.81	5.39	8.77	8.84	7.72
700–500	4.09	3.90	3.80	4.59	4.50	4.13	7.50	7.30	6.47
850–700	5.53	5.35	5.39	7.45	7.77	6.94	11.30	9.81	10.26
1000–850	7.90	7.59	8.27	9.59	10.50	9.17	14.33	13.50	13.13

improvements in transmittances, now permit a return to physical retrieval methods. Physical retrievals are intrinsically capable of achieving greater accuracy, and, importantly, reduce the reliance of the satellite product on the radiosonde network. At least two such schemes are being evaluated. As an example of the quality of high resolution TOVS physical sounding retrievals now possible, Fig. 9 shows a comparison of analyses of soundings obtained by one of the methods being tested using data from consecutive orbits of the NOAA-7 satellite over Europe and operational analyses from the European Centre for Medium Range Forecasting (ECMRF). Both sets of geopotential thickness analyses (proportional to the layer mean temperature) of the 1000–700 mb layer are similar. One can see good time continuity in these analyses for this region of complex terrain and highly differentiated underlying surfaces (deserts, mountains, sea). The greater detail on the TOVS analyses is presumably due to the relatively high density of satellite soundings. Yet the density of conventional meteorological data is higher over Europe than anywhere else in the world.

(2) *Atmospheric Soundings—Geostationary Satellites.* Geostationary meteorological satellites carry a sounding instrument known as the VAS. The VAS has

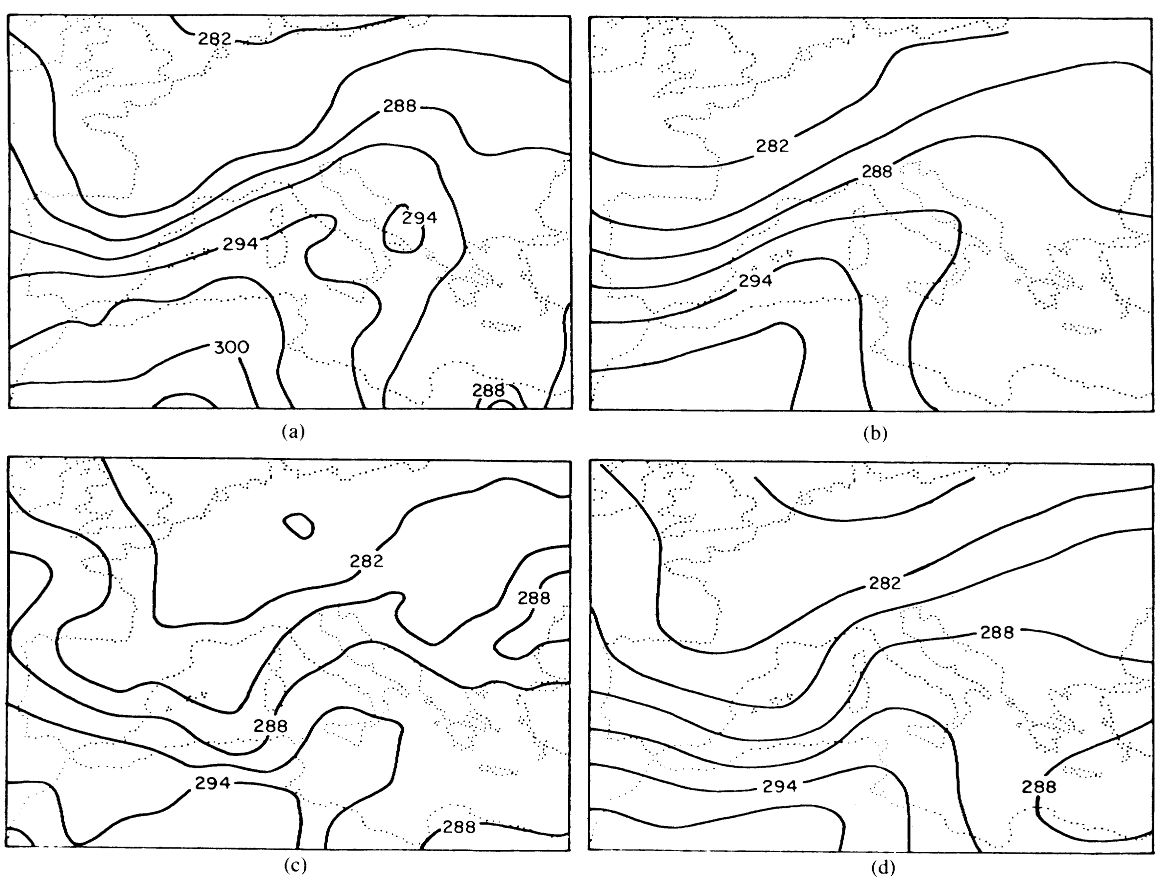
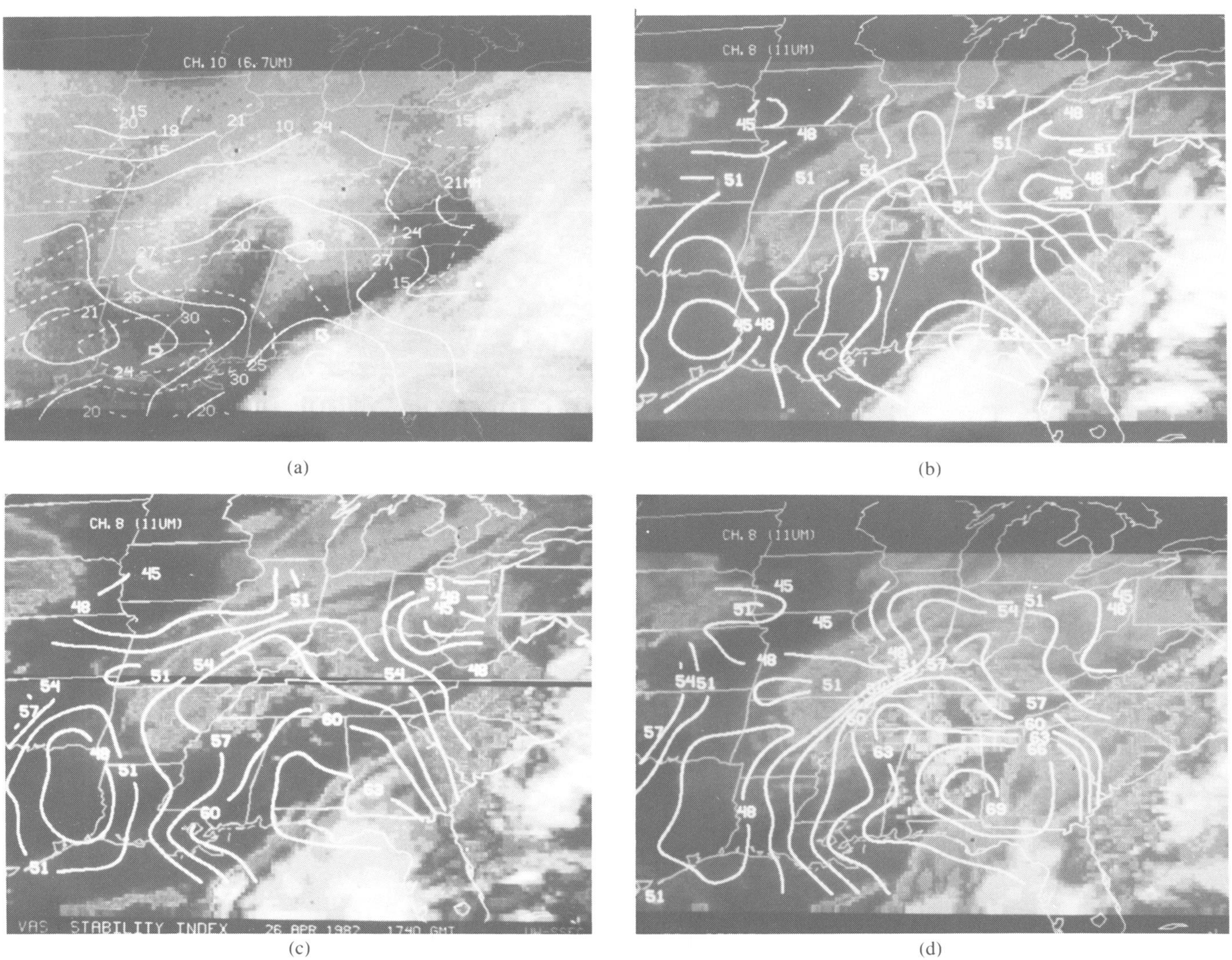


Fig. 9. Satellite retrieval of lower tropospheric thicknesses compared with analysis produced operationally at the European Center for Medium-Range Weather Forecasting. (a) 1000–700 mb ZT, March 4, 1982, 13Z SAT. (b) 1000–700 mb ZT, March 4, 1982, 12Z ECMWF. (c) 1000–700 mb ZT, March 5, 1982, 03Z SAT. (d) 1000–700 mb ZT, March 5, 1982, 00Z ECMWF.

detectors capable of moderately high resolution (7 and 14 km) imaging and sounding of the atmosphere in as many as 12 infrared spectral bands (2 window channels, 3 water vapor channels, and 7 carbon dioxide channels). Multispectral imagery or soundings can be obtained every hour. The spatial resolution of the soundings is about 75 km. For forecasting severe convective weather, the temporal as well as spatial resolution of the data is of key importance. An example of the application of VAS soundings to the forecasting of severe convective storms is shown in Fig. 10. Portrayed are analyses of various parameters derived from VAS soundings produced in real time on April 26, 1982. Fig. 10(a) illustrates midmorning analyses of total precipitable water vapor (solid contours) and upper troposphere (300 mb) wind speeds (dashed contours), also deduced from the VAS sounding data, superimposed on an image of upper tropospheric water vapor. Meteorologists are able to identify several features in this picture that should be conducive to development of convective weather in the region of Louisiana, Mississippi, and Alabama.

Fig. 10(b) contains an analysis, based on VAS data obtained near 0955 CST of an index frequently used by meteorologists to indicate the potential for severe convective weather, superimposed on a thermal infrared window channel image. Note that Alabama and Georgia are free of convective clouds but are under convectively unstable air (high index values). As shown in Figs. 10(c) and 10(d), the subsequent VAS sounding portrayed further destabilization of the atmosphere. By 2000 GMT [1400 CST, Fig. 10(d)] the index values over southeastern Alabama had reached values indicating a very high probability of extensive severe weather. Lines of convective storms had already developed over Georgia. During the 6 h period subsequent to the 2000 GMT VAS observations, extensive severe weather occurred over Alabama and western Georgia, including 13 tornadoes. Most of the severe weather occurred within the bounds of the 69 index contour in Fig. 10(d).

Research on the processing of VAS data continues as trial outputs are made available to the major forecast centers of the National Weather Service (National



(a) (b) (c) (d)

Fig. 10. Sequence of analysis of parameters relevant to severe weather potential produced from VAS data in real time. (a) VAS precipitation/water and 300 mb isotach, April 26, 1982, 1555 GMT. (b) VAS stability index, April 26, 1982, 1555 GMT. (c) VAS stability index, April 26, 1982, 1740 GMT. (d) VAS stability index, April 26, 1982, 2025 GMT.

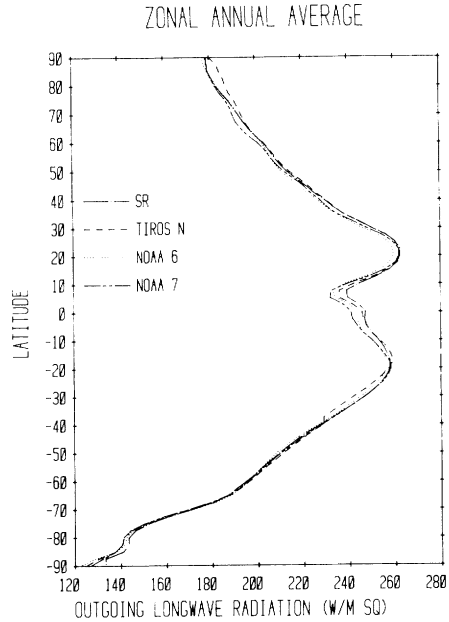


Fig. 11. Climatology of outgoing longwave (infrared) radiation escaping to space as estimated from data from four separate satellites.

Meteorological Center, National Hurricane Forecast Center, and National Severe Forecast) for their evaluation and recommendation.

(3) Earth Radiation Budget. The meteorological satellites were designed primarily to meet the needs of the Weather Service for data that will contribute to the ability to provide useful forecasts and to provide watches and warnings of severe weather. While serving this role the Weather Service has also served as an important source of data on the Earth's radiation budget. The National Environmental Satellite, Data, and Information Service (NESDIS) has been producing estimates of the planetary albedo and outgoing longwave radiation from operational spacecraft for nearly a decade. These estimates were initiated with the scanning radiometer (SR) instrument on an earlier series of polar orbiting satellites and were continued with the AVHRR on the TIROS-N series of satellites.

Fig. 11 shows a comparison of the zonal average outgoing longwave radiation measured by each satellite. In spite of significant differences among the instruments and the orbits of the satellites, there is a very strong agreement among the various profiles. This is important because these data are used by the National Weather Service and others in monitoring seasonal and interannual climate variations. Climate monitoring, much more than weather observing, places requirements of long-term stability and comparability on satellite measurements.

(4) Stratospheric Monitoring. Fig. 12 shows the record of total ozone amount derived from TOVS radiance measurements. As with the Earth radiation budget, these analyses are largely in support of climate studies, and long-term trends are of paramount interest. Thus the stability of the measurements from satellite to satellite is of great importance. The extension from satellite to satellite, using three satellites over a 4 year period, gives us reason to have confidence in this aspect of the measurement. Also shown in Fig. 12 are total ozone amounts deduced from the NASA Nimbus-7

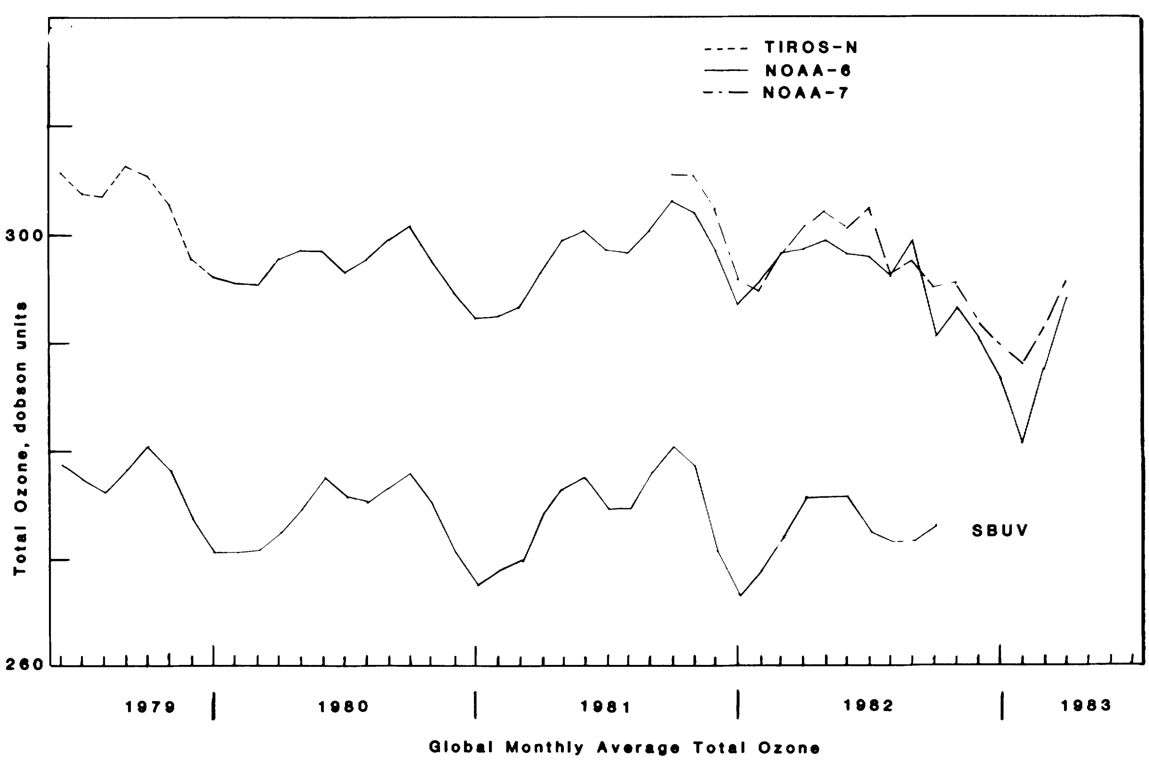


Fig. 12. Global (60 N to 60 S) monthly average total ozone amounts in Dobson Units (DU). (SBUV data supplied by NASA/Goddard Space Flight Center.)

SBUV. The large difference or bias between the two data sets is due to differences, now understood, in the basic physical parameters used in the ozone retrieval process. Future NOAA spacecraft launched into afternoon orbits will carry improved, SBUV/2 instruments, which give information on the vertical distribution of ozone as well as total amount.

(5) *Sea Surface Temperature.* Satellite-derived sea surface temperatures have improved significantly since the early 1960s, and measurements are now being obtained with an accuracy of 0.5 °C to 0.6°C compared with measurements made by drifting buoys (Fig. 13). This improvement makes possible major satellite contributions to understanding the influence of the oceans on the atmosphere and climate. One phenomenon of particular interest is the El Nino, an event that occurs at intervals of 4 to 6 years and is marked by a collapse of southeast trade winds, the cessation of upwelling along the equator, a general warming of waters along the South American coast, and very widespread meteorological implications. The El Nino of 1982 was particularly severe. The maps shown in Fig. 14 portray weekly average SST at a spatial resolution of 50 km for the weeks of November 23, 1981, and 1982. The absence of cooler water along the equator in 1982 is quite evident.

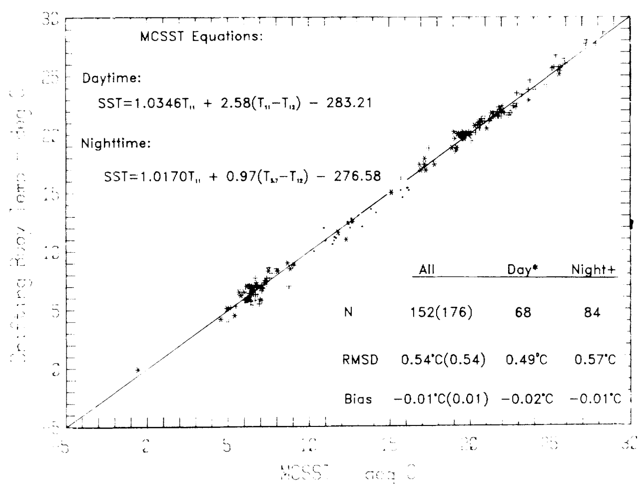


Fig. 13. Comparison of satellite determinations of sea surface temperature with in situ buoy measurements. $T_{3.7}$, T_{11}, and T_{12} refer to brightness temperatures from channels 3, 4, and 5 of the AVHRR instrument.

These SSTs are derived from the three infrared channels on the AVHRR instrument. In 1982 the volcano El Chichon (Fig. 15) introduced large amounts of aerosols into the stratosphere, introducing an unexpected bias into the SST retrievals. New algorithms that are largely insensitive to atmospheric aerosol loadings are now being tested.

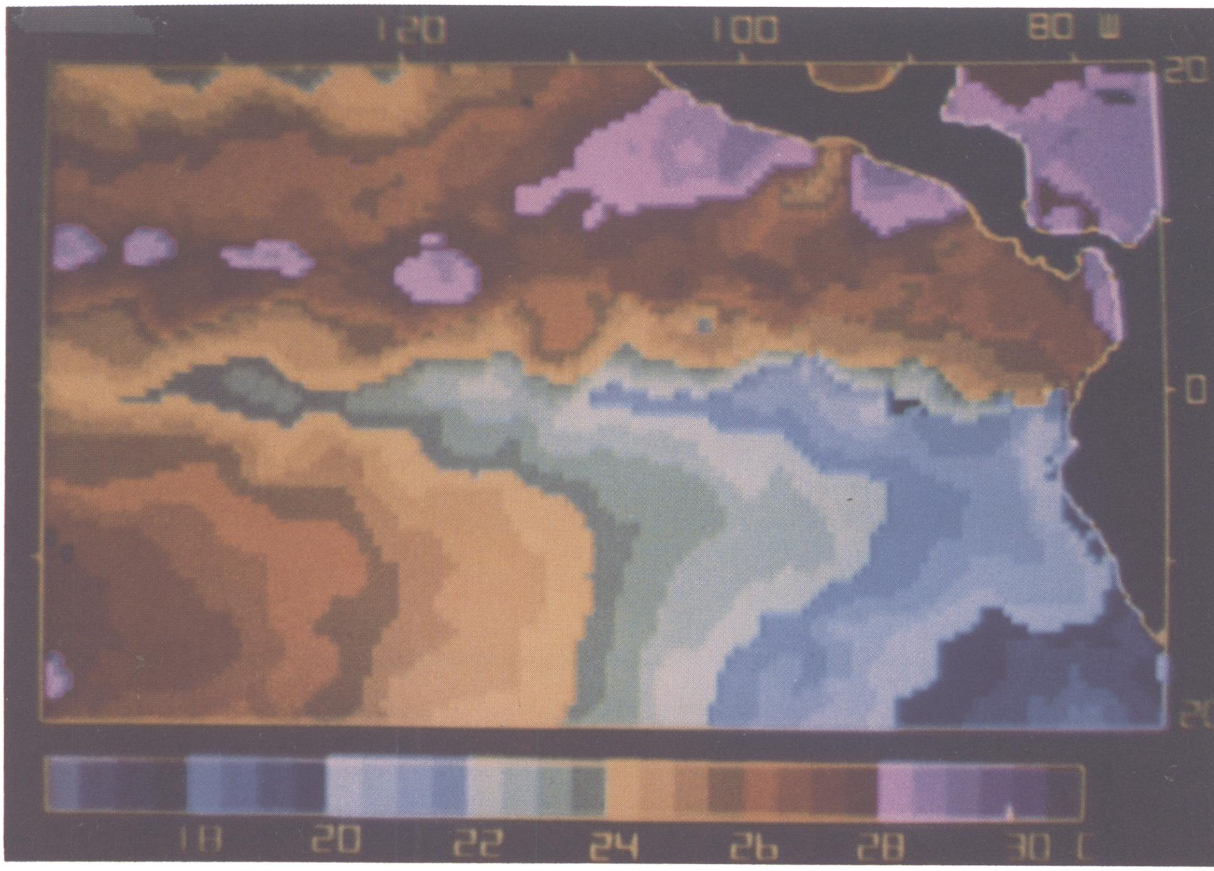
(6) *Vegetation Index.* Several United States government agencies, especially USDA and AID, have requirements to monitor and forecast crop conditions in the United States and other agriculturally important countries. NESDIS has been engaged in an effort to develop products from operational satellites that will supplement weather observations for agricultural monitoring. Other quantities useful for crop monitoring that are being estimated from the NOAA satellites on an experimental basis are precipitation, daily temperature ranges, insolation reaching the surface, and snow cover. A "vegetation index," derivable directly from satellite measurements, can be interpreted as a direct measure of the condition of vegetation.

The visible and near-infrared channels (channels 1 and 2) of the AVHRR provide the basis for the vegetation index. The reflectance of green vegetation in the visible part of the spectrum is low but is much higher in the near infrared. Other surfaces, such as water, bare ground, and clouds have reflectances that are nearly the same in the two bands. The difference between measurements in channels 1 and 2 is thus a sensitive indicator of vegetation. Figs. 16 and 17 are experimental depictions of the normalized difference (ch2 − ch1)/(ch2 + ch1), indices of vegetation over the Northern Hemisphere during contrasting seasons. Darker grey shades in these images connote "greener" areas on the ground. The data are accumulated by saving the greenest observation at each location over week-long periods to reduce the effects of clouds and other atmospheric effects.

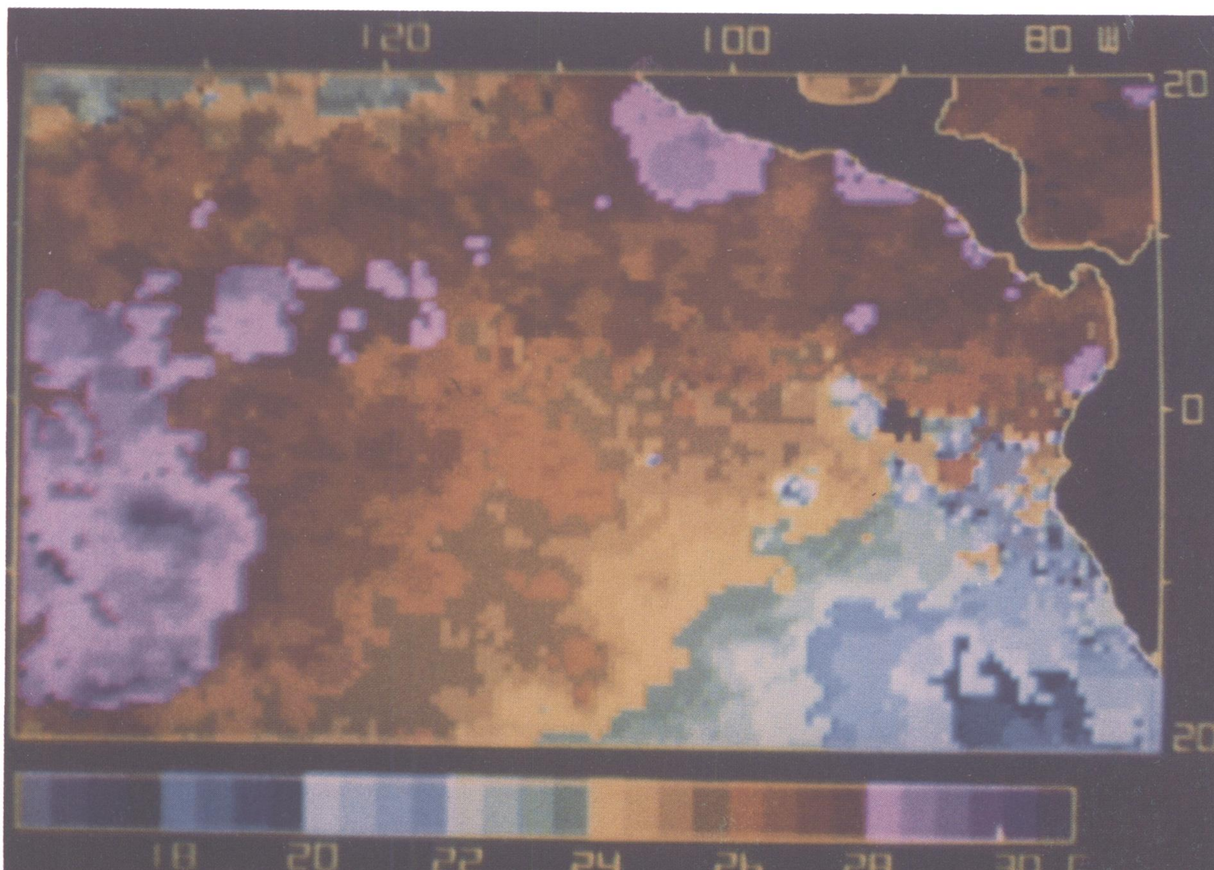
Image Interpretation

(1) *Severe Weather.* In spite of the tremendous progress made in computers and computer systems, there is still no substitute for the human eye and human judgment in extracting the large amounts of useful information implicit in the organization and spatial relations that satellite imagery provides. NESDIS still devotes substantial efforts to studies aimed at early identification of the key features or precursors of large convective storms. These researchers usually play the dual role of scientist and teacher. They are in great demand to offer training in the latest in satellite image interpretation both nationally and internationally.

Generally, organized convergence lines that trigger strong convection are detectable in satellite imagery prior to deep convective development along the lines. An example of a frontal system that develops into a severe squall line is shown in Fig. 18. Early squall line developments of this type are routinely detected in GOES imagery prior to deep convection development and their detection by radar. Near the time of the latest image shown in Fig. 18, large hail and funnel clouds were reported in South Dakota, a tornado injured 6 people in Minnesota, and a weak tornado was reported in Iowa. Later in the evening additional severe weather did damage from Kansas to Minnesota.



(a)



(b)

Fig. 14. Satellite derived sea surface temperatures for the third weeks of November 1982(a) and 1983(b) (before and during the El Nino event of 1983).

Fig. 15. The April 4, 1982, eruption of the El Chichon volcano as viewed in the visible for the NOAA-6 satellite.

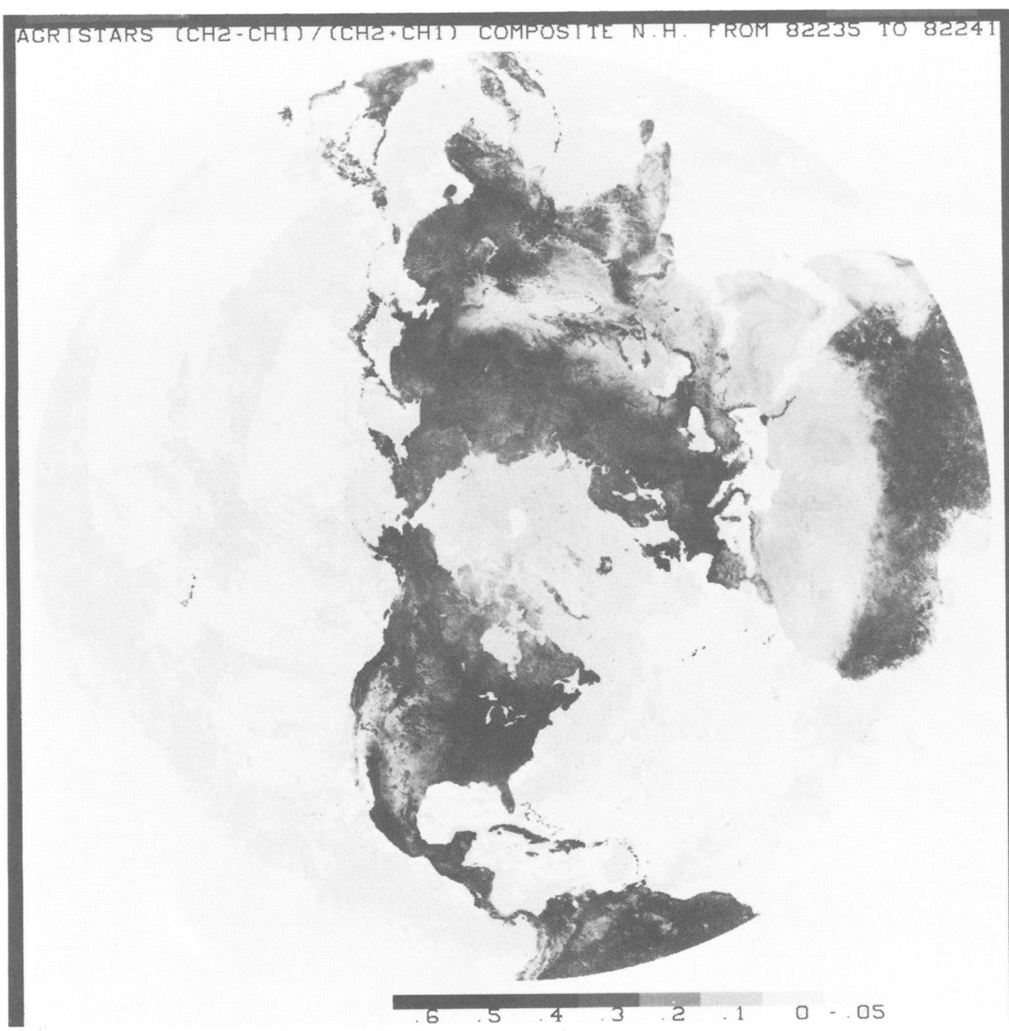


Fig. 16. Vegetation index generated from 4 km resolution AVHRR observations during the week of August 23–29, 1982.

Satellites and radar furnish independent information concerning the thunderstorm and its environment. Fig. 19(a) is a GOES infrared image displayed in a format to emphasize the overall pattern and depicts cloudtop temperatures every 1°C. The coldest temperatures are -69.2°C. Fig. 19(b) is the same image with an image from a research radar superimposed. At the time of the images, tornado activity was in progress in the more

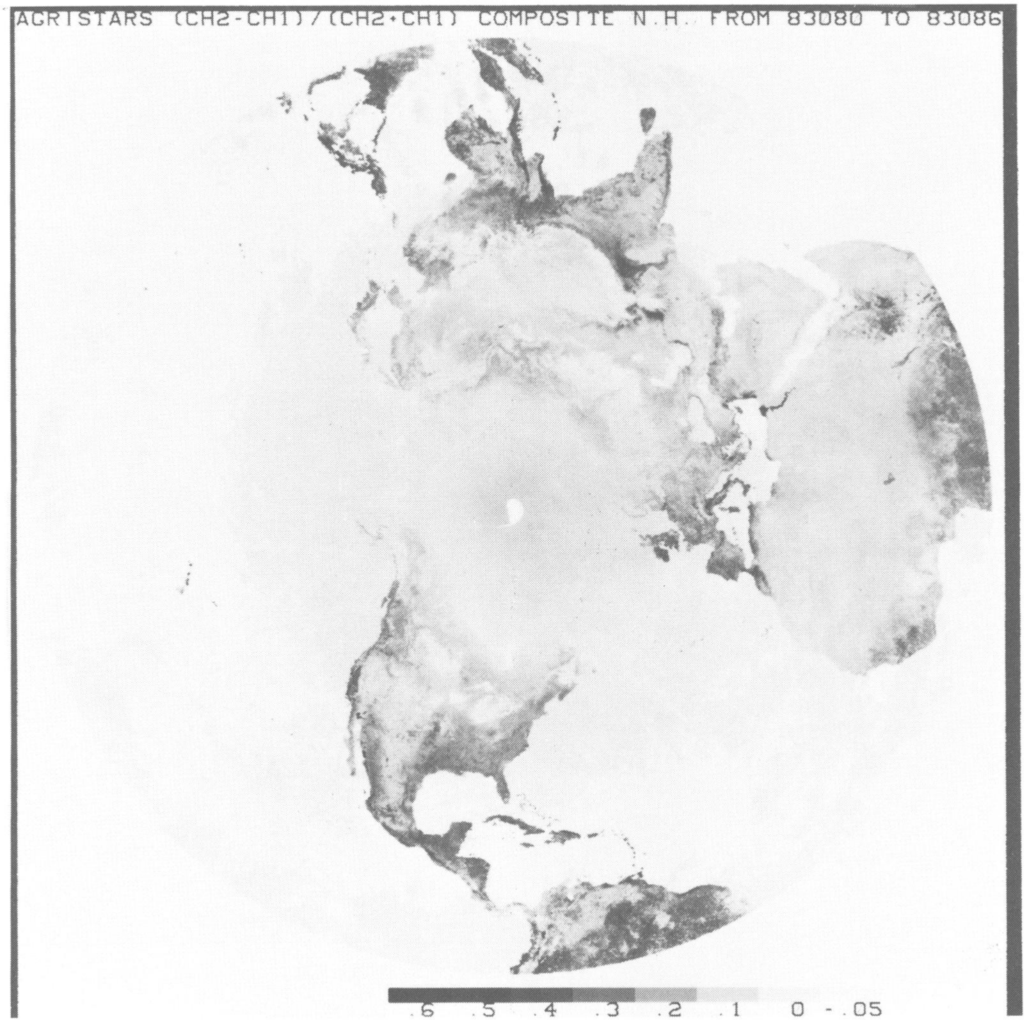


Fig. 17. Same as Fig. 8, except 6 months later (March 21–27, 1983).

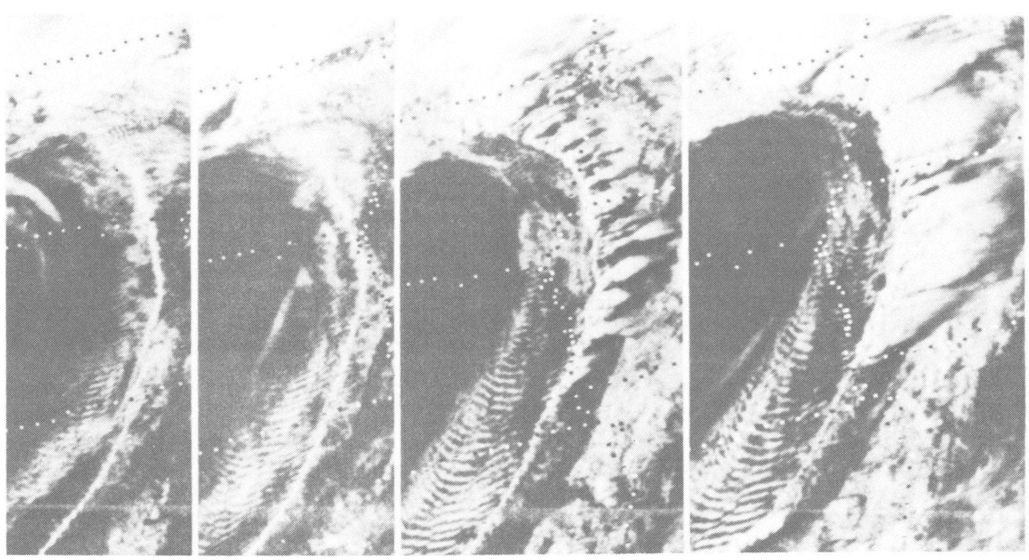
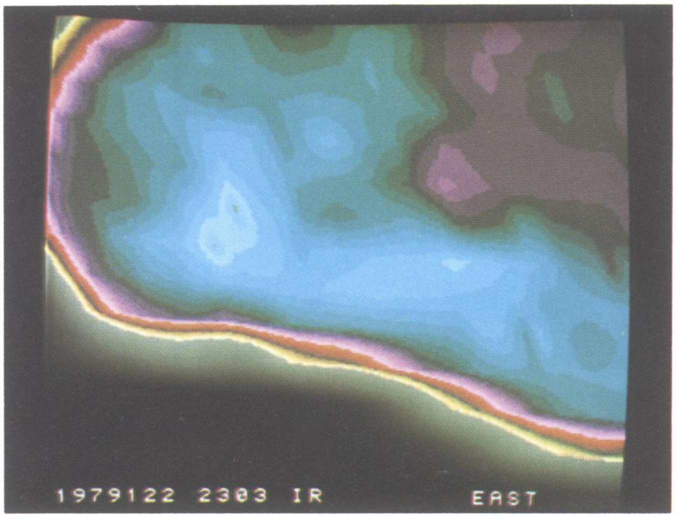


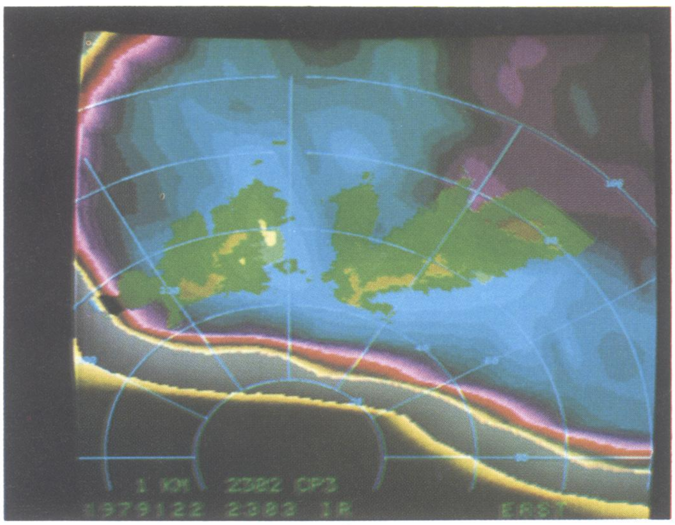
Fig. 18. Squall line developing on a cold front. Visible images from GOES VISSR at 1300, 1400, 1600, and 1700 CST.

easterly of the two storm complexes. The combination of radar and satellite data is a powerful tool for the thunderstorm investigator.

(2) *Continental Snow Cover.* Since November 1966, NESDIS has prepared a Northern Hemisphere weekly snow and ice cover chart. These charts show the areal extent and brightness of continental snow cover but do not indicate snow depth. The analysis is based on imagery from the polar-orbiting satellites. The snowline is representative of the latest cloud-free image of the



(a)



(b)

Fig. 19. (a) GOES-East infrared image for May 2, 1979, at 2302 GMT, displayed in an interpolated format with an enhancement table showing 1°C temperature changes. The coldest temperatures are −69.2 C. (b) The same image, but displayed with 2302 GMT 1 km Doppler radar reflectivity data. At the time of the images tornado activity was in progress in the eastern of the two storm complexes.

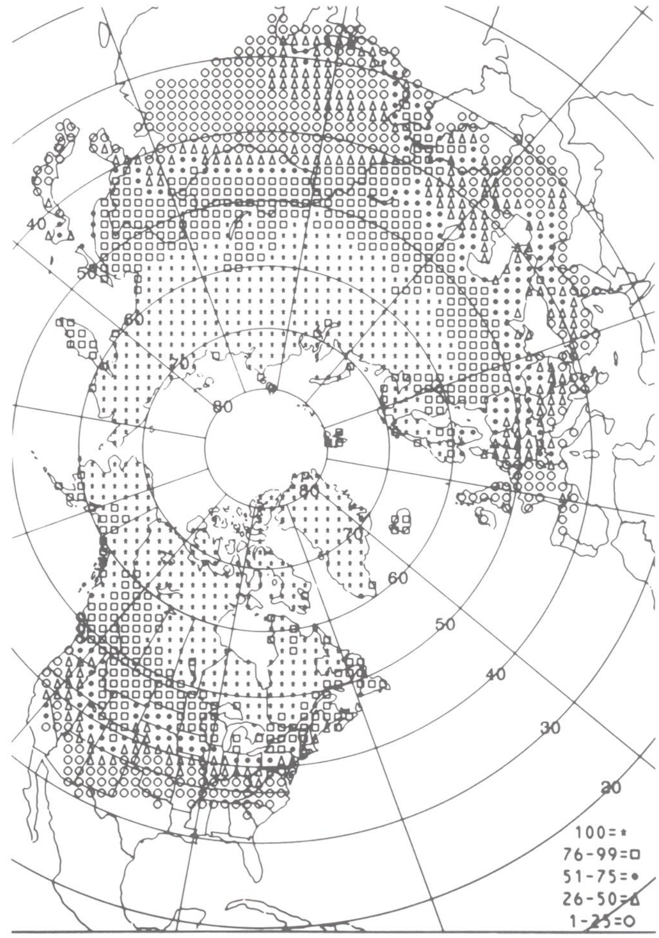


Fig. 20. Fifteen year snowcover climatology of the Northern Hemisphere with winter (December–February); symbols indicate relative frequency of snowcover as viewed in AVHRR imagery.

particular area. These data are now available in digital form. Fig. 20, a 15 year climatology of winter snow cover, is one example of the information available from this database. Snow cover is one of the variables identified for study in the International Satellite Land Surface Climatology Project being proposed as part of the World Climate Program.

(*3*) *Volcanoes*. Because of their global and frequent coverage, meteorological satellites are excellent platforms for observing major volcanic eruptions, especially in remote parts of the world. Recently, NOAA-6, NOAA-7, and GOES data were used to examine and track the stratospheric cloud associated with the eruptions of El Chichon in Mexico. It was determined that the eruption of April 4, 1982, reached an altitude between 24 and 31 km (Fig. 15) and that the resultant stratospheric ash cloud took 3 weeks to circle the globe, traveling from east to west.

Future Directions in Satellite Research and Development

(1) *Satellite Oceanography*. Satellites have demonstrated that the ocean surface features of winds, waves, temperature, sea and lake ice, ice sheets, ocean color, marine geoid, circulation, and currents can be measured quantitatively. Equally important, these satellites have shown that the ocean surface and near surface is physically and biologically more dynamic than anticipated.

Seasat carried 4 microwave sensors and 1 visible and infrared radiometer. The microwave sensors were a scatterometer, passive five-frequency radiometer, radar altimeter, and synthetic aperture radar (SAR) system. The scatterometer and SAR sensors are used here as illustrations. As one can see in Fig. 21, surface winds from buoys agree well with scatterometer-derived winds in the Gulf of Alaska. The winds from the west northwest direction compare well, but the strong windspeed gradient from southwest to northeast is not detected by the single

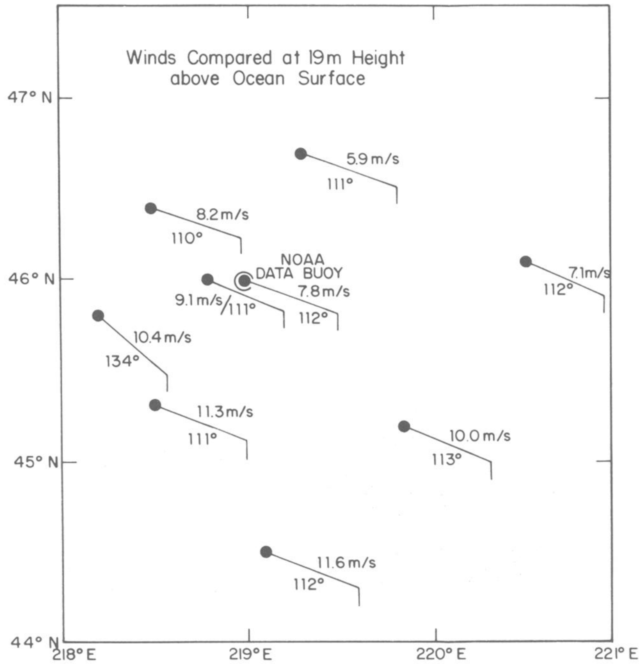


Fig. 21. Seasat-derived windfield in vicinity of a NOAA data buoy in the Gulf of Alaska (Rev. 1298).

point in situ systems. A satellite scatterometer is capable of acquiring 300 000 to 500 000 well-distributed wind reports per day, as compared with the 2000 to 4000 reports currently obtained from only selected parts of the world oceans by ships and buoys.

The complex nature of the ocean surface as observed by the Seasat SAR is shown in Fig. 22. This scene, as well as others, has been studied to understand the nature of the interaction of electromagnetic energy with the ocean surface and has shown that winds, waves, eddies, internal waves, currents, ship wakes, oil slicks, and bathymmetry all affect the radar return.

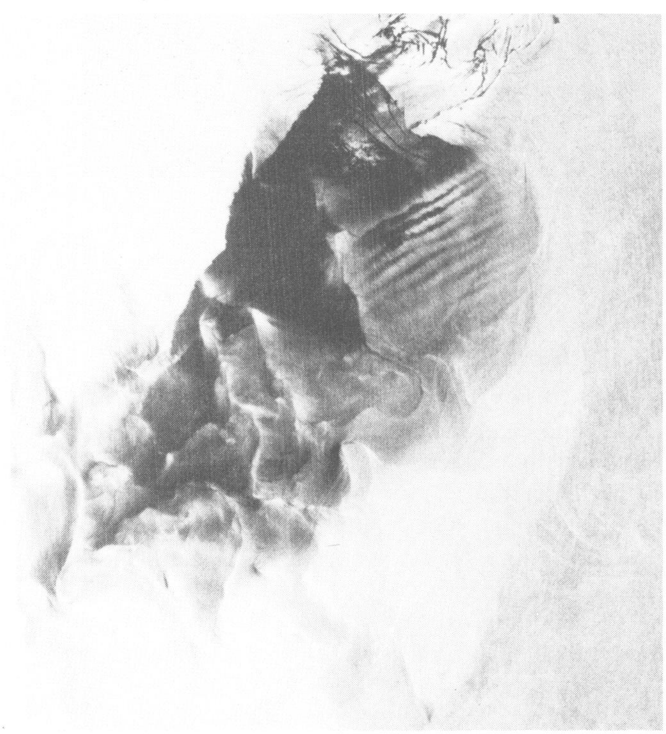


Fig. 22. Complex patterns detected by the Seasat SAR radar in a nearly calm region of ocean located just outside the mouth of Chesapeake Bay, September 28, 1978.

Ocean color as measured by the coastal zone color scanner (CZCS) on Nimbus-7 has increased the awareness of physical and biological oceanographers alike of the near-surface dynamics of the ocean. The purpose of the CZCS is to provide estimates of near-surface concentration of phytoplankton pigments and total seston (suspended matter) by measuring the spectral radiance backscattered out of the ocean. The radiance backscattered from the atmosphere (Rayleigh scattering) and/or sea surface (specular reflection) is typically at least an order of magnitude larger than the radiance scattered out of the water. Fig. 23(a) shows the total radiance measured at the satellite sensor; Fig. 23(b) shows the sea surface radiance after atmospheric correction; and Fig. 23(c) shows the phytoplankton pigment concentration of the Middle Atlantic Bight on June 10, 1979. Fig. 24 is a direct comparison of the total pigment concentration made by a ship following the track shown in Fig. 23(d) (solid line) and the CZCS derived concentrations. In addition to the potential quantitative application of these data, sequential images display complex temporal and spatial variability revealed by subtle changes in pigment concentration.

Future oceanic satellite systems will comprise the ensemble of sensors demonstrated on Seasat, Nimbus-7, and the TIROS-N/NOAA series. Increased marine requirements for research and operational data from a broad spectrum of users, both domestic and international, and a variety of applications will demand the fullest cooperation within the United States among the Navy, NASA, NOAA, and other ocean-interest agencies, coupled with joint programs involving the European Space Agency, Japan, Canada, France, and perhaps others.

(2) *Future Atmospheric Sounders.* The major deficiency of all methods for sounding the atmosphere from space is their relatively coarse vertical resolution. All current devices are passive multispectral radiometers that measure upwelling atmospheric thermal radiation. If the spectral interval in which the observation is made is very narrow, the atmospheric layer that contributes the radiation will be thinner. However, even if the radiation were monochromatic, the layers must all have a finite and, in meteorological terms, significant depth. The variation in atmospheric absorption within the observed spectral interval further broadens the layer from which the radiation is originating.

Research on sounders is generally aimed at overcoming these recognized limitations. The desired spectral resolution ($\Delta\nu/\nu = 0.1$ percent) is beyond the capabilities of filter radiometers, but it can be achieved from an Earth-oriented geostationary platform using a Michelson interferometer called high-resolution

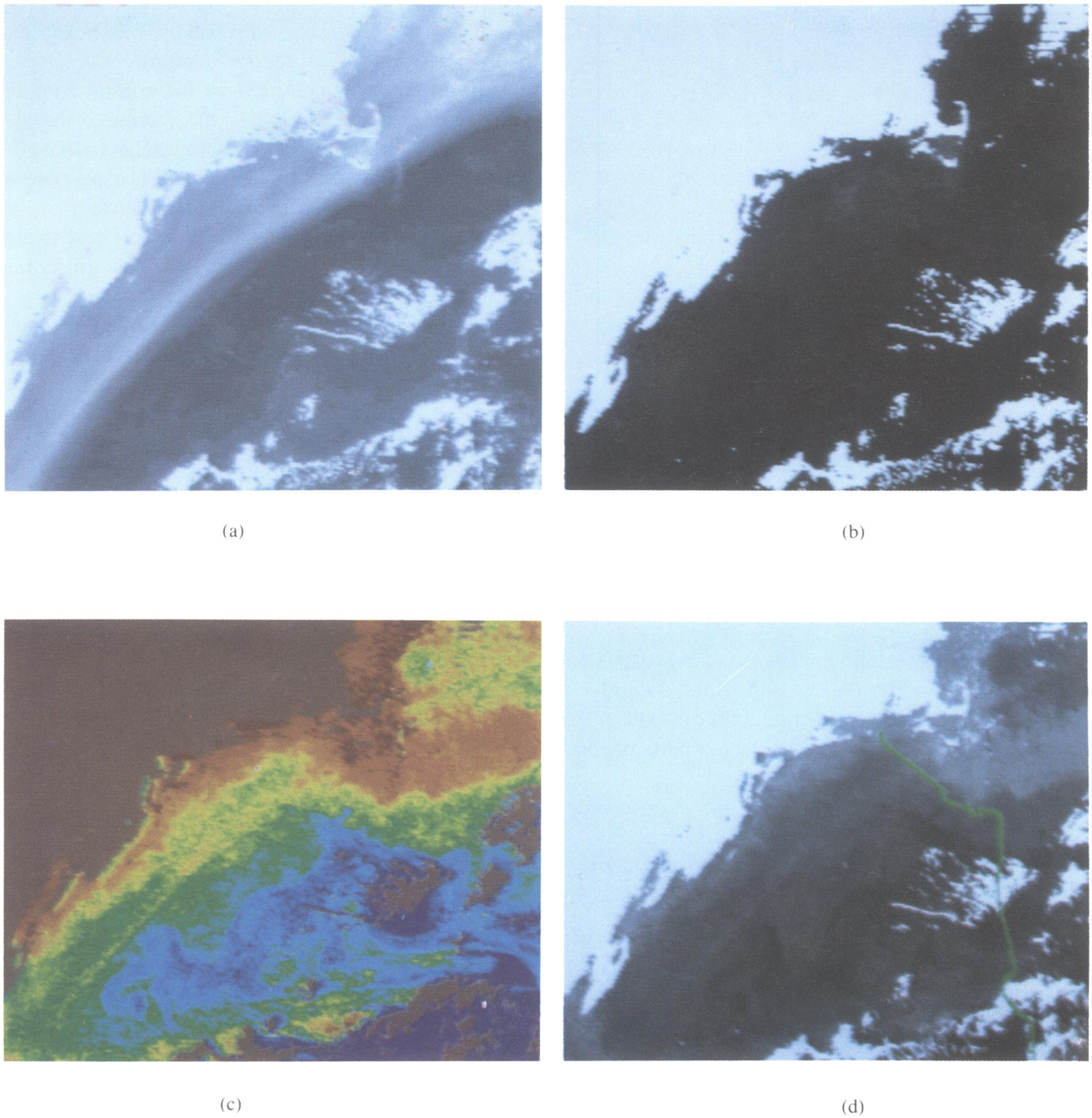


Fig. 23. CZCS analysis of June 10, 1979, off the East Coast of the United States. (a) Total radiance (550 nm). (b) Sea surface radiance (550 nm). (c) Phytoplankton pigment concentrations (mg/l). (d) Pigments with ship trackline (48 h).

interferometer sounder (HIS). The latest design, which uses partial interferogram sampling, is scheduled to be tested on an airplane later this year.

Perhaps somewhat further in the future, but with a potential of much higher vertical resolution, is the use of active rather than passive radiometric systems. NOAA's Wave Propagation Laboratory is investigating the feasibility of measuring the global wind field using an infrared coherent laser radar under a joint program with the Air Force. The development is particularly important because (1) it is designed to measure a parameter, the wind, that is of fundamental importance for weather analysis and prediction, but for which no global reliable method now exists; and (2) it would be designed to achieve a 1 km resolution. The lidar system measures the radial wind component along the line of sight of the transmitted pulse, with height resolution determined by the pulse duration. Two or more observations from different directions are required from each region to determine both components of the horizontal wind velocity (Fig. 25).

The basic pulsed CO_2 coherent laser radar for global wind measurement consists of a stable, single frequency CO_2 transverse excited atmospheric (TEA) laser, interferometer, transmit–receive optics with scanning telescope, attitude control system, an infrared detector, a velocity-frequency analyzer, and a data processor and display. TEA lasers have very high coherence and gain

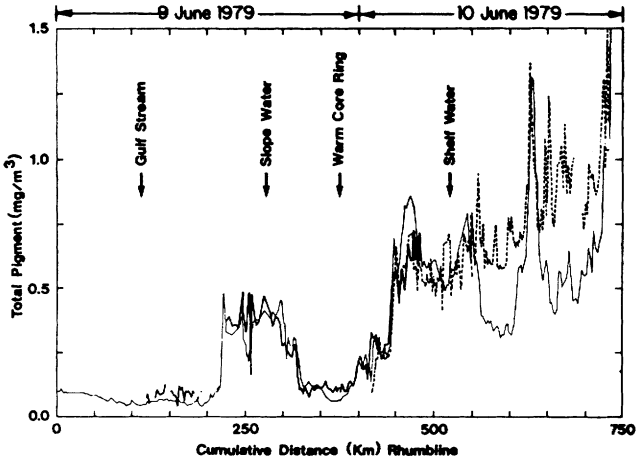


Fig. 24. Total pigment determined from CZCS Nimbus 7 (dashed lined) compared with shipboard measurements (solid lines).

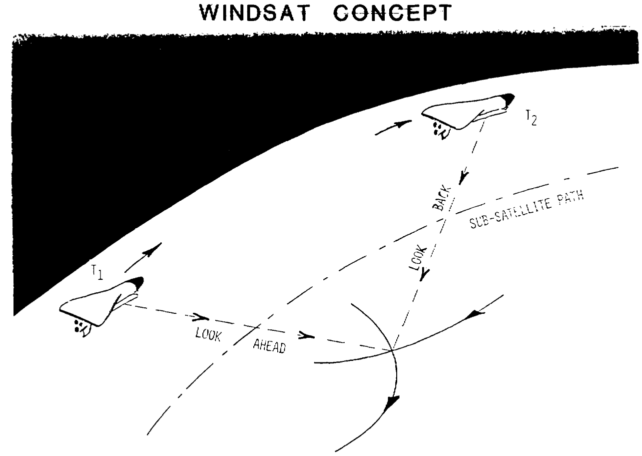


Fig. 25. Schematic depiction of the Windsat concept designed for test and evaluation aboard the Space Shuttle.

characteristics and can generate several joules of energy per pulse. It is this improvement in laser technology which makes global wind monitoring possible.

Tests of the concept aboard an aircraft, aboard a future flight of the Space Shuttle, and on a free-flying satellite are being considered.

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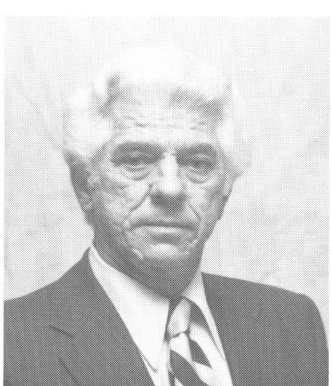

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