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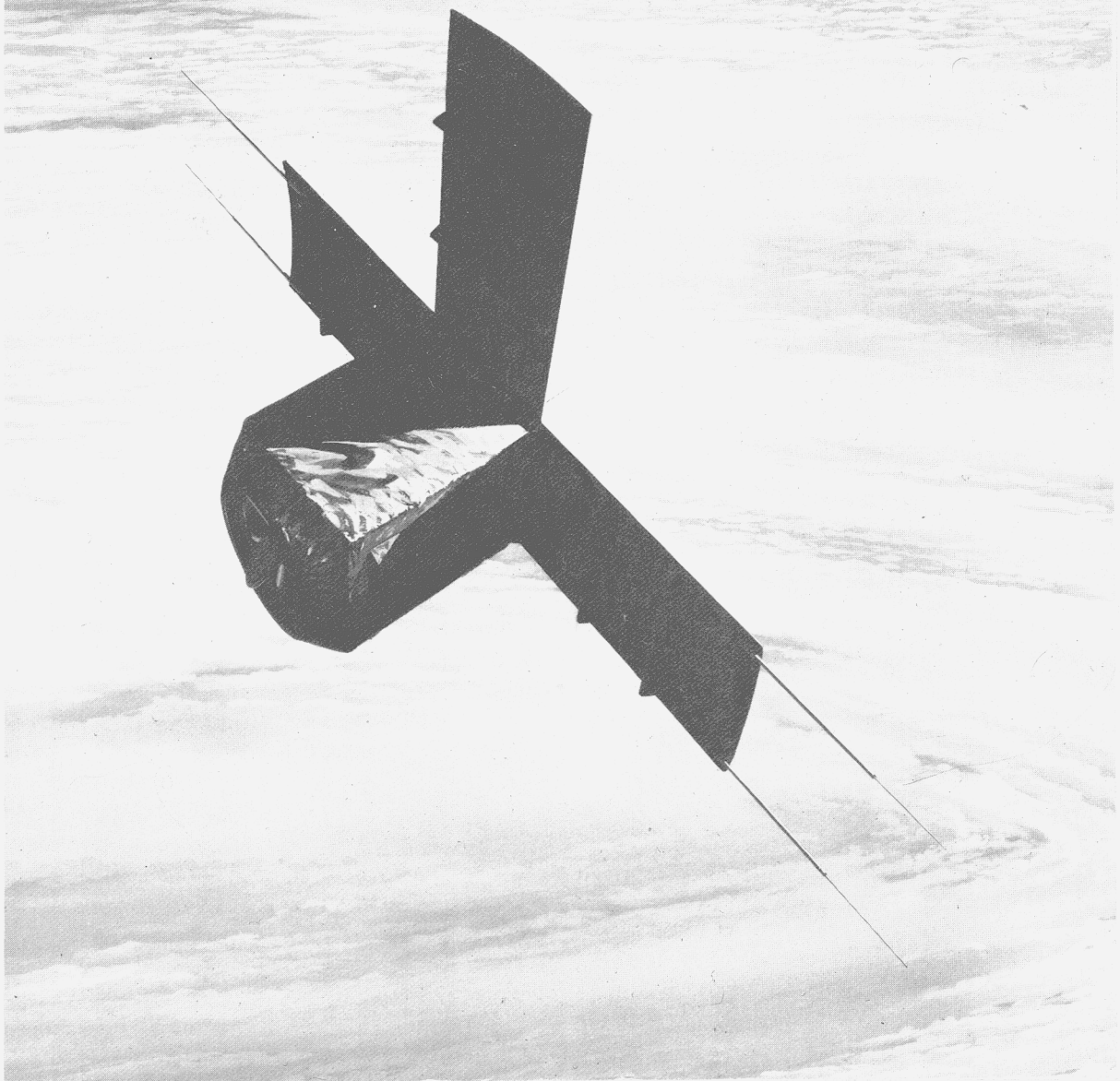
First Five Years of the Environmental Satellite Program

—AN ASSESSMENT

A Report to the Administrator of the National Oceanic and Atmospheric Administration



U.S. DEPARTMENT OF COMMERCE

National Oceanic and Atmospheric Administration

National Environmental Satellite Service

WASHINGTON, D.C.
February 1971

U.S. DEPARTMENT OF COMMERCE
Maurice H. Stans, Secretary
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Robert M. White, Acting Administrator
U.S. National Environmental Satellite Service, Washington, D.C.
David S. Johnson, Director

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First Five Years of the Environmental Satellite Program —An Assessment

A REPORT TO THE ADMINISTRATOR OF THE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Prepared by the
National Environmental Satellite Service

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National Oceanic and Atmospheric Administration
TIROS Satellites and Satellite Meteorology

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FOREWORD

In February 1971 the National Operational Environmental Satellite System will complete five years of uninterrupted service. During this time the weather satellites have provided regular global observations of cloud systems and other environmental features for the forecast and warning services of the United States and other nations around the world.

There have been many questions asked, domestically and internationally, about the value of the satellite system in terms of practical benefits. It seems appropriate at this time to assess the wide range of applications for which satellite data have been used. This report is based on such an assessment. It reveals how unique kinds of data obtained from this new vantage point hundreds or thousands of miles above the Earth have brought major advances in our understanding of the atmosphere and our ability to predict its behavior.

We are indebted to numerous satellite data user groups for providing the many examples of practical benefits forming the basis of this assessment. We wish particularly to acknowledge the assistance of the Applications Group of NESS, the various field offices of the National Weather Service of NOAA, the weather services of the U.S. Air Force and the U. S. Navy, and the meteorological agencies of many foreign governments. Dr. Robert L. Pyle of NESS has compiled and edited the material into the form of this report.

David S. Johnson

David S. Johnson, Director
National Environmental Satellite Service

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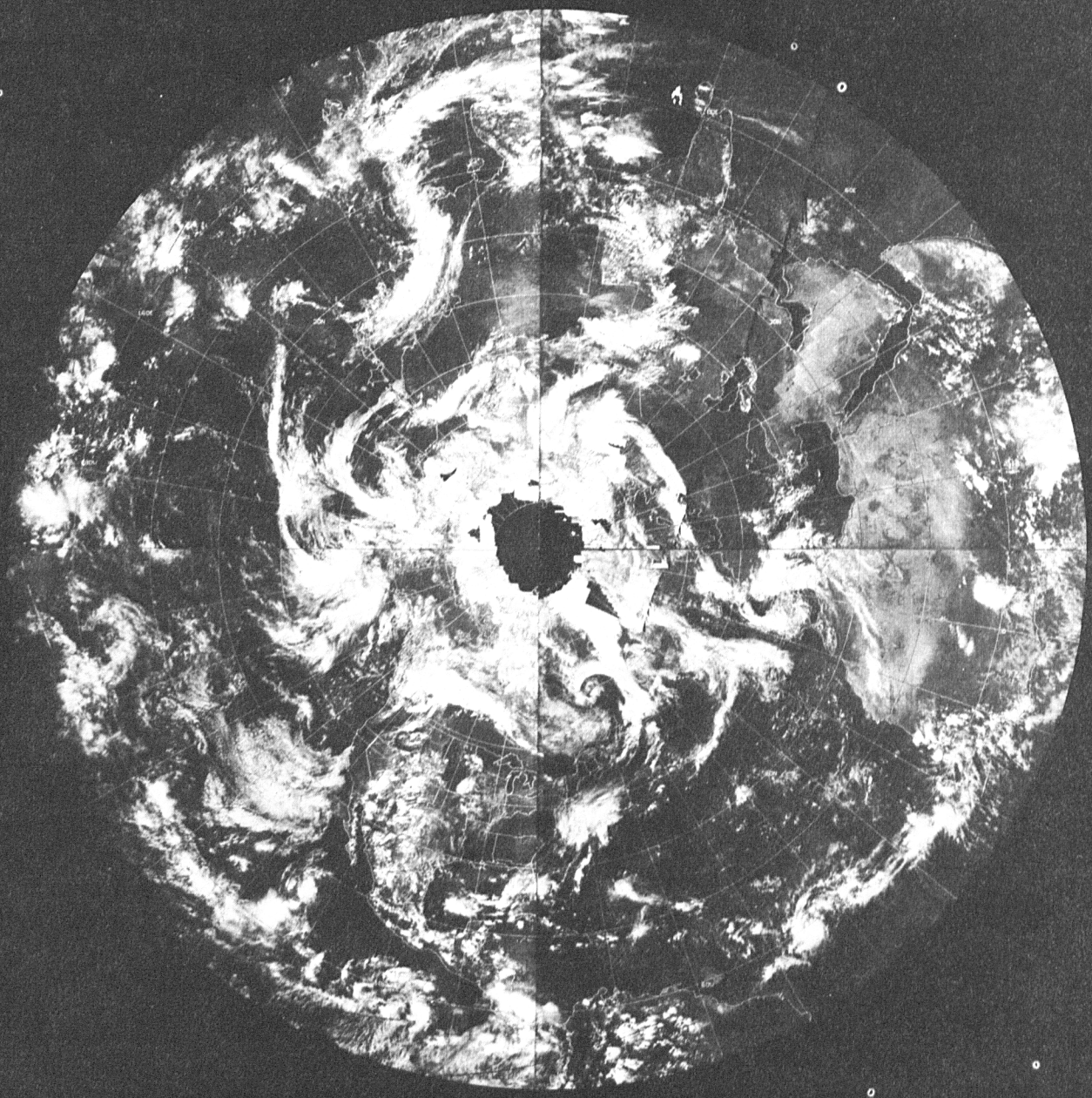
COVER PHOTO—Artist's conception of the Improved TIROS Operational Satellite looking down on the earth's cloud cover. This is the current polar orbiting satellite in the National Operational Meteorological Satellite System.



Introduction

The first TIROS experimental weather satellite was flown in 1960, and was an immediate success. The TIROS pictures showed the organization of weather systems with a clarity never before seen, and revealed phenomena that previously were unknown. Within a few days of the TIROS launch, the new data were being used operationally to improve weather services. More TIROS satellites followed, with improved cameras, longer lifetimes, and increasing applications to weather forecasting.

The success of this new observational system led to the establishment of the National Operational Meteorological Satellite System in early 1966. The System has produced an unbroken flow of data ever since. In the ensuing years, the System has been steadily improved and augmented. It now provides the following basic services:

pictures of the entire globe, day and night, every day;

continuous viewing of the Americas and adjacent oceans during daytime;

temperature measurements throughout the world, and wind measurements in selected parts of the Atlantic and Pacific Oceans.

Direct-readout pictures are transmitted directly from the satellite to weather stations throughout the world. These are used in preparing regional weather forecasts of all types, sea ice advisories, and numerous other service products. Stored pictures are received at the World Meteorological Center in Washington, mapped by computer, and distributed by facsimile circuits to a wide variety of users.

The World Meteorological Center in Washington uses satellite pictures, temperature soundings, and wind measurements to improve the accuracy of large-scale weather analyses and prognostic charts. These charts are transmitted via facsimile to all U.S. weather stations, both civil and military, and are used as basic guidance material for all weather forecasts. Air Force and Navy weather centrals use the satellite data in much the same way. Analysis centers which provide special services to agricultural, hydrologic, maritime and other interests use satellite data routinely to improve their products.

The direct picture transmission systems provide unprecedented observational coverage for other countries throughout the world. Underdeveloped nations tend to have inadequate weather observing networks, and lack the funds needed to mount extensive observing programs. By purchasing equipment for receiving cloud pictures transmitted directly from the satellite, they are now able to obtain complete area coverage at minimal cost.

Examples given in the following sections describe some of the more noteworthy and spectacular cases among the diverse applications of weather satellite data. Taken together, they produce public benefit far beyond the cost of the system. Where these benefits include the saving of lives and the reduction of human misery, they cannot be evaluated in terms of dollars and cents. Yet, the Operational System is so new that its potential has only begun to be realized.

Satellite photograph of Northern Hemisphere weather, September 13, 1969.

Examples of Benefits

WEATHER FORECAST AND WARNING SERVICES

The Killer Storms

Satellite data have powerful applications in the forecasting and warning of our most dangerous weather phenomena—the deadly and destructive hurricanes and tornadoes. These intense concentrations of atmospheric energy are produced by a delicate mix of conditions which must combine in just the right way. When they do, the ensuing effects on man, his property, and his surroundings can be devastating.

HURRICANES

Hurricanes are born as small disturbances in remote areas of the tropical oceans. Such small disturbances are present daily, moving westward across the tropical Atlantic or up through the tropical eastern Pacific where conventional weather observations are virtually non-existent. Only a few develop to hurricane intensity, but they may do so with explosive suddenness. Previously, there was no way to detect most of these in their earliest stages, to track their early progress, or to determine which were likely to develop to hurricane force.

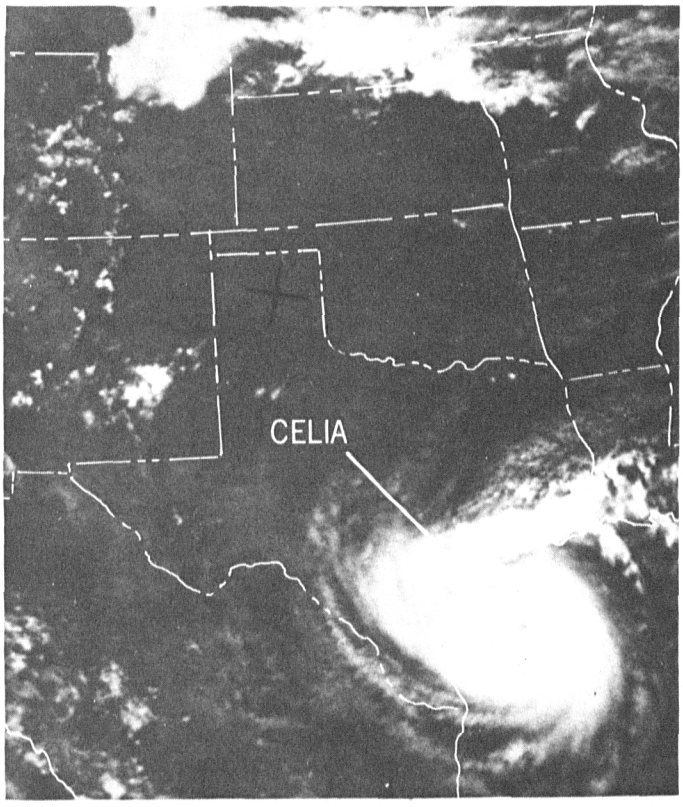
Satellites now provide daily blanket coverage of the tropical oceans, permitting detection and surveillance of every disturbance that occurs. Satellite pictures show the fine structure of the circulation, and whether or not it is intensifying. A set of models has been developed, by which wind speed, the most crucial element in storms at sea, can be estimated from satellite pictures. Studies have uncovered some of the unique characteristics which distinguish developing storms from their fellows. The result is earlier and more dependable forecasts of hurricane development, future path, and intensity.

Discovery and Tracking

Since inauguration of the operational satellite service, probably no tropical storm has gone undetected anywhere in the worldwide tropical oceans. Discovery is invariably by satellite. Previously, it was necessary to attempt to patrol great areas of the oceans with reconnaissance aircraft. This procedure was not only expensive but unsatisfactory, because only limited areas could be covered and storms were often missed. Now, hurricane reconnaissance planes are no longer used for exploratory surveillance; instead they are directed to the area where the satellite has shown that a disturbance exists. It is estimated that with the availability of satellite data, aircraft time and costs representing 1 to 2 million dollars annually have been reprogrammed from general surveillance to direct reconnaissance. Further, when more than one hurricane is threatening, aircraft often can not be spared to check the spawning grounds for new storms. The satellite now provides this insurance—and very reliably.

> Hurricane CELIA, which raged across Cuba, Florida, and South Texas in early August 1970, left in its wake more than 30 dead, nearly 1,000 injured, and property damage in the millions. But the Director of the National Hurricane Center in Miami says: "The death and injury toll would have been far greater had not satellite photos pinpointed CELIA in its early stages and led aerial observers to the storm in time to chart a projected course and issue warnings far in advance of its arrival."

During her erratic progress across the Gulf of Mexico, CELIA first intensified, then weakened, and then rapidly re-intensified. Although she was adequately observed by radar and aircraft reconnaissance, these data gave no indication of why she was behaving in this fashion. However, the satellite pictures showed significant changes in the feeder bands of thunderstorms which spiral in toward the storm center and which are known to be a prime energy source for hurricanes. This was the clue to CELIA's unusual behavior. With satellite data, hurricane forecasters can now watch the growth and decay of these convective cloud bands



Hurricane CELIA off the Texas coast, August 3, 1970.

on a continuous basis. This knowledge has been applied successfully to predictions for subsequent storms.

Saving Hurricane Preparedness Costs

Once a storm is forecast to become a hurricane, and a name is assigned to it, the communities, military bases, and commercial enterprises which lie in its path must take extensive precautions. For the city of Miami alone, the preparation cost has been calculated at two million dollars for a single storm. When all interests are considered, the cost of even one false alarm is exceedingly high.

On August 13 and 14, 1970, aircraft and satellites both observed a tropical disturbance moving across the Atlantic. The aircraft measured easterly winds of 50 to 70 miles per hour. Normally, when winds this strong are found, the disturbance is named, warnings are issued, and the wheels of preparation are set in motion. In this case, however, the satellite pictures showed that this was not a rotating storm, and that it was not in immediate danger of intensifying. The decision was made not to name the storm and not to forecast that it would become a hurricane. The storm subsequently weakened and passed into the U. S. mainland without reaching hurricane strength.

Eastern Pacific Hurricanes

More tropical storms and hurricanes arise along the shipping route between California and the Panama Canal than in any other area of the world. These storms develop suddenly from disturbances which cannot be detected by conventional means. Most of these hurricanes move out to sea and die, but each year a few change course and move into Mexico or southern California.

With satellite data, the Eastern Pacific Hurricane Center in San Francisco has been able to detect each of the storms while it was in its formative stages. Warnings are issued on the location of each storm and its track with an accuracy that was previously impossible.

These warnings not only help our ships at sea, but also those many small cities and towns in Mexico whose only information regarding their danger comes from the U. S. hurricane warning center. The storms that strike Mexico affect many United States interests, including shipping, commercial and sport fishing, and tourists ashore or on cruises in Mexican waters. Satellite pictures are the key factor which enable the forecast center to issue timely warnings of these destructive storms. One example:

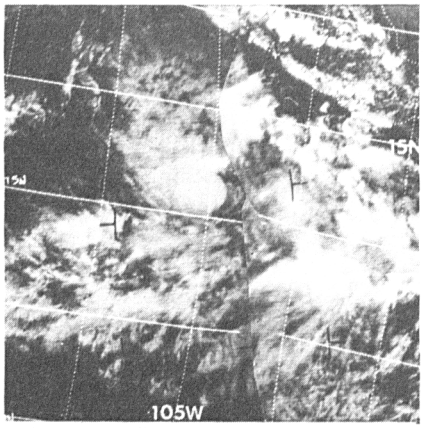
JENNIFER was far out at sea on October 11, 1969. That night the storm curved, accelerated rapidly toward Mexico, and struck the city of Mazatlan the next afternoon. Ship reports were lacking, but JENNIFER's changes in course and speed were detected in the morning satellite picture in time to warn Mazatlan of the impending disaster.

Hurricanes PAULINE (Sonora, October 1968), NAOMI (Mazatlan, September 1968), and HELGA (Baja, California, September 1966), are other cases in which satellite pictures played the crucial role in enabling forecasters to issue timely, accurate warnings.

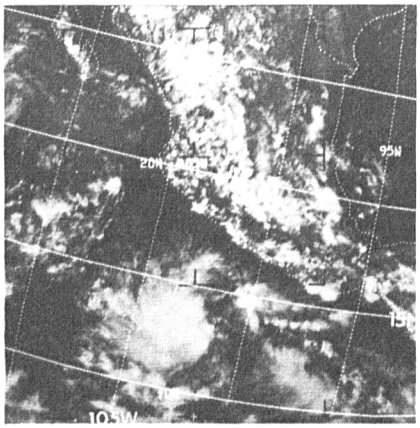
Heavy Surf from Hurricane

In mid-July, 1969, Hurricane BERNICE developed 1200 miles south-southeast of Los Angeles in an area devoid of weather reports. Based on satellite pictures, the Los Angeles Weather Bureau issued a heavy surf alert on July 14. Extra lifeguards were placed on duty and steps were taken to prevent beach erosion which can produce extensive property damage. Six-foot breakers struck the coast at 4 a.m. on the 16th. That day there were 250 rescues but only one drowning along the beaches.

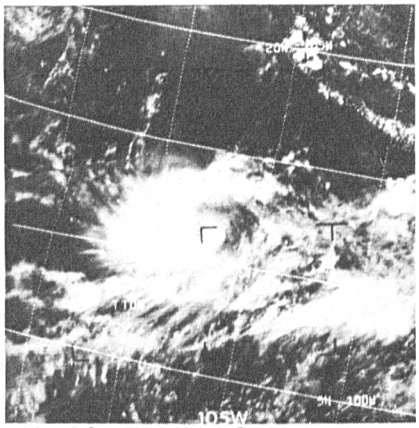
Hurricane BERNICE , July 8-16, 1969



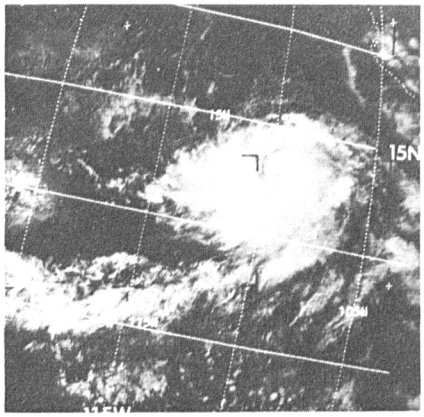
July 8 Depression



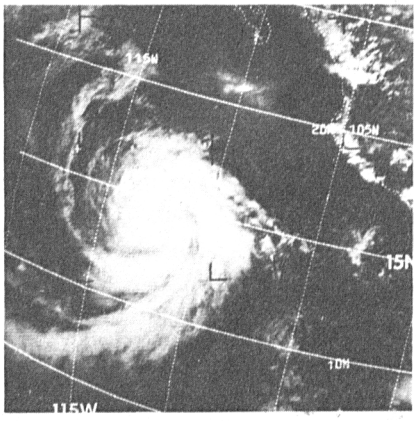
July 9 Depression



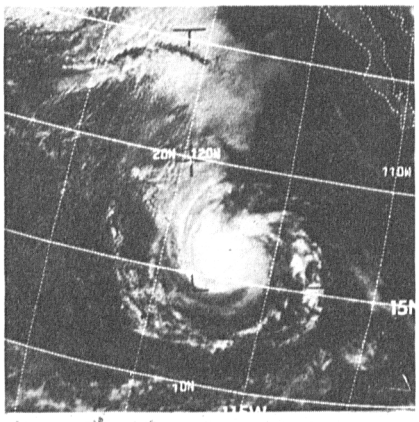
July 10 Tropical Storm



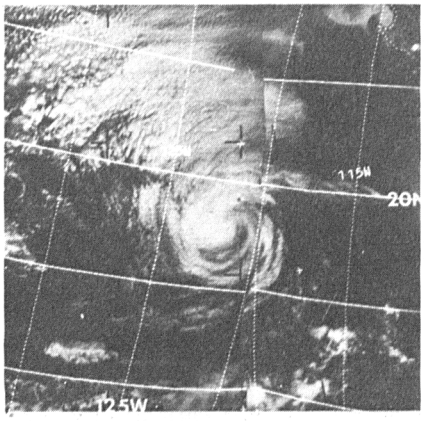
July 11 Tropical Storm



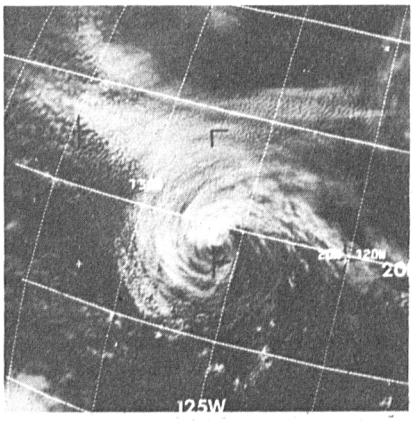
July 12 Hurricane



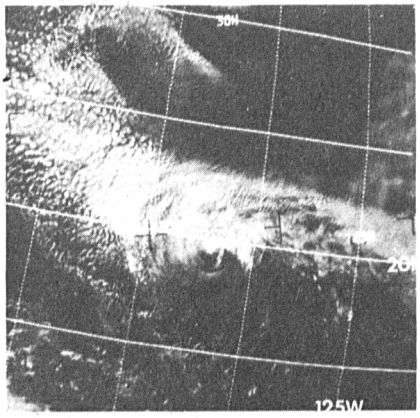
July 13 Hurricane



July 14 Hurricane



July 15 Tropical Depression



July 16 Tropical Depression

Hurricane BERNICE, July 8-16, 1969. The development and decay of an east Pacific hurricane.

TORNADOES AND SEVERE LOCAL STORMS

Tornadoes and severe thunderstorms are as dangerous to life and property as hurricanes, although they differ in basic characteristics. In contrast to hurricanes, they have lifetimes measured in hours rather than days, and they normally pass most or all of their life cycles in continental land areas where conventional weather observations are relatively dense. Their violence is concentrated in small areas, they are of short duration, and they strike suddenly and without warning. They present unique problems in observing and forecasting because they are too small and too short-lived to be detected (except in rare instances) by conventional weather observing networks.

The forecasting of severe local storms over the continental U. S. has advanced to the stage where area alerts and watches are issued routinely. These are for areas that are roughly the size of one or more states, and for periods covering several hours. However, the science of forecasting has not reached the stage of specifying the time and location at which a thunderstorm or tornado will strike within the alert area. Individual storms can only be discovered by personal sighting, or by weather radars with a range of 100 to 120 miles. These methods may provide warning only a few minutes in advance, which may be too late.

Satellite pictures now play a significant role because they cover areas that are beyond radar range, and show the early stage of storm development when distinctive cloud patterns first begin to form. These patterns appear in the satellite picture several hours before the clouds develop to a point where the water droplets in them are large enough to be detected by radar. Geostationary satellites, which can produce pictures at intervals as short as 15 minutes, provide the means for early discovery and continuous surveillance of dangerous local storms.

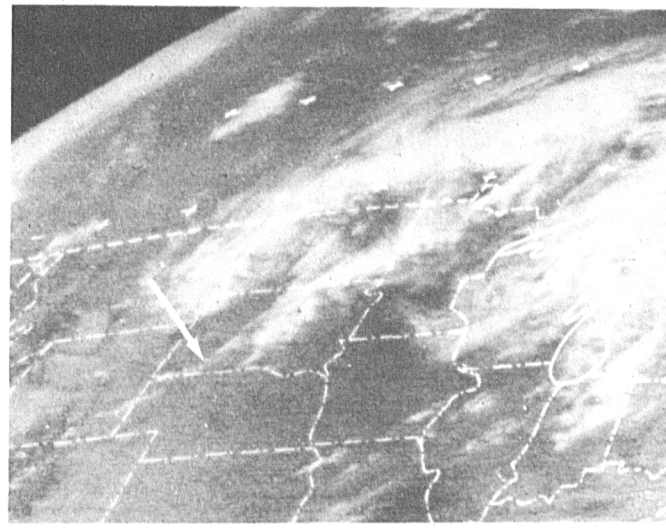
Satellite Data Available Earlier than Radar

On July 14, 1970, a thin line of clouds appeared in the morning satellite picture over Nebraska and South Dakota. The particular characteristics of this line caused forecasters to issue a severe weather watch, timed to the projected movement of the line. Not until four hours later was the squall line detected on radar. The value of early warning need not be dramatized in this case. The squall line produced 12 tornadoes, 4 funnel clouds, at least 15 occurrences of hail, and 19 cases of damaging surface winds.

Locating Jet Stream and Storm Clouds

On May 21, 1970, the satellite pictures showed a cloud pattern which defined the location of the jet stream, and another line of clouds in the early stages of thunderstorm development. The relation of these cloud patterns to each other was key information that led to a forecast of hail and damaging winds for parts of Iowa, Minnesota, and Wisconsin. Because of the satellite picture, the warning was issued earlier and was more accurate in location. Damaging winds with ¾-inch hail did occur in the forecast areas as predicted.

In a similar situation on June 21, satellite pictures led to the early issuance of a severe



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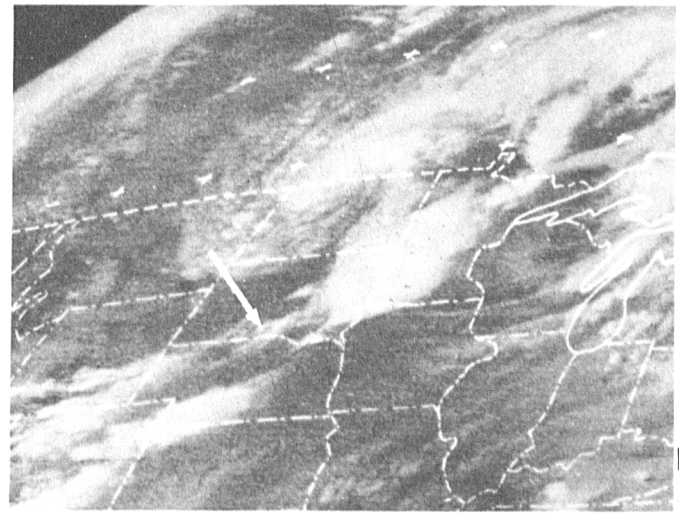

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4 p.m.

Arrows indicate a developing squall line responsible for tornadoes and thunderstorms, July 14, 1970.

weather watch for Virginia, the Carolinas, and Georgia. In this case there were seven reports of heavy wind damage, four waterspouts, and hail up to 2¾ inches across in the forecast area.

Public Weather Forecasts

Weather Service offices throughout the country are using satellite pictures as daily guidance for preparing routine public weather forecasts. The forecasts frequently are more accurate and more timely because satellite pictures have revealed impending weather features which otherwise would not have been considered in the forecast.

Satellite data have been especially effective in showing weather conditions in areas where other weather reports are sparse or lacking, and in showing details of the structure, movement, and growth of both large- and small-scale systems which affect the local forecast. Satellite observations are of particular value in showing weather systems approaching our coasts from data-sparse ocean areas. With satellite pictures showing graphically the weather systems over the oceans, preflight briefings for aircrews can be made more effective and understandable, and aviation interests generally can plan transoceanic operations more efficiently.

The following examples suggest the wide variety of ways in which satellite data have proven crucial to a successful forecast.

WEST COAST

Since weather systems in middle latitudes move mainly from west to east, the San Francisco forecast office and others on the west coast have derived special benefit from satellite observations over the eastern Pacific. The timing and intensity of weather moving in from the Pacific can be predicted more accurately, and forecasts of weather events of interest to the public can be stated in more confident terms.

Thunderstorms

On February 5, 1969, a winter cold front was located in the Pacific 300 miles west of San Francisco, and was expected to move through Northern California the next day. Normally, scattered showers and clearing are forecast after the passing of such fronts. In this case, a satellite picture showed an area of intense thunderstorms immediately behind the front. No other weather reports showed the presence of these storms. Thunderstorms are rare in coastal California. Nevertheless, based on the satellite picture, the Weather Service office issued a 24-hour forecast of thunderstorms for the California coast. On February 6th the most severe thunderstorms experienced in five years struck the San Francisco area. Wind damage from these storms exceeded one-quarter of a million dollars. This severe weather would not have been forecast without satellite data.

Heavy Rain and Snow

One of the most important applications of satellite data has been in the forecasting of precipitation along the U.S. west coast. On January 14, 1970, weather charts showed a storm in the Pacific approaching the coast. The initial forecast was for rain and snow in amounts normal for a winter storm. But when the morning satellite picture was received, it showed that the storm was no longer "normal". A deep moist airmass had joined the storm, moving up from the tropics where no ordinary weather reports were available. The San Francisco forecasters immediately recognized this unusual development, and changed the forecast to predict rainfall of four times the normal amount for a winter storm. The storm moved inland during the next 36 hours, bringing heavy rains and snows to much of the west coast. Four times the normal amount did fall, as predicted.

The next day the storm crossed southern California, giving heavy precipitation there. The forecast for these heavy rains also was based on the wide-spread cloudiness seen in the satellite pictures.

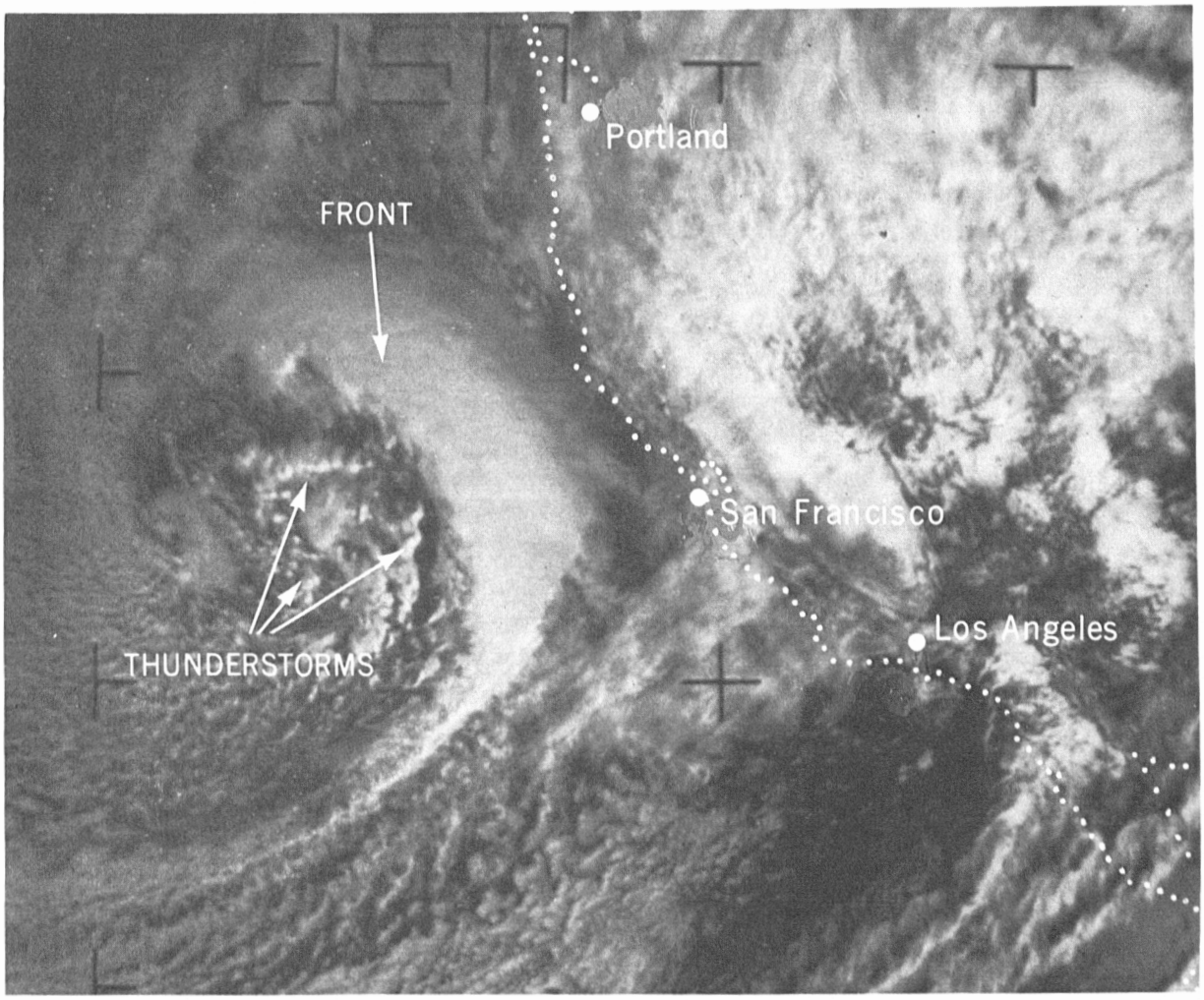
Athough this was an exceptional case, similar use is made of satellite pictures for the forecast of every major storm along our west coast. Accurate forecasts for these storms are not possible using only the data available from the few ships and airplanes in the eastern Pacific.

Adverse Flying Weather

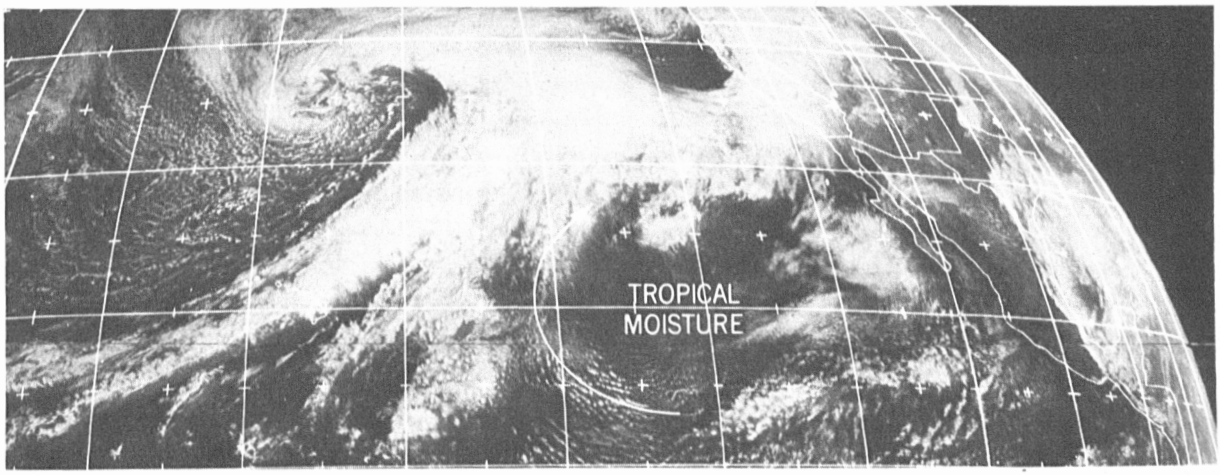
Reliable forecasts of cloud ceilings and visibility are vital to the operators of small aircraft. On August 12, 1970, all guidance available to the forecaster at Seattle indicated that the existing low clouds and fog would lift during the forenoon. But the morning satellite picture showed that conditions were not improving. Consequently, the meteorologist changed the aviation forecast to include continuing poor flying conditions for the state of Washington. The forecast was accurate, and was of great importance to pilots who were planning to fly in that area.

Holiday Forecast

Weather forecasts often determine the activities of many thousands of people on holiday weekends. On September 4, 1970, the Friday before Labor Day, the forecast based on routine guidance charts was for good weather over the



Thunderstorms behind a cold front approaching the California coast, February 5, 1969.



Clouds east of Hawaii reveal a moist tropical airmass joining a mid-Pacific storm, January 14, 1970.

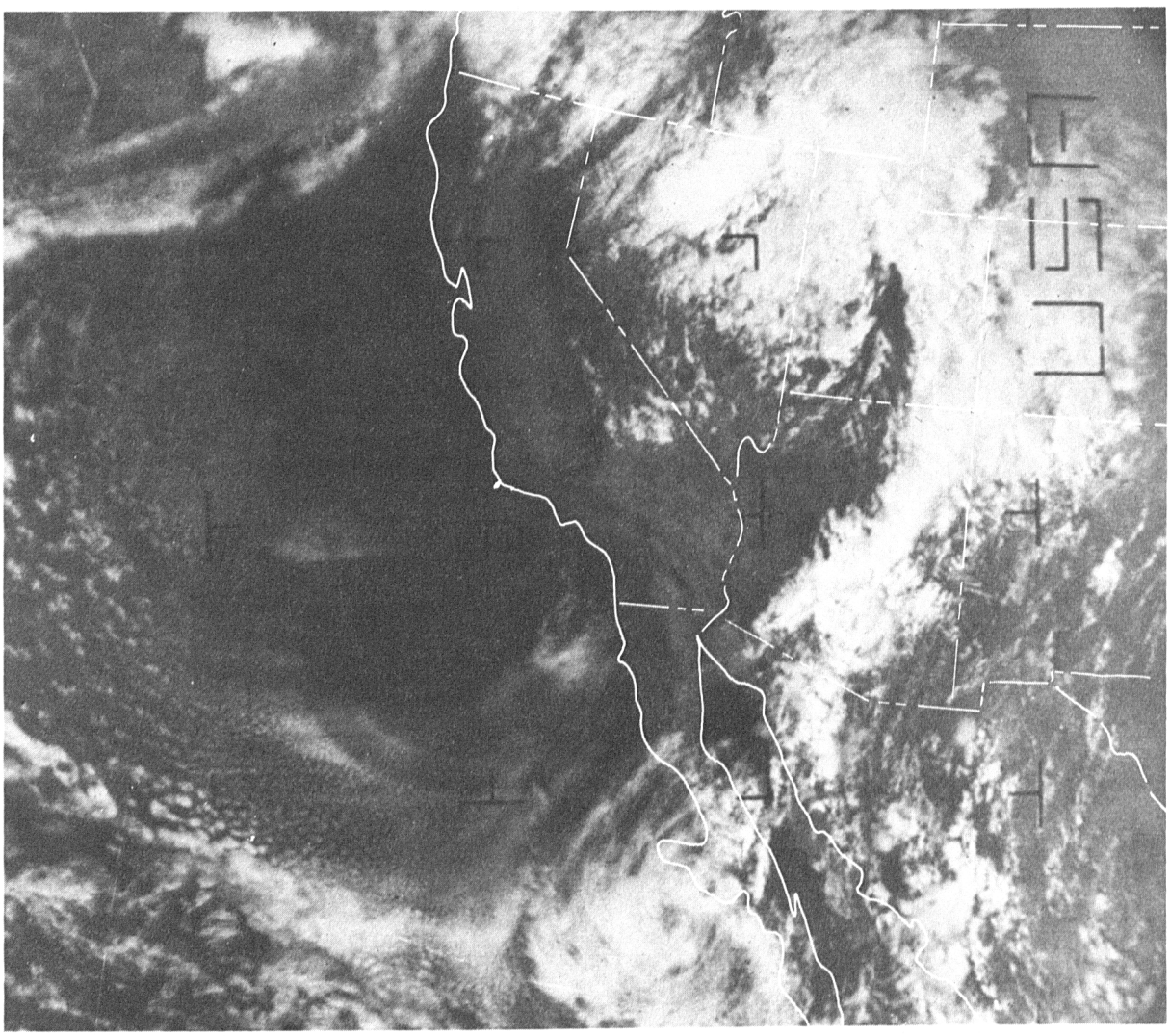
Pacific Northwest for the entire three-day weekend. However, features appearing in the satellite cloud picture acquired that morning caused a change in the forecast from fair weather to rain for the latter part of the period. Rain fell over much of the state of Washington during Sunday afternoon and evening.

SOUTHWESTERN REGION

Heavy Rain in Arizona and New Mexico

Summer thunderstorms over the Southwest are often produced by moist unstable air which moves into the area from northern Mexico. Few surface reports and no upper air soundings are made in this area. On September 4, 1970, the satellite picture showed thunderstorms in the current of warm air moving northward out of Mexico. It also showed a cold front moving from the north which would meet the warm, moist air over Arizona and New Mexico. The computer forecast did not indicate heavy precipitation. However, based on the timely and detailed information provided by the satellite picture, forecasters in both states called for heavy rain and flooding.

When the cold front and the tropical moisture met during the next 24 hours, record floods occurred. Without the satellite pictures, the effective flood warnings would not have been issued.



Moist tropical air meeting a cold front over Arizona and New Mexico, September 5, 1970.

EAST COAST

Heavy Weather at Sea

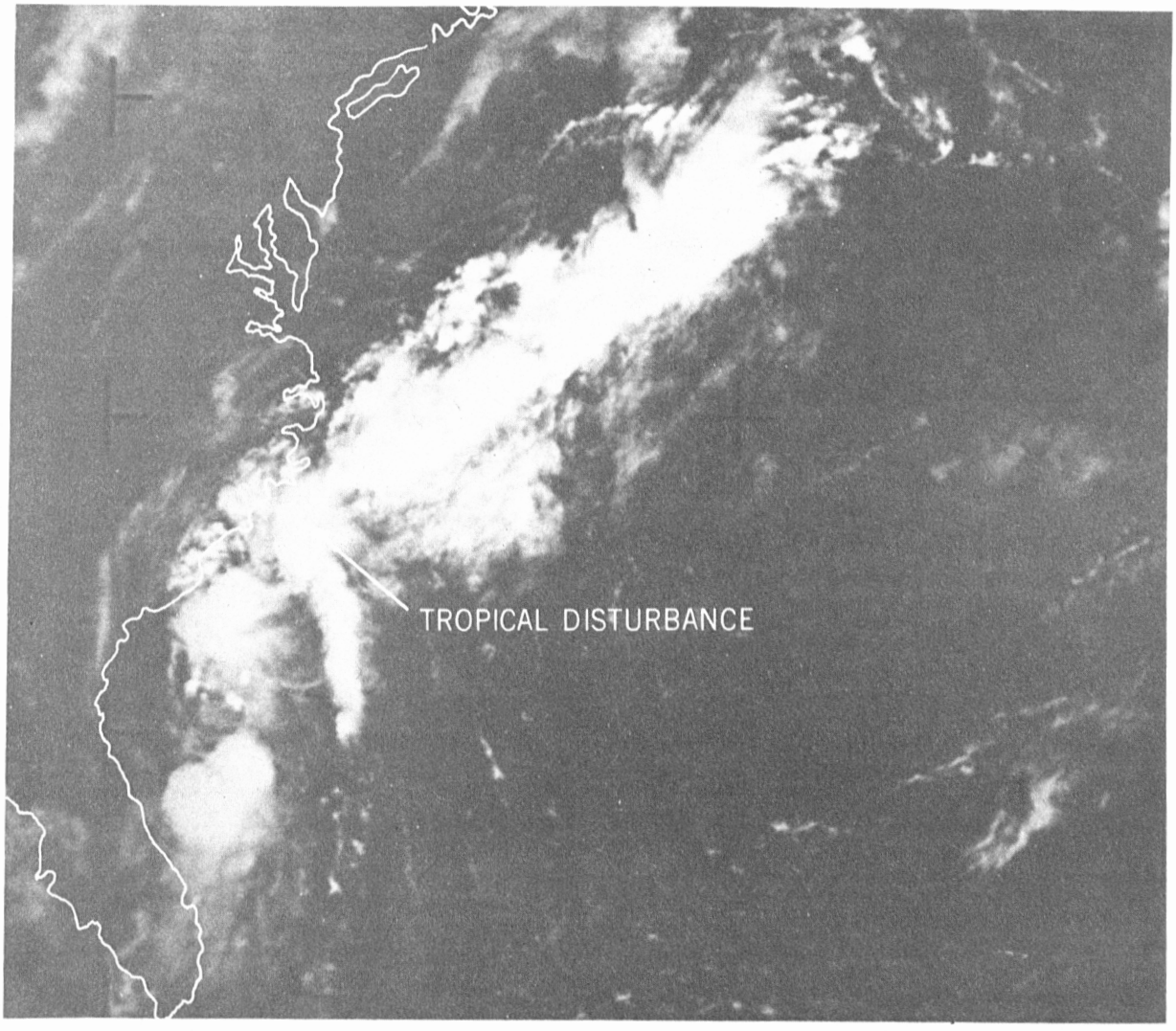
On November 5, 1969, forecasters in Boston used the morning satellite picture to brief a search and rescue party heading for a tanker breaking up in the Atlantic. Weather and clouds caused by a developing storm system were clearly displayed in the picture. The party was able to avoid areas of squalls and high seas enroute, thus saving valuable time in accomplishing the rescue.

Briefing Transatlantic Aircrews

Between December 1966 and June 1967, aviation forecasters at Kennedy International Airport, New York, issued satellite pictures to all departing crews as part of their flight folder. In answer to a questionnaire, 72 percent of the air crews felt a satellite picture was "better" to "much better" than the significant weather chart which is routinely issued.

Coastal Weather

On August 16, 1970, forecasters knew that a weak tropical disturbance was approaching the North Carolina coast, but were uncertain of its position and intensity. The satellite picture showed the exact location of the disturbance and its area of squally weather. Based on this information, an accurate forecast of high wind, beach erosion and coastal flooding was issued, enabling local residents to take action.



Tropical disturbance threatening the North Carolina coast, August 16, 1970.

INLAND SPARSE DATA REGIONS

Frontal Weather in the Mountains

Frontal weather systems are particularly difficult to locate in mountainous country where reporting stations are far apart and at varying elevations. Accurate information on fronts and their accompanying zones of weather change is especially important for fire-weather forecasts during summer and early fall, as well as for general weather predictions in more populated areas downstream. Satellite cloud pictures often show the positions of fronts, and the weather activity in them, more accurately and in more detail than conventional weather maps. Two recent examples:

On July 23, 1970, satellite pictures taken in morning and afternoon showed an unsuspected regeneration of heavy weather along an old front in the western mountains. This development would not have been recognized from the station reports. Further, the pictures revealed the front had moved into central Arizona and New Mexico, some 300 miles south of the position indicated on the weather maps.

On June 4, 1970, the extent of clouds and rain accompanying a front in the southern Appalachians could not be determined from the widely separated regular weather reports in this mountain region. Satellite pictures showed the extent of the frontal band and exposed the thicker rain clouds, thus contributing to more accurate forecasts as the system moved eastward into the Carolinas.

Stockmen's Warnings

Forecasts of weather conditions which endanger livestock are vital to western ranchers, especially in the fall when an early snow may occur before the animals have been brought to winter quarters. On October 13, 1969, satellite pictures revealed a large mass of moist air over the Pacific northwest. Thus alerted, forecasters in Great Falls, Montana issued a heavy snow warning. The forecast, based largely on the satellite picture, gave stockmen advance notice of the unseasonably early heavy snow that fell over much of western Montana the following day.

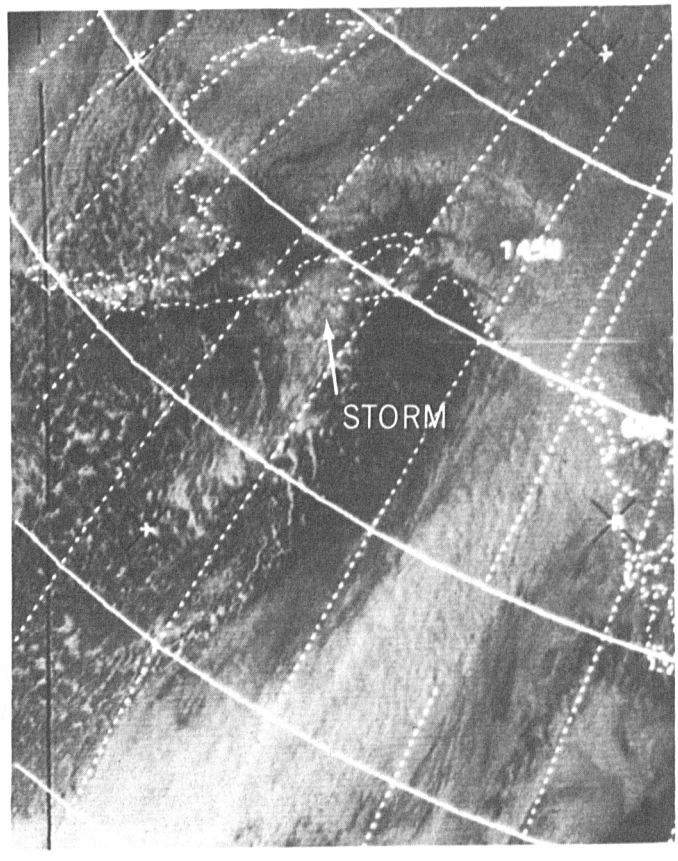
End of Drought

On September 12, 1967, heavy rains broke a severe drought in eastern Montana. This event was successfully forecast primarily because the satellite pictures revealed a developing weather system in the northern Rockies which was not indicated in the standard guidance charts.

ALASKA

Meteorological satellites have been particularly beneficial to weather forecasting services in Alaska because of the sparsity of weather observation stations throughout this vast, thinly populated region and its bordering seas. The pictures, received directly from the satellite as it passes overhead, are used in the Anchorage forecast office to identify cyclonic storms, jet streams, mountain turbulence, and other phenomena. The satellite information is depended upon to confirm and correct features on the regular weather charts, particularly in the ocean areas to the west and south which are source regions for most of Alaska's storms.

On October 14, 1970, skies were clear in Anchorage and weather maps gave no indication of an impending storm. However, in the noon satellite picture a small weather system was discovered near the entrance to Cook Inlet. This enabled forecasters to alert the public to the snowstorm which struck the area that afternoon and evening. Standard weather observations from stations in southern Alaska would not have led to a forecast of snow.



Small storm moving into Cook Inlet, Alaska, October 14, 1970.

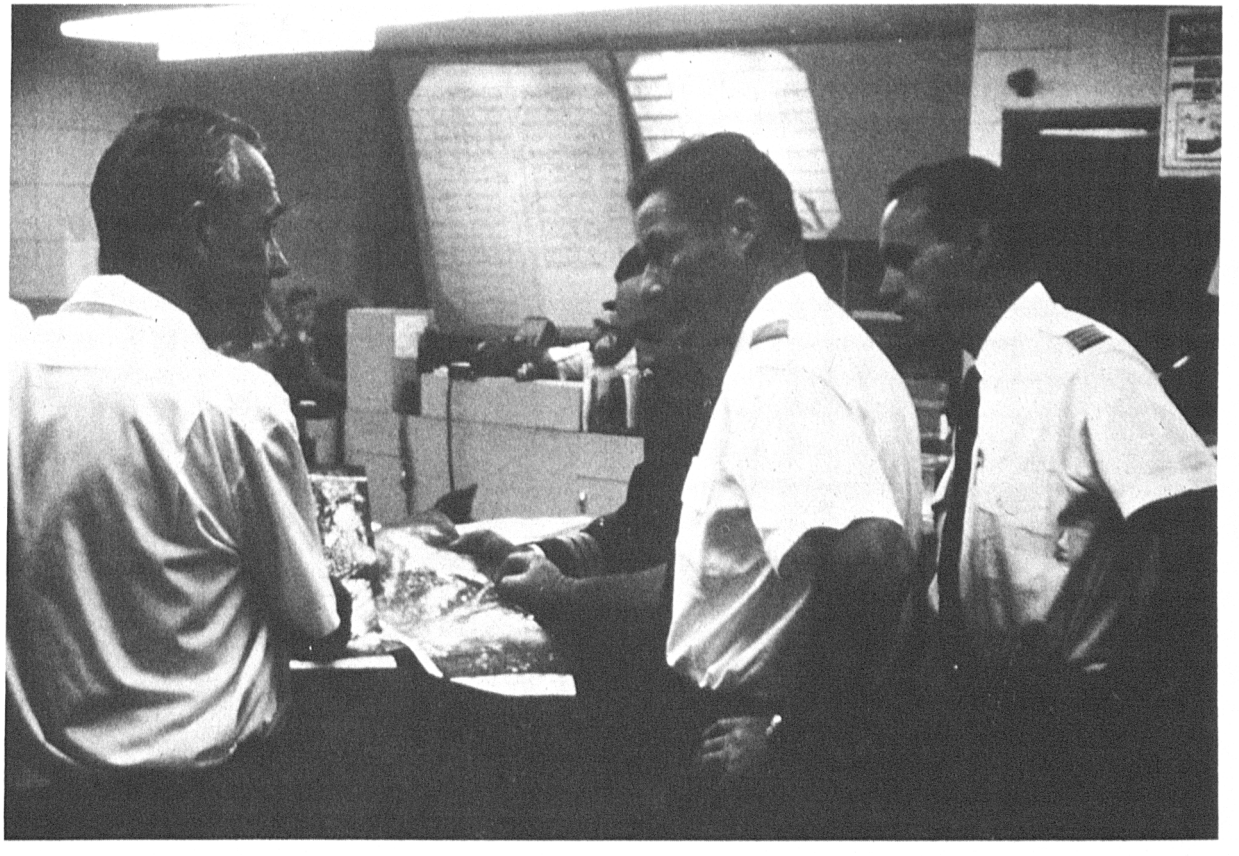
In the rugged interior regions of the state, satellite pictures show weather conditions in the mountain passes where there is no other information. Knowledge of whether or not these passes will be open for flying is vital to the "bush" pilots in small planes who provide so much of Alaska's essential transportation service.

When forecasters see certain specific weather patterns in the satellite pictures, they can make much better predictions of the location and duration of fair weather conditions over the rich fishing grounds north and south of the Aleutian chain. These two- to three-day weather outlooks are of great economic importance to commercial fishermen who need several days of good weather for a successful fishing operation at sea.

CENTRAL PACIFIC

Weather reports from islands, ships, and airplanes are scattered so thinly over the vast Pacific Ocean that, in the past, storms could form, grow, and move hundreds of miles without being detected until they chanced on a passing ship or hapless island. Now, satellites map the cloud systems of the Pacific with photographic detail. Forecasters at Honolulu and other isolated Pacific localities receive these displays directly from the satellite, within minutes after the picture is made. The information is used routinely in the weather and surf forecasts for island inhabitants, and for aviation and shipping interests throughout the Pacific. Forecasters can be confident that storm systems from mild centers to severe typhoons are accurately located and tracked, and that the nature of local weather developments are known well enough in advance to minimize the risk of unexpected disasters, particularly to the many small boatmen and fishermen active in the islands.

In Honolulu, the major hub for trans-Pacific aviation routes, each airline office is supplied routinely with a copy of the latest satellite picture. The graphic display provides flight crews with more effective, timely, and complete briefings on weather to be expected enroute. Jet streams, turbulence, and destination weather are more accurately predicted for the safety and comfort of passengers, and for the more efficient routing of aircraft.



Transpacific flight crew getting weather briefing from satellite picture, Honolulu.

Hawaiian Hurricanes

On the rare occasions when hurricanes move into the central Pacific, satellite observations now provide the primary means for watching their growth and movement, and assessing their potential threat to the Hawaiian Islands. In the virtual absence of other weather reports south and east of Hawaii, many tropical storms would go undetected without satellite surveillance, and a violent storm could strike the Islands without warning, as has happened in the past.

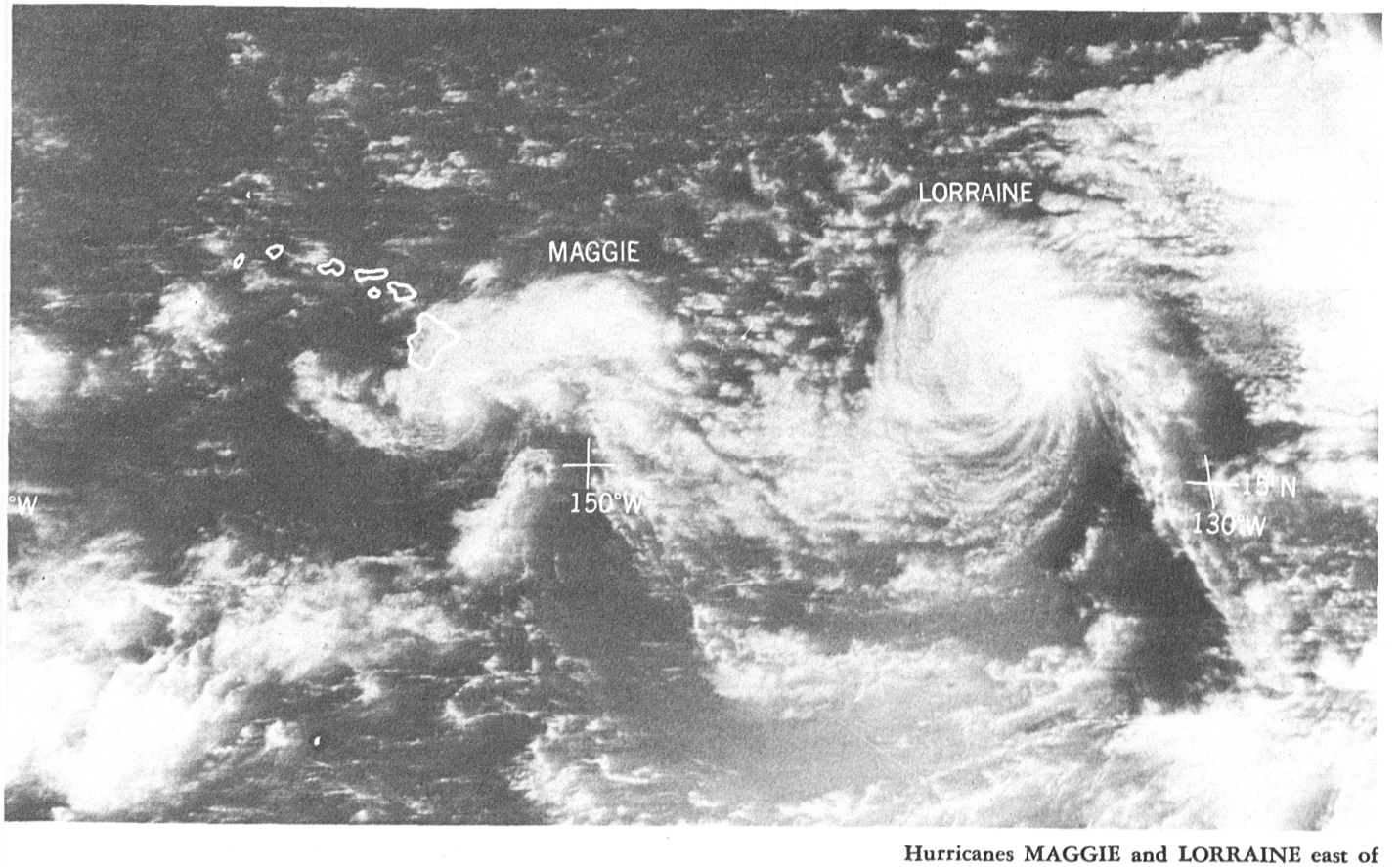
An example occurred this year. In late August, 1970 Hurricanes MAGGIE and LORRAINE were east of Hawaii and were thought to be weakening. But in the satellite picture for August 25, the cloud structure of MAGGIE, the nearer storm, showed she was still intense. On this basis, the forecaster called for much heavier precipitation than he otherwise would have. Next day, MAGGIE brushed by the big island of Hawaii and produced very heavy rainfall. LORRAINE, on the other hand, was correctly forecast from the satellite pictures to be no threat to the Islands.

Central Analysis and Forecast Guidance Products

BASIC GUIDANCE PRODUCTS

The National Meteorological Center (NMC) in Washington prepares and distributes maps and guidance charts which are basic to the weather forecasts issued by regional and local offices throughout the United States. These guidance products are derived from large-scale analyses, prepared by high speed computers, of weather over the Northern and Southern Hemispheres. Satellites now provide greatly increased observational coverage, particularly in data-sparse areas of the world, which permits improved analyses, better large-scale predictions, and hence better guidance products for local forecasts. The satellite data routinely used in these operations include worldwide vertical temperature soundings, wind measurements in selected areas of the Pacific and Atlantic, gross estimates of moisture content, and information on circulation patterns deduced from cloud pictures.

The use of satellite information in the National Meteorological Center has increased as the quantity



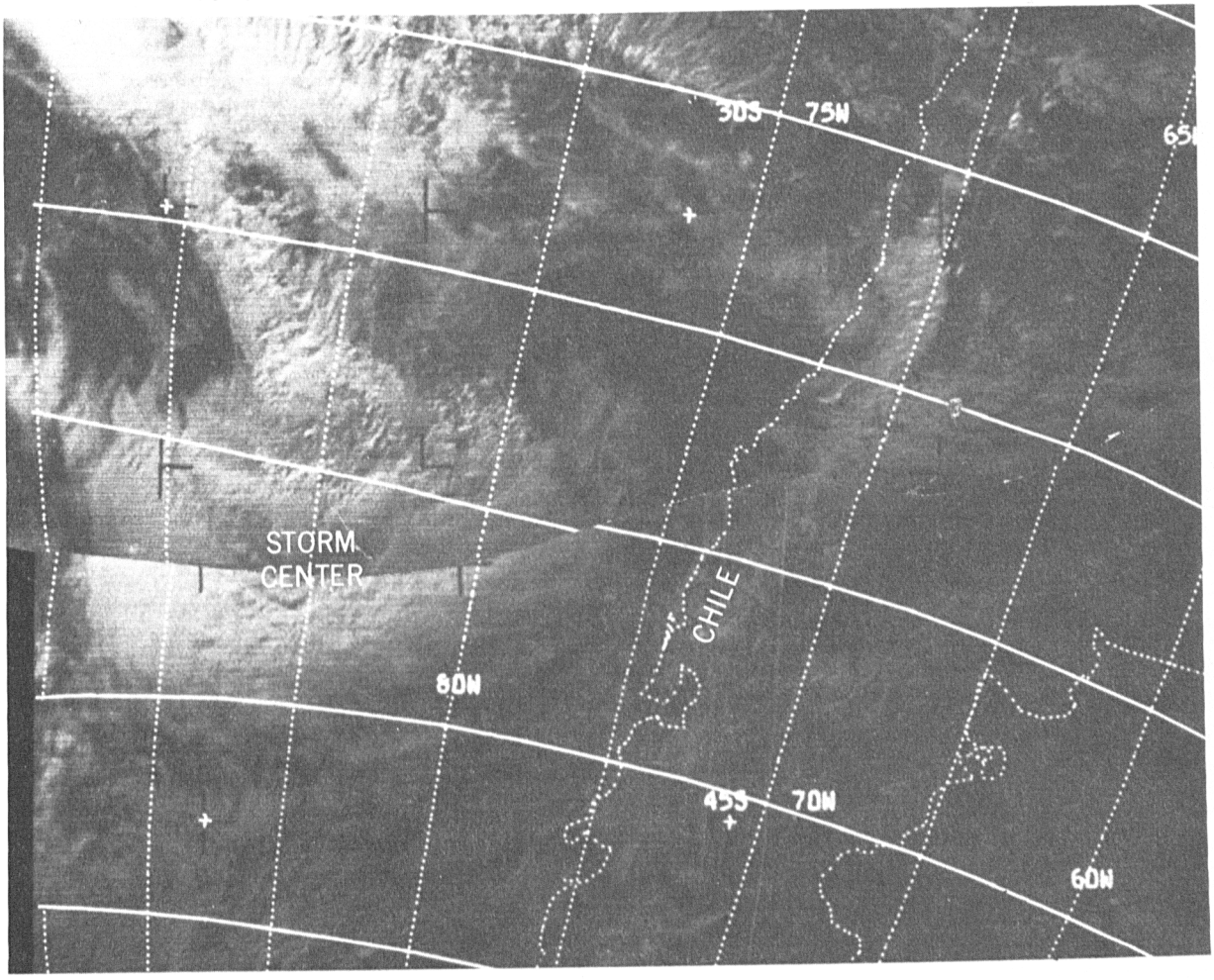
Hurricanes MAGGIE and LORRAINE east of Hawaii, August 25, 1970.

and quality of the data, and the ability to interpret them, have improved. The data are incorporated regularly and routinely into NMC products, and are the basis for numerous modifications and improvements made in the analyses and guidance forecasts. In the Southern Hemisphere where weather reports are scarce, satellite data enable the National Meteorological Center to analyze and evaluate storms to a degree never before possible. Some of these storms in the Pacific create high waves which travel across the equator and cause hazardous surf on Southern California beaches.

On July 25, 1969, the Los Angeles Weather Service Office was able to make a correct forecast of high surf, based on a National Meteorological Center guidance chart. Four days earlier, satellite data had shown a storm center west of Chile. Formerly, storms in that area often were undiscovered, and their effects unforeseen.

Analysts in the National Meteorological Center using satellite pictures to modify computer-produced weather chart.

Storm west of Chile, July 21, 1969.



HIGH ALTITUDE FORECASTS

More and more aircraft are flying in the stratosphere, above the heights normally reached by balloon soundings. Yet, accurate wind and temperature data are needed for safe and efficient aircraft operation at these levels. Radiation sensors on board current Nimbus satellites have more than doubled the amount of stratospheric data received daily by the National Meteorological Center. These data are used in preparing improved wind and temperature analyses which save flying time and reduce fuel consumption.

LONG RANGE FORECASTS

Substantial improvement in accuracy of long range weather forecasts prepared in the National Meteorological Center depends on better data of at least three kinds that satellites are uniquely able to provide:

- ☐ Data for large areas of the world where conventional observations are sparse or nonexistent. Current operational satellites have begun to meet this requirement.
- ☐ Data on interactions between Northern and Southern Hemisphere circulations, which take place in the data-poor equatorial regions, and which affect middle latitude weather days or weeks later. These processes are now under study using satellite data.
- ☐ Routine measurements of heat exchange between earth, atmosphere, and space. These cannot be obtained by conventional means. Sea surface temperature charts produced operationally from satellite data provide a measure of the oceanic heat reservoirs which are the main source of the atmosphere's energy. Satellite pictures define the extent of snow and ice fields, another factor affecting atmospheric heat exchange. Satellite instruments now being built will measure, for the first time, the radiation energy exchange between the entire globe, the atmosphere, and outer space.

Raisins drying in the sun, San Joaquin Valley, California.

Specialized Weather Services

RAISIN HARVEST

In late August and September an 80- to 100-million dollar crop of raisins is sun-dried in California's San Joaquin Valley. The drying raisins must be covered if more than one-tenth inch of rain is forecast. Covering requires 18 to 24 hours advance notice, and costs 100 to 200 thousand dollars—a significant percentage of a year's profits. Satellite data are used routinely in the raisin forecasts, and are relied upon as an essential ingredient for improving their reliability.

On August 29, 1970, a low pressure center was poised off the coast. Ordinarily, this situation would provide adequate basis for a forecast of rain, but the satellite picture showed that this low center did not pose a significant threat. A correct no-rain forecast was made, based primarily on the satellite information.

PUBLIC UTILITY

Utility companies find that sudden changes in weather directly affect public demand for gas and electric power. Accurate forecasts of the timing of these changes are critical in ordering power from distant sources. With advance knowledge of the intensity and timing of heavy storms, maintenance crews can be alerted and their work planned more efficiently.

Pacific Gas and Electric Company, serving some twenty million people in northern and central California, uses satellite data as a primary forecast tool in daily operations. PG&E meteorologists receive satellite pictures by direct facsimile line, and find them invaluable in forecasting the effects of weather systems aproaching the northern California area.

AERIAL PHOTOGRAPHY

Satellite data are used constantly in support of photo reconnaissance missions and aerial mapping projects in data-sparse areas. Aerial photo mapping requires clear skies below aircraft level over flight tracks 50 miles or more in length. Satellite pictures

are the only source of complete information on cloud cover over large areas. Thus they are of tremendous help in forecasting the most favorable days to photograph specific areas, and thereby reduce the number of expensive, unrewarding flights.

Satellite data enabled the U.S. Air Force to complete a photo-mapping project in Ethiopia a full year ahead of schedule (May 1967). Guided by satellite pictures, the unit achieved a substantial reduction in unsuccessful flight missions, leading to early completion of the project. Seventy-four people were released for reassignment one year earlier than planned, saving $375,000 in travel and subsistence costs alone. Direct project costs for aircraft and other equipment were reduced by more than $5 million.

When the mapping unit later moved to Brazil with a three million dollar annual operating budget, use of satellite pictures again increased productivity of the unit by 200 to 300 percent. Satellite picture receiving equipment is now a standard part of all Air Force photo-mapping operations, with consequent impact on the time and costs planned for aerial mapping projects.

Relying almost entirely on satellite data for day-to-day mission planning, the U.S. Navy completed an aerial mapping survey in Antarctica in one year instead of the expected three years. Continuing surveys are being conducted in Antarctica with an 80- to 100-percent increase in efficiency made possible by satellite pictures.

ANTARCTIC RESUPPLY

The Commander, U.S. Naval Support Force, Antarctica, has stated that improvements in weather forecasting services with the advent of satellites has reduced by 75 percent the number of aborts in trans-oceanic and Antarctic resupply missions. This has resulted in an annual decrease of 200 aircraft flight hours, with a resultant savings estimated at $500,000 per year.

Availability of satellite information was a major factor in discontinuing an ocean station vessel, used primarily as a weather observation platform midway between New Zealand and Antarctica. The annual cost of this station, approximately $1,200,000, was freed for other programs. Although other factors such as improved aircraft performance were involved, a major consideration was the use of satellite data not previously available to Antarctic forecasters.

MANNED SPACEFLIGHT

Meteorological satellites have been the major guide to weather conditions in the remote data-sparse ocean areas used as landing sites for the Mercury, Gemini, and Apollo spaceflights. The pictures provide basic information for day-by-day monitoring and forecasting of weather conditions in the planned recovery area and at emergency landing sites. Detailed satellite views of weather systems in the area permit a more accurate assessment of potential hazards to recovery operations. Satellite data have been the impetus for changing time and place of landing to avoid hazardous weather. Several examples can be cited of key contributions to the successful conclusion of manned space missions.

Apollo 13

After the explosion on Apollo 13, the weather forecasts for various emergency landing areas abruptly assumed greater significance. Forecasts were required for a dozen possible landing areas in the Southern Hemisphere where regular weather reports were virtually nil. The area finally used was in a region where disturbed weather conditions occur frequently. Satellite pictures showed that the predicted impact point would be in a small area of fair weather between larger disturbances. The spacecraft impact prediction and the weather forecast were both good. The reliable, pinpoint weather prediction would not have been possible without satellite data.

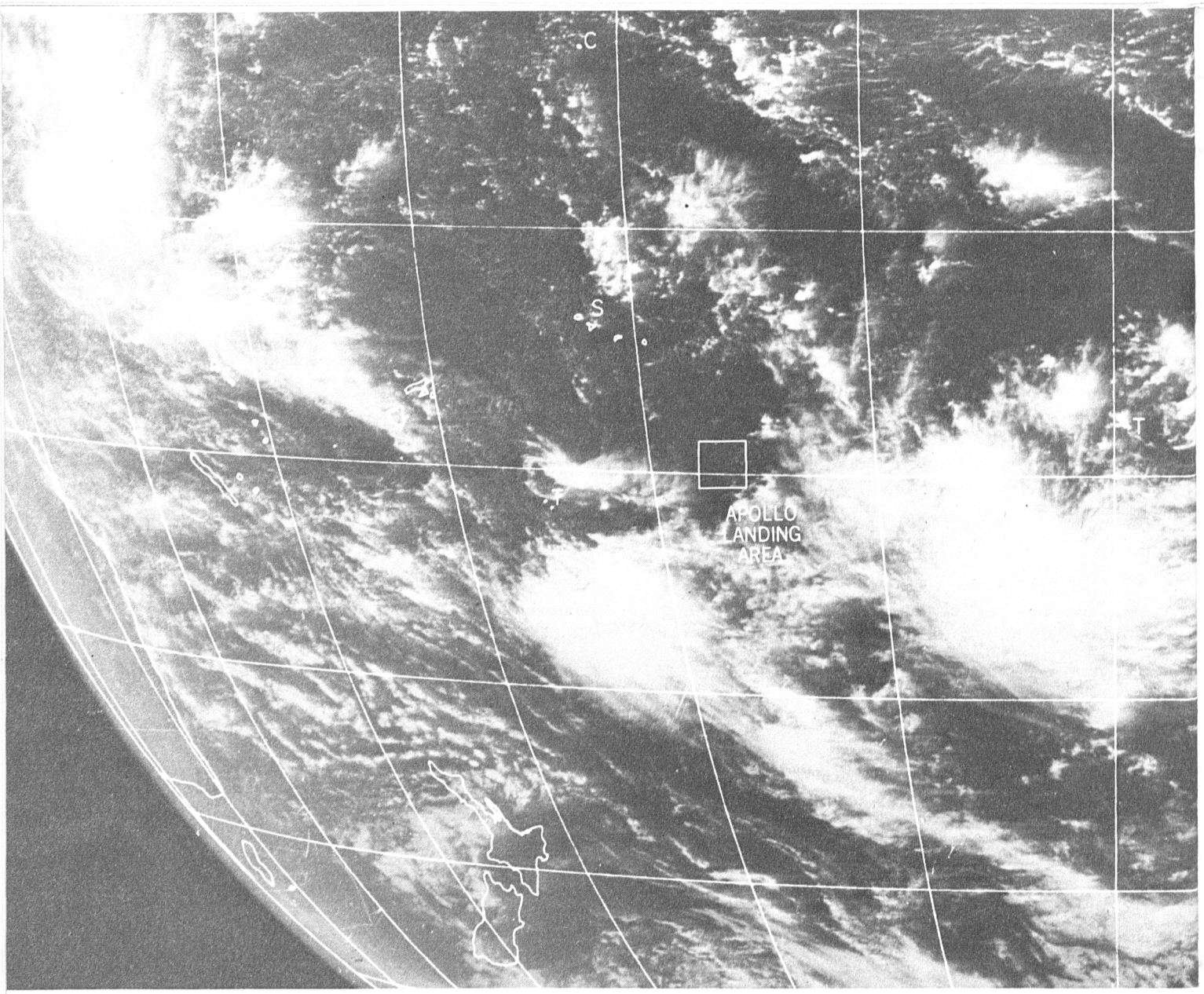
Gemini 5

A satellite picture taken during the Gemini 5 flight revealed a large tropical disturbance close to the planned landing area. The decision to terminate the flight one revolution earlier at a landing point farther north was based mostly on the satellite picture. The actual landing was smooth. Worsening weather at the original site would have made recovery more difficult and more uncomfortable for the crew.

ROCKET RANGE

In April 1968, a Scout Rocket launch was scheduled at Wallops Island, Va. The re-entry area near Bermuda was to be photographed. The weather forecast for the re-entry area, based on conventional data, was for excellent conditions. However, the satellite picture showed that a broad band of clouds was lingering in the area, and the likelihood of clearing by launch time, 12 hours later, was nil. Acting on this information, range officials postponed the mission and released launch personnel immediately. In the past, this kind of situation required that all personnel remain on station since the conventional forecast was for clearing conditions.

A normal Scout launching requires about 200 people, and many pieces of equipment, including



Apollo 13 landing area, between disturbed weather regions, April 16, 1970.

down range surface vessels, aircraft and other support items. A significant saving was realized in releasing the range 10 to 12 hours earlier. The Range Officer indicates that satellite information enables range officials to make clear-cut and immediate decisions of this type several times a year.

U.S. AIR FORCE OVERSEAS OPERATIONS

In their far-flung operations, Air Force planes constantly fly in regions where weather observations are sparse or non-existent. Satellite data now represent a major breakthrough in providing better weather information for these areas, and often providing it hours before the standard weather charts become available. The location and intensity of weather systems shown in the satellite pictures now provide a better basis for forecasts of weather conditions along the routes of long distance flights. Movement and development of these systems can be watched, and as they approach air bases from data sparse areas, their impact on weather forecasts for terminal operations can be accurately assessed.

Besides providing the information needed for accurate forecasts, the pictures themselves are a natural tool for giving pilots a graphic display of the weather conditions to be encountered enroute. Satellite pictures also have become a major part of daily weather briefings to headquarters staff who

must be in constant touch with weather conditions in remote areas under their command.

Air Force weather units in the Far East, the South Pacific, Alaska, both coasts of the U.S., the Caribbean, and Europe, all attest to a significant improvement in the reliability of flight forecasts. A few of the many comments received from Air Force units around the world:

"Introduction of satellite data into Detachment techniques resulted in a quantum jump in mission success. It is fair to say that the Detachment's efforts are now satellite data-dependent." (6th WW Unit, Virginia)

"Specific instances of satellite data usage are too numerous to mention as they are used on a daily basis to improve our product." (1st WW Unit, Korea)

"We have found the satellite data to be the most reliable and useful tool we have in our possession—bar none." (Tuslog Unit, Turkey)

"Meteorological satellite data are so integrated into our routine that each pass acquired results in a 'significant' improvement in our forecasting service." (European Weather Central, England)

In the western Pacific, Air Force forecasters use satellite data to identify and classify disturbances in their early stages. They can follow their subsequent developments and movements with much greater accuracy and confidence. Reconnaissance aircraft are sent out only to those storms which have reached dangerous intensity, thus releasing substantial amounts of aircraft time and supporting resources to other types of activities.

In 1967, a reconnaissance plane attempted to penetrate a storm near the Philippines, but encountered severe turbulence and was forced to withdraw. The pilot radioed the Weather Central at Guam, and learned that the latest satellite picture showed nearly clear sky in the opposite quadrant. Acting on this information, the plane circled the storm and penetrated to the center without difficulty. Satellite information made it possible to complete the mission, and to do so with far less danger to crew and aircraft.

Accurate satellite information on the position and intensity of all tropical storms makes possible improved weather forecasts for aircraft flights in the area, resulting in more effective flight planning. Jet aircraft cruise above most clouds, but propeller-driven transports, of which the Air Force still has a large number, are confined to lower levels where they are endangered by storms. Formerly, they had to be routed around stormy areas, and flights were sometimes postponed if severe weather was thought to be occurring along the route. Satellite data pinpoint the most active areas of fronts, and show the breaks where planes may fly through, so that flying is safer, and flight planning is more efficient.

When severe storms and typhoons approach land areas, satellite pictures contribute significantly to improved warnings of their timing and intensity, permitting more informed planning for aircraft evacuation and other precautionary steps as necessary.

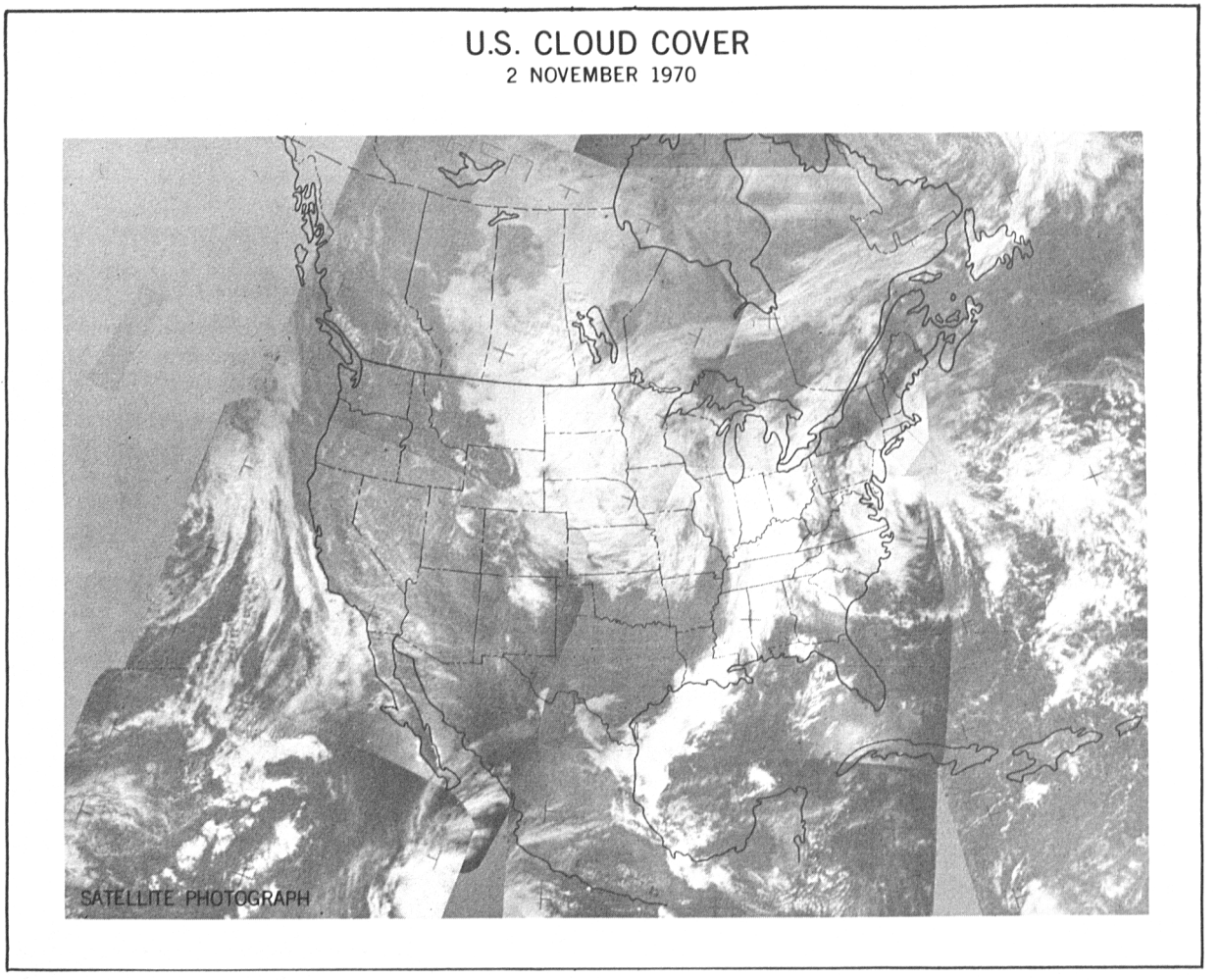
Typhoon FLOSSY off Okinawa in October 1969 and tropical cyclone MARTHA off Panama in late November 1969 are two cases in which satellite data enabled Air Force forecasters to issue more accurate warnings to local installations.

Apart from the basic route and terminal forecasting, a number of specialized Air Force activities have benefitted from applications of weather satellite data.

- ☐ In aerial refueling missions over the Atlantic, the Pacific, and remote land areas, satellite data now provide detailed cloud information enabling aircraft to proceed directly to locations where sky conditions are suitable for the refueling operation.
- ☐ A most useful application of satellite pictures is in support of operations to recover other satellite capsules returning to earth from space. These operations require a nearly clear sky. Weather satellite pictures are used in selecting the recovery area and the specific landing point.
- ☐ Satellite pictures have proven invaluable to the many search and rescue missions flown in remote areas of Alaska and adjoining waters. In many instances satellite data are the only weather information available.
- ☐ For training flights off the California and Oregon coasts, satellite pictures are used in locating stratus-free areas for use as emergency ditching sites.

Direct Use in Public News Media

Photographs from space of large scale cloud patterns are valuable additions to the weather information presented in the newspapers and on television. Cloud pictures make the situation more realistic and comprehensible to the public. Disaster warnings are more convincing to people when they can see for themselves that storm clouds are approaching. Many newspapers and TV stations carry the day's satellite photograph routinely, and find it an effective means of communication which the public now accepts and demands. Dr. Frank



Example of satellite picture mosaics provided daily to news media.

Field, Science Editor, WNBC-TV, gives the following evaluation of its use on network television: "The satellite photograph transmitted via the Associated Press is a standard feature of NBC News weather in New York City. We find the viewers look forward to it each night and do not dare omit it from the daily weather report. I find it a most effective visual aid and the listener response to the daily photographs most gratifying."

At Station KUTV in Salt Lake City, Chief Meteorologist Mark Eubank reports:
"We are extremely pleased at the operational capability of being able to show our million plus viewers today's view of the weather from space. When you talk about a cold front moving into a region it is one thing, but when you can show the viewer the associated clouds and where the clear areas are, he can identify with the forecast that follows. In today's space age, we find our viewers are eager to know of the things that go on around them and the satellite pictures help, in a very modern space-age way, to bring this information to them."

Bob Welti, Staff Meteorologist at Station KSL in Salt Lake City, comments:
"In my opinion, the use of satellite pictures in TV weather presentations is the single most spectacular advancement ever made in weather forecasting. We use the daily satellite composite every broadcast, and the time-lapse films whenever available. These pictures never fail to evoke comments of awe and admiration. Because of the frequency of use (twice per day in prime TV time) it is hard to imagine a more effective way to communicate with the general public. As a public service, and as a means of public relations, the weather satellite is of inestimable value."

MARITIME SERVICES

Meteorological satellites are bringing direct benefits to sea-going activities by providing data of unprecedented scope on three quite different aspects of the marine environment—weather and sea state, ice, and sea surface temperature.

Marine Weather and Sea State Forecasts

Satellite data depict weather systems over the vast data-sparse oceans, and thereby contribute significantly to the accuracy of marine weather forecasts. These forecasts benefit shipping and other maritime interests in ways comparable to the benefits already described for trans-oceanic aircraft operations.

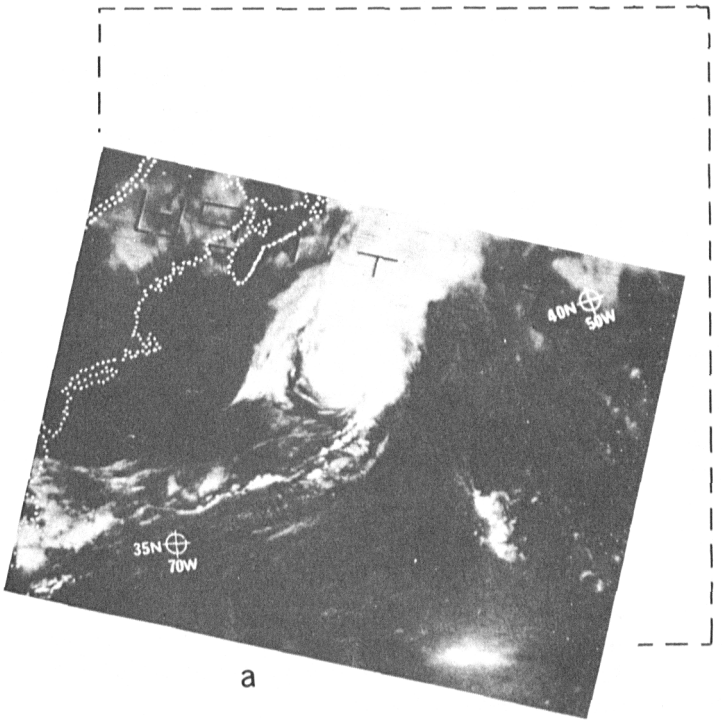
MARINE ADVISORIES

U. S. merchant vessels are relying more and more on ship routing programs to avoid unfavorable weather and high seas. Computer forecasts are generally successful in the prediction of large-scale winter storms and their accompanying high winds, but tend to be inadequate in the treatment of small-scale storms, particularly those of tropical origin. Now, these storms are detected and tracked from satellite pictures, and forecasters can prepare more accurate advisories to shipping. Unexpected storms can cause great damage from freight breaking loose in the ship's hold, particularly in summer when storms are infrequent and protective measures often are omitted to save time and expense.

An example occurred on August 18, 1970. An old tropical depression was moving northeast from Cape Hatteras. Its status was unknown because there were no ship reports in the area. The morning satellite pictures showed that the storm had intensified rapidly and could be expected to produce surface winds of 50 to 60 knots. Based on this interpretation, the depression was upgraded to storm intensity with winds of 60 to 65 knots forecast near the center. Three different ship reports during the early afternoon verified this forecast with wind reports of 65 knots and higher. In this case, the satellite picture enabled the forecaster to provide accurate information on wind velocity, and to define the limited area where the strong winds occurred.

In the eastern Pacific, most tropical cyclones originate south of the shipping lanes leading to the Panama Canal, and hence usually go undetected by ships. By monitoring these storms in satellite pictures, the Hurricane Center in San Francisco has been able to issue timely advisories to ships and fishing fleets in the area. This has resulted in better service to U.S. shippers as well as enabling the U.S. to better meet its international commitments for marine services.

SATELLITE PICTURES APPLIED TO MARINE FORECASTING



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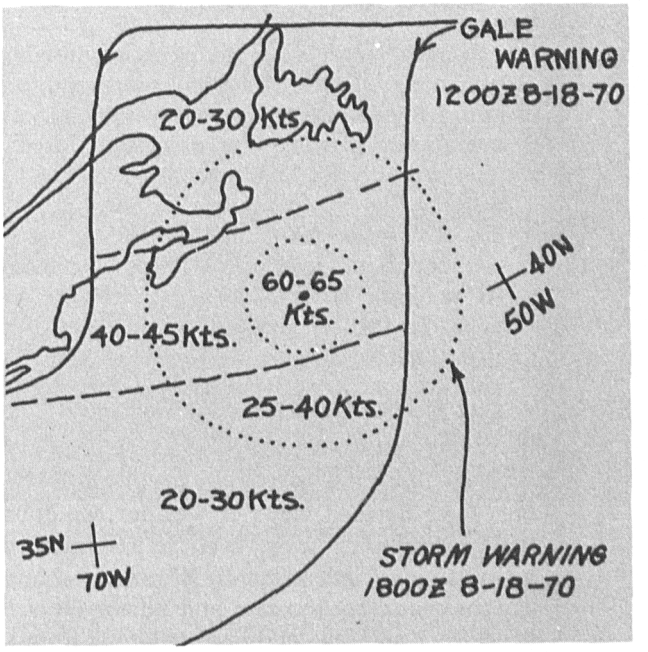

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a. Satellite picture showing a well-developed storm off New England at 1418Z August 18, 1970.
b. Marine forecast prior to satellite picture (solid lines), and after satellite picture (dotted lines).

A recent example is that of Hurricane LORRAINE in August of 1970. On August 18 the U.S. freighter Norma Lykes was sailing westward from the Panama Canal toward Hawaii. On the basis of the Tropical Storm Advisory, she diverted course abruptly to the northeast and then delayed sufficiently to allow LORRAINE to pass on to the northwest, after which she resumed course to Hawaii. The advisory was based entirely on satellite pictures.

Fog and low stratus which reduce visibility are also continuing hazards to ships at sea. They are hard to avoid because conventional data are too sparse for precise determination of the fog-bound areas.

On July 27, 1970, fog covered much of the New England coastal area. The marine forecaster at Boston could not accurately advise marine interests of these conditions because the seaward boundary of this region of poor visibility was not defined by surface reports. The mid-morning satellite picture showed precisely the region covered by fog, enabling the forecaster to issue a more accurate and detailed marine advisory.

U. S. NAVY OPERATIONS

The U.S. Navy uses satellite data extensively in its far-flung activities throughout the world's oceans. The Commander in Chief of the U.S. Pacific Fleet affirms the appreciable benefits realized from weather satellites as follows:

> "These pictures are giving us an insight, not previously possible, into our weather problems and are proving to be a very valuable aid to operational planning for our naval forces, not only in Southeast Asia but throughout the Pacific as well. The extent of cloud systems, not always obvious from an examination of standard weather charts, is shown by the pictures, enabling us to follow systems likely to affect our operations. In fact, reports from fleet units indicate that satellite pictures are proving to be a valuable adjunct to our standard weather prediction tools."

Naval vessels are equipped to receive pictures directly from satellites passing overhead. Thus they now have detailed views of weather conditions in their surrounding area, even in the most data-sparse regions, independently of normal communications channels. Accurate and reliable knowledge of weather and sea conditions obtained from satellites has evident advantages for routing ships, for scheduling routine operations at sea, and for severe storm detection and warnings to the fleet. Also, satellite data have proven beneficial for various specialized activities of the Navy.

For example, ships which must remain at sea for extended periods use satellite pictures in selecting relatively calm regions as rendezvous points for transferring supplies, fuel, and men at sea. Satellite observations can help an aircraft carrier hide from aerial reconnaissance, or locate clear areas to facilitate takeoff and landing operations. Carrier training exercises in the stable weather areas southwest of California are conducted more efficiently because of satellite data. Vessels equipped to receive direct satellite information accomplish significantly more flight training per cruise than do those without satellite equipment. The difference is related directly to time lost in searching for cloud-free areas acceptable for the practice exercises.

Sea and Lake Ice Forecasts

Satellite pictures display the extent and character of ice fields in the Arctic and Antarctic seas, and on the Great Lakes, with a frequency and geographic coverage never before approached. They have brought substantial improvement in the mapping of sea and lake ice, and in monitoring seasonal formation and breakup of polar ice packs. This information is of great value to ship operations in these waters.

Ice reconnaissance by ship or plane is expensive and unsatisfactory in both coverage and frequency. It is unfeasible to cover more than a small fraction of the desired areas by these means. Using satellite pictures, ice fields throughout the polar regions and the Great Lakes can be mapped daily. Pictures for several days are combined in a special way to eliminate clouds. The pictures reveal the extent and character of pack ice, the locations of open leads, and even large icebergs.

The Naval Oceanographic Office makes daily use of satellite photographs in preparing regional ice charts and forecasts for Naval operations in the Arctic and Antarctic, and for National Science Foundation missions in Antarctic waters. Ice reconnaissance flights are requested and planned on the basis of information contained in the satellite pictures, resulting in more efficient deployment of reconnaissance aircraft, and more effective preflight briefing of observers.

Satellite data obtained steadily through the polar summer when ice changes are most significant are used in compiling ice climatological surveys and ice atlases with completeness and detail unachievable by any other means.

ARCTIC

In the Arctic, ice maps, forecasts, and warnings serve shipping, commercial fishing, offshore drilling, and mining activities. Particularly significant this summer were the satellite-aided pack ice forecasts issued for the heavy barge traffic around Point Barrow to the Prudhoe Bay oil fields. U. S. Coast Guard icebreakers use pictures received directly from satellites in planning their daily operations. Satellite coverage enables the Coast Guard's International Ice Patrol to monitor the ice pack more effectively, and to provide North Atlantic shipping with better information on sea ice and icebergs. Next year, forecasting of the drift and decay of large icebergs will be aided by sea surface temperature charts prepared from satellite radiation data.

GREAT LAKES

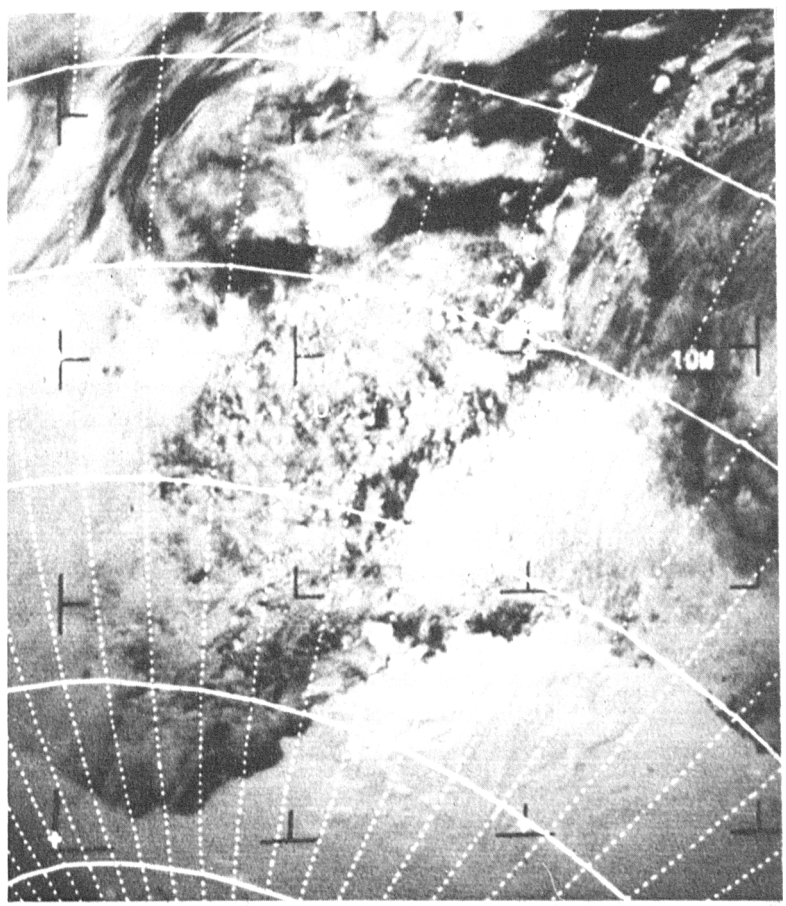
Ice charts for the Great Lakes derived solely from satellite pictures are produced in Washington and distributed by facsimile network. The Detroit Weather Bureau Office uses these charts and the latest satellite picture in preparing freeze and thaw forecasts and weekly ice reports. These satellite-aided forecasts serve shippers, ferries, drawbridge and lock tenders, water and power plant operators, marinas, and U. S. Coast Guard cutters and icebreakers.

ANTARCTIC

In the south polar area, the safe operation of ships in the treacherous and often uncharted waters of Antarctica have been enhanced immeasurably by satellite data utilization. It is considered standard operating procedure by the Commander of the U. S. Naval Support Force, Antarctica, to refer to satellite photographs of sea ice in determining an optimum track through areas of ice for vessels under his operational control.

During the Antarctic summer of 1967-68, satellite pictures played a dramatic role in guiding two supply ships through the pack ice. After examining satellite photographs, ice analysts of the Scott Polar Research Institute sent radio reports to the two ships, describing the route where they would be most likely to find a way through the ice. The Captain of the JOHN BISCOE followed the suggested route, although somewhat against his better judgment since it was far to the west of the usual route for shipping. He got through without trouble. The Captain of the PERLA DAN was unconvinced and followed the usual route; he was brought to a standstill on January 9, 1968, by an ice jam that was clearly visible in the satellite photographs at the Institute. He asked for advice on how to circumnavigate the problem area. This was given him by radio, after which he proceeded without further difficulty.

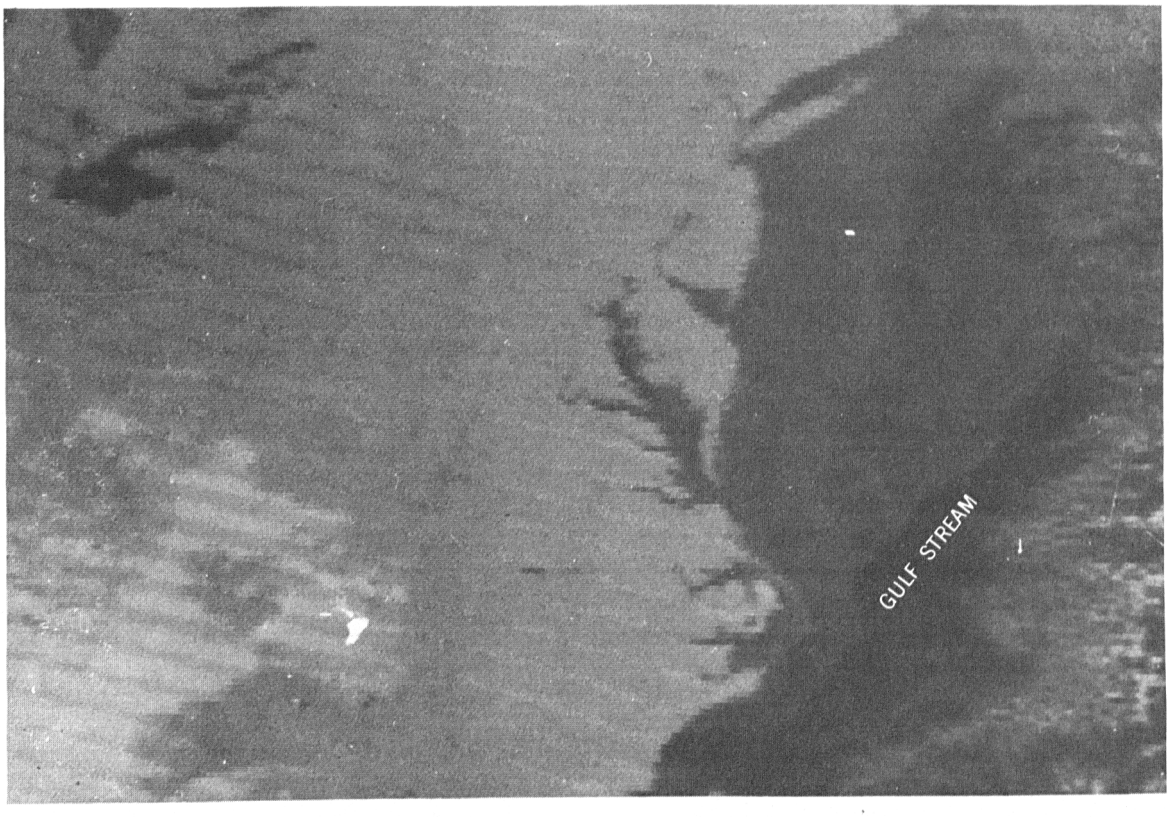
In a National Science Foundation program studying seals in Antarctica, satellite pictures showing extent and condition of the ice pack have proven effective in revealing areas favorable for seal concentrations, thereby contributing to more effective scheduling of aerial census missions. In operational planning for other NSF South Polar missions, satellite pictures have made valuable contributions through their frequent monitoring of ice conditions around the continent, particularly in the Weddell Sea. The pictures also have been used to map the seaward boundary of the Larsen Ice Shelf, whose position had changed significantly since it was mapped in 1947.



Clouds and ice in the Antarctic, January 7, 1968.
a. Heavy pack ice under thin cover of banded clouds.
b. Loose pack ice under scattered cumulus clouds.
c. Heavy pack ice under relatively dense cloud cover.

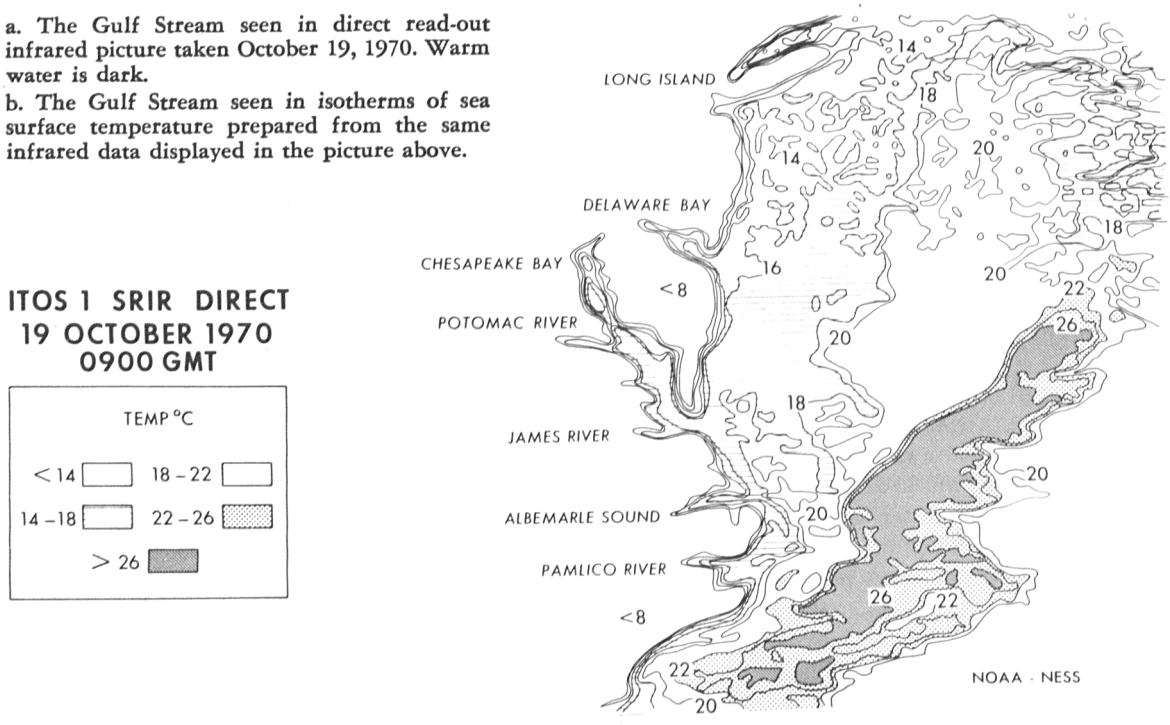
Sea Surface Temperature

Sea surface temperature charts can be produced from satellite measurements with coverage and frequency unattainable from conventional observations alone. Thermal boundary zones appearing in these charts locate ocean currents of interest to shipping, and identify water masses and their edges which are highly significant indicators of the distribution of harvestable fish and other marine life. The figures illustrate the complete coverage and detail obtainable from satellite measurements during a single day.



a

a. The Gulf Stream seen in direct read-out infrared picture taken October 19, 1970. Warm water is dark.
b. The Gulf Stream seen in isotherms of sea surface temperature prepared from the same infrared data displayed in the picture above.



b

HYDROLOGIC SERVICES

Application of satellites to Hydrology is just beginning, but exploratory use of the data has already brought recognizable improvement to certain aspects of the river and flood forecasting service. Satellite pictures are used in measuring the area covered by snow, particularly in remote mountain areas, and even in making some gross estimates of snow depth.

SNOW FIELDS

In the winter of 1969-70, when ground observations were fewer than in the previous year, some unreported snow fields in northern Montana were discovered in the satellite pictures. On the basis of the satellite information, ground crews were dispatched to the area to establish snow depths, thereby developing important data for use in runoff forecasts in the spring of 1970.

Satellite photos also were used as a supplement to ground observations in forecasting floods in the upper Midwest during the spring of 1969. In spite of the unusually heavy snow cover that year, damage was minimal because of the extensive preparations which were made in response to the forecasts.

HEAVY RAINS

Cloud patterns revealed in satellite pictures can be critical in forecasting the timing and intensity of heavy rainfall. The heavy rainstorms which cause severe flooding on the west coast can be forecast more accurately with the aid of satellite photographs which show the influx of moisture from the tropical Pacific.

In January 1969, record-breaking rains fell in California from a succession of storms moving in from the Pacific. The heavy rains were produced by a deep layer of moist air which appeared in the satellite pictures as a broad band of rain clouds moving northward from an area in the tropics where no conventional weather reports are made. Between January 18 and 26, Weather Bureau forecasters at both Los Angeles and San Francisco used satellite data to time the arrival of periods of heavy rainfall and to forecast above normal amounts.

On January 18, after three days of rain, the standard weather charts indicated the rains would diminish, but satellite pictures showed a new surge of moisture moving towards Southern California. Based on the satellite pictures, the Los Angeles office successfully forecast the heavy rains which fell on the 19th, and gave timely advance warnings to the various flood control districts.

On January 24, another surge of moist air moved out of the tropics toward northern California. As before, the moisture appeared in the satellite pictures but was not shown on the guidance charts. The San Francisco office made an accurate forecast for heavy rain. This forecast was especially critical for flood warnings because of the large amount of rain which had already fallen during the previous week.

The early, accurate forecasts of heavy rain, based on satellite pictures, were of tremendous help to the River Forecast Center in Sacramento in planning operations and deploying personnel. Even with the warnings and precautions, extensive flooding and mud slides during the 8-day period still caused $107 million in property damage in southern California, and 57 deaths in Los Angeles County alone.

New sensors and capabilities on satellites being built for flight in 1972 will bring a significant increase in benefits to hydrologic forecasting. First, a new high resolution radiometer will show snow fields, ice on rivers, and flood areas with greater detail than ever before. Second, the new geostationary satellites will be equipped to receive data by radio from automatic rain gages and river gages in remote areas, and relay the information to the river forecast offices. This technique has been tested experimentally and can provide critical information to forecast offices in time to issue much earlier warnings of impending emergencies.

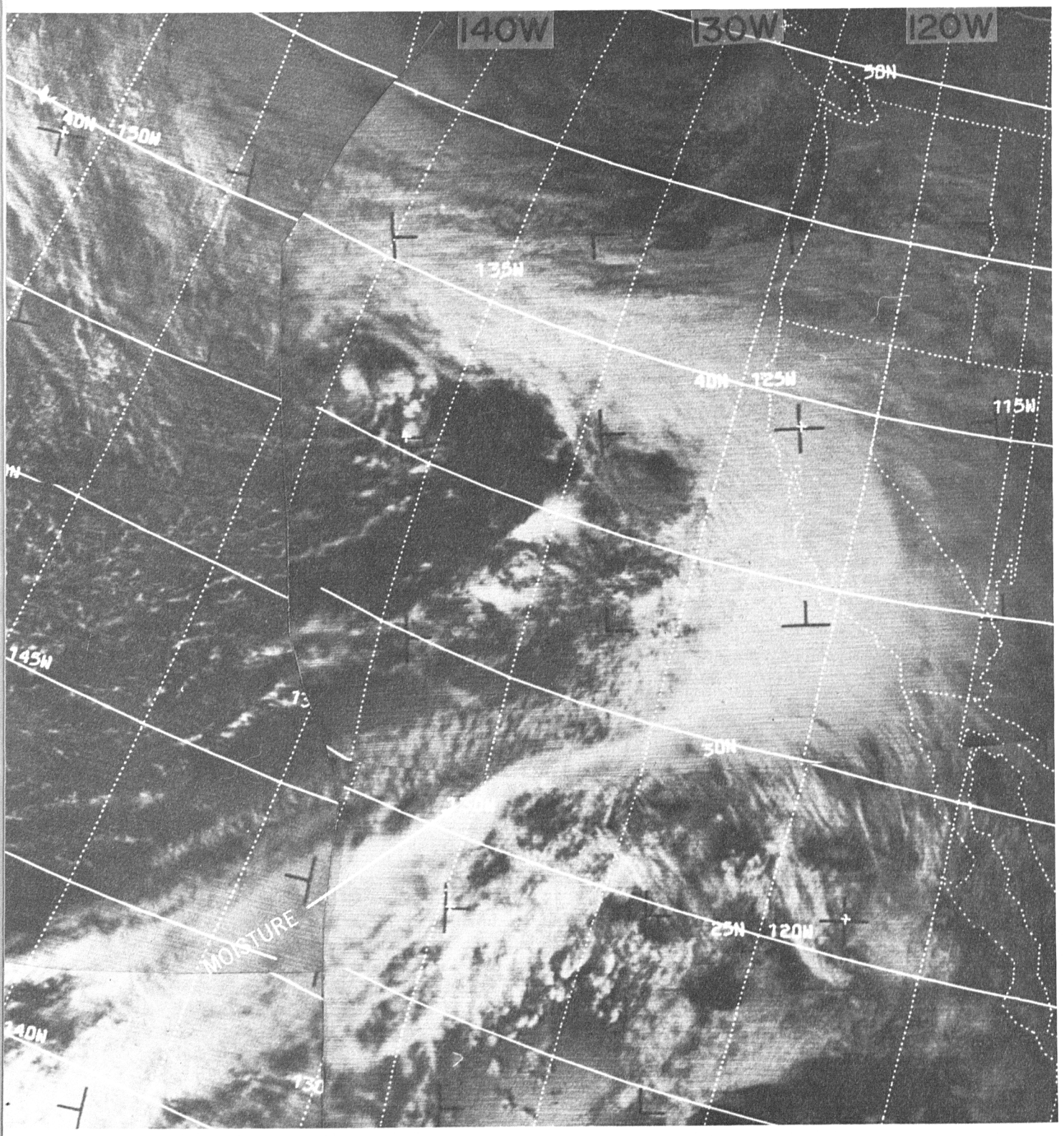
SPACE ENVIRONMENT SERVICES

Solar Proton Density

The ITOS satellites, first launched in early 1970, carry a Solar Proton Monitor to provide near real-time information on the flux of solar protons. This simple and inexpensive instrument is already finding broad applications in the observation and forecasting of geophysical parameters in near-space.

The data are used routinely in the Space Disturbances Forecast Center for mapping short-range fluctuations of solar proton intensity. This information enables the Center to improve its forecasts of ionospheric and geomagnetic storms, and to issue warnings of impending interference with radio and radar communications. Only with satellites can these measurements be obtained in situ and delivered in time for use in short-range forecasting.

The ITOS proton monitor data were used in direct support of the Apollo 13 lunar mission. A



Broad cloud band west of Mexico indicating new surge of moisture approaching California, January 18, 1969.

measure of electron densities in the Van Allen radiation belt was critically needed in order to assess possible effects on spacecraft communications and bring the astronauts safely back to earth.

Satellites are the only means for obtaining long-term synoptic observations of solar protons present in the near-earth environment. As these data accumulate, they are being used to learn more about solar proton propagation, a vitally important parameter of the space environment.

Radio Propagation Prediction

Satellite photographs are used routinely to detect specific types of cloud formations which indicate atmospheric conditions favorable for extended-range radio propagation. Times and places where these conditions occur are important for telecommunications, radio navigation, radar control, and other activities.

The satellite pictures are also used to locate thunderstorms and associated precipitation whose electrical effects produce radio interference. The information is used in correlating atmospheric conditions with interference levels in earth-to-satellite as well as ground-to-ground communication links, and will be applied in designing improved communication systems.

MISCELLANEOUS SERVICES

Earth Mapping

From their vantage point hundreds of miles up, satellites have a unique view of the earth's surface. They can show in a single picture the large-scale landforms and their locations relative to each other which cannot be done in photography from aircraft altitudes. Study of cloud-free regions in current satellite pictures has demonstrated the potential value for mapping and earth surveys that can be expected from high-resolution sensors to be flying soon on the ITOS and Earth Resources Satellites. Even the present satellite pictures have given new insight into the character of certain landforms. They also have revealed changes in beachlines, and corrections to the location of landmark features, particularly in remote areas where ground survey may be impractical and aerial survey is incomplete.

In the Antarctic, Mt. Siple, long used as a landmark for aerial and ground-based mapping, was relocated a distance of 40 miles on the basis of weather satellite pictures. In a recent Antarctic mapping project of the American Geographic Society, satellite pictures were used to update the shape of the ice shelves forming the perimeter of the continent.

In the far north, a volcanic eruption near Jan Mayen Land was discovered first in satellite pictures received in Scotland.

Data Collection and Relay

Satellites in geostationary orbit high above the earth are in a unique position for collecting observations by radio from remote instrument platforms over a broad region of the earth, and relaying the data to a central receiving station. Conversely, processed information and warnings can be sent from a central station to the satellite and re-broadcast widely for reception by any users within range of the satellite.

The use of the Applications Technology Satellites for broadcasts of satellite picture mosaics and other weather information is highly successful. These broadcasts are received at remote U.S. and foreign installations and ships at sea throughout most of the western hemisphere. The acknowledged benefits of having this information available for forecasting in data-sparse areas of the world have been described above.

An interesting example of the benefits derived from satellite broadcast of information was that of a Commerce Department field party on location at remote Pitcairn Island to take precise geodetic measurements. Their very precise clock, needed to obtain exact times for their measurements, was accurately set using WWV time signals relayed through the ATS–I satellite. This avoided the long and costly delay entailed in transporting a time standard out to the remote island by ship.

Capability to collect data from thousands of automatic observing stations at the surface will be a major function of the operational geostationary satellite system to be inaugurated in 1972. Seismometers and tide gages for tsunami warnings, rain and river gages for flood forecasting, data buoys and ships at sea, and automatic weather stations in remote areas are among the platforms planned for use with the satellite. Some preliminary experiments conducted with current satellites have demonstrated the feasibility and potentially enormous benefits to be derived from this rapid, effective new means for collecting information at forecast and warning centers.

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International Aspects

Satellites operate globally by nature. Hence, satellite systems established to meet U.S. needs can, and do, serve other nations of the world without extra cost. The Automatic Picture Transmission (APT) system was developed specifically to broadcast pictures continuously as the satellite orbits the earth. Any station with a relatively inexpensive receiver anywhere in the world may receive these pictures when the satellite is overhead. More than 500 APT receivers are now operating in well over 50 foreign countries. These are funded by the nations themselves, or by special foreign aid programs outside the satellite service. This investment demonstrates the great worldwide interest in meteorological satellites, and the value placed on their benefits to weather forecasting and other services.

The Meteorological Satellite System, as a peaceful use of outer space available to all, is considered a powerful instrument of U.S. foreign policy. In a letter to the Administrator of the Environmental Science Services Administration (now a part of NOAA), Mr. Herman Pollack, Director of International Scientific Affairs of the State Department, commented:

> "Statements by Presidents Kennedy and Johnson in the United Nations and in other forums as far back as 1960 supported the establishment of an operational meteorological satellite program emphasizing not only meteorological benefits, but also the utility of such a program in international relations. The international reception of the global system established in cooperation with NASA, and which you now operate, most graphically verifies these early predictions. It is a matter of pride to represent the United States in international affairs and to be able to point to the routine availability of such an instrument to all nations, developed and underdeveloped, all over the world."

The Meteorological Services of a number of countries have written specifically to express enthusiasm about the contributions satellite data have made to weather forecasting and other activities. The advantages stem largely from the satellite's comprehensive and timely portrayal of weather conditions in and around a country's area of interest where, in many cases, little or no other information is reported. A few examples may be cited to indicate the wide variety of tangible benefits, often involving matters of life and death:

- ☐ Satellite Storm Advisories were sent to India in October 1967, warning of a severe tropical storm in the Indian Ocean that was approaching the coast. The Indian Government credits the Satellite Advisories with substantially reducing the death toll. Similar examples of lives and property saved by timely warnings of approaching storms have been reported by the governments of Burma, Fiji, Mexico, Mozambique, and others.
- ☐ A weather satellite is credited with saving the Mexican town of Gomez Palacios from devastation in November 1968. The pictures were a key factor in helping Mexican authorities manage a reservoir that threatened to break its dam and inundate the city.
- ☐ The Hospital Ship HOPE, caught in a severe storm off Madagascar in February 1969, appealed via amateur radio to the U. S. Satellite Center for aid. The position and direction of movement of the storm, as determined from satellite pictures, were relayed back. The ship changed course accordingly, and was able to escape the storm.

- In Canada, Iceland, Sweden, Argentina, and other countries, satellite pictures are contributing substantially to the preparation of sea ice bulletins and charts which are vitally important to fishing and shipping interests, and as guidance for ice-breaking operations.
- In Asmara, Ethiopia, the locust control agency for eastern Africa uses satellite pictures to watch for weather conditions favorable for breeding, and follows the movement of wind patterns that tend to concentrate locusts in destructive swarms.
- The Republic of South Africa is going to great effort and expense to install APT receiving equipment on remote Gough Island, midway between Africa and South America. This extension of their direct satellite coverage in the data-blank South Atlantic is expected to upgrade forecasting services throughout southern Africa.

Many countries have commented on the great value of satellites as routine suppliers of real-time weather information of special significance for their particular forecasting problems. Satellite data have come to be accepted—indeed, depended upon—as a basic information source for their daily weather services.

"Satellite data are proving of such enormous value that it is difficult to contemplate a situation without such information"—South Africa

"It is no exaggeration to say that we now treat meteorological satellite data as of greater importance in providing information on the existence and development of weather systems over our region than the routine surface synoptic charts"—Singapore

"The Meteorological Satellite Service is the most useful aid to forecasting available to us in the Caribbean"—Antigua

Convinced of the real and lasting benefits of meteorological satellites as demonstrated by the U.S. operational system, other countries soon may be willing to share in supporting an overall global satellite system. Present long-range plans of the World Weather Program under the World Meteorological Organization call for an operational system composed of two polar orbiting satellites and four geostationary satellites. The current United States commitment is for only one polar and one or two geostationary satellites. The additional spacecraft to complete the WMO plan would obtain complementary coverage of considerable value to the United States as well as to other parts of the world. Possible contributions of other countries might be developed from the following areas:

- the USSR in its COSMOS System has polar orbiting meteorological satellites operating continuously;
- other experimental polar orbiters are under consideration in the United Kingdom and in the European Space Research Organization. The U.K. is also considering furnishing remote sounding instruments for use on United States operational spacecraft.
- France and Japan both are seriously considering development of geostationary satellites in support of the Global Atmospheric Research Program of the World Weather Program.

Thus, United States plans plus contributions by other nations may bring the system proposed under the World Weather Program into existence without major expansion of the current U.S. satellite program.

Importance of the Development Program

The many benefits described in the foregoing sections have been achieved because of an ambitious program of preparatory studies on the application of satellite data. Imaginative investigation and experiment with this totally new kind of information yield large rewards in new and better ways to exploit it. A new class of techniques for utilizing meteorological observations has been developed through inquiring scientific examination of the satellite data. For example:

- Development of a system for classifying hurricanes, based entirely on their shape and appearance in satellite pictures, now permits forecasters to estimate accurately the maximum winds in storms as soon as they are seen in the picture.
- Techniques for measuring winds from cloud movements in satellite pictures are used operationally now only because a start has been made on solving the horrendous technical problems in determining precise three-dimensional positions of the clouds in each picture.
- Techniques to convert satellite radiance measurements into atmospheric temperature soundings for operational use required years of theoretical development.
- Satellite sea surface temperature charts for all the oceans can now be produced operationally because of ingenious techniques developed to overcome interference from clouds.

Carefully study of satellite data has revealed new basic scientific information which helps in understanding the atmosphere and the way it works. This leads in time to more accurate and longer range forecasts, in ways that could not be achieved without the satellite contribution. Improved understanding of jet stream dynamics is one example. Another is the new insight into large-scale energy transfers within the atmosphere.

Another important part of the development program is directed toward new sensing devices and techniques for future operational satellites. Observing instruments on satellites are very complex; they require a lengthy period of sophisticated design and development. SIRS, the first remote atmospheric sounder to be used operationally, took ten years to design, engineer, and construct. It operated for 17 months before an unrelated spacecraft failure cut off its data flow. Its dramatic success was due to painstaking scientific development. Other new instruments now being developed and built for future satellites will take less time to complete. These include:

- improved atmospheric sounders and better wind measurement techniques to help improve weather forecasts;
- a new radiometer for measuring radiation from sun and earth, needed to make better predictions 5 days to 2 weeks ahead, and to monitor long-range climatic change;
- satellite instruments to collect data from in situ observation platforms on earth and in the air, and relay the data instantly to ground control centers for fast response actions.

As strong, effective study and development program brings continuing benefits in refining data application techniques, increasing basic knowledge of the atmosphere, and developing new instruments to exploit further the enormous potential of satellite services.

Overall Assessment

Weather satellites are providing a wide variety of direct, continuing benefits to environmental observation and prediction programs in the United States and overseas. Major applications are in weather analysis and forecasting services, derived largely from the large-scale cloud patterns dramatically displayed in the satellite pictures. These show the location of atmospheric systems and give new insight into their motion and structure, which are critically important parameters for skillful weather forecasts. Satellite data are used to an increasing extent in other environmental services—maritime activities, hydrology, space disturbance monitoring, and others. Many examples have been cited to demonstrate how satellites are contributing materially to better weather forecasts, more accurate maritime bulletins, and more reliable warnings of environmental hazards.

The unique value of satellite data stems from several factors which distinguish these data from other kinds of environmental observations. One primary characteristic is paramount: the effectiveness of the satellite in providing information, routinely and dependably, in areas where conventional data are sparse or absent. Closing observational gaps over oceans and remote land areas is cited time and again as the basic contribution of satellites to improved weather forecasts and other environmental services.

Another factor is the rapidity with which forecast offices receive pictures and weather charts transmitted directly from satellites. In some remote areas, satellite data are received and used hours ahead of the regular data arriving through normal communication channels.

A third aspect that has proven of great value in numerous applications is the overall view of the earth and atmospheric features obtained from orbital altitude. Observations from this vantage point reveal large-scale organization and structure of cloud systems and sea ice distribution that are not attainable from aircraft or conventional ground-based observations.

In general it is difficult to put a meaningful dollar value on the benefits from satellite data. It is hard to define quantitatively the value of a good weather forecast, or to place a dollar sign on a satellite's specific contribution to these forecasts. In certain circumstances where satellite pictures directly support a specific operation, some estimates can be made. For example, consider aerial photography missions, scheduling of weather and ice reconnaissance aircraft, Antarctic resupply operations, hurricane preparedness decisions, raisin drying operations, and rocket range utilization.

In these operations alone, estimates of monetary benefits resulting directly from use of satellite data total many millions of dollars annually. Thus the United States, through direct use of satellite data in operational decision-making, already achieves savings and increased efficiency that probably equal the cost of the operational weather satellite system. Additional benefits resulting from improved weather forecasts and warnings, that can be documented only in a qualitative way, are significant in the protection of life and property, in the economy, and in the activities of the general public.

Among the indirect benefits is the enormous enthusiasm with which other nations have received and utilized data from U.S. meteorological satel-

lites. The costs of APT receiving equipment represent a considerable investment for smaller nations, attesting to the value these nations place on the benefits of satellite data. The World Meteorological Organization, and individual nations as well, have enthusiastically acclaimed the contribution of the U.S. satellites to international weather services, with resulting enhancement of prestige and good will for the United States.

Utilization of satellite data is still in its infancy. New applications are being developed as experience with the data increases and as the satellite capabilities expand. Several new satellite instruments are now being built for inclusion in the operational system by 1972. Pictures with substantially higher resolution will show weather features in greater detail. Improved atmospheric soundings on a regular operational basis will fill data gaps in hemispheric analyses and lead to better forecast guidance charts. Continuous viewing through the night as well as in daytime will provide round-the-clock monitoring of rapidly developing atmospheric systems. Satellite collection of data from various kinds of ground stations will provide more data faster for warnings of quick-response hazards such as floods and tsunamis.

Finally, the Global Atmospheric Research Program, designed to be the greatest systematic investigation of the atmosphere ever undertaken, will depend heavily on satellite observations to support the planned international experiments during the 1970's. Results of these experiments can bring potentially significant benefits to the United States in increased understanding of atmospheric processes, and consequent improvement in the range and accuracy of weather forecasting services.

NOAA-1 launch.

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