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## THE USE OF SATELLITE CLOUD PHOTOGRAPHY TO INFER OCEANOGRAPHIC PHENOMENA

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### ABSTRACT

Several years of satellite cloud photography were examined to determine to what extent oceanographic phenomena might be revealed through their influence on the local cloud structure. The region of the Peru Current was selected for the study. As anticipated, indications of known oceanographic features including the Peru Current itself and local upwelling centers were noted. Previously unknown features such as an apparent band of warmer water off the Peruvian coast and anomalous patches of calm water in mid-ocean were also found. A seasonal cloud climatology for the Peru Current area was developed. The importance of coordinated studies using satellites, ships and aircraft is emphasized.

### INTRODUCTION

The time and space scale advantages of satellite observations have been argued many times. The objection which is always raised, however, is that for the most part, meaningful observations require a clear and unobstructed view of the earth's surface. So that unless measurements are made in the cloud-piercing microwave portion of the electromagnetic spectrum, at least 40% of the ocean's surface will be missed on any given day due to the ever-present cloud patterns. In this study which was performed for the Woods Hole Oceanographic Institute, it was our intent to demonstrate that the very presence (or absence) of the cloudiness can at times be used to infer a considerable amount of information about the ocean's surface. Obviously, the influence of the ocean's surface on the local cloudiness is generally overshadowed by the overall dynamics of the atmosphere itself. By studying a long time-sequence of satellite pictures, however, or by restricting observations to periods of minimal atmospheric activity, cloud anomalies occur which cannot be explained without reference to the influence of underlying surface properties.

The Peru Current area was the specific site for our study. This is one of the major Eastern Boundary Currents, featuring coastal upwelling as well as occasional shoreward fluxes of warmer water. As anticipated, many of the known features of this particular ocean area were reflected in the corresponding cloud patterns. The persistence of other cloud formations, however, indicate that there may be other oceanographic

phenomena present which have not as yet been fully explained or even observed. This points up the importance of the satellite's unique ability to view widely separated areas nearly simultaneously and to repeat these observations on a regular basis. The final interpretation of the anomalous cloud formations, however, requires that the spacecraft observations be tied to in situ aircraft or ship measurement programs.

### RELATED STUDIES

The use of satellite cloud photography to infer oceanographic surface properties has a considerable precedent in a number of isolated studies. In analyses of color pictures from the 1966 manned Gemini series, prepared for the National Council on Marine Resources and Engineering Development, it was found that cloud patterns were useful in interpreting such ocean surface features as upwelling and convergence zones<sup>(1)</sup>. Both Morton<sup>(2)</sup> and LaViolette<sup>(3)(4)</sup> of NAVOCEANO have prepared informal reports relating cloud formation to water temperature structure. Morton's work was done using ESSA 3 data over the eastern Gulf of Mexico while LaViolette's included observations of the Spring transition in the Bay of Bengal and seasonal upwelling off the coast of the Somali Republic and along the west coast of India. Both authors caution that due to the generally data-sparse nature of most of the world's ocean, much work still has to be done in identifying the proper sequence of cause and effect between cloud cover and ocean surface thermal patterns.

A more recent study by Warnecke et al has looked at the general problem of ocean current and sea surface temperature observations from meteorological satellites<sup>(5)</sup>. One part of this study deals with the inference of ocean surface temperatures from satellite cloud observations. It is emphasized that the data available today are derived almost solely from satellites designed exclusively for meteorological purposes. As such, they do not have the spatial or spectral resolutions necessary for developing quantitative temperature/cloudiness relationships. It is concluded in the Warnecke report, however, that "present satellite photography can provide information useful in detecting pronounced sea surface temperature discontinuities, essentially along contrasting ocean surface currents."

## DESCRIPTION OF PERU CURRENT FEATURES

This section presents a general overview of those features of the Peru Current which might be expected to have some influence on the ambient cloudiness. The information presented here was compiled from the following sources: The Oceans, by Sverdrup et al<sup>(6)</sup>; The Encyclopedia of Oceanography<sup>(7)</sup>; and "Peru Current" in Science and the Sea<sup>(8)</sup>.

The Peru (or Humboldt) Current is a system of relatively shallow currents flowing equatorward along the west coast of South America. It has its origins in the sub-Antarctic region where the water flowing eastward across the Pacific Ocean is directed toward the north when it approaches the American continent. The system forms the eastern branch of the counterclockwise circulation of the South Pacific and is one of a family of current systems known as Eastern Boundary Currents. Upon leaving the South American coast at about 4°S the waters of the Peru Current join the South Equatorial Current which flows all the way across the Pacific toward the west.

Although there is some disagreement, most investigators distinguish between a narrow coastal current and a broad offshore oceanic current flowing in the same general direction. The cooler inshore water mass is sometimes differentiated as the Peru Coastal Current in contrast to the main Peru Oceanic Current. The dividing zone between these two systems seems to be somewhere near 20°S. Recent observations even suggest a southward counter current between these two northward components of the system<sup>(9)</sup>. Because so little is known of the Peru Oceanic Current, we have limited our studies to the inshore current along the Peruvian coast. In this manner, we were in a better position to correlate the satellite data with known oceanographic features.

The prevailing wind flow along the coast of Peru is principally from the southeast and south. These trade winds blow steadily from more or less the same direction throughout the year, and with greater strength during the southern winter (July, August). In the Southern Hemisphere a southerly (equatorward) wind blowing along a west coast will establish an Ekman transport, driving the surface-layer water seaward. These surface waters are replenished by colder, deeper lying waters from depths of a few hundred meters. The intensity of upwelling is related to the intensity of wind stress, and since the trades are the strongest during the southern winter, the effect of upwelling is to exaggerate the annual temperature range. During the southern summer, particularly in February and March, the trades are considerably weakened or even reversed, producing coastal sinking and occasionally inducing warm equatorial water to flow southward.

The cool northward current and the abundance of marine life along the Peruvian coast were noted by the first Europeans to visit Peru, at the time of the Spanish conquests. The first extensive oceanographic investigations of the area, however,

were not carried out until the 20th century. The report and the observations of Gunther in 1936<sup>(10)</sup> still stand as one of the basic information sources for this remote area. It was found by both Schott in 1931<sup>(11)</sup> and Gunther in 1936 that upwelling does not occur uniformly along the South American coast, but rather in localized upwelling centers. Although both authors recognize four major regions between 3°S and 33°S, they do not agree on the exact location or extent of the different regions. We were primarily concerned with the two northern regions which, according to Gunther, occur at about 5 to 6°S and 15 to 16°S.

South of each of the two northern areas of intense upwelling, tongues of warm water occasionally approach the coastal area. These inshore movements of the outlying warmer water (locally called *Aguaje*) occur predominantly in the early southern winter from April to June. The northern swirl annually brings warmer waters into the coastal area between 9 and 12°S. At this latitude, the *Aguaje* displaces the cold Peru Current and causes destruction of plankton and fish life. The dead fish which accumulate on the beaches rot and lead to the formation of hydrogen sulphide which, when combined with sea fog, may even blacken the paint on ship hulls. This phenomenon is also known as the *Callao Painter* from the coastal town of the same name. Some evidence of this phenomenon was found in the satellite pictures examined.

An even more disastrous phenomenon occurs on the average of every 7 years when the annual southward penetration of the Equatorial Counter becomes more pronounced than usual and turns southward along the coast of Peru rather than northward along the coasts of Ecuador and Colombia. During the El Niño there may be torrential rains followed by heavy flooding in coastal areas of northern Peru which are adapted to a normally arid climate. As with the *Aguaje* effect, there is widespread destruction of plankton, fish life and sea birds. The most recent noteworthy El Niño occurred in 1958. A less intense invasion of the warmer waters was noted as recently as 1966<sup>(12)</sup>. No hint of such an occurrence was noted in the 1968 and 1969 satellite data, although it is felt that the El Niño could easily be detected by the southward extension of convective-type cloudiness into areas which are normally clear at this time of year.

## DATA SOURCES AND LIMITATIONS

The World Atlas of Sea-Surface Temperatures published by the Hydrographic Office of the U. S. Navy was used as a source of mean monthly climatological surface-temperature values. These data, compiled by Scripps, are presented as isotherms at intervals of 5°F and at a scale of about 1:43,000 so that only the larger scale features are generally visible.

For more recent temperature data, Part II of the California Fishery Market News Monthly Summary, published by the Tuna Resources Laboratory of the Bureau of Commercial Fisheries, was employed. These data are compiled from the reports of a num-

ber of organizations and ships and published in degrees Fahrenheit by  $1^{\circ}$  latitude-longitude squares. These data were available for all of calendar year 1968. Although these data represent relatively current information, the data density along the western South American coast is generally sparse.

The most useful temperature data were those provided by the Instituto del Mar de Peru. Surface observations of temperature, salinity, wind direction, and wind speed from approximately nine separate oceanographic cruises were received for the period from late 1966 to early 1969. Most of the data were for calendar year 1968.

Television images of ocean areas have been available to the general scientific community since the launch of TIROS I in 1960. Because of the scanning and orbital characteristics of the early TIROS series of satellites, it was virtually impossible to employ these data in a comprehensive oceanographic study program. Particular geographic areas could be viewed only on an irregular basis for short periods of time. The sun-synchronous orbits of the Nimbus and ESSA satellite series were a significant improvement, permitting all areas to be monitored twice daily at 12-hour intervals. Although these orbits were most useful for studying day-to-day or seasonal changes, diurnal effects could not be observed.

With the initiation of the geo-synchronous ATS satellite series in December 1966, continuous monitoring of specific geographic areas became possible. From their orbiting height of approximately 36,000 km, these spacecraft maintain a constant position in space relative to the earth. The first of the series was stationed over the mid-Pacific at about  $151^{\circ}$ W. Due to a malfunction in the launch vehicle, ATS II never became operational. ATS III, launched in late 1967, was stationed over the South American continent and was used as the major data source for this study. All of the ATS III data from April 1968 through March 1969 were employed. These data were supplemented by additional ATS III data for the period January 1968 through March 1968, as well as by ESSA satellite data for various months in 1966 and 1967. In order to correlate the satellite with the available surface-temperature data, calendar year 1968 was emphasized. Frequent references to the 1966 and 1967 ESSA data were made to ensure that the phenomena noted were not peculiar to a single year.

### ANNUAL CLOUD CLIMATOLOGY

In this section we shall trace the development of cloud patterns in the Peru Current area throughout an entire year. Indications of the presence of upwelling as well as other oceanographic phenomena will be noted. Diurnal variations in the cloud cover will also be included.

On April 10, 1967, one of the few pictures ever taken during the brief lifetime of ATS II caused a stir in the oceanographic community because of its sharp delineation of the Peru Current<sup>(3)</sup>.

A narrow band of cloud-free water ran along the coast of Peru and then turned westward toward the South Pacific following the historic course of the Peru Current. Since then, the ATS III spacecraft has recorded similar conditions on a great number of occasions, and on an almost daily basis during certain times of the year. One such example may be seen in Figure 1 (details of the exact date, time and camera for each picture will be included in the figure caption). At about this time of year the period of minimum upwelling has already occurred, and the southeast trade winds, which are part of the overall South Pacific anticyclone, begin to reestablish. Close examination of this early afternoon picture reveals isolated patches of stratus-type cloud (or fog) along the Peru coast at about  $7^{\circ}$ S and  $11^{\circ}$ S with a somewhat brighter patch at  $13^{\circ}$ S. These isolated patches of fog and cloudiness are generally more extensive earlier in the day and then burn off as the day progresses. They apparently result from the abrupt cooling of nighttime land-breeze air in contact with the cold water. The most persistent of the localized cloud areas would thus represent the locations of the coldest water.

To the west of the current, brighter convective-type cloudiness over warmer (relative to the Current) waters delineates the western boundary of the Peru Current. Just where the cloud edge occurs relative to the actual temperature discontinuity depends upon the interplay between the induced local circulations and the larger atmospheric flow patterns. Warnecke suggests that an allowance for a 10-km horizontal displacement toward the warmer water would tend to compensate for an induced mesoscale circulation which he likens to the sea-breeze phenomenon. The actual displacement could be smaller or larger depending upon the superimposed wind field. A comparison with a similar situation over the Gulf Stream where a greater amount of ground-truth data is generally available basically substantiates the 10-km figure<sup>(13)</sup>.

Toward the south, the convective-type cloudiness becomes more stratified in nature. As we will see, in the following months this stratiform cloudiness expands northward to encompass most of the Peru coastal area.

The month of May seems to represent a transition period as the southern winter approaches. During the early part of the month, the Peru Current remains reasonably well defined by a narrow band of clear sky conditions along the coast. The isolated patches and bands of fog or low stratus hugging the coast, however, become larger, brighter (thicker), and more frequent than in April. At this point, diurnal dissipation can be seen only along their outer edges. Figure 2 provides one example of this dissipation from about 1140 to 1400 local time in early May.

During the latter part of May, the current begins to lose its identity as the previously convective-type cloudiness becomes more stratified and begins spreading eastward. This trend continues into June, at which time there may be no indication of the Peru Current for days at a time. Figure 3

presents a typical early June example in which the Peru Coastal Current is totally obscured. Of particular note are two persistent clear patches at about 13 to 15°S and about 4 to 6°S. The location of these areas corresponds well with the two regions identified by Gunther as being associated with maximum upwelling. By June, the southeast trade winds are generally fully established and are directed northward nearly parallel to the coast. At both the clear areas noted above, the coastline jogs to the east, so that the mountain-channeled winds blow directly offshore. During June, the size of these open areas seems to fluctuate from day to day, probably as a function of the wind force. Behind both clear areas the land is generally cloud-free, indicating the presence of dry air. Thus, the clear sky areas seem to be not a direct effect of upwelling, but of the dry offshore winds which would cause both the clear skies and upwelling. At other points along the coast where there is no offshore wind component, stratiform foglike cloudiness can continue to develop undisturbed by the influx of drier air.

During the winter months the situation becomes rather stable, with little or no diurnal change. The sky cover along the current remains steadily overcast with very limited periods of broken cloudiness over isolated regions. The small clear pockets previously observed along the coast continue to persist, but on a much smaller scale.

Of interest in Figure 4, is the narrow, elongated band of much thinner stratus, or broken stratocumulus to the west of what would be the boundary of the Peru Coast Current. This narrow band running from about 5 to 20°S, is seen occasionally throughout the winter months, but its immediate cause is not known. It may mark the western boundary of the Peru Coastal Current, or may possibly be some indication of the presence of the warm counter current. Although the data are sparse, surface temperature reports for the month of September 1968 do indicate the existence of a narrow band of warmer water running parallel to the coast. Figure 4 also shows the sea surface temperature analysis drawn to the ship data from Cruise No. 6809 of the B. A. P. Unanne for the region from 12 to 20°S. Colder temperatures on either side of the warm strip apparently support the bright stratus bordering the clear band.

A diurnal variation in cloudiness which was first noticed in late September becomes fully established during the months of October and November. A striking example of this daytime dissipation is presented in Figure 5. These pictures show the breakdown in cloudiness over a 5-hour period from about 0915 to 1415 local time on a mid-October day. The two clear areas which were reduced in size during the winter months once again begin to expand and to fluctuate in size from day to day.

The December and early January satellite data to a large extent resemble those of late April or early May. The Peru Current is occasionally delineated by cloudiness to the west, as the south-

east trade winds begin to diminish.

It is during the summer months that the southeast trade winds generally reach their lowest point. During the early part of this period, the South Pacific waters are still relatively cool, although the warming process has begun. The extent of stratiform cloudiness diminishes considerably, with the result that the Peru coastal area is often cloud-free, and the Peru Current again becomes indistinguishable from the adjacent water. Figure 6 shows one such case from late January. No evidence of upwelling-induced fog or stratus may be seen along the coast.

As the season progresses and the South Pacific waters become warmer (and thus more capable of supporting convective cloudiness), there is a gradual transition from predominantly clear skies, occasionally interrupted by the passage of storm systems, to the current-defining conditions of late March and April.

## OBSERVATION OF SPECIFIC FEATURES

### The Current

As we have seen, the optimal period for delineation of the Peru Coastal Current in spacecraft pictures is from late March through April. During the months of May and June, the situation gradually deteriorates to the winter-time conditions of widespread cloudiness obscuring the entire area. For a brief period in December and early January the current may again be seen, but this is quickly replaced by the generally clear sky conditions of late January. During the summer months there is a gradual improvement as the current once again becomes distinguishable with increasing frequency.

Evidence of the Peru Oceanic Current is rarely seen, although its presence may be inferred from an occasional satellite picture. Figure 7 presents one such case. Here the undulating sharp edge of a convective cloud pattern may be seen extending westward from the South American coast, far south of the usual position of the Peru Coastal Current. Whether or not this cloud pattern really did outline the Peru Oceanic Current could not be determined from the available surface temperature data.

### Upwelling

In the absence of a coordinated satellite and ship effort the upwelling/cloud relationships cannot be definitely proven. The isolated fog patches which occur in late February through May and the two clear areas which persist throughout the winter months, however, do agree reasonably well with the locations of the upwelling centers observed by Gunther. Moreover, the cloud patterns associated with the summertime observations do fit the physical model of a cold underlying surface which would suppress the buildup of convective-type cloudiness while supporting nighttime and early morning fog formation. If a definite linkage can be

be established between the occurrence of upwelling and the local cloud fields, a continuous monitoring of these (and other) areas could provide valuable information for the fishing industry. This is particularly true of the more transitory, short-lived upwelling areas.

#### Aguaje

It has been noted that in the early southern winter from April to June, an occasional swirl of warmer water brings destruction to plankton and fish life along the Peruvian coast from about 9 to 12°S. One possible example of this phenomenon may be seen in Figure 8 where an area of convective cloudiness extends shoreward in May of 1967 to the coast at the latitude of Callao. Surface temperature data from Cruise 6705/6 of the Peruvian ship, Ilo, indicate the presence of a warm core of water just offshore at these latitudes. No suggestion of the El Niño Current was evident in the available satellite data. From the ease with which convective cloudiness buildup may be noted along the Inter-Tropical Convergence Zone, however, (see Figures 1, 2 and 7), it is felt that satellite photographic data could provide an effective means of monitoring the onset of the El Niño.

#### Other Features

During the months of February, March and April, a persistent isolated cloud band is frequently seen paralleling the coast from about 15 to 19°S. The cloud band seems convective in nature and occurs about 110 km offshore. Figure 9 shows this cloud band for two consecutive years. A preliminary investigation of the surface wind structure indicates that this may be an area of local convergence during these months. The location of the cloud band falls along one of the deepest portions of the Peru-Chili Trench, although this may very well be coincidental. Climatological sea surface temperature maps indicate that this cloudiness may also represent a band of particularly warm water. In any event, this is a recurring feature which, like many others, would require a coordinated study of both spacecraft and conventional data to fully comprehend.

In our study of the various oceanographic features which might be detected through their influence on the cloud patterns, a phenomenon was noticed which was quite independent of any cloud relationships. Sharp variations in brightness were noted within overall sunglint patterns<sup>(14)</sup>. Our first impression is that these variations seem to be due to small areas of relatively calm water in the midst of more turbulent seas. This hypothesis<sup>(15)</sup> is borne up by the findings of McClain and Strong who had actually discovered this phenomenon prior to our studies.

If the sea were perfectly calm, the sunglint would consist of a small, very bright specular-type reflection at a point on the earth determined by the laws of geometric optics. Because the sea is not smooth, sunglint always appears as a larger, more diffuse area. The rate of the transition from brightness at the center of the sunglint to

darkness at the outer edge has been suggested by some investigators<sup>(16)</sup> as a means to infer sea state. According to our model, a patch of calm water not at the center of the sunglint pattern would show up as a dark spot against the sunglint background. If the center of the sunglint pattern were to pass through this area of calm water, it would become considerably brighter than the background due to the specular-type reflection. As the center of the sunglint pattern then moves out of the calm area, it would once again become darker.

Figure 10 shows a typical sunglint sequence. In Figure 10a, the center of the sunglint pattern is nearing the western coast of South America at about 4°N. A darker area within the sunglint pattern may be seen at about the same latitude at 80°W. This is due north of the Gulf of Guayaquil. In Figure 10b, an hour later, the formerly dark area is now brightly illuminated. One-half hour after that, in Figure 10c, the sunglint center has passed on and the area in question is once again darker than its background.

A number of these sunglint areas have been detected along the sunglint track. Their positions seem relatively stable, although their shape is not. Just what these areas are, or whether they have any practical or economic significance, has yet to be determined.

#### CONCLUSIONS

On the basis of this study we have concluded that within the restriction of quasi-stable atmospheric conditions, ocean surface temperature patterns are often reflected in the overhead cloud structure. Due to the horizontal motions of the induced local circulation and the superimposed atmospheric circulation, however, the locations of ocean thermal patterns and their corresponding cloud features may not exactly agree. With the broad overall view that only a spacecraft can afford, known features such as the boundaries of major ocean currents and the locations of upwelling centers can be detected. By studying cloud effects associated with these known features, knowledge applicable to the discovery and interpretation of new phenomena can be obtained. When these new features are being sought, a large number of pictures must be scanned, seeking persistence against the more variable background of the dynamic atmosphere.

The ability to see the forest but not the trees is at once the strength and the weakness of satellite data. In this study, features were found which may never have been noticed using ship or aircraft observations. But to interpret these features and to discover their cause is a task which can only be accomplished through the use of these more conventional means. The isolated cloud band off the coast of southern Peru, and the mid-ocean patches to apparently calm water, are just two examples of oceanographic phenomena which will require a coordinated study of surface and spacecraft observations to properly interpret.

## ACKNOWLEDGEMENTS

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Figure 1. The Peru Current in Early April.  
(Green channel of ATS III color camera  
on 3 April 1968 at 182411Z.)



Figure 2a.

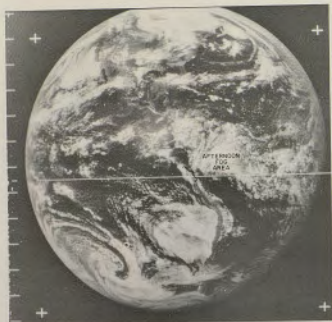


Figure 2b.

Figure 2. Diurnal Variation in Coastal Stratus in Early May. (Green channel of ATS III color camera on 3 May 1968 at 163956Z and 185711Z.)



Figure 3. Cloud-Obscured Peru Current in June. (Green channel of ATS III color camera on 4 June 1968 at 171652Z.)



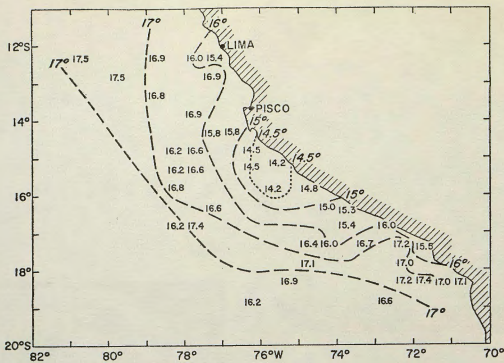


Figure 4a.



Figure 4b.

Figure 4. Satellite and Ship Data Representative of Wintertime Conditions. (Green channel of ATS III color camera on 24 June 1968 at 154906Z. Ship data from B. A. P. Unanne Cruise No. 6809, September 1968.)

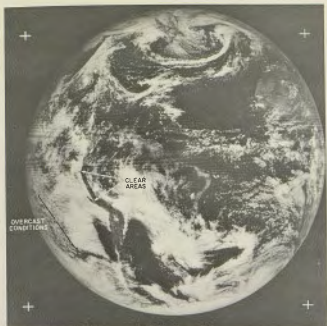


Figure 5a.

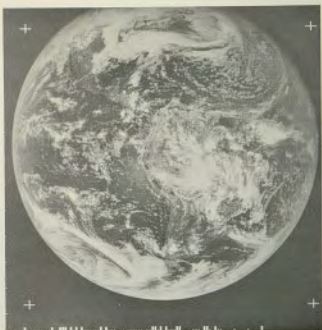


Figure 6. Cloud-Free Early Summer Conditions.  
(Green channel of ATS III color camera on  
20 January 1969 at 175818Z.)

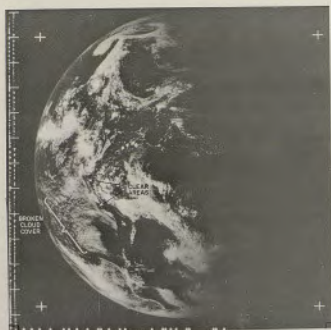


Figure 5b.

Figure 5. Diurnal Variation of October Cloudiness.  
(Green channel of ATS III color camera  
on 18 October 1968 at 141358Z and 191352Z.)

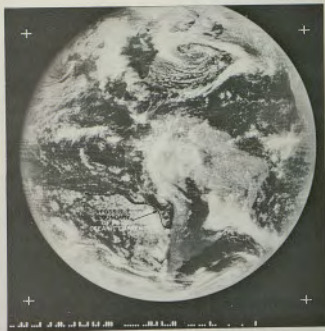


Figure 7. Possible Delineation of Peru Oceanic  
Current. (Green channel of ATS III  
color camera on 20 February 1969 at  
161957Z.)

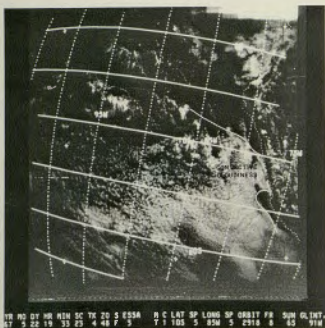


Figure 8. Possible Example of Aguaje Effect.  
(ESSA 3 on 22 May 1967 at 193323Z.)

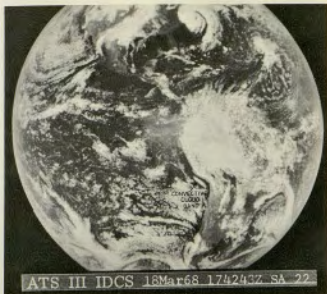


Figure 9a.



Figure 9b.

Figure 9. Isolated Cloud Band in Two Consecutive Years. (IDCS camera of ATS III on 18 March 1968 at 174243Z and Green channel of ATS III color camera on 12 February 1969 at 165908Z.)



Figure 10a.



Figure 10b.

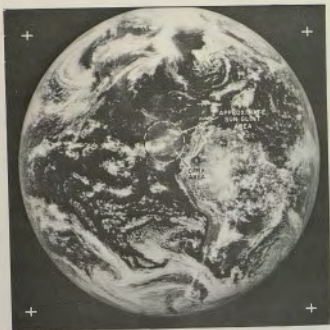


Figure 10c.

Figure 10. Sunlint Sequence. (Green channel of  
ATS III color camera on 17 April 1968 at:  
Figure 10a: 163742Z  
Figure 10b: 173234Z  
Figure 10c: 180003Z.)

