Atmospheric Water Vapor and Surface Flow Patterns over the Tropical Americas during May–August 1979

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ABSTRACT

Some meteorological features have been examined as part of a more extensive study on general circulation in the eastern Pacific and Central American region. The analysis is based on twice-daily data from May to August 1979. Different FGGE data sets (Level III-b, TIROS-N) were used to obtain fields of precipitable water (PW), 1000 mb wind, and surface water vapor fluxes. The results concerning precipitable water and wind are presented as monthly mean fields. The time and spatial evolution of three layers of PW (surface to 700 mb, 700–500 mb and 500–300 mb) show the synoptic characteristics prevailing during this period. The fields of PW reveal fluctuations that are associated with the number and trajectories of tropical perturbations observed over the Atlantic and Pacific Oceans. The time series of the 1000 mb water vapor flux for latitudinal and longitudinal segments around Mexico and the eastern equatorial Pacific Ocean were determined. The strongest horizontal mean flux takes place over the Gulf of Mexico and the eastern Pacific Ocean. Minimum intensity occurs during August, coincident with the month of observed fewer-than-normal tropical perturbations.

1. Introduction

Due to the lack of observations and different economic interests, past studies of the Western Hemisphere have dealt mainly with the characteristics of the atmosphere over North America and the Caribbean region. Some studies (Rasmussen, 1967, 1971) have shown that most of the atmospheric and oceanographic tropical influence on the Northern Hemisphere takes place over the Atlantic region. However, large-scale phenomena such as the El Niño/Southern Oscillation (ENSO) and observed planetary teleconnections during the recent years have drawn increasing attention to the synoptic atmospheric and oceanographic characteristics over the eastern Pacific and Central American region (Wyrtki, 1975; Rasmussen and Carpenter, 1982).

Some of the main characteristics of the global fields of total precipitable water have been described in past literature. Tuller (1968), using radiosonde data, showed that there is a latitudinal pattern with highs nearer the equator and lows nearer the poles throughout the year. Tuller's results, however, do not give a detailed description of the regional characteristics or the vertical structure within the troposphere. Rasmussen (1967, 1971), using twice-daily radiosonde data from the surface to 250 mb at 50 mb intervals, computed quantities such as water vapor flux and divergence flux, and performed budget analyses. His studies give useful results for regional and synoptic scales over the North American and Caribbean regions. Rasmussen (1967) also found that most prominent diurnal variations are in general due to variations in the wind field rather than in the specific humidity. Viswanadham et al. (1980), using radiosonde data, made a study of moisture conditions in the Southern Hemisphere, on a planetary scale and for seasonal averages. Peixoto et al. (1981) studied the seasonal variation of precipitable water (PW) and vertically integrated water vapor flux fields over the Northern Hemisphere from a composite of five years. Using the same data set, Rosen and Omolayo (1981) analyzed the water vapor flux across the coastlines of the Northern Hemisphere. Based on radiosonde data, Bryan and Oort (1984) studied the seasonal variation of the global water balance, i.e., evaporation minus precipitation during a 10-year period. From a comparison with FGGE analyses during a two-month period, they stressed the inadequacy of the operational rawinsonde network, which gives unreliable estimates of quantities such as evaporation minus precipitation. All these studies were hampered by the lack of data, especially over the oceans, and did not give much detail at the regional scale or for time scales less than a month.

On the other hand, most studies of the Pacific area have concentrated on surface wind and its relation to

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the ocean–atmosphere phenomena at rather long time-scales (see for example, Wyrki and Meyers, 1976; Hastenrath and Lamb, 1977; Goldenberg and O'Brien, 1981; Rasmusson and Carpenter, 1982). All of these studies based their analysis on ship data. Using ship and satellite data, Izawa (1972) made a statistical study on the disturbances in the lower atmosphere over the tropical Pacific, associating the Intertropical Convergence Zone (ITCZ) in the eastern Pacific with a marked cyclonic vorticity and convergence, low steadiness of the wind and high variances of the zonal and meridional wind components about their monthly means.

This paper presents an analysis of the general characteristics of atmospheric fields observed over the Central American and eastern Pacific regions during May–August 1979, using TIROS-N humidity data and a so-called FGGE data set. The monthly means and regional synoptic features of the fields of precipitable water, wind and surface water vapor flux are presented and discussed in this work.

2. Data and methodology

The basic meteorological data used in this study consisted of FGGE Level III-b, TIROS-N, cloud cover and radiosonde data sets. The basic processing and final preparation of the merged fields were described by Cadet (1983). Here we briefly mention the generalities of such preparation.

a. TIROS-N data

TIROS-N data obtained from NOAA consisted of measured precipitable water (PW) values in three different layers: surface to 700 mb, 700–500 mb and 500–300 mb. Gruber and Watkins (1979) analyzed TIROS-N moisture data. They found that moisture content in certain layers of the atmosphere can be depicted without an important bias. However, they also noted that TIROS-N soundings underestimate PW in deep moist layers whereas there is an overestimation for a relatively dry layer. Another problem arising from the use of IR channels to derive humidity information is the lack of moisture data in cloudy areas. To overcome this difficulty, Cadet (1983), based on Thomson and West (1967) and Smigielski and Mace (1970), estimated the water vapor content in strong convective regions using the temperature profiles derived from the microwave unit aboard TIROS-N and assuming a certain profile of relative humidity. An example of PW values from TIROS-N for the lower layer is shown in Fig. 1. Note the spatial gaps in the equatorial regions due to the inability of the satellite instrumentation to measure the water content within deep moist convective areas.

b. Bogus cloud cover data

Twice-daily satellite imagery during the period 29 April–15 September 1979 was analyzed to estimate the position and extension of strong convective areas. Us-

![Fig. 1. TIROS-N satellite data obtained for 1200 GMT over the Central American region on 1 May 1979. Precipitable water (numbers) for the first layer (surface–700 mb). The presence of strong convective activity is indicated by the circles.](image-url)
ing the temperature profiles from TIROS-N, and assuming a certain vertical profile of relative humidity (90% between surface and 700 mb; 80% between 700 and 500 mb and 70% between 500 and 300 mb), PW within the three layers was estimated (Cadet, 1983). Figure 1 also shows the position and the extension of convective areas (circles); note that the presence of the convective clusters correlate well with the gaps in TIROS-N humidity profiles.

c. Objective analysis

In order to have a regular grid in space and time of PW from satellite data, objective analysis was performed by use of the method of successive corrections (Tripoli and Krishnamurti, 1975). Objective analysis involves the successive modification of an initial guess field on the basis of observed data. In this paper, objective analysis was performed at 0000 and 1200 GMT from 29 April to 15 September 1979 and for the three atmospheric layers specified in section 2b on a 2 × 2 degree mesh using at each analysis time the data spanning a 30-hour period. The available TIROS-N and bogus cloud data are then fairly well distributed over the domain; hence, the choice of the initial guess field should not be very important (Tripoli and Krishnamurti, 1975). In order to obtain a reliable field on 1 May, we started the objective analysis on 29 April using as a first guess field constant precipitable water fields of 30 mm for the first layer, 10 mm for the second and 2.5 mm for the upper layer.

The resultant field is also the first guess field for the next time of analysis, which forces a 24-hour filter. Consequently, the time and space resolution of the analyzed fields permits only features of the order of days and spatial scales greater than 200 km.

Different weights were subjectively selected for both data sources. Following Cadet (1983), the final selection gave a reliability factor of the bogus PW data of one-fifth of that of the TIROS-N data. Figure 2 gives the analyzed PW field for the first layer, based only on TIROS-N data. The cloudy areas of Fig. 1 appear as zones where the water content is slightly higher, but without clear details. On the other hand, Fig. 3 shows the influence of the bogus data on the TIROS-N analyzed fields. Note that PW considerably increased for the South American equatorial regions where deep convective clouds were detected from the satellite imagery. The water content over the cloudy areas is enhanced, and the PW field becomes more representative. Note the effect of mountains in Figs. 2 and 3, due to the fact that the satellite provides PW from the surface to 700 mb.

d. FGGE Level III-b data

Level III-b twice-daily basic data (pressure, geopotential height, air temperature, relative humidity and wind), from the European Centre for Medium Range Weather Forecasts, were available at the 1000, 850, 700, 500, 400 and 300 mb levels for a rectangular grid at 1.875° latitude/longitude interval, bounded from

![Fig. 2. Analyzed field of precipitable water for the first layer (surface–700 mb) on 1 May 1979 from assimilated TIROS-N data only. Contour interval is 4 mm.](image-url)
20°S to 40°N and from 140° to 50°W. For computational purposes, the basic level III-b data were interpolated by means of a two-dimensional cubic-spline to obtain a rectangular grid at 2° latitude/longitude interval. Mixing ratio was vertically integrated (Saucier, 1955) to give PW fields in the three layers.

Surface values of pressure, air temperature and relative humidity were calculated with the aid of the geopotential height and surface elevation. The trapezoidal rule was applied to integrate the values of PW over different layers. Large discrepancies can be seen between Figs. 3 and 4, especially over the domain west of 100°W and south of 10°N where very large values of PW are given by the level III-b data set. The large values extending south to 10°S seem unrealistic and are due to the poor conventional data coverage over that area.

e. Final merging fields

Because the quality of the FGGE and satellite PW fields is not the same, they were merged to obtain the final fields. Level III-b data were expected to have better accuracy over land than over ocean because many more observations were available from land stations than over the open ocean, especially for the eastern tropical Pacific where only a small number of reconnaissance flights were performed during SOP-II [special observing period, May-June] and only two TWOS (tropical wind observing ships) were on duty. Because of these restrictions on the derivation of Level III-b fields, analyzed TIROS-N data over the ocean were assumed to be more accurate. The reader is referred to Fig. 6 of Cadet (1983) for the weights given to the different data sets. To ensure continuity at land-ocean boundaries, the merging at each grid point was made over nine points; the points located at 2 deg from the central point were given a weight equal to half the weight of the central point. Figure 5 shows the final merged field for 1 May 1979. This field is smoother than both TIROS-N (Fig. 3) and Level III-b (Fig. 4). The smoothing process improves the quality of the PW field over open oceanic and continental regions. However, over nonhomogeneous regions, especially when high rising mountains are located near the ocean, the smoothing process in this study and in the original TIROS-N data processing underestimates PW values over land and overestimates PW over the ocean (for example, the region of the Andes and the Peru Current).

f. Accuracy of the final merged fields

Due to the lack of reliable and sufficient dropsonde data over the eastern Pacific region, the accuracy of the final fields has been estimated using radiosonde data over the southeast of the United States region. Because of the 24-h filtering described above, and considering that over land the horizontal water content is much more nonhomogeneous than over the open ocean, we did the comparison as follows: Values of
PW from the merged fields at nine grid points were averaged over space and time, to obtain averaged merged PW for every three-day interval. Similarly, the available upper-air data within the same nine grid points were averaged in space and time to obtain a data set for the upper-air stations. The results of the comparison are presented in Fig. 6 for the surface to 700 mb layer.

Fig. 4. As in Fig. 2 except level III-b data only.

Fig. 5. As in Fig. 2 except merged (level III-b, TIROS-N and bogus) fields have been used.
For the first layer, the relative difference defined as $|PW_x - PW_y|/PW_x$, where $s$ corresponds to radiosonde and $f$ to the fields, is about 5%. This allows us to ensure that the monthly mean fields obtained can be accepted with sufficient statistical confidence and may be used for further analysis. On the other hand, the second and third layers (not shown) did not give as reliable a statistical comparison. (The statistical results for the mean values in these layers are also shown in Fig. 6.) The regression line indicates an underestimation of low values and an overestimation of high values in agreement with Gruber and Watkins (1979).

3. Mean fields

a. Monthly mean fields of PW

1) Surface to 700 MB layer

The main large-scale features of Fig. 7 indicate an expected pattern (Tuller, 1968). Compared to a previous analysis referenced in the Introduction, at synoptic scale much better resolution is achieved and enhanced details are detected: High values over the tropics, especially over the eastern Pacific ($\sim 38$ mm),

![Fig. 6. Scatter plot of the averaged radiosonde data against the averaged merged data of precipitable water for the first layer (surface-700 mb). The dashed line represents $x=y$. The regression line (solid) shows the linear relation between the two data sets. The table shows the statistical values for the three layers considered.](image)

![Fig. 7. Monthly mean fields of precipitable water in the first layer (surface-700 mb) for (a) May, (b) June, (c) July, (d) August. Contour interval is 2 mm.](image)
decreasing away from the equator; low values over the Rockies and the Andes; higher amounts of PW over the North Atlantic than over the North Pacific for the same latitude and a northward penetration of PW as northern summer evolves. Some of the most interesting findings include the combined effects of land, altitude and low SST over the California and Peru Currents associated with relatively low amounts of PW. Also note the development of moist tongues (≈34–36 mm) over the eastern Pacific and western Atlantic associated with the intensification of tropical perturbations as northern summer developed. In this layer the strong effect on PW due to evaporation from tropical waters is evident; this will be further discussed in section 4.

During May, the isolines of PW show a relative horizontal symmetry over the tropical oceanic areas, with a maximum located southwest of Central America (about 5°N); both the South and North America continental regions show strong asymmetries. During June, moist tongues begin to develop over the Caribbean and the Gulf of Mexico; the maximum PW shifts northward (8°N) penetrating over Central America, coincident with the intensification of the rainy season in the same region. The Pacific area also starts to develop a moist tongue over the southwest of Mexico. July shows a sharp northward water vapor flow penetration with an intensification of 6 mm of PW higher than in June over the northern part of the Gulf of Mexico and over the southwest of Mexico, due to the surface flux of water vapor from the Caribbean Sea and the Gulf of Mexico. During this month, above normal temperatures and below normal precipitation were observed over Mexico (Servicio Meteorológico Nacional, 1979). Four tropical perturbations detected in July did not penetrate over the continent, except for the southern portion of the Gulf of California, where above normal precipitation was observed. August was the most anomalous month of this summer. The northeast Pacific side evidenced a relative decrease of PW. The Atlantic side shows a relative decrease of PW for the northern part of the Gulf of Mexico and no significant change from July over the Caribbean Sea. This was in accordance with the observed precipitation over Mexico: below normal in the west and north and above normal in the south and southeast. The number of tropical perturbations in both oceans was well below normal and they did not directly affect Mexico.

2) 700 MB TO 500 MB (FIG. 8)

There are some pattern differences from the lower layer; maximum values are found over the southern tropics (western Brazil). It can be seen how a maximum PW develops over the Gulf of Mexico, as northern summer evolves, reaching the south and central parts of the United States and Mexico by July. Note the relatively low values over the central equatorial Pacific (~6.5 mm), and over the Andes. In this layer, the zonal advection of water vapor from the Atlantic Ocean is quite evident. As the easterly moist flow penetrates the Mexican plateau the altitude effect predominates.

In May, a maximum core of the order of 11 mm is located over the Amazon and is related to the high convective activity characteristic of northern Brazil. The Northern Hemisphere middle latitudes indicate subsidence associated with the anticyclones over the Pacific and Atlantic oceans. During June the maximum shifts northward from the Amazon to Venezuela and Colombia, and the moist tongue (~10 mm) prolongates toward southern Mexico. For July, a sharp increase of PW over Mexico and a decrease over northern South America and the Caribbean Sea occur. In August

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FIG. 8. As in Fig. 7 except for the 700–500 mb layer. Contour interval is 1 mm.
a weakening (relative to July) is detected over North America and Mexico.

3) 500 MB TO 300 MB LAYER (FIG. 9)

The monthly patterns observed in this layer are similar to those obtained for the 700–500 mb layer: relatively high values over Brazil and a high center developing over Mexico as summer evolves. During May, the maximum concentration (≈ 3.8 mm) lies over the Amazon, extending northward to the Caribbean Sea. In June, a relatively homogeneous field exists in which the maximum is shifted toward Central America.

b. Monthly mean fields of the 1000 mb wind components

The 1000 mb level wind is a rather interesting field, both from the meteorological and oceanographical points of view, since all of the air–sea interaction processes directly depend on it. Because anomalous features with respect to climatology will be pointed out, the reader is referred to the studies of Hastenrath and Lamb, 1977; Izawa, 1972; and Goldenberg and O'Brien, 1981 for a detailed description of the climatological surface wind field. Shaded areas on Figs. 10 and 11 refer to southward and westward flow for the meridional (v) and zonal (u) wind component, respectively.

The equatorial trade winds meet in a well-defined belt or zone of confluence. This zone of confluence, over the eastern Pacific, constitutes a discontinuity between the northeasterly trades and a broad southeasterly flow originating in the Southern Hemisphere (Hastenrath and Lamb, 1977). It can be seen, for the meridional flow on Fig. 10, that the trade winds from the Southern Hemisphere intensified slightly, resulting in the zone of confluence during summer 1979 occurring south of its climatological position (Reyes and Vogel, 1981). This is also associated with the below normal tropical storm season for the eastern tropical Pacific, where a total of 9 tropical disturbances of storm strength occurred, compared with a yearly average of 15 (Gutierrez, 1980). This was evident during August, when the northerly winds totally covered central and south America, restraining the influence of the southerly trades on tropical perturbation formation. (See Table 1.) The zonal flow (Fig. 11) is more homogeneous than the meridional flow. Westward maximum speeds are of the order of 5 m s⁻¹, with cores located over the Caribbean Sea and over the subtropical highs of the southeast and northeast Pacific. Note that over the central part of the domain a latitudinal narrowing occurs from July to August.

The persistence of the wind (Fig. 12), defined as the percentage ratio of the wind magnitude to the monthly mean wind speed, shows three major high persistence (85%) zones, corresponding to the subtropical anticyclones of the south and northeastern Pacific and the Caribbean Sea regions; low persistence (<85%) zones are located over the equatorial belt in the east Pacific and over continental America. These results follow the climatological pattern observed by Hastenrath and Lamb (1977) for the Caribbean Sea and by Izawa (1972) over the eastern Pacific. Nevertheless, some important differences are noticed: 1) over the Caribbean Sea, Hastenrath and Lamb detected a northward displacement of the high persistence zone, while the observed data for 1979 show a quasi-stationary pattern with strong discontinuities over the eastern part of Central American and a rapid retreat to the south from August to September; 2) over the eastern Pacific, the persistence reached a minimum (<50%) during the
months of July and September covering a wide area from the equator to Mexico. This pattern broke down during August, when the minimum persistence reached values of the order of 75%. At this point, recall from Figs. 10 and 11, and Table 1 that August was also associated with a rather anomalous flow circulation, with only two tropical perturbations observed in the Pacific and one in the Atlantic oceans.

4. Water vapor surface flux

Twice-daily time series of meridional and zonal water vapor surface (1000 mb) flux have been calculated by means of the following expression (Cadet and Reverdin, 1981):

\[ F = \rho l q V, \]  

(1)

where \( \rho \) is density of the air, and \( q \) (specific humidity at 1000 mb) is obtained from the PW values in the three layers by a cubic spline interpolation; \( V \) is the meridional or zonal component of the 1000 mb wind field and \( l \) is the length of the horizontal segment (10 degrees long). The mean flux of water vapor over space \([F]\) is given by:

\[ [F] = [\rho q v l], \]  

(2)

where the brackets denote space mean.
Table 1. Climatological mean of tropical storms and hurricanes 1953–83, and the values for 1979 for the Pacific and the Atlantic oceans.

<table>
<thead>
<tr>
<th>Month</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
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<td>Pacific</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Total (1961–83)</td>
<td>8</td>
<td>64</td>
<td>87</td>
<td>92</td>
<td>70</td>
<td>45</td>
<td>7</td>
<td>373</td>
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<tr>
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<td>2.8</td>
<td>3.8</td>
<td>4.0</td>
<td>3.0</td>
<td>1.9</td>
<td>0.3</td>
<td>16.2</td>
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<tr>
<td>1979</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td></td>
<td>9</td>
</tr>
<tr>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (1961–83)</td>
<td>8</td>
<td>28</td>
<td>34</td>
<td>58</td>
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<td>243</td>
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<tr>
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<td>1.5</td>
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<td>8</td>
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</table>

Time series of water vapor surface flux for the period 1 May–15 September 1979 have been computed for 35 longitudinal segments and for 32 latitudinal segments. As an example, we present only the time series obtained for a rectangular grid comprising Mexico. Note that these computations refer to space-averages over every 10 degrees for each segment. Positive/negative values correspond to northward/southward and eastward/westward fluxes, respectively. Figure 13 shows time series of the mean total flux for the southern (segments 1, 2 and 3), eastern (4 and 5), northern (6, 7 and 8) and western (9 and 10) boundaries around the Mexican region. One of the most interesting features is the appearance of a net northward flux over the southern boundary, indicating the seasonal northward shift of the trade winds, as northern summer evolves. The largest fluxes appear over the northeastern area (segments 5 and 6), showing the important penetration of northwestern flow over the northern portion of the Gulf of Mexico. This is in good agreement with the results of Hastenrath and Lamb (1977) and Rasmussen (1967). Segments 1, 2 and 10 also show an important transfer of water vapor over the eastern tropical Pacific toward the southwest during May and June, but a noticeable reversal to northward flux for July and August. Note that during August a northwestward flux is observed, showing a break in the Pacific surface flux toward Mexico.

The large fluxes observed across these five segments give an indication of the influence of evaporation from the adjacent ocean areas. Hastenrath and Lamb (1978), in their heat budget study of the tropical Atlantic and eastern Pacific oceans, show rather large latent heat values on the order of 140 and 160 W m$^{-2}$ for the Caribbean Sea and the eastern equatorial Pacific, respectively. On the other hand, segments 3 and 4, al-

![Fig. 12](image-url)
though over tropical regions, show weaker low-level fluxes of water vapor: this could be explained by the nearness of the continental land, the associated low persistence, and the low wind speed observed for this region. (See Figs. 10, 11 and 12.) Segments 8 and 9 show relatively less southwestward flux of water vapor. This region is strongly influenced by the midlatitude high pressure belt and the presence of the cold California current, which is associated with strong subsidence and a very shallow moist boundary layer. Finally, segment 7 shows very weak water vapor flux. This is a direct result of the continental influence on the surface atmospheric water field.

5. Conclusions

Mean monthly characteristics of precipitable water over the tropical Americas during May–August 1979 have been studied using twice-daily assimilated data fields. TIROS-N satellite data, bogus estimates of PW from cloud images and level III-b data sets have been combined to obtain fields of precipitable water in three layers: surface–700, 700–500 and 500–300 mb. The surface (1000 mb) fluxes of water vapor, through different latitudinal and longitudinal segments around the Mexican domain, were also calculated.

For the Mexican region in particular, 1979 was characterized by below normal temperature conditions during winter and summer (Servicio Meteorológico Nacional, 1979); consequently, the associated low pressure system was also weaker. This, along with a weaker flow over the southeast Pacific, resulted in a weak and unsteady cross-equatorial flow, which, in turn, did not allow strong evaporation from the ocean, necessary for the development of tropical storm perturbations and high atmospheric water content.

The main results of this study are

1) The general monthly patterns of precipitable water were characterized by the development of moist tongues over the eastern Pacific and western Atlantic, as northern summer evolved.

2) The surface–700 mb layer of precipitable water showed the strong influence of the land and ocean. Low moisture amounts were found over the Andes and Rocky Mountain chains, and higher amounts were found over the northwestern Atlantic than over the northeastern Pacific.

3) The 700–300 mb layers gave evidence of the low-level convergence generated by the strong convective activity characteristic of northern Brazil and Mexico.

4) The largest quantities of mean total surface water vapor flux were found over the Gulf of Mexico and the eastern tropical Pacific Ocean.

5) The fluctuations of the northwestern surface flux over the eastern tropical Pacific were related to the break in precipitation over Mexico and to the small number of tropical perturbations that developed during the northern summer of 1979.

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