THE CLIMATOLOGY OF THE SUB-TROPICAL JET STREAM ASSOCIATED WITH RAINFALL OVER EASTERN AUSTRALIA

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ABSTRACT

Seasonal mean 200 mb charts were constructed corresponding to widespread rains in two regions of eastern Australia for a period of 10 years, and mean geostrophic vorticity advection fields found from them. These were related to surface weather patterns, the amount and distribution of rain, and comparisons made between seasons and classes of rainfall episodes.

1. INTRODUCTION

In the Northern Hemisphere the close association between the polar front jet and the rainfall belts in this hemisphere has been the object of a number of studies. However, with one or two exceptions, these studies have been directed more towards the value of the upper air patterns for the forecasting of rainfall, rather than the climatological aspects of the phenomena. Moreover, these studies (climatological or otherwise) were primarily concerned with the polar front jet and little work has been done in relation to the sub-tropical jets of either hemisphere.

Current meteorological theory indicates that there should be areas of divergence in the upper troposphere, at the right front and left rear quadrants of a velocity maximum, in the case of westerly jets in the Southern Hemisphere. The strength and distribution of this divergence field depends on both the curvature of flow and on the windshear. While any jet maximum has this characteristic distribution, its effects at the surface are usually much greater in the case of the polar front jet than for any other jet. Nevertheless, in individual situations the sub-tropical jet displays the same associations between upper level divergence and vertical motion, and may be expected to show some relationship with rainfall patterns.

This paper reports on an investigation into the role of the sub-tropical jet, over eastern Australia, in producing upper divergence coupled with the ascending motion necessary for rainfall in this region of the continent. Particular attention was paid to preferred geographic location and to seasonal changes in position and strength.

2. LOCATION OF THE STUDY

The regions taken to represent rainfall along the eastern seaboard were chosen because of their location with respect to the mean position of the sub-tropical jet. The southern region (Region 1) is the Hunter Valley drainage basin, which lies about 4.5° south of the mean jet latitude. The second region (Region 2) consists of the drainage basin of the Brisbane River and lies very near the mean jet latitude.

The period of rainfall and jet stream activity considered in this investigation runs from December 1955 to November 1965, the data used being daily rainfall records from 24 stations and positive microfilm copies of the 2300 GMT 200 mb charts prepared by the Central Analysis Office of the Bureau of Meteorology.

This study deals only with rainfall episodes in which falls occur over large areas, and it is assumed that conditions over the area are conducive to rain during all or part of this time, that is, there is widespread destabilization of the lower troposphere because upward motion is in progress. Such widespread upward motion can only be the result of dynamic processes within
the large scale air flow and the Dines' compensation has been assumed to hold in each of the
rain episodes investigated.

Maximum values of divergence are found at the level of maximum wind in the upper
troposphere in association with jet streams, or more particularly, with individual jet maxima.
The sub-tropical jet stream is generally located above the sub-tropical high pressure belt,
showing on the average, upper convergence and sinking motion. In individual cases, however,
the same relations between vorticity advection, divergence and vertical motions apply as they
do with the polar front jet.

3. THEORY OF THE APPROACH

To make an assessment of the role of the sub-tropical jet in the development of
widespread rainfalls, geostrophic vorticity advection fields at the 200 mb level were computed
for each rain episode. This quantity, rather than divergence, was used because, although the
computed geostrophic vorticity values at low latitudes were rather inaccurate, larger errors
occur in the direct calculation of values of divergence than in values of vorticity advection.

The evaluation of the geostrophic vorticity advection fields corresponding to rainfall
episodes was based on the geostrophic form of the vorticity equation. In the general case, if
\( Q \) is the absolute vorticity and \( \mathbf{V} \) is the wind, this equation can be written as:

\[
\frac{dQ}{dt} = -Q \cdot \mathbf{V} + A + B
\]

In the context of this study this can be simplified to the autobarotropic case, that is, the vortex-
tube and solenoidal terms \( A \) and \( B \) can be neglected. This is permissible, to a first approxima-
tion, because air mass contrasts in the area are usually not pronounced (and only mean situations
are considered) and in the developmental stages, before vertical motion becomes well established,
the atmosphere is quasi-barotropic.

Thus:

\[
\frac{dQ}{dt} = -Q \cdot \mathbf{V}_H
\]

the subscript \( H \) denoting the horizontal wind.

But \( \frac{dQ}{dt} \) may be expanded as:

\[
\frac{dQ}{dt} = \frac{\partial Q}{\partial t} + u \frac{\partial Q}{\partial x} + v \frac{\partial Q}{\partial y} \quad \text{for horizontal motion,}
\]

\[
= \frac{\partial Q}{\partial t} + \mathbf{V}_H \cdot \mathbf{V}_H \ Q
\]

At 200 mb, particularly when the jet stream is present, the wind velocity is much greater than
the wave velocity, so that \( \frac{\partial Q}{\partial t} \) is small. During the developmental stages of a disturbance,
the vorticity advection is large, so that \( \frac{\partial Q}{\partial t} \) may be neglected by comparison;

\[
\text{i.e.} \quad \frac{dQ}{dt} = \mathbf{V}_H \cdot \mathbf{V}_H \ Q
\]
Therefore, from above

\[ \mathbf{v} \cdot \mathbf{v}_H = -\frac{1}{Q} \mathbf{v} \cdot \mathbf{v}_H Q. \]

It can be seen that the vorticity advection associated with the horizontal wind provides a measure of the divergence field at the 200 mb level.

The accuracy of the geostrophic approximation is determined by the magnitude of the relative vorticity \( \zeta \) in comparison with that of the Coriolis parameter \( f \).

If these are the same size, then the error in the absolute vorticity \( Q \) is approximately 25 percent (Petterssen, 1953). In fact, the values of \( \zeta \) obtained here were generally less than \( f \) at the appropriate latitude.

It must be emphasized that the only cases discussed here are those in which rain fell over a considerable area, that is, the assumption is made that other conditions necessary for rainfall are present.

### 4. Method

In attempting to relate rainfall to upper air flow, an index of rainfall which measures only widespread falls was selected. To accomplish this, the notion of a rainfall episode is used, in the formal sense as defined by Riehl and Elsberry (1964). This implies areally integrated precipitation, extending over some defined time period. The basis of the rainfall episodes is daily rainfall at each station. However, most of the stations recorded only 48-hour totals over weekend periods. Such 48-hour totals were apportioned in the ratio given by the nearest station recording 24-hour totals. Other missing records were interpolated using the method of Conrad and Pollack (1950). The results are shown in Table 1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Areal Rain (Inches)</th>
<th>Areal Rain from Episodes &gt; 60 points (Inches)</th>
<th>Number of Episodes &gt; 60 points</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Region 1</td>
<td>Region 2</td>
<td>Region 1</td>
</tr>
<tr>
<td>1956</td>
<td>36.6</td>
<td>49.6</td>
<td>19.1</td>
</tr>
<tr>
<td>1957</td>
<td>16.1</td>
<td>26.2</td>
<td>5.7</td>
</tr>
<tr>
<td>1958</td>
<td>26.8</td>
<td>32.3</td>
<td>14.6</td>
</tr>
<tr>
<td>1959</td>
<td>33.5</td>
<td>48.3</td>
<td>21.1</td>
</tr>
<tr>
<td>1960</td>
<td>25.5</td>
<td>28.2</td>
<td>9.0</td>
</tr>
<tr>
<td>1961</td>
<td>28.6</td>
<td>32.3</td>
<td>17.2</td>
</tr>
<tr>
<td>1962</td>
<td>32.5</td>
<td>33.2</td>
<td>21.2</td>
</tr>
<tr>
<td>1963</td>
<td>41.3</td>
<td>37.8</td>
<td>24.6</td>
</tr>
<tr>
<td>1964</td>
<td>28.7</td>
<td>37.3</td>
<td>16.8</td>
</tr>
<tr>
<td>1965</td>
<td>15.2</td>
<td>27.6</td>
<td>5.7</td>
</tr>
<tr>
<td>TOTAL</td>
<td>286</td>
<td>353</td>
<td>155</td>
</tr>
</tbody>
</table>
The minimum daily areal precipitation considered associated with large scale weather disturbances was arbitrarily set at 60 points. This figure was chosen because it limited the number of cases to manageable proportions, but at the same time provided a reasonably good measure of the total annual areal rain over the regions. This is indicated by the high correlations in the first line of Table 2. This table also gives correlations between total areal rain and the total number of rain days as well as with the number of episodes with rain greater than 60 points.

Table 2. Rank Correlations between total areal rain and some sampling measures - for 10 year period

<table>
<thead>
<tr>
<th></th>
<th>For 10 years</th>
<th>Region 1</th>
<th>Region 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Episode Rain, Episodes &gt; 60 points</td>
<td>0.94</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>Total No. of Rain Days</td>
<td>0.88</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>No. of Episodes &gt; 60 points</td>
<td>0.79</td>
<td>0.91</td>
<td></td>
</tr>
</tbody>
</table>

These rainfall episodes of more than 60 points were then divided into two groups, those over 120 points and those less than 120 points (see Table 3). Again this division is arbitrary but was made because it was felt that real differences between large and small storms, both in terms of upper air flow and surface weather processes, were likely. This later proved to be the case.

Table 3. Mean Magnitude, Intensity and Length of Episodes* over 10 years

<table>
<thead>
<tr>
<th>Season</th>
<th>Region 1</th>
<th>Region 2</th>
<th>Region 1</th>
<th>Region 2</th>
<th>Region 1</th>
<th>Region 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60pts &lt; Episodes ≤ 120 pts</td>
<td>Episodes &gt; 120 pts</td>
<td>60pts &lt; Episodes ≤ 120 pts</td>
<td>Episodes &gt; 120 pts</td>
<td>60pts &lt; Episodes ≤ 120 pts</td>
<td>Episodes &gt; 120 pts</td>
</tr>
<tr>
<td>Summer</td>
<td>Mean</td>
<td>92</td>
<td>196</td>
<td>91</td>
<td>216</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intensity</td>
<td>37.9</td>
<td>65.8</td>
<td>45.3</td>
<td>56.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>2.4</td>
<td>3.0</td>
<td>2.0</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>Autumn</td>
<td>Mean</td>
<td>87</td>
<td>223</td>
<td>89</td>
<td>217</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intensity</td>
<td>35.7</td>
<td>70.8</td>
<td>39.4</td>
<td>62.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>2.4</td>
<td>3.2</td>
<td>2.3</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>Mean</td>
<td>92</td>
<td>142</td>
<td>88</td>
<td>224</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intensity</td>
<td>34.6</td>
<td>42.6</td>
<td>48.6</td>
<td>105.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>2.7</td>
<td>3.3</td>
<td>1.3</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td>Mean</td>
<td>93</td>
<td>148</td>
<td>85</td>
<td>192</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intensity</td>
<td>41.5</td>
<td>59.3</td>
<td>35.6</td>
<td>69.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>2.2</td>
<td>2.5</td>
<td>2.4</td>
<td>2.8</td>
<td></td>
</tr>
</tbody>
</table>

* Mean Magnitude in points; Intensity in points per day; Length in days.
The selection of the 200 mb charts corresponding to each episode is based on the high
degree of association between the amount of rain falling on the wettest day of each episode and
the total magnitude of the episode. The product moment correlation between these two is 0.85
for the Hunter Valley and 0.81 for the Brisbane River Valley, both highly significant. That is,
if the day of greatest rainfall in an episode ends at 9 a.m. on, say, the 16th, the corresponding
200 mb chart is taken to be the one for 9 a.m. on the 15th.

The 200 mb charts chosen by the above method were then checked and the latitude of
the maximum wind zone noted. This checking process verified the choice in over two-thirds of
the cases. To resolve questions about the remainder they were checked against the corresponding
700 mb and surface charts. This resulted in the elimination of 20 percent of the total number
of episodes. There were three types of episodes eliminated - tropical cyclones, no recognizable
or significant features at the 200 mb level and those episodes occurring in conjunction with anti-
cyclonic flow at 200 mb. Only the last of these is numerically important, comprising about
15 percent of the total storms in both regions. They were not considered because separately
there were insufficient to form mean height charts in each season, and including them in mean
charts of upper trough situations would have been meaningless. Seasonal means of the remaining
200 mb charts were prepared for the 10-year period.

During the preliminary analysis the latitude of the zone of maximum wind was noted
and hence a mean latitude for each season and class found. This was used in the positioning
of the grid in later analysis, by placing a fixed reference point on the grid at this mean latitude for
each case. This method was adopted rather than that of placing the grid at the most appropriate
latitude for each episode, because in a number of cases the 200 mb troughs were at such a low
latitude that the grid points to the north fell within 10 or 15 degrees of the equator, much too
close for a geostrophic analysis. The above method is far from desirable; however, it does
allow some account of seasonal variation in latitude to be taken.

The mean longitude for each composite chart was found from the longitudes of each
of the wave troughs at 200 mb, but in this case the reference point of the grid was placed at the
appropriate longitude for each episode.

Because jet latitudes oscillate, averaging with respect to space fixed coordinates
leads to a flattened wind profile and a positive vorticity centre to the south of the mean jet core.
To determine the extent of this effect on the mean charts corresponding to each rainfall episode,
a random sample of single charts from all the different episode groups was analysed and the
distance of the vorticity maxima south of the wind maxima measured. The average value for
these random cases was 6.8° south of the jet core, while for the episode mean charts the average
was 7.9°. Hence it appears that the mean charts can be considered to be a reasonable
representation of the situation in individual cases.

The analysis was based on a grid suggested by Sawyer and Matthewman (1951) with a
spacing of 200 nautical miles. The original grid was rectangular with 10 x 11 points and was
constructed to a scale of 1:20,000,000 to correspond to the normal working charts. Some small
errors arise because scale variations across the map alter with change in position of the grid,
but these are minor. The positive microfilm maps were projected onto this grid, scales being
matched, and heights read off for each point.

5. RESULTS

The results of the analysis are displayed below in Table 4 and in the accompanying
maps. For reasons of space not all the maps used have been reproduced here.
Table 4. Seasonal (Summer = S, etc.) maximum values of the Mean Geostrophic Wind, Mean Vorticity and Mean Vorticity Advection at 200 mb*

<table>
<thead>
<tr>
<th>Episode Group</th>
<th>Region 1</th>
<th></th>
<th>Region 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of Episodes</td>
<td>V Max.</td>
<td>GV Max.</td>
<td>GVA Max.</td>
</tr>
<tr>
<td>S</td>
<td>19</td>
<td>73</td>
<td>14.3</td>
<td>20.7</td>
</tr>
<tr>
<td>A (a)* W</td>
<td>13</td>
<td>89</td>
<td>15.1</td>
<td>30.6</td>
</tr>
<tr>
<td>S</td>
<td>4</td>
<td>117</td>
<td>15.8</td>
<td>36.4</td>
</tr>
<tr>
<td>A (b)* W</td>
<td>4</td>
<td>85</td>
<td>14.2</td>
<td>13.9</td>
</tr>
</tbody>
</table>

* V = Wind Speed in knots  
GV = Geostrophic Vorticity \(\times 10^{-5} \text{ sec}^{-1}\)  
GVA = Geostrophic Vorticity Advection \(\times 10^{-10} \text{ sec}^{-2}\)  
* (a) = Episodes > 120 pts  
(b) = 60 < Episodes < 120 pts  
GVA\+ Location of the maximum GVA derived from the corresponding seasonal mean height chart.

In cases of cyclonic curvature, which is the case with the maps analysed, the geostrophic approximation leads to an overestimate of both the wind and the vorticity. Thus the advection of geostrophic vorticity can often be grossly exaggerated. Petterssen (1953) obtained values of over \(200 \times 10^{-10} \text{ sec}^{-2}\) and Dixon (1964) values of \(150 \times 10^{-10} \text{ sec}^{-2}\) for individual storm cases, both these being much larger than likely actual values. Petterssen shows that real values may be only 25 percent of calculated geostrophic values. Values obtained in this study are much less because of the effects of averaging over a number of storms.

(a) Summer Rain Episodes – December, January, February

The dominance of different processes in determining the occurrence and production of rainfall in different seasons is well illustrated by the fact that the geostrophic vorticity advection for summer is low, despite this being the season of greatest rainfall. Two cases are illustrated by Figs. 1, 2. The two most important factors contributing to higher summer rainfall are greater atmospheric moisture and stronger surface heating. The decrease in stability of the lower atmosphere in both regions is most marked during the summer and little correlation between rainfall activity and large scale vertical motion can be expected, particularly during the daytime. However, the mean vorticity fields for the summer seasons do show positive values over the rain areas, which are sufficient to produce destabilization in the atmosphere and allow the vigorous development of convective processes to occur, with widespread rains should conditions be suitable.
Values in excess of $20 \times 10^{-10} \text{ sec}^{-2}$ occur over the Hunter Valley region for summer episodes greater than 120 points, this being sufficient to promote the development of large scale vertical motion over this region. The smaller rain episodes are associated with somewhat lower values and this difference is reflected in the mean intensity of the rainfall on a daily basis, that is, the mean intensity expressed as points per episode day. For the larger episodes the intensity is 66 points/day and for the smaller 38 points/day.

There is a marked difference in the surface synoptic features associated with the two different classes of episodes. Those of more than 120 points most frequently occur after the development, near the region, of a low pressure centre. Although these may develop inland, heavy falls usually occur after the systems have moved east across the coast and intensified, and this is consistent with the mean field of vorticity advection displayed in Fig. 1. The smaller episodes occur on the other hand in cases where there is no dominating feature.

Over the Brisbane River region, the 200 mb vorticity advection patterns are similar, but weaker. These smaller values suffice because the region is further from the mean summer latitude of the sub-tropical highs and because both surface heating and atmospheric moisture content are greater, and therefore, more active in promoting convective development. Episodes of more than 120 points have a mean intensity of 56 points/day, somewhat lower than the southern region. Since the vorticity advection field is weaker this indicates that the upper-air processes are important in determining the magnitude of the episodes (at least on the large scale), if not the frequency of their occurrence. On the other hand, the mean intensity for the class of smaller episodes is 45 points/day - greater than in the south - despite the fact that the vorticity advection field is weaker. This increase in intensity can be entirely attributed to the greater instability and higher moisture content over the northern region.

(b) Autumn Rain Episodes — March, April, May

The most striking feature of rainfall in eastern Australia during autumn is the relatively frequent occurrence of heavy falls in the coastal zone as a result of the development of what are known as east coast cyclones (Clarke 1956, Kraus 1954). These low pressure systems may develop over the ocean, just east of the continent, but more usually develop well inland in south-west Queensland. In this latter case the centres move in a general south-easterly direction and on crossing the coastline intensify rapidly. Over the southern region, for the 10 year period, 42 percent of the heavy rainfalls occurred as a result of these cyclonic storms.

The development of such systems is amply indicated by the mean vorticity advection field for this season (Fig. 3), where the maximum value of more than $30 \times 10^{-10} \text{ sec}^{-2}$ occurs well inland over south-west Queensland. The stronger vorticity advection fields, together with the still unstable and moist atmosphere, lead to a higher mean intensity of 71 points/day.

On the other hand, the small rainfall episodes over the Hunter Valley region in this season have a lower intensity than in summer and are usually associated with the passage of a cold front or trough in the westerlies. The distribution of vorticity advection in this case (not shown) indicates a secondary maximum well to the south.

Over the northern region, rainfall episodes are similar to those of summer in the case of those between 60 and 120 points (Fig. 4). The larger episodes, however, show a greater intensity of 63 points/day to match the increase in strength of the vorticity advection field, which has a maximum value of over $25 \times 10^{-10} \text{ sec}^{-2}$.

(c) Winter Rain Episodes — June, July, August

Winter is the driest season in both regions, and over the span of 10 years only relatively few episodes occurred. Because the westerly wind circulation is so strongly developed during this season, the inter-regional contrasts are the most striking. Compared to other seasons the number of days with rain is much greater to the south of the mean jet, but the intensities are much lower. This again reflects the influence of moisture availability on storm occurrence and size, because it is during the winter with greatly increased upper wind-speeds that the highest values of vorticity advection occur.
Fig 1. 200 mb Geostrophic Vorticity Advection x 10^{11} sec^{-2}
Region 1, Episodes >120 points : Summer

Fig 2. 200 mb Geostrophic Vorticity Advection x 10^{16} sec^{-2}
Region 2, Episodes >120 points : Summer
Fig 3. 200 mb Geostrophic Vorticity Advection x 10^{15} sec^{-2}
Region 1, Episodes >120 points: Autumn

Fig 4. 200 mb Geostrophic Vorticity Advection x 10^{15} sec^{-2}
Region 2, Episodes >60, ≤120 points: Autumn
In the northern region higher rainfall intensities occur indicating the strength of the westerly circulation, but at the same time the episodes are considerably shorter than in other seasons so that episode size is much the same as in summer and autumn. These much higher rainfall intensities occur over the Brisbane region during winter, because the air is still relatively moist in these more northerly latitudes and because the jet stream associated with them is in lower latitudes, with higher wind speeds (Fig. 5).

In both regions, the larger episodes arose from the activity of a surface low nearby. The smaller episodes on the other hand usually occurred in a southerly stream in the rear of a low centred out over the ocean. This difference is reflected in the vorticity advection fields which show positive centres over the regions for the larger episodes, but in the case of the smaller the positive centres are well to the east (Figs. 6, 7, 5, 8).

(d) Spring Rain Episodes – September, October, November

In general, the vorticity advection fields during spring episodes are similar in magnitude to those of autumn, but spring is also a dry season and rainfall episodes are not nearly so frequent.

Most episodes in spring are associated with the passage over the regions of a surface cold front or trough, whereas during autumn this event is much less common.

Only four episodes of more than 120 points occurred in 10 years over the southern region, but the number of smaller episodes was much larger. Both classes have short mean durations compared to the other seasons, the cause of this being the strong association of these episodes with surface troughs. This short mean duration of the storms means that the intensity is rather high, particularly in the case of the smaller storms - 42 points/day.

Episodes over the Brisbane region during this season are similar to those of the southern region and again occur most often with the passage of a cold front. However, the falls are confined mostly to the northerly stream ahead of the trough or to the actual front itself, whereas to the south the falls often occur after the front has passed, in a southerly air stream.

The vorticity advection fields (Figs. 9, 10) are very similar to those of autumn in magnitude and latitude, but have their maximum values somewhat closer to the coastline. Since most autumn rains over this region result from low pressure centres or easterly troughs, many of which lie well inland over northern Queensland, this difference is to be expected.

6. CONCLUSIONS

A very large proportion of significant rainfall episodes in eastern Australia occur in advance of 200 mb troughs, which have preferred longitudinal positions for the two regions considered. Episodes in the Newcastle region occur most frequently with a trough lying near 143°E, while for the Brisbane region the preferred longitude is 145°E. However, the distribution of trough longitude differs between these two in that troughs corresponding to episodes over the Brisbane region have a much more closely clustered distribution, while those over the south are more scattered and tend to fall into two groups, one centred at about 142°E, the other at 150°E. This is a direct result of the different surface systems associated with rainfall in the two regions, rain associated with frontal passages being much more important to the south.

Generally the vorticity advection fields vary in strength and position with seasonal changes in the general circulation. At the same time changes in position of the maxima in the fields correspond to the changes in rainfall producing systems at the surface.

It would seem that an evaluation of the changes in frequency and intensity of rain systems could be made in the future, when the number and length of records are such as to allow real rather than geostrophic evaluations, and to allow comparisons between the general flow, its annual fluctuations, and the individual and mean flows associated with rain episodes.
Fig 5. 200 mb Geostrophic Vorticity Advection x 10^{12} sec^{-2}
Region 2, Episodes > 120 points - Winter

Fig 6. 200 mb Geostrophic Vorticity Advection x 10^{15} sec^{-2}
Region 1, Episodes > 120 points - Winter
Fig 7. 200 mb Geostrophic Vorticity Advection $\times 10^{15}$ sec$^{-2}$.
Region 1. Episodes $>60$, $\leq 120$ points: Winter

Fig 8. 200 mb Geostrophic Vorticity Advection $\times 10^{15}$ sec$^{-2}$.
Region 2. Episodes $>60$, $\leq 120$ points: Winter
Fig 9. 200 mb Geostrophic Vorticity Advection x 10^16 sec^{-2}
Region 2, Episodes >120 points : Spring

Fig 10. 200 mb Geostrophic Vorticity Advection x 10^16 sec^{-2}
Region 2, Episodes >60, ≤120 points : Spring
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